

Subsector- and State-level Analysis of Industrial Electrification in the U.S.

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ABSTRACT

There is a significant opportunity to decarbonize the industrial sector by electrification of process heating. We present a bottom-up industrial subsector, systems, and technology-level analysis of electrification potential for the container glass and beer industries in 20 states. Because of space constraint, we only presented detailed results for two subsectors in this paper. The study identifies specific processes that could be electrified in the near-term with commercially available technologies and analyzes the expected changes in energy use, CO₂ emissions, and energy costs. Our results show that electrification will significantly reduce industrial total final energy use in all states studied. Indiana, Ohio, Illinois, Iowa, and Michigan are the states with largest energy savings potentials from electrifying industries included in this study. We found that the glass container and beer industries can successfully decarbonize through electrification in most states by 2030. The energy costs of the industry would be higher using baseline electricity costs forecast as compared to natural gas but could be lower if using lower cost for renewables electricity in the future. The difference of energy cost varies across states.

1. Introduction

The United States set an economy-wide target of reducing its net greenhouse gas (GHG) emissions by 50-52 percent below 2005 levels in 2030 and set a goal to reach 100% carbon pollution-free electricity by 2035 (UNFCCC 2021). Meeting these goals will likely 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 federal 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 across all sectors of the U.S. economy including the industry sector (The White House 2022).

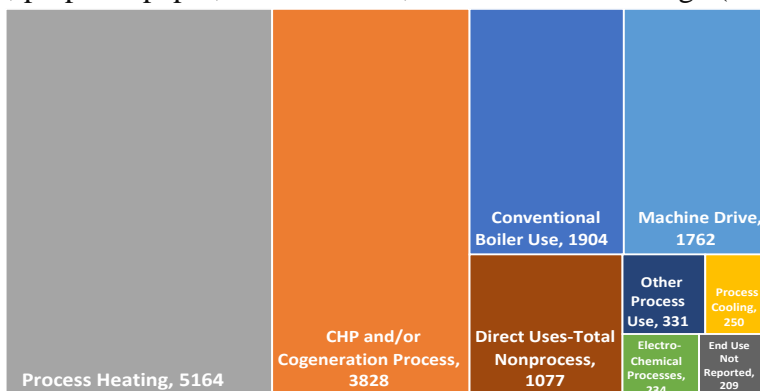
There is a significant opportunity to decarbonize the industrial sector by shifting heat production away from carbon-intensive fossil fuels to clean sources such as electrification where low- or zero-carbon electricity is used. Globally, more than 50% of final energy demand is for heating, and about half of that is for industrial heating (IEA, 2018). Much of the electrification discussion to date has focused on the transportation and building sectors, with little attention paid to the industrial sector. This paper aims to fill some of that void by examining profiles of heat consumption in industrial subsectors and the potential for electrification based on different heat

demand profiles and electrification technologies available to meet those heating needs, as well as barriers to industrial electrification and proposals that, if implemented, could help the industrial sector to overcome those barriers.

This paper is comprised of a bottom-up industrial subsector, systems, and technology-level technical assessment for electrification of industry in selected states. The technical assessment provides an analysis of the current state of industrial electrification needs, the technologies available, and the potential for electrification in the container glass and beer industry. We conclude the paper by providing several key recommendations to stakeholders in the U.S.

2. Energy use and heat consumption in U.S. industry

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 U.S. industry is fossil fuels. In Manufacturing Energy Consumption Survey (MECS), taken in 2014, thermal processes accounted for 74% of total manufacturing energy use in the U.S.; of which process heating accounted for 35%; combined heat and power/cogeneration for 26%; conventional boilers for 13% (US DOE, 2019) (Figure 1). Industrial process heating operations include drying, heat treating, curing and forming, calcining, smelting, and other operations. 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 (US DOE/EIA, 2017).



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.

Figure 1. U.S. manufacturing energy use by end uses- values in Trillion Btu (US DOE, 2019)

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, material is heated by heat transfer from a heat source such as a flame, steam, hot water, 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 process parameters, system design, and operating practices (ORNL, 2017).

