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Industrial Electrification in the Southwest States



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Executive Summary

The industrial sector accounts for approximately a quarter of energy use and greenhouse gas (GHG) emissions in the U.S. As emissions from electricity generation continue to decline, addressing thermal energy needs in the industry, especially for process heating, becomes a critical challenge in the pursuit of industrial deep decarbonization.

Heat represents two-thirds of all energy demand in the industrial sector. Despite this, only 10% of this demand is currently met using renewable energy sources. A significant opportunity lies in decarbonizing the industrial sector by transitioning heat production away from carbon-intensive fossil fuels and towards cleaner alternatives such as electrification, where low- or zero-carbon electricity is utilized.

This report is a follow-up study to our previous reports, "[Electrifying U.S. Industry: A Technology- and Process-Based Approach to Decarbonization](#)" and "[Industrial Electrification in the U.S. States](#)". In the previous reports, we studied industrial electrification potential at the national level as well as state level, but the southwest states were not included in our state-level study. In this report, we analyze the electrification potential for 14 industries (aluminum casting, container glass, ammonia, recycled plastic, steel reheating, beer, beet sugar, milk powder, wet corn milling, soybean oil, cheese, meat processing, ethanol, and hydrogen) in six southwest states: Arizona, Colorado, Nevada, New Mexico, Utah, and Wyoming.

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, CO₂ 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.

The southwest states included in this study are shown in Figure ES1. This figure shows that electrification could significantly reduce the total final energy use of industry in all states studied (note that negative values in Figure ES1 imply reduction). Colorado has the largest energy-saving potential from the electrification of industries included in this study. Differences in energy savings across states are due to different levels of production in the industries studied.

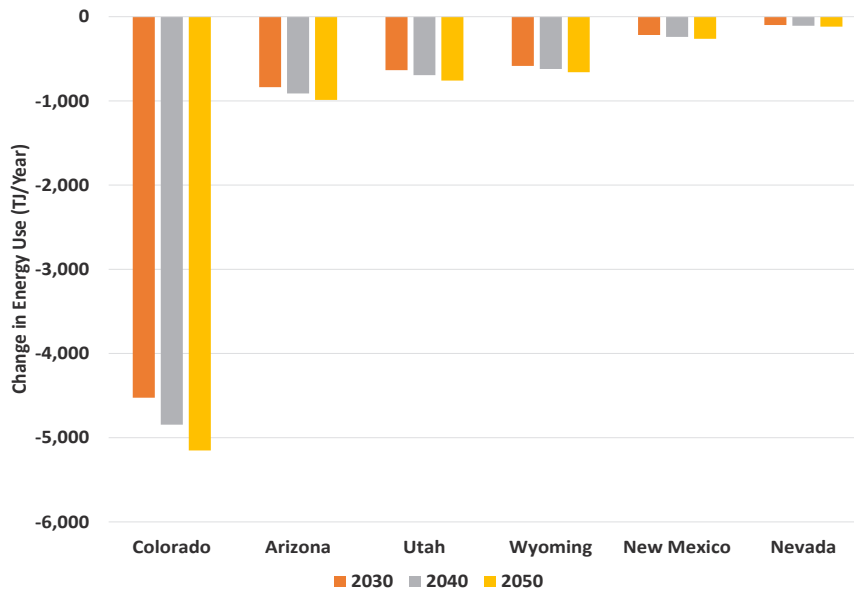


Figure ES1. Total change in energy use in different states using electrified processes in eleven industries (all except ammonia, hydrogen, and plastic recycling) (This is the technical potential assuming a 100% adoption rate).

Figure ES2 shows the change in industrial CO₂ emissions in different states after electrification under a baseline scenario where a zero-carbon grid is achieved in 2050. Because grid emissions factors vary across states, full electrification of these industries in 2030 would result in an increase in CO₂ emissions in all states studied except Arizona and Nevada. In these states, the relatively lower grid emissions factor in 2030 helps to achieve CO₂ emissions reductions. We also developed a State policy scenario that aligns with each state’s target for achieving a zero-carbon grid. The state policy scenario shows a quicker and substantially larger CO₂ emissions reduction potential in future years than the baseline scenario because of the more rapid decarbonization of the grid assumed.

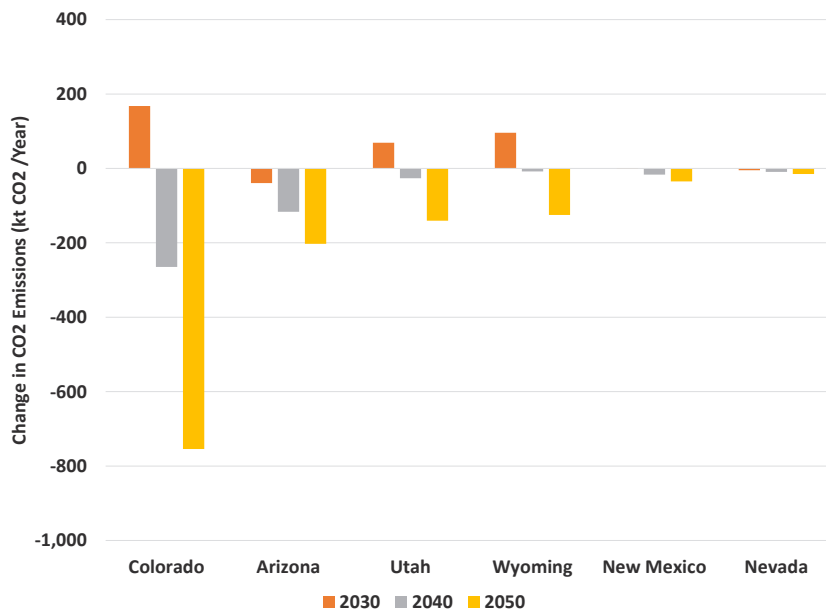


Figure ES2. Change in industrial CO₂ emissions in different states using electrified processes in eleven industries (all except ammonia, hydrogen, and plastic recycling) - baseline scenario (This is the technical potential assuming a 100% adoption rate).

This study also emphasizes the positive impact of electrification on reducing CO₂ emissions over the lifetime of the technology by calculating the cumulative change in CO₂ emissions from 2030 to 2050 (Figure ES3). Colorado demonstrates the largest reduction in cumulative CO₂ emissions, while Nevada experiences the smallest reduction. In all states, industrial electrification leads to a net decrease in CO₂ emissions over the lifetime of the technologies, assumed to span from 2030 to 2050. This indicates that, even if industrial electrification initially causes an increase in annual CO₂ emissions in some states due to the high carbon-intensity of the electricity grid, the long-term effect of electrification will result in a net reduction of CO₂ emissions. Consequently, this contributes to climate change mitigation efforts and showcases the benefits of adopting electrification technologies.

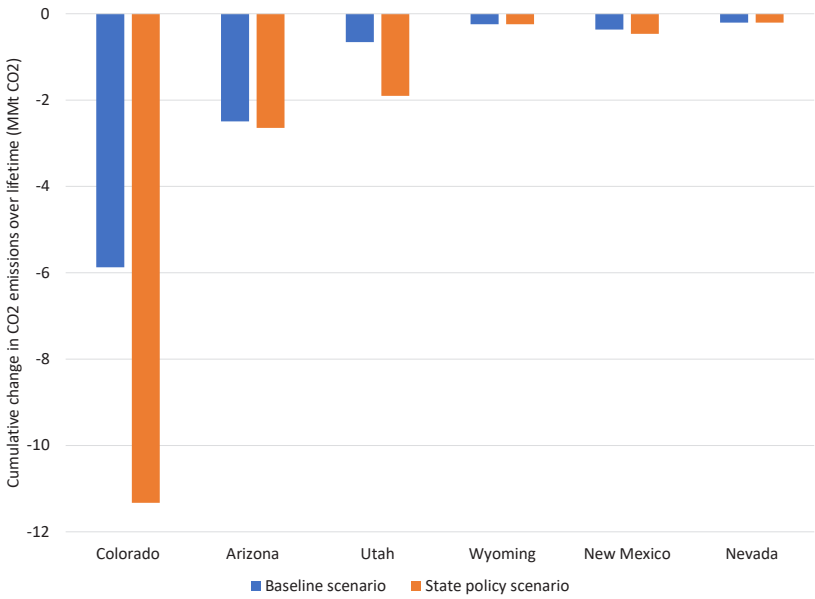


Figure ES3. Cumulative change in CO₂ emissions over the lifetime of electrified technologies over the period of 2030 - 2050 in eleven industries studied (all except ammonia, hydrogen, and plastic recycling) (This is the technical potential assuming a 100% adoption rate).

The changes in total final energy use and CO₂ emissions are shown in Table ES1 for all states in both baseline and state policy scenarios. Colorado, Arizona, and Utah have the largest energy saving and CO₂ emissions reduction potential in 2050 among the states.

Table ES1. Change in total final energy use and CO₂ emissions from electrification in different states using electrified processes in eleven industries (all except ammonia, hydrogen, and plastic recycling)

	Change in total final energy use after electrification (TJ/Year)			Change in sector's net CO ₂ emissions after electrification (kt CO ₂ /year) Base case scenario			Change in sector's net CO ₂ emissions after electrification (kt CO ₂ /year) State policy scenario		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Colorado	-4,525	-4,845	-5,151	168	-265	-754	-13	-711	-754
Arizona	-837	-913	-988	-39	-116	-203	-58	-121	-203
Utah	-635	-695	-759	69	-27	-140	28	-129	-140
Wyoming	-585	-622	-659	96	-8	-125	96	-8	-125
New Mexico	-218	-239	-263	-1	-17	-35	-7	-23	-35
Nevada	-98	-108	-118	-5	-10	-15	-5	-10	-15

Note: Negative values imply a reduction in energy use or emissions. States are sorted based on 2050 values.

