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Industrial Electrification in U.S. States

An industrial subsector and state-level techno-economic analysis

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Foreword by the authors

This report is a follow-up study to our previous report, "**Electrifying U.S. Industry: A Technology- and Process-Based Approach to Decarbonization.**" In the previous report, we studied the electrification potential for U.S. industry across 12 sub-sectors at the national level. In this report, we analyze the electrification potential for the same 12 sub-sectors, but at the state level, focusing on 20 states. The differences in industries, energy prices, and electricity grid emissions factors across different states are considered in this study to determine the electrification potential.

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Executive Summary

The United States set an economy-wide target to reduce its net greenhouse gas (GHG) emissions to 50-52% below 2005 levels by 2030 and set a goal to reach 100% carbon pollution-free electricity by 2035. Meeting these goals will require a concentrated effort to develop and deploy clean technologies across sectors. The U.S.'s emissions reduction targets place a new emphasis on industrial emissions, highlighting the need for commercialization and deployment of cleaner industrial technologies. Unleashing US$369 billion in climate and clean energy incentives, the Inflation Reduction Act (IRA) provides powerful tailwinds for achieving these climate change mitigation targets.

The industrial sector accounts for about a quarter of energy use and GHG emissions in the U.S. While emissions from electricity generation continue to decline, thermal energy needs in industry, especially for process heating, are a significant challenge for climate change mitigation efforts.

There is a significant opportunity to decarbonize the industrial sector by shifting away from carbon-intensive fossil fuels to clean sources such as electrification, where low- or zero-carbon electricity is used. As can be seen in Figure ES1, electrifying just the processes included in the study has the potential to realize significant emissions reductions throughout the country.

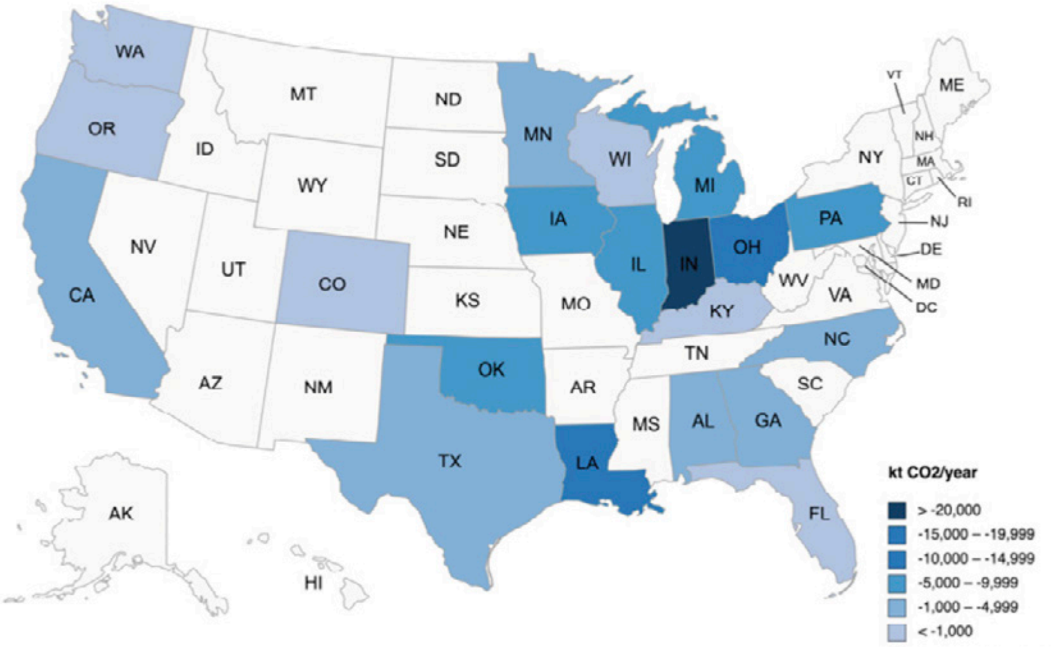

Figure ES1. Change in emissions from select industrial process electrification in 2050 (Source: this study)

This report is a follow-up study to our previous report, "Electrifying U.S. Industry: A Technology- and Process-Based Approach to Decarbonization." In the previous report, we studied industrial electrification potential at the national level. In this report, we analyze the electrification potential for 12 industries (aluminum casting, pulp and paper, container glass, ammonia, methanol, recycled plastic, steel, beer, beet sugar, milk powder, wet corn milling, and soybean oil) in 20 states. The industries with the highest emissions reduction potential in each state are shown in Figure ES2.

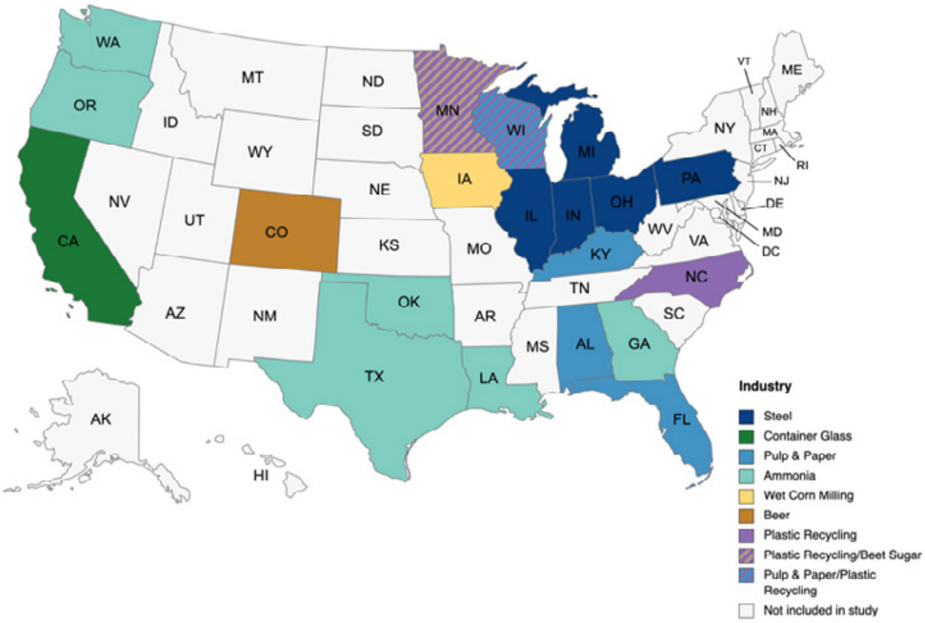

Figure ES2. Industries with the highest emissions reduction potential from electrification in 2050 (Source: this study)

The report identifies specific processes that could be electrified in the near term with commercially available technologies and analyzes the expected changes in energy use, CO_2 emissions, and energy costs. Understanding which conventional processes could be electrified and how this impacts emissions and costs can help industrial facilities identify which of their processes may be suitable candidates for electrification. In addition, understanding the potential growth in industrial electricity demand that will result from electrification can help utilities, grid operators, and electricity generators plan for these changes and ensure equipment and generation resources are available to meet the growing demand for renewable electricity.

It should be noted that, in practice, electrification projects will happen at the plant level. If a given industrial facility in any state electrifies its process heating demand today and purchases renewable electricity (e.g., through a power purchase agreement (PPA)) to supply the electricity demand of the electrified process heating, the CO_2 emissions reductions from electrification can be achieved immediately. Therefore, our state-level results that are based on expected grid-wide decarbonization timelines should not over-ride the immediate decarbonization impact of an electrified plant partnered with a new renewable energy purchase. Plants do not need to wait until the grid is decarbonized to have emissions reduction impacts.

Emissions reductions have global benefits, helping to mitigate climate risks and climate change impacts around the world. But reducing emissions has local benefits too. When industrial facilities use fossil fuels on-site, surrounding communities can be impacted by the resulting air pollution. In the U.S., low-income communities are often exposed to higher levels of air pollution in urban and rural areas, and in all states. Industrial electrification offers an opportunity to reduce localized emissions and improve health outcomes for communities.

Electrifying industrial processes and realizing these benefits will require a multifaceted effort to solve significant challenges in renewable electricity generation and transmission, technology development and deployment, and workforce development. This report recommends six impactful changes that would support increased industrial electrification: 1) Support demonstration of emerging electrification technologies and new applications of existing technologies, 2) Financially incentivize electrification, 3) Increase renewable electricity generation capacity, 4) Enhance the electricity grid, 5) Engage communities, and 6) Develop the workforce.

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1 Introduction

The United States set an economy-wide target to reduce its net greenhouse gas (GHG) emissions to 50-52% below 2005 levels by 2030 and set a goal to reach 100% carbon pollution-free electricity by 2035. (UNFCCC 2021). Meeting these goals will require a concentrated effort to develop and deploy clean technologies across sectors. The electricity generation and transportation sectors have benefitted from two decades of supportive policies for and investments in technology research and development, while similar support for the industrial sector has lagged behind. The U.S.'s emissions reduction targets place a new emphasis on industrial emissions, highlighting the need for commercialization and deployment of cleaner technologies. Unleashing US$369 billion in climate and clean energy incentives, the Inflation Reduction Act (IRA) provides powerful tailwinds for achieving these climate change mitigation targets.

Industrial electrification offers a pathway to decarbonize numerous industrial thermal processes. Further renewable electricity deployment reduces grid emissions factors across the country, creating a near-term opportunity to reduce industrial thermal emissions through electrification. This report identifies specific industrial thermal processes that could be electrified, many with commercially available technologies.

1.0. The Industrial Thermal Energy Challenge

Industrial thermal energy needs, especially for heat, are a significant challenge for climate change mitigation efforts. Heat represents two-thirds of all energy demand in the industrial sector (IEA 2018a). However, only 10% of this demand is met using renewable energy (OECD/IEA 2014). In the United States, due in large part to the country's relatively inexpensive natural gas, fossil fuel combustion to produce heat and steam used for process heating, reactions, evaporation, concentration, and drying creates about 52% of the country's industrial direct GHG emissions (McMillan 2017).

Despite industrial thermal's significant contributions to global energy demand and GHG emissions, scalable, cost-effective solutions to address thermal energy emissions from the process and other on-site heating and cooling needs are not widely available. This is contrasted with the transportation and power sectors, where available renewable electricity, electric vehicles, and new mobility strategies reflect important progress over the past two decades.

Renewable thermal energy solutions, including electrification solutions, face many technology, market, and policy barriers that hinder their development and deployment at scale, as described in our prior report (Hasanbeigi et al. 2021). Thermal energy faces several unique challenges when compared with renewable electricity. Thermal needs vary tremendously from one industrial process to another and are often site- or sector-specific. Processes also require heat at widely different temperatures, and solutions for high-temperature processes differ greatly from low-temperature processes.

Many industrial thermal energy buyers have set for themselves ambitious, science-based emissions reduction targets, recognizing the urgent need to reduce emissions not only from electricity generation but also from thermal energy consumption. But meeting these individual goals, as well as the nation's emissions reduction goals, will prove challenging without further development and deployment of emissions-reducing technologies.

1.1. The Electrification opportunity

There is a significant opportunity to decarbonize the industrial sector by shifting heat production away from carbon-intensive fossil fuels to clean sources such as electrification, where low- or zero-carbon electricity is used. Globally, more than 50% of the final energy demand is for heating, and about half is for industrial heating (IEA 2018b). There is substantial unrealized potential to electrify industrial processes at low and medium temperatures. Some industries have also electrified high-temperature processes, such as the steel industry using electric arc furnaces.

However, much of the electrification discussion to date has focused on the transportation and building sectors, with little attention paid to the industrial sector. This report aims to fill some of that void by examining industrial subsectors' heat consumption profiles and electrification potential based on existing heat demand profiles and electrification technologies available to meet those heating needs.

The report identifies specific processes that could be electrified in the near term with commercially available technologies and analyzes the expected changes in energy use, CO_2 emissions, and energy costs. Understanding which conventional processes could be electrified and how this impacts emissions and costs can help industrial facilities identify which of their processes may be suitable candidates for electrification. In addition, understanding the potential growth in industrial energy demand that will result from electrification can help utilities, grid operators, and electricity generators plan for these changes and ensure equipment and generation resources are available to meet the growing demand for renewable electricity.

Electrifying industrial processes has the potential to reduce emissions throughout the states studied, as seen in Figure 1. This map shows the change in emissions from industrial process electrification in 2050 .

Industrial electrification and associated emissions reductions offer potential co-benefits, including improved air quality and public health, reduced air pollution abatement costs, labor productivity, and crop yield benefits. However, it is important to ensure that these co-benefits are equitably realized, as nearly all major emission source sectors, including industry, disproportionately affect people of color, and while air quality has improved in the U.S. over the past several decades, people of color, particularly Black and Hispanic Americans, are still exposed to higher-than-average levels of air pollution. Identifying and analyzing all co-benefits when developing industrial electrification programs, plans, and policies can help to increase uptake. Additional information on co-benefits is found in chapter 5.

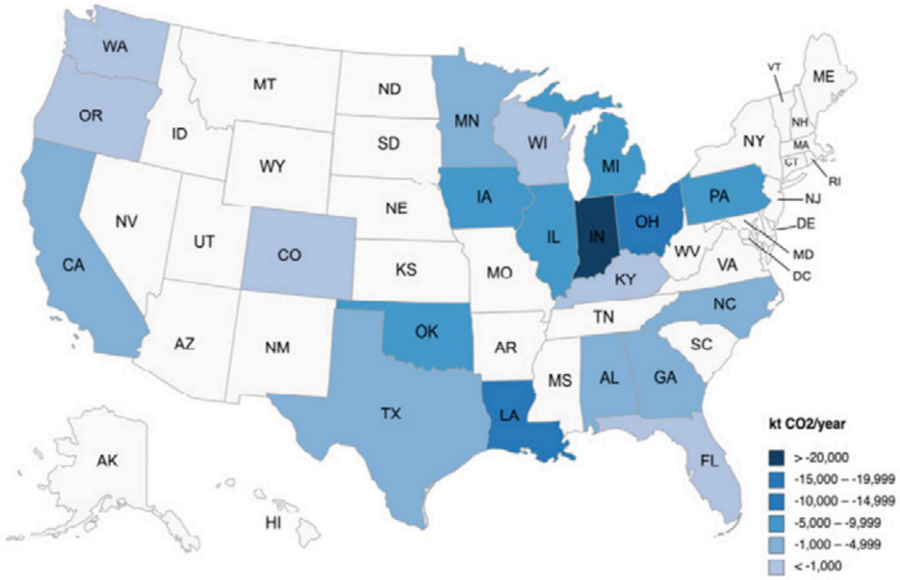

Figure 1. Change in emissions from industrial process electrification in 2050

1.2. A Sector- and State-Specific Analysis

This report is comprised of a bottom-up industrial subsector, systems, and technology-level assessment of the technologies available and the potential for electrification, in 12 industrial subsectors in 20 states in the U.S. As can be seen in the map in Figure 2, the sectors with the highest emissions reduction potentials vary across the states studied, though several trends do emerge. There is clear potential to reduce emissions in the Great Lakes region through steel electrification, while the Pacific Northwest and Gulf Coast regions, as well as Georgia, could see the largest emissions reductions from ammonia electrification. Electrifying the pulp and paper industry has the potential to significantly reduce emissions in several states, including Alabama, Florida, Kentucky, and Wisconsin. Additional state-level analysis looking across industrial subsectors is found in the individual state factsheets in Appendix 4.

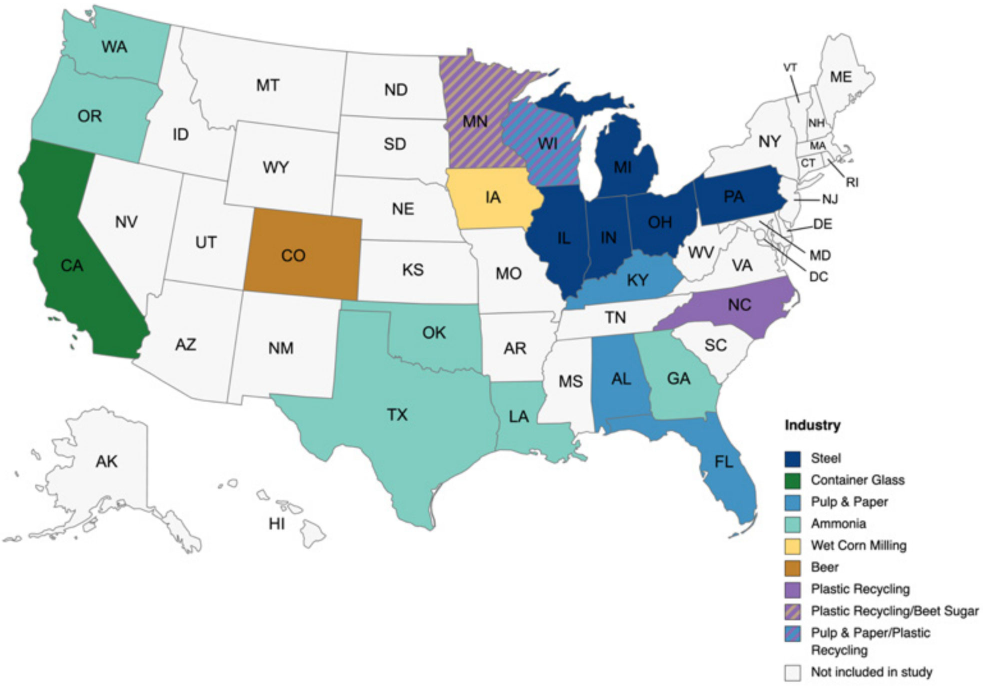

Figure 2. Industries with the highest emissions reduction potential in 2050

The report also considers the implications of industrial electrification on future electricity generation, transmission, and distribution in chapter 4. As the buildings, transportation, and industrial sectors push to electrify and decarbonize, demand for renewable electricity will increase, placing additional strain on already aging electricity grid infrastructure. These grid impacts must be considered and addressed to ensure a smooth transition to electrification and to realize emissions reductions.

As noted above, the report also examines the importance of identifying and quantifying industrial electrification co-benefits in chapter 5. Taking near-term co-benefits such as improved air quality into account when developing and assessing industrial electrification projects can offer a holistic view of a project and make the benefits more tangible. While the U.S. has already realized public health and ecosystem benefits from improved air quality programs, these benefits have not been equally felt across our communities, as people of color continue to have higher exposures to poor air quality and resulting negative health outcomes. Industrial electrification offers an opportunity to reduce emissions in frontline communities and equitably distribute climate mitigation resources. Finally, in chapter 6, the report offers six recommendations that would have the most impact on increasing industrial electrification.

2 U.S. Industrial Energy use and Heat Consumption Profile

The U.S. industrial sector accounts for about a quarter of energy use and greenhouse gas (GHG) emissions in the U.S. The majority of the energy used in the U.S. industry is fossil fuels (U.S. DOE/EIA 2020). In 2018, thermal processes accounted for 74% of total manufacturing energy use in the U.S.; process heating accounted for 35%, combined heat and power or cogeneration accounted for 26%, and conventional boilers accounted for 13% (estimated from U.S. DOE/EIA 2021 and U.S. DOE 2019) (Figure 3).

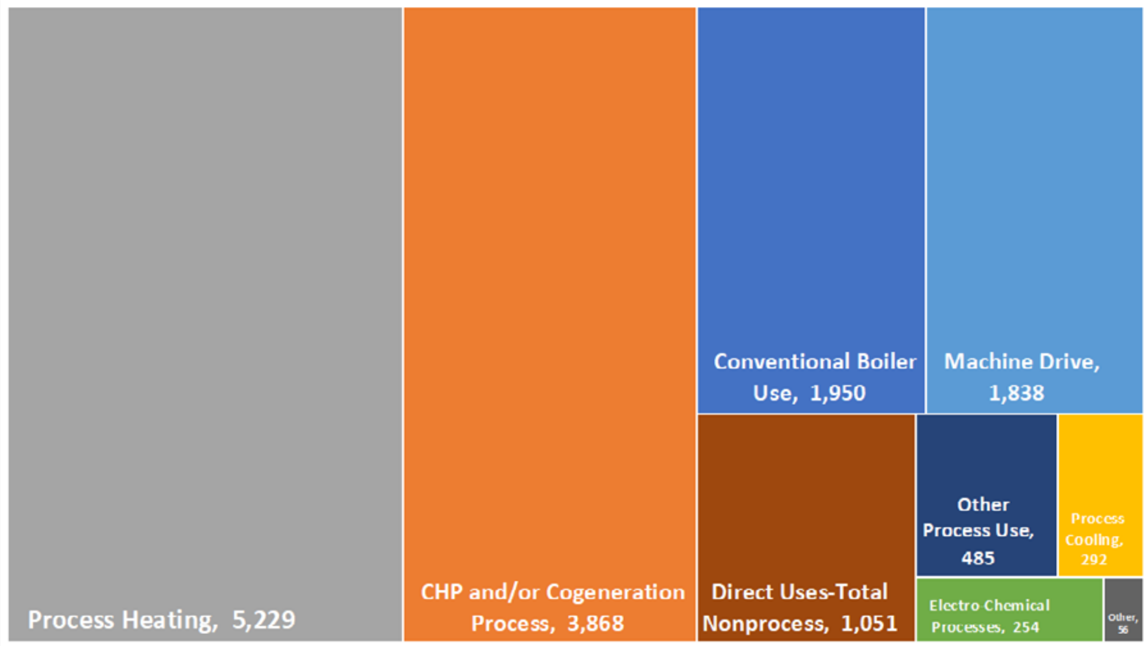

Figure 3. U.S. manufacturing energy use by end uses in 2018 - values in trillion Btu[1] (estimated from U.S. DOE/EIA 2021 and U.S. DOE 2019)

Note: Process heating, process cooling, machine drives, and other processes use steam. We only report the energy use for steam under conventional boiler and CHP to avoid double counting.

Five industries account for more than 80% of all U.S. manufacturing thermal process energy consumption: petroleum refining, chemicals, pulp and paper, iron and steel, and food and beverage (U.S. DOE/EIA 2021).

The level of industrialization varies across states. Some states, such as Texas, Louisiana, California, Illinois, Ohio, and Indiana, have a large industrial sector and are among the highest industrial energy-consuming states, while states such as Rhode Island, New Hampshire, Vermont, and Hawaii have small industrial sectors. Figure 4 shows the ranking of all 50 states in terms of annual industrial energy consumption.

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[1] 1 trillion btu = 1,055 TJ

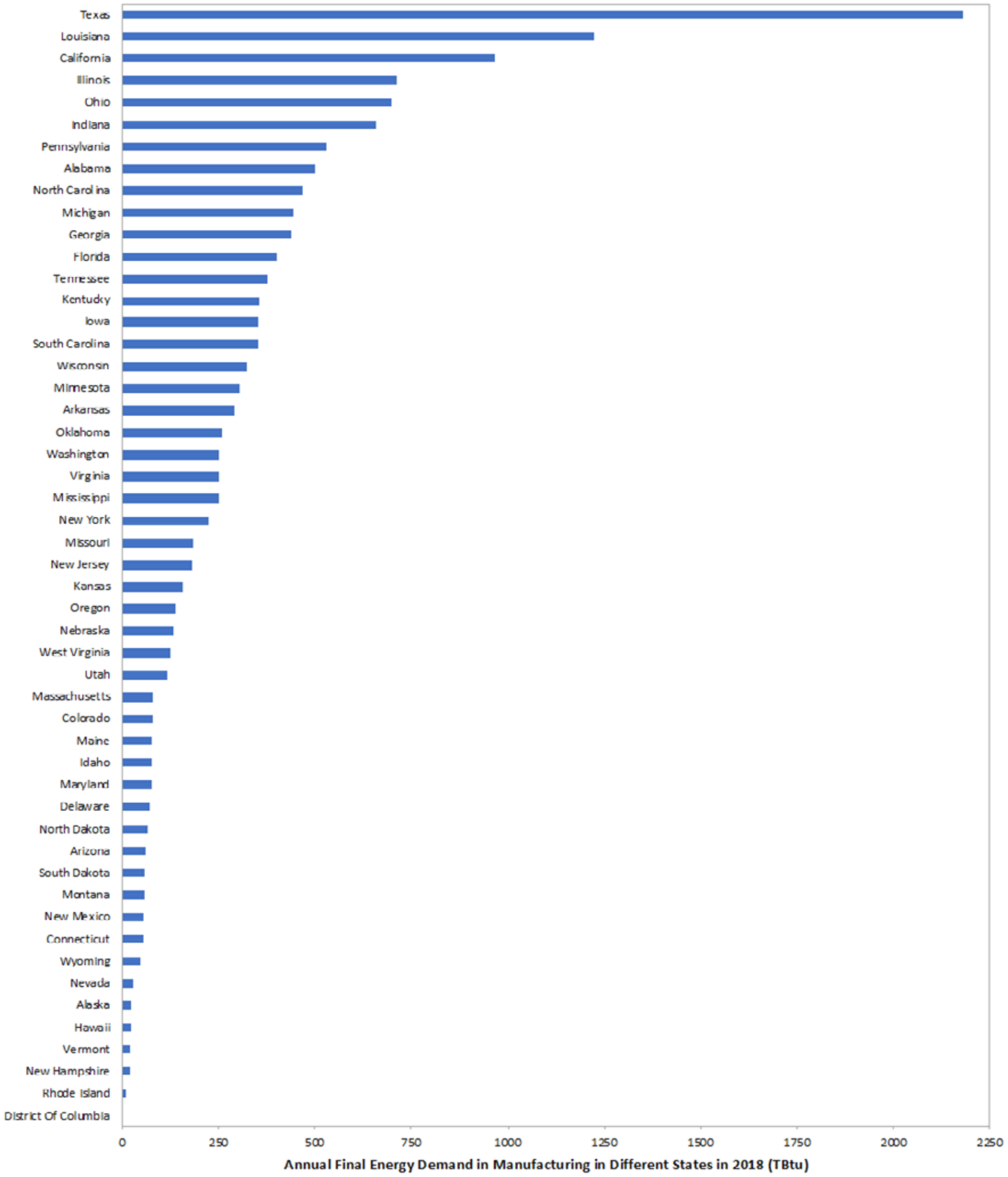

Figure 4. Annual energy demand by the manufacturing sector in each U.S. state in 2018 (values in Trillion Btu) (Estimated based on: U.S. DOE/EIA 2021, U.S. DOE 2019, and McMillan et al. 2018)

Industrial process heating operations include drying, heat treating, curing and forming, calcining, and smelting. Process heating technologies can be grouped into four general categories based on the type of energy consumed: direct fuel-firing, steam-based, electric-based, and hybrid systems (which use a combination of energy types). In process heating, the material is heated by heat transfer from a heat source such as a flame, steam, hot gas, or an electrical heating element by conduction, convection, or radiation — or some combination of these. In practice, lower-temperature processes tend to use conduction or convection, whereas high-temperature processes rely primarily on radiative heat transfer. Energy use and heat losses from the system depend on process heating parameters, system design, operating practices, and other factors (ORNL 2017).

Around 30% of total U.S. industrial heat demand is required at low temperatures below 100°C. Two-thirds of U.S. industrial process heat is for applications below 300°C, considered medium temperatures (Figure 5) (McMillan 2019). In the food, beverage, and tobacco; transport equipment; machinery; textile, and pulp and paper industries, the share of heat demand at low and medium temperatures is about, or even above, 60% of the total heat demand. With a few exceptions, it is generally easier to electrify low-temperature processes than high-temperature processes because of lower capital cost, availability of electrification technologies, and other reasons. Therefore, there is significant potential for industrial process electrification for low- or medium-temperature heating applications.

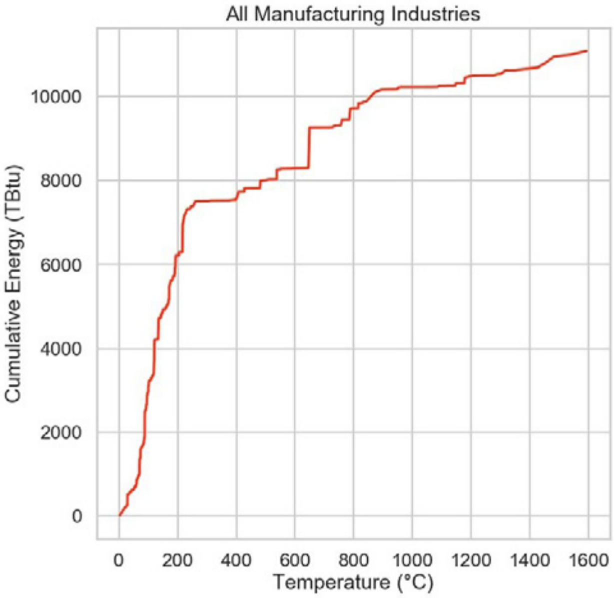

Figure 5. Cumulative process heat demand by temperature in 2014 (McMillan 2019)

The industrial sector uses a wide variety of processes employing different types and designs of heating equipment. Process heating methods used in manufacturing operations largely depend on the industry, and many companies use multiple operations. For example, steelmaking facilities often employ a combination of smelting, metal melting, and heat-treating processes. Chemical manufacturing facilities may use fluid heating to distill a petroleum feedstock and a curing process to create a final product, as well as other process heating methods for the production of other products (ORNL 2017).

Unsurprisingly, many of the states with the highest industrial energy consumption also have the highest industrial CO_2 emissions. Figure 6 shows industrial CO_2 emissions for all 50 states. Texas, Louisiana, and California have the highest levels of both industrial energy consumption and industrial CO_2 emissions.

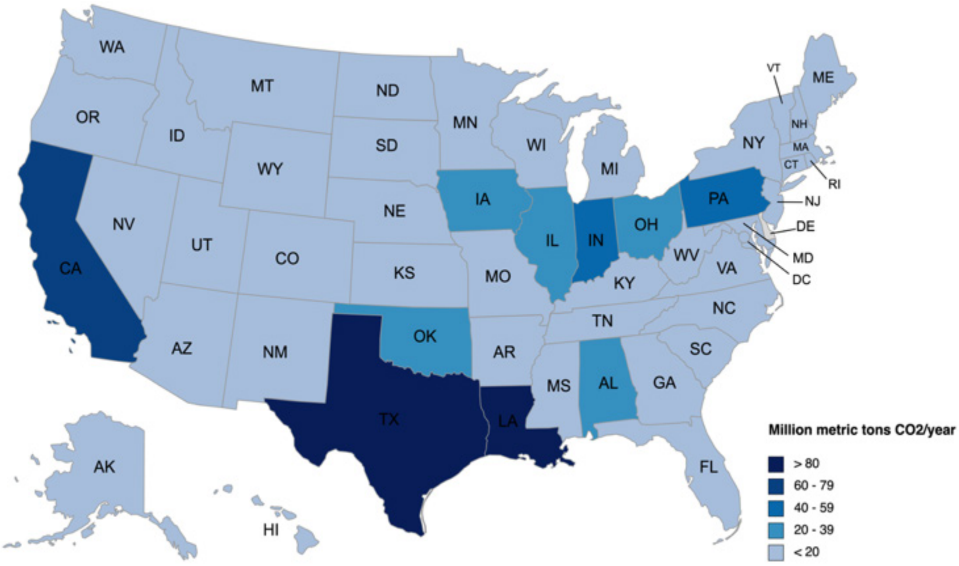

Figure 6. Industrial CO_2 emissions in 2019 (million metric tonnes of CO_2/year)

3

State-level Industrial Electrification Potential

3.0. Methodology

This chapter presents the results of our analysis of electrification potential in 12 industrial subsectors in 20 U.S. states (Table 1). This section describes the methodology for the analysis as well as scenario descriptions and key assumptions.

Industries:

The sector-specific electrification analysis focuses on electrifying the end-use technologies as opposed to electrifying the steam boilers only. In most industrial processes, steam is used as a heat carrier, and steam itself is not needed in the process. Therefore, instead of using steam (regardless of whether it is generated by fuels or electric boilers), we can consider using end-use electrification technologies (such as those described in Appendix 1) to provide the heat for the process. Electrifying end-use processes have the advantage of increasing efficiency by removing steam distribution losses.

Table 1. U.S. industrial subsectors analyzed in this study

No.	Industry subsector	No.	Industry subsector
1	Aluminum casting	7	Steel
2	Pulp and paper	8	Beer
3	Container glass	9	Beet sugar
4	Ammonia	10	Milk powder
5	Methanol	11	Wet corn milling
6	Recycled plastic	12	Crude soybean oil

States:

Figure 7 shows the 20 states included in this study and their industrial energy use. All selected states are among the top 20 industrial energy-consuming states in the U.S., except Colorado (21) and Oregon (32), which are included because of their forward-looking energy and climate policies. The other states in the top 20 but not included in this study are Tennessee (18) and South Carolina (19).

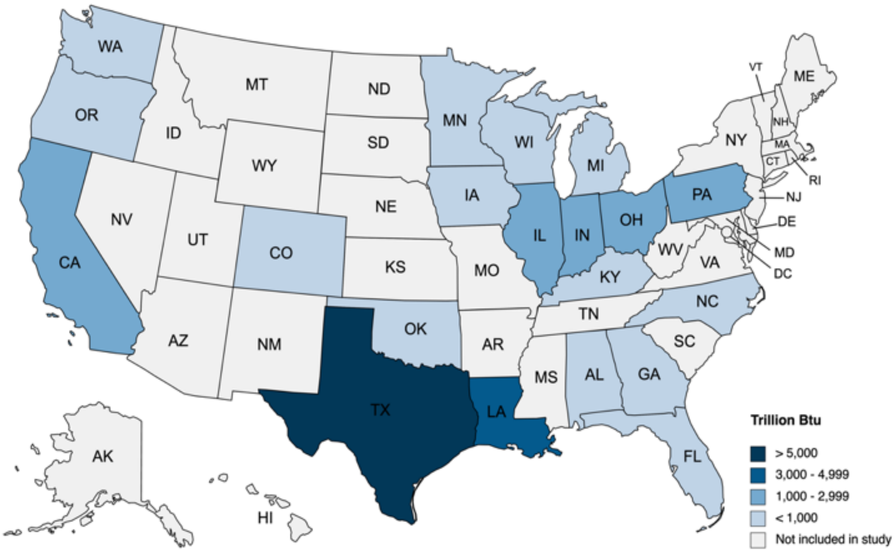

Figure 7. Industrial energy use in 2019 (trillion Btu)

Analysis:

To conduct this bottom-up, systems- and technology-level electrification analysis for each industrial subsector, we followed four steps, as shown in Figure 8. We analyzed the existing heating systems used in the main processes for each subsector, including the heat demand and temperature profile. Then, we identified suitable electrification technologies that can provide the same heat and function for each thermal process. Almost all of the electrification technologies we identified and assigned to processes are commercially available. In some cases where commercial electrified technologies were not available, we used information about an emerging electrified technology that was applicable to the process under investigation based on the information from the literature. Then, we did a high-level assessment of technology integration needs in each sector. Having the energy intensity of process heating technologies for both conventional and electrified processes, we then calculated the energy use, CO_2 emissions, energy cost, and electricity grid implications of electrification in each industry.

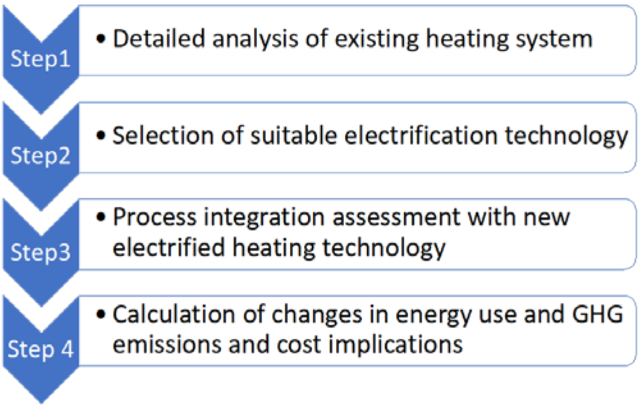

Figure 8. Methodology to estimate electrification potential in U.S. industrial subsectors

We also used projections for the production for each subsector as well as projections in the grid emissions factor and unit price of energy in order to project the energy use, GHG emissions, and energy cost implications of electrification in each industry. The electricity grid emissions factor and average unit price of natural gas used in our analysis for each state are shown below.

It should be noted that the changes in energy use and GHG emissions estimated for each subsector are the total technical potentials assuming a 100% adoption rate. Actual industrial electrification technology adoption will be gradual and over time. For the energy intensity of processes and technologies used in our analysis, we kept the intensities constant during the study period of 2021-2050. We did not take into account the technology learning curve and gradual improvement in technologies' energy performance (both for conventional and electrified technologies) in our analysis. This was primarily due to a lack of information for projections of energy performance improvement for the range of technologies considered in the analysis.

Energy use:

The change in energy use results in final energy terms, which means electricity is not presented in primary energy using average electricity generation efficiency and transmission and distribution losses.

CO_2 emissions:

Two grid emissions factor scenarios are modeled through the analysis: A *baseline* scenario that assumes the national electricity grid achieves zero carbon emissions in 2050 and incorporates earlier state zero-emissions targets and a *stated policy* scenario that aligns with the U.S.'s commitment to achieving a zero-carbon grid by 2035. Additional details are included below.