Around 30% of the total U.S. industrial heat demand is required at temperatures below 100°C. Two-thirds of process heat used in U.S. industry are for applications below 300°C (572°F) (McMillan, 2019). In the food, beverage, and tobacco, transport equipment, machinery, textile, and pulp and paper industries, the share of heat demand at low (below 100°C) and medium (below 300°C) 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 with existing commercial technologies such as electric boilers, high temperature heat pumps, and other electric heating technologies (Beyond Zero Emissions 2019). Therefore, there is significant potential for electrification of industrial processes for low or medium heating applications.

3. Methodology

The sector-specific electrification analysis focuses on electrifying the end-use processes including the direct-fire processes 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 to provide the heat for the process. Electrifying end-use processes have the advantage of increasing efficiency by removing steam distribution losses as well as boiler losses. We specifically analyzed electrification opportunities in the container glass and beer industries in this paper. A similar treatment of 10 additional industries is available in a separate report (Hasanbeigi et al. 2023).

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

There are 20 states included in this study (Figure 3). 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).

To conduct this bottom-up, systems- and technology-level electrification analysis for each industrial subsector, we followed four steps as shown in Figure 2. 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. Having the energy intensity of process heating technologies for conventional and electrified process, we then calculated the energy use, GHG emissions, and energy cost implications of electrification in each industry.

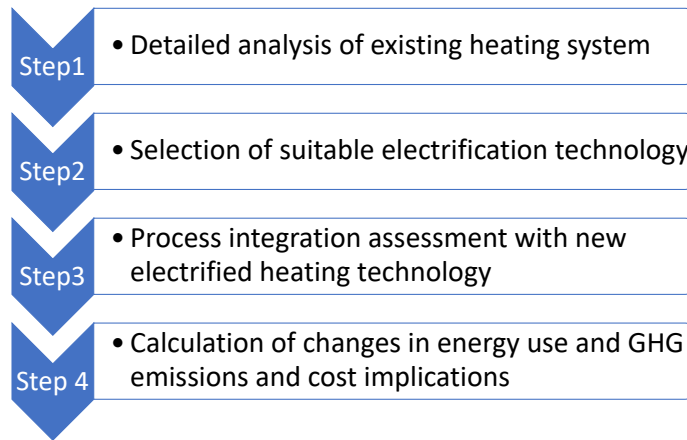


Figure 2. Methodology steps to estimate electrification potential in U.S. industrial subsectors

We also used projections for the production for each subsector as well as projections in grid emissions factor and unit price of energy in 2030, 2040, and 2050 in order to project the energy use, GHG emissions, and energy cost implications of electrification in each industry (Hasanbeigi et al. 2023). The U.S. electricity grid emissions factor and average unit price of natural gas and coal used in our analysis are shown in Figure 3.

It should be noted that the change in energy use and GHG emissions estimated for each subsector in the following sections are the total technical potentials assuming a 100% adoption rate. The actual adoption of electrification technologies in industry 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; 2019-2050.

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 3 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 CO₂ 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.