The changes in total final energy use and CO₂ emissions in all studied industries are shown in Table ES2 for both baseline and state policy scenarios. Hydrogen production, ammonia, ethanol, steel reheating, and the beer industry are the top five industries in terms of CO₂ emissions reduction potential from electrification, with hydrogen production showing the most CO₂ emissions reduction potential by far.

Table ES2. Change in total final energy use and CO₂ emissions from electrification for all studied industries.

	Change in total final energy use after electrification (TJ/Year)			Change in sector's net CO ₂ emissions after electrification (kt CO ₂ /year)			Change in sector's net CO ₂ emissions after electrification (kt CO ₂ /year)		
				Base case scenario			State policy scenario		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Hydrogen	2,376	2,517	2,682	1,385	-529	-2,691	915	-1,583	-2,691
Ammonia	-366	-403	-443	561	102	-454	561	102	-454
Ethanol	-750	-806	-841	159	-129	-447	45	-379	-447
Steel reheating	-789	-868	-955	52	-54	-182	16	-137	-182
Beer	-2,781	-2,946	-3,100	-35	-101	-174	-61	-164	-174
Beet sugar	-690	-728	-767	88	-23	-146	78	-48	-146
Container glass	-827	-910	-1,001	4	-63	-143	-22	-127	-143
Milk powder	-808	-888	-977	-35	-56	-80	-41	-65	-80
Cheese	-55	-61	-67	23	-4	-36	11	-27	-36
Meat processing	-51	-56	-62	16	-6	-33	8	-25	-33
Wet corn milling	-73	-77	-81	16	-3	-23	8	-22	-23
Plastic recycling	-211	-232	-255	-13	-11	-9	-12	-10	-9
Aluminum	-51	-57	-62	0	-3	-6	-1	-5	-6
Soybean oil	-23	-25	-26	0	-1	-3	-1	-3	-3

Note: Negative values imply a reduction in energy use or emissions. Industries are sorted based on 2050 CO₂ emissions value.

We also compared the energy cost per unit of production for the electrified and conventional process in each industry in 2030 and its projection up to 2050 under different future electricity, natural gas, and carbon price assumptions. Under the baseline energy prices, in many cases, the energy cost per unit of production for an electrified process is higher than that of the conventional process in 2030. However, even under the baseline energy price forecast, in 2050, for more than half of industries, the electrified process can have a lower energy cost per unit of production compared with the conventional process. A scenario with lower electricity prices in 2030 and 2050 can substantially reduce the energy cost of the electrified production processes, making them even more cost-competitive compared with the conventional process in the majority of industries and most states (Table ES3).

It should also be noted that our cost comparison focuses only on energy costs (with assumed prices on carbon from 2030 onward) and does not include capital costs and other costs or benefits for electrified technologies (see the methodology section). Table ES3 shows the comparison of the energy cost of the electrified vs. conventional technologies for different industry sectors in Colorado.

Table ES3. Energy cost comparison of the electrified vs. conventional technologies in Colorado

Industry sector	Energy cost of electrified technologies vs. conventional technologies -EIA prices scenario		Energy cost of electrified technologies vs. conventional technologies - 50% of EIA prices scenario	
	2030	2050	2030	2050
Hydrogen	Higher	Higher	Higher	Lower
Ethanol	Higher	Higher	Lower	Lower
Steel reheating	Higher	Lower	Lower	Lower
Beer	Lower	Lower	Lower	Lower
Beet sugar	Higher	Lower	Lower	Lower
Container glass	Higher	Lower	Lower	Lower
Milk powder	Lower	Lower	Lower	Lower
Cheese	Higher	Higher	Higher	Lower
Meat processing	Higher	Higher	Higher	Lower
Wet corn milling	Higher	Higher	Lower	Lower
Plastic recycling	Lower	Lower	Lower	Lower
Aluminum	Higher	Lower	Lower	Lower
Soybean oil	Higher	Lower	Lower	Lower

Non-energy benefits of electrification projects can result in substantial cost savings in both capital costs and operating costs for industrial companies. Co-benefits of industrial electrification should be quantified for electrification projects based on plant-level information and taken into account in the cost-benefit analysis of electrification projects, which will help to demonstrate electrification’s economic viability.

The electrification solutions examined in this analysis represent just a subset of the potential options for each process and subsector. There may be other electrified heating technologies currently available or emerging that could be applicable to these processes. Furthermore, there could be additional processes within the studied subsectors that have unexplored electrification potential. Consequently, the energy savings and CO₂ reduction potentials highlighted in this study only capture a fraction of the total potential achievable through comprehensive electrification of the industrial subsectors in the examined states.

Reducing emissions not only provides worldwide advantages by alleviating climate risks and the impacts of climate change but also yields local benefits. Industrial facilities utilizing fossil fuels on-site contribute to air pollution, which adversely affects nearby communities. In the U.S., low-income communities, both urban and rural, experience greater exposure to air pollution across all states. By adopting industrial electrification, it is possible to decrease localized emissions and enhance the well-being of these communities.

This report suggests six main recommendations for the U.S. government, especially the U.S. Department of Energy, state energy offices, and electric utilities to bolster industrial electrification:

- The U.S. DOE should engage with leading industries in these sectors to discuss the opportunities and challenges with electrification, and to perform additional detailed feasibility studies.

- Support demonstrations of emerging electrification technologies and novel applications of existing technologies, ensuring their practicality and effectiveness in real-world scenarios. The U.S. DOE and state energy offices can support this through its various demonstration programs.
- Provide financial incentives for electrification, making the transition to cleaner technologies more affordable and attractive for industries. The U.S. DOE can support this through its financial incentive programs for industrial decarbonization.
- Develop training programs in selection, sizing, and process engineering to apply these electrification technologies to these and other industrial sectors. The U.S. DOE can support training programs associated with these technologies through its various grant programs.
- Rapidly expand renewable electricity generation capacity to meet the demand for clean electricity in the industrial sector.
- Strengthen the electricity grid to ensure reliable and efficient energy transmission as the demand for electricity increases due to industrial electrification.
- Engage communities by actively involving them in the decision-making process and highlighting the benefits of industrial electrification for their health and environment.



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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 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.

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.

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 2018). 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 analyze the expected changes in energy use, CO₂ 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. 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 low-income communities. Identifying and analyzing all co-benefits when developing industrial electrification programs, plans, and policies can help to increase uptake.

This report is comprised of a bottom-up industrial subsector, systems, and technology-level technical assessment of the technologies available and the potential for electrification in fourteen industrial subsectors in 6 states in the U.S.

The report also considers the implications of industrial electrification on future electricity generation, transmission, and distribution in chapter 4. As numerous sectors, including transportation and buildings in addition to industry, move to electrify to gain access to renewable resources, additional strain will be placed on the aging electricity grid infrastructure. These grid impacts must be considered and addressed to ensure a smooth transition to electrification and realize emissions reductions.

Finally, the report offers six recommendations that would have the most impact on increasing 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, community engagement, and workforce development.

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 (US 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 US DOE/EIA 2021 and US DOE 2019) (Figure 1).

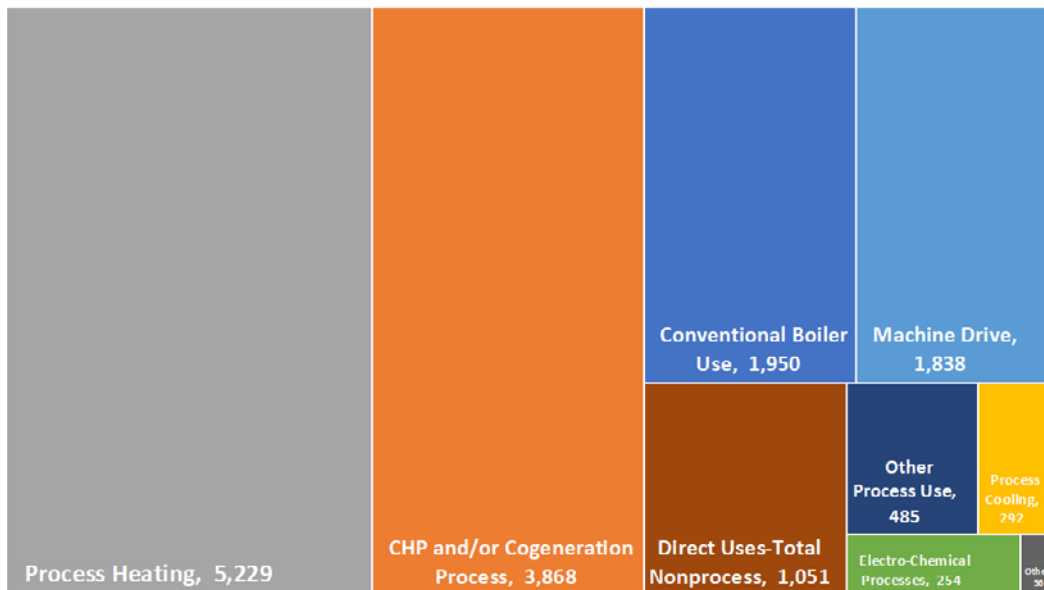


Figure 1. U.S. manufacturing energy use by end uses in 2018 - values in trillion Btu¹ (estimated from US DOE/EIA 2021 and US DOE 2019).

Note: Process heating, process cooling, machine drives, and other processes use steam. We only report the energy use for steam under the 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 (US DOE/EIA 2021).

The level of industrialization varies across states. Some states, such as Texas, Louisiana, California, Illinois, Ohio, and Pennsylvania, have a large industrial sector and are among the highest industrial energy-consuming states, while states such as Rhode Island, New Hampshire, Alaska, and Hawaii have small industrial sectors. Colorado has the highest industrial energy consumption among the southwest states and ranks 23rd in the U.S.

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.

¹ 1 trillion btu = 1,055 TJ

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 (McMillan 2019). In the food, beverage, and tobacco; transport equipment; machinery, and textile 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.