Figure 9 shows the electricity grid emissions factors in 2021 and 2030 in the states studied under the baseline scenario and stated policy scenario. For the projections of the grid emissions factor in different states, the baseline scenario assumes that the electricity grid will achieve zero-carbon emissions in 2050 unless a state has a specific target to achieve a zero-carbon grid before 2050. In those cases, we used that state's target year to achieve zero-carbon emissions for their electricity grid. We also developed a stated policy scenario where we assumed all states achieve a zero-carbon grid in 2035. This is the stated policy of the current Biden-Harris Administration. The CO_2 emissions reduction results show both scenarios. This study assumes a linear trend in the grid emissions factor between 2021 and 2050 in the baseline scenario and 2035 in the stated policy scenario.

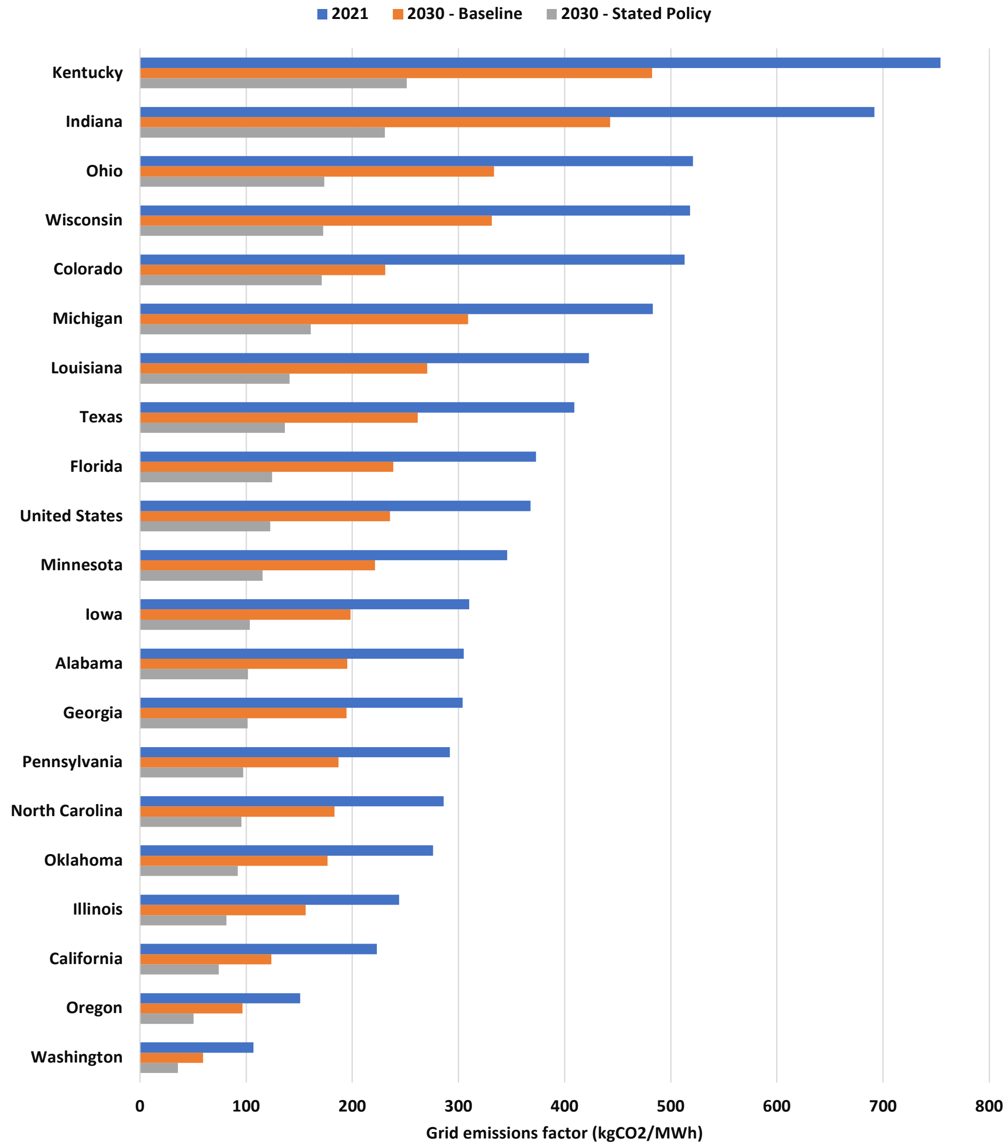

Figure 9. Electricity grid emissions factors in 2021 and 2030 ($kgCO_2/MWh$)

It should also be noted that the electrification technologies we considered in our analysis for each process and subsector may not be the only electrification options. Other electrified heating technologies might be available and applicable to the processes analyzed. In addition, other processes within the subsectors studied might have electrification potential that is not considered in this study. In summary, the energy savings and CO_2 reduction potentials shown in our study are only a portion of the total savings potential that can be achieved by full electrification of these industrial subsectors in each state.

Energy cost:

Two energy cost scenarios are modeled throughout the analysis: *EIA electricity price forecast* and *lower renewable energy (RE) price forecast*. Additional details are included below.

In our energy cost analysis, we assumed natural gas as the main fuel used in U.S. industries, except for the steel industry, where we assumed coal as the main fuel used in the primary steelmaking process. Energy prices vary significantly from state to state within the U.S. The results of our cost per unit of production comparisons are highly sensitive to the unit price of energy. Figures 10 and 11 show the unit price of electricity and natural gas in 2021 in the states included in this study. When considering the economic viability of industrial electrification based on energy prices, the ratio of industrial electricity to natural gas prices (as shown in Figure 12 for different states) is more important than absolute energy prices themselves. The lower this ratio, the more attractive industrial electrification is from the energy cost savings perspective.

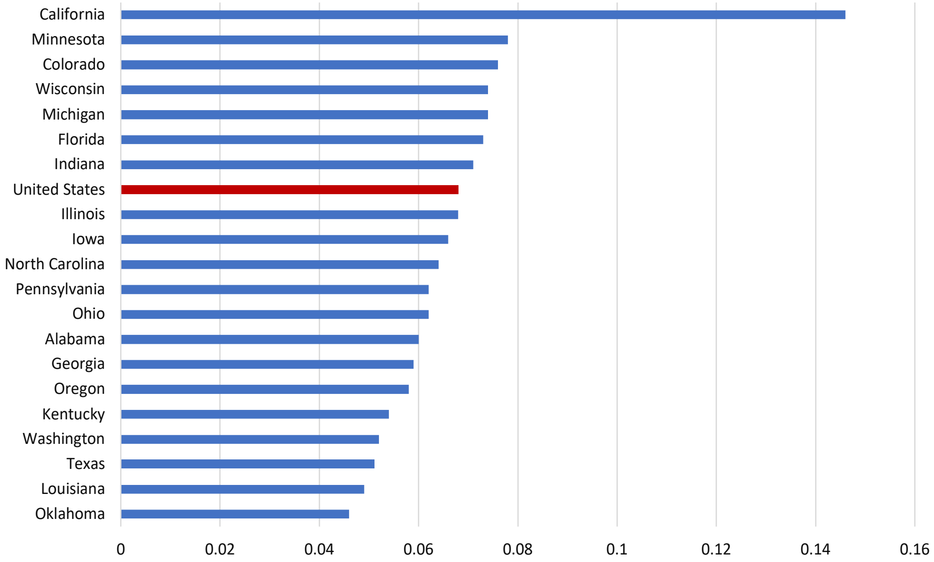

Figure 10. Industrial electricity unit price in 2021 ($/kWh) (Adapted based on U.S. DOE/EIA 2021)

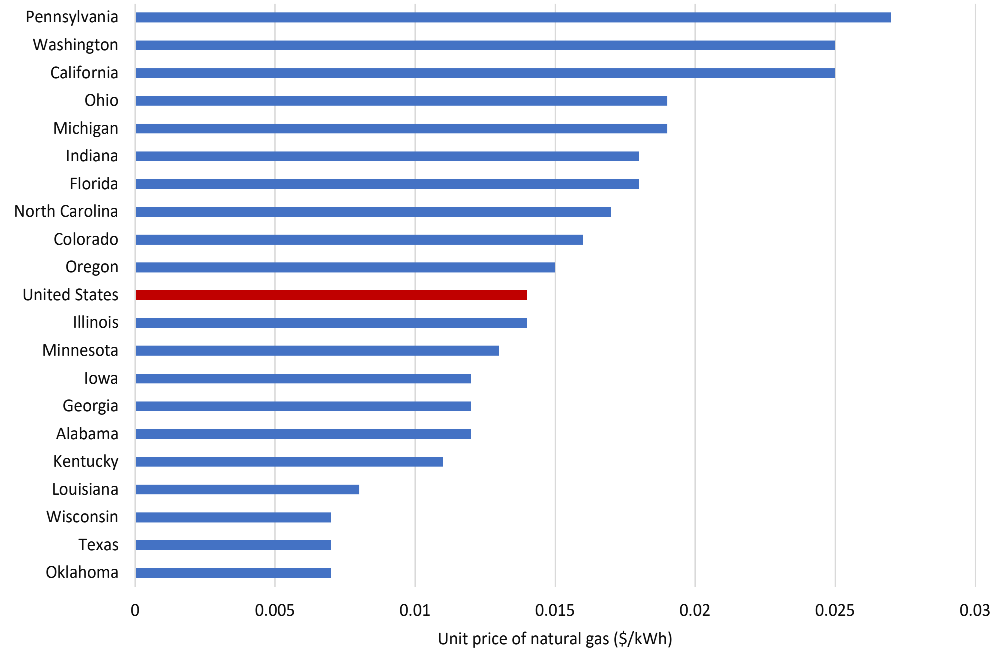

Figure 11. Industrial natural gas unit price in 2021 ($/kWh) (Adapted based on U.S. DOE/EIA 2021)

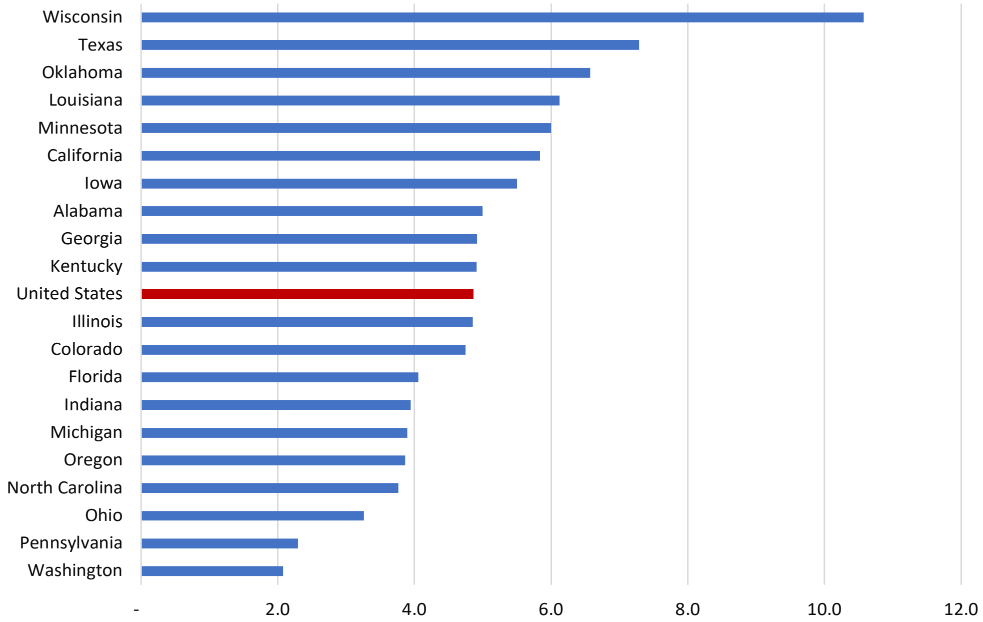

Figure 12. The ratio of the industrial unit price of electricity to natural gas in 2021

In addition, renewable electricity prices could decrease more substantially than what we assumed in our Baseline scenario based on U.S. DOE/EIA projections up to 2050, making electrification technologies more competitive. To address this issue, we added a scenario with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the EIA forecast.

EIA has historically overestimated the unit price of electricity in industry and underestimated the adoption rate and decrease in renewable electricity cost. In fact, current solar and wind power purchase agreement (PPA) prices in the U.S. are around half of the current average price of electricity for the industry in the U.S. (LBNL 2022a, b). It is foreseeable that renewable electricity prices will further decline by 2030 and 2050.

It is also possible that the price of natural gas and other fossil fuels may increase more than we projected up to 2050 (based on U.S. DOE/EIA projections), especially if a carbon tax or carbon price is introduced in the U.S. We have not included such consideration in our natural gas and coal price projections; we used the fuel price projections rates from U.S. DOE/EIA (2018).

3.1. Aluminum Casting Industry

Specific aluminum casting processes have been developed based on each industry's requirements. In 2021, the total quantity of primary aluminum production in the U.S. was 1.1 million metric tonnes. Approximately 30 percent of primary aluminum is casted (OEM Tech Brief, 2019) and the total quantity of aluminum casting products produced in the U.S. was about 330 thousand tonnes in 2021 (Thomasnet 2019).

Casting is defined as a simple and low-cost process that can be utilized for forming aluminum into a wide variety of products. It is the most widely used process for the production of aluminum products. The fundamental principle behind the casting process involves pouring molten aluminum into a mold to obtain the desired pattern. The three most popular techniques are die casting, permanent mold casting, and sand casting (The Aluminum Association 2010).

A detailed explanation of conventional and electrified processes for the aluminum casting industry is provided in our previous report (Hasanbeigi et al. 2021). Table 3 compares the energy intensity of the aluminum casting industry's conventional and electric processes.

Table 3. Conventional and electric aluminum casting processes' energy intensities (Beyond Zero Emissions, 2019)

Conventional System Processes		Process Steps	All Electric Processes	
Reverberatory Furnace	Tower Furnace		Induction Coreless Furnace	Single-shot induction
(kWh/tonne)	(kWh/tonne)		(kWh/tonne)	(kWh/tonne)
1332	1066	Melting	700	657
123	123	Holding	-	-
137	137	Transfer and Holding	137	-
1592	**1326**	**Total**	**837**	**657**

Energy use

Figure 13 shows that electrification will significantly reduce the total final energy use for aluminum casting in different states during the study period 2030-2050. The energy savings increase over time because of the assumed production increase in this sector up to 2050. Our savings calculation is based on maximum energy savings by replacing reverberatory furnaces with electrified single-shut induction furnaces. Wisconsin, Ohio, Kentucky, Michigan, and Indiana are the states with the largest energy savings potentials from switching to electric aluminum casting processes.

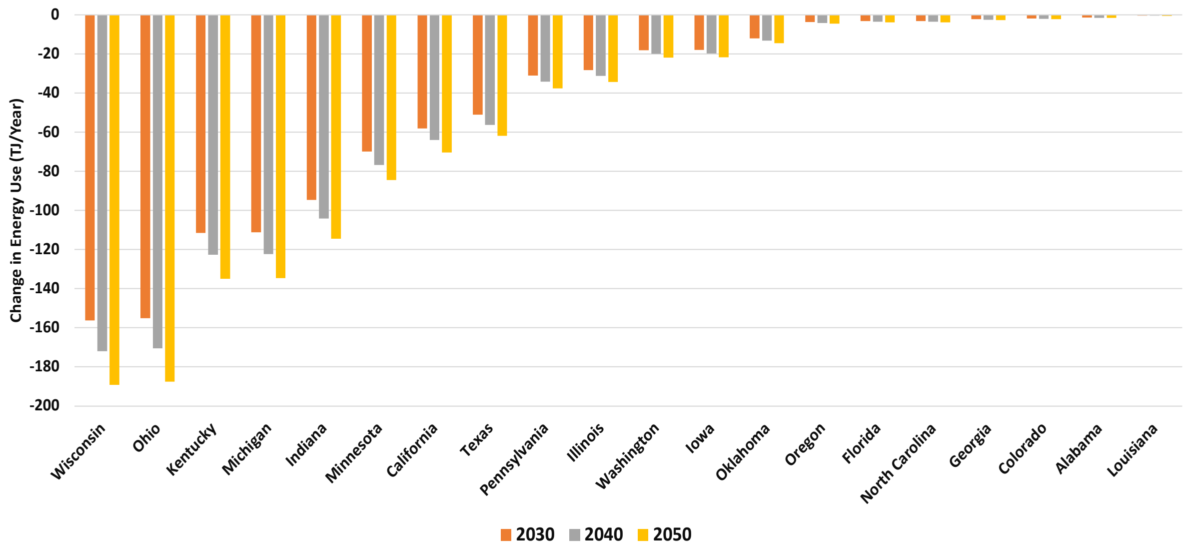

Figure 13. Change in the aluminum casting industry's total final energy use after electrification (technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 14 shows the change in net CO_2 emissions of the aluminum casting industry in different states after electrification under the baseline scenario. Electrification of aluminum casting can result in a decrease in CO_2 emissions in 2030 in 18 out of 20 states studied. In the other two states (Indiana and Kentucky), the relatively higher grid emissions factor in 2030 (Figure 9) causes a slight increase in CO_2 emissions in 2030. Electrification can help realize substantial annual CO_2 emission reductions by 2050 in all states. This CO_2 emissions reduction results from the electricity grid's declining CO_2 emissions factor (grid decarbonization) in 2050 in all states.

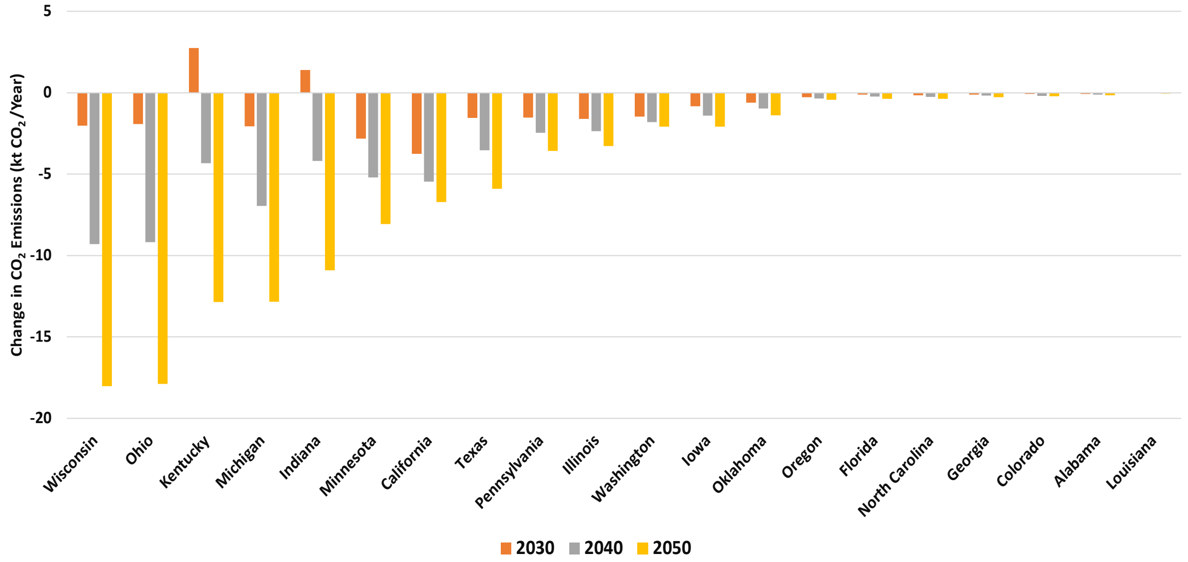

Figure 14. Change in the aluminum casting industry's net CO_2 emissions after electrification - baseline scenario (technical potential assuming 100% adoption rate)

Figure 15 shows the aluminum casting industry's change in net CO_2 emissions in states after electrification under the stated policy scenario. Under this scenario, the CO_2 emissions reduction potential in future years (2030, 2040, and 2050) is substantially higher than the baseline scenario because more rapid grid decarbonization is assumed under the stated policy scenario.

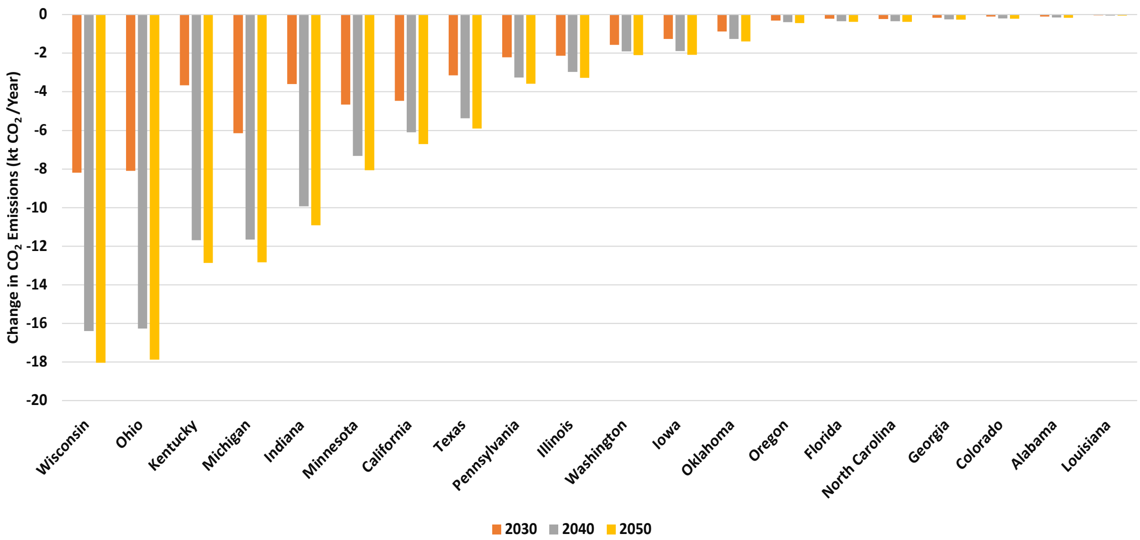

Figure 15. Change in the aluminum casting industry's net CO_2 emissions after electrification - stated policy scenario (technical potential assuming 100% adoption rate)

The rate of CO_2 emissions reduction from electrification varies across states. This is illustrated more clearly in Figures 16 and 17 showing the change in net CO_2 emissions in the aluminum casting industry after electrification in Indiana and California. The CO_2 emissions initially increased in Indiana in 2030 under the baseline scenario, but as Indiana's grid decarbonizes over time, electrification of the aluminum casting industry results in CO_2 emissions reductions. In California, however, electrification of the aluminum casting industry will result in CO_2 emissions reductions in 2030 because California has a lower grid emissions factor (see Figure 9).

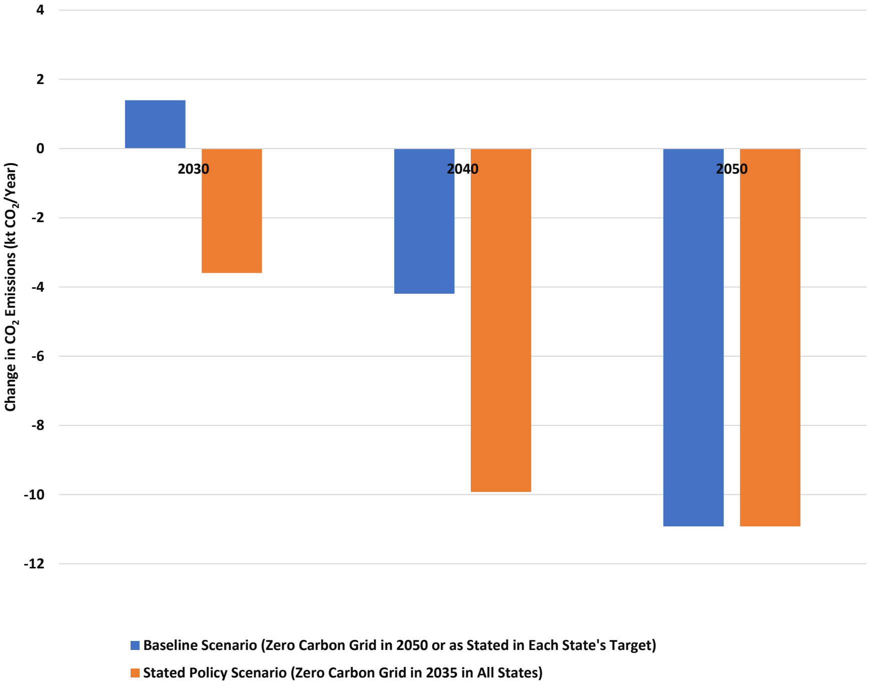

Figure 16. Change in the aluminum casting industry's net CO_2 emissions after electrification in Indiana

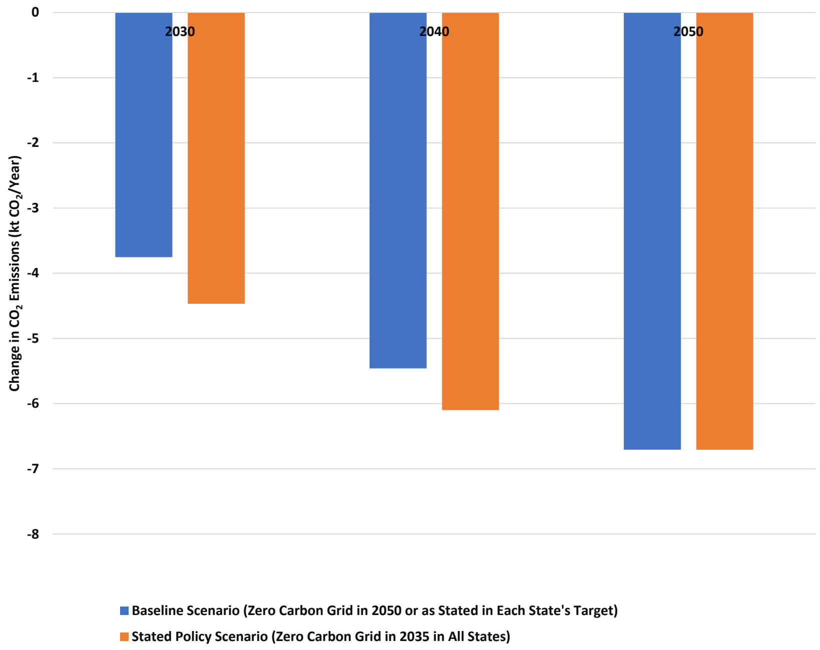

Figure 17. Change in the aluminum casting industry's net CO_2 emissions after electrification in California

Energy cost

Figure 18 shows that under the scenario with the EIA electricity price forecast, the energy cost (in 2021) $ per unit of production (tonne of cast aluminum) in 2030 for the electrified process in the aluminum casting industry is substantially higher than that of the conventional process in 2021 in most states except Pennsylvania and Washington. This is because these two states have a relatively lower ratio of the industrial unit price of electricity to natural gas (see Figure 12).

Figure 18 also shows the energy cost per unit of production for an electrified aluminum casting process in 2050 under two scenarios, one with higher and another with lower electricity prices in each state. It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified aluminum casting process, making it even more cost-effective than the conventional process in most states studied.

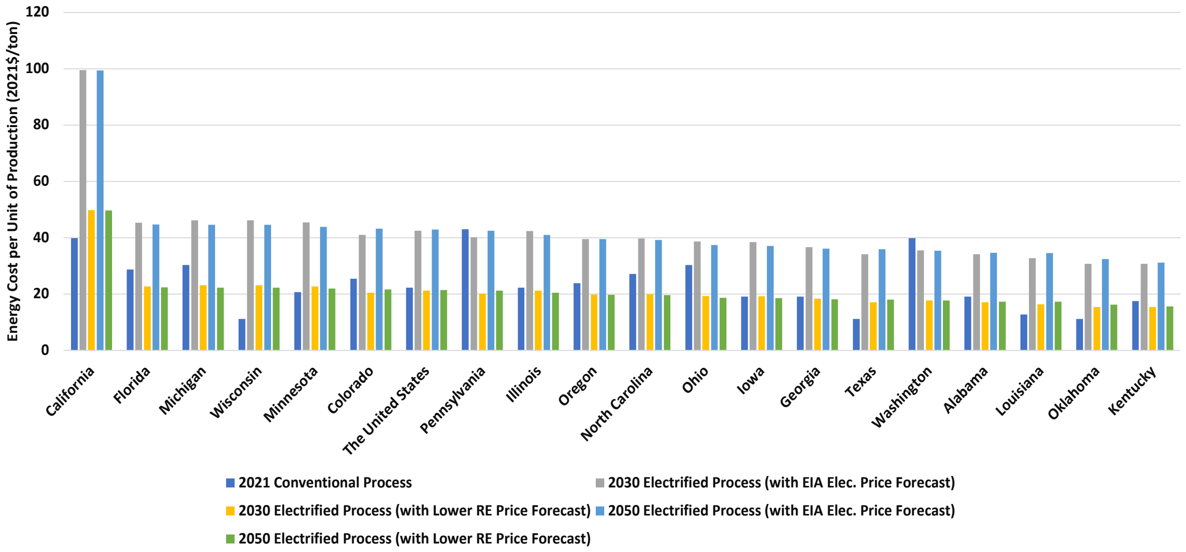

Figure 18. Energy cost per unit of production in the aluminum casting industry

Also, natural gas prices could increase more substantially up to 2050 than what is assumed in this study. It should be noted that our cost comparison focuses only on energy costs. A more comprehensive cost analysis that takes into account the change in capital costs, operation and maintenance costs, and electrified technologies' non-energy benefits (such as improved product quality, reduced waste, increased production rate, and reduced maintenance) could make electrified technologies more financially attractive.

3.2. Pulp and Paper Industry

In 2017, the total paper and cardboard production across the globe was around 419 million metric tonnes. China, the U.S., and Japan are the top paper manufacturing nations (Garside 2020d). The pulp and paper manufacturing industry is the third largest energy consumer in U.S. manufacturing. The pulp and paper industry in the U.S. is comprised of pulp mills, mills dedicated to manufacturing paper and paperboard, and integrated mills that process pulp as well as manufacture paper. More than 50% of total U.S. production occurs in the South, while the Northeast, North Central, and Western regions represent the remaining production in the U.S. There are an estimated 386 pulp, paper, and pulp and paper mills distributed across 41 states (Brueske et al. 2015). In 2017, the total pulp, paper, and paperboard production in the U.S. was close to 72 million metric tonnes (FAO 2017).

A detailed explanation of conventional and electrified processes for the pulp and paper industry is provided in our previous report (Hasanbeigi et al. 2021). Table 4 compares the energy intensity of the pulp and paper industry's conventional and electric processes.

Table 4. Conventional and electric pulp and paper production processes' energy intensities (Our analysis based on Brueske et al. 2015)

Conventional System Process			Process steps	Process Using Electric Dryer		
Equipment	Thermal Demand (kWh/tonne)	Electrical Demand (kWh/tonne)		Thermal Demand (kWh/tonne)	Electrical Demand (kWh/tonne)	Equipment
Liquor Evaporator	996	46	Liquor Evaporation	996	46	Liquor Evaporator
Pulp machine	567	40	Pulping Chemical Preparation	567	40	Pulp machine
Cooking machine	656	95	Wood Cooking	656	95	Cooking machine
Conventional bleaching plant	312	75	Bleaching	312	75	Conventional bleaching plant
Steam/ fuel-based dryer	1,245	128	Paper Drying	0.0	1,236	**Infrared dryer**
Paper making machine	310	296	Paper Machine Wet End	310	296	Paper making machine
	4,088	**682**	**Subtotal**	**2,842**	**1,791**	
4,771			**Total Energy**	**4,633**		

Energy use

Figure 20 shows that electrification will significantly reduce the total final energy use for pulp and paper in numerous states during the study period. The slight reduction in annual saving potential between 2030-2050 is due to an assumed slight reduction in primary paper production during this period. Georgia, Alabama, Wisconsin, North Carolina, and Florida are the states with the largest energy savings potentials from switching to electric drying in the paper industry.

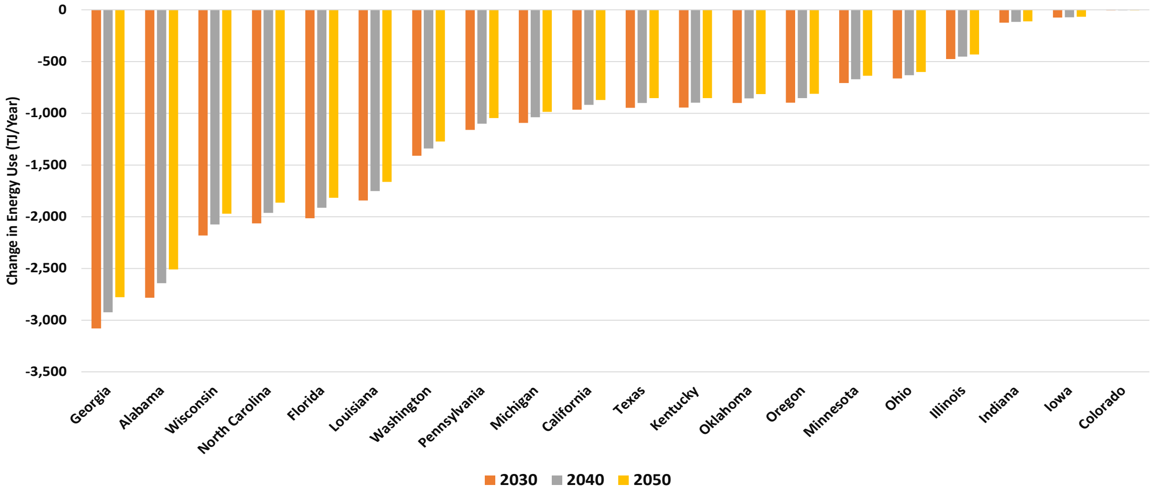

Figure 20. Change in the pulp and paper industry's total final energy use after electrification (technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 21 shows the pulp and paper industry's change in net CO_2 emissions after electrification under the baseline scenario. The industry's electrification would result in an increase in CO_2 emissions in 2030 in all states studied except Washington, which has the lowest grid emissions factor. It should be noted that around 67% of fuel used in the paper industry is biomass which is a by-product of the pulping process (U.S. DOE 2019). In our CO_2 emissions analysis, we took this into account and assumed biomass was carbon neutral. That is the main reason why electrification causes an increase in CO_2 emissions of the paper industry in most states up to 2040 until the grid is fully decarbonized in 2050 to show the CO_2 benefit of electrification in this sector. Note the carbon accounting for biomass under the GHG protocol is undergoing revision and could change how biomass is treated. If it does, biomass waste material may not be considered carbon neutral automatically as it is now, and the estimated carbon and cost benefits could change dramatically.

Electrification can help realize annual CO_2 emissions reductions in all states in 2050 under the baseline scenario (Figure 21) and in 2040 under the stated policy scenario (Figure 22). This substantial reduction in CO_2 emissions is the consequence of a decline in the electricity grid's CO_2 emissions factor between 2021 and 2050 in all states.

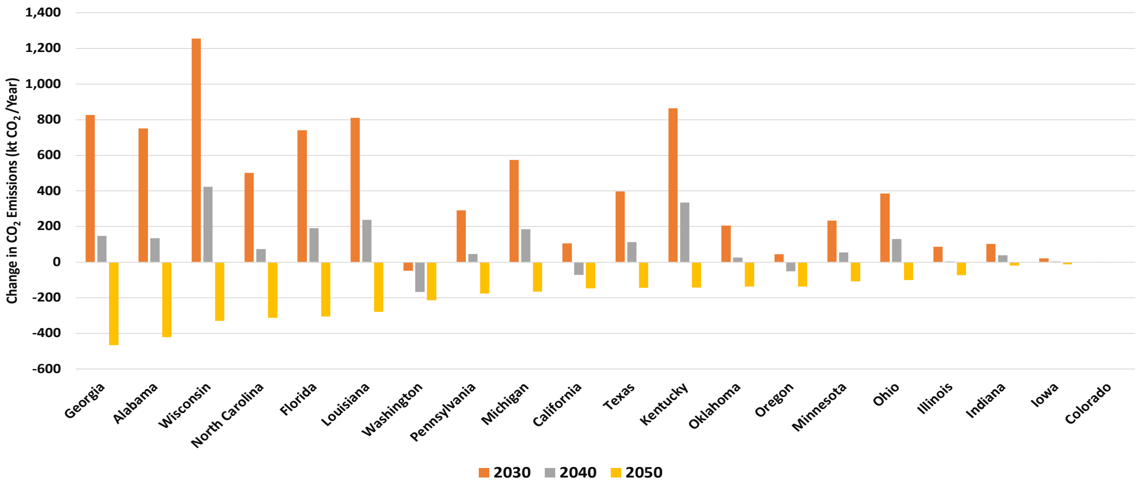

Figure 21. Change in the pulp and paper industry's net CO_2 emissions after electrification - baseline scenario (technical potential assuming 100% adoption rate)

Figure 22 shows the change in net CO_2 emissions of the pulp and paper industry in different states after electrification under the stated policy scenario. Under this scenario, the CO_2 emissions reduction potential in future years (2030, 2040, and 2050) is substantially higher than the baseline scenario because of more rapid grid decarbonization assumed under the stated policy scenario.