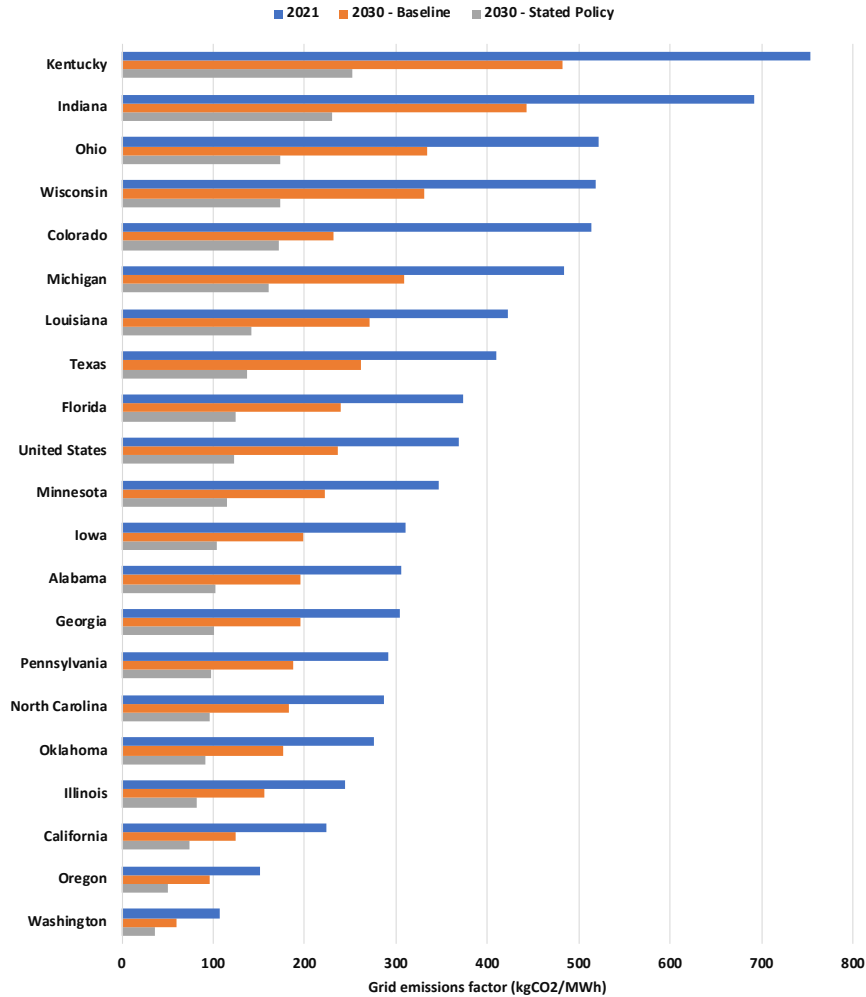


Figure 3. Electricity grid emissions factors in 2021 and 2030 (kgCO₂/MWh)

4. Results and discussions

4.1. Electrification of the 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.

In 2021, the total revenue generated by the U.S. glass manufacturing industry was around \$30 billion. The total glass production in the U.S. was around 20 million metric tonnes in 2017 (Garside 2020). 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 US 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 forehearth
Gas-fired Annealing lehr	25	210	Post Forming (Annealing)	183	Electric Annealing lehr
	416	1465	Subtotal	1308	
	1881		Total Energy	1308	

Container glass production was identified in 18 of the 20 states included in this study. Figure 4 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. Overall, electrified container glass production results in 30% saving in final energy use compared to the conventional production. The total energy saving from electrification of container glass industry in all 18 states is over 22,300 TJ/year in 2050.

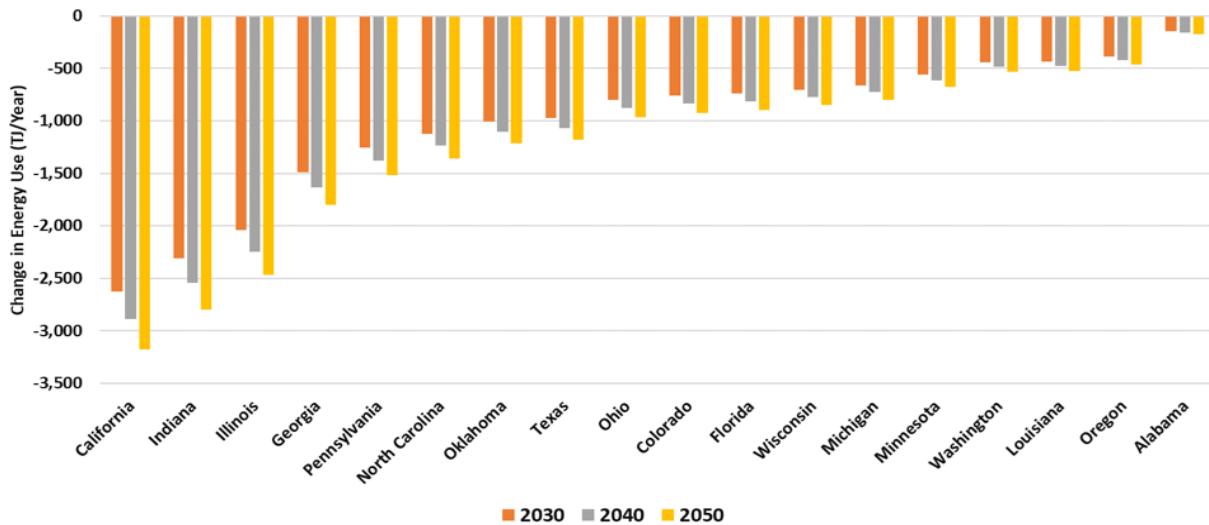


Figure 4. Change in the container glass industry’s total final energy use after electrification (Technical potential assuming 100% adoption rate)

Figure 5 shows the container glass industry’s change in net CO₂ emissions after electrification under the baseline scenario. The container glass industry’s electrification can result in a decrease in CO₂ emissions in 2030 in all states except Indiana, which has a high grid emissions factor in 2030 (see Figure 3). As the grid decarbonizes in Indiana, electrification can help realize substantial annual CO₂ emissions reductions by 2040 in that state as well.