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).



3.0. Methodology

This chapter presents the results of our analysis of electrification potential in 14 industrial subsectors (Table 1) in six U.S. southwest states. This section describes the methodology for the analysis as well as scenario descriptions and key assumptions for our analysis of electrification potential in 14 industrial subsectors in six southwest states in the U.S.

Industries:

Table 1 shows U.S. industrial subsectors analyzed in this study. 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 to provide the heat for the process. Electrifying end-use processes has the advantage of increasing efficiency by removing steam distribution losses. It is important to note that there are other sectors with potential for electrification that have not been included in this study. For example, the cement and petroleum refining industries are important sectors in some of these six states, and are not included in this study since their electrification is particularly challenging due to several techno-economic barriers. Electrification technologies suitable for cement and petroleum refining industries are either in the early stages of development or not yet commercially available.

Table 1. Industrial subsectors analyzed in this study

No.	Industry subsector	No.	Industry subsector
1	Aluminum casting	8	Wet corn milling
2	Container Glass	9	Crude soybean oil
3	Ammonia	10	Steel reheating
4	Recycled plastic	11	Cheese production
5	Beer	12	Meat processing
6	Beet Sugar	13	Ethanol
7	Milk Powder	14	Hydrogen (Steam methane re-forming)

States:

This study focuses on six southwest states, including Arizona, Colorado, Nevada, New Mexico, Utah, and Wyoming.

Analysis:

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. 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, CO₂ emissions, energy cost, and electricity grid implications of electrification in each industry.

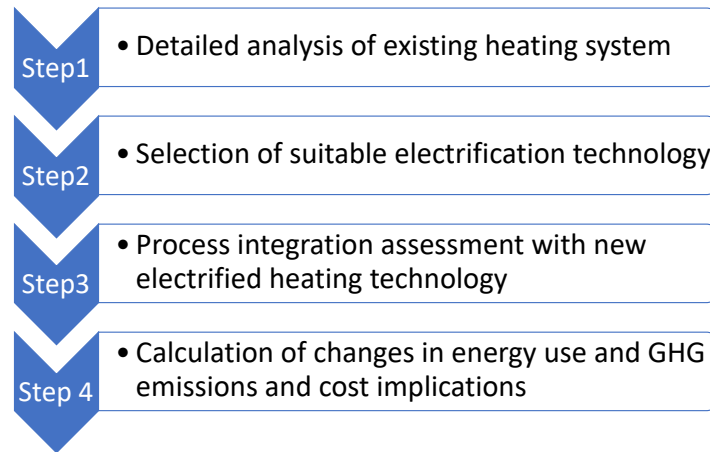


Figure 2. Methodology to estimate electrification potential in U.S. industrial subsectors

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.

To estimate the impact of electrification on energy savings and CO₂ emissions, obtaining the state-level production data for selected industries was needed. We utilized data provided by the National Renewable Energy Laboratory (NREL), which offers county-level industrial energy use based on the North American Industrial Classification System (NAICS) codes to estimate the production data based on the ratio of energy use at the state level and national level. By combining this information with other references, we were able to estimate state-level production amounts for each industry. In certain instances, we validated production data using additional available sources to ensure accuracy.

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.

CO₂ 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 a **state policy** scenario that aligns with the announced policy of each state. Figure 3 shows the electricity grid emissions factors in 2021 and 2030 in the states studied under the baseline scenario and state 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. We also developed a state policy scenario based on the announced policy of each state and their state policy for electricity grid decarbonization. For Wyoming and Nevada, which do not have a state policy for grid decarbonization, their state policy scenario is the same as the baseline policy scenario. The state grid emission factors (kg CO₂/MWh) are presented in Appendix 1. The CO₂ emissions reduction results in sections below show both scenarios.

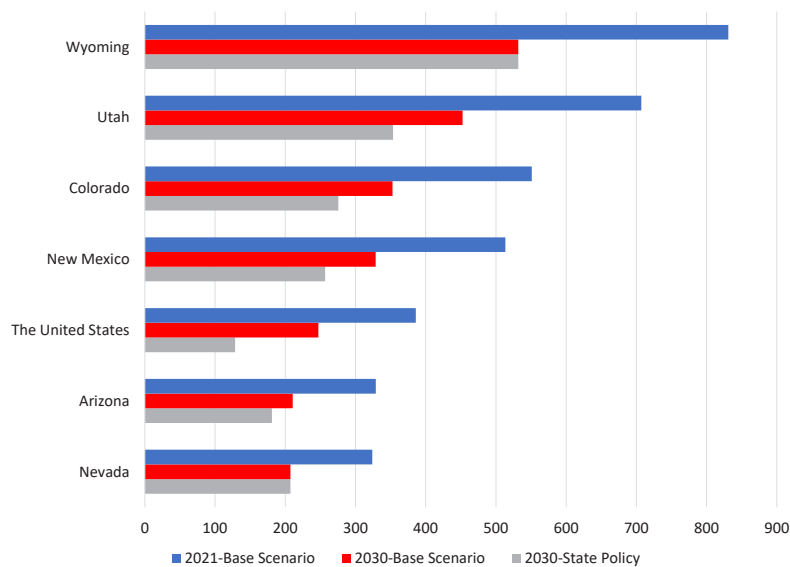


Figure 3. Electricity grid emissions factors in 2021 and 2030 (kgCO₂/MWh)

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 CO₂ 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:

In this study, energy costs analysis includes the electricity and natural gas costs and also an assumed price on carbon from 2030 to 2050, as discussed below. In our energy cost analysis, we assumed natural gas as the main fuel used in U.S. industries. 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 4-5 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 6 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.

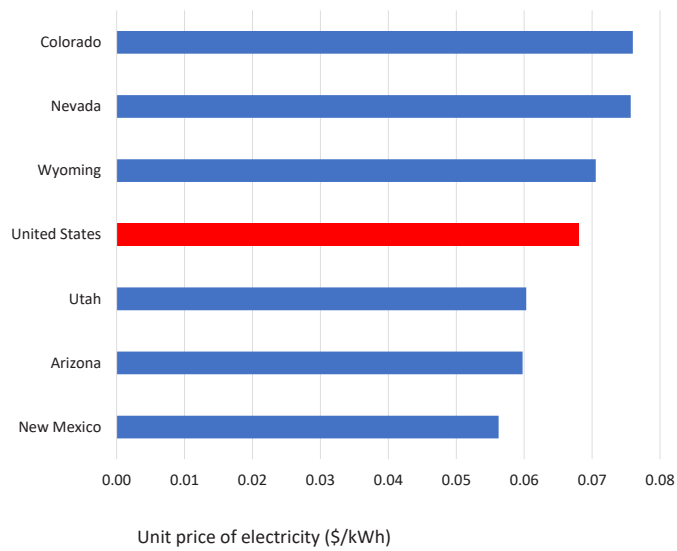


Figure 4. Industrial electricity unit price in 2021 (\$/kWh) (Adapted based on US DOE/EIA 2021)

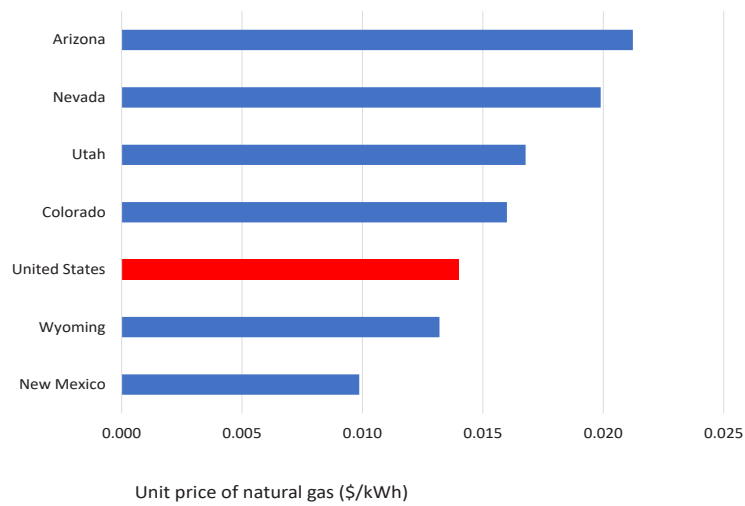


Figure 5. Industrial natural gas unit price in 2021 (\$/kWh)² (Adapted based on US DOE/EIA 2021)

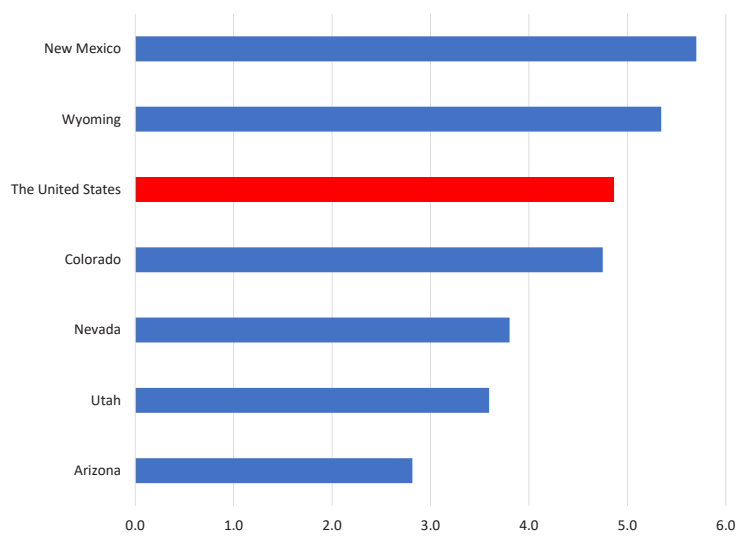


Figure 6. The ratio of the industrial unit price of electricity to natural gas in 2021

2 1 \$/kWh is equal to 277.8 \$/GJ or 293.1 \$/MBtu.

