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DECARBONIZING THE U.S. INDUSTRIAL SECTOR

Regional, economic, and technical realities

Nader Sobhani
Climate Policy Associate | Niskanen Center
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Abstract

Fully decarbonizing U.S. industry is essential to achieving net-zero greenhouse gas (GHG) emissions by midcentury. This paper evaluates the regional, economic, and technical realities of decarbonizing U.S. industry in order to inform state and federal strategies to address this category of emissions.

The analysis focuses on reducing emissions from four industrial sectors: 1) chemicals, 2) metals, 3) minerals, and 4) pulp & paper manufacturing. It identifies three key technologies that are critical to reducing industrial GHG emissions across these sectors: 1) carbon capture, 2) electrification, and 3) zero-carbon hydrogen.

Previous research has found that the viability of these technologies will be influenced by local characteristics such as the availability of low-cost zero-carbon electricity, carbon storage resources, and supportive infrastructure. Thus, strategies to reduce industrial GHG emissions will vary widely among sectors and regions. This analysis builds upon previous research to better understand how decarbonization strategies might vary across U.S states and regions. A key insight is that the abundance of carbon storage resources and CO2 pipelines in the Gulf Coast make carbon capture and sequestration a viable technology for industrial facilities located in this region, while abundant and low-cost renewable electricity can be used to electrify production processes or produce zero-carbon hydrogen to reduce emissions from industrial facilities in the Midwest.

This work does not attempt to estimate the economic impact of the transition to a low-carbon industrial system. However, information on how much each industry contributes to state GDP and to state-and county-level employment is presented to provide context for the amount of economic activity these sectors provide in relevant regions. Many counties and states still rely on the manufacturing sector as an important source of GDP and employment.

Well-designed policies can accelerate innovation and deployment for a wide array of technologies by taking advantage of regional industrial characteristics and resources. A comprehensive federal and state policy context will help industries decarbonize by leveraging the CO2 storage capacity and cheap renewables where they are most available, and will create a robust innovation environment to move pilot-phase technology to commercial markets. This analysis provides a foundation for developing these critical policies and partnerships.

Contents

Overview

Decarbonizing the industrial sector is critical if we are to mitigate the most dangerous impacts of climate change, but doing so remains one of the most complex challenges. The industrial sector's emissions are large and diverse and come from a variety of manufacturing processes. Moreover, the sector is an important source of economic activity for countries and regions around the world, and manufacturers often operate on tight profit margins.

Industrial activities such as manufacturing and construction are responsible for nearly a third of global greenhouse gas (GHG) emissions.[1] The industrial sector is also the largest source of emissions in the U.S. when accounting for its electricity use. The nearly 2 billion metric tons of carbon

1. Hannah Ritchie and Max Roser, "Emissions by Sector," Our World in Data, 2016.

dioxide equivalent (CO_{2e}) it contributed to U.S. emissions in 2018 represented roughly a third of the nation's total.[2]

Industrial emissions come from a broad range of industries that manufacture steel, cement, chemicals, fertilizer, glass, paper, and a multitude of other materials. The greenhouse gases contributed by industrial production are accounted for in two main categories, direct and indirect. Direct emissions come from the on-site combustion of fossil fuels for heat or power or are emitted as byproducts of industrial activities.[3] Indirect emissions come from commercial power plants that are burning fossil fuels for use by an industrial facility. Even if commercial power generation produced zero carbon, direct emissions from industry would still be responsible for about 20 percent of U.S. emissions.[4]

The industrial sector is a major employer and contributes roughly 15 percent of U.S. GDP.[5] The industrial sector is composed of commodity industries that operate on very tight margins and are highly exposed to international competition, meaning a slight change in production costs could have serious implications for these firms. Additionally, industrial facilities are long-lived critical assets worth billions of dollars, so the potential for stranded assets i.e., "assets that at some time prior to the end of their economic life are no longer able to earn an economic return" in this sector is high. [6]

There is also opportunity. The industrial sector is central to developing the clean energy technologies of the 21st century such as renewables, carbon capture technologies, electric vehicles, and energy-efficient buildings.[7] Achieving net-zero GHG emissions by 2050 necessitates fully decarbonizing industry, and doing so will require effort by all levels of government.

The U.S. electricity sector offers a prime example of how the interaction of state and federal policies can spur significant emission reductions. Federal tax credits for wind and solar have helped propel these technologies forward, driving investment into the renewable energy industry.[8] The growth of the renewable energy industry can also be attributed to state clean electricity standards (CES). 29 states have some form of CES requiring a "certain percentage of retail electric sales to come from renewable and other eligible clean sources."[9] The interaction of these two policy levers has helped the price of wind and solar resources drop by 70 and 90 percent over the last decade.[10] Over the same period, wind and solar technologies grew from supplying less than 2 percent of total U.S. electricity to supplying nearly 10 percent today, all while electricity sector emissions dropped

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2. U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks," 2020.

3. U.S. Environmental Protection Agency, "Sources of Greenhouse Gas Emissions."

4. Ibid.

5. Federal Reserve Bank of St. Louis "Value Added by Private Industries: Manufacturing as a Percentage of GDP."

6. Lisa Wong, "Can Green Bonds Help Us Manage Climate Risk," World Economic Forum, Oct. 25, 2018.

7. Chris Bataille et al., "Technologies and Policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070," Applied Energy, May 15, 2020.

8. Julia Pyper, "*Corporate Renewable Energy Deals Smash Records in 2018*," Greentech Media, October, 2019.

9. Dan Lashof and Lori Bird, "Insider: 29 States Have Clean Electricity Standards. Are They Good Policy?" World Resources Institute, May 21 2019.

10. Lazard, "Lazard's Levelized Cost of Energy Analysis-Version 14.9,"October 2020.

nearly 20 percent.[11] The combination of federal and state policies has helped bring down the costs of renewable energy technologies to the point where the private sector has begun investing and deploying these technologies at an unprecedented rate. The success the electricity sector has had in making renewable energy sources competitive and reducing GHG emissions should motivate policymakers to push for similar gains in the industrial sector.

In order to help guide policymakers, this paper develops a blueprint of the regional, technical, and economic realities of decarbonizing the U.S. industrial sector. The paper provides a bottom-up spatial analysis of industrial emissions and economic activity and highlights regional characteristics that suggest the technology strategies different parts of the country can pursue to decarbonize the U.S. industrial sector.

Methodology

This paper focuses on four main manufacturing sectors within the industrial category: chemicals, metals, minerals, and pulp & paper production. In 2018, these four sectors produced 435 million metric tons (MMT) of CO_2e, roughly one third of total U.S. industrial emissions.[12]

Data sources

This bottom-up analysis was conducted using 2018 data from the Environmental Protection Agency's Facility Level Information on Greenhouse Gases Tool (FLIGHT). The FLIGHT database contains data reported by over 8,000 facilities and covers roughly 85-90 percent of total U.S. emissions. It includes information on each facility's location, sector, subsector, and reported annual GHG emissions. This facility-level emissions data was aggregated to get estimates of county- and state-level emissions for the sectors analyzed. There are instances where one facility produces industrial GHG emissions in multiple sectors. Only GHG emissions from evaluated sectors were considered for each facility.

GHG emissions data was also paired with facility-level data on criteria air pollutants (CAP). The EPA's National Emissions Inventory point-source dataset was used to compile facility-level CAP emission levels for seven pollutants: nitrogen oxide, PM10, PM2.5, carbon monoxide, volatile organic compounds, ammonia, and sulfur dioxide. Facility-level CAP levels were also aggregated to the county level.

The economic footprint of the industrial sector is captured by using state-level Gross Domestic Product and employment levels for each of the sectors analyzed. GDP data was collected for each state and each industrial sector using the GeoFRED database provided by the St. Louis Fed and is represented as millions of chained 2012 dollars. Employment statistics were gathered from the Bureau of Economic Analysis' regional datasets and represent private nonfarm employment for each of the sectors analyzed. In order to normalize economic statistics across states, GDP figures represent millions of dollars provided by the sector for every $10 billion in GDP, while employment is represented as jobs in each sector per every 100,000 jobs. County-level employment figures were collected from the U.S. Census Bureau's Annual Economic Survey from 2017.

11. Energy Information Administration, "Electricity generation, capacity, sales in the United States," March 18, 2021.

12. EPA, "Facility Level Information on Greenhouse Gas Emissions Tool," 2018.

The combination of these datasets allows us to map and visualize both the environmental and economic footprint of U.S. industry. This mapping provides the necessary information to understand which decarbonization strategies different regions must focus on if we are to address industrial emissions.

Evaluating the realities of decarbonizing industry

An understanding of the geographic distribution of emissions across these sectors allows us to compile a list of targeted states and regions on which to focus decarbonization efforts. Doing so will give us a starting point from which to evaluate the regional, technical, and economic realities of decarbonizing U.S. industry, and help inform both state and federal policy strategies. Three key metrics will be used to better understand how each state with a significant footprint in the targeted sectors could reduce its industrial emissions.

1. **Emissions profile:** This analysis will break down the industrial sector of each of the analyzed states to better understand which sectors contribute most to the state's industrial emissions.
2. **Technical strategy:** Evaluating the technical opportunities and obstacles of reducing emissions within an industrial sector will require an understanding of what technologies currently exist to reduce emissions from that sector and which still need to be developed. The main technological pathways to reducing industrial emissions are based on an analysis conducted by McKinsey and are presented below.[13]
    a. **Energy-efficiency improvements:** Increases in energy efficiency can reduce costs and cut fuel consumption for energy use by 15-20 percent across sectors.[14]
    b. **Electrification of heat**: fossil fuels to generate heat can be replaced by switching to furnaces, boilers, and heat pumps that run on zero-carbon electricity. This could potentially eliminate all energy-related CO2 emissions associated with heat production.[15] Electrifying heat, however, will likely involve a change in production processes.
    c. **Electrolysis-derived hydrogen:** Fossil fuels used to generate heat and as certain feedstocks can be replaced with zero-carbon hydrogen. This strategy would require using zero-carbon electricity for the electrolysis of water to produce the hydrogen. For example, ammonia production could reduce its emissions footprint more than 90 percent by replacing the natural gas feedstock with zero-carbon hydrogen.[16]
    d. **Biomass:** Sustainably produced biomass can be used instead of some fuels and feedstocks. Studies have found this can result in GHG reductions of 60-70 percent.[17]

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13. Arnout de Pee et al., "Decarbonization of Industrial Sectors: The Next Frontier," McKinsey & Company, June 2018.

14. Ibid.

15. Silvia Madeddu et al., "The CO2 reduction potential for the European industry via direction electrification of heat supply," *Environmental Research Letters* 15, (November 2020).

16. Sebastian Timmerberg et al., "Hydrogen and hydrogen-derived fuels through methane decomposition of natural gas — emissions and costs," *Energy Conversion and Management* 7 (September 2020).

17. Paul Gilbert and Patricia Thornley, "Decarbonizing The Fertilizer Industry: The Potential Role of Biomass Gasification," University of Manchester Research, 2011.

e. **Carbon capture:** Carbon capture, utilization, and sequestration technology (CCUS), captures CO_2 from industrial processes and either stores its underground or uses it as a feedstock in other processes. This could potentially achieve emissions reductions of 80-90 percent.[18]

Because energy efficiency improvements generally result in incremental emissions reductions, this paper will focus on technologies that can help achieve deep decarbonization of the industrial sector, i.e., emission reductions of 80 percent or more. Local characteristics such as cheap zero-carbon electricity, biomass availability, and carbon storage locations influence the feasibility of decarbonization options in each region.[19] The main criteria used to evaluate these options are the renewable-energy technical potential of each state, the availability of geologic storage locations, enhanced oil recovery projects using CO_2 (CO_2-EOR), and CO_2 pipeline infrastructure. Renewable energy technical potential for each state is based on the National Renewable Energy Laboratory's U.S. renewable-energy technical potential analysis, and considers the availability of renewable energy resources, technical system performance, topographic limitations, and land-use constraints.[20] Evaluation of geologic storage potential of each state is based on data from the carbon storage atlas developed by the National Energy Technology Laboratory.[21]

3. **Economic entanglement:** This metric evaluates the level of economic entanglement of the sector in question for each state. This is measured by the share of GDP and employment coming from each sector. Employment statistics are also presented at the county level and reflect the share of employment coming from each sector for top-emitting counties across the U.S. It is outside of the scope of this paper, however, to understand how the transition to a low-carbon economy will impact GDP and employment from relevant sectors.

Results

This section of the paper will present the geographic distribution of both the emissions and economic activity of each of the sectors analyzed. This spatial analysis is the first step in understanding where efforts could be concentrated to reduce industrial sector emissions. The next step is to evaluate the composition of these emissions, technologies available to address them, and regional characteristics that could be leveraged to pursue specific decarbonization strategies.

Geographic distribution of U.S. industrial sector emissions and economic activity

In 2018, the chemical, metal, mineral, and pulp & paper manufacturing sectors produced 435 MMT of CO_2e from 1,360 different facilities. The spatial distribution of these emissions is shown in Figure 1. The top panel aggregates these emissions, while the bottom panel breaks them down to the facility level. The states with the highest level of emissions from the analyzed sectors are Texas, Louisiana, Indiana, Ohio, California, Florida, and Alabama. These seven states account

18. Environmental Protection Agency, "Carbon Dioxide Capture and Sequestration: Overview," January 2017.

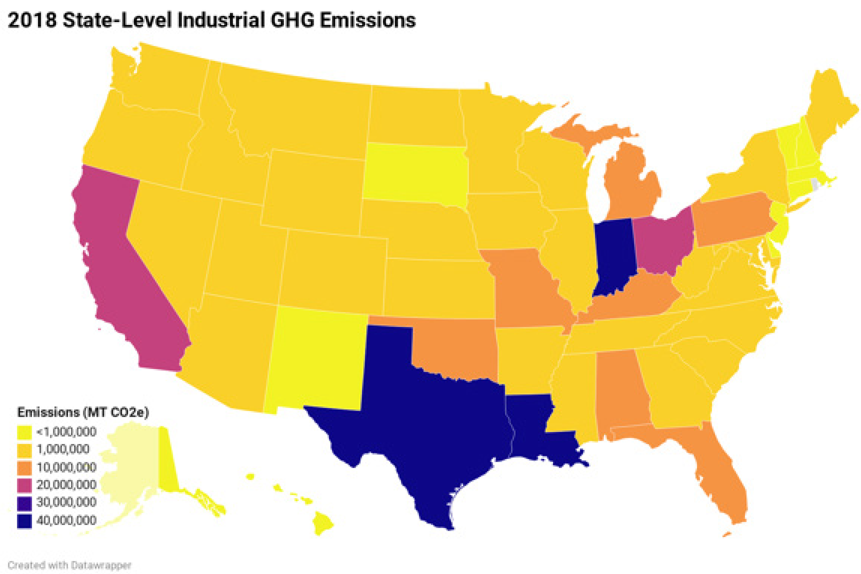
19. Arnout de Pee et al., "Decarbonization of Industrial Sectors: The Next Frontier," McKinsey & Company, June 2018.

20. Anthony Lopez et al., *U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis*, (National Renewable Energy Laboratory: July 2012).

21. National Energy Technology Laboratory, Carbon Storage Atlas, Fifth Edition, (U.S. Department of Energy, 2015).

for about 50 percent of total emissions from the targeted sectors. As demonstrated in the bottom panel, most industrial facilities are located in the area of the U.S. that stretches from the Midwest to the East Coast. The largest emitters are concentrated around the Gulf Coast and the Great Lakes, with the facilities located by the Gulf mostly engaged in chemical production and the ones around the Great Lakes mostly producing metal. Any meaningful decarbonization strategy will need to address emissions from top emitters such as Texas, Louisiana, California, Indiana, Ohio, and Alabama.