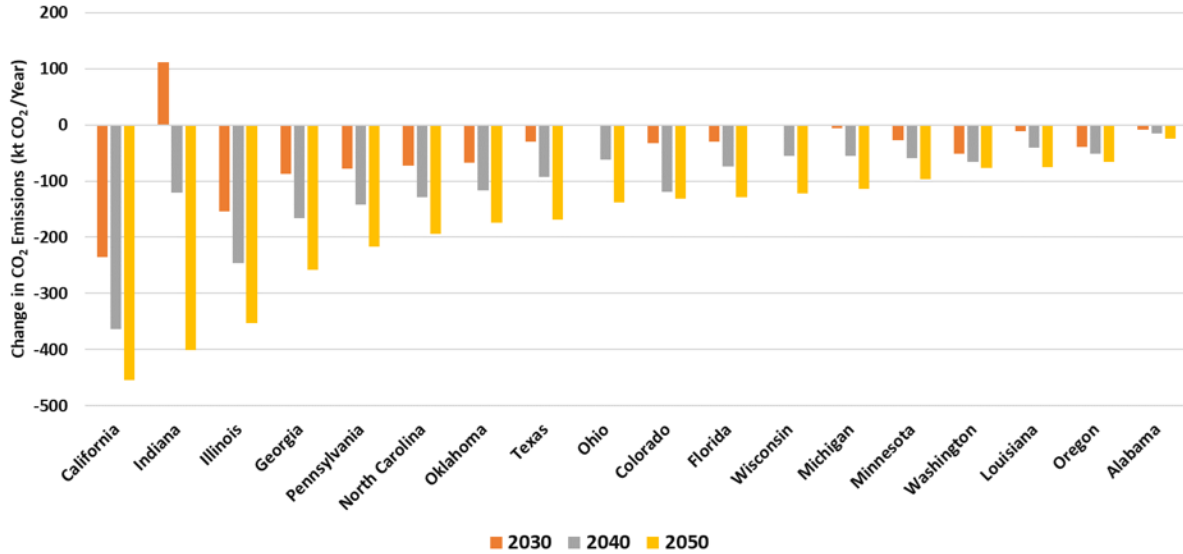


Figure 5. Change in the container glass industry’s net CO₂ emissions after electrification - baseline scenario (technical potential assuming 100% adoption rate).

Figure 6 shows the container glass industry’s change in net CO₂ emissions after electrification under the stated policy scenario. Under this scenario, the CO₂ 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. The total CO₂ emissions reduction from electrification of container glass industry in all states studied is around 3,200 kt CO₂/year in 2050.