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 sensitivity option with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the EIA forecast. The result of this sensitivity analysis is shown as negative error bars on cost figures.

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 US DOE/EIA projections). To address this issue, we added a sensitivity analysis with a higher natural gas price forecast that assumes 50% higher natural gas prices compared with the EIA forecast. The result of this sensitivity analysis is shown as positive error bars on cost figures.

We have included a carbon price in our cost analysis. We assumed carbon price of \$30, \$60, and \$120 per tonne of CO₂ in 2030, 2040, and 2050, respectively. The carbon price was included in the energy cost analysis and graphs. The assumed carbon price increases the energy cost per unit of production (\$/ton product) of conventional technologies over time.

A thorough cost analysis that considers changes in capital costs, operation and maintenance costs, as well as non-energy benefits of electrified technologies could make these technologies more financially appealing. The challenges of estimating capital costs for all the analyzed technologies should be acknowledged. Generally, initial capital costs will contribute to the difficulties in electrifying these processes, unless replacing equipment at the end of their useful lifetime.

Electrified technologies in the industrial sector offer several advantages in terms of operation and maintenance costs, as well as non-energy benefits. The operational costs of electrified technologies are often lower due to their higher efficiency and reduced dependence on volatile fossil fuel prices. Maintenance costs can also be minimized as electrified systems typically have fewer moving parts, which results in less wear and tear, and require less frequent maintenance interventions.

Non-energy benefits of electrified technologies that industrial companies, government, and other stakeholders should consider when considering industrial electrification could include:

- Precise temperature control: Electrified heating systems can provide more accurate and stable temperature control, ensuring consistent product quality and reducing the risk of defects or waste.
- Faster heating and cooling: Electrified systems can heat and cool more quickly, allowing for shorter production cycles and higher throughput.
- Improved process control: Electrified technologies often come with advanced monitoring and control systems, enabling better process optimization and increased efficiency.

- **Enhanced safety:** Electrified systems can reduce the risk of explosions, fires, and other safety hazards associated with fossil fuel-based heating systems.
- **Reduced downtime:** Electrified technologies tend to have fewer moving parts, which can result in lower maintenance requirements and less downtime for repairs or servicing.
- **Improved energy efficiency:** Electrification can lead to more efficient energy use, reducing energy costs and waste, and potentially increasing productivity.
- **Environmental benefits:** By reducing criteria air pollutants emissions, electrified technologies can contribute to a cleaner production environment, which can have a positive impact on personnel's health.
- **Integration with digital technologies:** Electrified systems can be more easily integrated with digital technologies such as IoT, data analytics, and automation, driving further improvements in product quality and productivity.
- **Scalability and flexibility:** Electrified technologies can be more easily scaled up or down, allowing for more flexible production capabilities and quicker adaptation to changing market demands.
- **Reduced noise and vibration:** Electrified systems tend to produce less noise and vibration than their fossil fuel-based counterparts, which can lead to a better production environment.

3.1. Aluminum casting industry

Aluminum plays an important role in shaping modern industry. Typically, engineering design considerations include size, shape, complexity, and required dimensional accuracy. 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 cast (OEM Tech Brief, The U.S. Aluminum Casting Industry, 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 2 compares the energy intensity of the aluminum casting industry's conventional and electric processes.

Table 2. 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 7 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. Utah and Nevada are the states with the largest energy savings potentials from switching to electric aluminum casting processes.

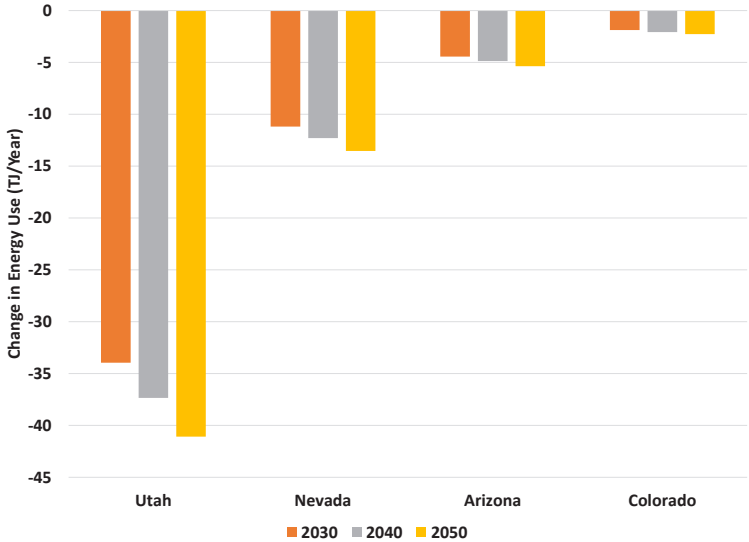


Figure 7. Change in the aluminum casting industry's total final energy use after electrification (technical potential assuming a 100% adoption rate)



CO₂ emissions

Electrification can help realize substantial annual CO₂ emissions reductions by 2050 in all states. This CO₂ emissions reduction results from the electricity grid's declining CO₂ emissions factor (grid decarbonization) in 2050 in all states.

Figure 8 shows the change in net CO₂ 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 CO₂ emissions in 2030 in 3 out of 4 states studied. In the remaining state (Utah), the relatively higher grid emissions factor in 2030 (Figure 3) causes a slight increase in CO₂ emissions in 2030.

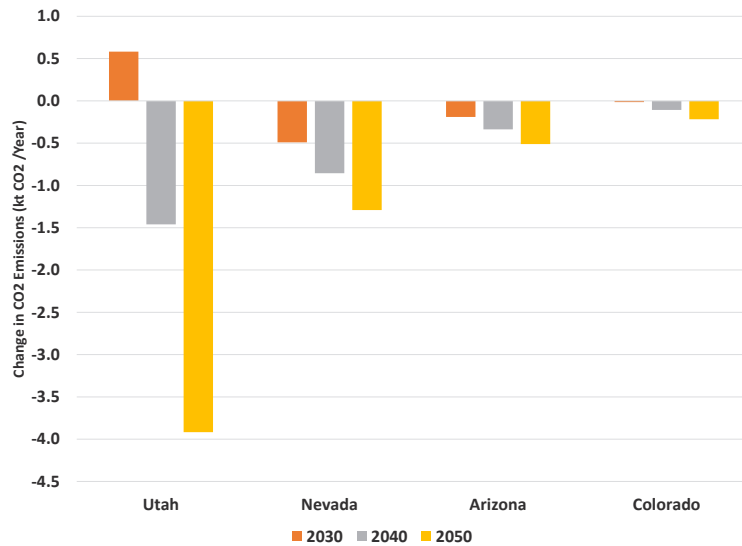


Figure 8. Change in the aluminum casting industry's net CO₂ emissions after electrification - baseline scenario (technical potential assuming a 100% adoption rate)

Figure 9 shows the aluminum casting industry's change in net CO₂ emissions in states after electrification under the state policy scenario. Under this scenario, the CO₂ emissions reduction potential in future years (2030, and 2040) is substantially higher than the baseline scenario because more rapid grid decarbonization is assumed under the state policy scenario.

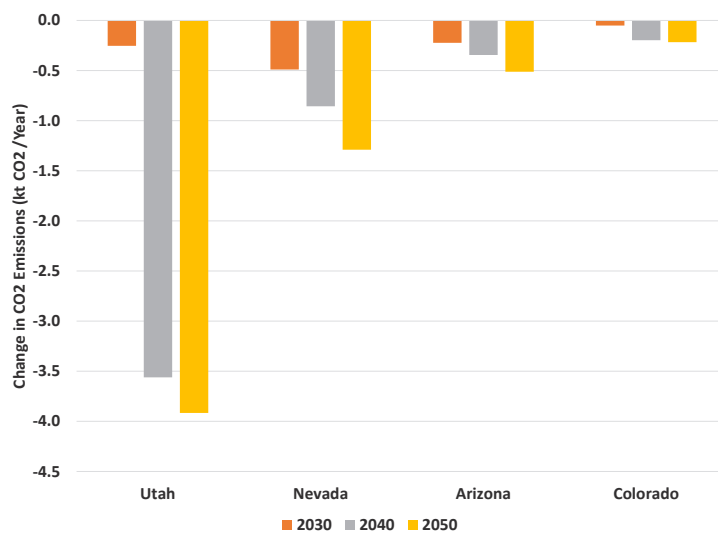


Figure 9. Change in the aluminum casting industry's net CO₂ emissions after electrification - state policy scenario (technical potential assuming a 100% adoption rate)

Figure 10 shows the cumulative change in CO₂ emissions in the aluminum casting industry over the lifetime of electrified technologies over the period of 2030 – 2050 for both baseline and state policy scenarios. Our calculation shows that Utah has the highest and Colorado has the lowest CO₂ emissions reduction during this period from electrification of the aluminum casting sector.

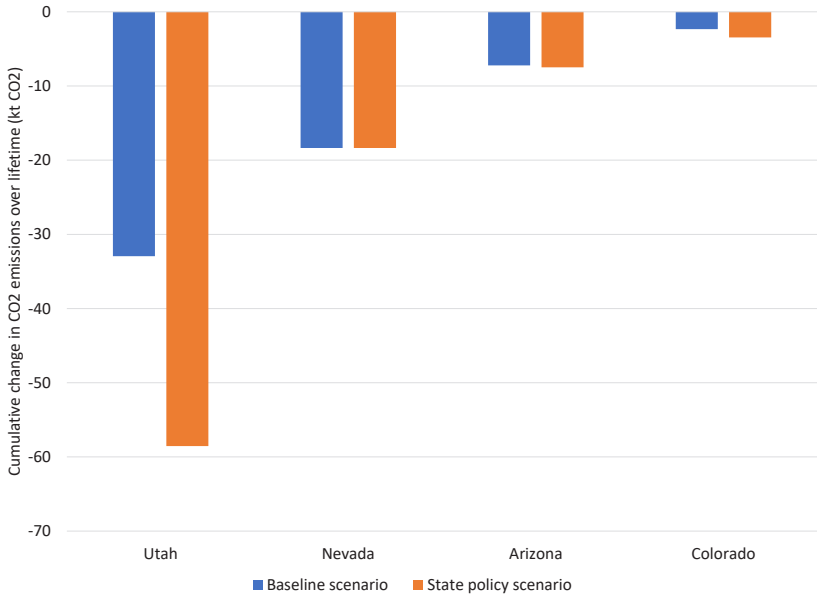


Figure 10. Cumulative change in CO₂ emissions in the aluminum casting industry over the lifetime of electrified technologies over the period of 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

Figure 11 shows that using 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 lower than that of the conventional process in Nevada, Utah, and Arizona and higher in Colorado.