Figure 1: Spatial Distribution of Industrial Sector GHG Emissions



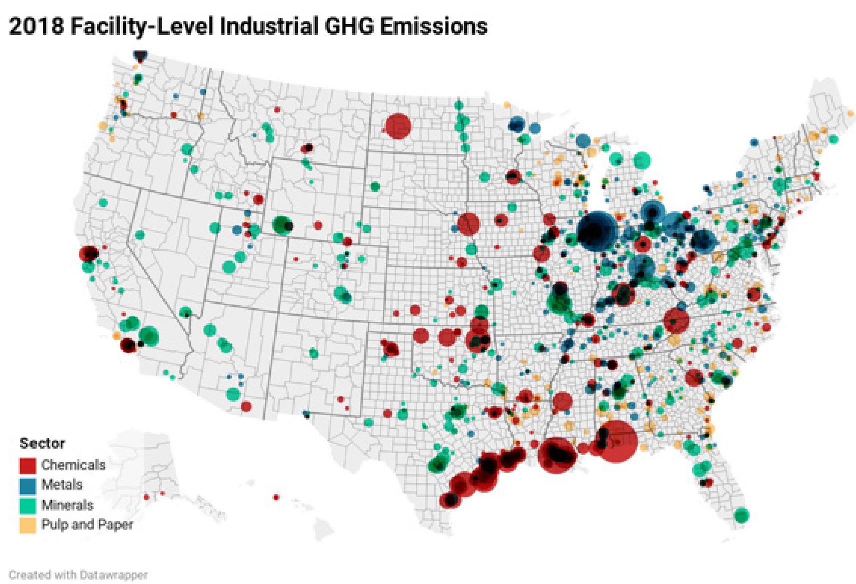
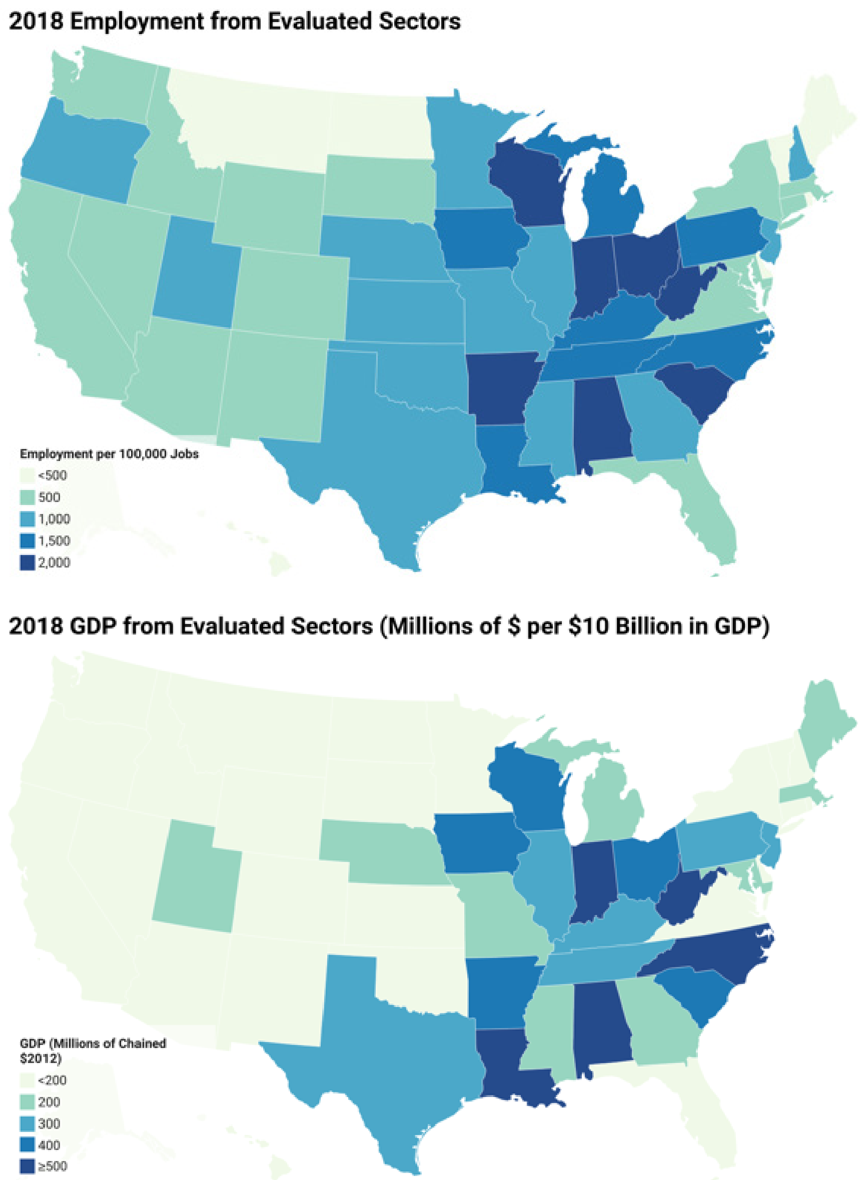


Figure 2 displays the geographic distribution of economic activity coming from these four sectors. The top panel depicts their share of employment, represented as employment per every 100,000 jobs. The bottom panel displays the share of GDP the analyzed sectors supply for each state, measured as millions of dollars these sectors contribute for every $10 billion in GDP. The states with the highest share of employment coming from these sectors are Indiana, Wisconsin, West Virginia, Alabama, Ohio, and South Carolina. The states with the highest shares of GDP coming from these sectors are Indiana, Louisiana, North Carolina, Alabama, West Virginia, and Ohio. While there is some overlap between distribution of emissions and economic activity, some of the largest emitting states, like Texas and California, have large, diversified economies that do not primarily rely on these sectors for employment or GDP.

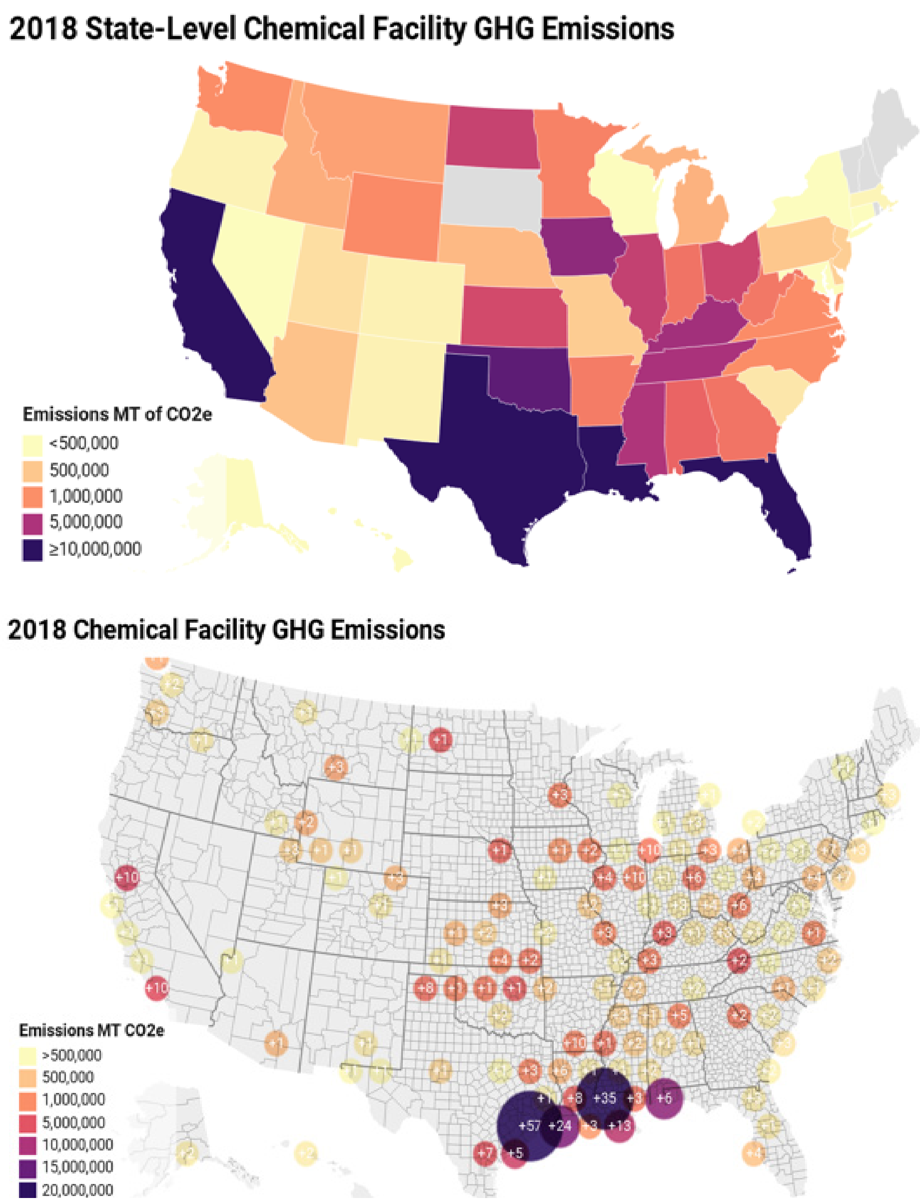
Figure 2: Spatial Distribution of Economic Activity in the Four Sectors



Distribution of chemical sector emissions & economic activity

The chemical sector is the largest-emitting industrial sector. It produced 191 MMT of CO_2e from 457 facilities across the U.S. in 2018. Over half (55 percent) of the emissions from this sector come from facilities that produce petrochemical products and hydrogen, with a majority of remaining emissions coming from facilities that manufacture ammonia (18.7 percent), adipic acid (6.2 percent), and nitric acid (5.1 percent), and other chemicals (10 percent).[22] Figure 3 displays the geographic distribution of these emissions, with the top panel aggregating these emissions at the state level and the bottom panel breaking down these emissions at the facility level. The states with the highest level of GHGs coming from this sector are Texas, Louisiana, Florida, California, Oklahoma, and Iowa. The six states produced over 70 percent of total chemical sector emissions in 2018.

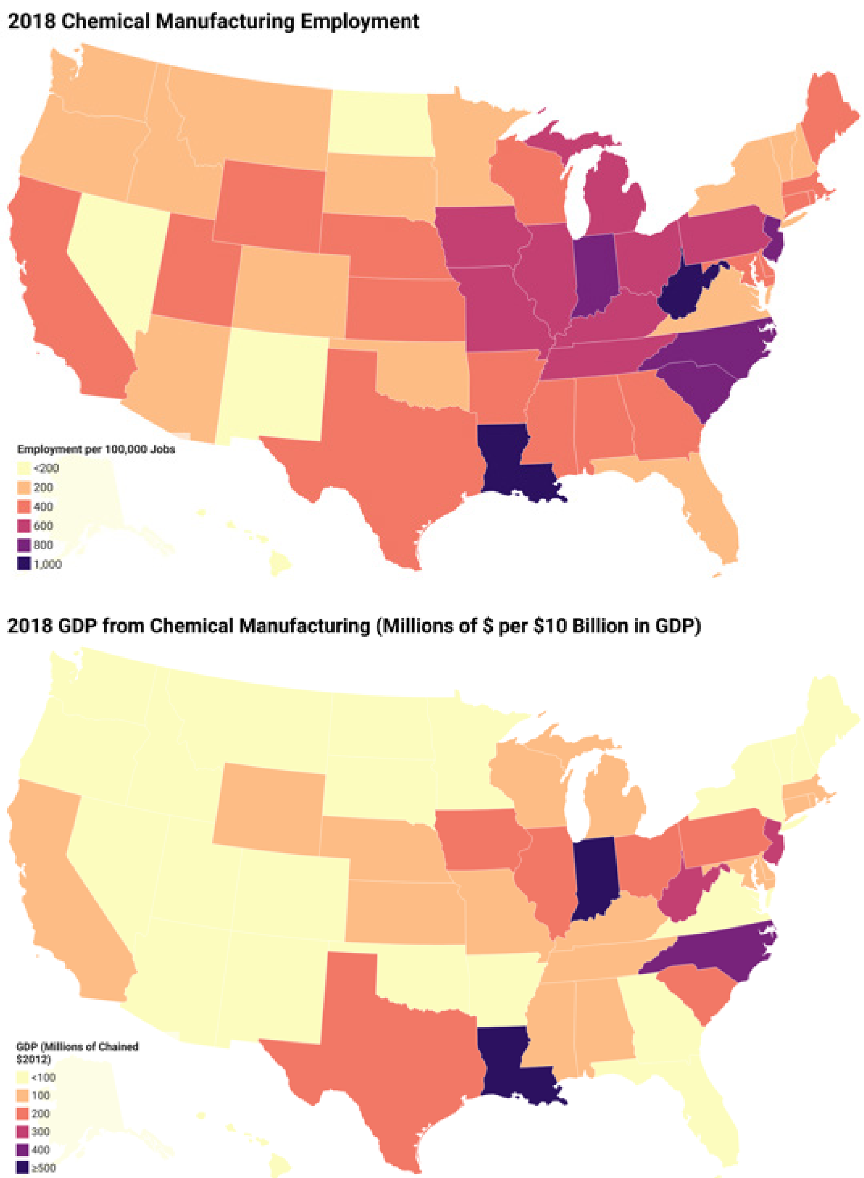
Figure 3: Geographical Distribution of Chemical Sector Emissions



22. Environmental Protection Agency, "Greenhouse Gas Reporting Program: Chemicals".

Figure 4 displays the geographic distribution of both employment and GDP coming from the sector. The states with the highest share of employment coming from the chemical manufacturing sector are Louisiana, West Virginia, South Carolina, New Jersey, and Indiana. The states with the highest share of GDP coming from this sector are Indiana, Louisiana, North Carolina, West Virginia, New Jersey, and Texas. Louisiana and Texas are the only two top-emitting states that have a relatively high level of economic entanglement with the chemical manufacturing sector.

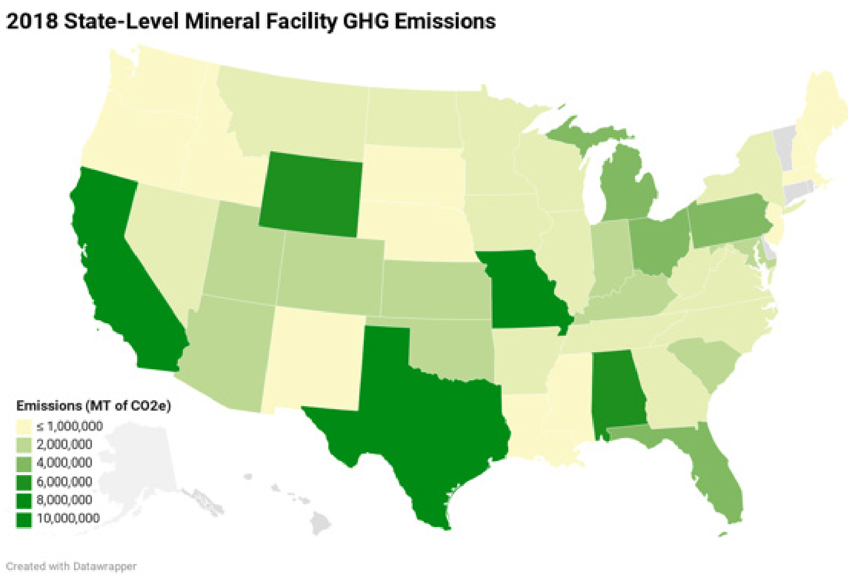
Figure 4: Geographical Distribution of Chemical Sector Economic Activity



Distribution of mineral sector emissions & economic activity

The mineral manufacturing sector is the second-largest source of industrial emissions in the U.S., producing roughly 116 MMT of CO_2e in 2018 from 383 different facilities. Figure 5 depicts the geographic distribution of these emissions. The states with the highest level of GHG emissions coming from the mineral manufacturing sector are Texas, Missouri, California, Alabama, Wyoming, and Florida. These six states produce roughly 44 percent of total emissions from this sector.