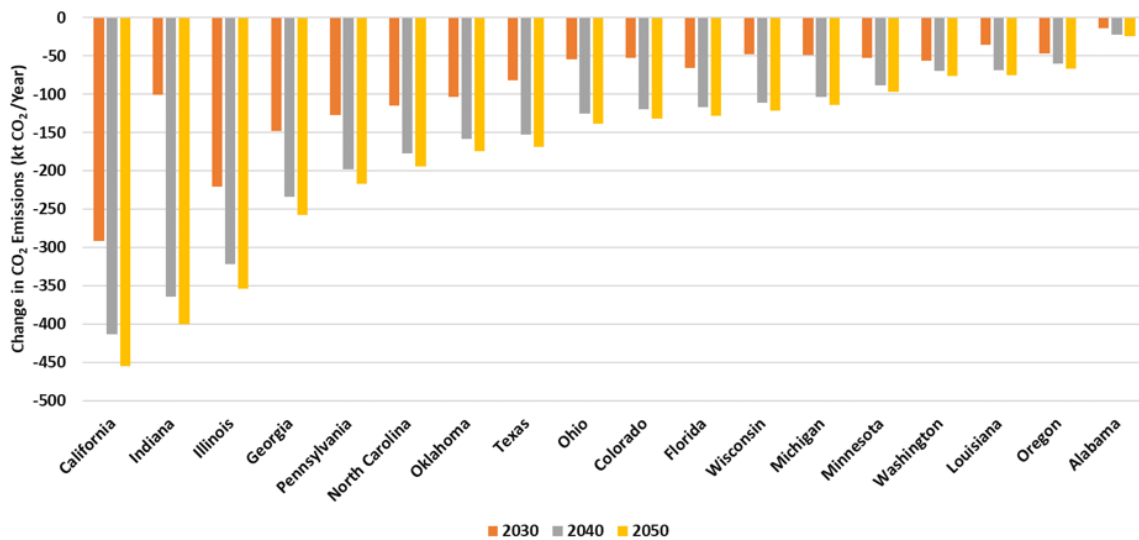


Figure 6. Change in the container glass industry’s net CO₂ emissions after electrification - stated policy scenario (technical potential assuming 100% adoption rate)

Figure 7 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 relatively lower ratio of the industrial unit price of electricity to natural gas. However, under the Lower RE price forecast scenario which assumes 50% lower electricity process compared to the base case price forecast, 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.

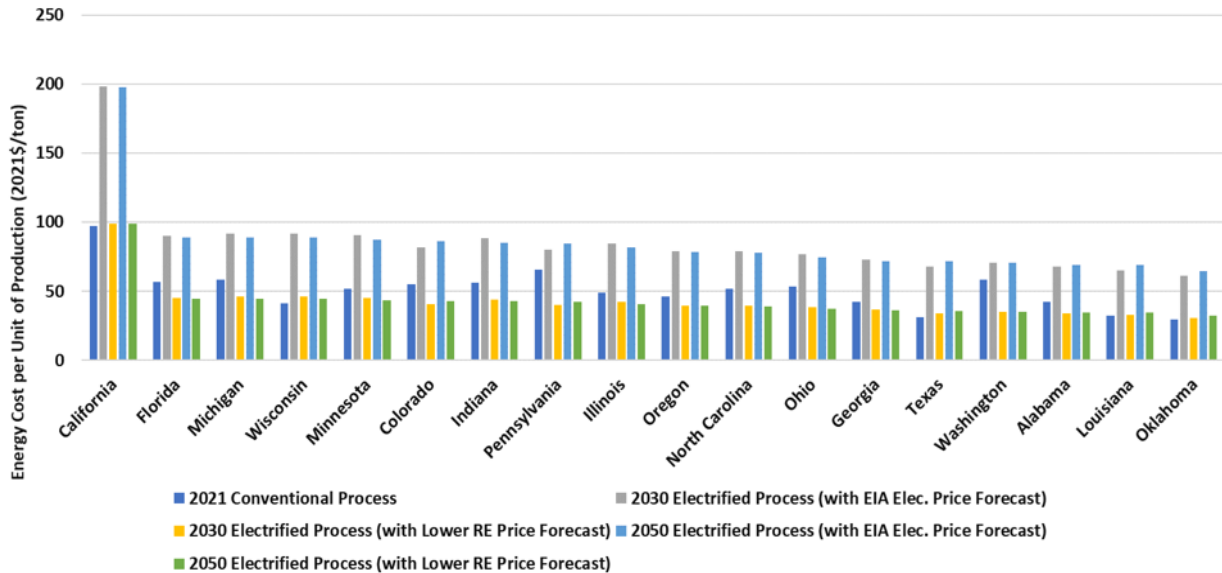


Figure 7. Energy cost per unit of production in the container glass industry

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). Therefore, the results for the electrification of container glass industry presented here cannot be directly extrapolated for the flat glass industry.

4.2. Electrification of the beer industry

In 2021, there were reported to be over 8,000 U.S. breweries (Conway 2020), with around 211 million barrels of total annual beer production. In 2050, production is expected to rise to 252 million barrels (US DOE 2017b). Brewing is one of the food and beverage industry’s highest energy-consuming subsectors.