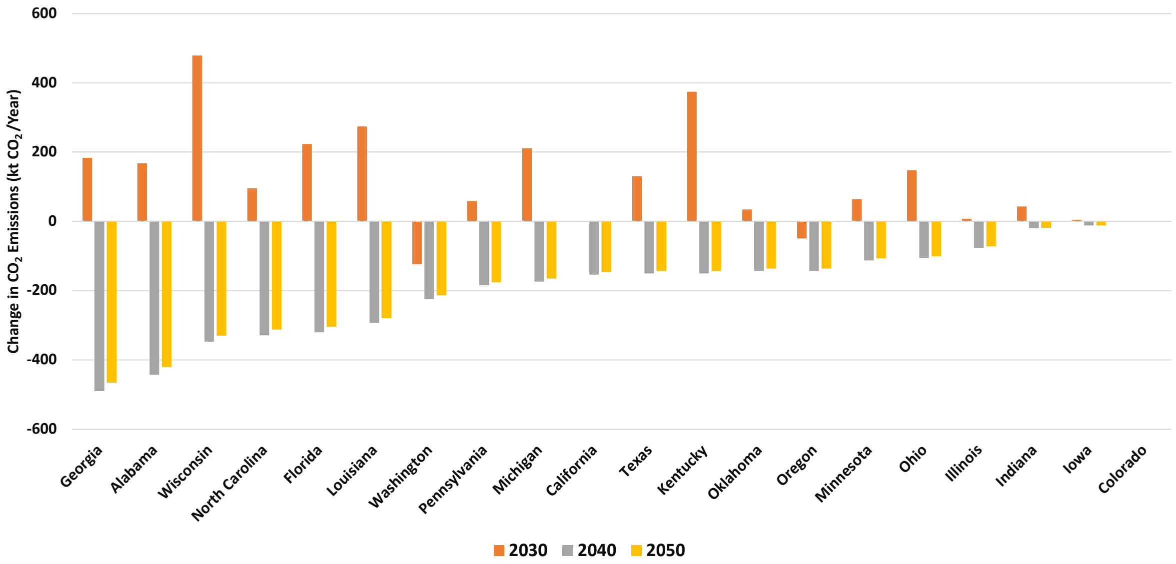

Figure 22. Change in the pulp and paper industry's net CO_2 emissions after electrification - stated policy scenario (technical potential assuming 100% adoption rate)

The rate of CO_2 emissions reductions in future years varies from state to state, as shown in the map in Figure 23. States in the Southeast, as well as Wisconsin, have the greatest emissions reduction potentials from pulp and paper electrification in 2050.

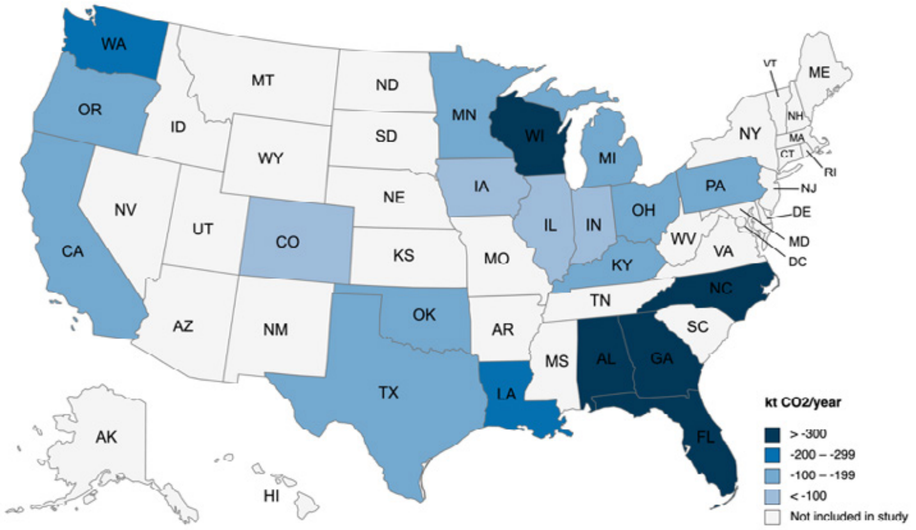

Figure 23. Change in emissions in the pulp and paper industry in 2050

The differences among states are illustrated further in Figures 24 and 25, showing changes in the pulp and paper industry's net CO_2 emissions after electrification in Georgia and Washington. In Georgia, CO_2 emissions reductions will be achieved in 2040 under the stated policy scenario. In Washington, however, CO_2 emissions reductions from electrification of the pulp and paper industry start in 2030 under both scenarios because of the lower grid emissions factor in Washington (see Figure 9).

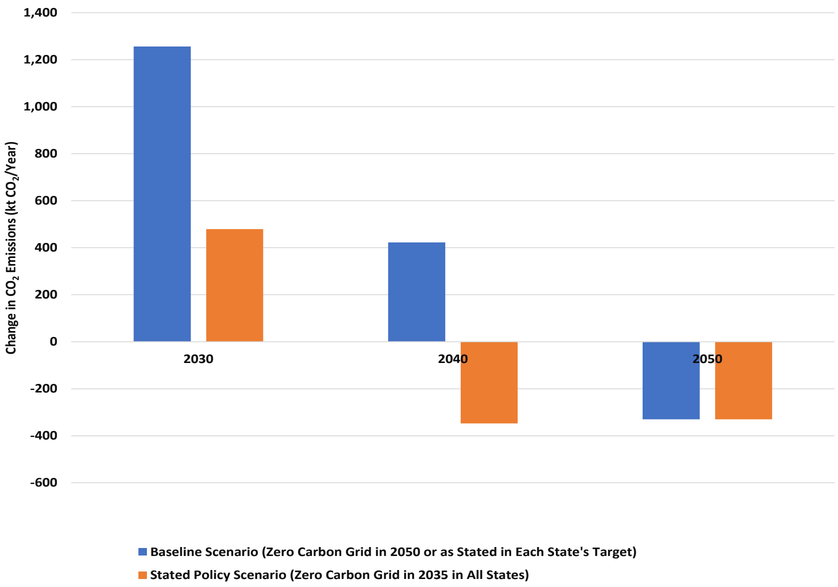

Figure 24. Change in the pulp and paper industry's net CO_2 emissions after electrification in Wisconsin

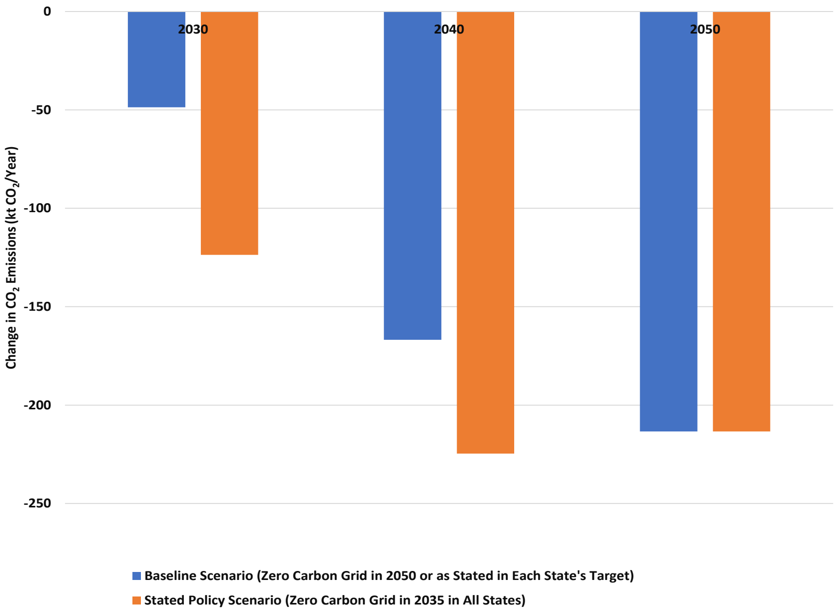

Figure 25. Change in the pulp and paper industry's net CO_2 emissions after electrification in Washington

Energy cost

Figure 26 shows that under both electricity price forecasts, the energy cost per unit of production (tonne of paper) in 2030 for the electrified process in the pulp and paper industry is substantially higher than that of the conventional process in 2021 in all states. It should be noted that only the drying process is electrified in this analysis, so 40-55% of the cost shown for the electrified process in Figure 26 is related to natural gas used in processes other than drying.

Figure 26 also shows the energy cost per unit of production for an electrified pulp and paper process in 2050 under two scenarios, one with higher and another with lower electricity prices in each state. Around 67% of the fuel used in a conventional pulp and paper plant that produces paper from virgin pulp is from biomass and pulping liquor (black liquor), which are pulping process byproducts (U.S. DOE 2019). These byproduct biomass fuels are available to pulp and paper plants at a very low cost. The cost analysis and comparison here assumes zero cost for byproduct fuels used in the conventional process and assumes the electrified process uses no byproduct fuels, but rather natural gas would be the remainder of fuel used in an integrated pulp and paper plant, so natural gas costs are included.

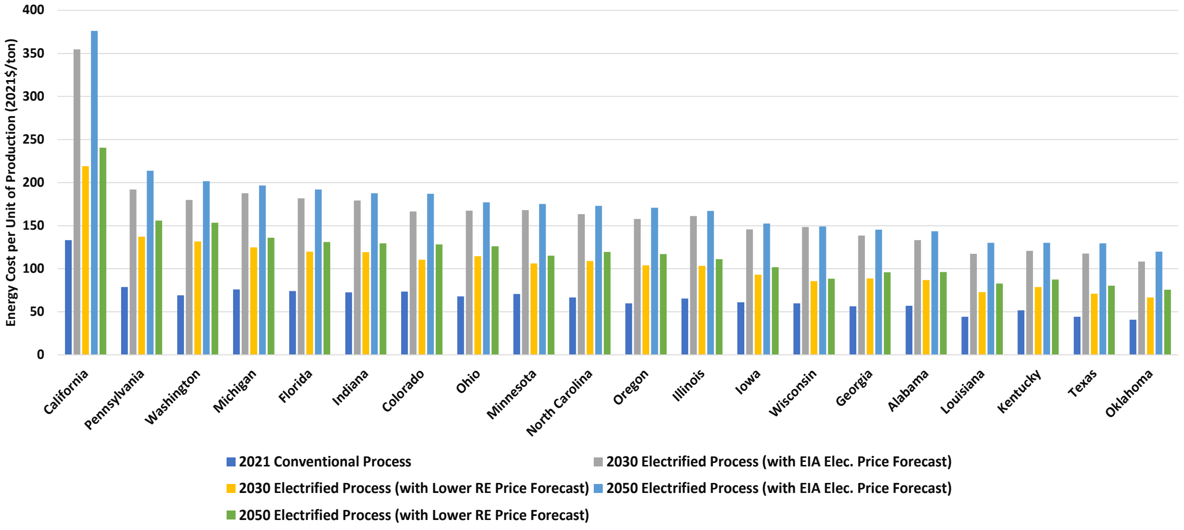

Figure 26. Energy cost per unit of production in the pulp and paper industry

3.3. Container Glass Industry

The glass industry manufactures a wide range of products used across various key sectors of the U.S. economy, including construction, household markets, and automotive. The four major glass products are flat glass, pressed or blown glass, glass containers, and products made from purchased glass (IBISWorld 2020).

In 2021, the total revenue generated by the U.S. glass manufacturing industry was around $30 billion (Garside 2020b). The total glass production in the U.S. was around 20 million metric tonnes in 2017 (Gaile 2017). Since container glass products account for around half of U.S. glass production (U.S. DOE 2017a), the total quantity of container glass production in the U.S. is estimated to be approximately 10 Mt in 2021.

A detailed explanation of the container glass industry's conventional and electrified processes is provided in our previous report (Hasanbeigi et al. 2021). Table 5 compares the energy intensity of the container glass industry's conventional and electric processes.

Table 5. Conventional and electric container glass production processes' energy intensities (Our analysis based on U.S. DOE 2017a and Beyond Zero Emissions 2019)

Conventional System Process			Process steps	All Electric Process	
Heating Equipment	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)	Heating Equipment
Electrically-powered mixer/crusher	161	0	Mixing	161	Electrically-powered mixer/crusher
Gas-fired furnace	204	1150	Melting	860	Electrically-powered glass melter
Forehearth and forming equipment	26	105	Conditioning & Forming	104	Electric forehearths
Gas-fired Annealing lehr	25	210	Post Forming (Annealing)	183	Electric Annealing lehr
	416	**1465**	**Subtotal**	**1308**	
	1881		**Total Energy**	**1308**	

Energy use

Container glass production was identified in 18 of the 20 states included in this study. Figure 27 shows energy savings from container glass production electrification across states in 2030-2050. The slight energy savings increase over time is because an increase in container glass production is assumed up to 2050. California, Indiana, Illinois, Georgia, and Pennsylvania are the states with the potential to save the most energy by switching to electric container glass production.

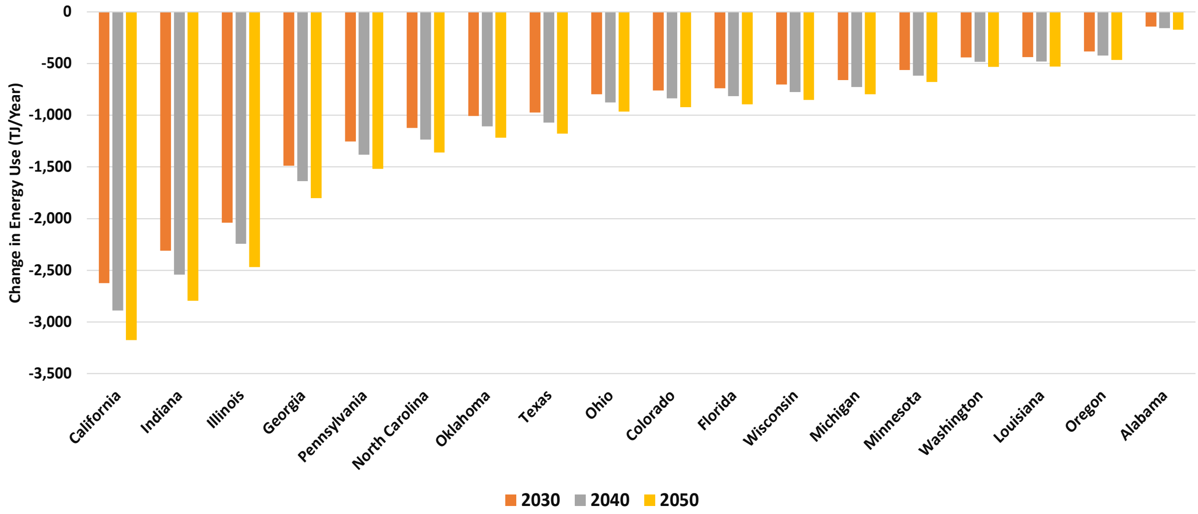

Figure 27. Change in the container glass industry's total final energy use after electrification (technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 28 shows the container glass industry's change in net CO_2 emissions after electrification under the baseline scenario. The container glass industry's electrification can result in a decrease in CO_2 emissions in 2030 in all states except Indiana, which has a high grid emissions factor in 2030 (see Figure 9). As the grid decarbonizes in Indiana, electrification can help realize substantial annual CO_2 emissions reductions by 2040 in that state as well.

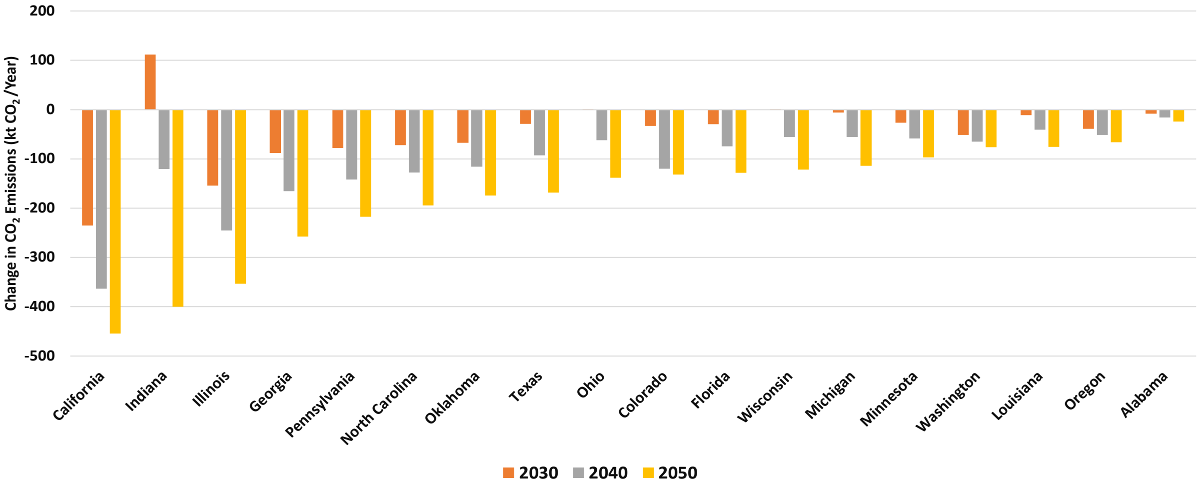

Figure 28. Change in the container glass industry's net CO_2 emissions after electrification - baseline scenario (technical potential assuming 100% adoption rate)

Figure 29 shows the container glass industry's change in net CO_2 emissions after electrification under the stated policy scenario. Under this scenario, the CO_2 emissions reduction potential in future years (2030, 2040, and 2050) is substantially higher than the baseline scenario because more rapid grid decarbonization is assumed under the stated policy scenario.

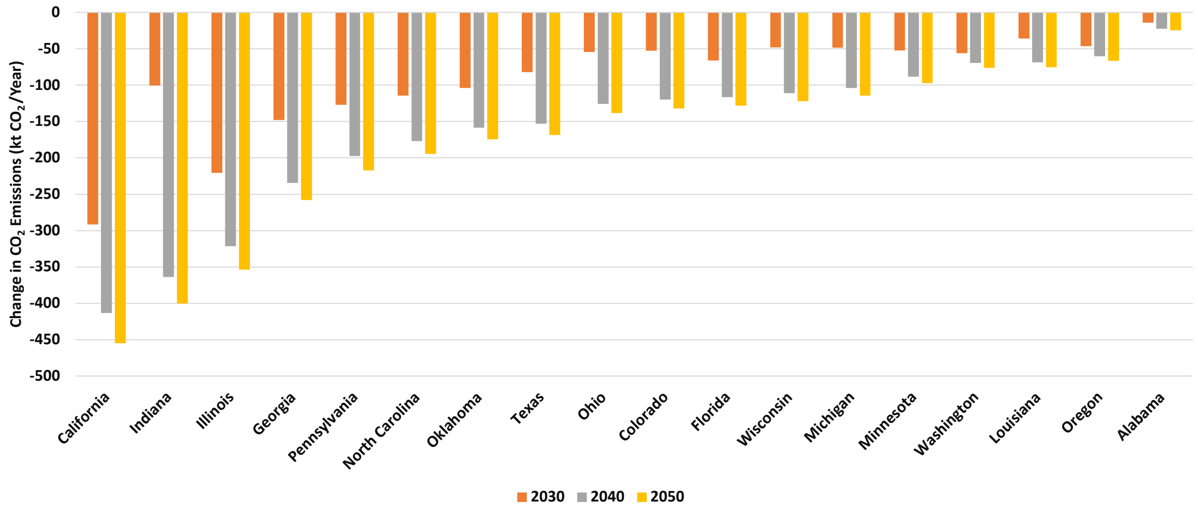

Figure 29. Change in the container glass industry's net CO_2 emissions after electrification - stated policy scenario (technical potential assuming 100% adoption rate)

The map in Figure 30 shows the emissions reduction potential across the states included in the analysis. California and Indiana have the highest potential to reduce emissions in the container glass industry by 2050.

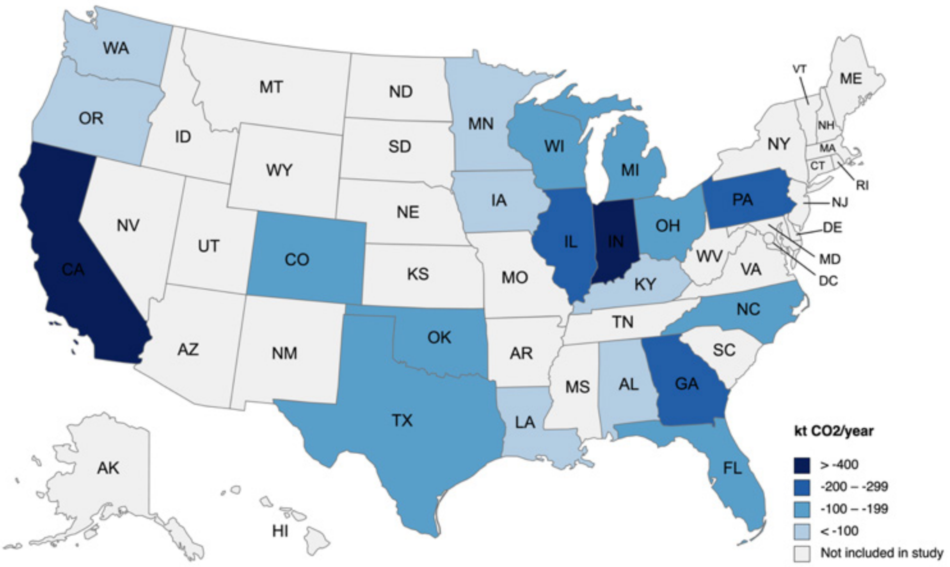

Figure 30. Change in emissions in the container glass industry in 2050

Figures 31 and 32 show the container glass industry's change in net CO_2 emissions after electrification in two major container glass manufacturing states, Indiana and California. In Indiana, the CO_2 emissions will increase in 2030 under the baseline scenario. In California, however, the lower grid emissions factor allows CO_2 emissions reductions from the container glass industry's electrification in 2030 as well as in future years.

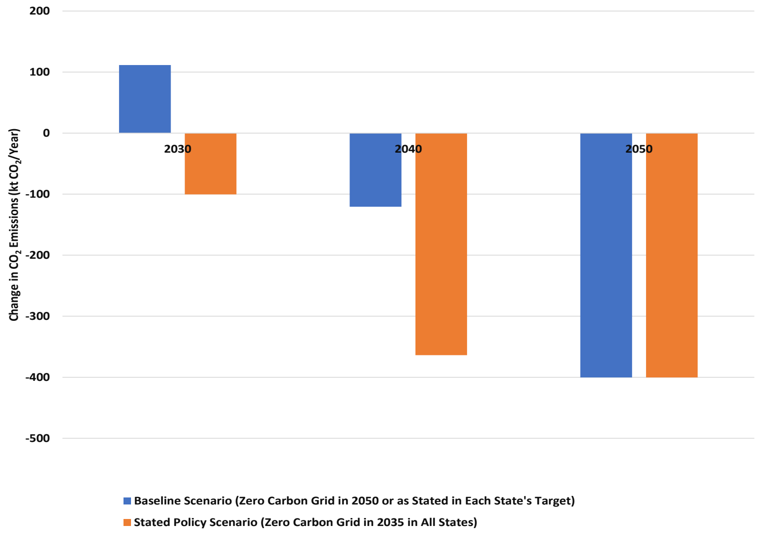

Figure 31. Change in the container glass industry's net CO_2 emissions after electrification in Indiana

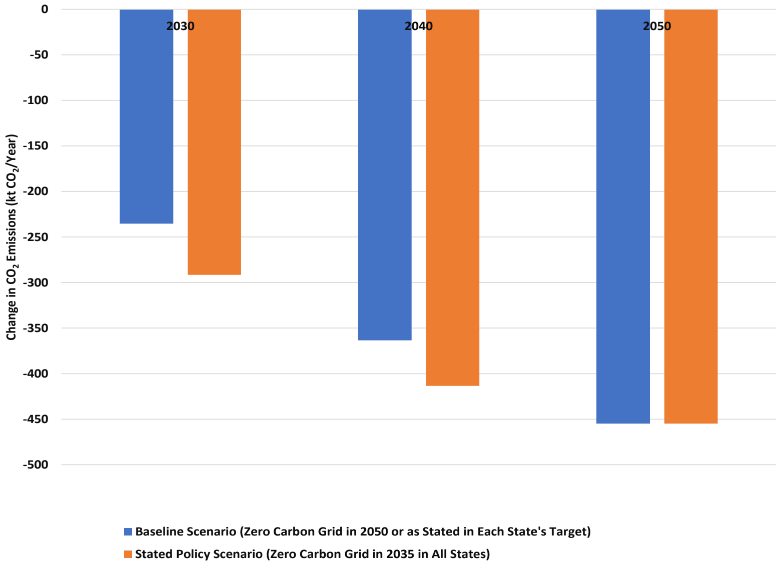

Figure 32. Change in the container glass industry's net CO_2 emissions after electrification in California

Energy cost

Figure 33 shows that under the scenario with the EIA electricity price forecast, the energy cost per unit of production (tonne of container glass) in 2030 for an electrified container glass production process is significantly higher than that of the conventional process in 2021 in most states except Pennsylvania and Washington. This is because these two states have a lower ratio of the industrial unit price of electricity to natural gas (see Figure 12). However, under the Lower RE price forecast scenario, the energy cost per unit of production in 2030 for the electrified process is lower than that of the conventional process in 2021 in almost all states.

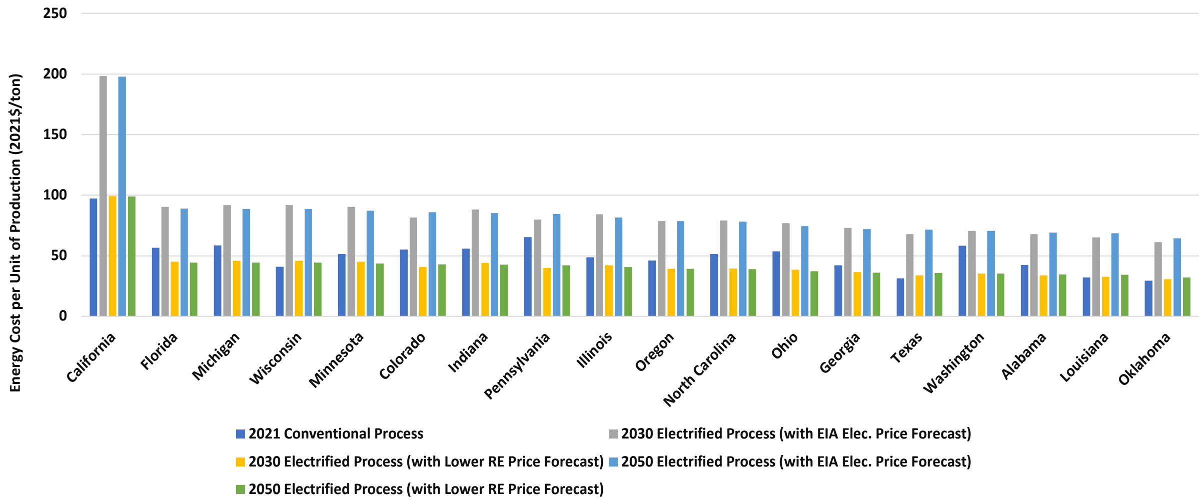

Figure 33. Energy cost per unit of production in the container glass industry

The quality requirement for most flat glass is significantly higher than for container glass. This makes electrifying melting for flat glass production more challenging. In fuel-fired container glass furnaces and all-electric container glass furnaces, melting and refining are achieved in one tank. In contrast, in flat glass production, melting and a certain degree of refining take place in the main melting chamber, and a secondary refining chamber completes the process, resulting in a comparatively longer processing time. Electric boosting in a fuel-fired flat glass furnace can and is applied, though not as widely as in container glass production (Stormont 2020).

3.4. Ammonia Industry

Ammonia-based fertilizers and chemicals play a significant role in crop-yield growth. Over the past few decades, engineers successfully developed processes that result in wider access to ammonia at highly reduced costs. The U.S. is one of the world's leading producers and consumers of ammonia. In 2021, 15 U.S. companies produced a total of approximately 14 million metric tonnes of ammonia across 34 facilities (Garside 2020a). Around 88% of ammonia manufactured globally is utilized for fertilizer production, and the remainder is used to support formaldehyde production (AIChE 2016).

To make ammonia, hydrogen and N_2 are needed. The current process uses steam methane reforming (SMR) to produce hydrogen. In the all-electric process, hydrogen is produced via electrolysis. A detailed explanation of the ammonia industry's conventional and electrified processes is provided in our previous report (Hasanbeigi et al. 2021). Table 6 compares the energy intensity of conventional and electric processes for the ammonia industry.

Table 6. Conventional and electric ammonia production processes' energy intensities (Beyond Zero Emissions 2019)

Conventional System Process			Process steps	All Electric Process	
Equipment	**Electrical Demand (kWh/tonne)**	**Thermal Demand (kWh/tonne)**		**Electrical Demand (kWh/tonne)**	**Equipment**
Primary Reformer Feedstock (SMR to produce H_2)	-	5,694	Using different process methods	30	Desalination
Primary Reformer Fuel	-	4,083		8,824	Electrolysis
Secondary Reforming	-	-		90	Air separation to acquire nitrogen
CO_2 Removal	-	333		550	Hydrogen and nitrogen reaction in the Haber-Bosch process
Methanation	-	83		-	-
Ammonia Synthesis*	-	-555		-	-
Boiler **	-	-1,388		-	-
Turbine, Compressor, Others (Electrical)	1,694	-		-	-
	1,694	**8,249**	**Subtotal**	**9,494**	
9,943			**Total Energy**	**9,494**	

* Hydrogen and nitrogen are reacted at 450 °C and 200 bar pressure over a catalyst to form ammonia.

** Primary and secondary reforming and ammonia synthesis all produce waste heat which is reused in the boilers.

Energy use

Ammonia production was identified in nine of the 20 states included in this study. Electrification will significantly reduce the ammonia industry's total final energy use during the study period (Figure 34). The energy savings increase over time because an increase in ammonia production is assumed up to 2050.

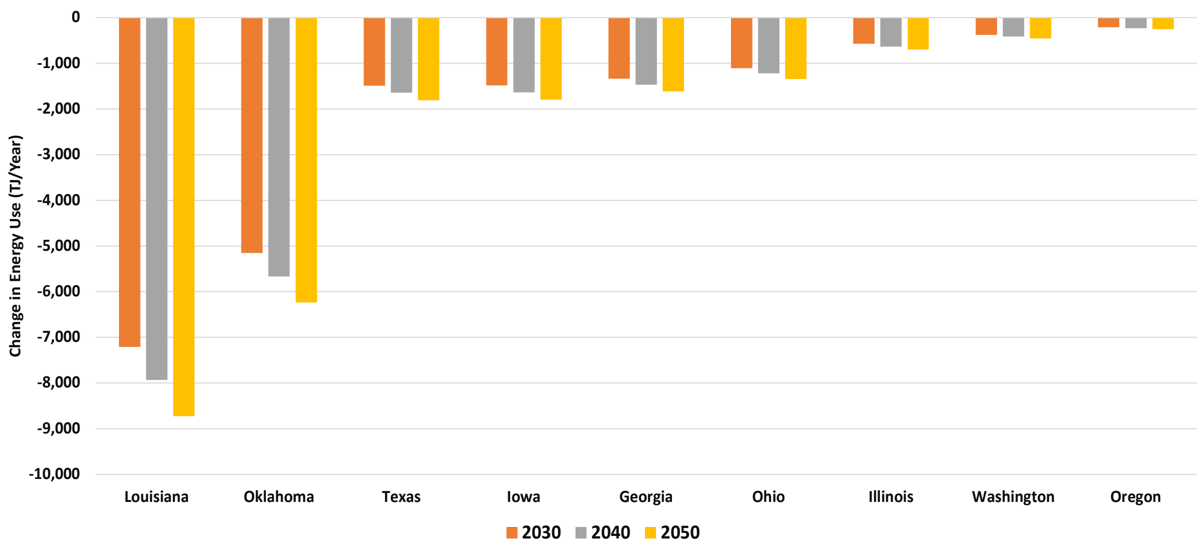

Figure 34. Change in the ammonia industry's total final energy use after electrification (technical potential assuming 100% adoption rate)

CO_2 emissions

Ammonia production electrification through the production of hydrogen by electrolysis would result in an increase in CO_2 emissions in 2030 in Louisiana, Texas, and Ohio (Figure 35). The relatively lower emissions factors of the other six ammonia-producing states (see Figure 9) allow for CO2 emissions reductions in 2030. As the electricity grid decarbonizes in Louisiana, Texas, and Ohio in 2040 and 2050, we see substantial annual CO_2 emission reductions from ammonia production electrification in these states as well.

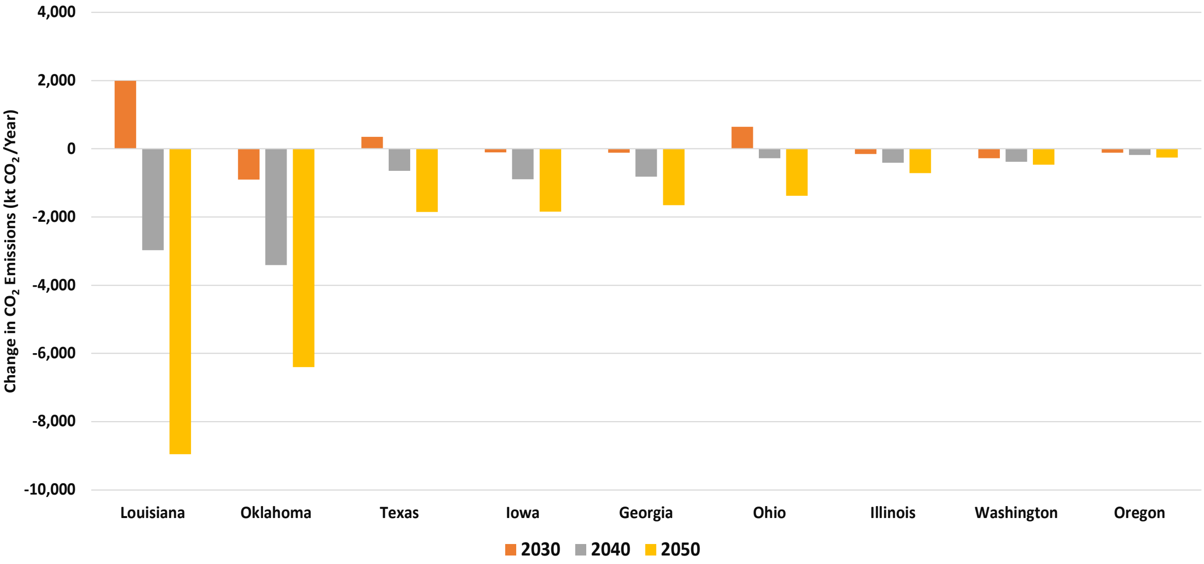

Figure 35. Change in the ammonia industry's net CO_2 emissions after electrification - baseline scenario (technical potential assuming 100% adoption rate)

If a zero-carbon grid is achieved earlier in all states, the CO_2 emissions reduction potential in future years (2030, 2040) is substantially higher (Figure 36) than the baseline scenario. Figures 35 and 36 show that in some states, CO_2 emissions will increase in 2030 under the baseline scenario but decrease in 2030 under the stated policy scenario because the electricity grid decarbonizes more rapidly.

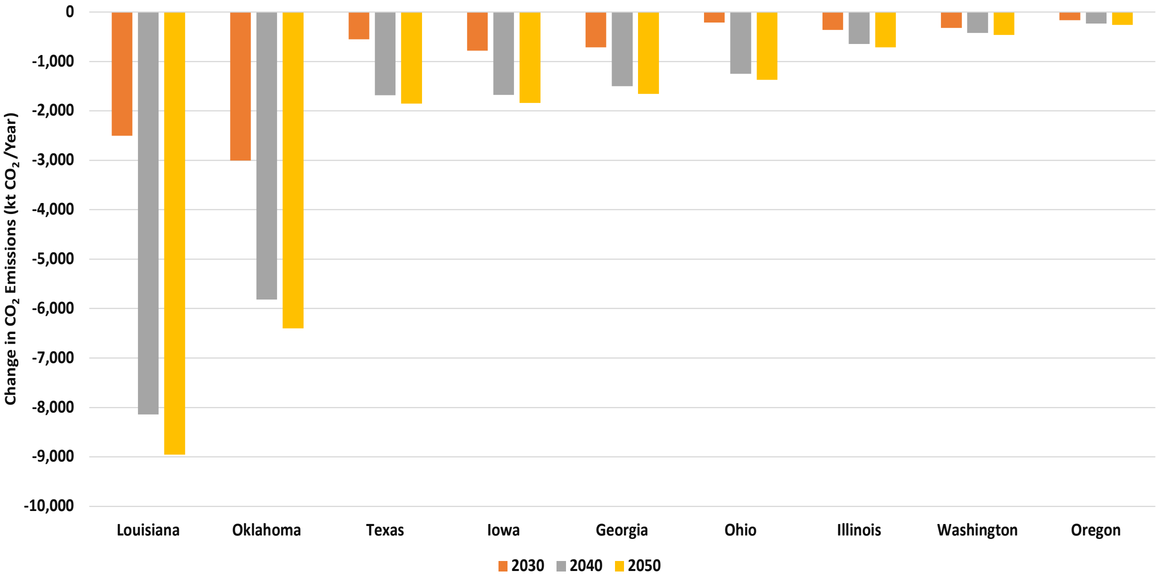

Figure 36. Change in the ammonia industry's net CO_2 emissions after electrification - stated policy scenario (technical potential assuming 100% adoption rate)

The map in Figure 37 shows the emissions reduction potential across the states included in the analysis. While the Gulf Coast region has a significant potential to reduce emissions by electrifying ammonia production, so too do several other states interspersed in other regions, including Georgia, Ohio, and Iowa.