It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified aluminum casting process. We have provided sensitivity options with a lower electricity price forecast that assumes 50% lower electricity prices compared with the EIA forecast (shown in negative error bars) and a higher natural gas price forecast that assumes 50% higher natural gas prices compared with the EIA forecast (shown in positive error bars).

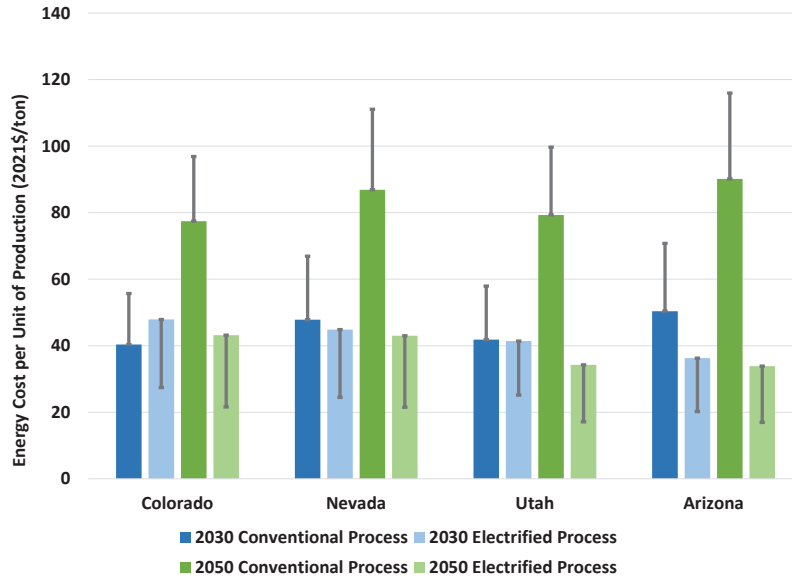


Figure 11. Energy cost per unit of production in the aluminum casting industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast. The positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.

3.2. 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 2020). The total glass production in the U.S. was around 20 Mt 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. Among the southwest states, only Colorado and Nevada have meaningful amount of container glass production.

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

Table 4. 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 forehearths
Gas-fired Annealing Lehr	25	210	Post Forming (Annealing)	183	Electric Annealing Lehr
	416	1465	Subtotal	1308	
	1881		Total Energy	1308	

Energy use

Only Colorado and Nevada have meaningful amounts of container glass production. Figure 12 shows energy savings from container glass production electrification in Colorado and Nevada in 2030-2050. The slight energy savings increase over time is because an increase in container glass production is assumed up to 2050. A substantial amount of energy saving potential can be achieved from electrification of heating in the container glass industry in Colorado.

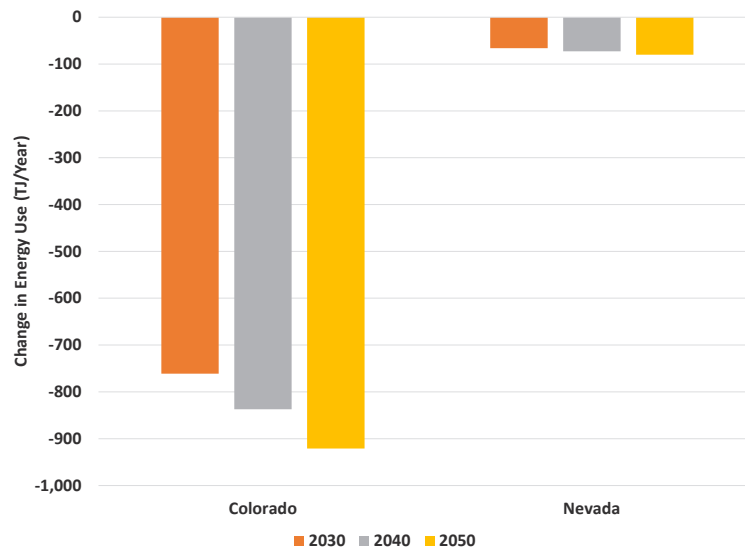


Figure 12. Change in the container glass industry's total final energy use after electrification (Technical potential assuming a 100% adoption rate)

CO₂ emissions

Figure 13 shows the container glass industry's change in net CO₂ emissions after electrification under the baseline scenario (See methodology section for definition of baseline and state policy scenarios). Electrification can result in a decrease in CO₂ emissions in 2030 in Nevada. Since Colorado has higher grid CO₂ emissions factor, electrification will result in an increase in emissions in 2030 if the grid electricity is used. As the grid decarbonizes in Colorado and Nevada, electrification can help realize substantial annual CO₂ emissions reductions by 2040 in both states as well.

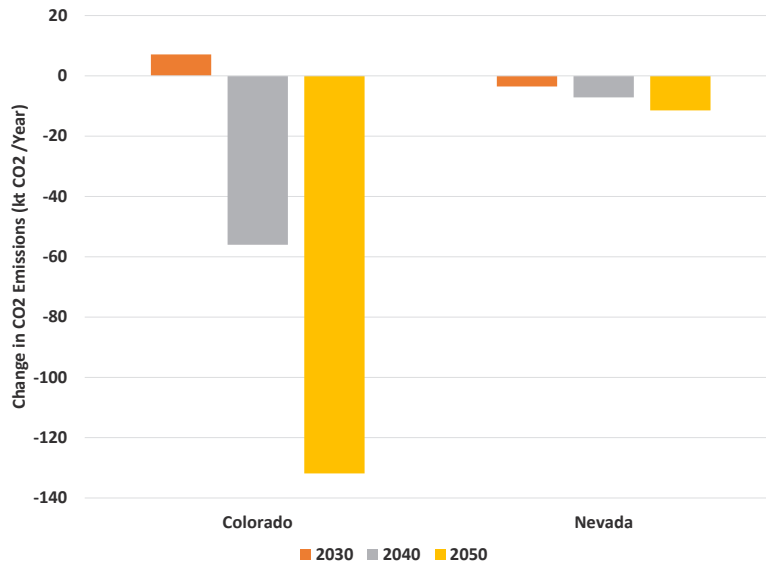


Figure 13. Change in the container glass industry's net CO₂ emissions after electrification - baseline scenario (technical potential assuming a 100% adoption rate)

Figure 14 shows the container glass industry's change in net CO₂ emissions after electrification under the state policy scenario. Under this scenario, the CO₂ emissions reduction potential in Colorado in years 2030 and 2040 is substantially higher than the baseline scenario because more rapid grid decarbonization is assumed under the state policy scenario.

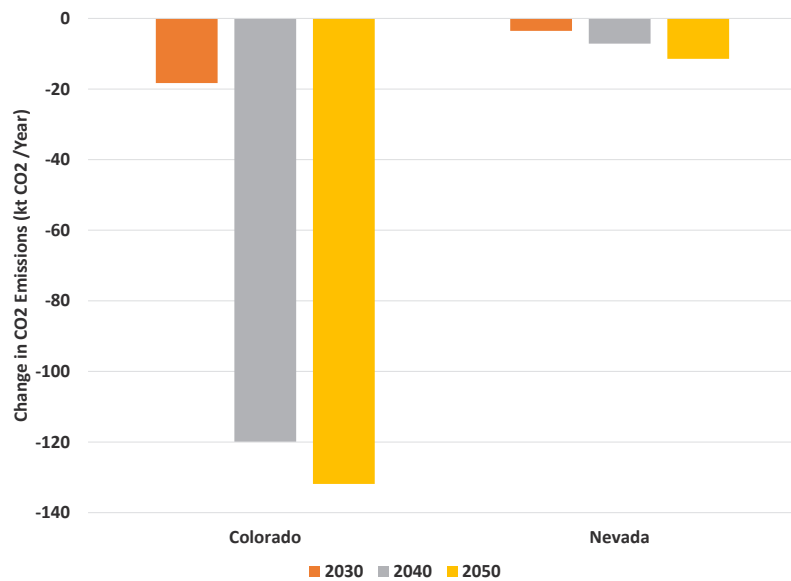


Figure 14. Change in the container glass industry's net CO₂ emissions after electrification - state policy scenario (technical potential assuming a 100% adoption rate)

Figure 15 shows the cumulative change in CO₂ emissions in the container glass industry over the lifetime of electrified technologies over the period of 2030 – 2050 for both baseline and state policy scenarios. The figure indicates that the adoption of electrification can lead to a significant decrease in CO₂ emissions - over 2,000 kilotons (kt) in Colorado and 154 kt in Nevada - during this twenty-year span under the projected state policy scenario.