Figure 5: Geographical Distribution of Mineral Sector Emissions



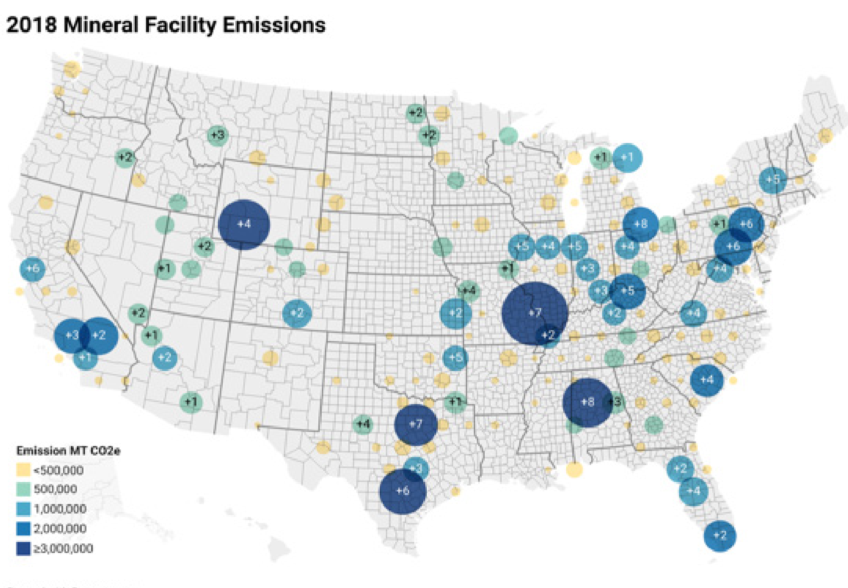
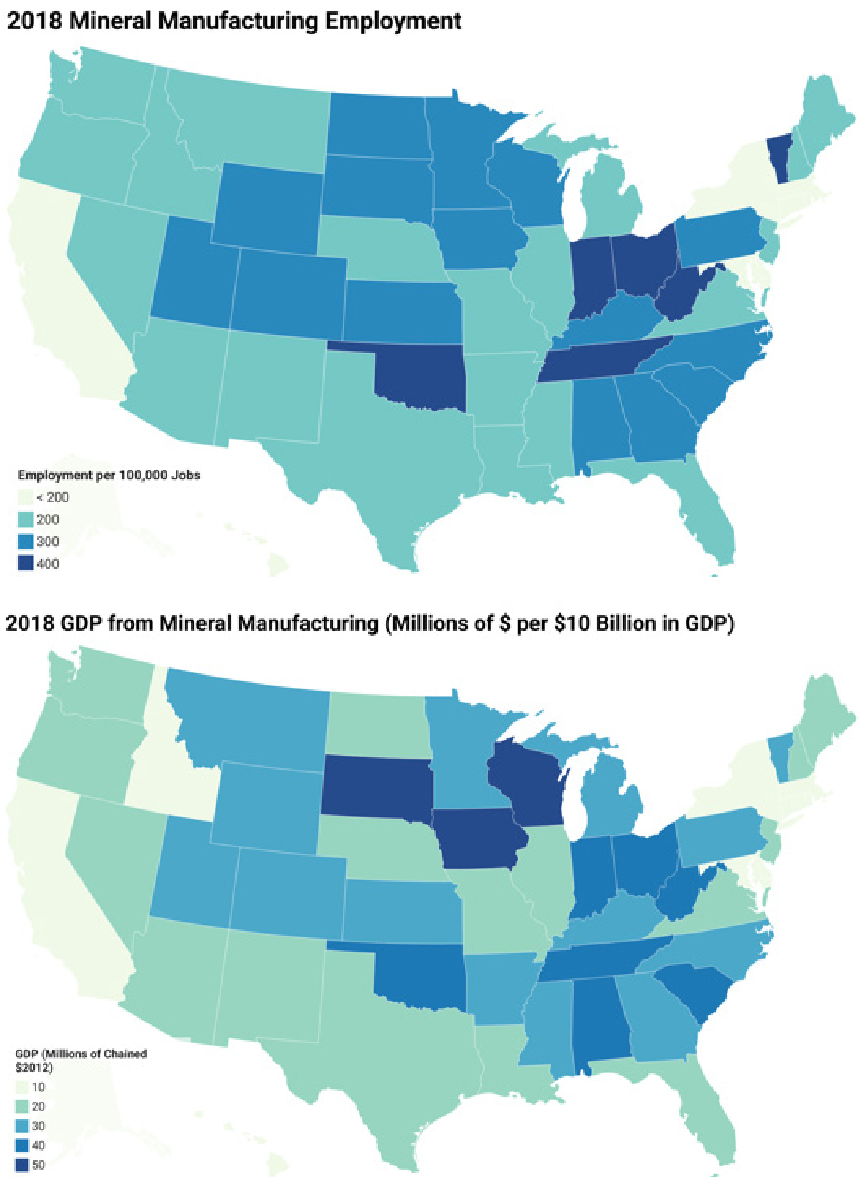


Figure 6 depicts the geographic distribution of employment and GDP coming from this sector. The states with the highest share of employment from this sector are Vermont, Ohio, Tennessee, Indiana, Oklahoma, and West Virginia. The states with the highest share of GDP from this sector are Iowa, Wisconsin, South Dakota, Ohio, Oklahoma, and Indiana. There is very little overlap between states with high mineral sector emissions and states that have a high share of employment or GDP coming from the mineral manufacturing sector.

Figure 6: Geographical Distribution of Mineral Sector Economic Activity



Distribution of metal sector emissions & economic activity

The metal manufacturing sector is the third-largest source of industrial sector emissions, producing 94 MMT of CO2e from 304 facilities in 2018. Figure 7 displays the geographic distribution of these emissions. As displayed in the top panel, the states bordering the Great Lakes are the main source of metal manufacturing emissions. The top emitting states are Indiana, Ohio, Pennsylvania, Michigan, Alabama, and Minnesota. These states produced roughly 75 percent of all metal-related emissions in the U.S. in 2018.

Figure 7: Geographical Distribution of Metal Sector Emissions

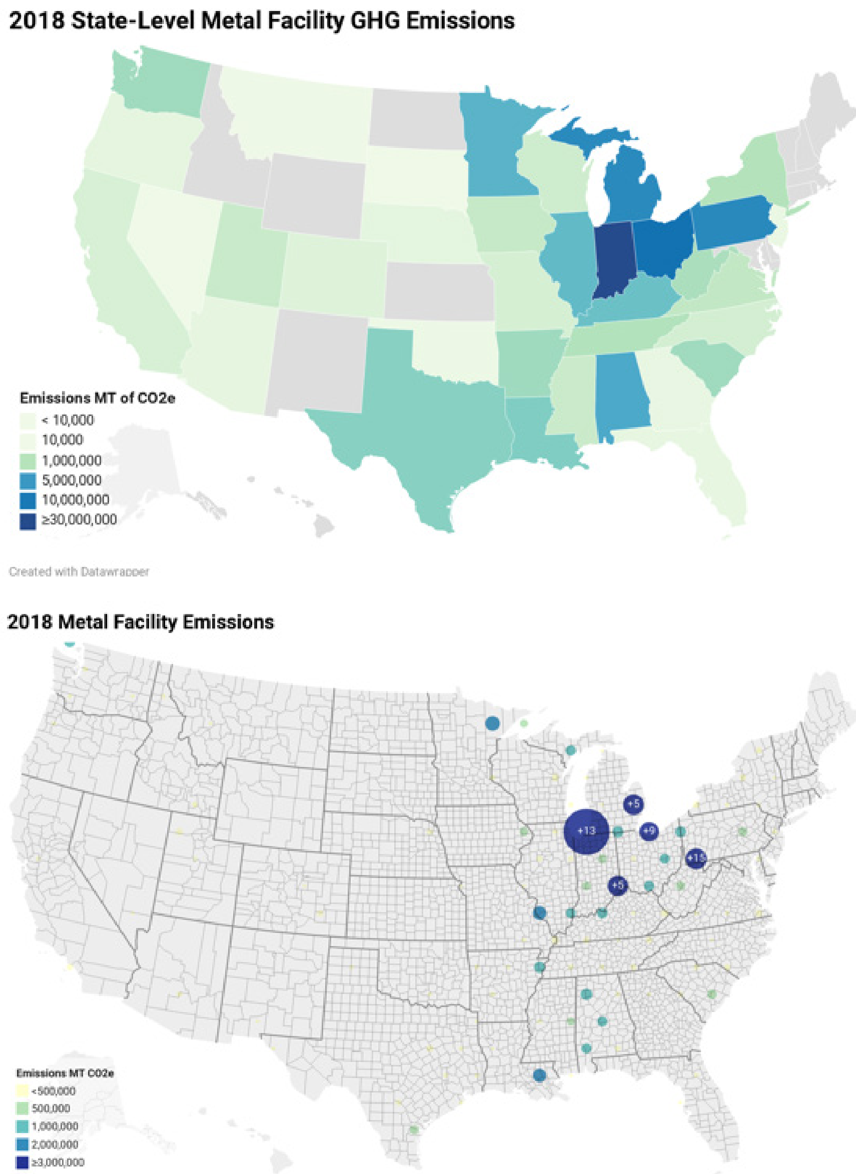
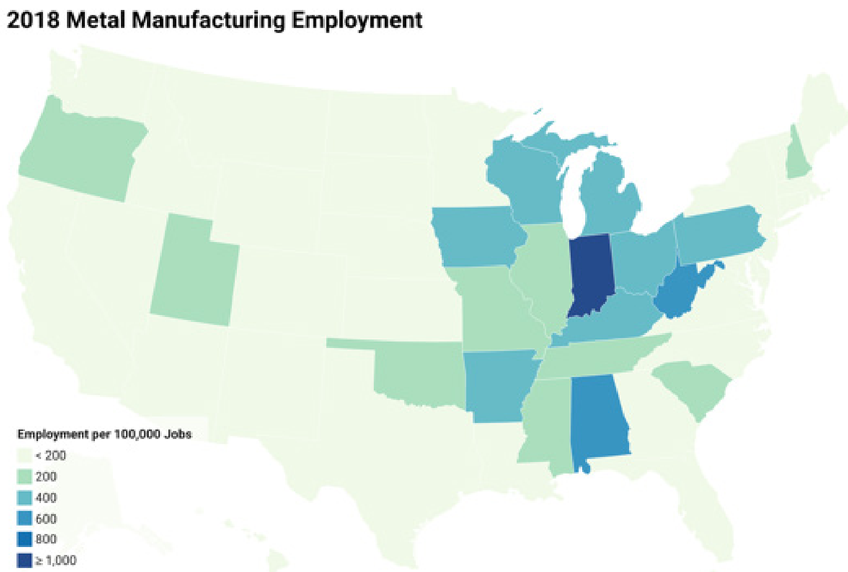
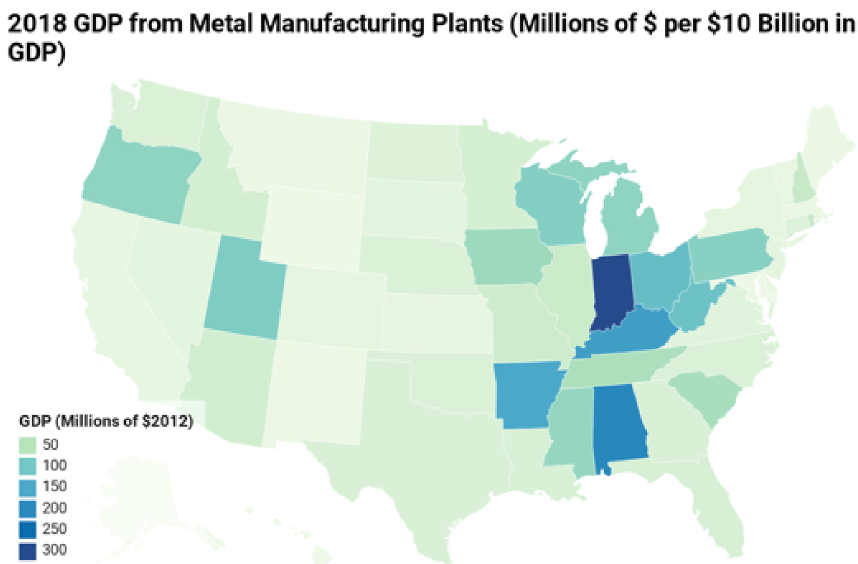


Figure 8 displays the geographic distribution of both employment and GDP coming from the metal manufacturing sector. The states with the highest share of employment coming from the metal manufacturing sector are Indiana, Alabama, Ohio, Arkansas, West Virginia, and Kentucky. The states with the highest percentage of GDP coming from this sector are Indiana, Alabama, Kentucky, Arkansas, Ohio, and West Virginia.

Figure 8: Geographical Distribution of Metal Sector Economic Activity





Distribution of pulp & paper sector emissions & economic activity

Of the four sectors analyzed here, the pulp & paper sector is the smallest source of industrial emissions. It produced 36 MMT of CO_2e in 2018 from 218 different facilities across the U.S. Figure 9 displays the geographic distribution of emissions at the state level and facility level. Most pulp & paper producing facilities are located on the East and Gulf Coasts of the U.S. The states with the highest levels of GHG emissions coming from this sector are Georgia, Wisconsin, Alabama, Louisiana, Pennsylvania, and Virginia. These six states produced over 45 percent of total GHG emissions coming from the pulp & paper manufacturing sector.