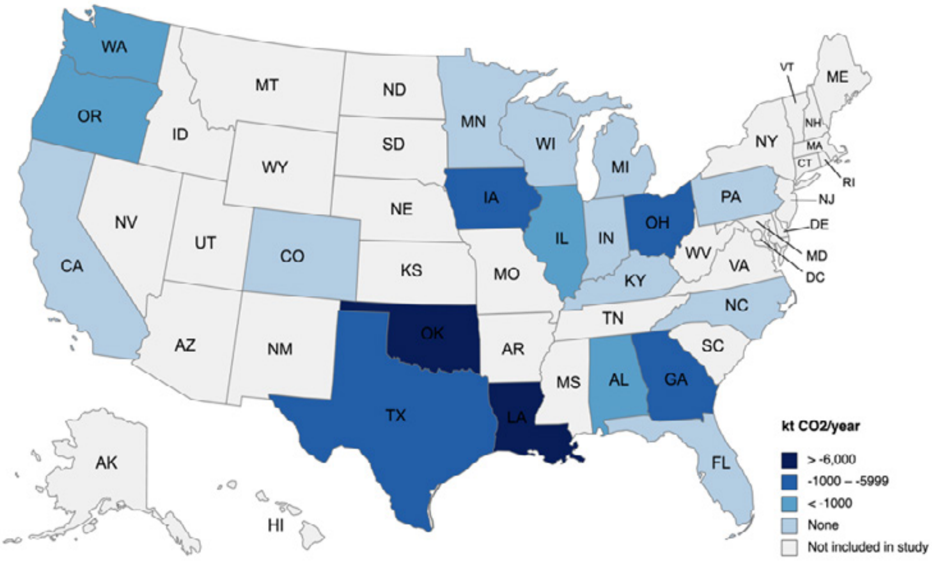

Figure 37. Change in emissions in the ammonia industry in 2050

Energy cost

Figure 38 shows that under the scenario with the EIA electricity price forecast, the energy cost per unit of production (tonne of ammonia) in 2030 for ammonia's electrified process is substantially higher than that of the conventional process in 2021 in all states. However, under the Lower RE price forecast scenario, electrified ammonia production can be cost-competitive with the conventional process in several states such as Ohio and Washington.

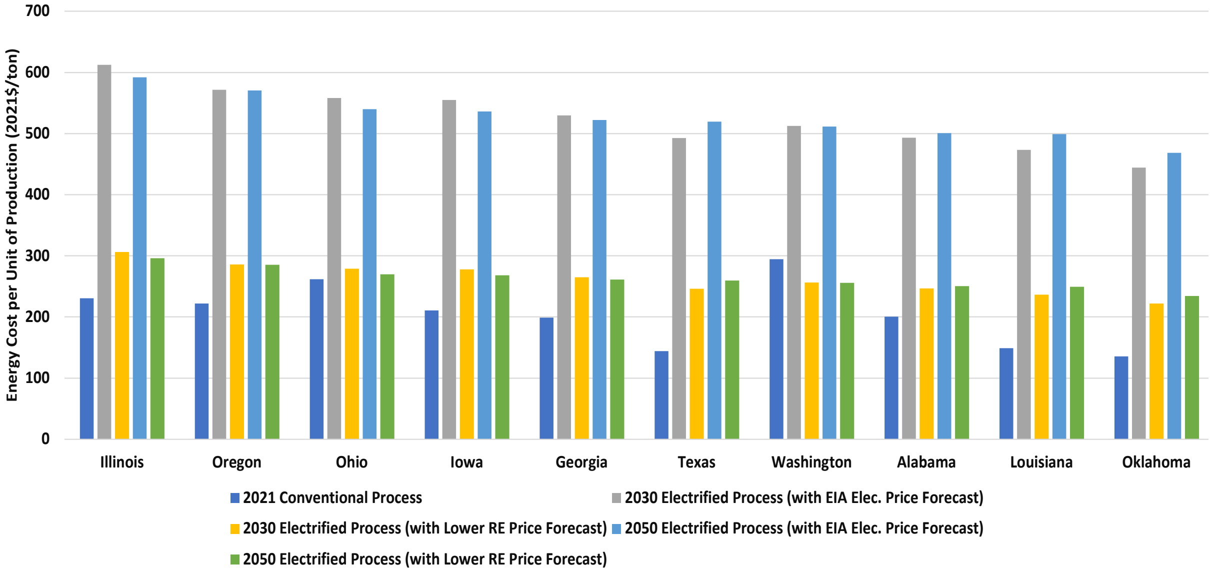

Figure 38. Energy cost per unit of production in the ammonia industry

3.5. Methanol Industry

Methanol (CH_3OH) is a liquid chemical that serves as a building block for thousands of daily-use products, such as plastics, paints, cosmetics, and fuels. It is the world's most commonly shipped chemical commodity (Hobson et al., 2018). Currently, methanol is mostly manufactured for non-fuel use in the U.S. The substantial demand for methanol in North America is due to the increasing demand for methyl tertiary butyl ether (MTBE), acetic acid, and formaldehyde (Grand View Research 2019).

In 2021, U.S. total methanol production volume was estimated to be around 5.7 million metric tonnes. The vast majority of methanol plants are located in the Gulf Coast region, and with additional plants in final phases of construction (EIA, 2019).

A detailed explanation of conventional and electrified methanol industrial processes is provided in our previous report (Hasanbeigi et al. 2021). Table 7 compares the energy intensity of conventional and electric processes for the methanol industry.

Table 7. Conventional and electric methanol production processes' energy intensities (Hasanbeigi et al. 2021)

Conventional System Process			Process steps	All Electric Process	
Equipment	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)	Equipment
Steam Methane Reforming	280	1,546	H_2 Production	6,238	Electrolysis system
Conventional Steam Boiler	-	467	MeOH Synthesis	381	Electric steam Boiler
Distillation Unit	-	638	MeOH Distillation	-	-
Motors	240	-	Others	240	Motors
	520	**2,651**	**Subtotal**	**7,055**	
3,171			**Total Energy**	**7,055**	

Electric steam boilers can be used instead of conventional fossil fuel boilers to meet the all-electric process requirement. As the efficiency of electric boilers (>99%) is higher than conventional ones (typically 75-80%), the required amount of energy is lower.

Energy use

Methanol production was identified in two out of 20 states included in this study, Louisiana and Texas. Electrification will significantly increase the total final energy use for methanol production in both states during the study period (Figure 39). The substantial amount of energy required by the water electrolysis process for hydrogen production is the main reason for the rise in energy use for the methanol electrification process.

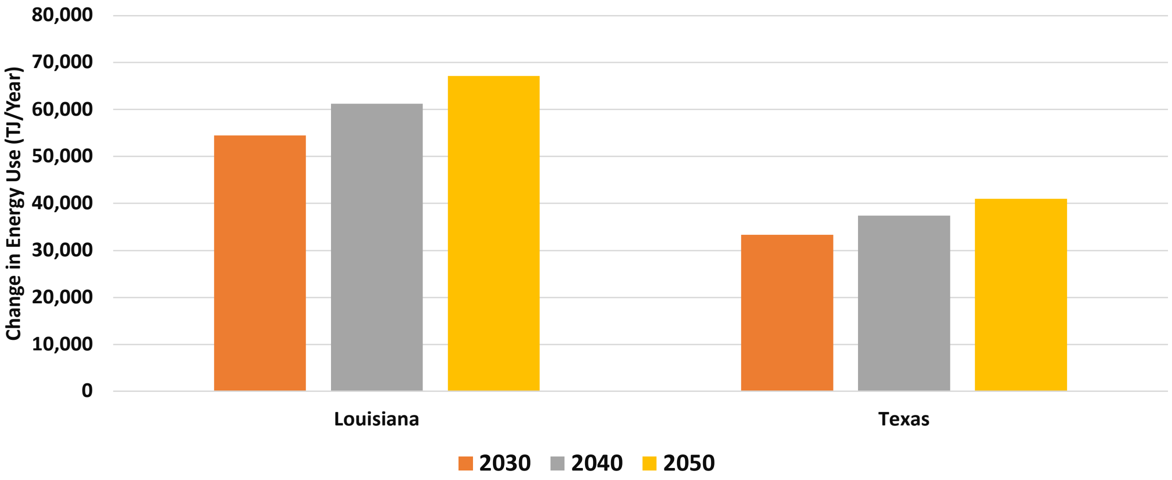

Figure 39. Change in the methanol industry's total final energy use after electrification (technical potential assuming 100% adoption rate)

CO_2 emissions

Methanol production electrification can result in an increase in CO_2 emissions in 2030-2040 under the baseline scenario in both states (Figure 40). As the electricity grid decarbonizes in both states in 2050, we will see a reduction in annual CO_2 emissions.

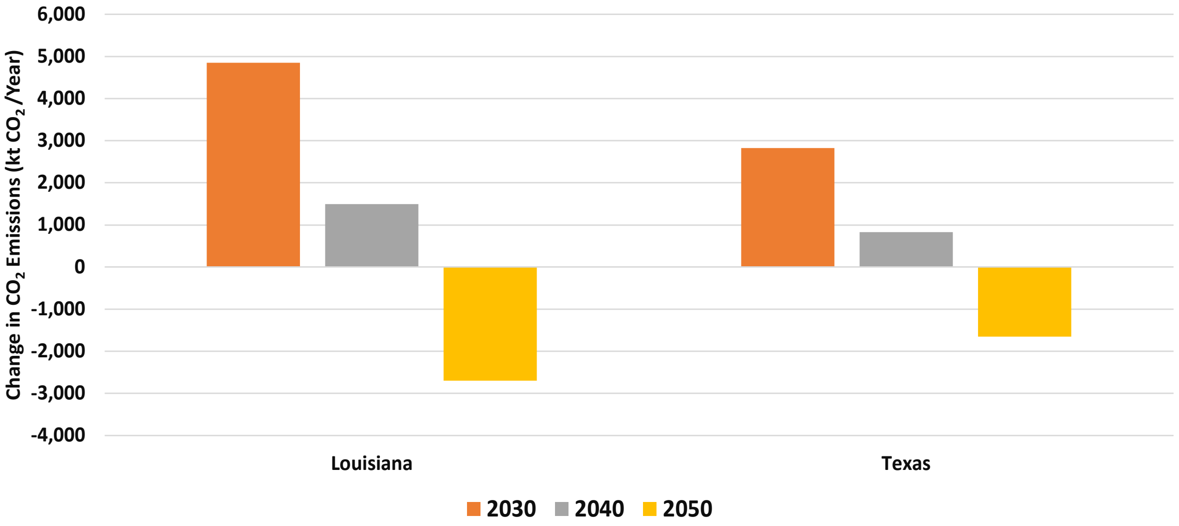

Figure 40. Change in the methanol industry's net CO_2 emissions after electrification - baseline scenario (technical potential assuming 100% adoption rate)

If a zero-carbon grid is achieved in 2035 in both states, CO_2 emissions reductions will be achieved earlier than in the baseline scenario, in 2040 rather than 2050. Also, the CO_2 emissions increase in 2030 under the stated policy scenario is much smaller than that in the baseline scenario because the electricity grid decarbonizes more rapidly.

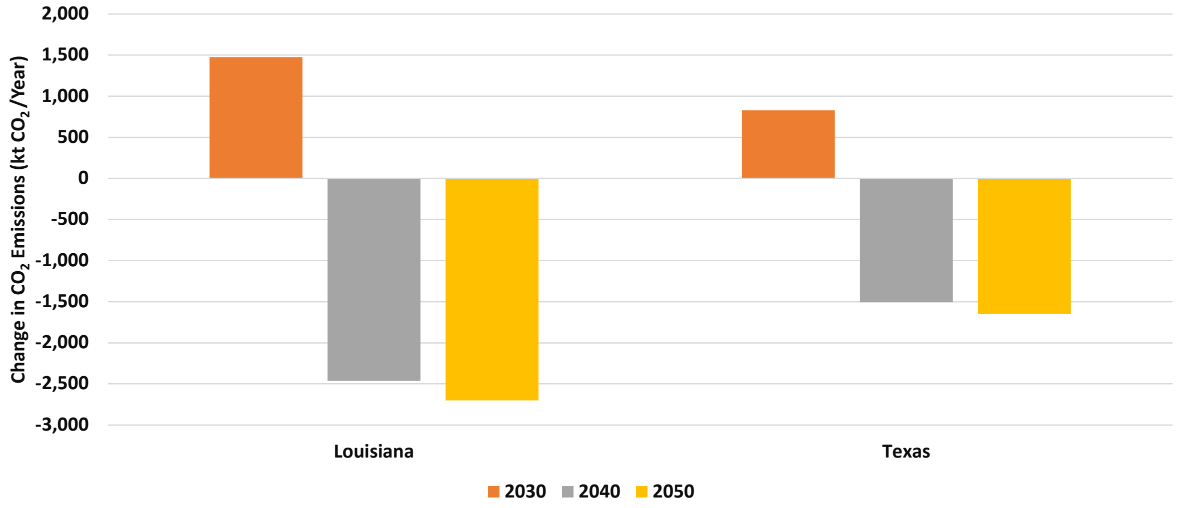

Figure 41. Change in the methanol industry's net CO_2 emissions after electrification - stated policy scenario (technical potential assuming 100% adoption rate)

Energy cost

Figure 42 shows that using the EIA electricity price forecast, the energy cost per unit of production (tonne of methanol) in 2030 for the electrified methanol production process is around seven times higher than that of the conventional process in 2021 in both states. Using a lower electricity price forecast scenario, electrified methanol production is still more than three times more expensive compared with the conventional process in both states.

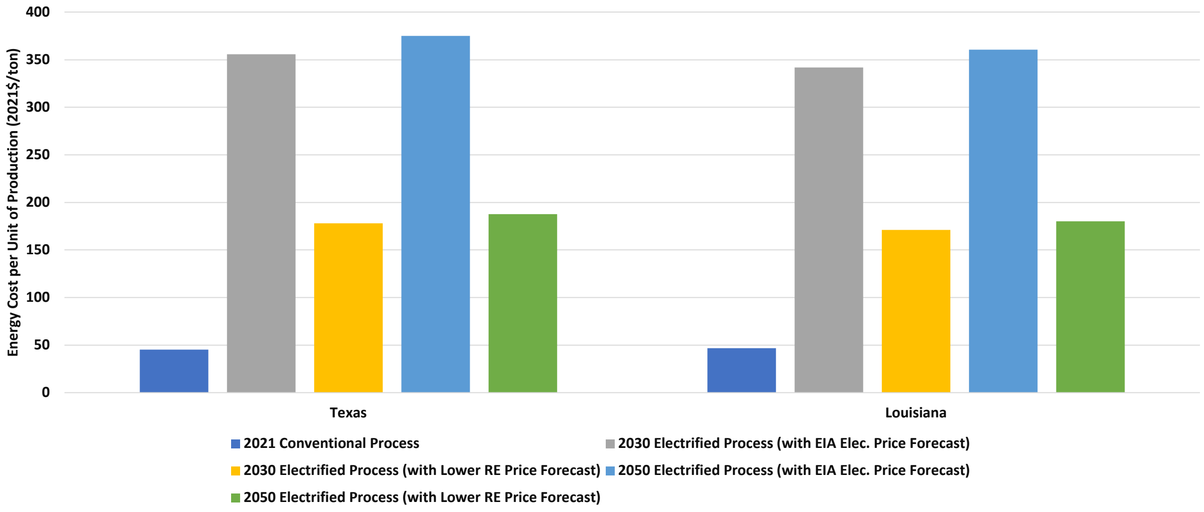

Figure 42. Energy cost per unit of production in the methanol industry

Other researchers also estimate methanol's production cost based on fossil fuel and electrolysis-based processes.Despite renewable electricity cost reductions, it is clear that manufacturing methanol with the electrified process is not and will not be cost competitive with the conventional fossil-fuel based production process (Bos et al. 2020).

3.6. Plastic Recycling Industry

Plastics are a rapidly rising proportion of municipal solid waste (MSW). Different types of plastics are included in the range of MSW categories: In the U.S., the containers and packaging category accounted for the highest plastic tonnage (around 14 million tonnes) in 2017. Major products included under this category are bags, packaging materials, polyethylene terephthalate (PET) bottles, jars, high-density polyethylene (HDPE) bottles, and other containers (EPA 2017). The main goals of recycling plastics are to reduce plastic pollution and use fewer virgin materials for plastic product manufacturing. In 2015, the U.S. recycled around 3.14 million tonnes of plastics, equivalent to about 9% of total plastic production in the U.S. that year (Leblanc 2019).

Here, we compare the energy intensities of the electrified plastic recycling process and the traditional virgin resin production method in petrochemical plants. The energy- and emissions-saving potential of the electrified plastic recycling process is in addition to the other environmental benefits that plastic recycling delivers. It should be noted that virgin resins produced in petrochemical plants can be used in a wide range of low-to-high-value applications, while recycled plastics typically have applications in the low-value range.

A detailed explanation of conventional and electrified processes for plastic manufacturing is provided in our previous report (Hasanbeigi et al. 2021). Tables 8 and 9 compare the energy intensities of the conventional and electric processes for plastic manufacturing.

Table 8. Original polymer production energy intensity (Used as plastic main raw materials) (Gervet, 2007)

	Thermal Demand (kWh/tonne)	Electrical Demand (kWh/tonne)	Total (kWh/tonne)
Polyethylene (PE)	15,274	4,166	19,439
Polypropylene (PP)	16,107	4,166	20,272
polyethylene terephthalate (PET)	8,609	14,718	23,327
Average	13,329	7,683	21,012

Table 9. All-electric plastic recycling process energy intensity (Beyond Zero Emissions, 2018)

Process	Temperature (°C)	Electrical Demand (kWh/tonne)
Shredding	-	0 *
Water cooling	10	70
Air compression	-	20
Melting	190	270
Extrusion/Molding	-	120
Lighting	-	60
Total energy		540

* value is less than 0.5.

Energy use

Figure 43 shows that using the electrified plastic recycling process will significantly reduce the total final energy use in plastic production compared to virgin resin production during the study period up to 2050. Ohio, Texas, Michigan, Minnesota, and Indiana are the states with the largest energy-saving potentials from switching to electrified plastic recycling production.

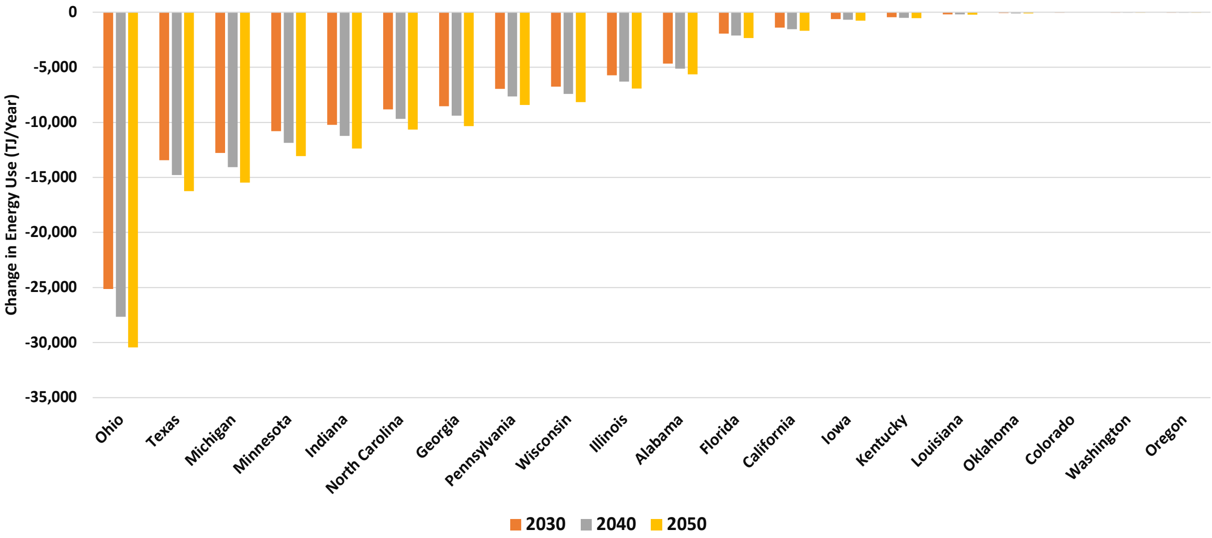

Figure 43. Change in the plastics industry's energy use using electric plastic recycling process (technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 44 shows the plastic industry's change in net CO_2 emissions after electrification under the baseline scenario. Because of the substantial energy savings from plastic production electrification (shown in Figure 43), electrification results in CO_2 emissions reductions in 2030 in all states studied. The decline in the CO_2 emissions reduction potential between 2030 and 2050 shown in Figures 44 and 45 results from a decline in the electricity grid's CO_2 emissions factor in this period: as the grid decarbonizes, virgin resin production emissions intensity will decrease, thereby reducing the difference between the conventional virgin resin process and the electrified recycled plastic process.

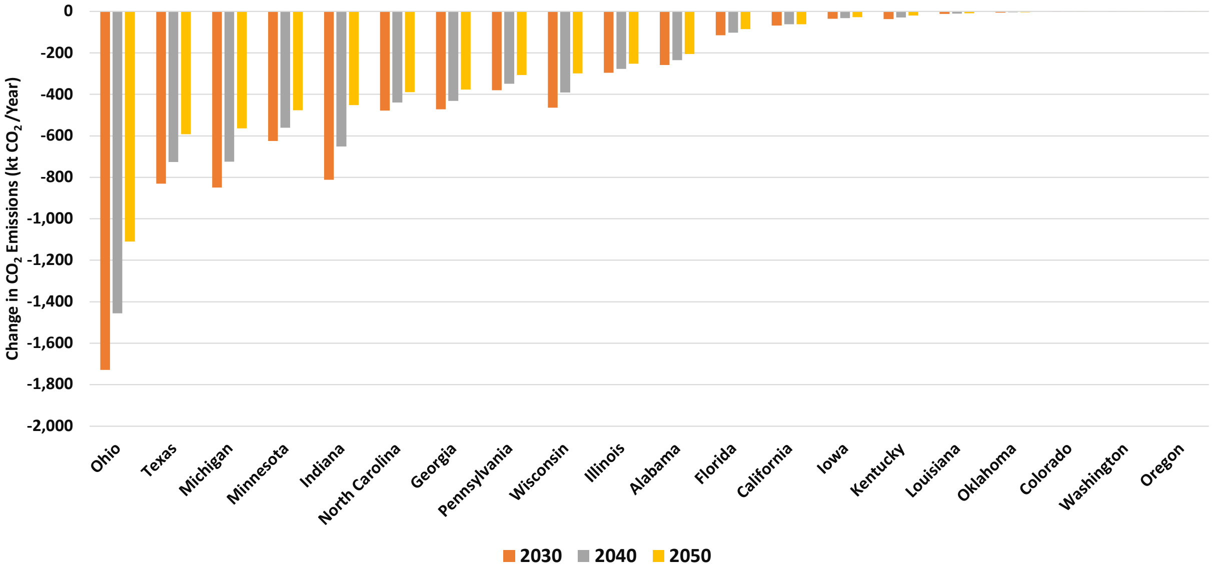

Figure 44. Change in the plastics industry's net CO_2 emissions using electric plastic recycling process - baseline scenario (technical potential assuming 100% adoption rate)

Figure 45 shows the plastic industry's change in net CO_2 emissions after electrification under the stated policy scenario. Under this scenario, the CO_2 emissions reduction potential in 2030 and 2040 are substantially higher than the baseline scenario because more rapid decarbonization is assumed under the stated policy scenario.

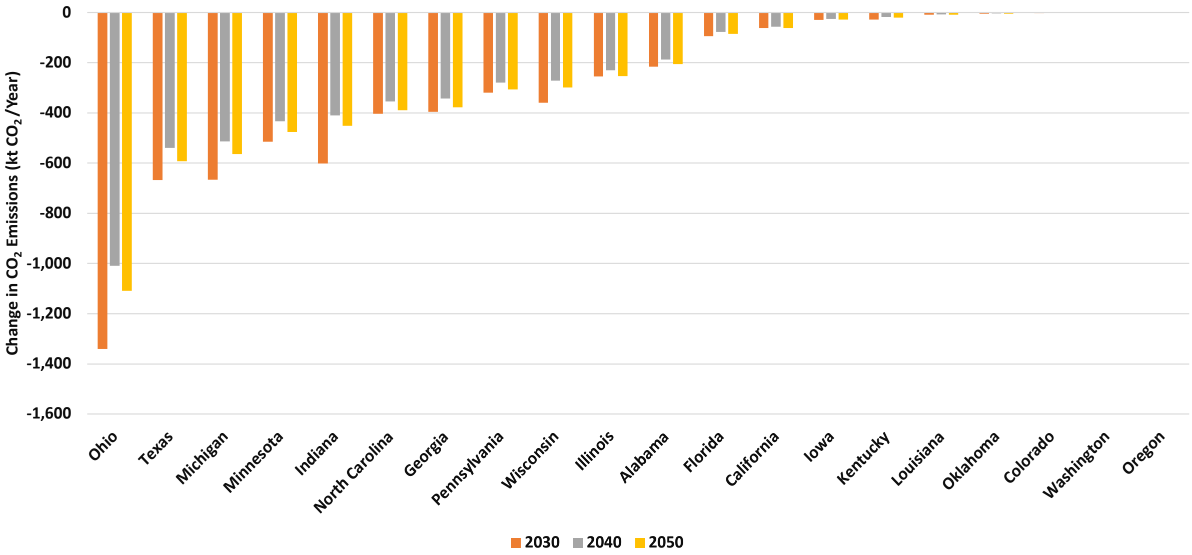

Figure 45. Change in the plastics industry's net CO_2 emissions using electric plastic recycling process - stated policy scenario (technical potential assuming 100% adoption rate)

Figure 46 shows that numerous states have an opportunity to reduce emissions by employing an electrified plastics recycling process to replace the conventional virgin resin process. Texas and Ohio have the highest potential to reduce emissions by making this change.

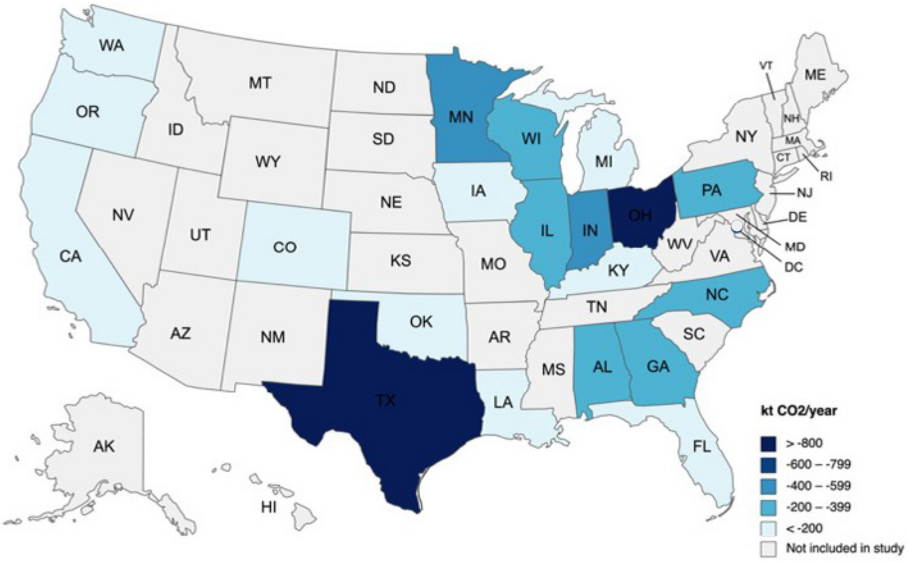

Figure 46. Change in emissions in the plastic recycling industry in 2050

Energy cost

Figure 47 shows that the energy cost per unit of production (tonne of plastic) for the electrified plastic recycling process in 2030 is less than 5% of the cost of a conventional plastic manufacturing process in 2021. It should be noted that the energy related to the transportation and sorting of recycled plastic and the cost associated with them are not included in this analysis.

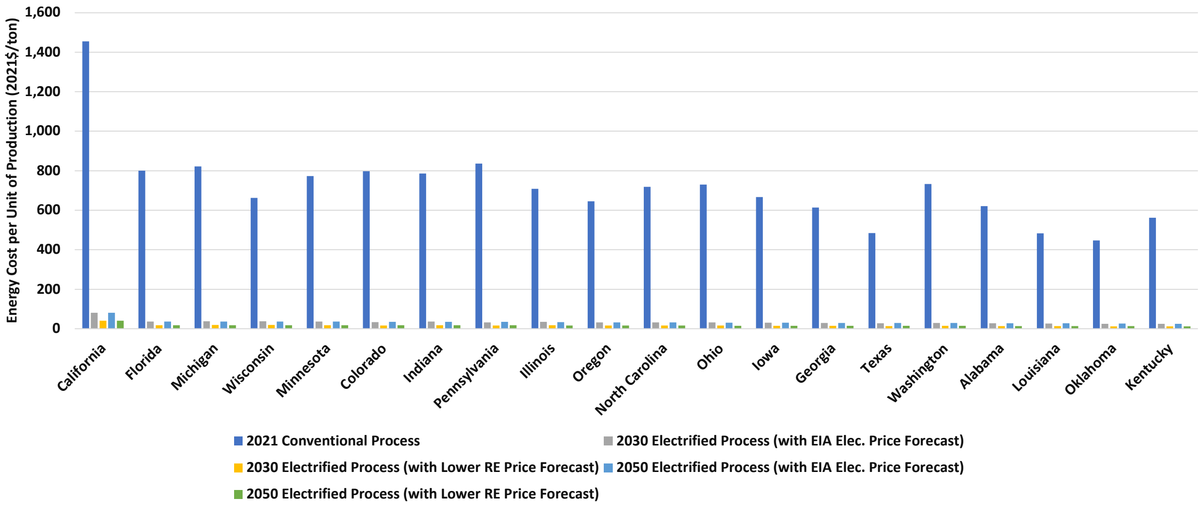

Figure 47. Energy cost per unit of production in the conventional plastics industry and electrified plastics recycling process

3.7. Steel Industry

The U.S. steel industry produced 87 million tonnes (Mt) of crude steel in 2021: 30% was produced by primary steelmaking plants using blast furnace-basic oxygen furnaces (BF-BOF), and 70% was produced by electric arc furnaces (EAFs), which mainly use steel scrap. The U.S. also imported 27 Mt and exported 6.7 Mt of steel mill products in 2020. The value of raw steel produced by the U.S. iron and steel industry in 2021 was about $92 billion. Three U.S. companies operate BF-BOF plants that produce pig iron and crude steel and have integrated steel mills in nine locations in Indiana, Ohio, Illinois, and Michigan. Fifty companies own EAF steel plants, producing crude steel at 98 mini-mills. Indiana accounted for an estimated 26% of total raw steel production, followed by Ohio with 12%, Michigan with 5%, and Pennsylvania with 5%. No other state has more than 5% of total domestic raw steel production (USGS 2020).

Iron and steel manufacturing is one of the most energy-intensive industries worldwide. it production has among the highest CO_2 emissions of any industry, given the volume of steel produced and that coal is the primary fuel and feedstock for iron oxide chemical reduction. The iron and steel industry accounts for around 11% of global CO_2 emissions and 7% of global GHG emissions (Hasanbeigi, 2021).

A detailed explanation of conventional and electrified processes for the steel industry is provided in our previous report (Hasanbeigi et al. 2021). Table 10 compares the energy intensity of the steel industry's conventional and electric processes.

Table 10. Conventional and (mostly) electric steelmaking processes’ energy intensities

Steel Production Types	Process Steps	Thermal Demand (kWh/tonne)	Electrical Demand (kWh/tonne)	Total Energy (kWh/tonne)
BF-BOF Steel Production	Sintering/Pelletization Coke Making Blast Furnace Basic Oxygen Furnace Casting, Rolling, and Finishing	4,861	621	5,482
Scrap-EAF Steel Production	EAF Casting, Rolling, and Finishing	667	710	1,377
H_2 DRI-EAF Steel Production	H_2 Production DRI Production EAF Casting, Rolling, and Finishing	667	3,500	4,167
Steel Production by Electrolysis	Electrolysis of Iron Ore Casting, Rolling, and Finishing	556	3,300	3,856

* H_2 DRI EAF: Hydrogen Direct Reduced Iron (DRI) - EAF steelmaking process

All U.S. integrated BF-BOF steel plants are located in Indiana, Ohio, Illinois, Pennsylvania, and Michigan. The analysis quantifies the energy, GHG emissions, and cost implications of converting all BF-BOF steelmaking in these four states to electrified steelmaking using one of the three electrified steelmaking processes shown in Table 10.

Energy use

Figures 48 to 50 show energy savings from electrified steelmaking using one of the three electrified processes in 2030-2050. Electrification will significantly reduce the steel industry’s total final energy use in these five states during the study period in all three electrified technology cases. Switching to Scrap-EAF steel production creates the largest energy savings. The energy savings increase over time because an increase in steel production is assumed up to 2050.

It should be noted that the energy savings achieved from these three electrified steelmaking processes cannot be combined. These are three separate technology scenarios to show the energy savings and GHG implications if one electrified steelmaking process were used to replace BF-BOF steelmaking.

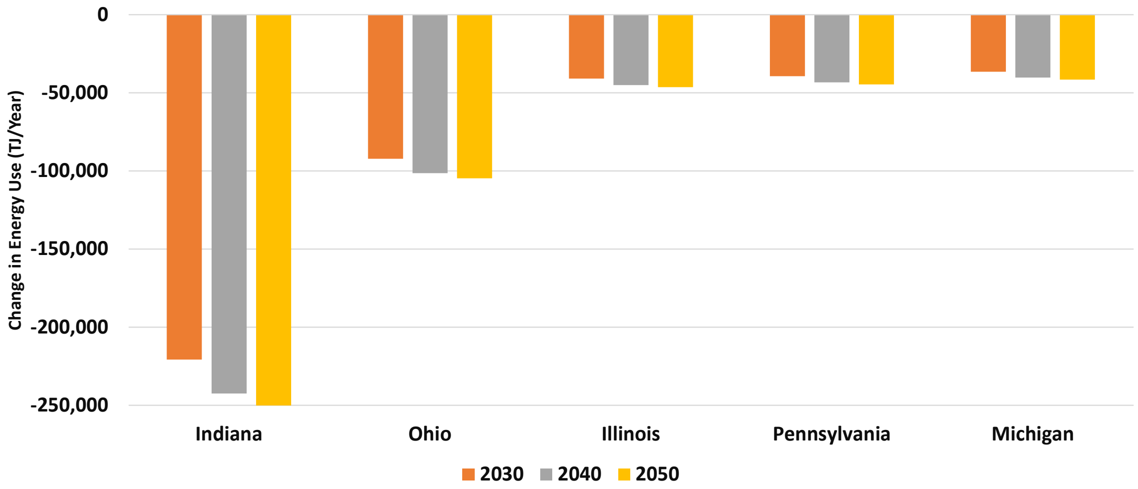

Figure 48. Change in the steel industry’s total final energy use after electrification using Scrap-EAF technology (technical potential assuming 100% adoption rate)

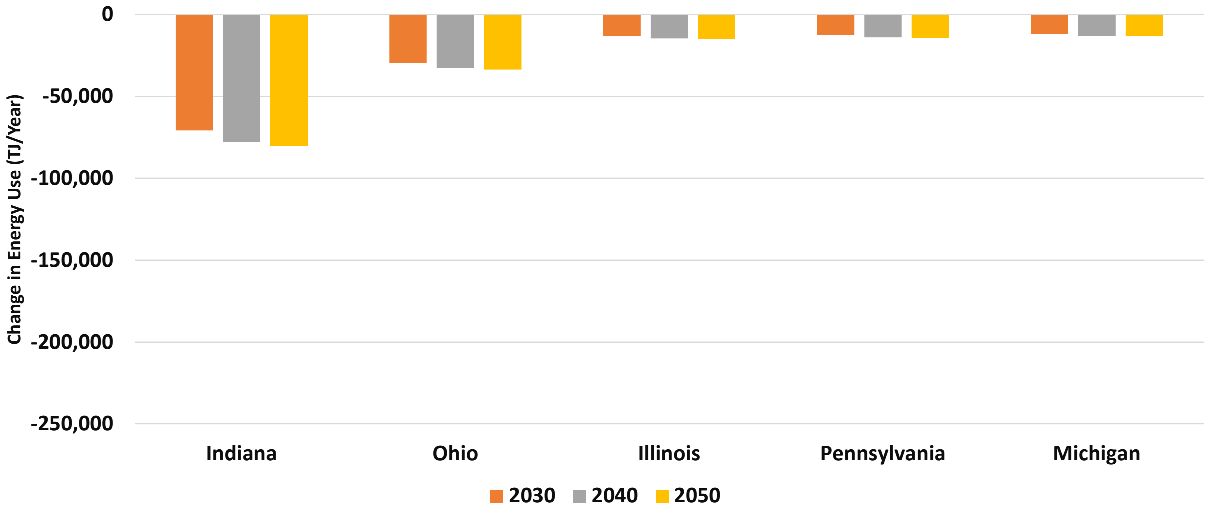

Figure 49. Change in the steel industry's total final energy use after electrification using H_2 DRI-EAF technology (technical potential assuming 100% adoption rate)

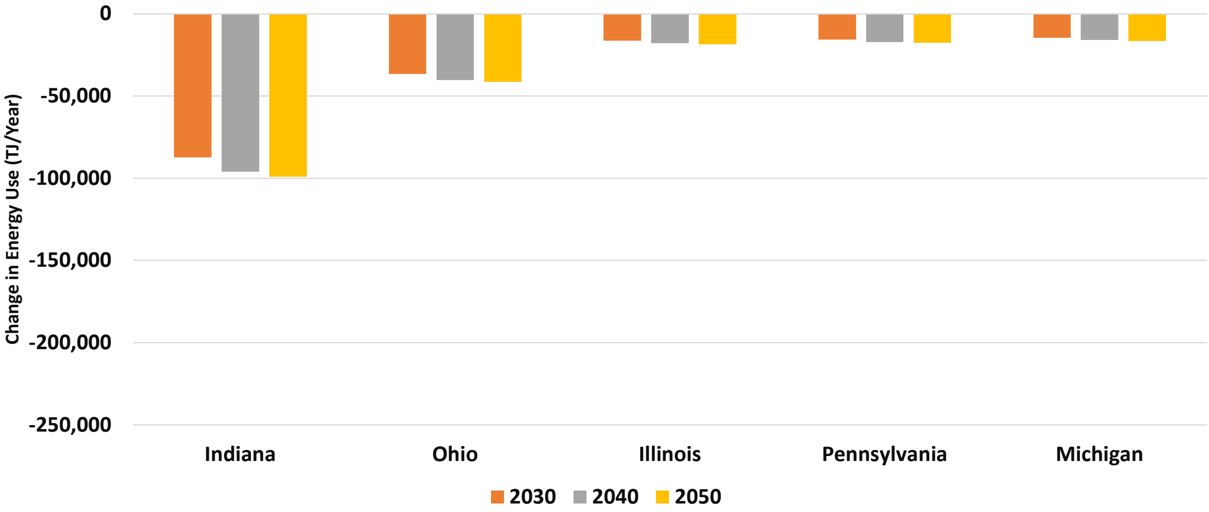

Figure 50. Change in the steel industry's total final energy use after electrification using electrolysis technology (technical potential assuming 100% adoption rate)

CO_2 emissions

Steel production electrification with Scrap-EAF technology could result in a substantial drop in CO_2 emissions in 2030 in all five states (Figure 51). However, electrification with H_2 DRI-EAF and electrolysis technology can result in a smaller drop in CO_2 emissions in 2030 (Figures 52-53). As the electricity grid decarbonizes in these states between 2030 and 2050, substantial annual CO_2 emission reductions from steel production electrification occur with these technologies.