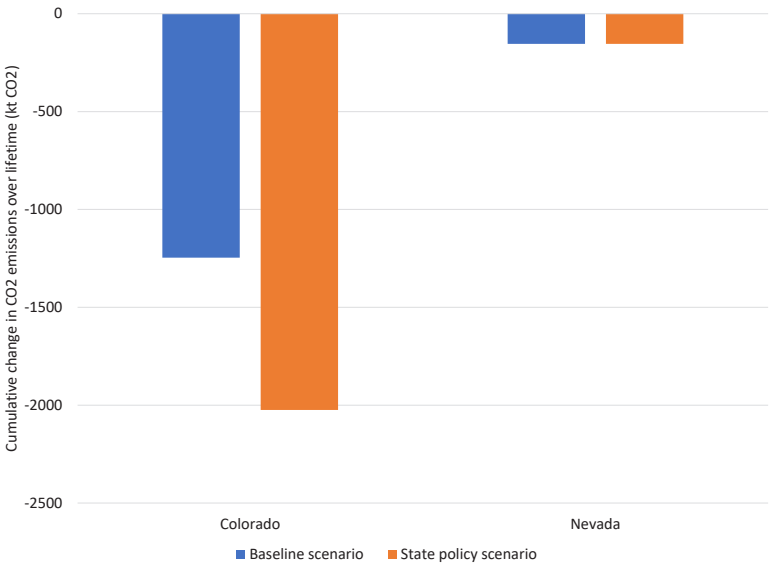


Figure 15. Cumulative change in CO₂ emissions in the glass industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

Figure 16 illustrates that when factoring in the EIA electricity price forecast, the per-unit energy cost for each tonne of glass produced in 2030 using electrified methods in the container glass industry is higher than that of conventional methods in both Colorado and Nevada. However, the availability of low-cost electricity can significantly decrease the energy costs associated with the electrified production process in the container glass industry. Upon examining these sensitivity cases, it is feasible that the energy price of the electrified process could compete favorably with that of the conventional process in both Colorado and Nevada by 2030.

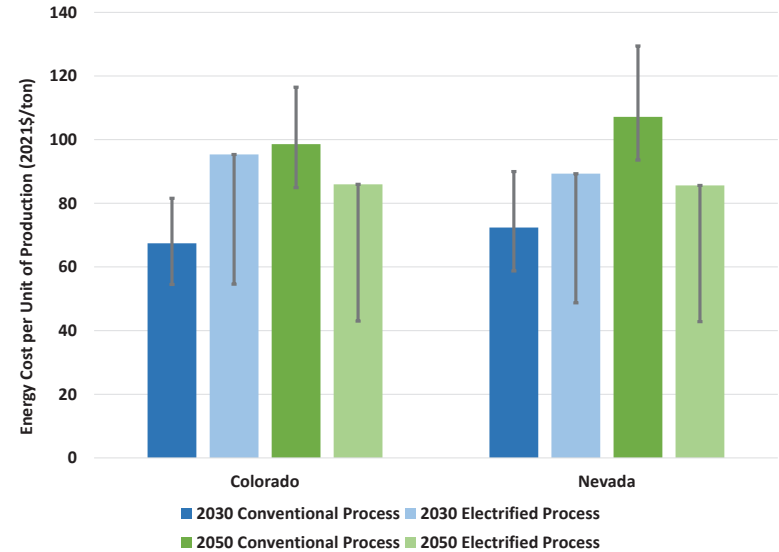


Figure 16. Energy cost per unit of production in the container glass industry
 Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast. The positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.

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).

3.3. 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 tons of ammonia across 34 facilities (Garside 2020). Around 88% of ammonia manufactured globally is utilized for fertilizer production and the remainder is used to support formaldehyde production (AIChE 2016). Among the southwest states, only Wyoming meaningful amount of ammonia production.

To make ammonia, hydrogen and Nitrogen are needed. The current process uses steam methane reforming (SMR) to get 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 5 compares the energy intensity of conventional and electric processes for the ammonia industry.

Table 5. Conventional and electric ammonia production processes’ energy intensities of (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 only in Wyoming among the six states studied. Electrification will significantly reduce the ammonia industry's total final energy use during the study period (Figure 17). The energy savings increase over time because an increase in ammonia production is assumed up to 2050.

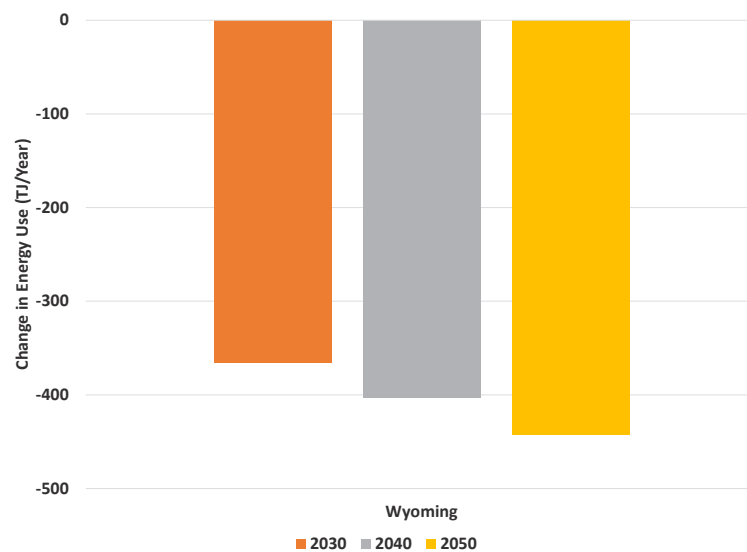


Figure 17. Change in the Wyoming ammonia industry's total final energy use after electrification (Technical potential assuming a 100% adoption rate)

CO₂ emissions

Ammonia production electrification via hydrogen production through electrolysis could initially cause an uptick in CO₂ emissions in 2030 and 2040 in Wyoming under both scenarios, as depicted in Figure 18. With the substantial decarbonization of the electricity grid by 2050, considerable annual reductions in CO₂ emissions are seen as a result of electrifying ammonia production in this state. Wyoming has the most carbon-intensive electricity grid among the six states studied (831 kg CO₂/MWh in 2021). That is why producing ammonia via electrolysis using grid electricity will not result in CO₂ emissions reduction until after 2040. However, it should be noted that in majority of cases around the world, renewable electricity (not carbon-intensive grid electricity) is proposed to be used to produce green hydrogen that is then used to produce ammonia.



Figure 18. Change in the ammonia industry's net CO₂ emissions after electrification in Wyoming (Technical potential assuming a 100% adoption rate)

Figure 19 depicts the total change in CO₂ emissions within Wyoming’s ammonia industry over the lifespan of electrified technologies during the period 2030 to 2050. Under both scenarios, electrification could lead to an increase in CO₂ emissions by approximately 1,607 kt over these two decades in Wyoming. This is because, in this analysis, carbon-intensive grid electricity is assumed to be used in the electrified process.

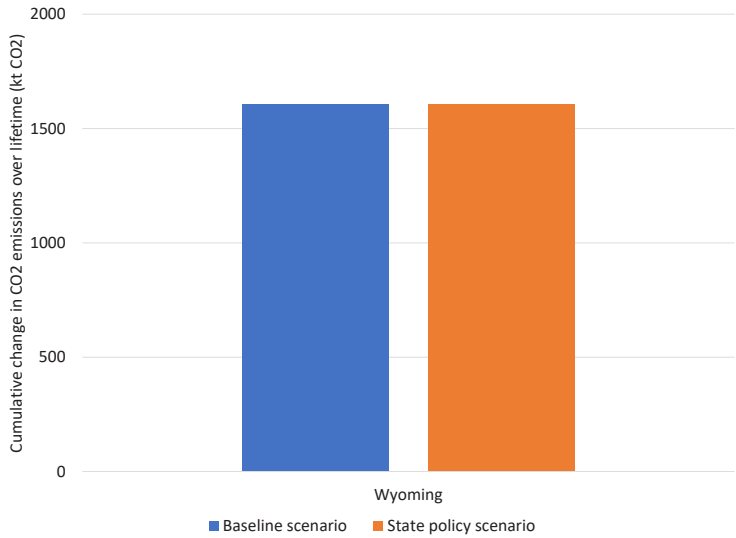


Figure 19. Cumulative change in CO₂ emissions in the ammonia industry in Wyoming over the lifetime of electrified technologies over the period of 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

Under the EIA electricity price forecast, the energy cost per unit of production (tonne of ammonia) in 2030, using electrified process in the ammonia industry, is over twice as much as the energy cost associated with the conventional process in Wyoming (Figure 20). However, assuming a future scenario with decreased electricity prices and increased natural gas prices, the energy cost for the electrified process has the potential to be economically competitive with the conventional process after 2030.

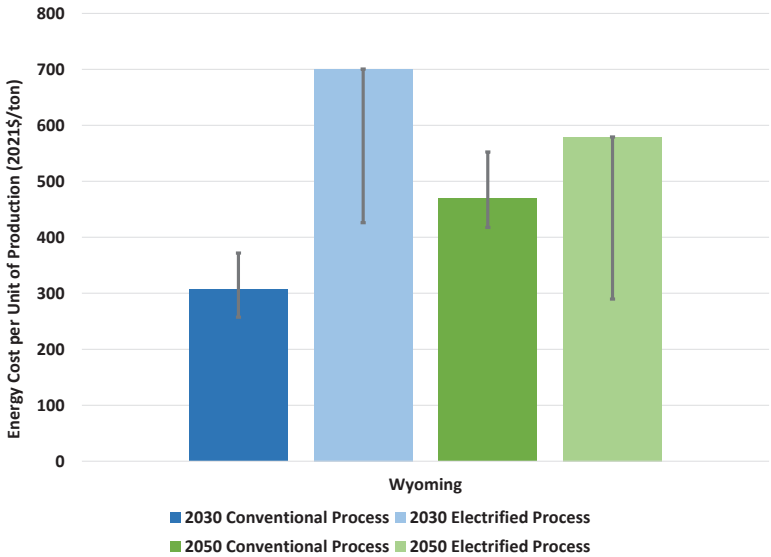


Figure 20. Energy cost per unit of production in the ammonia industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast. The positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.