Figure 9: Geographical Distribution of Pulp & Paper Sector Emissions

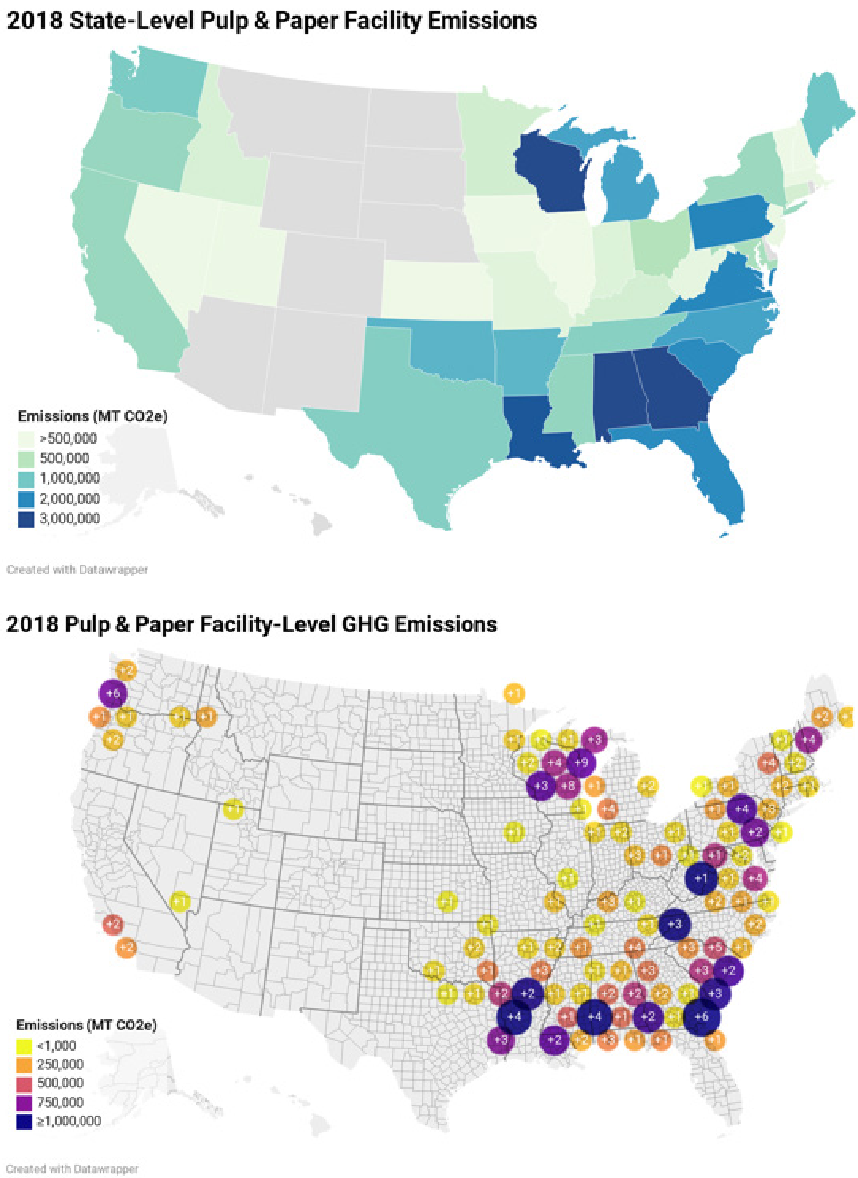
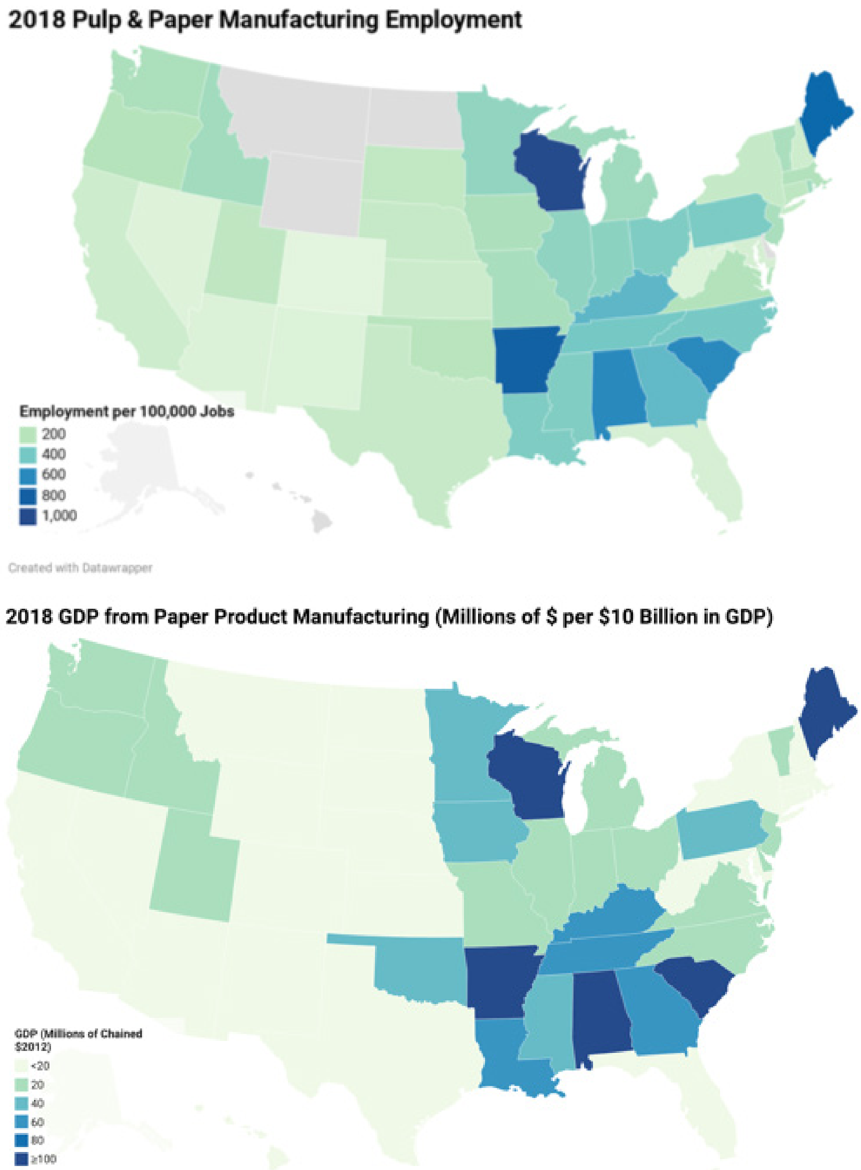


Figure 10 depicts the geographic distribution of employment and GDP from the pulp & paper product manufacturing sector. The states with the highest share of employment coming from this sector are Wisconsin, Arkansas, Maine, Alabama, South Carolina, and Kentucky. The states with the highest share of GDP coming from this sector are Arkansas, Wisconsin, Alabama, Maine, South Carolina, and Louisiana.

Figure 10: Geographical Distribution of Pulp & Paper Sector Economic Activity



Regional Characteristics Inform Regional Decarbonization Strategies

The upshot of the geographic analysis above is that emissions from each sector are generally contained to specific regions. For example, most chemical facilities are located in the Gulf Coast, while almost all metal facilities are located in the states around the Great Lakes. The availability of low-cost zero carbon electricity, carbon storage locations, and supportive infrastructure in these regions should inform regional decarbonization strategies. This section will evaluate these regional characteristics to better understand which technological approaches — e.g., CCUS, electrification, or electrolysis-derived hydrogen — each state and region can best utilize to reduce its industrial emissions.

Decarbonizing the chemical sector

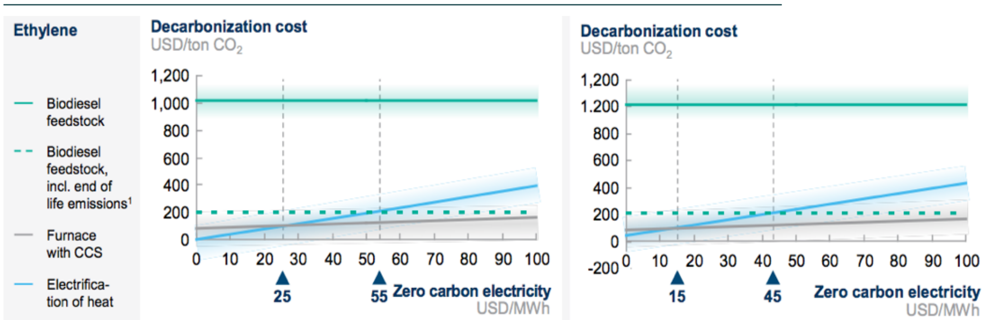
As Figure 3 demonstrates, the largest sources of GHG emissions in the chemical sector are concentrated around the Gulf Coast, with other major emitters located in the Midwest and in California. While Florida was found to be a large source of chemical GHG emissions, 95 percent of those emissions came from one adipic acid manufacturing facility, and it thus was omitted from the analysis below.

GHG emissions from the chemical sector are dominated by two Gulf Coast states, Texas and Louisiana. In 2018, chemical facilities in these two states emitted roughly 99 MMT of CO_2e, which represents 50 percent of total U.S. chemical sector emissions. As Table 1 shows, chemical sector emissions in both these states are dominated by petrochemical facilities.

The EPA classifies any facility that produces ethylene, ethylene dichloride, acrylonitrile, ethylene oxide, methanol, or carbon black as engaged in petrochemical production.[23] This analysis will focus on addressing emissions from ethylene production, but the conclusions are likely to be relevant for other categories of petrochemical production, as production processes for these chemicals are similar. The ethylene production process described below comes from a McKinsey report on decarbonizing options for the industrial sector.[24] The emissions from ethylene production come from the combustion of fuels to heat cracking furnaces, which produce ethylene in a high-temperature process known as steam cracking, and is the only step in conventional ethylene production where CO_2 is generated. [25] The options for decarbonizing ethylene production are listed below:

1. Using zero-carbon hydrogen or biomass for heat production
2. Switching to zero-carbon electricity for heat production
3. Applying CCUS to exhaust gases from cracking furnaces: CCUS cost estimates are between $70 and $85 per metric ton of CO2 abated.[26]

Figure 11: Cost of Decarbonization Options for Ethylene Production



Source: Arnout de Pee et al., "Decarbonization of Industrial Sectors: The Next Frontier," McKinsey & Company, June 2018

23. EPA, "2015 Revisions and Confidentiality Determinations for Data Elements Under the Greenhouse Gas Reporting Rule," *Federal Registrar* 81, no. 237, (Dec. 9 2016).

24. Arnout de Pee et al., "Decarbonization of Industrial Sectors: The Next Frontier," McKinsey & Company, June 2018.

25.ibid.

26. Duncan Leeson et al., "Techno-Economic Analysis and Systemic Review of CCS applied to Iron and Steel, Cement, Oil Refining, and Pulp and Paper Industries, as well as other High Purity Sources," *International Journal of Greenhouse Gas Control* 61, (June 2017): 71-84.

The price thresholds for which decarbonization strategy is most competitive come from a McKinsey & Company report on industrial decarbonization options, and are demonstrated in the figure above. The vertical axis represents the cost of decarbonization per ton of CO2. Electrification of furnace heat will become cheaper than deploying CCUS in locations where zero-carbon power is available at or below $25/MWh for greenfield projects and $15/MWh for brownfield projects.[27]

Table 1: Chemical GHG Emissions Profile for Texas and Louisiana

State	GHG Emissions (MT CO2e)	Facilities
Texas	**58,732,132**	**104**
Petrochemical Production	34,898,458	36
Hydrogen Production	13,364,610	22
Other Chemicals	7,570,355	43
Adipic Acid Production	1,641,713	1
Ammonia Manufacturing	1,232,579	1
Fluorinated Gas Production	24,417	1
Louisiana	**39,806,464**	**74**
Petrochemical Production	16,162,381	24
Ammonia/Nitric Acid	11,795,105	5
Hydrogen Production	7,689,822	15
Other Chemicals	2,915,823	24
Fluorinated Gas Production	737,443	3
Titanium Dioxide Production	262,853	1
Phosphoric Acid Production	121,118	2
Total	98,538,596	178

Despite Texas having the highest renewable-energy technical potential for both solar and wind resources in the U.S., wind purchase power agreement (PPA) prices in the southeast portion of the state, where petrochemical facilities (and their emissions) are located, are around $25-$35/MWh, making CCUS a more competitive option to decarbonize these facilities, at least until zero-carbon electricity generation becomes cheaper in this region.[28] Louisiana has poor renewable energy potential. In terms of utility-scale solar photovoltaic (PV) technical potential, Louisiana ranks 30th out of the 50 states, and it ranks 41st for onshore wind potential.[29] While technology improvements could make wind and solar technologies viable in low-resource areas, the fact that wind and solar make up less than 1 percent of the current electricity generation mix in Louisiana make it unlikely the state can leverage zero-carbon electricity sources for electrification or electrolysis-derived hydrogen in the next few years.[30] Both Texas and Louisiana do have high offshore wind potential, but costs for this technology remain prohibitively high, and scaling this technology

27. Arnout de Pee et al., "Decarbonization of Industrial Sectors: The Next Frontier," McKinsey & Company, June 2018.

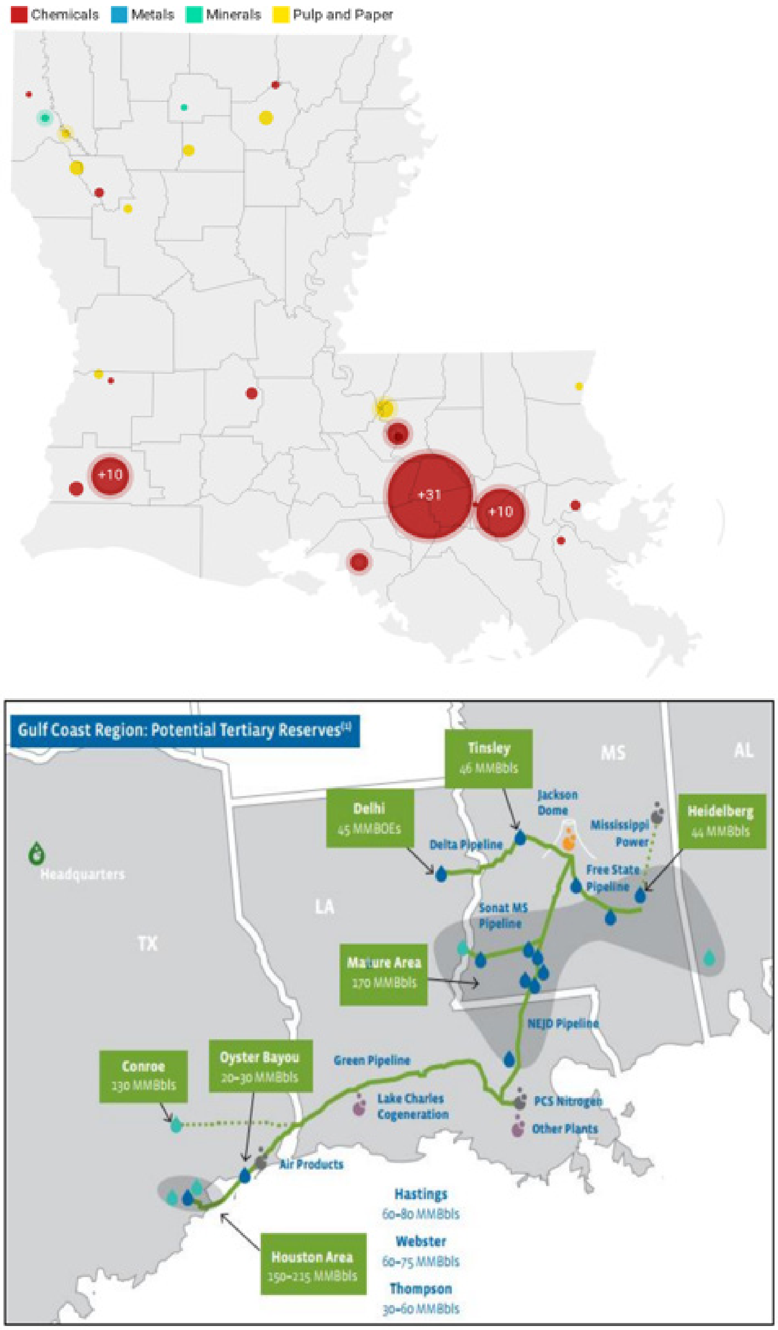
28. Ryan Wiser and Mark Bolinger, *2018 Wind Technologies Market Report* (U.S. Department of Energy,) Aug. 2019.

29. Anthony Lopez et al., *U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis*, (National Renewable Energy Laboratory: July 2012).

30. Energy Information Administration, "Louisiana Electricity Profile 2019," Nov. 2, 2020.

to the required levels would involve a significant investment of time and capital.[31] Rather, both Louisiana and Texas can leverage significant carbon storage resources to scale CCUS technology in these states over the next decade.