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

Heat pumps could be utilized to electrify the beer production process in four process stages. The coefficient of performance (COP)¹ 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		Process steps	All Electric Process	
Heating Equipment	Thermal Demand (kWh/Hectoliter)		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.

Beer production electrification will significantly reduce the total final energy use during the study period (Figure 8). 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. Overall, electrified beer production cuts the total final energy use by two-third compared to the conventional production. The total energy saving from electrification of beer industry in all states studied is over 15,400 TJ/year in 2050.

¹ The coefficient of performance or COP of a heat pump is a ratio of useful heating provided to work (energy) required. Higher COP equate to higher efficiency, lower energy consumption and thus lower operating costs.

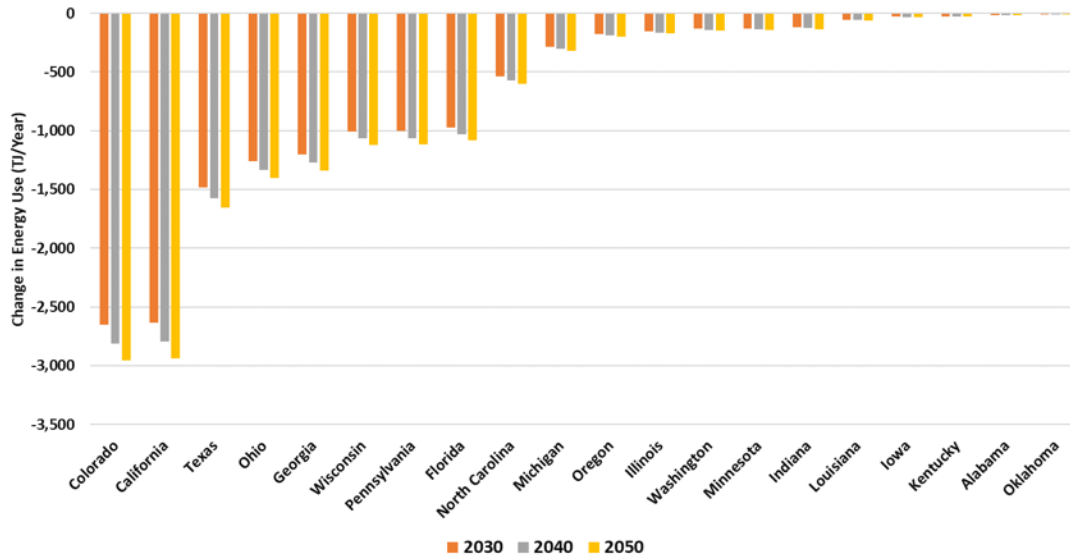


Figure 8. Change in the beer industry’s total final energy use after electrification (Technical potential assuming 100% adoption rate)

Figure 9 shows the beer industry’s change in net CO₂ emissions after electrification under the baseline scenario. Beer production electrification will result in a drop in CO₂ emissions in 2030 in all states studied. Electrification further reduces annual CO₂ emissions by 2050 in all states because of grid decarbonization. The total CO₂ emissions reduction from electrification of beer industry in all states studied is around 870 kt CO₂/year in 2050.