3.4. Plastic recycling industry

Plastics are a rapidly rising proportion of municipal solid waste (MSW). A variety of plastics form this expanding MSW category in the U.S. The containers and packaging sector reported the highest contribution of plastic waste, approximating 14 million tonnes, in 2017. This category predominantly comprises items such as bags, packaging materials, polyethylene terephthalate (PET) bottles and jars, high-density polyethylene (HDPE) bottles, along with other types of containers (EPA 2017).

Plastic recycling aims to curb plastic pollution and reduce reliance on virgin materials for manufacturing plastic goods. In 2015, the U.S. recycled approximately 3.14 million tons of plastics, which constituted roughly 9% of the total plastic production within the U.S. that year (Leblanc 2019). Plastic recycling industries are prevalent in all southwestern states, with the exception of Wyoming.

This section evaluates the energy requirements of both traditional virgin resin production in petrochemical plants and the electrified plastic recycling process. It highlights the potential for energy and emission reductions offered by the electrified plastic recycling approach, noting that there are additional environmental advantages to plastic recycling. However, it is worth noting that while virgin resins, produced in petrochemical plants, find use across a broad spectrum of applications from low to high value, recycled plastics are typically constrained to lower-value applications. A more comprehensive explanation of traditional and electrified processes for plastic production can be found in our previous publication (Hasanbeigi et al. 2021). Tables 6 and 7 present a comparison of energy requirements for traditional and electrified approaches to plastic production.

Table 6. Original polymer production energy intensity (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 7. All-electric plastic recycling process energy intensity (Beyond Zero Emissions, 2018).

Process	Temperature (°C)	Electrical Demand (kWh/tonne)
Shredding	-	<0.5
Water cooling	10	70
Air compression	-	20
Melting	190	270
Extrusion/Molding	-	120
Lighting	-	60
Total energy		540

Energy use

Figure 21 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. Nevada and Arizona are the states with largest energy saving potential from switching to electrified plastic recycling production.

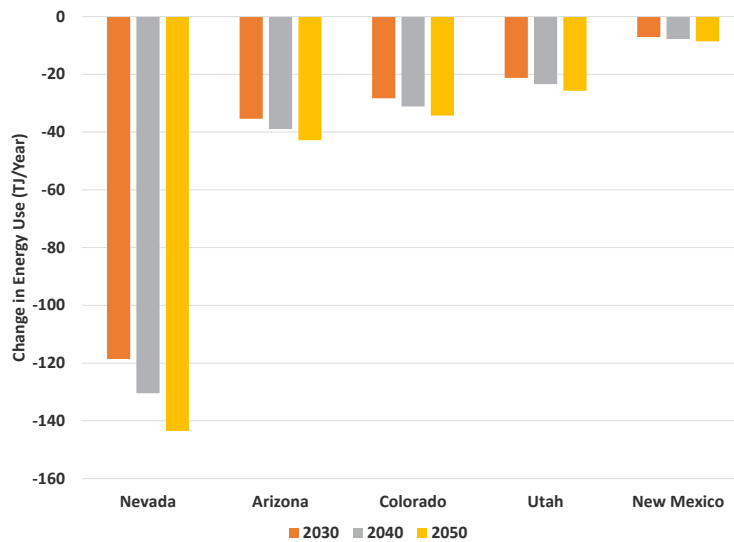


Figure 21. Change in the plastics industry’s energy use using electric plastic recycling processes (Technical potential assuming a 100% adoption rate)

CO₂ emissions

Figure 22 shows the plastic industry’s change in net CO₂ emissions after electrification under the baseline scenario. Because of the substantial energy savings from plastic production electrification (shown in Figure 23), electrification results in CO₂ emissions reductions in 2030 in all states studied. However, there is a decline in the CO₂ emissions reduction potential between 2030 and 2050 shown in Figures 24 and 25, resulting from a decline in the electricity grid’s CO₂ emissions factor in this period: as the grid decarbonizes, virgin resin production emissions intensity will reduce, thereby reducing the difference between the conventional virgin resin process and the electrified recycled plastic process.

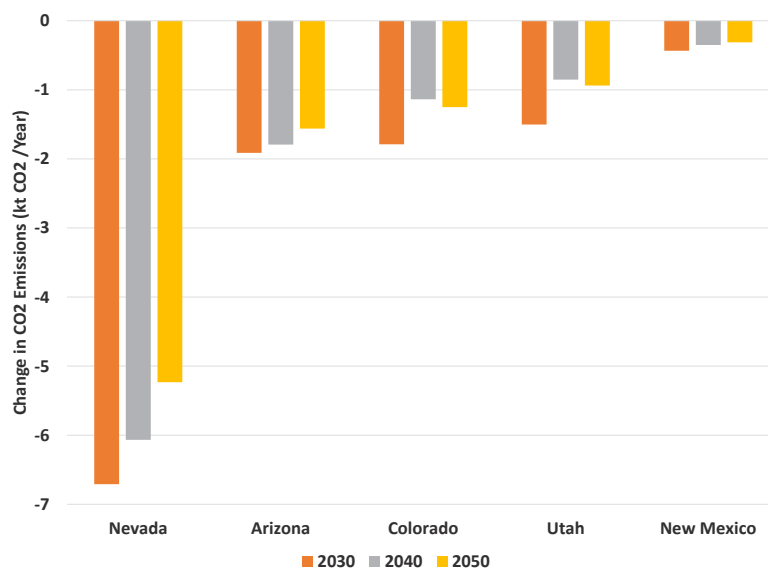


Figure 22. Change in the plastics industry’s net CO₂ emissions using an electrified plastic recycling process - baseline scenario (Technical potential assuming a 100% adoption rate)

Figure 23 shows the plastic industry’s change in net CO₂ emissions after electrification under the state policy scenario. Since the conventional process uses a considerable amount of electricity, under the state policy scenario the CO₂ emissions reduction potential is slightly lower than the baseline scenario.

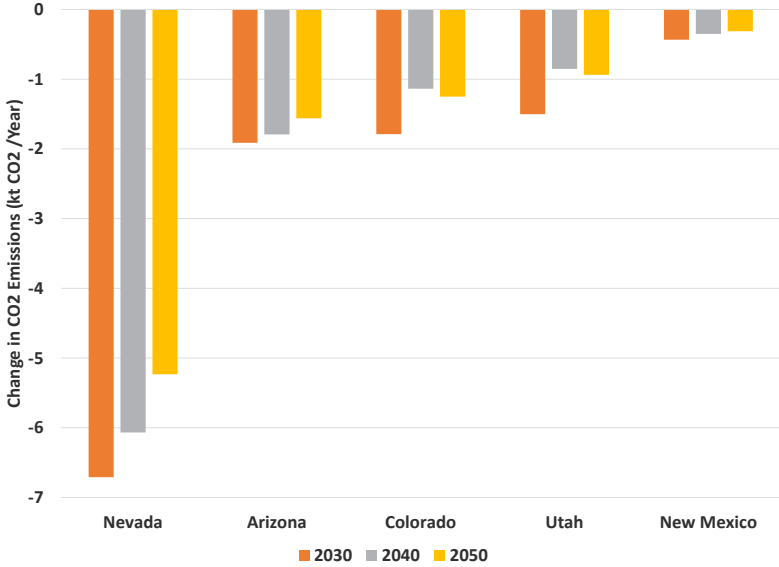


Figure 23. Change in the plastics industry’s net CO₂ emissions using electric plastic recycling process - state policy scenario (technical potential assuming a 100% adoption rate)

Figure 24 illustrates the impact of electrification on the total change in CO₂ emissions from 2030 to 2050, encompassing both baseline and state policy scenarios. This figure reveals that electrification could potentially reduce CO₂ emissions by around 38 kilotons over two decades in Arizona in the baseline scenario. Given the variations in production and grid emission factors, our calculations indicate that Nevada will have the most CO₂ savings, while New Mexico would have the least during this period. This parallels the findings presented in Figure 23. The conventional process consumes a substantial amount of electricity, yet the energy saved (both electrical and fuel) in the electrified recycling process surpasses 95%. Therefore, the potential for CO₂ emissions reduction under the state policy scenario is slightly lower than that of the baseline scenario.

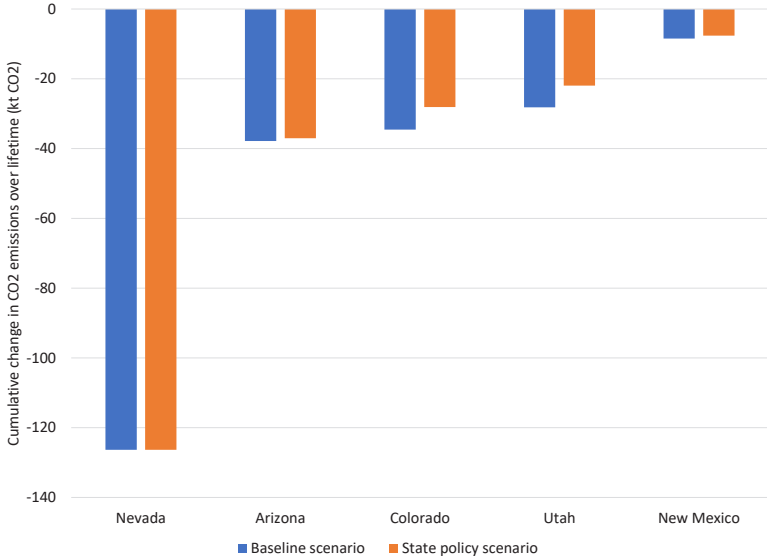


Figure 24. Cumulative change in CO₂ emissions in the plastic recycling industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

Figure 25 shows that the energy cost (in 2021\$) per unit of production (tonne of plastic) in 2030 and 2050 for the electrified plastic recycling process is significantly lower than that of the conventional process in all states. The main reason is that energy savings (for both electricity and fuel) in the electrified recycling process is more than 95%.