Figure 12: LA Industrial Facilities and CO2 Pipelines



Source: Denbury, "Gulf Coast CO_2 Pipelines"

31. Lazard, "Levelized Cost of Energy Analysis-Version 14.0," October 2020.

The two Gulf states have significant resources, both in terms of CO_2 storage and pipeline infrastructure, that can be leveraged to deploy CCUS technology and deeply decarbonize their industrial sectors. Texas and Louisiana have the best CO_2 storage resources in the U.S., with a combined storage capacity of 2,418 billion metric tons of CO_2.[32] Additionally, the greatest volume of offshore sequestration potential in the U.S. is in the Gulf of Mexico, which is easily accessible for the largest GHG-emitting industrial facilities.[33] As the figure above demonstrates, the Gulf Coast has 740 miles of CO_2 pipelines already built, much of which runs through the largest GHG-emitting sources in that area. These pipelines can be used to move CO_2 from these industrial sources to the region's CO_2-"enhanced oil recovery" (EOR) projects. The Denbury Green pipeline in this region is already transporting third-party CO_2 from anthropogenic sources to oilfields in the region.[34] Texas is home to 77 CO_2-EOR projects, the most in the U.S., while Louisiana already transports CO_2 to two CO_2-EOR projects in the state.[35] The ample storage resources, pipeline infrastructure, and market in the Gulf Coast region make CCUS a competitive and viable decarbonization strategy for chemical facilities in Texas and Louisiana, relative to other decarbonization strategies.

While CCUS is a viable decarbonization strategy for the chemical facilities located on the Gulf Coast, this does not necessarily hold for chemical facilities in other regions. For example, Oklahoma and Iowa have the fifth- and sixth-highest chemical sector emissions in the U.S., respectively. The table below provides a breakdown of these states' chemical-sector GHG emissions, 90 percent of which come from ammonia manufacturing.

Table 2: Chemical GHG Emissions Profile for Iowa and Oklahoma

State	GHG Emissions (MT CO2e)	Facilities
Iowa	**6,173,827**	**6**
Ammonia/ Nitric Acid	5,651,026	4
Petrochemical Production	448,021	1
Other Chemicals	74,780	1
Oklahoma	**8,079,113**	**9**
Ammonia/ Nitric Acid	7,382,460	4
Petrochemical Production	276,691	1
Hydrogen Production	270,408	2
Other Chemicals	149,554	2
Total	14,252,940	15

The ammonia production process described below comes from a McKinsey report on decarbonizing options for the industrial sector.[36] The first step in ammonia production is making hydrogen, which is usually done by a process known as steam methane reforming (SMR) that uses natural gas as a feedstock. SMR produces Co_2 as a byproduct. The CO_2 is removed and the hydrogen is mixed

32. National Energy Technology Laboratory, *Carbon Storage Atlas, Fifth Edition*,(U.S. Department of Energy, 2015).

33. Harry Vidas et al., "Analysis of the Costs and Benefits of CO2 Sequestration on the U.S. Outer Continental Shelf," (U.S. Department of the Interior, Sep. 2012).

34. Denbury, "Gulf Coast CO2 Pipelines".

35. Mathew Wallace et al. "A Review of the CO_2 Pipeline Infrastructure in the U.S." (National Energy Technology Laboratory, April 21, 2015).

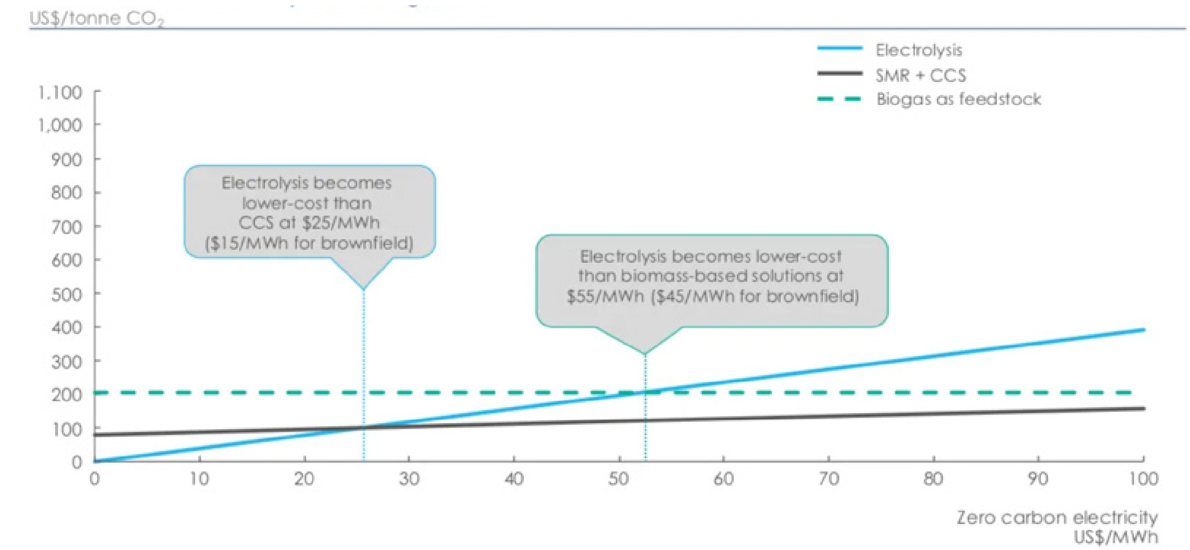
36. Arnout de Pee et al., "Decarbonization of Industrial Sectors: The Next Frontier," McKinsey & Company, June 2018.

with nitrogen in the so-called Haber-Bosch process to produce ammonia. Below are options for decarbonizing ammonia production. [37]

1. Switching to electrolysis-derived hydrogen as a feedstock
2. Applying CCUS to capture the pure steam CO_2 generated from hydrogen: The cost of applying CCUS on ammonia plants is roughly $23-$33 per ton of CO_2.[38]

Figure 13: Cost of Decarbonization Options for Ammonia Production

Source: Trevor Brown, "Mission Possible: decarbonizing ammonia," Energy Transitions Commission November 1, 2018



Source: McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

The figure above comes from an Energy Transitions Commission report that uses cost assumptions from McKinsey and demonstrates the price thresholds at which each carbon abatement technology becomes competitive. According to the report, electrolysis-derived hydrogen "offers a cheaper route to decarbonization than the biomass-based solution when carbon-free electricity drops to $55/MWh for new plants and $45/MWH for existing plants. Electrolysis then becomes cheaper than CCUS at an electricity price below $25/MWh for new plants or $15/MWh for existing ones."[39] At $25/MWh, electrolysis-derived hydrogen becomes more cost-competitive than conventional inputs, considering the current commodity prices of natural gas as a feedstock.[40]

Iowa has the seventh-highest onshore wind potential of all U.S. states while Oklahoma ranks ninth, and these two states already get a sizeable portion of their electricity from renewable sources.[41] In 2019, Iowa was the third-largest wind power producer in the U.S. and wind accounted for 42

37.Ibid.

38. Energy Futures Initiative, "Advancing Large Scale Carbon Management Expansion of the 45Q Tax Credit," May, 2018

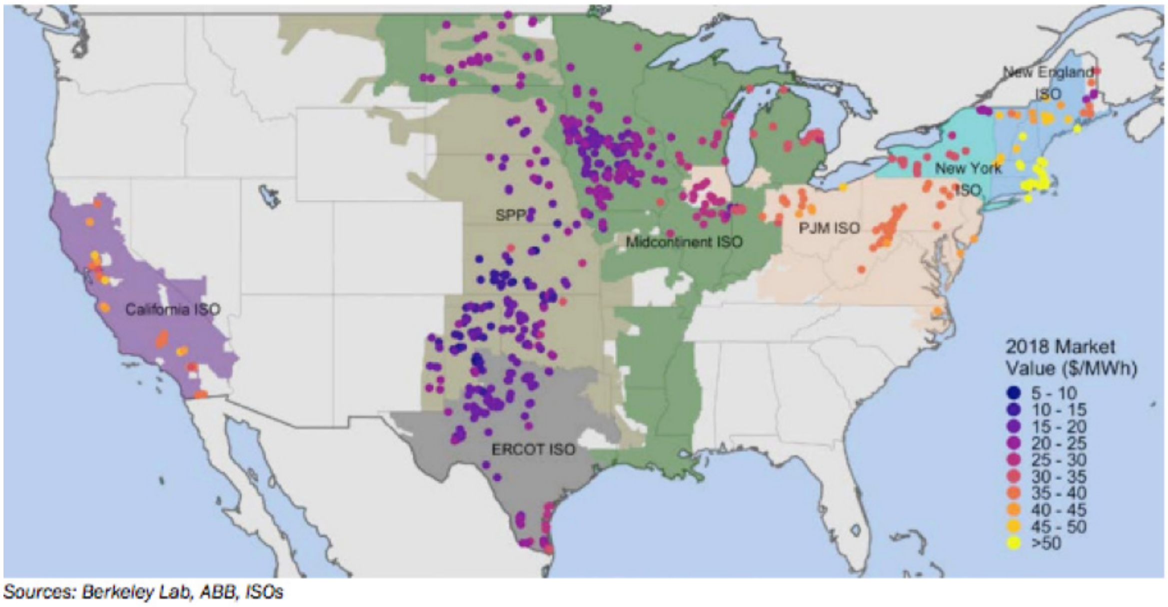
39. Trevor Brown, "Mission Possible: decarbonizing ammonia," Energy Transitions Commission November 1, 2018

40. Arnout de Pee et al., "Decarbonization of Industrial Sectors: The Next Frontier," McKinsey & Company, June 2018.

41. Anthony Lopez et al., *U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis*, (National Renewable Energy Laboratory: July 2012).

percent of its electricity, the highest share of any state.[42] Wind and solar resources supplied about 32 percent of Oklahoma's electricity in the same year.[43] As the figure below demonstrates, both these states boast some of the lowest wind prices in the entire country, coming in between $10 and $25/MWh.[44]

Figure 14: 2018 Wind Purchase Power Agreement Prices



Source: Ryan Wiser and Mark Bolinger, Wind Technologies Market Report, (U.S. Department of Energy, Aug. 2019).

At these prices, electrolysis-derived hydrogen is not only cost-competitive with CCUS, but can compete with conventionally produced ammonia inputs. Chemical facilities in these two states, and across the Midwest, could leverage their plentiful and cheap wind resources to decarbonize their facilities.

The last state with significant chemical sector emissions is California. In 2018, California had the third-highest chemical sector emissions in the U.S., producing roughly 11 MMT of CO_2e, with 98 percent of those emissions coming from hydrogen production. The two main approaches for decarbonizing hydrogen-producing facilities are using electrolysis-derived hydrogen or equipping facilities with CCUS. Applying CCUS to hydrogen-producing facilities is comparatively cheap because they generate a relatively pure stream of CO_2, with capture costs ranging from $23 to $33 per ton of CO_2 emitted.[45]

California has the 10th highest utility-scale solar potential of all states and the 20th highest onshore wind potential.[46] Currently, onshore wind PPA prices in CAISO, the independent system operator

42. Energy Information Administration, "Iowa Electricity Profile 2019," Nov. 2020

43. Energy Information Administration, "Oklahoma Electricity Profile 2019," Nov. 2, 2020.

44. Ryan Wiser and Mark Bolinger, *Wind Technologies Market Report*, (U.S. Department of Energy, Aug. 2019).

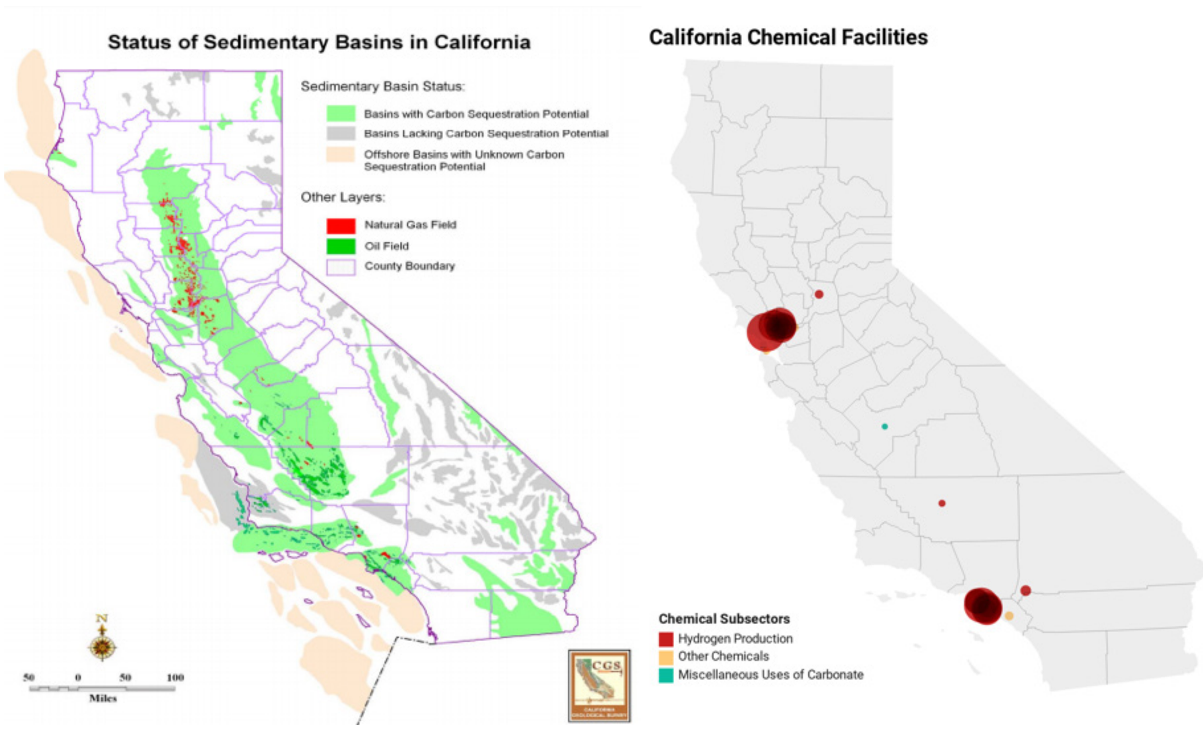
45. Energy Futures Initiative, "Advancing Large Scale Carbon Management Expansion of the 45Q Tax Credit," May, 2018.

46. Anthony Lopez et al., *U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis,* (National Renewable Energy Laboratory: July 2012).

that provides electricity to California, are around $35/MWh, and solar PV PPA prices in the state hover between $20 and $40/MWh, meaning that zero-carbon electricity is still too expensive to compete with CCUS as a decarbonization strategy.[47]

In terms of carbon capture potential, California has the 11th-highest CO_2 storage resources in the country, capable of storing 152 billion metric tons of CO_2.[48] Although the state does not have any EOR projects or CO_2 pipelines, the figure below demonstrates that California's largest GHG-emitting chemical facilities are located in the northern and southern sections of the state, both areas with good carbon-sequestration potential based on their geology.[49] However, the hydrogen facilities in the lower portion of the state could potentially use low-cost solar PV from the Southwest, specifically Arizona, to decarbonize their facilities. In 2018, portions of the Southwest had solar PV PPA prices at $20/MWh, very close to the price point at which electrolysis-derived hydrogen becomes cost-competitive with applying CCUS to these facilities. In short, California's immense size and geographic and economic diversity means that different strategies will make sense for different sections of the state.

Figure 15: California Sedimentary Basins and Chemical Facilities



Source: Deepika Nagabhushan "CCUS in California: Climate Opportunity and Policy Need," Clean Air Task Force, April 9, 2020

47. Mark Bolinger et al., "Utility-Scale Solar Data Update: 2020 Edition," Lawrence Berkley National Laboratory, Nov. 2020.

48. National Energy Technology Laboratory, *Carbon Storage Atlas, Fifth Edition*, (U.S. Department of Energy, 2015).

49. Deepika Nagabhushan "CCUS in California: Climate Opportunity and Policy Need," Clean Air Task Force, April 9, 2020.

Decarbonizing the metal sector

As Figure 7 demonstrates, GHG emissions from the metal sector are concentrated in states around the Great Lakes. Any meaningful decarbonization strategy will need to address pollution from top emitters such as Indiana, Ohio, Pennsylvania, and Michigan. Together, these states produce 66 percent of total metal sector emissions. Iron and steel production account for 80.5 percent of the metal sector's emissions nationwide, and more than 90 percent in these key states.