Although the H_2 DRI-EAF and electrolysis process routes result in relatively smaller total energy savings, since the majority of energy used in H_2 DRI-EAF and electrolysis is electricity (for H_2 production needed in H_2 DRI and electrolysis process in the electrolysis of iron ore), their CO_2 emissions reductions are comparable with Scrap-EAF in 2050 as the electricity grid is decarbonized.

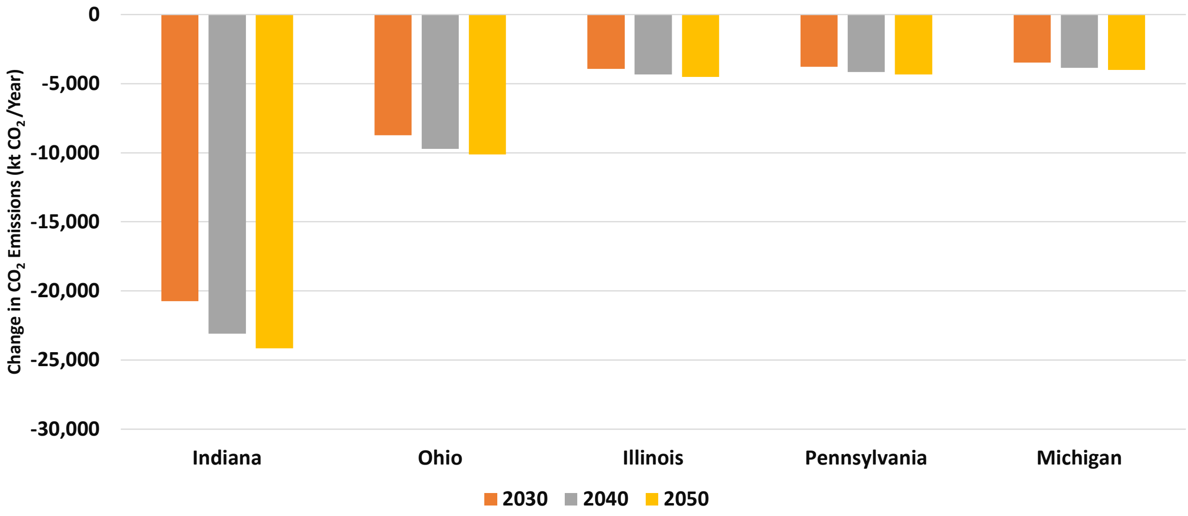

Figure 51. Change in the steel industry's net CO_2 emissions after electrification using Scrap-EAF technology - baseline scenario (technical potential assuming 100% adoption rate)

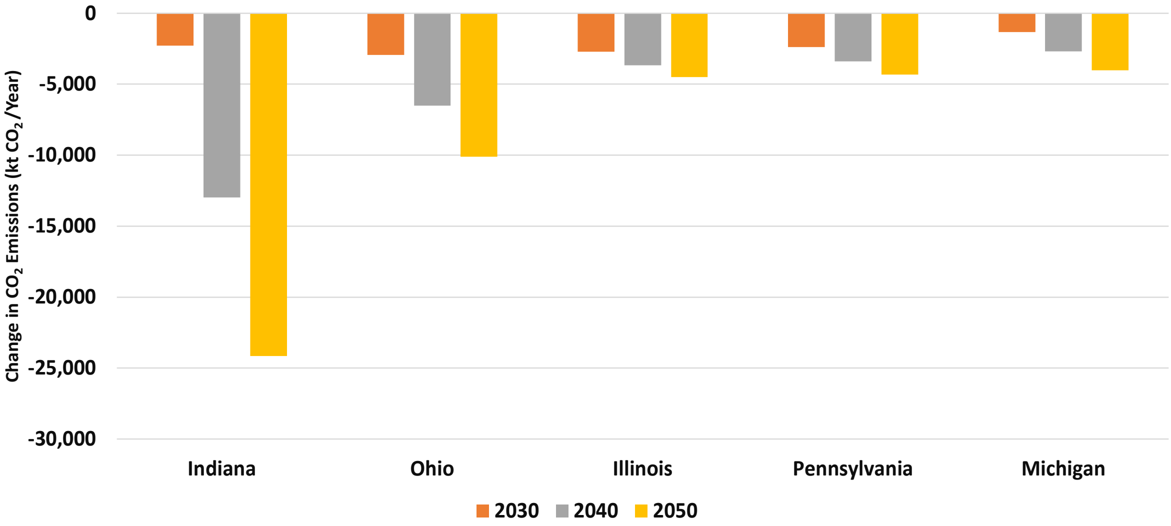

Figure 52. Change in the steel industry's net CO_2 emissions after electrification using H_2 DRI-EAF technology - baseline scenario (technical potential assuming 100% adoption rate)

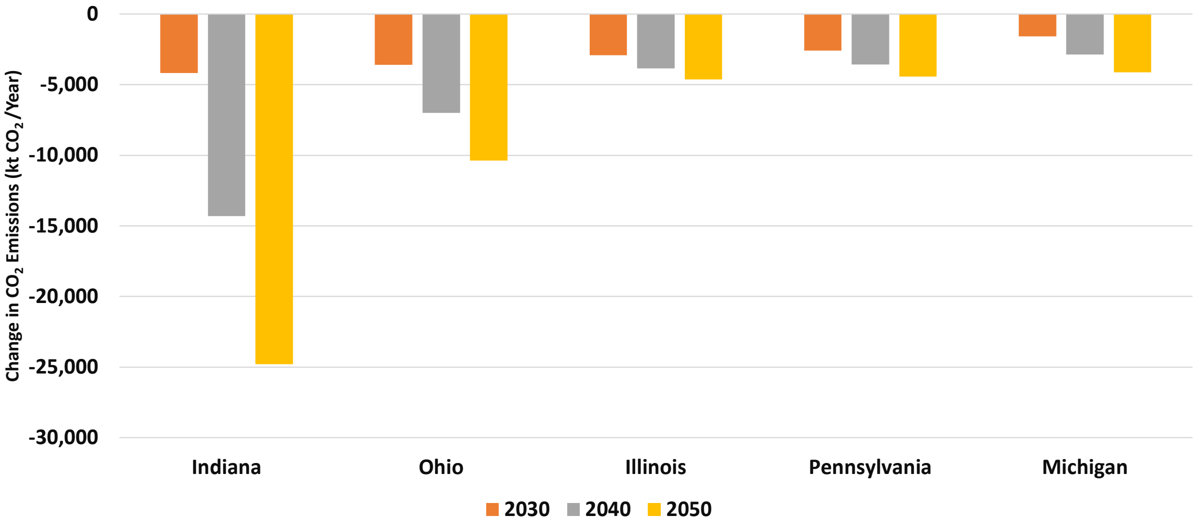

Figure 53. Change in the steel industry's net CO_2 emissions after electrification using electrolysis technology - baseline scenario (technical potential assuming 100% adoption rate)

If a zero-carbon grid is achieved earlier in these states, the CO_2 emissions reduction potential in future years (2030, 2040, and 2050) is substantially larger (Figure 54) than the baseline scenario.

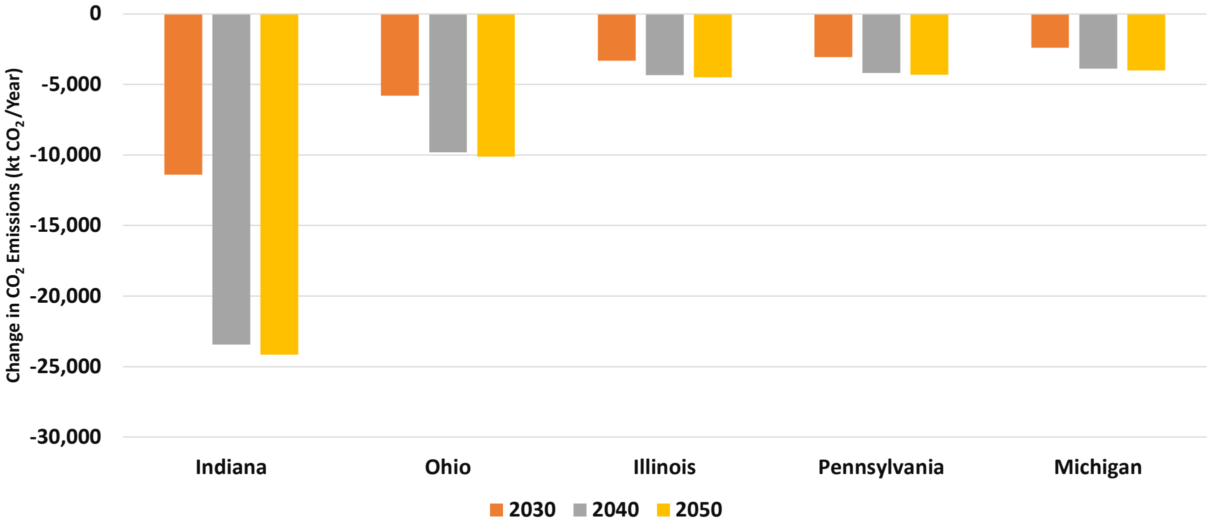

Figure 54. Change in the steel industry's net CO_2 emissions after electrification using H_2 DRI-EAF technology - stated policy scenario (technical potential assuming 100% adoption rate)

The map in Figure 55 shows that steel production in the U.S., and thus emissions reduction potential from electrifying the steel industry with H_2 DRI-EAF technology, is concentrated in the Great Lakes region.

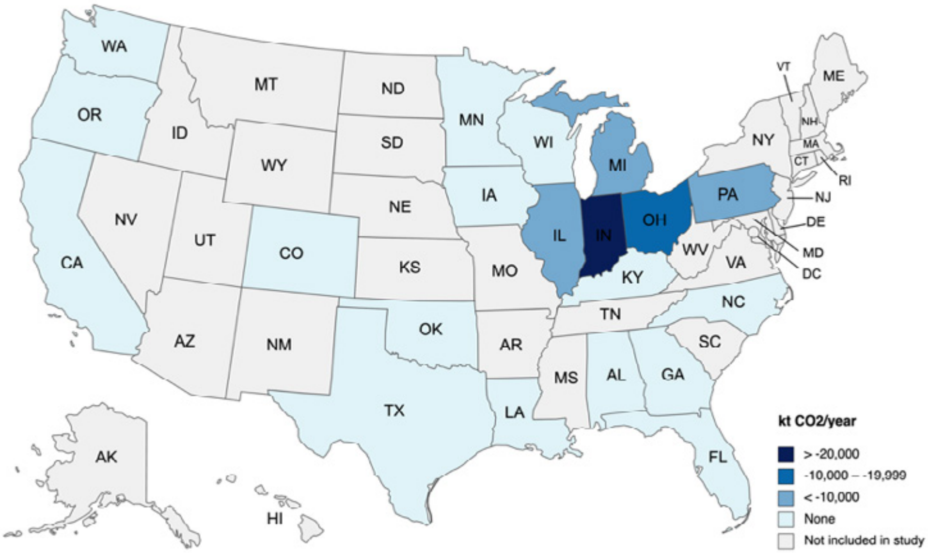

Figure 55. Change in emissions in the steel industry using H_2 DRI-EAF in 2050

Energy cost

Figures 56 to 58 show the energy cost per unit of production (tonne of steel) for the BF-BOF and three electrified steel technologies. Compared with BF-BOF steel production, under the scenario with the EIA electricity price forecast, the energy cost per unit of product is substantially lower for Scrap-EAF technology and significantly higher for the H_2 DRI-EAF and electrolysis technologies in 2030 in all states. The Scrap-EAF has a lower energy cost than BF-BOF steelmaking and the other two electrified processes mainly because Scrap-EAF has substantially lower energy demand (Table 10) than the other processes. Under the Lower RE electricity price forecast, both H_2 DRI-EAF and electrolysis technologies have a lower energy cost per unit of production compared with the BF-BOF steel production in all states studied except Illinois.

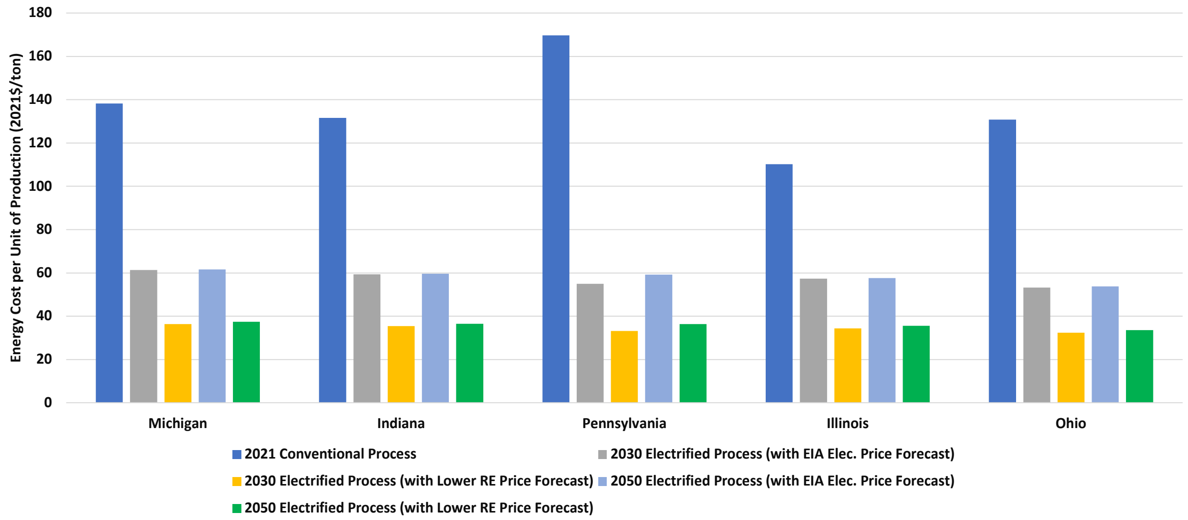

Figure 56. Energy cost per unit of production in the steel industry for conventional and Scrap-EAF technology

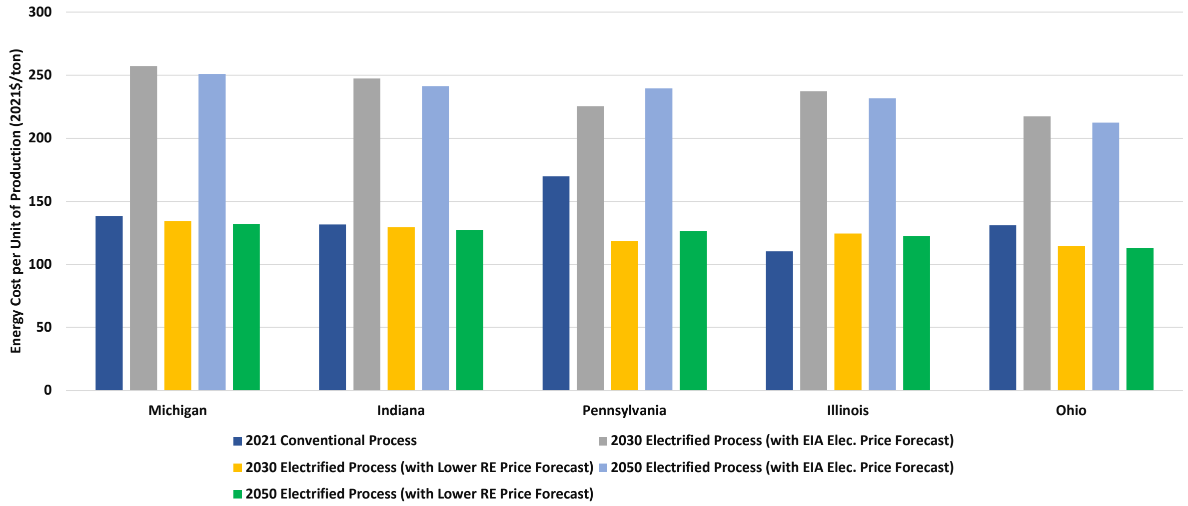

Figure 57. Energy cost per unit of production in the steel industry for conventional and H_2 DRI-EAF technology

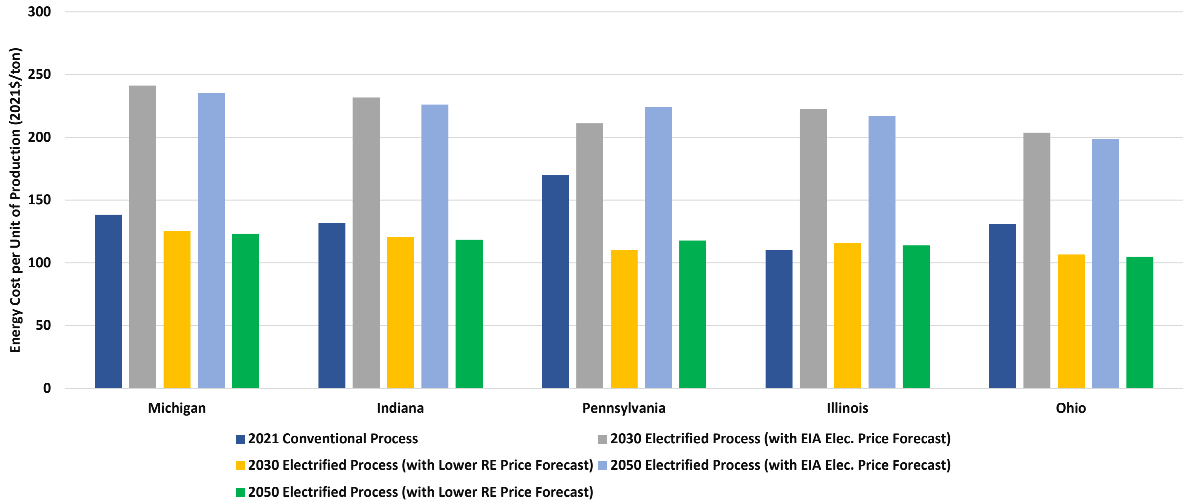

Figure 58. Energy cost per unit of production in the steel industry for conventional and electrolysis technology

3.8. Beer Industry

In 2021, there were reported to be over 8,000 breweries in the U.S., collectively producing around 211 million barrels of total annual beer. In 2050, production is expected to rise to 252 million barrels (U.S. DOE 2017b). Brewing is one of the food and beverage industry's highest energy-consuming subsectors (U.S. DOE/EIA, 2017).

The brewing process is a procedure that transforms yeast, water, grains, and hops into beer. Ingredient variation and production conditions, such as varietals and temperature, yield a wide range of beer types and styles (Sánchez 2017).

Heat pumps could be utilized to electrify the beer production process in four process stages. The coefficient of performance (COP)[2] of these heat pumps is included in Table 11.

Table 11. Heat pump specifications (Beyond Zero Emissions, 2019)

	Process Stage	Output Temperature (°C)	Coefficient of Performance
Heat Pump 1	Boiling	110	1.8
Heat Pump 2	Boiling	110	1.8
Heat Pump 3	Pasteurization	60	5
Heat Pump 4	Mashing & Cleaning	80	4

A detailed explanation of the beer industry's conventional and electrified processes is provided in our previous report (Hasanbeigi et al. 2021). Table 12 compares the energy intensity of beer production's conventional and electric processes.

Table 12. Conventional and electric beer production processes' energy intensities (Beyond Zero Emissions 2019)

Conventional System Process			All Electric Process	
Heating Equipment	Thermal Demand (kWh/Hectoliter)	Process steps	Electrical Demand (kWh/Hectoliter)	Heating Equipment *
Centralized Gas Boiler System	2.9	Mashing	0.6	Heat Pump 4
Centralized Gas Boiler System	12.9	Boiling	6.1	Heat Pump 1&2
Centralized Gas Boiler System	5.2	Pasteurization	0.9	Heat Pump 3
Centralized Gas Boiler System	12.0	Cleaning & Production Support	2.6	Heat Pump 4
	33.0	**Subtotal**	**10.2**	
33.0		**Total Energy**	**10.2**	

* Heat pump numbers in this column refer to the type of heat pump as indicated in Table 11

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[2] The coefficient of performance or COP of a heat pump is a ratio of useful heating provided to work (energy) required. Higher COP equates to higher efficiency, lower energy consumption and thus lower operating costs.

Energy use

Beer production electrification will significantly reduce the total final energy use during the study period (Figure 59). The energy savings increase over time because an increase in production is assumed up to 2050. Colorado, California, Texas, Ohio, and Georgia are the states with the largest energy savings potentials from switching to electrified beer production processes.

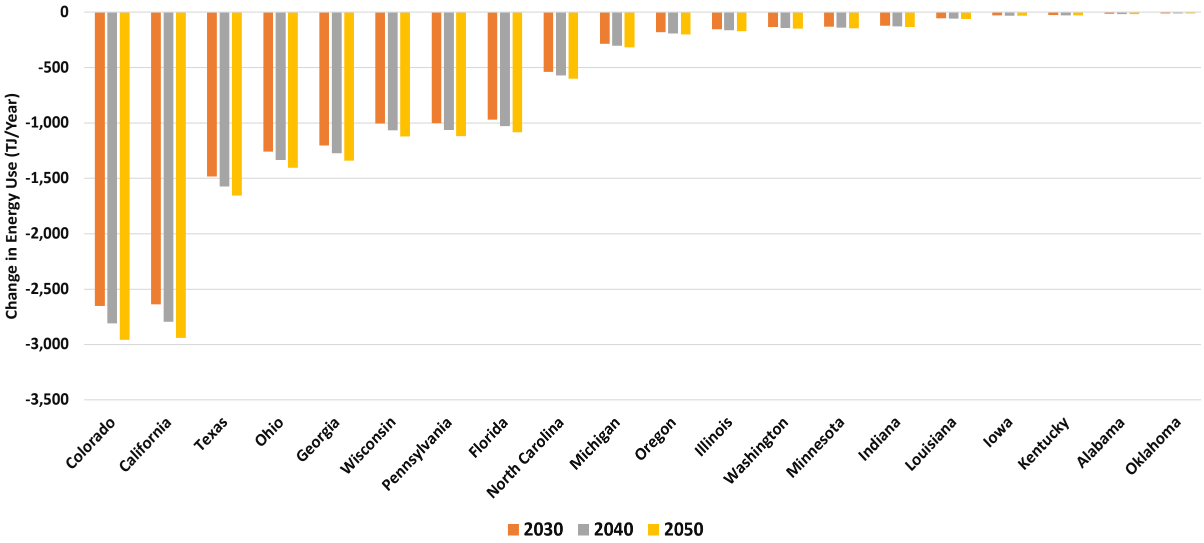

Figure 59. Change in the beer industry’s total final energy use after electrification (technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 60 shows that states across the country have the opportunity to realize emissions reductions in 2050 with an electrified beer production process. Colorado and California have the highest emissions reduction potential.

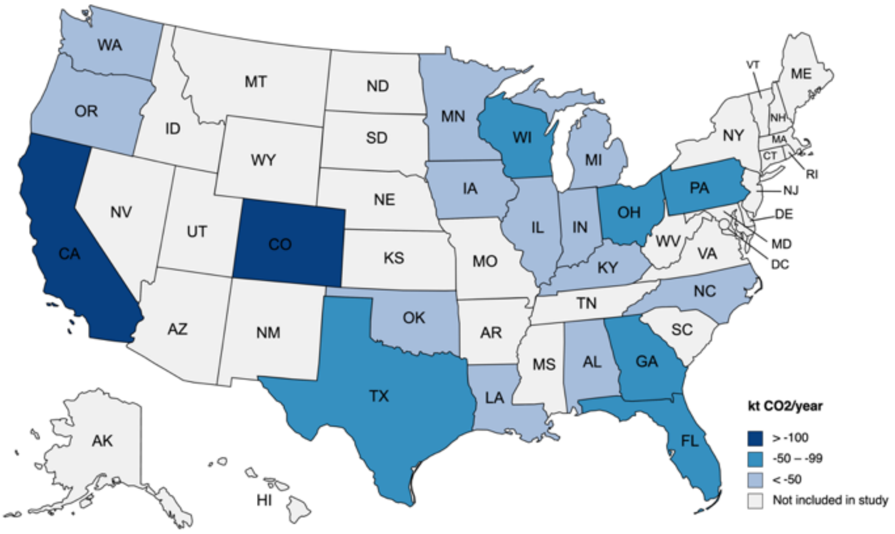

Figure 60. Change in emissions in the beer industry in 2050

Figure 61 shows the beer industry’s change in net CO_2 emissions after electrification under the baseline scenario. Beer production electrification will result in a drop in CO_2 emissions in 2030 in all states studied. Electrification further reduces annual CO_2 emissions by 2050 in all states because of grid decarbonization.

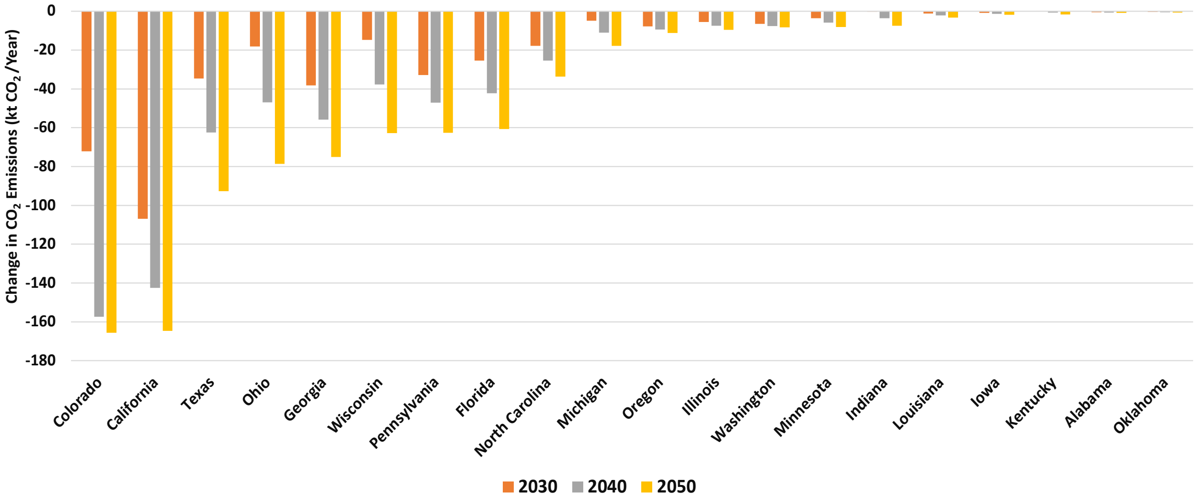

Figure 61. Change in the beer industry's net CO_2 emissions after electrification - baseline scenario (technical potential assuming 100% adoption rate)

Figure 62 shows that under the stated policy scenario, the CO_2 emissions reduction potential in 2030 is substantially higher than in the baseline scenario because more rapid grid decarbonization is assumed.

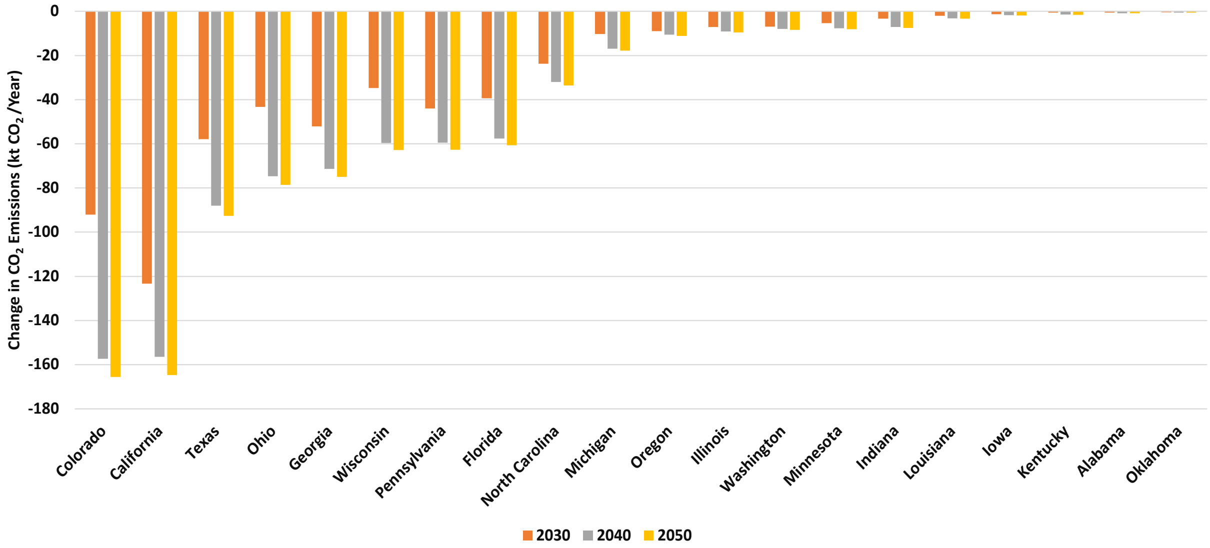

Figure 62. Change in the beer industry's net CO_2 emissions after electrification - stated policy scenario (technical potential assuming 100% adoption rate)

Energy cost

Figure 63 shows that under the scenario with the EIA electricity price forecast, the energy cost per unit of production in 2030 for the electrified process in the beer industry is higher than that of the conventional process in 2021 in some states (including California, Texas, and Oklahoma), almost equal in some states (including Florida, Michigan, and North Carolina), and lower in other states (including Pennsylvania, Washington, and Ohio). This is because states like California, Texas, and Oklahoma have a relatively lower ratio of the unit price of electricity to natural gas. (see Figure 12).

Figure 63 shows the energy cost per unit of electrified beer production processes in 2050 under two scenarios, one with higher and another with lower electricity prices in each state. Even under the higher 2050 electricity price scenario, an electrified beer production process is cost-competitive compared to the conventional process in many states studied.

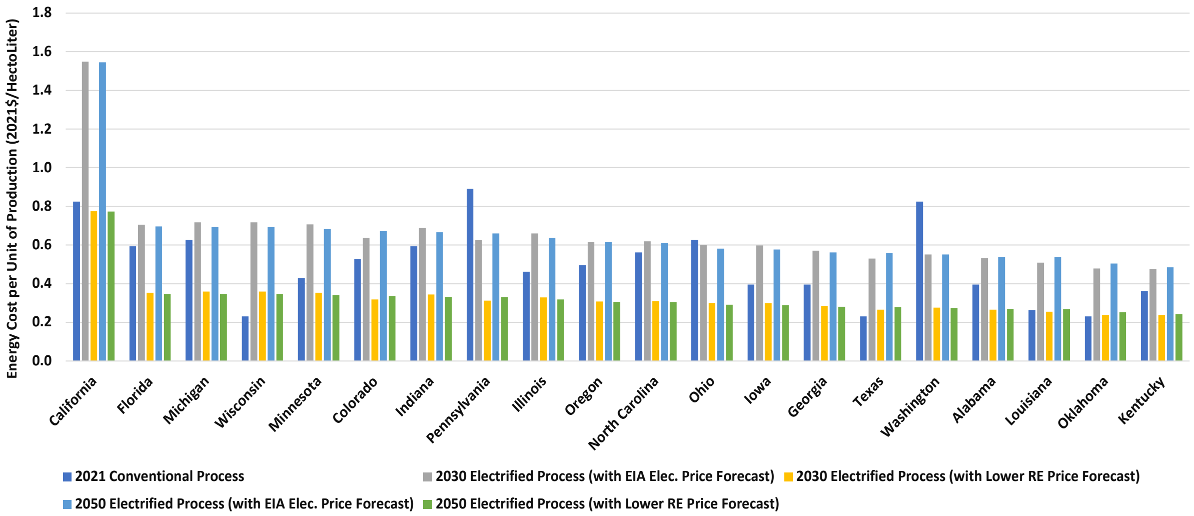

Figure 63. Energy cost per unit of production in the beer industry

3.9. Beet Sugar Industry

One of the most popular and widely available sweeteners, granulated white sugar, is extracted from sugar cane and sugar beet plants. It is colloquially referred to as “sugar” or table sugar and is among the purest (about 99.95%) food products. The sugar content of beet and cane juices is quite similar, but impurity amounts differ. Impurities in beet and cane juice are around 2.5% and 5%, respectively. The processes and the chemicals utilized for refining cane and beet sugars vary due to differences in impurities and the products’ compositions (Campos 2020).

Bagasse, a dry pulpy residue obtained as a by-product of the sugar cane sugar manufacturing process, is utilized as a fuel in cogeneration systems that provide heat and electricity for the sugar production process. Over the last few years, numerous sugar cane factories have produced excess electricity that can be sold to the grid, providing an additional revenue stream (Ensinas 2006). Therefore, sugar cane production electrification was deemed less likely, and the study focused on beet sugar production electrification. Total annual U.S. beet sugar production is estimated to be around 4.6 million metric tonnes (U.S. DOE 2017b). It is also one of the food and beverage industry’s highest energy-consuming subsectors.

A detailed explanation of conventional and electrified processes for the beet sugar industry is provided in our previous report (Hasanbeigi et al. 2021). Table 13 compares the energy intensity of beet sugar production’s conventional and electric processes.

Table 13. Conventional and electric beet sugar production processes' energy intensities (Hasanbeigi et al. 2021)

Conventional System Process				All Electric Process	
Heating Equipment	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)	Process steps	Electrical Demand (kWh/tonne)	Heating Equipment
Conventional Steam Generator	153	778	Juice Diffusion	464	Heat Pump
Conventional Steam Generator			Juice Purification		Heat Pump
Conventional Steam Generator			Evaporation		Heat Pump
Conventual Steam Generator			Crystallization		Electric Steam Boiler
Direct Fuel Base Dryer		806	Pulp Drying	806	Electric Air Dryer
	153	**1,584**	**Subtotal**	**1,270**	
	1,737		**Total Energy**	**1,270**	

Energy use

We identified beet sugar production in eight of the studied states. Electrification will reduce the total final energy use for beet sugar production in all eight states (Figure 64). The energy savings increase over time because an increase in beet sugar production is assumed up to 2050.