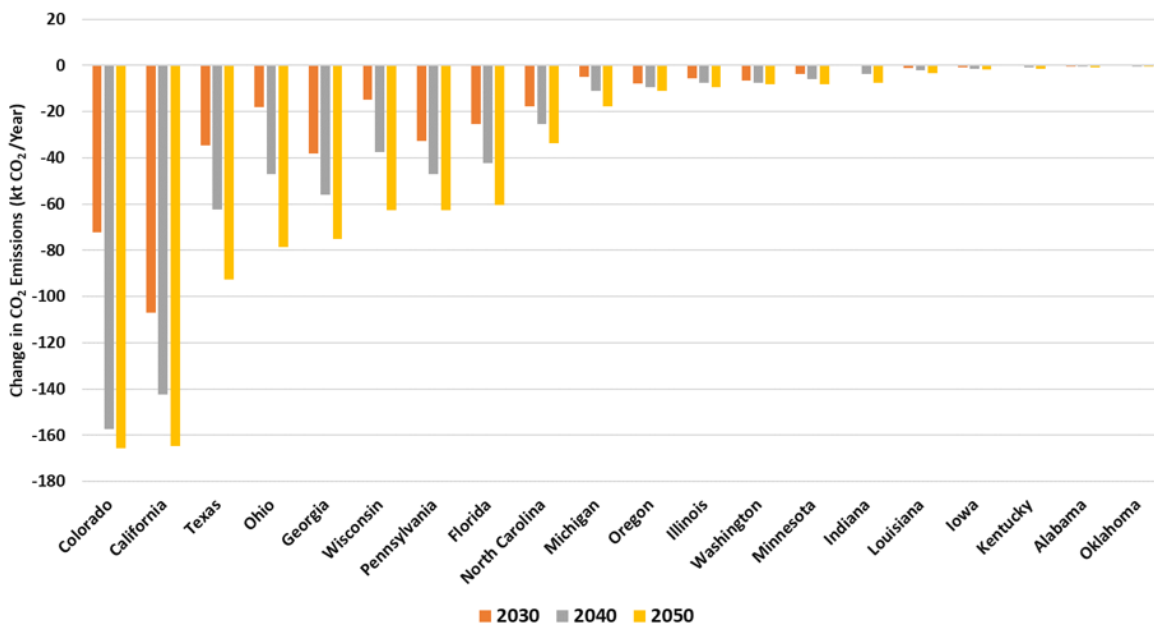


Figure 9. Change in the beer industry’s net CO₂ emissions after electrification - baseline scenario (Technical potential assuming 100% adoption rate)

Figure 10 shows that under the stated policy scenario, the CO₂ emissions reduction potential in 2030 years is substantially higher than in the baseline scenario because more rapid grid decarbonization is assumed.

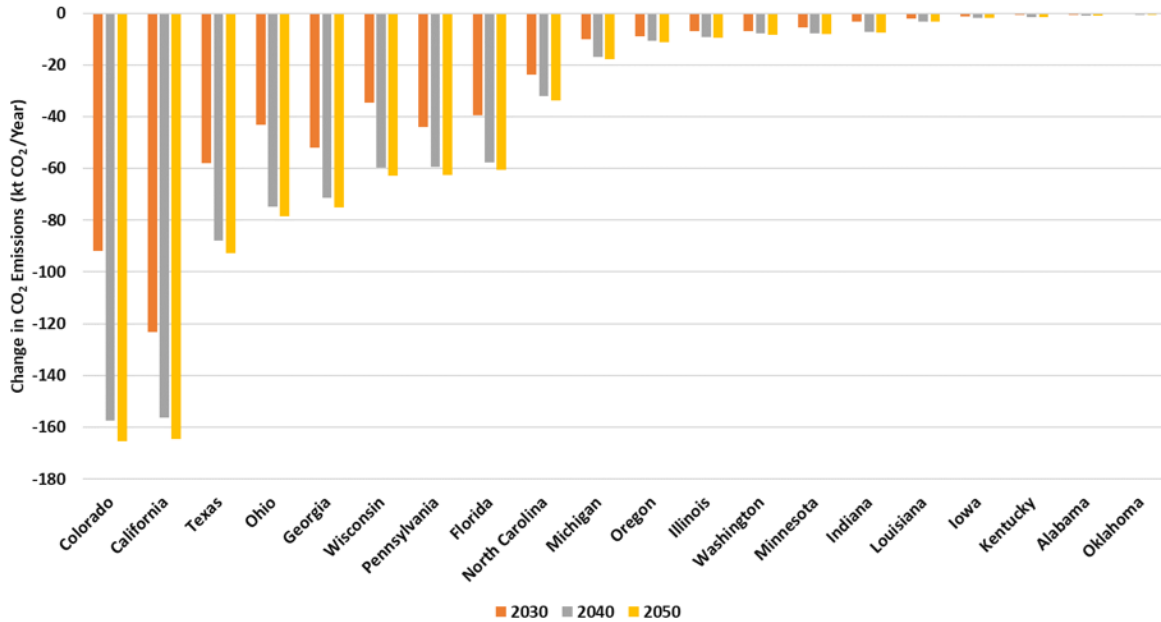


Figure 10. Change in the beer industry’s net CO₂ emissions after electrification - stated policy scenario (technical potential assuming 100% adoption rate)

Figure 11 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 in the industry. Figure 11 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.