The steel production process described below comes from a McKinsey report on decarbonizing options for the industrial sector.[50] The production of steel follows two processes. Blast furnace-basic oxygen furnace (BF-BOF) production uses coal to generate high amounts of heat to melt iron ore, which is then used to produce steel. In the second process, electric arc furnaces (EAF) use scrap steel to make recycled steel or use direct-reduced iron (DRI) to produce virgin steel. The DRI used to make virgin steel uses natural gas a feedstock. BF-BOF produced steel has much higher CO_2 emissions per produced ton of steel than DRI-EAF method of steelmaking. The options for decarbonizing steel production are listed below.[51]

1. Applying CCUS at BF-BOF steel mills
2. Using charcoal instead of coal at BF-BOF steel mills
3. Using electrolysis-derived hydrogen instead of natural gas in DRI production
4. Using zero-carbon electricity to power EAF

50. Arnout de Pee et al., "Decarbonization of Industrial Sectors: The Next Frontier," McKinsey & Company, June 2018.

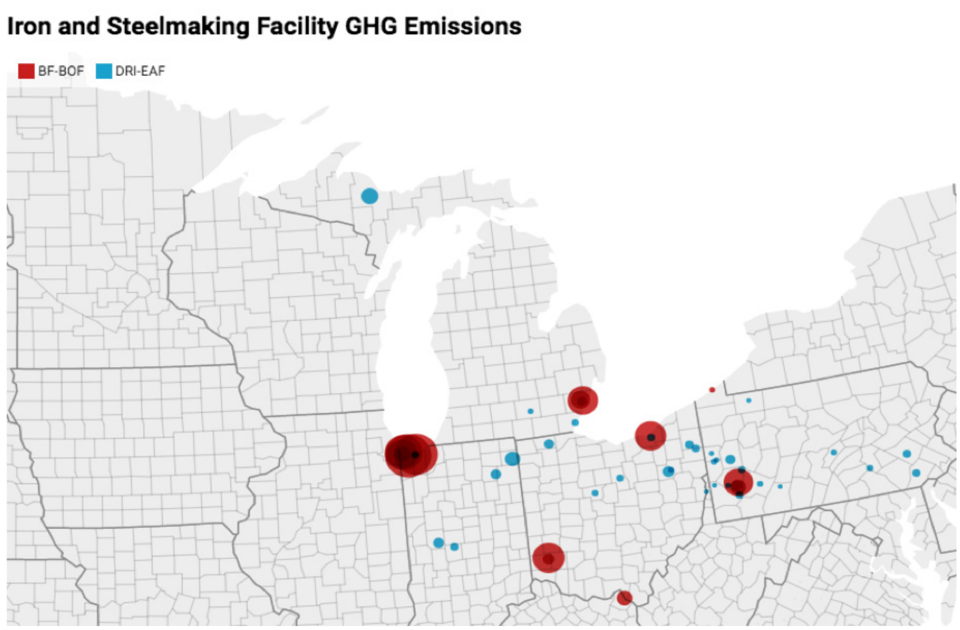
51. Ibid.

Table 3: Metal GHG Emissions Profile for Great Lakes States

State	GHG Emissions (MT CO2e)		Facilities
Indiana	**32,868,645**		**31**
Iron and Steel Production		31,046,259	10
Other Metals		1,047,471	17
Aluminum Production		470,891	1
Magnesium Production		174,739	1
Lead Production		129,285	2
Ohio	**12,941,823**		**33**
Iron and Steel Production		11,527,493	14
Other Metals		620,779	15
Ferroalloy Production		475,262	2
Magnesium Production		318,289	2
Pennsylvania	**7,503,739**		**33**
Iron and Steel Production		6,505,330	19
Other Metals		726,767	12
Zinc Production		164,031	1
Lead Production		107,611	1
Michigan	**7,281,876**		**16**
Iron and Steel Production		6,876,137	6
Metals		375,357	8
Magnesium Production		30,382	2
Total	60,596,083		113

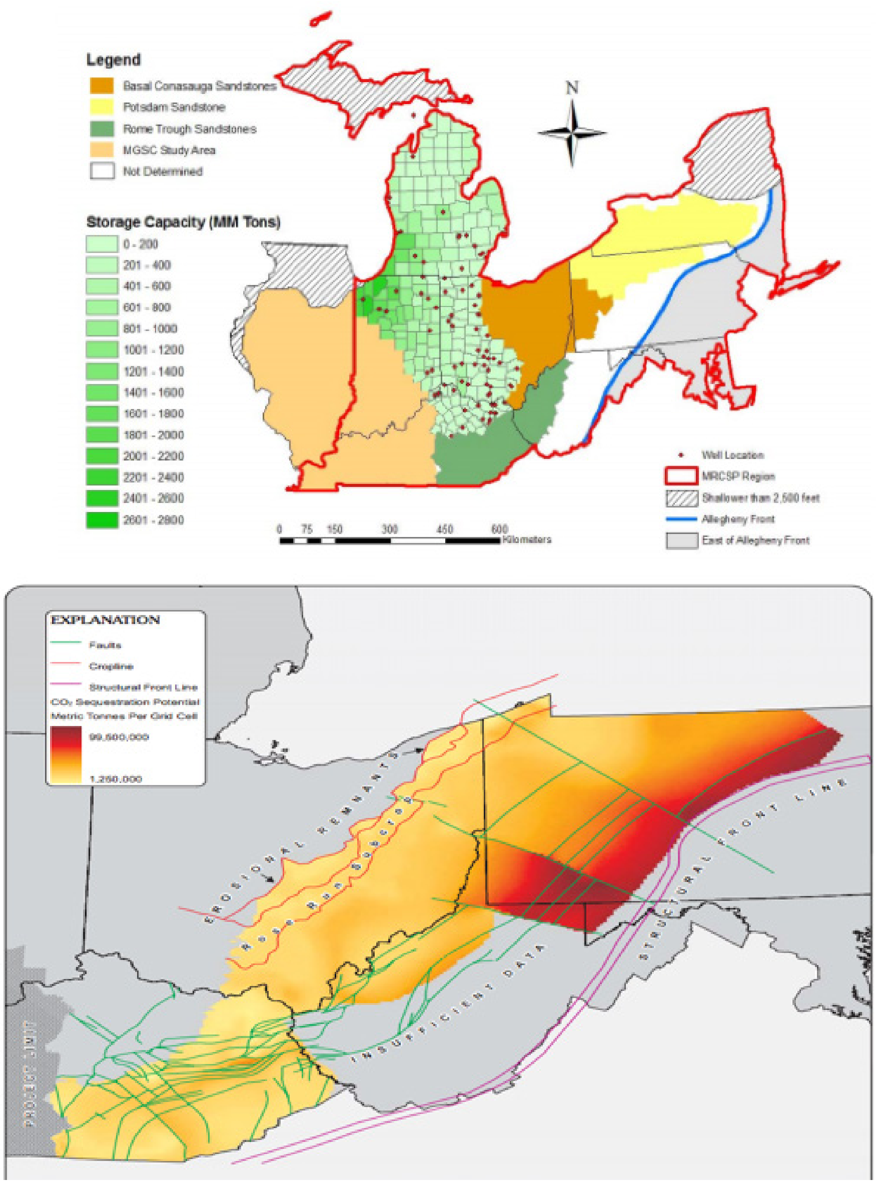
As demonstrated in the figure below, BF-BOF facilities produce 90 percent of steel mill GHG emissions despite making up only a third of the number of steel mills.

Figure 16: Iron and Steel Facility Emissions in Great Lake States



Decarbonizing BF-BOF facilities is going to require applying CCUS because of the limited GHG emission reductions that can be achieved by using charcoal. Despite these states currently having no CO_2 pipelines, all save Ohio have fairly abundant CO_2-storage resources. Indiana, the state with the highest emissions and number of BF-BOF facilities, ranks 17th in the U.S. for CO_2 storage resource potential, while Ohio, Pennsylvania, and Michigan rank 33rd, 27th, and 21st, respectively.[52]

Figure 17: CO_2 Sequestration Potential in Great Lakes States



Source: Larry Wickstorm et al., "Characterization of Geologic Sequestration Opportunities in the MRCSP Region," Midwest Regional Carbon Sequestration Partnership, 2005

52. National Energy Technology Laboratory, *Carbon Storage Atlas, Fifth Edition*, (U.S. Department of Energy, 2015).

The figure above displays where the highest CO_2 storage potential is found in each of these states.[53] The largest GHG-emitting facilities in Indiana are located in Lake and Porter counties in the northwestern portion of the state, which is also the area of the state with the highest CO_2 storage potential. The same holds true for Pennsylvania's BF-BOF in Allegheny County. However, the BF-BOF facilities in both Ohio and Michigan are in parts of the state with low CO_2 storage capacity, and currently neither of these states has the CO_2 pipeline infrastructure to be able to move captured carbon. Decarbonizing these facilities will require either a significant buildout of CO_2 transport infrastructure, or rebuilding them as DRI-EAF facilities.

The remaining DRI-EAF steel facilities in these states will require cheap zero-carbon electricity to decarbonize. However, none of these states have exceptional renewable energy technical potential, and zero-carbon electricity sources currently make up a small share of their electricity supply. Renewable sources currently make up less than 4 percent of the region's electricity generation, and while the region does have high penetration of nuclear power it could use to produce zero-carbon hydrogen, the poor economics of nuclear energy make it unlikely that new nuclear plants will be built in the next few years.[54] As such, relying on zero-carbon electricity to power EAFs or to produce electrolysis-derived hydrogen as a feedstock is not currently feasible. Getting there would require an extensive buildout of renewable resources in these states or transmission lines to move cheap renewable power from the Midwest to these states.

Decarbonizing the mineral sector

Compared with the chemical or metal manufacturing sectors, the mineral manufacturing sector is less concentrated and is spread across a variety of states. However, formulating a decarbonization strategy for the mineral sector could start with the largest emitters: Texas, Missouri, and California. These three states alone account for over a quarter of mineral sector emissions. Table 4 below breaks down the mineral sector GHG emissions of each of these states. Cement manufacturing dominates, accounting for more than 75 percent of the emissions.

53. Larry Wickstorm et al., "Characterization of Geologic Sequestration Opportunities in the MRCSP Region," Midwest Regional Carbon Sequestration Partnership, 2005.

54. Geoffrey Haratyk, "Early Nuclear Retirements in Deregulated U.S. Markets: Causes, Implications and Policy Options,"CEEPR working paper 2017-009 (MIT Center for Energy and Environmental Policy Research, March 2017).

Table 4: Mineral GHG Emissions Profile for Texas, California, and Missouri

State	GHG Emissions (MT CO2e)		Facilities	
TX	**12,171,349**		**38**	
Cement Production		9,204,514		11
Lime Manufacturing		1,685,524		5
Glass Production		723,989		8
Other Minerals		557,322		14
MO	**11,343,133**		**12**	
Cement Production		7,360,422		5
Lime Manufacturing		3,793,699		3
Glass Production		1,55,890		3
Other Minerals		33,122		1
CA	**8,715,250**		**21**	
Cement Production		7,844,277		8
Glass Production		496,608		6
Other Minerals		213,798		5
Lime Manufacturing		160,567		2
Total	32,229,732		71	

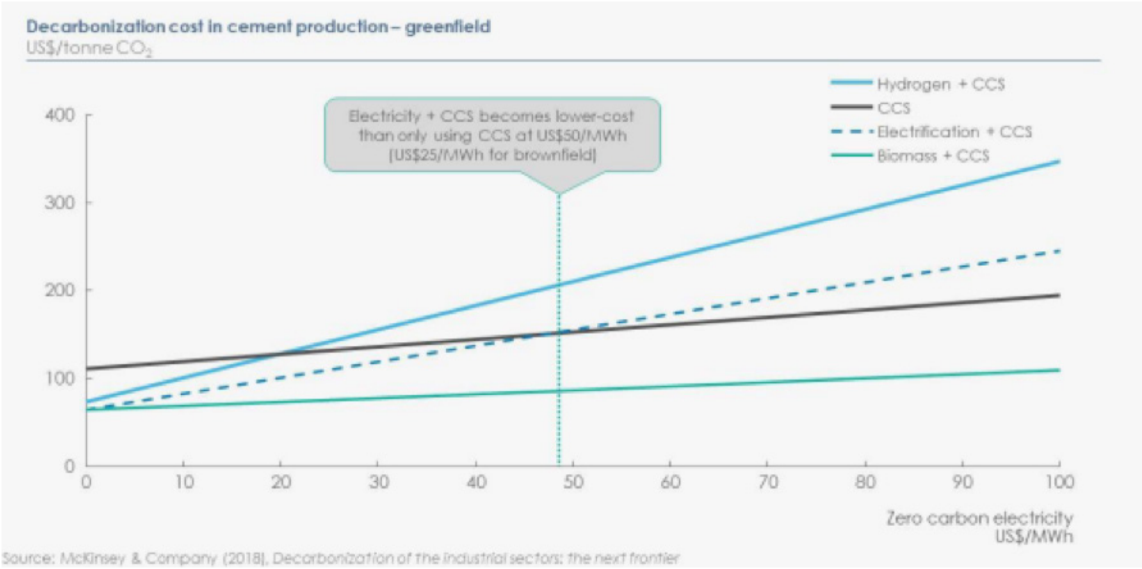
The use of fossil fuels to heat cement kilns accounts for roughly 40 percent of CO_2 emissions associated with cement manufacturing. The remaining 60 percent come from calcination, the process in which heated limestone decomposes to produce calcium oxide and CO_2.[55] The resulting substance, known as clinker, is ground with other minerals to form cement. Options for decarbonizing cement production are listed below.[56]

1. Switching to a zero-carbon fuel to power cement kilns
2. Using electricity as a heat source
3. Applying CCUS to cement kilns
4. Replacing limestone/clinker with other minerals

55. Arnout de Pee et al., "Decarbonization of Industrial Sectors: The Next Frontier," McKinsey & Company, June 2018.

56. Ibid.

Figure 18: Cost of Decarbonization Options for Cement Production



Source: Energy Transitions Commission, "Mission Possible: Reaching Net-Zero Carbon Emissions from Harder to Abate Sectors by Mid-Century: Sectoral Focus: Cement," Nov. 2018

McKinsey estimates that zero-carbon electricity would need to be available at a cost below $50/MWh at greenfield sites, and $25/MWh at brownfields, for electrification to be competitive with applying CCUS to combustion emissions.[57] However, "process emissions from cement production cannot be abated by a fuel change and thus require CCUS" or innovations in other mineral feedstocks.[58] For the states listed in Table 4, a significant portion of the GHG emissions from cement manufacturing facilities are process emissions, and can only be reduced with CCUS technology. The Global CCS institute estimates that applying CCUS at cement facilities in the U.S. would cost around $124 per metric ton of CO_2.[59]

As discussed in previous sections, both Texas and California have plentiful CO_2 storage resources, and these can be leveraged to reduce GHG emissions from cement manufacturing. However, both these states would need to construct new CO_2 pipelines to move carbon captured at cement facilities to the areas of the state most suitable for CO_2 storage. The figure below displays the location of mineral facilities in Texas and California. In the case of Texas, CO_2 pipelines would need to be built from the central portion of the state to the Gulf Coast to move captured CO_2 to EOR sites. This could be done by expanding the existing Denbury Green pipeline into central Texas.