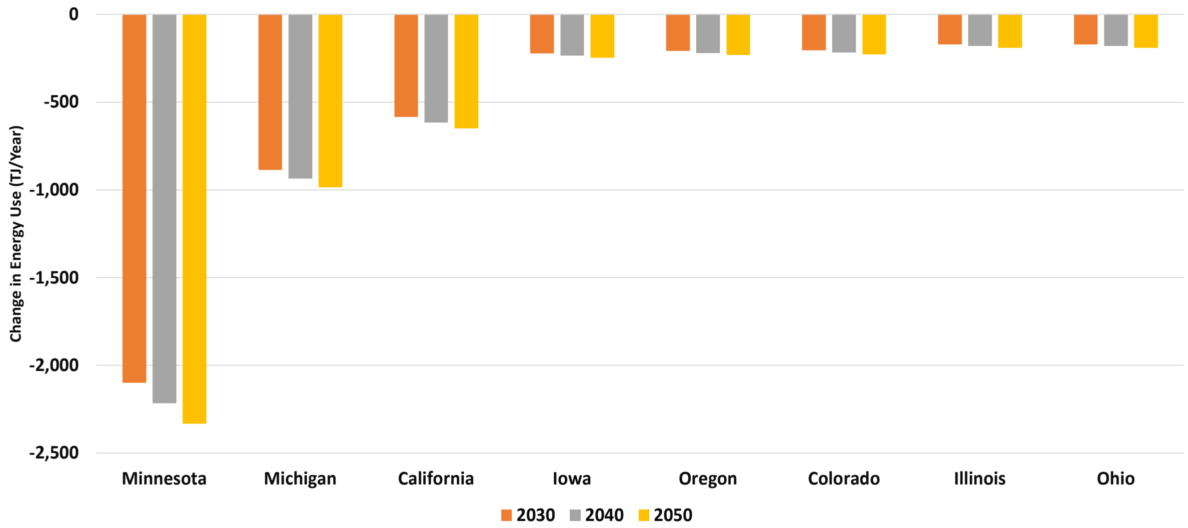

Figure 64. Change in the beet sugar industry's total final energy use after electrification (technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 65 shows which states in this study have the potential to reduce CO_2 emissions in 2050 by electrifying the beet sugar industry. Minnesota has the highest potential to reduce emissions, while Michigan and California also have a relatively high potential.

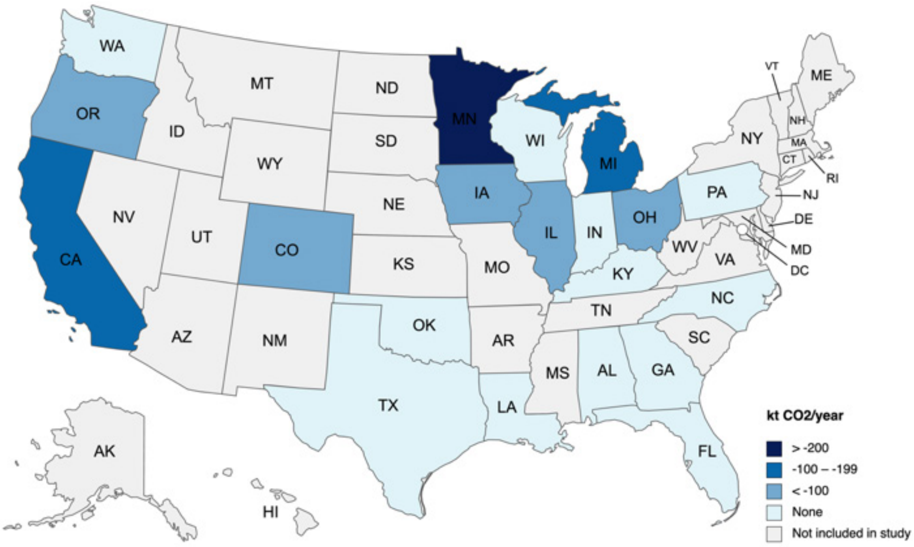

Figure 65. Change in emissions in the beet sugar industry in 2050

Beet sugar production electrification could result in a slight increase in CO_2 emissions in 2030 in Michigan and Ohio because of their relatively higher grid CO_2 emissions compared to other beet sugar-producing states (Figure 66). As the electricity grid decarbonizes in these two states between 2030 and 2050, they will realized annual CO_2 emissions reductions through electrifying beet sugar production.

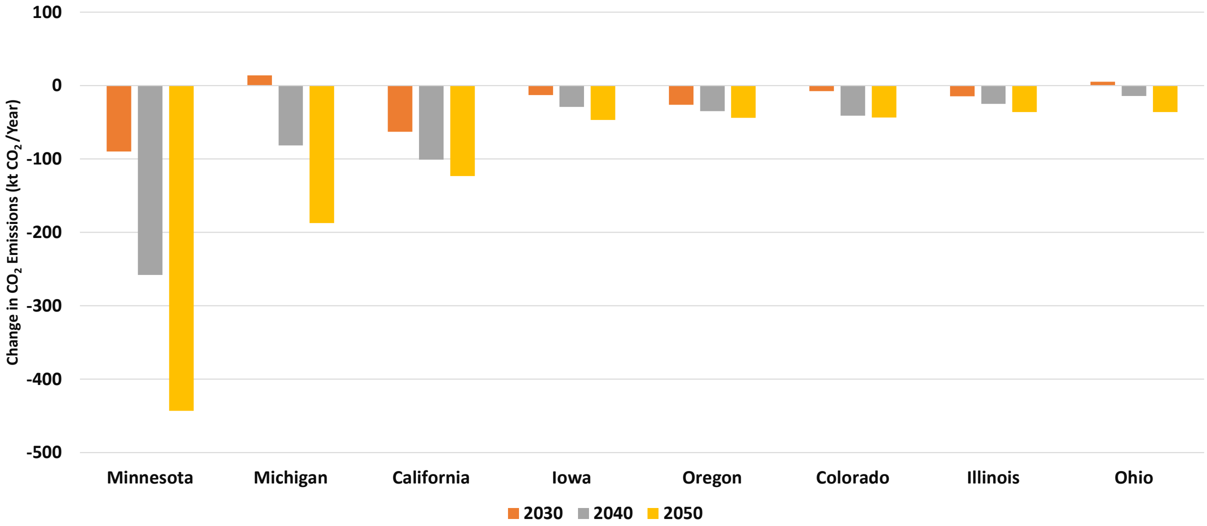

Figure 66. Change in the beet sugar industry's net CO_2 emissions after electrification - baseline scenario (technical potential assuming 100% adoption rate)

If a zero-carbon grid is achieved earlier in all states, the CO_2 emissions reduction potential in future years is substantially higher (Figure 67) than the baseline scenario. In Michigan and Ohio, CO_2 emissions will increase in 2030 under the baseline scenario, but CO_2 emissions will decrease in 2030 under the stated policy scenario because more rapid electricity grid decarbonization is assumed.

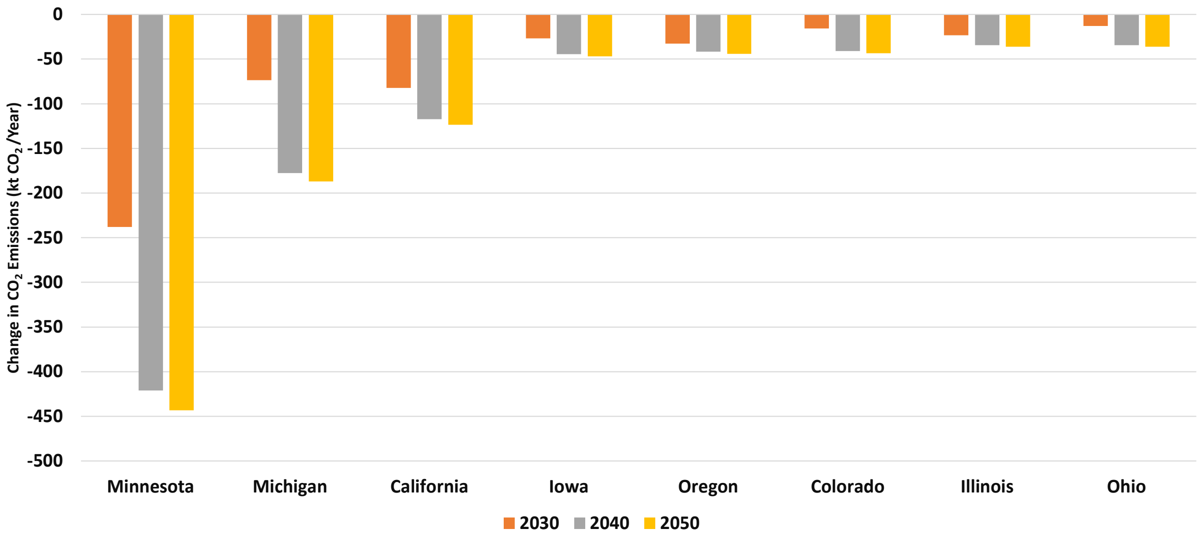

Figure 67. Change in the beet sugar industry's net CO_2 emissions after electrification - stated policy scenario (technical potential assuming 100% adoption rate)

Energy cost

Figure 68 shows that the energy cost per unit of production (tonne of beet sugar) in 2030 for the electrified beet sugar process is more than two times higher than that of the conventional process in 2021 in all states under the scenario with the EIA electricity price forecast. Using the Lower RE price forecast scenario, electrified beet sugar production can be cost-competitive with the conventional process in all states in both 2030 and 2050 except in California.

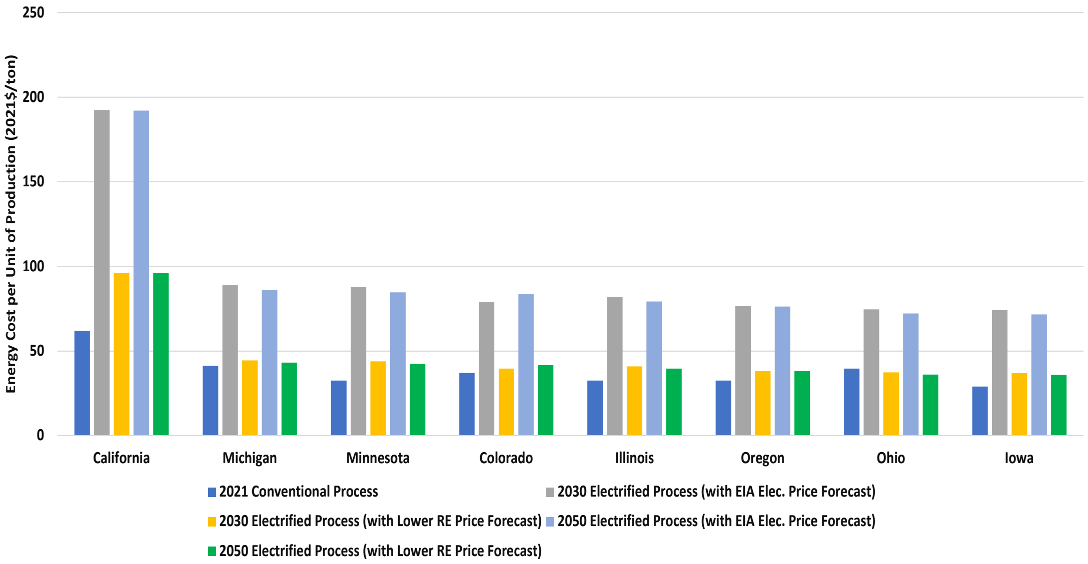

Figure 68. Energy cost per unit of production in the beet sugar industry

3.10. Milk Powder Industry

Dehydrating liquid milk using drying processes creates powdered milk or dried milk. Milk preservation is one of the main reasons to dry it since milk powder has a much longer shelf life as compared to liquid milk and has no refrigeration requirements (Rotronic 2015). The U.S.

is the world's single largest manufacturer of skim milk powder (SMP) or nonfat dry milk, with close to 1.1 million tonnes produced in 2019. U.S. SMP production continues to rise, and the country currently produces almost a quarter of SMP globally. U.S. SMP exports have risen, with over 50% of production destined for overseas markets (U.S. Dairy Export Council 2015). The dairy industry is also one of the largest energy-consuming food and beverage subsectors.

A detailed explanation of conventional and electrified processes for the milk powder industry is provided in our previous report (Hasanbeigi et al. 2021). Table 14 compares the energy intensity of the milk powder industry's conventional and electric processes.

Table 14. Conventional and electric milk powder production processes' energy intensities (Beyond Zero Emissions 2018)

Conventional System Process			Process Steps	All Electric Process	
Equipment	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)	Equipment
Centrifuge	13	3	Separation	13	Centrifuge
-	-	-	Reverse Osmosis	35	Reverse Osmosis Pump
Steam Boiler	-	388	Pre-Heating	47	Heat Pump 1
Mechanical and Thermal Vapor Recompression	90	133	Evaporation	27	Mechanical and Thermal Vapor Recompression
Steam Boiler	50	1,139	Drying	492	Heat Pump 2, Electric Air Heater
Fluidized Bed	45	111	Cooling	148	Fluidized Bed
	198	**1,774**	**Subtotal**	**762**	
1,972			**Total Energy**	**762**	

Energy use

All states studied have milk powder production except Louisiana. Electrification would reduce the milk powder industry's total final energy use (Figure 69). California, Wisconsin, Michigan, Pennsylvania, and Minnesota are the states with the largest energy savings potentials from switching to electrified milk powder production.

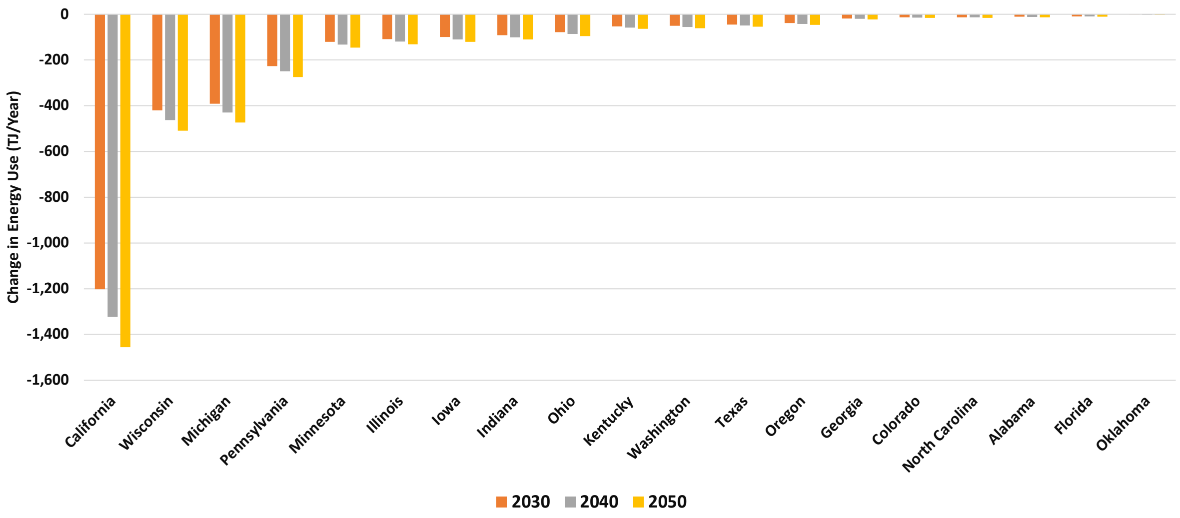

Figure 69. Change in the milk powder industry's total final energy use after electrification (technical potential assuming 100% adoption rate)

CO_2 emissions

Milk powder process electrification has the potential to reduce emissions throughout the country. As shown in Figure 70, California has the highest potential to reduce emissions.

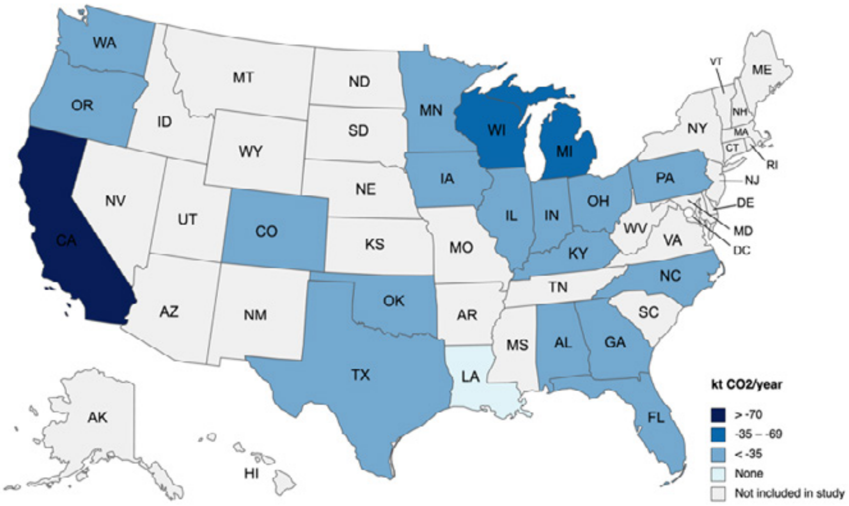

Figure 70. Change in emissions in the milk powder industry in 2050

Milk powder process electrification can decrease CO_2 emissions in 2030 in all milk powder-producing states studied (Figure 71). Figure 72 shows the milk powder industry's change in net CO_2 emissions after electrification under our stated policy scenario, where higher CO_2 emissions reductions are achieved in future years.

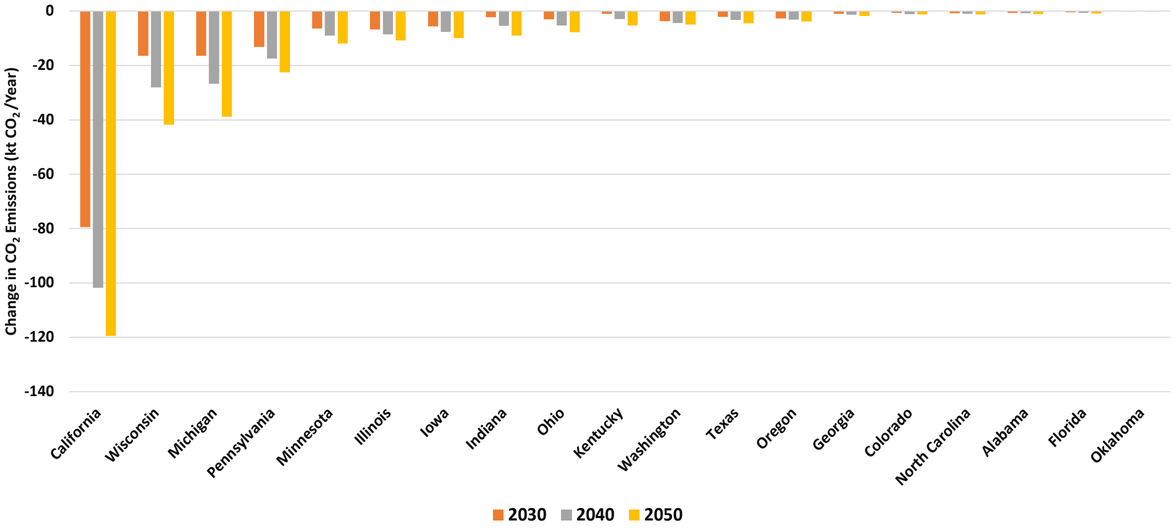

Figure 71. Change in the milk powder industry's net CO_2 emissions after electrification - baseline scenario (technical potential assuming 100% adoption rate)

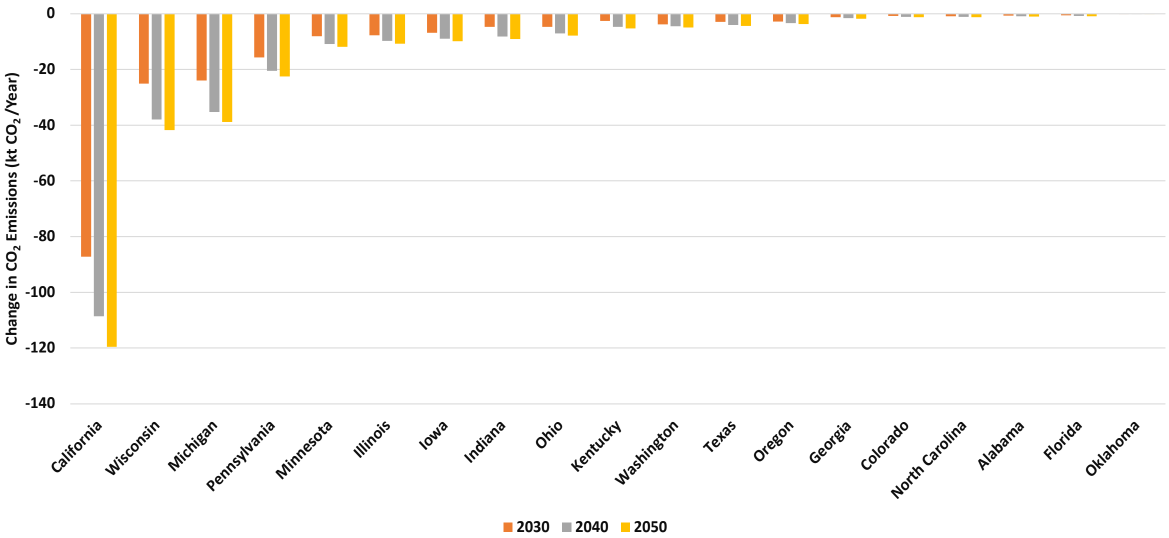

Figure 72. Change in the milk powder industry’s net CO_2 emissions after electrification - stated policy scenario (technical potential assuming 100% adoption rate)

Energy cost

Figure 73 shows that under the scenario with the EIA electricity price forecast, the energy cost per unit of production for an electrified milk powder process in 2030 is substantially higher than that of the conventional process in 2021 in some states (including California, Texas, and Oklahoma), almost equal in some states (including Florida, Michigan, and Indiana), and lower in other states (including Pennsylvania, Washington, and Ohio). This is primarily driven by the ratios of the unit price of electricity to natural gas in each state (see Figure 12).

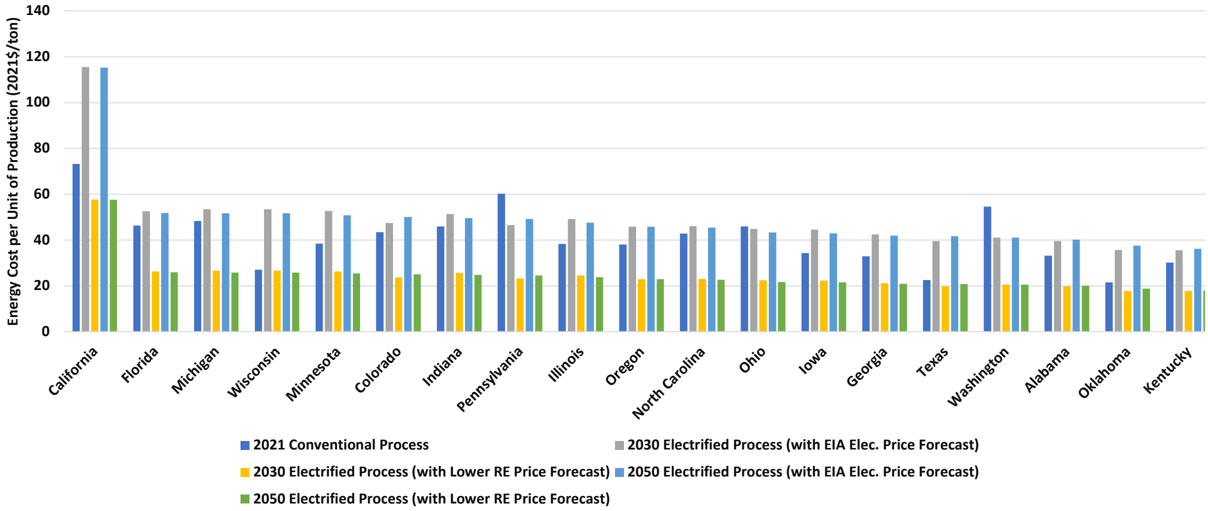

Figure 73. Energy cost per unit of production in the milk powder industry

3.11. Wet Corn Milling Industry

In the U.S., wet milling and dry milling are the two common techniques to process corn. Ethanol is the primary product of the dry milling process and is a byproduct of the wet corn milling process. The wet milling process’s primary products are corn starch and edible corn oil (O’Brien and Woolverton 2009). The wet corn milling process efficiently separates components and shelled corn parts for food and industrial purposes. This study focuses on the wet corn milling process.

In the U.S., there are 25 corn refining plants and four additional processing plants. In 2018, the manufacturing value added by the corn refining industry was estimated to be around $12 billion (CRA 2019). The U.S. wet corn milling industry’s total production in 2021 was around 30 million tonnes (U.S. DOE 2017b). The industry is also one of the food and beverage industry’s largest energy-consuming subsectors (U.S. DOE/EIA, 2017).

A detailed explanation of the conventional and electrified wet corn milling processes is provided in our previous report (Hasanbeigi et al. 2021). Table 15 compares the energy intensity of the wet corn milling industry’s conventional and electric processes.

Table 15. Conventional and electric wet corn milling production processes’ energy intensities (Hasanbeigi et al. 2021)

Conventional System Process			Process Steps	All Electric Process	
Heating Equipment	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)	Heating Equipment
	4.9	-	Corn receiving	5	
Central Steam Systems	2.5	36	Steeping	11	Heat Pump @ 51 °C
Central Steam Systems	6.1	225	Steep water evaporation	70	Mechanical Vapor Recompression
	7.9	-	Germ recovery (1st grind)	8	
	4	-	Germ recovery (2nd grind)	4	
	0.3	-	Germ recovery (germ washing)	0	
Conventional Fluidized Bed Dryer	5.1	78	Germ dewatering and drying	5	Electrical Fluidized Bed Dryer
	24.9	-	Fiber recovery	25	
	4.4	-	Fiber dewatering	82	
	11.5	-	Protein (gluten) recovery	12	
Conventional Rotary Dryer	5.9	41	Gluten thickening and drying	47	Electrical Rotary Dryer
	5.5	-	Starch washing	6	
Conventional Rotary Dryer	30.8	312	Starch dewatering and drying	343	Electrical Rotary Dryer
Conventional Ring Dryer	11.2	259	Gluten feed dryer	270	Electrical Ring Dryer
	125	**951**	**Subtotal**	**888**	
1,076			**Total Energy**	**888**	

Energy use

Wet corn milling production was identified in 15 of the 20 states studied. Figure 74 shows that electrification will significantly reduce the wet corn milling industry's total final energy use during the study period. The energy savings increase over time because an increase in wet corn milling production is assumed up to 2050. Iowa, Illinois, Indiana, Minnesota, and Ohio are the states with the largest energy savings potentials from switching to electrified wet corn milling processes.

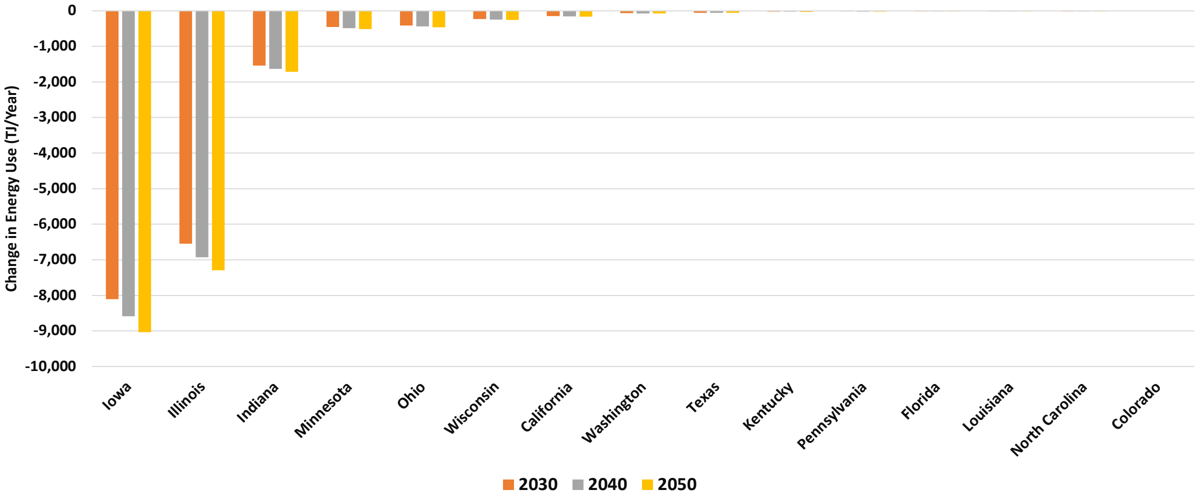

Figure 74. Change in the wet corn milling industry's total final energy use after electrification (technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 75 shows the wet corn milling industry's change in net CO_2 emissions after electrification under the baseline scenario. Wet corn milling electrification could result in an increase in CO_2 emissions in 2030 in Indiana, Ohio, Texas, Kentucky, and Wisconsin due to the higher 2030 grid emissions factors in these states (see figure 9). Electrification can help realize large annual CO_2 emission reductions by 2050 in all states due to a decline in the electricity grid's CO_2 emissions factor between 2030 and 2050.

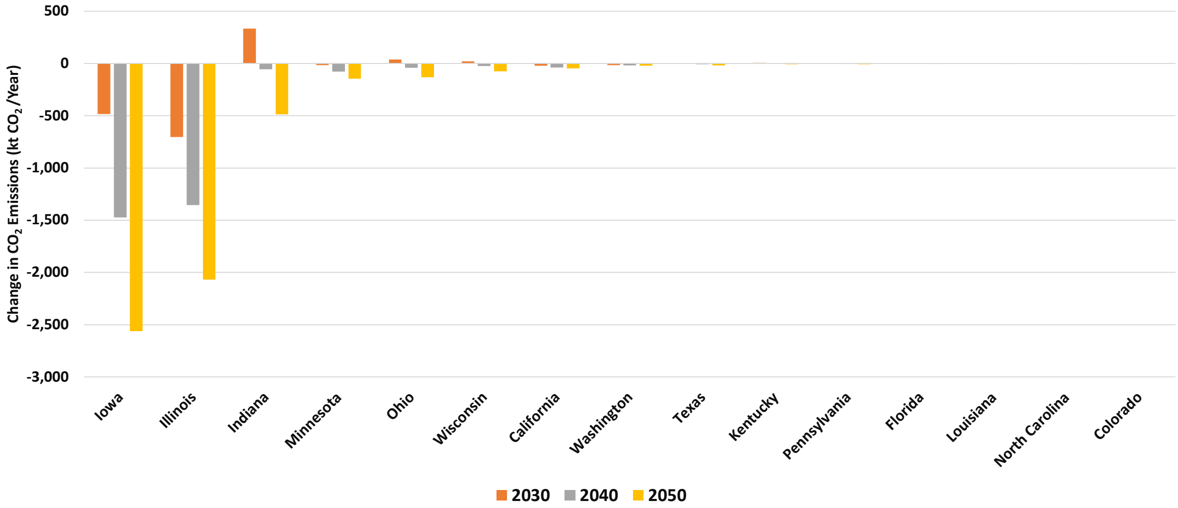

Figure 75. Change in the wet corn milling industry's net CO_2 emissions after electrification - baseline scenario (technical potential assuming 100% adoption rate)

Figure 76 shows the wet corn milling industry's change in net CO_2 emissions after electrification under the stated policy scenario. The CO_2 emissions reduction potential in future years is substantially higher than the baseline scenario because more rapid grid decarbonization is assumed.

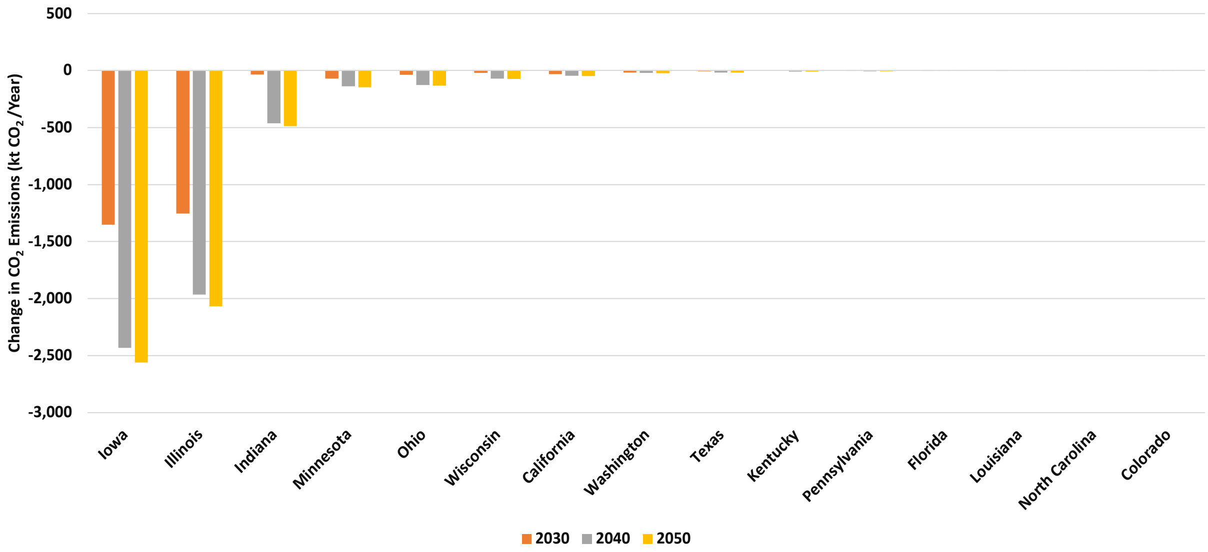

Figure 76. Change in the wet corn milling industry's net CO_2 emissions after electrification - stated policy scenario (technical potential assuming 100% adoption rate)

The rate of CO_2 emissions reductions from electrification varies across states, as shown in the map in Figure 77. Iowa and Illinois have the greatest emissions reduction potentials in 2050.

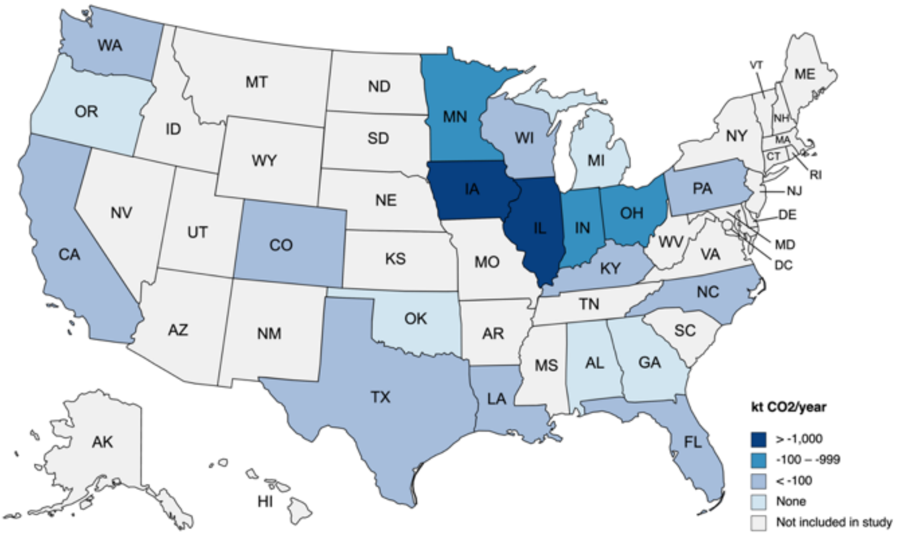

Figure 77. Change in emissions in the wet corn milling industry in 2050

The differences among states are illustrated further in Figures 78 and 79, showing the wet corn milling industry's change in net CO_2 emissions after electrification in Indiana and Illinois. In Indiana, CO_2 emissions will initially increase in 2030, but as the state's grid decarbonizes, the CO_2 emissions reduction potentials are realized from wet corn milling electrification. In Illinois, however, the lower grid emissions factor in 2030 allows wet corn milling electrification to achieve CO_2 emissions reductions by 2030 (see Figure 9).

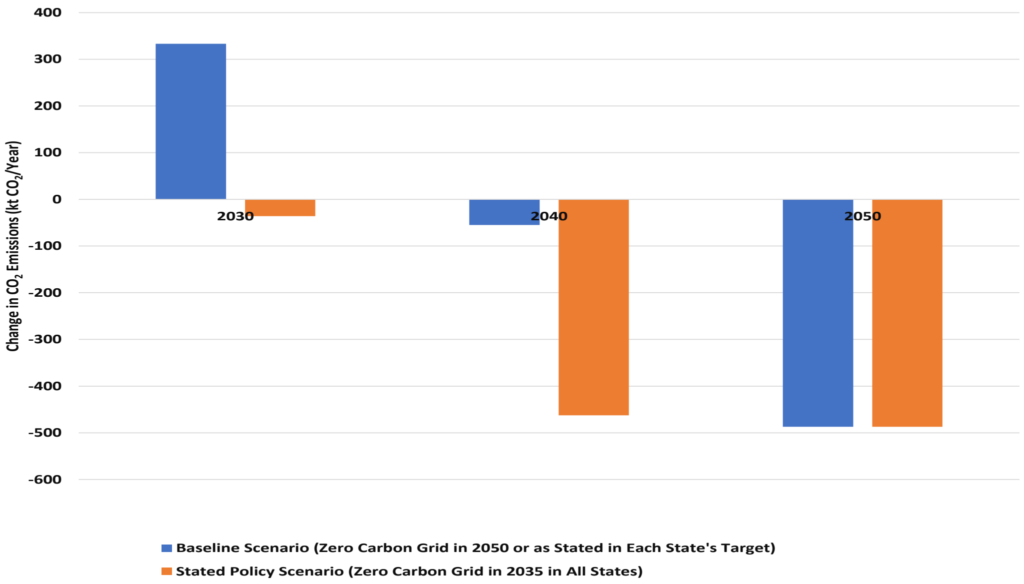

Figure 78. Change in the wet corn milling industry's net CO_2 emissions after electrification in Indiana

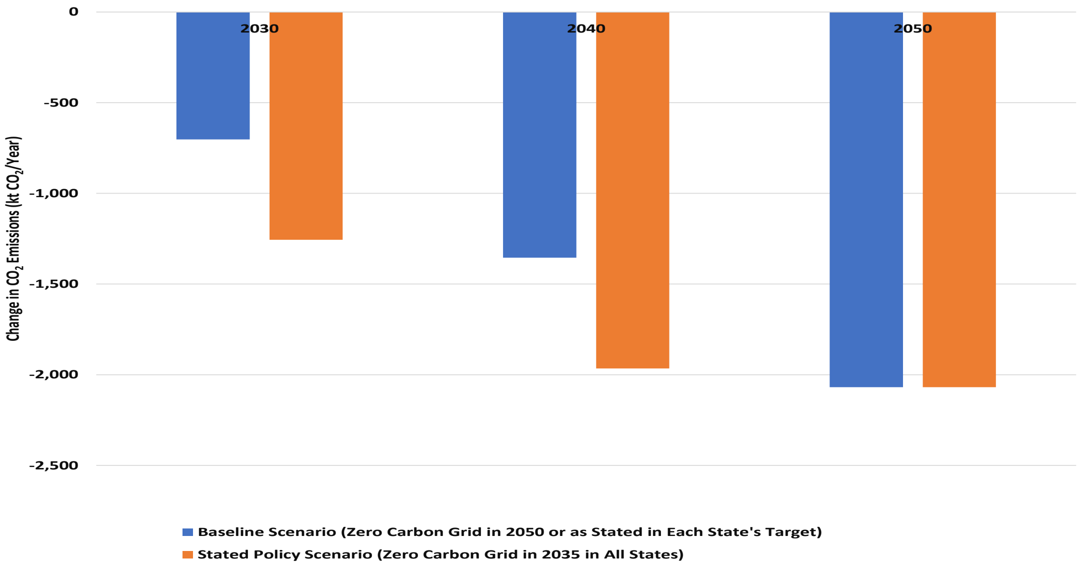

Figure 79. Change in the wet corn milling industry's net CO_2 emissions after electrification in Illinois

Energy cost

Figure 80 shows that the energy cost per unit of production for the electrified wet corn milling process in 2030 is substantially higher than that of the conventional process in 2021 in all states under the scenario with the EIA electricity price forecast. Access to low-cost electricity in the future can substantially reduce the electrified wet corn milling production process' energy cost, making it more cost-effective with the conventional process in all states studied, as shown in the Lower RE price scenario on the graph.