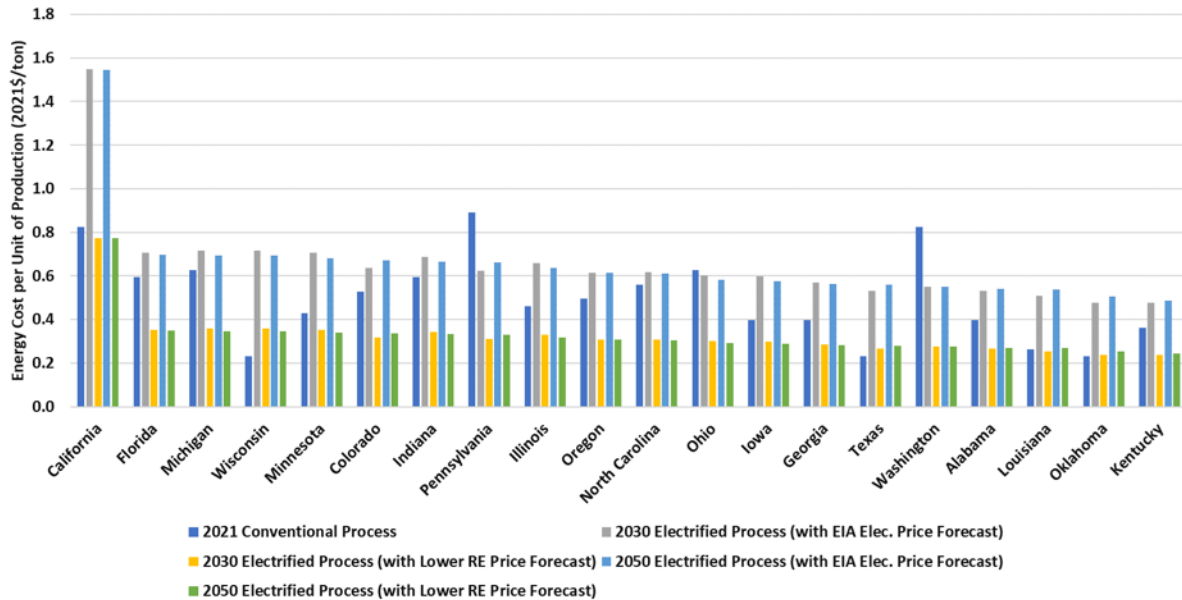


Figure 11. Energy cost per unit of production in the beer industry

5. Conclusions

This study assesses the anticipated changes in energy use, CO₂ emissions, and energy costs and identifies specific processes that could be electrified in the near future using commercially available technologies. Industrial facilities can determine which of their traditional processes may be appropriate candidates for electrification by understanding which conventional processes could be electrified and how this influences emissions and costs. Additionally, utilities, grid operators, and electricity generators can plan for these changes and make sure that machinery and generation resources are available to meet the rising demand for renewable electricity by being aware of the potential growth in industrial energy demand that will result from electrification.

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. Electrified container glass production results in 30% saving in final energy use compared to the conventional production. The total energy saving from electrification of container glass industry in all 18 states is over 22,300 TJ/year in 2050. The total CO₂ emissions reduction from electrification of container glass industry in all states studied is around 3,200 kt CO₂/year in 2050.

The electrified beer production cuts the total final energy use by two-third compared to the conventional production. The total energy saving from electrification of beer industry in all states studied is over 15,400 TJ/year in 2050. The total CO₂ emissions reduction from electrification of beer industry in all states studied is around 870 kt CO₂/year in 2050.

The study reveals that the energy cost per unit of production for an electrified process in both the container glass and beer industries by 2030 will be higher than the conventional process in 2021 under the EIA electricity price forecast, except in states with lower industrial electricity to natural gas price ratios like Pennsylvania and Washington. However, under a scenario

assuming 50% lower renewable energy prices, the electrified process becomes more economical in almost all states. While states such as California, Texas, and Oklahoma display higher costs for electrified processes in the beer industry due to their lower electricity to natural gas price ratios, states like Pennsylvania, Washington, and Ohio demonstrate cost competitiveness. Projections for 2050 suggest that even under higher electricity prices, electrified beer production will be cost-competitive in many states.

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 across income levels, 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 paper 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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