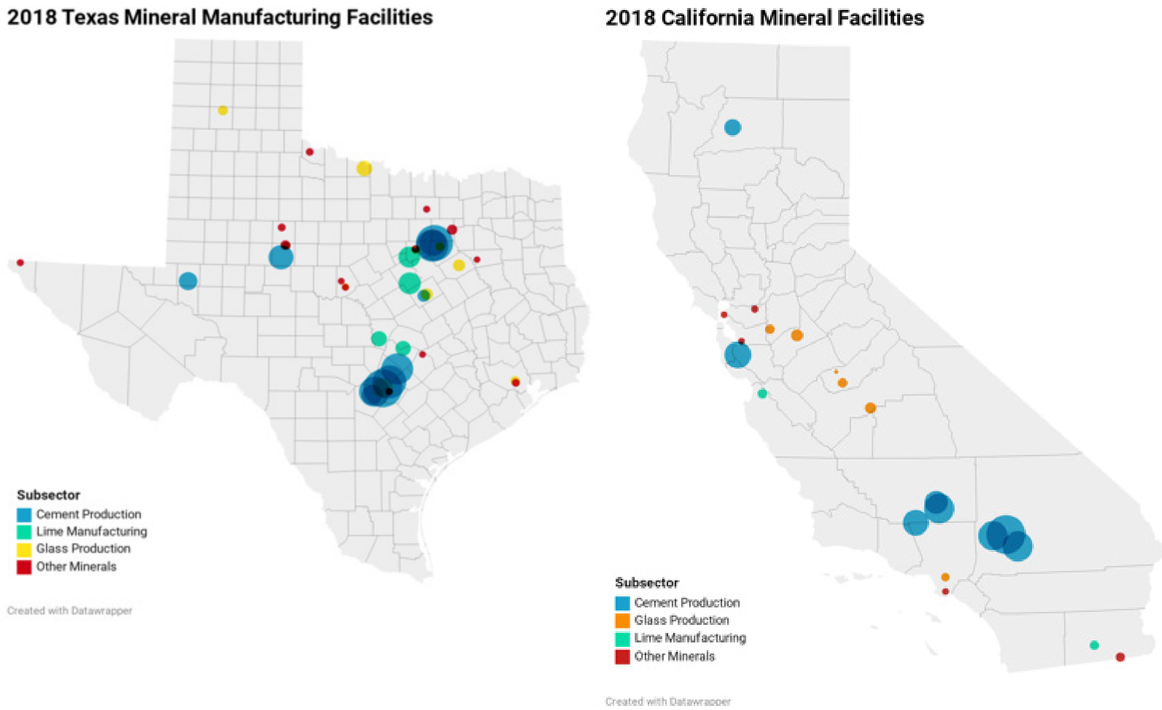
In California, some of the largest cement manufacturing facilities are located in the southern portion of the state, which according to the sedimentary map presented in Figure 15 has plentiful storage resources. However, the largest cement manufacturing facility, the CEMEX Construction materials plant, is located in San Bernardino County, which has inadequate storage resources.

57. Energy Transitions Commission, "Mission Possible: Reaching Net-Zero Carbon Emissions from Harder to Abate Sectors by Mid-Century: Sectoral Focus: Cement," Nov. 2018.

58. Arnout de Pee et al., "Decarbonization of Industrial Sectors: The Next Frontier," McKinsey & Company, June 2018.

59. Lawrence Irlam, "Global Costs of Carbon Capture and Storage," Global CCS Institute, June 2017.

Figure 19: Mineral Facility GHG Emissions in Texas and California



While a CCUS strategy is viable for the mineral sector in both California and Texas, reducing GHG emissions from Missouri, the state with the second-largest GHG emissions footprint from mineral facilities, presents more of a challenge. CCUS in Missouri would be very difficult to incentivize, considering the state has very poor storage resources. According to the Carbon Storage Atlas, Missouri is capable of storing just .11 billion metric tons of CO_2, which ranks 43rd in the U.S.[60] The state also does not have any CO_2-EOR projects currently in place or CO_2 pipeline infrastructure that it can use to transport captured CO_2. Decarbonizing Missouri's cement manufacturing facilities will likely rely on new innovations in cement admixtures to reduce process emissions.

Decarbonizing pulp & paper facilities

With the exception of Wisconsin, the states with the highest GHG emissions from the pulp & paper sector are all in the Southeast: Georgia, Alabama, and Louisiana. Together, these four states account for over a third of total GHG emissions from the pulp & paper sector. All emissions from the papermaking process come from using fossil fuels for heat and power — there are no process emissions, so decarbonizing these facilities will require switching to zero-carbon fuel sources or the application of CCUS.[61]

Georgia, Alabama, and Louisiana together produced over 9 MMT of CO_2e from this sector in 2018. While all these states have poor renewable resources, they all have excellent geological characteristics to build out a robust CCUS environment. As previously mentioned, Louisiana has

60. National Energy Technology Laboratory, *Carbon Storage Atlas, Fifth Edition*, (U.S. Department of Energy, 2015).

61. Duncan Leeson et al., "Techno-Economic Analysis and Systemic Review of CCS applied to Iron and Steel, Cement, Oil Refining, and Pulp and Paper Industries, as well as other High Purity Sources," *International Journal of Greenhouse Gas Control* 61, (June 2017): 71-84

the second-best CO_2 storage potential, while Georgia and Alabama have the 11th- and sixth-best storage resources in the U.S.[62] Additionally, the largest-emitting pulp & paper facilities in these states are located in the areas with high CO_2 storage potential.

While CCUS is a viable strategy to decarbonize pulp & paper facilities in the Southeast, this is not a technology that can be applied effectively in Wisconsin, the state with the second-largest GHG emissions from pulp & paper. According to the National Energy Technology Laboratory, Wisconsin has zero CO_2 storage resources.[63]

One potential option for decarbonizing pulp & paper facilities in Wisconsin is to use electrolysis-derived hydrogen as a fuel source. While Wisconsin currently has low renewable-energy penetration levels, it borders both Iowa and Minnesota, and as displayed in Figure 14, both these states have some of the cheapest wind PPA prices in the U.S. Wisconsin can leverage these cheap renewable resources and use electrolysis-derived hydrogen to decarbonize its pulp & paper facilities.

Employment in Counties with High Industrial GHG Emissions

It is critical to understand how decarbonization of the industrial sector will affect employment. While employment in manufacturing at the national level has declined over the past two decades, many counties still rely on the manufacturing sector as a major source of jobs.[64]

The table below displays the six counties with the highest GHG emissions from chemical manufacturing in the U.S., as well as the share of employment in each county coming from chemical manufacturing. All six counties, with the exception of Escambia, Fla., had a higher share of their workforces in chemical manufacturing than the national average of 15 employees per 1,000 jobs. Two of them, Ascension and St. Charles counties in Louisiana, had over 10 percent of their workforces in chemical manufacturing. Nationwide, 17 counties across the U.S. had more than 10 percent of their workforces in the chemical manufacturing sector.

Table 5: Chemical GHG Emissions and Employment from Top-Emitting Counties

County	Emissions (MT of CO2e)	Employment per 1,000 Jobs
Harris, TX	16,804,457	28
Ascension, LA	14,543,564	108
Escambia, FL	11,584,960	10
Brazoria, TX	11,561,822	94
Jefferson, TX	10,114,764	47
St. Charles, LA	5,333,829	124

The table below displays the six counties with the highest GHG emissions from mineral manufacturing in the U.S., as well as the share of employment in each county coming from mineral manufacturing. Three of them had a higher share of their workforces in mineral manufacturing than the national average of 12 employees per 1,000 jobs. However, only one had more than 10

62. National Energy Technology Laboratory, *Carbon Storage Atlas, Fifth Edition*, (U.S. Department of Energy, 2015).

63. Ibid.

64. Federal Reserve Bank of St. Louis, "*A Plateau for Manufacturing?*," 2018

percent of its workforce in this sector — Ste. Genevieve, Mo., where almost 20 percent of workers are in the industry. Nationwide, 17 counties had more than 10 percent of their workforces in the mineral manufacturing sector.

Table 6: Mineral GHG Emissions and Employment from Top-Emitting Counties

County	GHG Emissions (MT of CO2e)	Employment per 1,000 Jobs
Ste. Genevieve, MO	6,948,167	193
Sweetwater, WY	5,382,190	1
Shelby, AL	4,641,358	2
San Bernardino, CA	4,108,382	84
Ellis, TX	3,210,613	90
Comal, TX	3,049,054	9

The table below displays the counties with the highest GHG emissions from metal manufacturing in the U.S., as well as the share of employment in each county coming from metal manufacturing. Three had a higher share of their workforces in metal manufacturing than the national average of 15 employees per 1,000 jobs. However, only one, Porter County, Ind., had about 10 percent of its workforce in this sector. Eight counties across the U.S. had more than 10 percent of their workforces in the metal manufacturing sector.

Table 7: Metal GHG Emissions and Employment from Top-Emitting Counties

County	GHG Emissions (MT of CO2e)	Employment per 1,000 Jobs
Lake, IN	20,749,704	66
Porter, IN	8,784,160	99
Wayne, MI	5,595,688	8
Allegheny, PA	5,148,078	10
Butler, OH	4,843,080	17
Cuyahoga, OH	4,405,281	6

Strategies to decarbonize the sectors outlined in this paper have to be cognizant of their impact on employment. Critical considerations include whether or not a facility can be retrofitted with new technology; whether it can be relocated to take advantage of cheap renewables or CO_2 storage resources; whether supportive infrastructure can be built around it; or whether the facility will become a stranded asset. Although analyzing the employment effects of decarbonizing industry is outside the scope of this paper, analysis from the Rhodium Group concluded that investment in carbon capture retrofits would lead to the creation of 67,000-100,00 jobs on average per year over the next 15 years across 21 states.[65] Future research must also focus on exactly how these jobs are spread out across and within states, so that we may fully understand the effects of the decarbonization transition.

65. John Larsen, "The Economic Benefits of Carbon Capture: Investment and Employment Estimates for the Contiguous United States," Rhodium Group, October 2020.

Air Quality Impact of Reducing Industrial GHG Emissions

Deep decarbonization of the four sectors outlined in this paper will require significant investment in multiple areas, such as expansion of zero-carbon electricity, extensive retrofitting of industrial facilities with carbon capture and linkages to usage and storage systems, and a buildout of infrastructure to support a low-carbon economy. One way to strengthen the argument for rapid investment in these technologies is to highlight cases in which they would provide the dual benefit of reducing criteria air pollutants as well as GHG emissions.

Air pollutants and GHG emissions often come from the same sources. Overlaying the National Emissions Inventory point source dataset with EPA's FLIGHT database shows that five of the top 10 industrial GHG-emitting counties in the U.S. also have some of the highest levels of criteria air pollutant (CAP) emissions. For example, Lake and Porter counties in Indiana have the highest levels of CAP in the U.S and rank first and seventh, respectively, in terms of industrial GHG emissions.

Lake County has both the highest level of industrial GHG emissions and CAP in the entire state. The highest GHG-emitting facility, the U.S. Steel Gary Works facility, is also the largest source of CAP in the county and state. Porter County has the second highest level of industrial GHG emissions and CAP in the state. The largest source of emissions in Porter County, the ArcelorMittal steel facility, is also the largest source of CAP. There is a similar overlap between GHG and CAP-emitting facilities in other states and sectors. Many of the top GHG-emitting facilities in California, for example, are also significant sources of CAP. San Bernardino County, which has the third-highest GHG emissions in the state, has the second-highest level of CAP. The largest source of both GHG emissions and CAP is the CEMEX cement plant.

While carbon capture, electrification, and zero-carbon hydrogen can all contribute significantly to cutting GHG emissions, special consideration must be given to the wider environmental consequences of these technologies, specifically their ability to reduce CAP. Electrolysis-derived hydrogen produced with zero-carbon electricity would result in virtually zero criteria air pollutant emissions; however, this is not necessarily the case for other GHG emissions reduction technologies.[66]

A key challenge for the uptake of carbon capture technology is the increased energy that must be devoted to powering the CCUS process. Capturing and compressing CO_2 is an energy-intensive process, and energy demands can be increased 15-25 percent depending on the CCUS technology used, thus requiring more fuel to be combusted. Since more fuel is burned, but only carbon is captured, CCUS technology can increase conventional air pollution.[67] A study from the European Environment Agency found that fine particulate matter and nitrogen oxide increase roughly in proportion to fuel consumption, while ammonia emissions can more than triple if amine-based sorbents are used to capture the CO_2.[68] Emissions of sulfur dioxide, however, do decrease, since its removal is a technical requirement for CO_2 capture to take place.

66. Department of Energy, "*Hydrogen Production: Electrolysis*" 2020.

67. Toon van Harmelen et al., "Air Pollution Impacts from Carbon Capture and Storage,."EEA technical report 14/2011, (European Environment Agency, 2011).

68. Ibid.

An understanding of these synergies and tradeoffs among air pollutants and GHG emissions is critical to properly inform communities and policymakers of the advantages and disadvantages of using different decarbonization strategies and technologies.

Federal and State Policy Opportunities

While low-carbon industrial technologies and processes are not presently cost-competitive with conventional processes, public policy has barely begun to address either technological breakthroughs or commercial deployment for alternatives in these sectors.

A comprehensive federal and state policy context will help industries decarbonize by leveraging CO_2 storage capacity and cheap renewables where they are most available, and will create a robust innovation environment to move pilot-phase technology to commercial markets. This section will outline a policy framework that federal and state governments can begin to implement to incentivize the deployment and application of these technologies.

Federal policy opportunities

The federal government has a significant role to play if the U.S. is to achieve deep decarbonization of its industrial sector. Federal policy must provide an overarching framework if the U.S. is to reduce emissions across industrial sectors and across regions, and it can provide a robust backdrop for states to develop their own plans to address these emissions. This section reviews federal policy options.[69]

Carbon pricing with trade measures

CO_2 emissions are not currently priced, meaning emitters do not face costs for the societal damages caused by this pollution. This market failure requires a policy response. Carbon pricing is the most cost-effective climate policy since it internalizes the societal damage of CO_2 pollution, while providing flexibility for industry to implement the most cost-efficient emission reduction strategies. Carbon pricing is also a technology-neutral approach as it incentivizes a full range of decarbonization strategies. Incentivizing a wide basket of technologies is critical for industrial sector decarbonization, as different sectors and processes will require different technologies to decarbonize.

There are fears that a carbon price might lead to carbon leakage, or the reallocation of emitting industrial activities to jurisdictions with less stringent or no carbon pricing policies. For example, a study of the U.S. cement industry found that a carbon price of $60 per ton of CO_2, with all permits auctioned, would reduce U.S. emissions by almost 1,000 metric tons and increase foreign emissions by about 200 metric tons, a leakage rate of around 20 percent.[70] However, policies can be designed to address leakage and competitiveness concerns with a border tax adjustment, which imposes a tax to reflect embodied emissions on imported goods and a provides a rebate on exports.[71] The same study on the U.S. cement industry found that

69. The taxonomy of federal policy options to decarbonize industry comes from personal communications with Rick Duke, non-resident senior fellow at the Brookings Institution.

70. Meredith Fowlie et al., "Market-Based Emissions Regulation and Industry Dynamics" *Journal of Political Economy* 124, no. 1, (Feb. 2016).

71. Shuting Pomerleau, "Border Adjustments in a Carbon Tax," Niskanen Center, July 30, 2020).

application of a border tax adjustment would lead to a negative leakage rate, which means that this policy "reduces emissions among foreign producers relative to an unregulated baseline."[72]

Supply-side push incentives

Supply-side, push incentives for low-carbon technologies include measures that aim to deploy new technologies, either in the form of retrofits on existing facilities or the construction of new low-carbon facilities.