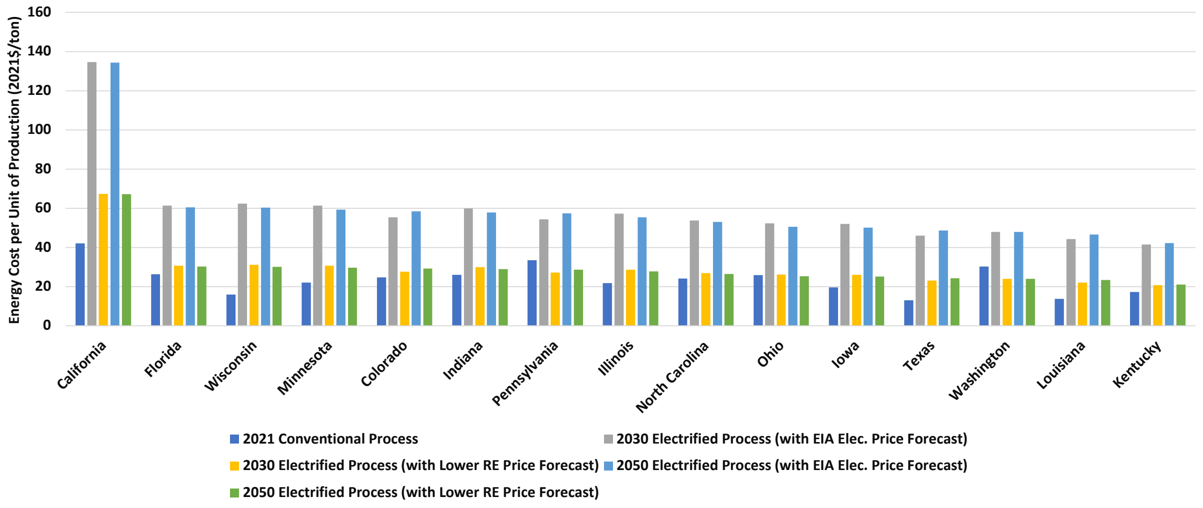

Figure 80. Energy cost per unit of production in the wet corn milling industry

3.12. Soybean Oil Industry

Soybean oil, extracted from soybean seeds, is among the world's most broadly used natural oils. It is used for a vast range of applications, such as nutritional supplements, cosmetics, food, and agriculture. The industry is driven by the rising demand for soybean meal for livestock, resulting in a considerable increase in soybean oil production (EMR 2020). In 2019, the U.S. produced an estimated 9.5 million tonnes of soybean oil (U.S. DOE 2017b). Soybean oil production is also one of the food and beverage industry's largest energy-consuming subsectors (U.S. DOE/EIA 2017a).

A detailed explanation of the soybean oil industry's conventional and electrified processes is provided in our previous report (Hasanbeigi et al. 2021). Table 16 compares the energy intensity of the soybean oil industry's conventional and electric processes.

Table 16. Conventional and all-electric crude soybean oil production processes' energy consumption (Hasanbeigi et al. 2021)

Conventional System Process			Process steps	All Electric Process	
Heating Equipment	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)	Heating Equipment
Conventional Steam Generator	-	17	Leaching	7	Heat Pump
Conventional Steam Generator	-	143	Evaporators	124	Electric Steam Boiler
Conventional Steam Generator	-	501		501	Indirect Resistive Heating
Conventional Steam Generator	-	18	Stripping	16	Electric Steam Boiler
Conventional Steam Generator	-	815	Desolventizer	212	Fluidized Bed Using Air/Nitrogen
Conventional Steam Generator	-	293	Tail gas stripper	-	
	125	-	Electrical devices	125	
	125	**1,787**	**Subtotal**	**984**	
	1,912		**Total**	**984**	

Energy use

Figure 81 shows that electrification will reduce the soybean oil industry's total final energy use during 2030-2050. Iowa, Indiana, Illinois, Minnesota, and Ohio are the states with the largest energy savings potentials from switching to electrified soybean oil production processes.

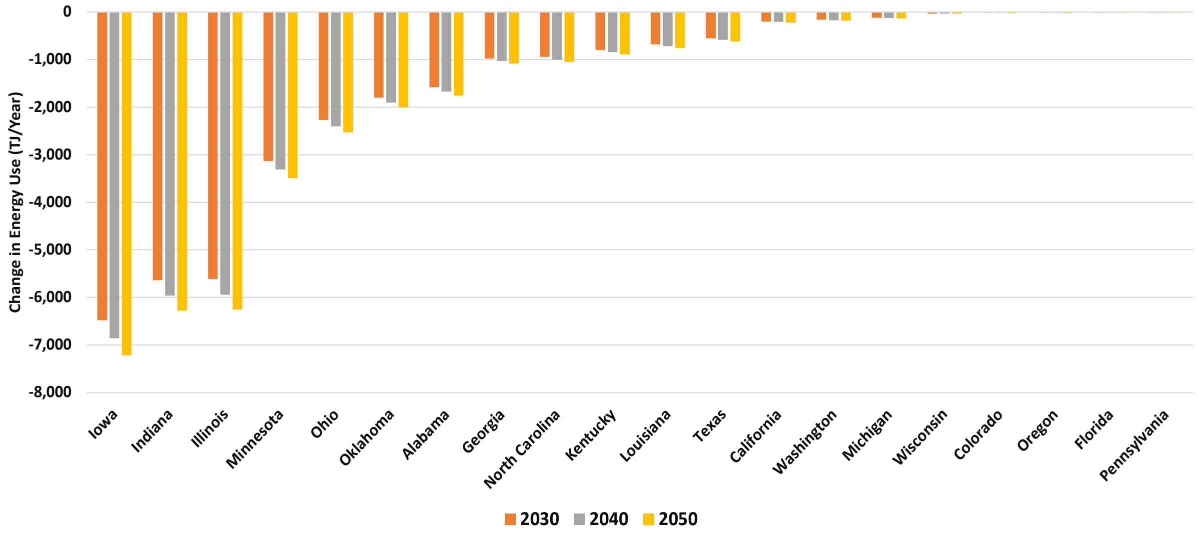

Figure 81. Change in the soybean oil industry's total final energy use after electrification (technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 82 shows the change in the soybean oil industry's net CO_2 emissions after electrification under the baseline scenario. Soybean oil production electrification could result in CO_2 emissions increases in 2030 in Indiana and Kentucky because of their relatively higher grid emissions factors compared with that of other soybean oil-producing states.

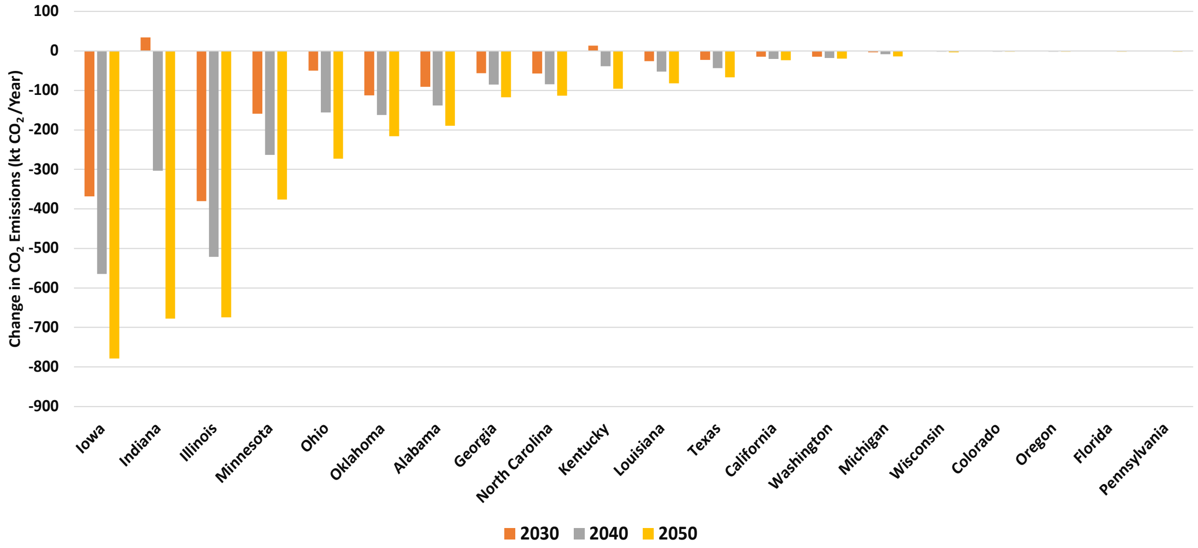

Figure 82. Change in the soybean oil industry's net CO_2 emissions after electrification - baseline scenario (technical potential assuming 100% adoption rate)

Figure 83 shows the soybean oil industry's change in net CO_2 emissions after electrification under the stated policy scenario. Under this scenario, the CO_2 emissions reduction potential in future years (2030, 2040, and 2050) is substantially higher than the baseline scenario because more rapid grid decarbonization is assumed under the stated policy scenario.

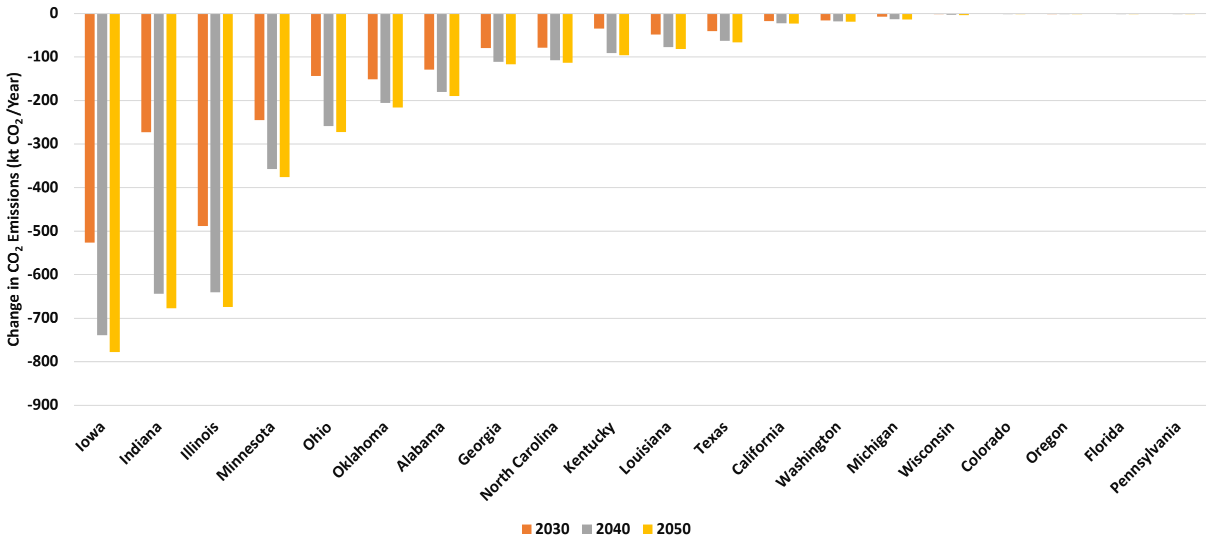

Figure 83. Change in the soybean oil industry's net CO_2 emissions after electrification - stated policy scenario (technical potential assuming 100% adoption rate)

Figure 84 shows CO_2 emissions reductions in 2050 for the soybean oil industry. Iowa, Illinois, and Indiana have the greatest emissions reduction potential in 2050, while additional Great Lakes and Southeastern states, as well as Oklahoma, have a relatively high opportunity to decarbonize.

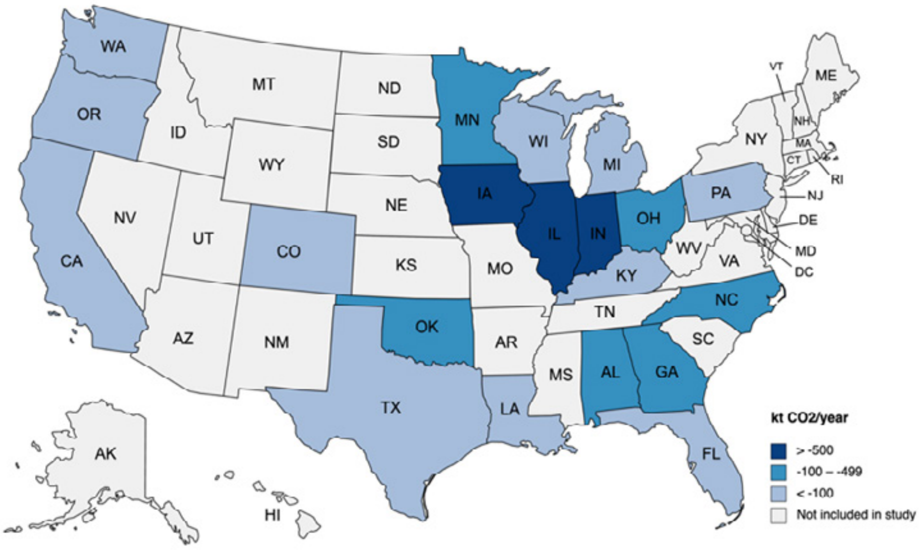

Figure 84. Change in emissions in the soybean oil industry in 2050

Figures 85 and 86 show the soybean oil industry's change in net CO_2 emissions after electrification in Indiana and Iowa, illustrating how different grid emissions factors impact emissions reductions in the medium and long term. In Indiana, CO_2 emissions initially increase in 2030, but in later years, CO_2 emissions reduction potentials are realized as the grid decarbonizes. In Iowa, however, CO_2 emissions reductions from soybean oil production electrification could be achieved in 2030 because the state has a lower grid emissions factor (see Figure 9).

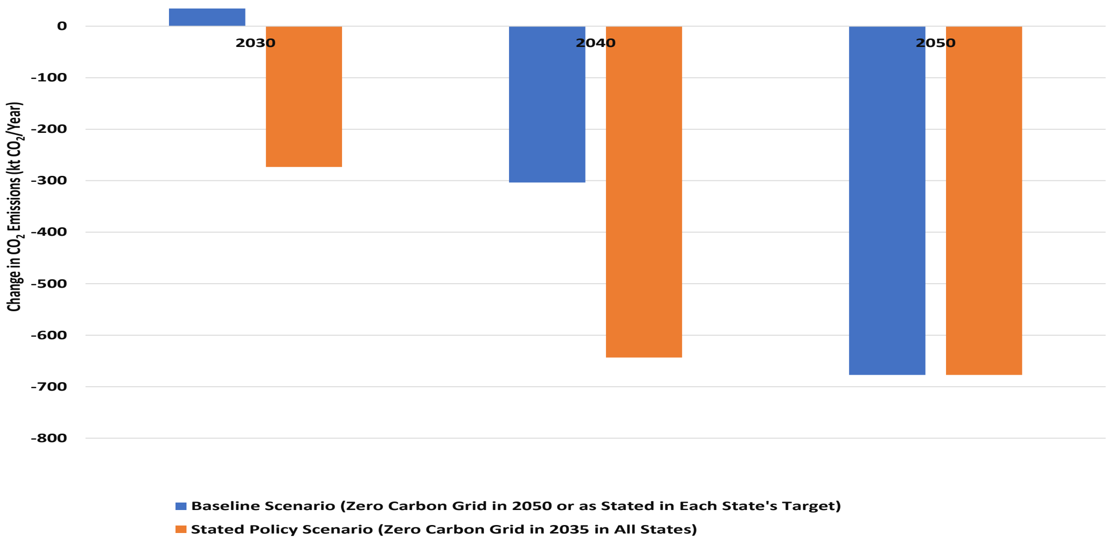

Figure 85. Change in the soybean oil industry's net CO_2 emissions after electrification in Indiana

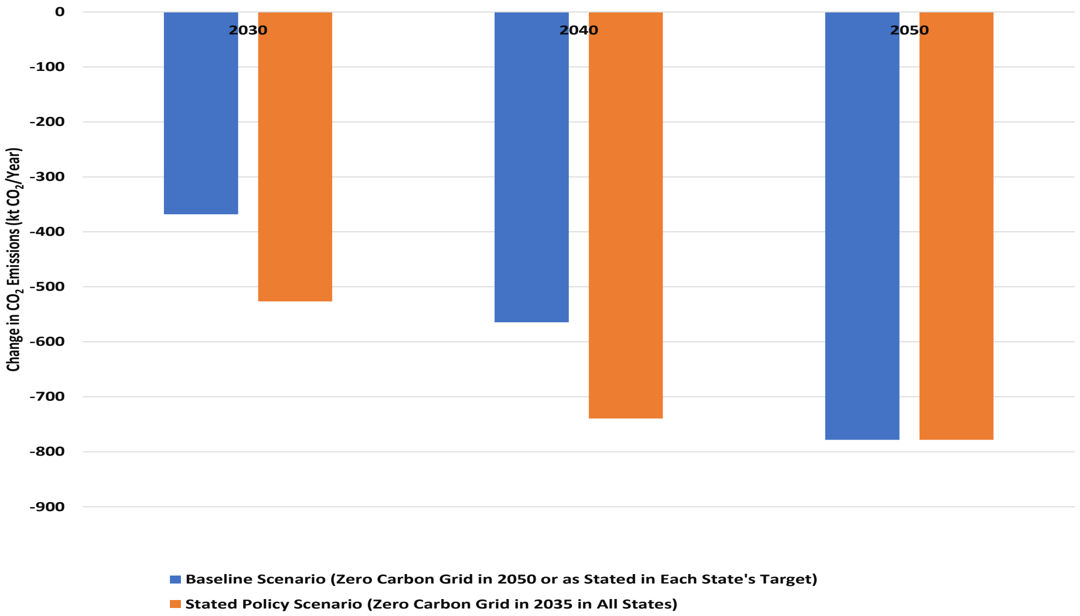

Figure 86. Change in the soybean oil industry's net CO_2 emissions after electrification in Iowa

Energy cost

Figure 87 shows that under the scenario with the EIA electricity price forecast, the energy cost per unit of production in 2030 for soybean oil electrified processes is substantially higher than that of the conventional process in 2021 in most states except Pennsylvania and Washington. This is because these two states have a relatively lower ratio of the unit price of industrial electricity to natural gas (see Figure 12).

A scenario with lower electricity prices can substantially reduce the energy cost of electrified soybean oil production, making it even more cost-effective than the conventional process in all states studied except California, Texas, and Oklahoma.

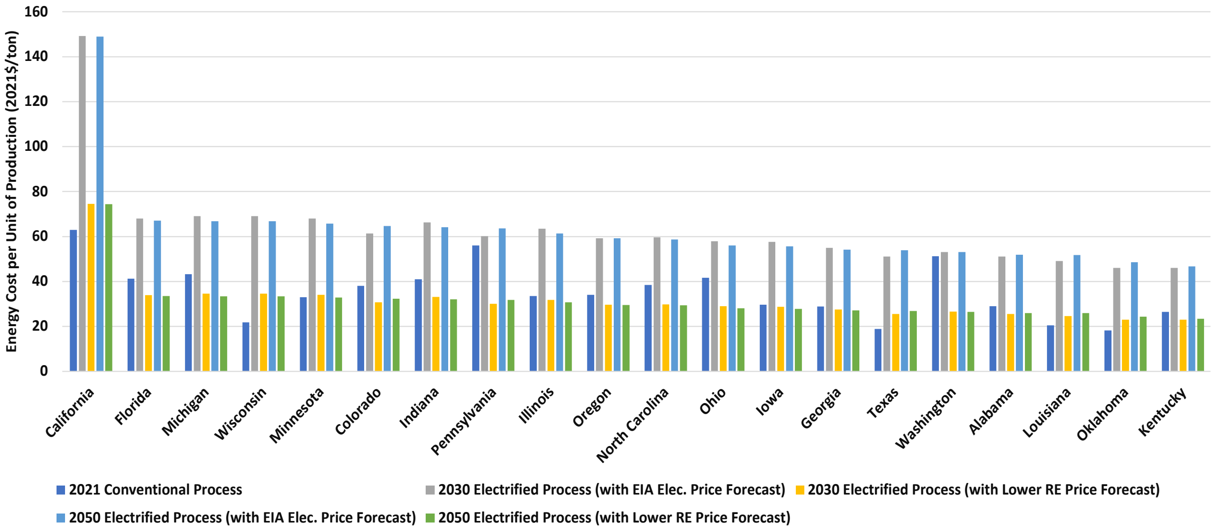

Figure 87. Energy cost per unit of production in the soybean oil industry

3.13. Total Energy Savings and CO_2 Emissions Reduction Potential

This section presents the total energy savings and CO_2 emissions reduction potentials that can be achieved in all 20 states from the electrification of 9 of the 12 industrial subsectors included in this study.

The total energy savings and CO_2 emissions reduction presented in this section do not include the ammonia, methanol, and plastic recycling industries. Ammonia and methanol are not included because the electrification impacts are a result of electrifying hydrogen, which is a feedstock, not an energy source, through electrolysis. In the methanol industry, the switch from natural gas-based hydrogen production to electrolysis-based hydrogen production results in a substantial increase in final energy use, which balloons the total energy and CO_2 results. Because hydrogen is a feedstock, this large energy change impacts the study's ability to produce a true apples-to-apples electrification effects comparison. Plastic recycling is excluded because the study compares mechanical electrified plastic recycling with traditional virgin resin plastic production. The energy savings of the recycled process are great enough in comparison to the traditional process, that the impact of electrification alone is dwarfed, impacting the comparability of the final results across industries.

Figure 88 shows that electrification will significantly reduce industrial total final energy use in all states studied. Indiana, Ohio, Illinois, Iowa, and Michigan are the states with the largest energy savings potentials from electrifying nine industries included in this study (excluding ammonia, methanol, and plastic recycling industries for the reasons explained above). For context, every 10,000 TJ of energy can power around 260,000 U.S. households per year.

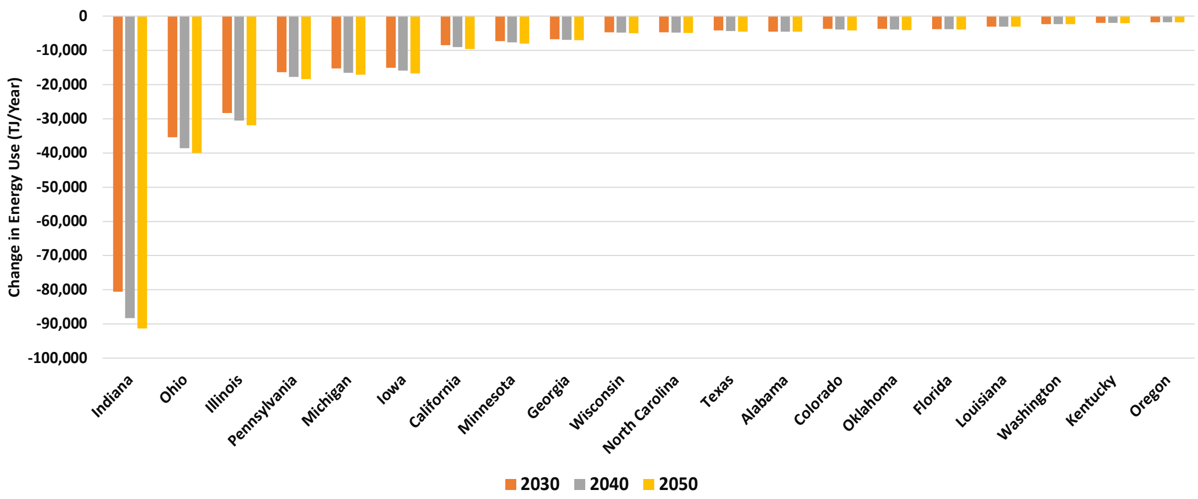

Figure 88. Change in industrial energy use using electrified processes in nine industries studied (Excludes ammonia, methanol, and plastic recycling industries, technical potential assuming 100% adoption rate)

Figure 89 shows the change in industrial net CO_2 emissions after electrifying the nine industries under the baseline scenario, which assumes full grid decarbonization by 2050. Electrifying these nine industries could result in CO_2 emissions reduction in 2030 in most states, and all states by 2050. For context, reducing annual CO_2 emissions by 1,000 kt is equal to taking about 217,000 internal combustion engine passenger cars off the road.

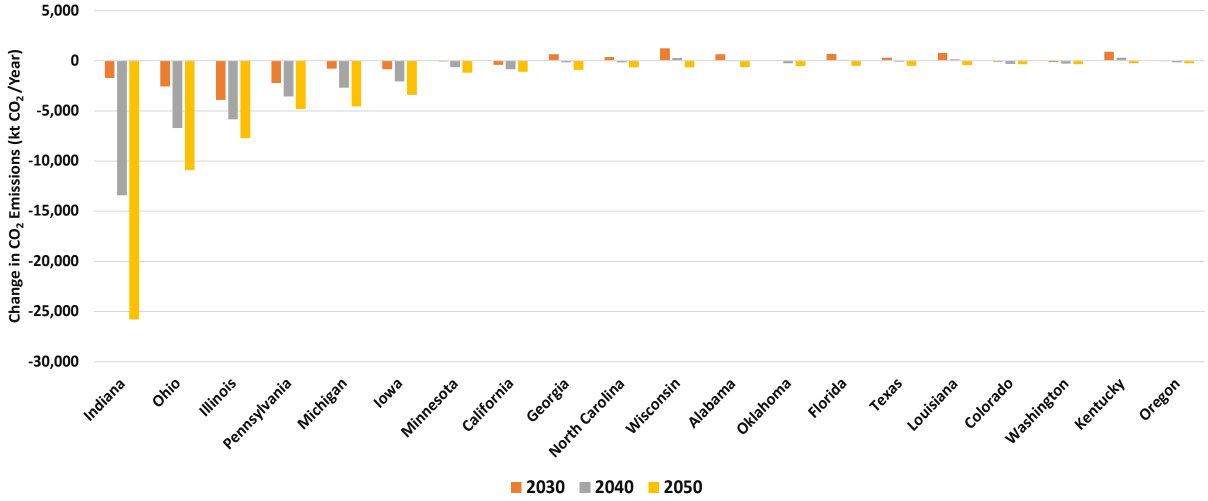

Figure 89. Change in industrial net CO_2 emissions using electrified processes in nine industries studied (excludes ammonia, methanol, and plastic recycling industries - baseline scenario, technical potential assuming 100% adoption rate)

Figure 90 shows the change in industrial net CO_2 emissions after electrifying these nine industries under the stated policy scenario. This scenario shows a substantially higher CO_2 emissions reduction potential in future years than the baseline scenario because more rapid grid decarbonization is assumed under the stated policy scenario.

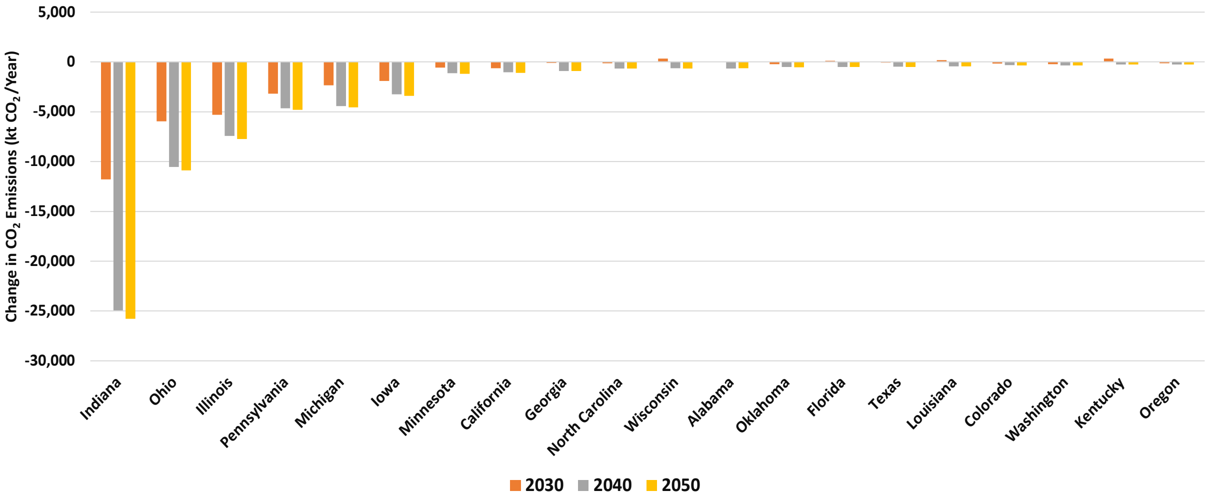

Figure 90. Change in industrial net CO_2 emissions using electrified processes in nine industries studied - stated policy scenario (excludes ammonia, methanol, and plastic recycling industries, technical potential assuming 100% adoption rate)

4

Industrial Electrification's Impact on the Electricity Grid

Industrial electrification has the potential to reduce emissions across industrial subsectors and around the country, but aging infrastructure and competing demands for renewable electricity resources pose challenges to realizing these reductions. As discussed further in Chapter 6, investing in the electricity grid will help to accelerate industrial electrification and contribute to meeting the nation's emissions reduction goals.

4.0. The U.S. Electricity Grid

The U.S. electricity grid is a complex, interconnected system linking both utility-scale and distributed generation resources to customers with varying and variable electricity needs. As of the end of 2020, there were 11,070 utility-scale (a nameplate capacity of at least 1 MW) electric power plants in the U.S. (EIA 2022a). The country's power system also includes nearly 160,000 miles of high-voltage power lines and millions of low-voltage power lines and distribution transformers, connecting 145 million customers (EIA 2016).

In 2021, about 4,116 billion kilowatt-hours (kWh) of electricity were generated at utility-scale electricity generation facilities from a variety of resources and technologies: about 61% was from fossil fuels, about 19% was from nuclear, and about 20% was from renewables (EIA 2022b). Electricity generation from renewable resources has increased over time, while coal use has declined in recent years. Major factors that have contributed to changes in the generation mix include lower natural gas prices, state requirements to use more renewable resources, financial incentives for building new renewable generation capacity, federal air pollution emission regulations for power plants, and slowing electricity demand (EIA 2021a).

Managing the grid's resources, infrastructure, and energy flows is a considerable undertaking. Trends towards distributed energy generation, renewable electricity, and electrification, as well as dealing with aging infrastructure and more frequent severe weather impacts, increase grid management complexity. Major infrastructure upgrades are needed to reliably incorporate new technologies and systems, changing market dynamics, and shifting consumer preferences (NCSL 2021). Additional pressure will be placed on an already strained grid system as multiple sectors, including transportation and buildings in addition to industry, move to electrify to access renewable resources and reduce their emissions. To deliver electrification at scale, investment will be needed to build or upgrade key infrastructure, including electricity production, energy transmission, and distribution networks, and end-user infrastructure (IRENA 2019, 13).

High-capacity long-distance transmission lines can be designed and built rapidly enough to ensure transmission grid capacity does not cause a delay in electrification, but disputes around planning, design, and building power lines have the potential to cause delays (ETC 2018, 136). As discussed further in Chapter 6, engaging communities early in the process can ameliorate delays and offer opportunities to consider and address environmental and energy justice concerns at the outset. While grid upgrades and reinforcement can be done on a shorter timeframe and do not typically provide the same opposition as long-distance transmission projects, if significant reinforcement is required in many parts of the network simultaneously, this could create bottlenecks in project management and construction capacity (ETC 2018).

Developing a coherent power strategy is essential to accelerate the pace of power decarbonization, plan for the electrification of a broader set of economic sectors, and anticipate related power grid investment needs (ETC 2018). The U.S.'s long-term strategy to achieve economy-wide net-zero emissions by 2050 notes that grid infrastructure investments – including building out new long-distance, high-voltage transmission projects – can enhance resilience, improve reliability, better integrate variable generation resources, lower electricity costs, and connect clean energy resources to demand centers (State/EOP 2021).

4.1. Industrial Electrification's Electricity Grid Impacts

The analysis results clearly show that in 11 of the industrial sectors studied, electrification results in a reduction in the total annual final energy use. The exception is methanol production electrification, where an electrolysis process produces hydrogen and increases the annual energy use.

While electrification decreases net final energy demand, electricity demand increases. Figure 91 shows that electrifying nine industries; excluding ammonia, methanol, and plastic recycling as explained in Chapter 3.13; results in an increase in annual electricity consumption in 2030 (GWh/year). This translates into an increase in electricity load after industrial electrification in 2030 (MW), as shown in Figure 92.

For example, to fully electrify the nine of the twelve industries (excluding ammonia, methanol, and plastic recycling for reasons mentioned in Chapter 3.14) included in this study with the processes described in this report, Indiana will need an additional 23.7 GW, Texas an additional 1.3 GW, and California an additional 2 GW of power generation capacity in 2050. For comparison, in 2021, the U.S. had around 1,200 GW of power generation capacity. To estimate these additional loads, we assumed all the additional load is coming from clean renewable energy sources. We further assumed that that two-third of this additional load is coming from solar power and one-third from wind power.

Utilities, policymakers, industry, and other stakeholders should pay attention to this potential increased demand for renewable electricity, and the associated need for more renewable electricity generation, additional energy storage, demand response programs, transmission and distribution system expansion, and grid modernization. As noted above, multiple sectors, including transportation and buildings, are also looking to increase electrification as a way to access renewable energy resources and reduce their emissions. Ensuring that sufficient renewable resources are brought online and connected to demand centers will be critical to a smooth energy transition and rapid multisector decarbonization.