In the United States, the most prominent example of supply-side, push policies to decarbonize the industrial sector are clean energy tax credits. These include the 45Q tax credit for carbon capture utilization and storage technology, the investment tax credit (ITC) for solar projects, and the production tax credit (PTC) for onshore wind technology. The ITC and PTC have been critical to expanding the renewable energy industry in the U.S., and the 45Q tax credit has made the U.S. a global leader in CCUS technology, home to over half of the large-scale carbon capture facilities.[73] To qualify for the PTC, projects must have begun construction before the end of 2020, while the ITC for commercial solar projects phases down to 10 percent for projects beginning construction after 2021.[74] To be eligible for the 45Q tax credit, CCUS projects must begin construction before 2024.[75] However, the COVID-19 pandemic has stalled the development of clean energy projects, and has slowed down tax equity markets that have traditionally been used to finance these projects.[76] Policymakers could extend the project eligibility deadlines to account for the impact COVID-19 has had on clean energy projects. Additionally, tax credits could be expanded for other low-carbon technologies that will be critical to decarbonizing the industrial sector, such as electrolyzers, offshore wind, and battery storage technology.

Most promising low-carbon technologies for the industrial sector are stuck in either the research or pilot phase. If the industrial technologies needed for decarbonization of this sector are going to scale in a timely manner, the U.S. will need a policy mechanism to move innovative technologies from the R&D phase to full-scale deployment.

The Clean Industrial Technology Act of 2019 looks to address this by requiring the DOE to offer grants and cost-sharing programs to firms that are ready to move from emission reduction technologies from the R&D and pilot phases to full-scale deployment in the industrial sector.[77]

Government Procurement

Creating demand for decarbonized industrial goods helps low-carbon manufacturers scale their operations because it provides them with the certainty that they can sell their goods. Just as the

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72. Meredith Fowlie et al., "Market-Based Emissions Regulation and Industry Dynamics" *Journal of Political Economy* 124, no. 1, (Feb. 2016).

73. Global CCS Institute "*The Global Status of CCS Report 2020*," 2020.

74. Bidisha Bhattacharyya "Renewable Energy tax Credits; The Case for Refundability" Center for American Progress, May 28, 2020.

75. Angela Jones and Molly Sherlock, "The Tax Credit for Carbon Sequestration (Section 45Q)," Congressional Research Service March 12, 2020.

76. Brian Eckhouse, "Covid Created a U.S. Clean Energy Shortfall of Up to $23 Billion," Bloomberg New Energy Finance, July 15. 2020.

77. Rep. Sean Casten "*H.R. 4230-Clean Industrial Technology Act of 2019*," August 14, 2020.

government has done for energy efficiency and renewable energy, it could set procurement standards for major segments of the industrial sector.

Federal, state, and city governments directly or indirectly buy significant volumes of industrial products. Federal and subnational government procurement accounts for about "90 percent of cement and concrete, 50 percent of steel and 5 percent of fuels," giving the federal government an excellent opportunity to leverage its buying power to transition industry production to focus on low-carbon products.[78] A federal procurement policy can provide an important backstop to encourage and scale state policies to pursue industrial sector decarbonization. This amount of procurement could very well lead to the economies of scale required to make decarbonized industrial processes and technologies cheaper than current industrial practices.

Research & Development funding

Research, development, and demonstration is critical to ensure long-term deep decarbonization of the industrial sector. Despite attempts by the Trump administration to slash the budget for energy R&D, Congress has approved increases for DOE's energy-related research every year since 2015.[79] However, significantly more funding is needed if the U.S. is going to scale up critical technologies for industrial decarbonization. Out of a total budget of nearly $4.8 trillion in FY 2020, about $38.6 billion was authorized for DOE funding, with only $8 billion of that supporting energy innovation.[80] When measuring R&D for energy as a percentage of GDP, the U.S. ranks 14th, significantly lower than China, Japan, and Korea.[81]

One potential avenue to ensure that energy R&D is not only maintained, but grows to the levels required to accelerate decarbonization, is for the U.S. to fulfill its overdue pledge under the multilateral 2015 Mission Innovation framework to increase the federal energy R&D budget to $12.8 billion.[82] This amount of R&D funding could allow DOE to focus on industrial technologies that can replace natural gas, oil, or coal -fired processes used today.

Support infrastructure

A decarbonized industrial sector and the low-carbon technologies that support it will require overhauling the systems we use to deliver energy and feedstocks across the country. This will include new transmission to move renewable and other carbon-free electricity from where it is produced to industrial facilities that demand it, additional CO_2 pipelines to transport captured CO_2 from areas with few storage resources to areas with more storage potential, and pipelines to bring carbon-free hydrogen to industrial facilities. The federal government can play a key role in facilitating the development of this infrastructure by streamlining permitting and helping with financing.

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78. Julio Friedmann "Challenges and Solutions for U.S. Industrial Decarbonization," Columbia Center on Global Energy Policy, Sep. 18, 2019.

79. Colin Cunliff, "Energy Innovation in FY 2021 Budget: Congress Should Lead," Information Technology & Innovation Foundation, March 30, 2020.

80. Ibid.

81. Ibid

82. Department of Energy, "Mission Innovation at DOE,".

For example, financing of CO_2 and hydrogen pipelines via DOE's Loan Programs Office could leverage low-interest loans and provide the upfront capital needed to build these pipelines.[83] Additionally, these infrastructure projects could be streamlined by expanding the scope of the Transportation Infrastructure Finance and Innovation Act.[84] This program provides long-term low-interest loans and other instruments so that projects do not have to rely on pay-as-you-go funding mechanisms, which allows for projects to be constructed years earlier.[85]

State policy and regulatory opportunities

The federal policies mentioned above provide important context to complement state policies and plans to reduce industrial GHG emissions. Just as GHG emission reductions experienced in the electricity sector were largely driven by state policy, the states offer a promising environment to test policies for industrial sector GHG emission reductions and to cooperate in regional decarbonization strategies. State legislatures and regulatory bodies have options at their disposal to encourage the deployment of the technologies that will be critical to decarbonizing U.S. industry.

A growing number of U.S. states have set goals to reach net-zero emissions by midcentury, including Michigan, California and Louisiana.[86] The industrial sector makes up roughly 11, 20, and 60 percent of total CO_2 emissions in these states respectively.[87] Industrial emissions will need to be addressed sooner rather than later if these states are to meet their targets.

Expanding the scope of RPS

A state-level policy that has been critical to driving down electricity sector GHG emissions is the imposition of renewable portfolio standards (RPS). RPS require utilities to produce "either a percentage of load or a set amount of generation from renewable resources."[88] Currently, 29 states plus Washington, D.C., have adopted RPS.[89] Reforming RPS to include a wider basket of other low- and zero-carbon electricity sources would set an important foundation for electrification and electrolysis-derived hydrogen to effectively reduce emissions, while also pushing CCUS technology down the cost curve. Expanding these policies across U.S. states would allow regional markets to decarbonize in line with local resources, which would be cheap wind power in the Midwest, CCUS in the Gulf Coast, and solar power in the Southwest.

State-based carbon pricing schemes

The U.S. currently has two subnational emission trading programs, the Regional Greenhouse Gas Initiative (RGGI) and California's cap-and-trade program. RGGI is a cooperative effort among 10

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83. *21st Century Energy Infrastructure: Policy Recommendations for Development of American CO2 Pipeline Networks* (State CO2-EOR Deployment Work Group, 2017).

84. William Mallett, *The Transportation Infrastructure Finance and Innovation Act Program*, CRS Report R45516 (Congressional Research Service, Feb. 15, 2019).

85. Ibid.

86. Kassia Micek "Commodities 2021: States Racing to set goals toward net-zero emissions, 100% renewable electricity" S&P Global Platts, Dec 24, 2020.

87. Energy Information Administration "Energy-Related CO2 Emission Data Tables" March 2021.

88. Kiera Zitelman et al., "Carbon Capture, Utilization, and Storage: Technology and Policy Status and Opportunities," National Association of Regulatory Utility Commissioners, November 2018.

89. Center for Climate and Energy Solutions, "U.S. State Electricity Portfolio Standards," Nov. 2019.

states in the Northeast to cap and reduce CO_2 emissions from the power sector. RGGI incentivizes technologies that will be critical to reducing industrial sector emissions. A more direct approach would be to create an emission trading scheme that covered industrial sectors directly.

California's cap-and-trade program covers approximately 80 percent of economywide emissions, and is applied to major industrial emitters such as cement, glass, hydrogen, iron and steel, and pulp & paper producers.[90] Since it launched in 2013, total GHG emissions in California have fallen roughly 6 percent, and total industrial sector GHG emissions in the Golden State have also fallen, although by a smaller margin.[91] By applying the cap-and-trade program apply to the industrial sector, California is not only helping scale the more well-developed technologies such as CCUS and renewable hydrogen, but also providing firms with incentives to develop other low-carbon technologies — for example, cement admixtures that do not release process emissions.

The auctioning of credits in these cap-and-trade programs raises revenue that the states use for other emission reduction activities. For instance, revenue raised through RGGI auctions goes primarily towards energy efficiency upgrades, but also supports initiatives to deploy more clean and renewable energy and to provide direct bill assistance to consumers in the RGGI region.[92] The revenue raised by California's cap-and-trade goes towards supporting the state's electric vehicle tax programs, renewable energy goals, and other environmental programs carried out by local governments.[93] Policymakers could use a portion of the revenue raised by cap-and-trade programs to support pilot programs to deploy more innovative technologies relevant to industrial decarbonization.

Low-carbon fuel standard

Another state policy that has the potential to grow across the U.S. is the low-carbon fuel standard, which California has implemented. While the LCFS is designed to reduce GHG emissions in the transportation sector, it can help improve the economics of both renewable hydrogen and CCUS technology and thus make it more cost-competitive to apply these technologies at industrial facilities. An LCFS works by setting an annual carbon intensity, which declines over time, and then lets the market determine which mix of fuels will be used to reach the program targets. For example, California's Air Resource Board has targeted a 20 percent decline in the carbon intensity of the state's transportation fuels, relative to a 2010 baseline, by 2030.[94] In California, this state policy has helped hydrogen become a more cost-competitive fuel source, and can now also help the deployment of CCUS technology since it was recently expanded to allow transportation fuels produced using CCUS to generate credits.[95]

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90. International Carbon Action Partnership "USA-California Cap-and-Trade Program," March 2021.

91.California Air Resources Board, "California Greenhouse Gas Emissions for 2000 to 2018," 2020.

92. Regional Greenhouse Gas Initiative "The Investment of RGGI Proceeds in 2018," July, 2020.

93. California Air Resources Board, "California Climate Investments Using Cap-and-Trade Auction Proceeds," March, 2019.

94. Tani Colbert-Sangree, "The Low Carbon Fuel Standard Has Succeeded, But How Does It Work?," GHG Management Institute, January 22, 2020.

95. Alex Townsend and Ian Havercroft, *The LCFS and CCS Protocol: An Overview for Policymakers and Project Developers*, (Global CCS Institute, 2019).

Buy Clean programs

Just as California implemented the first carbon trading scheme in the U.S. the state also was the first to institute a Buy Clean standard, which requires government agencies to consider "suppliers' greenhouse gas emissions when purchasing materials such as steel and glass for infrastructure projects."[96] Currently, California's Buy Clean program covers just four construction materials: "concrete-steel rebar, flat glass, structural steel, and mineral-wool board insulation."[97] Considering California spends $10 billion per year on in-state infrastructure projects, this is a serious incentive for manufacturers to reduce the carbon intensity of their goods.[98]

However, the scope of the program could be widened to include other major industrial emitters in the state. Cement, which is the second-largest source of industrial GHG emissions in the state, was not included in the program. Other states, such as Washington, Oregon, and Minnesota, are currently considering adopting Buy Clean programs.[99]

Underground injection control program primacy

A critical aspect of deploying more CCUS technology at facilities across the U.S. is clearing up the regulatory barriers that govern this technology, specifically the permitting structure for CO_2 sequestration. The current permitting structure for CO_2 sequestration in wells is onerous, with CO_2-EOR storage wells, permanent underground storage wells (which require a permit process from the EPA), and storage wells in state lands (including offshore/coastal areas) all requiring a separate permitting process.[100] States can substantially clear up all these blurry lines and permitting pathways by applying to take over the so-called Class VI permitting process from the EPA. In 2018, EPA granted North Dakota's request to enforce its own Class VI program, and later Wyoming was also given the go-ahead to permit Class VI wells.[101] States around the Gulf, primarily Texas, could follow suit to create the necessary regulatory environment to rapidly deploy CCUS technology.

Long-term sequestration liability

Long-term liability for carbon storage sites also creates regulatory uncertainty around CCUS. While EPA has provided some regulation on storage of CO_2 in the subsurface, "responsibility for the long-term management of a storage site after it has been formally closed by the EPA still needs to be resolved."[102] As of now, five states — "Illinois, Louisiana, Montana, North Dakota, and Texas — have passed legislation that transfers liability for CO_2 storage sites to the state after a certain amount of time."[103] In Texas, the State only manages the long-term liability of offshore wells. Louisiana and North Dakota assume liability 10 years after well closure. Transferring long-term liabil-

96. Sam Ricketts et al., "States are Laying a Road Map for Climate Leadership," Center for American Progress, April 30, 2020.

97. Kriston Capps, "Is the Buy Clean California Act Clean Enough," Royal Institute of Chartered Surveyors, January 8, 2020.

98. Construction Climate Challenge, "California Introduces 'Buy Clean' law to drive low-carbon procurement," 2018.

99. Sam Ricketts et al. "States are Laying a Road Map for Climate Leadership," Center for American Progress, April 30, 2020.

100. Tracey Hester and Elizabeth George, "The Top-Five Legal Barriers to Carbon Capture and Sequestration in Texas," Forbes, Nov. 19 2019.

101. Ibid.

102. Steven Anderson, "Risk, Liability, and Economic Issues with Long-Term CO2 Storage-A Review," *Natural Resources Research* 26 No. 1, (January 2017).

103. Kiera Zitelman et al., *Carbon Capture, Utilization, and Storage: Technology and Policy Status and Opportunities*, (National Association of Regulatory Utility Commissioners, November 2018).

ity of storage sites to the state requires sufficient funding to ensure that the state can effectively manage the site. Kansas, Louisiana, Montana, North Dakota, Wyoming, and Texas have funds for the long-term management and monitoring of carbon storage sites, but more states could follow suit to create a more stable investment environment for CCUS.[104]

Conclusion

Fully decarbonizing U.S. industry is essential if we are to achieve climate stabilization and reach net-zero greenhouse gas emissions by midcentury. The geographic analysis presented in this paper provides an understanding of the regional, technological, and economic realities of decarbonizing U.S. industry. It is critical that we scale up the full range of technologies — carbon capture, electrification, and zero-carbon hydrogen. But each region will need a different mix based on its profile — specifically, the availability of low-cost zero-carbon electricity and carbon sequestration resources. An analysis of these local characteristics reveals that CCUS will likely play a large role in the decarbonization strategies of industrial facilities in the Gulf, while industrial facilities in the Midwest can leverage cheap and abundant zero-carbon electricity resources. These decarbonization strategies must be supported by a robust policy environment at both the federal and state levels to ensure that the industrial sector at the core of developing low-carbon solutions is low-carbon itself.

About the Author

Nader Sobhani is a climate policy associate at the Niskanen Center. His areas of research include environmental tax reform and clean energy policy. Prior to joining the Niskanen Center in 2018, he was an analyst at the Foreign Policy Group, where he focused on identifying the economic impacts and policy implications of emerging trends, with a special focus on energy and global health. He graduated from the London School of Economics and Political Science with a Master of Science in Environmental Economics & Climate Change and holds a B.A. in International Relations from Virginia Tech.

104. Ibid.