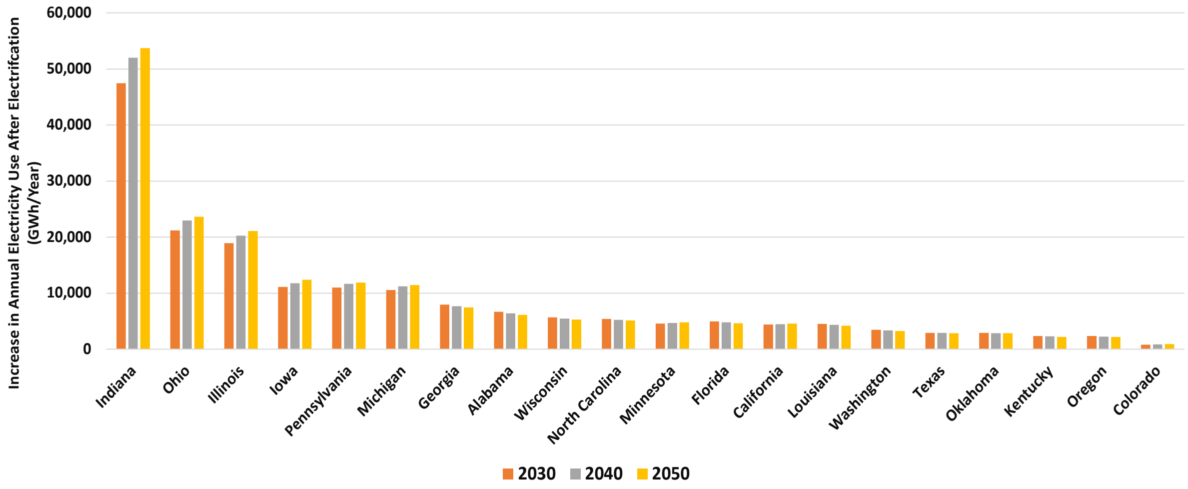

Figure 91. Increase in annual electricity consumption after industrial electrification in 2030-2050 (GWh/year) (assuming 100% adoption rate)

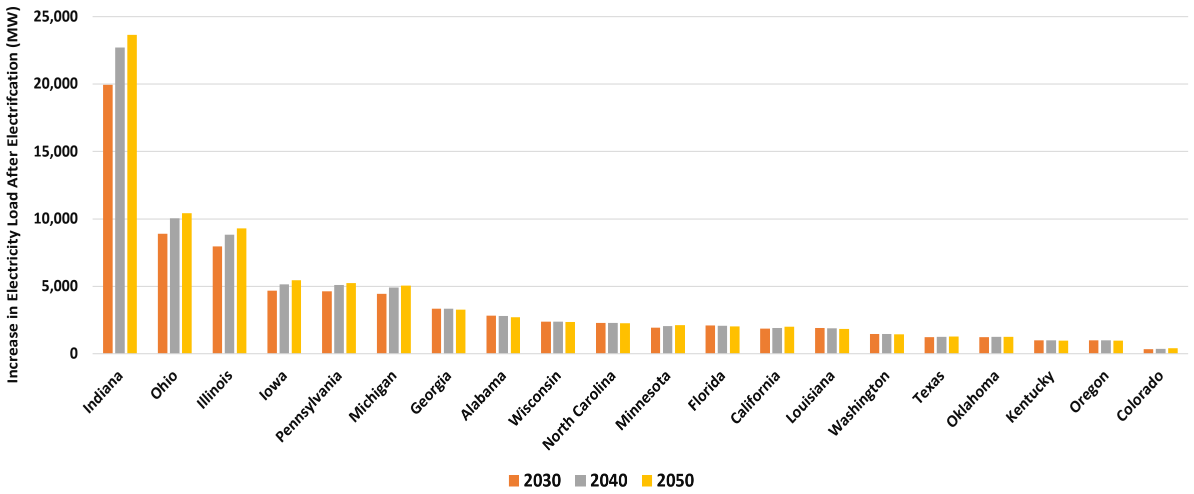

Figure 92. Increase in electricity load after industrial electrification in 2030, 2040, and 2050 (MW) (assuming 100% adoption rate)

5 Industrial Electrification Co-Benefits

Industrial electrification, energy efficiency improvements, and switching to lower-carbon energy sources can significantly decrease GHG emissions and reduce climate change impacts. A growing body of research has found that these measures can also directly mitigate many non-climate change related human health hazards and environmental damage (Williams et al. 2012).

5.0. What are Co-Benefits?

Co-benefits are most easily understood as the benefits that accrue from the implementation of a program or policy that are in addition to the program or policy's primary objective. The Intergovernmental Panel on Climate Change (IPCC) defines co-benefits as, "the benefits of policies that are implemented for various reasons at the same time – including climate change mitigation – acknowledging that most policies addressing GHG mitigation have other . . . equally important rationales" (Metz et al. 2001). Others increase the scope of co-benefits to include other policy measures, defining co-benefits as, "those derived from the intentional decision to address air pollution, energy demand, and climate change in an integrated manner, but also considers the other unspecified benefits that may arise such as improved transport and urban planning, reduced health and agricultural impacts, improved economy or reduced overall policy implementation cost" (Castillo et al. 2007).

Many studies group co-benefits within four broad categories of impacted systems: health, ecological, economic, and social co-benefits (Davis et al. 2000). Co-benefits can also be categorized by the particular endpoint impacted, for example, the IPCC's Fourth Assessment Report separates industrial GHG emissions mitigation strategy co-benefits as those affecting human health, emissions, waste, production, operations and maintenance, working environment, and "other" (Metz et al. 2007). Example co-benefits that fall into each category are provided in Table 17.

Table 17. Co-benefits of energy efficiency and decarbonization policies and programs (Metz et al. 2007)

Category of co-benefit	Examples
Health	Reduced medical/hospital visits, reduced lost working days, reduced acute and chronic respiratory symptoms, reduced asthma attacks, increased life expectancy.
Emissions	Reduction of dust, carbon monoxide (CO), CO_2, nitrous oxides (NO_x) and sulfur dioxide (SO_2); reduced environmental compliance costs.
Waste	Reduced use of primary materials; reduction of waste water, hazardous waste, waste materials; reduced waste disposal costs; use of waste fuels, heat and gas.
Production	Increased yield; improved product quality or purity; improved equipment performance and capacity utilization; reduced process cycle times; increased production reliability; increased customer satisfaction.
Operation & maintenance	Reduced wear on equipment; increased facility reliability; reduced need for engineering controls; lower cooling requirements; lower labor requirements.
Working environment	Improved lighting, temperature control and air quality; reduced noise levels; reduced need for personal protective equipment; increased worker safety.
Other	Decreased liability; improved public image; delayed or reduced capital expenditures; creation of additional space; improved worker morale.

In addition to human health, agricultural land area, and ecosystem services impacts, reduced air pollution abatement costs, employment impacts, and changes in the price of primary production inputs such as fuels and raw material can be considered industrial electrification and decarbonization co-benefits.

5.1. Improving Air Quality and Health Outcomes

The U.S. has already seen how improving air quality can result in numerous co-benefits. Since 1970, Clean Air Act (CAA) programs have lowered levels of numerous pollutants, leading to dramatic improvements in air quality and achieving significant public health benefits. Lower air pollution levels also mean less damage to ecosystem health, including plants and animals, and crop and timber yield improvements (EPA 2022).

While air quality improvement programs have associated costs, these are outweighed by significant benefits. The EPA has found that CAA programs yield direct benefits to the American public that vastly exceed compliance costs. In addition to direct benefits exceeding direct costs, economic welfare and economic growth rates improved because cleaner air results in fewer air-pollution-related illnesses, requiring less money spent on medical treatments and lower absenteeism among workers (EPA 2022).

Though these programs have been successful, there is still work to be done. In 2017, air pollution was associated with about 100,000 annual premature deaths in the U.S. and has been linked to myriad negative health impacts (Liu et al. 2021). Moreover, while air quality has improved in the U.S. over the past several decades, people of color, particularly Black and Hispanic Americans, are still exposed to higher-than-average levels of air pollution (Lane et al. 2022).

5.2. Controlling Costs

Industrial electrification can reduce air pollution abatement costs. Some energy- and carbon-intensive industrial plants must install air pollution control technologies to reduce their criteria air pollutant emissions (such as PM, SOx, and NOx) to align with regulatory air emissions standards. These air pollution control technologies could cost millions of dollars to install and have high operating and maintenance costs. In addition, industrial plants sometimes have to pay additional fees for emissions released from their facilities. Switching industrial plants' thermal processes and heating systems from fossil fuel-based to electrified systems can help to reduce or even eliminate the cost of installing air pollution control technologies or paying air pollution fees. This can result in substantial cost savings in both capital costs and operating costs for industrial companies. Such industrial electrification co-benefits should be quantified for electrification projects based on plant-level information and taken into account in electrification project cost-benefit analyses, as discussed further below.

5.3. Ensuring Equitable Realization of Co-Benefits

Air pollution and its associated health impacts are not equally distributed by race, ethnicity, and income. Research has documented higher-than-average air pollution exposures for racial and ethnic minority populations and lower-income populations in the U.S. (Liu et al. 2021). Racial and ethnic and socio-economic disparities in air pollution exposure in the U.S. are well documented and have persisted despite overall decreases in $PM_{2.5}$ pollution (Tessum et al. 2021).

From 1990-2010, air pollution concentrations declined and absolute racial and ethnic exposure disparities also declined. However, in 2010, racial and ethnic exposure disparities for multiple pollutants remained across income levels, in urban and rural areas, and in all states (Liu et al. 2021). The causes of systemic racial/ethnic air pollution exposure disparities are complex and rooted in part in historical patterns of exclusion and discrimination, including in policymaking, investment, and land use decisions. (Lane et al. 2022).

Nearly all major emission source sectors, including industry, disproportionately affect people of color (Tessum et al. 2021). Infrastructure and land use decisions made many years ago continue to shape present-day spatial distributions of pollution sources: the locations of emitting infrastructure, including industrial facilities, are typically long-lived (Lane et al. 2022).

Industrial electrification offers an opportunity to improve upon historical and systemic wrongs that have negatively impacted communities of color. Industrial electrification that reduces fossil fuel use in industrial plants also lowers or eliminates criteria air pollutants, helping to improve the health and quality of life in communities living close to the industrial plants. But, it is also critical to engage local communities that will be impacted by changes to industrial infrastructure, including ancillary infrastructure such as transmission and distribution lines and equipment and renewable generation and energy storage resources.

Structural inequality can limit the effectiveness of participatory and consultative approaches, improving procedural justice through better public participation and engagement in decision-making processes can ensure that community voices are heard and allow infrastructure developers to address community concerns (Hess, McKane, and Pietzryk 2021).

Those deploying electrification technologies and related infrastructure can take cues from the federal government's Justice40 Initiative, a plan to deliver 40% of the overall benefits of climate investments to disadvantaged communities (OMB 2021). All actors, whether or not they are subject to the Initiative, can look to the federal guidance to maximize benefits to disadvantaged communities. For example, those deploying infrastructure can:

- Avoid potential burdens to disadvantaged communities;
- In evaluating project proposals, consider whether proposals include community engagement, planning, and feedback;
- Apply cost savings from project implementation to benefit disadvantaged communities, for example by reinvesting savings in the local community to promote workforce development and community health;
- Support technical assistance and capacity building within communities; and
- Foster job training.

Additional recommendations for community engagement can be found in Chapter 6.

5.4. Analyzing Near-term Benefits

Reducing emissions and thus improving air quality can result in near-term, nationwide benefits, including improved human health, labor productivity, and crop yield benefits, and additional benefits from reduced heat exposure increase around 2060 (Shindell et al. 2021).
However, climate change mitigation policies are often framed as global, long-term, and subject to uncertainties. Increasing the emphasis on the localized, near-term, air quality-related benefits of reducing emissions could help to eliminate the mismatch between the perception of climate as a future risk and the need to act quickly now to mitigate long-term climate change (Shindell et al. 2021).

Many climate policies and programs, including for industrial electrification and decarbonization, at times face political resistance, partially because it is difficult to quantify their full benefits. Incorporating co-benefits into industrial electrification and decarbonization policy and program analysis might significantly increase the uptake of these policies. Faster policy uptake is especially important in this decade in view of net-zero GHG emissions targets. Ongoing development efforts that do not consider co-benefits may lock in suboptimal technologies and infrastructure and result in high costs in future years.

Over the past two decades, studies have repeatedly documented that non-climate change related energy efficiency and decarbonization benefits that result from GHG mitigation strategies can be valued from between 30% to over 100% of the costs of such policies and programs strategies (Williams et al. 2012). Monetized benefits from air quality improvements and reduced heat exposure are in the tens of trillions of dollars for avoided deaths and tens of billions for labor productivity, crop yield increases and reduced hospital expenditures (Shindell et al. 2021). Policy makers around the world are increasingly interested in including both GHG and non-GHG impacts in analyses of industrial electrification, energy efficiency, and decarbonization policies and programs.

Identifying all the relevant co-benefits is a high priority for co-benefit studies as many policies, especially in developed countries, are explicitly driven by a cost-optimization requirement to arrive at the “best” emissions level considering all costs and all benefits. Including additional monetary and non-monetary co-benefits allows policy makers to increase the stringency of and resources to their programs and reap considerable administrative and public benefits (U.S. EPA, 2011).

6 Recommendations to Accelerate Industrial Electrification

Electrifying industrial processes produces numerous benefits including reduced energy demand and emissions. However, barriers still inhibit electrified technologies' development and deployment, as described in our previous report (Hasanbeigi et al. 2021). This chapter recommends the six most impactful changes that would support increased industrial electrification. These changes will require numerous actors to work together to solve significant challenges in renewable electricity generation and transmission, technology development and deployment, and workforce development.

1. Increase Renewable Electricity Generation Capacity

Additional renewable electricity generation resources are needed to maximize emissions reductions from industrial electrification. Ensuring that renewable electricity is used when electrifying industrial processes will allow the emissions reductions potentials described in this report to be achieved. As the industrial, transportation, and buildings sectors all look to increase renewable electricity use, significant amounts of renewable electricity resources will need to be constructed.

States have tools to encourage additional renewable electricity generation capacity. States can increase their renewable portfolio standard (RPS) requirements, requiring increasing percentages of electricity to come from renewable resources. Incentivizing distributed renewable generation resources at industrial sites would also increase renewable capacity and have the benefit of being generated close to where it is consumed, reducing the need for additional transmission and distribution capacity. States can also support utility-scale renewable generation projects to increase capacity and work towards a zero-carbon electricity grid mix. In addition, ensuring that state siting and permitting processes allow additional projects to be constructed will increase capacity.

Utilities will also need to ensure that renewable resources are able to connect to the transmission and distribution system. Interconnection of significant additional generation resources will require grid upgrades, as discussed further below.

It is also critical to engage communities where renewable energy generation resources will be located and communities that may be impacted in other ways, such as preservation of and access to cultural resources. Further recommendations around community engagement are offered in recommendation 3, below.

2. Enhance the Electricity Grid

As noted above, the industrial, transportation, and buildings sectors are all working to increase renewable electricity use, requiring significant amounts of renewable electricity resources to be added to the resource mix. This increased demand across sectors will require not only additional renewable electricity supply, but also an electric transmission and distribution (T&D) system that can adequately manage the increased energy volume.

States can work in regional collaborations, including with their independent system operators (ISOs) or regional transmission organizations (RTOs), to address T&D inadequacies at a regional level. States, through their public utility commissions and with electric utilities, will need to examine the impact of increased electric demand on the system as a whole. New and upgraded equipment will be needed to meet the increasing demand.

Given the increase in severe weather events that result from climate change, the electricity grid will also need to be hardened to ensure its resilience and reliable electricity service. Resiliency measures will depend on local conditions– appropriate hardening efforts will likely be different in coastal communities than they are in regions that receive significant amounts of snow and ice, and urban and rural areas may find different approaches most effective.

Interstate transmission upgrades may require federal action to make transmission siting and permitting reforms. It will be necessary for power to flow seamlessly from one part of the country to another, bringing renewable electricity from where it is generated, frequently in more rural areas in the middle of the country, to where it will be consumed by industrial customers, many of which are located along the coasts and in more densely populated areas. The wholesale market's operation may also require federal intervention to ensure that transactions are simple.

For grid upgrades too, it is critical to engage communities where new or upgraded equipment will be located or where its impacts will be felt. Further recommendations around community engagement are offered in Recommendation 3, below.

3. Engage communities

As noted in Recommendations 1 and 2, above, project developers must engage communities that will be impacted by industrial electrification and changes to industrial infrastructure, including ancillary infrastructure such as transmission and distribution lines and equipment and renewable generation and energy storage resources. Project developers should seek out and encourage community participation early on in planning processes.

Project developers should recognize the historical context of industrial facility locations and how poor air quality and other negative environmental impacts have and continues to disproportionately affect communities of color. Developers should also consider how their projects can ensure the preservation of and access to communities' cultural resources.

When engaging communities, project developers should consider the environmental and energy justice concerns of the communities and look for opportunities to reverse historical and systemic wrongs including racial, ethnic, and socioeconomic disparities in access to clean energy resources, access to education and well-paid jobs, disparate health impacts from pollution, and preservation of and access to cultural resources.

As noted in Chapter 5, structural inequality can limit the effectiveness of participatory and consultative approaches. Project developers should work to improve procedural justice through better public participation and engagement in decision-making processes. Developers must ensure that community voices are heard and address community concerns.

4. Support demonstration of emerging electrification technologies and new applications of existing technologies

While states may not conduct their own electrification technology research and development, they can support technology demonstration and deployment. States can create their own pilot projects or incentive programs to further electrification technologies.

In addition, states can look for opportunities to access federal resources to support industrial electrification. For example, the 2021 Infrastructure Investment and Jobs Act appropriates $500 million to the Industrial Emissions Reduction Technology Development Program for grants, contracts, cooperative agreements, and demonstration projects focused on emissions reductions for heavy industry achieved through alternative pathways to heat generation, including electrification. States can access these resources or support manufacturers in applying for funds directly.

Many of the technologies included in this report are commercially available and ready for deployment. In cases where an “off the shelf” solution is not possible, industrial companies can work with original equipment manufacturers to further develop and refine electrified technologies that meet their specific process and application requirements. This can be supported through available federal funding and access to this funding can be supported by state governments.

5. Financially incentivize electrification

Energy prices can vary significantly from state to state or even from county to county. Comparisons of the cost per unit of production are highly sensitive to unit price of energy. EIA projects that electricity prices in 2050 will be somewhat higher than they are today. However, it is anticipated that renewable electricity prices will continue to decline, and may decline faster than predicted. This would make electrification technologies more competitive with conventional fossil fuel-based technologies. Therefore, this analysis considers costs of electrification using both the EIA-forecasted prices as well as prices 50% lower.

In addition, natural gas and other fossil fuel prices may increase more than projected, especially if a carbon pricing policy is introduced in the U.S. Such considerations were not included in this study, but could also make electrification technologies more competitive.

Energy cost is only a small portion of total manufacturing cost for most industrial subsectors, except for industries such as the cement and steel industries where energy accounts for 30%-40% of total manufacturing cost. In sectors where energy cost is only a small portion of production cost, a small or even moderate increase in energy cost per unit of product resulting from electrification will have a minimal impact on the price of final product. Therefore, it will have minimal impact in the price that final consumers will pay for the product or products made from those materials. However, it should be noted that energy-intensive industries run typically at low margins, operate in a very competitive global market, and hence can be sensitive increases in energy costs. Therefore, appropriate policy measures should be in place to address this issue.

States and manufacturers may be able to reduce costs, especially for pilot or demonstration projects, by accessing federal financial, technical, or program support. States may also implement their own policies and programs aimed at reducing costs associated with electrification technology adoption. Such policies could include tax incentives, reduced permitting costs, or rate-based utility infrastructure upgrade costs.

Grants for switching to electrified technologies would reduce manufacturers’ upfront costs, incentivizing changes. Grants could be made for pilot projects to encourage early adoption and demonstrate success.

The way utility rates are structured can also incentivize electrification. Electricity rates and ratemaking vary across states, so individualized approaches appropriate to each state would be needed.

Finally, financiers require additional information about electrification technologies and their benefits. Those that could provide financing for electrified technologies may not be aware of industrial electrification's benefits or companies' or interest in pursuing it as a way to reduce energy use and emissions. Better understanding industrial electrification technologies' capabilities and the need for additional investment and support can improve investment decisions.

6. Develop the workforce

Employees and contractors at industrial facilities may require training on new technologies and their installation, operation, and maintenance. States can utilize their educational programs in high schools, technical schools, community colleges, and universities to provide training on current electrified technologies and ensure that the future workforce is ready to develop the next generation of technologies.

States should look across their agencies and offices, including education, higher education, energy, public utility commission, and economic development, to receive input on educational program development. Input from utilities, trade associations, teachers, and students will also be valuable to ensure training programs are meeting current and future needs.

Those developing the workforce should engage with underserved communities and work together to develop relevant educational and training programs to ensure these communities can equitably participate in the clean energy economy.

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Appendices

Appendix 1. Industrial Electrification Technologies

This appendix provides a brief description of some of the main electrification technologies applicable to the industrial sector. More detailed information about these electrification technologies can be found in the references cited within the text.

While many of the electric technologies needed for electrification in industry are fully commercialized, some are at the development or pilot stage, especially for high-temperature processes. Further investment in research and development (R&D) is needed, particularly to address some of the high-temperature heating processes used in cement, glass, and some chemical production.

Electric Boiler

Electric boilers typically utilize electric powered resistive heating elements that help convert electricity into heat. The flow of electric current and the in-turn heating are controlled by a thermostat. The generated heat can be utilized for purposes such as providing hot water for heating systems or generating steam for industrial processes (Alabama Power, 2020). Larger electric boilers are typically electrode boilers (jet type) that use electricity flowing through streams of water to create steam. A key benefit associated with electric boilers is that they are able to convert electricity into heat with an efficiency of almost 100%, with minimal radiation losses observed from exposed boiler surfaces (Alabama Power, 2020). On average, the capital cost of an electric boiler is nearly 40% less than that of an equivalent natural gas-fired boiler (Jadun et al., 2017).

Heat Pump

Heat pumps are devices that extract and transfer heat from one place to another. Common examples of this technology include refrigerators and air conditioners. Inside a heat pump, a refrigerant is cycled across two heat exchanger coils. In the first coil, it undergoes evaporation by gathering heat from its surroundings and in the second coil, the refrigerant is condensed, leading to the release of absorbed heat (NRCan, 2020). The technology offers a high coefficient of performance (COP) and has the potential to save costs through the replacement of gas-fired heating processes (Beyond Zero Emissions, 2018).

Electric Arc Furnace

Electric arc furnaces melt metals via direct and radiant heating, generated by means of electricity that jumps from the energized to the grounded (neutral) electrode, resulting in high voltage electric arcs (Flournoy, 2018). These furnaces are most commonly utilized for melting steel for recycling, producing almost 30% of the world's steel output. They utilize substantially lower energy compared to primary steel production using blast furnace-basic oxygen furnace (Beyond Zero Emissions, 2018).

Induction Heating

Induction heating occurs by placing the material that needs to be heated inside an electromagnetic field generated by passing electricity through a conductor or coil. The electromagnetic field helps heat the material by inducing circulating electric currents within the material (GH Induction Atmospheres, 2020). The process is utilized for a wide range of applications including metal hardening, soldering, and annealing. Some of the advantages of this technology are: enhanced process efficiency, uniform and precise heating, and no on-site emissions (GH Electrotermia, 2011; Britannica, 2011).

Radio-frequency Heating

Radio-frequency heating is a form of dielectric heating with systems operating in the 10-30 MHz frequency and 10-30 meters wavelength ranges. The process works by agitating the molecules of the material, resulting in the generation of heat within the material. Since the entire thickness of the material is heated simultaneously, the process offers uniform heating at low temperatures (Radio Frequency Co, 2020). This technique works well with materials that are poor conductors of heat and electricity due to its greater depth of penetration and is much more efficient than conventional heating processes (Beyond Zero Emissions, 2018).

Electric Infrared Heater

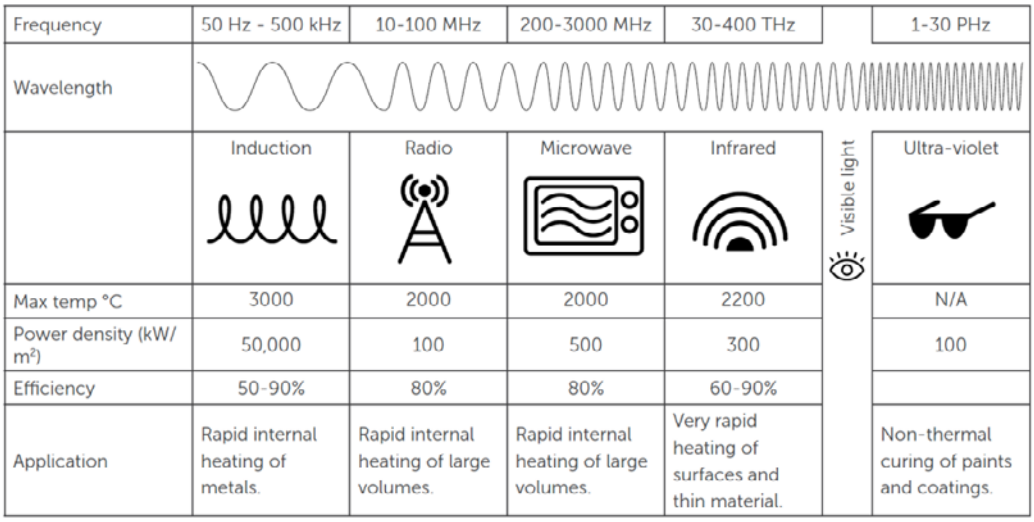
Electric infrared heaters operate through the conversion of electricity into radiant heat. The process involves the direct heating of the object instead of heating the air in between, thus ensuring the efficient transfer of heat (Herschel, 2020). These systems can be designed with temperature requirements and the target material's ability to absorb infrared radiation in mind. The technology offers numerous advantages, including high overall efficiency, faster response time than gas convection systems, low cost, and minimal maintenance effort (Beyond Zero Emissions, 2018).

Ultra-violet (UV) Heating

UV radiation is primarily utilized for the efficient curing of coatings such as paints, inks and adhesives. The process works by exposing UV formulations (inks, coatings or adhesives containing a small proportion of photo initiators) to UV radiation, resulting in their instant curing. Some advantages of the UV curing process include improved resistance to abrasion, faster production speeds, low energy intensity, and reduction in processing times (Heraeus Group, 2020). The technology is utilized for various applications such as adhesive bonding, general electronics, packaging, semiconductors, and coatings (LightTech, 2020).

Microwave Heating

Microwave heating is a form of dielectric heating with systems operating in the 900-3000 MHz frequency and 10-30 centimeters wavelength ranges. The process works by agitating the molecules of the material, resulting in the generation of heat within the material (Beyond Zero Emissions, 2018). This process is utilized for a wide variety of industrial applications, including simple heating, drying, and defrosting. It is especially useful for heating products or materials with poor thermal conductivity, large volume and small surface area, and high sensitivity to large surface and bulk temperature differentials (MKS, 2014). Figure A.1. shows some of the characteristics of electromagnetic heating technologies.



Frequency	50 Hz - 500 kHz	10-100 MHz	200-3000 MHz	30-400 THz		1-30 PHz
Wavelength						
	Induction	Radio	Microwave	Infrared	Visible light	Ultra-violet
Max temp °C	3000	2000	2000	2200		N/A
Power density (kW/m^2)	50,000	100	500	300		100
Efficiency	50-90%	80%	80%	60-90%		
Application	Rapid internal heating of metals.	Rapid internal heating of large volumes.	Rapid internal heating of large volumes.	Very rapid heating of surfaces and thin material.		Non-thermal curing of paints and coatings.

Figure A.1. Electromagnetic heating technologies (Beyond Zero Emissions, 2018)

Electric Induction Melting

The working principle behind electric induction furnaces is the induction of a low voltage, high current in a metal (secondary coil) with the help of a primary coil at a high voltage (Atlas Foundry Company, n.d.). The induced current leads to the development of a stirring motion, which maintains the molten metal at a constant temperature, ensuring a homogenous and good quality output. Induction furnaces are categorized into channel induction furnaces and crucible induction furnaces. Channel induction furnaces are utilized for melting non-ferrous metals with lower melting points, operating at an efficiency of around 80 to 90%. Crucible induction furnaces are utilized for melting metals with higher melting points (such as steel and cast iron) and they operate at an efficiency of 80% (Beyond Zero Emissions, 2018).

Plasma Melting

In the process of plasma arc melting, the partly ionized inert gas acting as the plasma arc torch column serves as the source of heat. The metal melting process occurs at a pressure range of around 300 – 1000 mbar (abs.) under inert gas conditions (ALD, 2019). The technique is utilized for a wide range of process heating applications across various industries such as metal, chemical, mineral, and plastic. and has the potential to displace natural gas furnaces (EPRI, 2009). Some of the numerous advantages of the process are reduced impurities, high stability and ease of temperature adjustment, and reduced air pollution (Svirchuk, 2011).

Electrolytic Reduction

Electrolytic reduction utilizes the process of electrolysis to extract metals from their compounds. The technique is utilized for the smelting of alumina, where the metal in the ore undergoes chemical reduction, resulting in the production of aluminum (Beyond Zero Emissions, 2018). Another electrolytic technology is electrolysis of iron ore to produce steel (Boston Metal, 2020).

The major advantages of this process include reduced impurities and the potential to achieve substantial reduction in CO_2 emissions when low-carbon electricity is used for electrolysis. (Irfan, 2013).

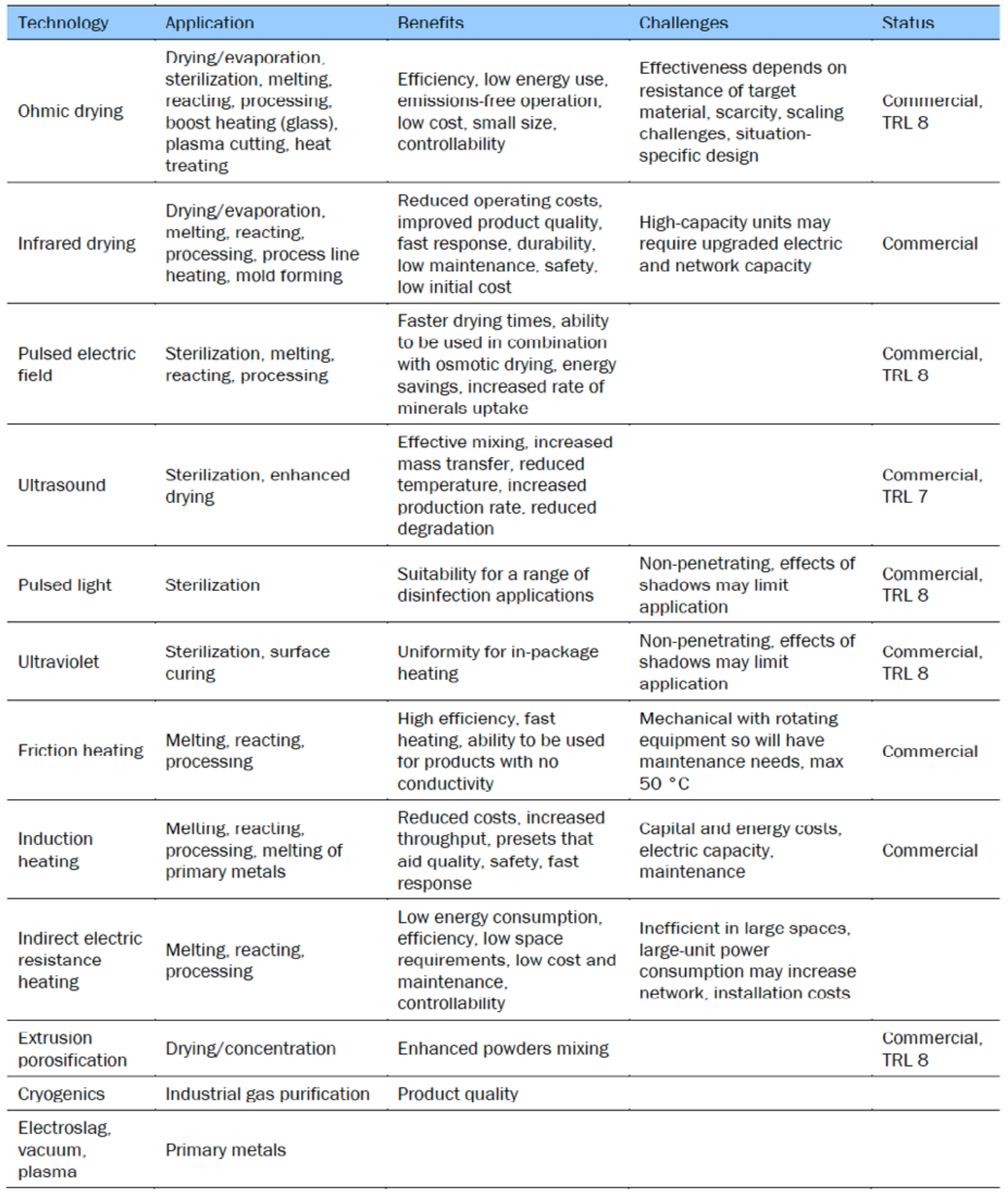
Indirect Electrification

Indirect electrification is when renewable electricity is used to produce hydrogen via the electrolysis of water into oxygen and hydrogen, and this hydrogen is then used as a substitute for natural gas in thermal industrial processes (Deason et al. 2018). Hydrogen produced with electrolysis using renewable electricity is known as “green” hydrogen. The cost of production and distribution of hydrogen, especially from renewable energy sources, is high.

Appendix 2. Industrial Electrification Technologies' Benefits and Challenges

Table A.1. Electrification technologies for industry and their benefits and challenges (Rightor et al. 2020)

Technology	Application	Benefits	Challenges	Status
Hybrid boiler	Heating, process heat	Flexibility on energy source, ability to take advantage of price and availability, resilience, minimizing price volatility impact	Somewhat more expensive, support needed for two systems	Commercial
Electric boiler	100–150 °C process heat, food, chemicals, plastics	Low CO_2 when powered by renewable energy, less expensive/ lower capital cost	Low efficiency with thermally produced electricity, higher energy costs on energy basis than natural gas	Commercial
Heat pump, 90–160 °C	Sterilization, melting, reacting, processing	Efficient, convenient, avoid boiler house costs, fast response, safe, durable, low maintenance, cooling and heating options	Requires close proximity to heat source/load for highest efficiency, high electric supply needs, complexity	Experience limited, higher-temperature units emerging
Direct arc melting	Steel and metal transformation of ores	High melt rates and pouring temperatures, excellent control of melt chemistry		
Resistance heating	Primary metals, plastics, chemicals processing	Backup heat for heat pumps below 40 °C		
Electric steam generators	100–150 °C process heat	Convenience, compactness, low capital costs, efficiency, fast response, durability, safety, low downtime, dry steam	Displacement of legacy steam systems, possible need to increase electricity capacity, feed water and steam system O&M still required	Commercial
Heat pumps < 90 °C	Drying/evaporation	Fast response, safety, durability, low maintenance, combined cooling/heating/ dehumidification	Most efficient close to heat source, < 7 °C heat quality varies, higher-capacity units need high power	Commercial
Microwave, radiofrequency	Drying/evaporation, sterilization, melting, reacting, processing	Reduced drying times/ higher throughput, energy efficiency, uniform heating, targeted heating, compactness, increased reaction yields	Materials must be compatible, requires electrical capacity upgrades, payback can be longer	Commercial, TRL 4-8 depending on application



Technology	Application	Benefits	Challenges	Status
Ohmic drying	Drying/evaporation, sterilization, melting, reacting, processing, boost heating (glass), plasma cutting, heat treating	Efficiency, low energy use, emissions-free operation, low cost, small size, controllability	Effectiveness depends on resistance of target material, scarcity, scaling challenges, situation-specific design	Commercial, TRL 8
Infrared drying	Drying/evaporation, melting, reacting, processing, process line heating, mold forming	Reduced operating costs, improved product quality, fast response, durability, low maintenance, safety, low initial cost	High-capacity units may require upgraded electric and network capacity	Commercial
Pulsed electric field	Sterilization, melting, reacting, processing	Faster drying times, ability to be used in combination with osmotic drying, energy savings, increased rate of minerals uptake		Commercial, TRL 8
Ultrasound	Sterilization, enhanced drying	Effective mixing, increased mass transfer, reduced temperature, increased production rate, reduced degradation		Commercial, TRL 7
Pulsed light	Sterilization	Suitability for a range of disinfection applications	Non-penetrating, effects of shadows may limit application	Commercial, TRL 8
Ultraviolet	Sterilization, surface curing	Uniformity for in-package heating	Non-penetrating, effects of shadows may limit application	Commercial, TRL 8
Friction heating	Melting, reacting, processing	High efficiency, fast heating, ability to be used for products with no conductivity	Mechanical with rotating equipment so will have maintenance needs, max 50 °C	Commercial
Induction heating	Melting, reacting, processing, melting of primary metals	Reduced costs, increased throughput, presets that aid quality, safety, fast response	Capital and energy costs, electric capacity, maintenance	Commercial
Indirect electric resistance heating	Melting, reacting, processing	Low energy consumption, efficiency, low space requirements, low cost and maintenance, controllability	Inefficient in large spaces, large-unit power consumption may increase network, installation costs	
Extrusion porosification	Drying/concentration	Enhanced powders mixing		Commercial, TRL 8
Cryogenics	Industrial gas purification	Product quality		
Electroslag, vacuum, plasma	Primary metals			

Appendix 3. Base Year and Projected Industrial Energy Prices

EIA's Annual Energy Outlook (2019) forecasts industry-specific energy prices until 2050 for different U.S. geographical regions under their reference case scenario. Based on the future price development presented in Table A.2 (U.S. DOE/EIA 2019), this study projects the future energy prices for the industry located in different states (Table A.3).

Table A.2. Projected EIA industrial energy price indices for different U.S. geographic regions (Data source: U.S. DOE/EIA, 2019)

Region	Electricity			Natural gas		
	2030	2040	2050	2030	2040	2050
United States	0.95	0.95	0.96	1.18	1.29	1.48
New England	0.98	0.97	0.97	0.97	1.05	1.19
Mid-Atlantic	0.99	1.01	1.04	1.07	1.15	1.28
East North Central	0.95	0.92	0.92	1.15	1.24	1.39
West North Central	0.89	0.89	0.86	1.20	1.31	1.50
South Atlantic	0.95	0.94	0.93	1.14	1.22	1.37
East South Central	0.87	0.87	0.88	1.18	1.28	1.44
West South Central	1.02	1.04	1.07	1.24	1.38	1.58
Pacific	1.04	1.06	1.04	1.17	1.29	1.48
Mountain	0.82	0.84	0.86	1.21	1.32	1.53

Region	Coal		
	2030	2040	2050
United States	1.07	1.08	1.10
New England	1.10	1.16	1.23
Mid-Atlantic	1.07	1.09	1.10
East North Central	1.05	1.06	1.07
West North Central	1.03	1.05	1.06
South Atlantic	1.10	1.15	1.20
East South Central	1.08	1.09	1.14
West South Central	1.09	1.11	1.11
Pacific	1.01	1.00	1.01
Mountain	1.01	1.01	1.02