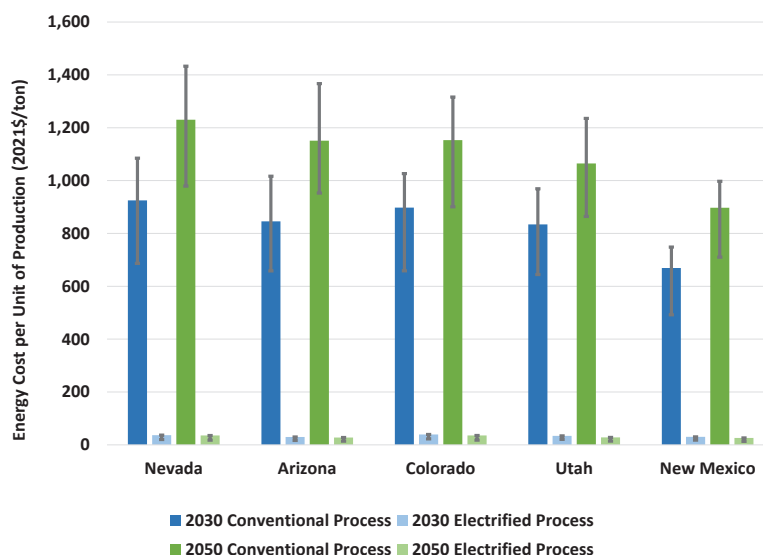


Figure 25. Energy cost per unit of production in the plastics recycling industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast and the positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.

3.5. Beer industry

In 2021, there were reported to be over 8,000 breweries in the U.S. (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 (US 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 grain varieties 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, described in Table 8 below. The coefficient of performance (COP)³ of these heat pumps is included in Table 8.

Table 8. 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

³ The coefficient of performance or COP of a heat pump is a ratio of useful heating provided to work (energy) required. Higher COP equates with higher efficiency, lower energy consumption and thus lower operating costs.

A detailed explanation of the beer industry’s conventional and electrified processes is provided in our previous report (Hasanbeigi et al. 2021). Table 9 compares the energy intensity of beer production’s conventional and electric processes.

Table 9. 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 8.

Energy use

Beer production electrification will significantly reduce the total final energy use during the study period (Figure 26). The energy savings increase over time because an increase in production is assumed up to 2050. Colorado is the state with the largest energy savings potential from switching to electrified beer production processes.

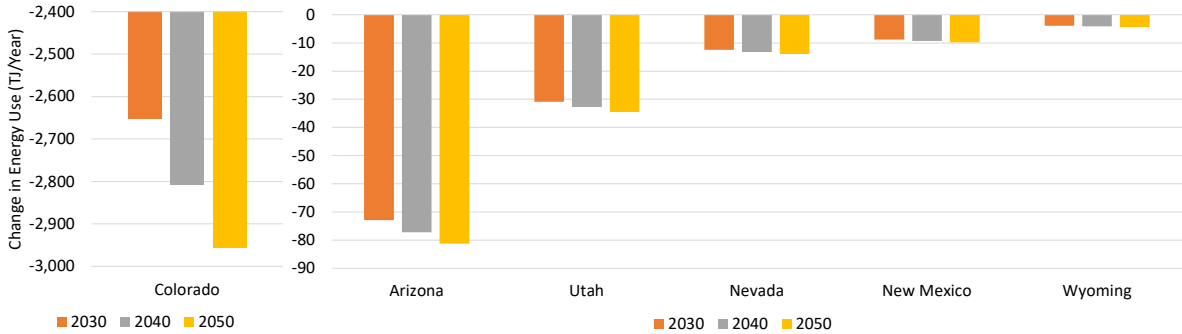


Figure 26. Change in the beer industry’s total final energy use after electrification (Technical potential assuming a 100% adoption rate)

CO₂ emissions

Figure 27 shows the beer industry’s change in net CO₂ emissions after electrification under the baseline scenario. Beer production electrification results 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.

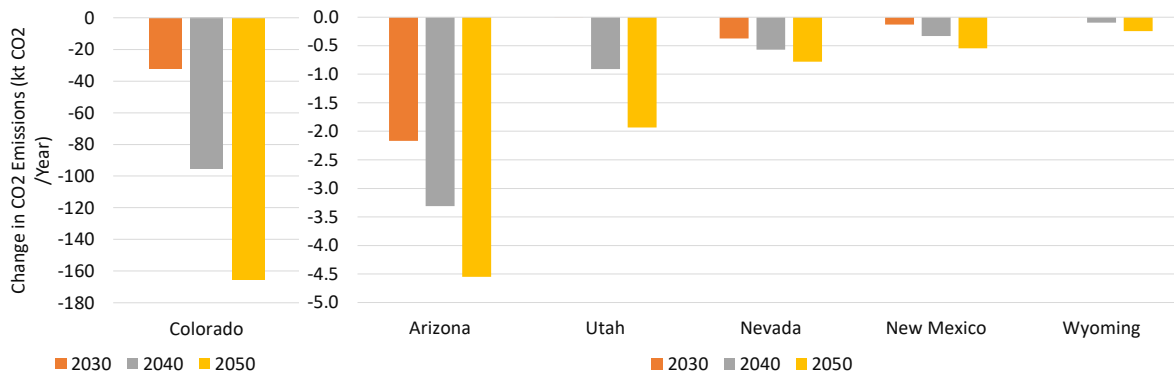


Figure 27. Change in the beer industry' net CO₂ emissions after electrification - baseline scenario (Technical potential assuming a 100% adoption rate)

Figure 28 shows that under the state 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.

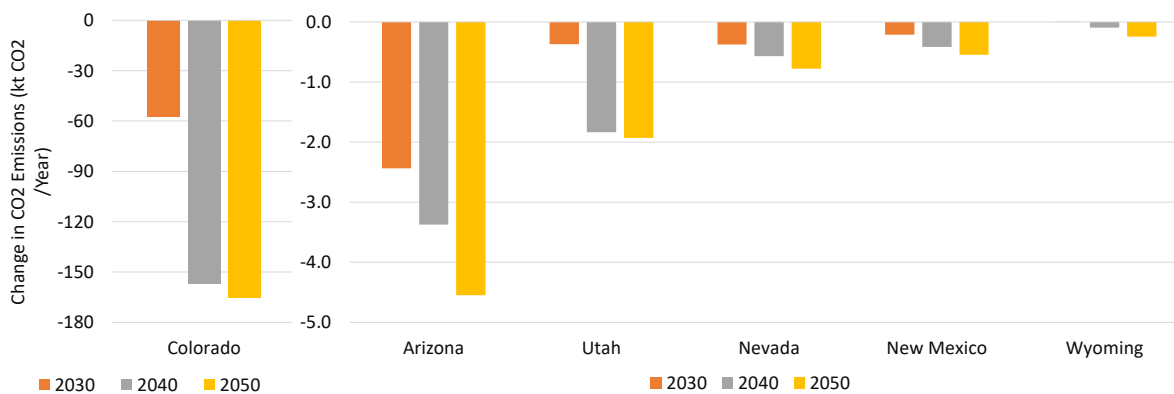


Figure 28. Change in the beer industry's net CO₂ emissions after electrification - state policy scenario (technical potential assuming a 100% adoption rate)

Figure 29 shows the effect of electrification on total CO₂ emissions change from 2030 to 2050 for both the baseline and state policy scenarios. As seen in this figure, electrification can reduce CO₂ emissions by between 2 and 72 kilotons during the study period across states, based on the state policy scenario, while Colorado has a very high emissions reduction potential at nearly 2800 kilotons. Due to their differences in production rate and grid emission factors, our calculation shows that Colorado has the most and Wyoming has the least CO₂ saving during this period.

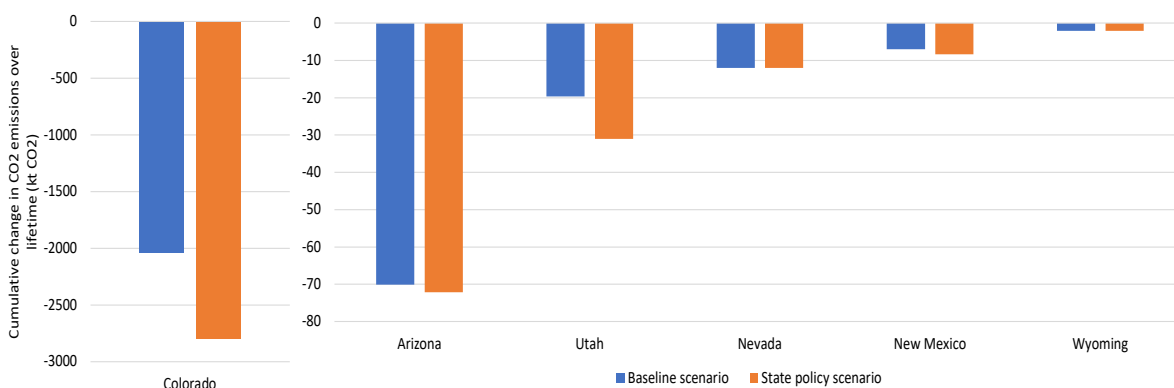


Figure 29. Cumulative change in CO₂ emissions in the beer industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

Figure 30 demonstrates that with the Energy Information Administration's (EIA) electricity price forecast, the energy cost (measured in 2021 dollars) per unit of beer production (hectoliter) in 2030 is lower for the electrified process compared to the conventional method in all surveyed states, with Wyoming as the sole exception. Access to low-cost electricity has the potential to significantly lower the energy expenses involved in the electrified beer production process. We incorporated sensitivity options that presume a 50% reduction in electricity costs relative to the EIA forecast, as represented by the negative error bars indicating a lower renewable energy (RE) price forecast. The positive error bars reflect a higher natural gas price forecast, which assumes a 50% increase in natural gas prices compared to the EIA forecast. Considering these assumptions, the energy cost of the electrified process could rival the conventional method in terms of cost-effectiveness, even in Wyoming, by 2030.

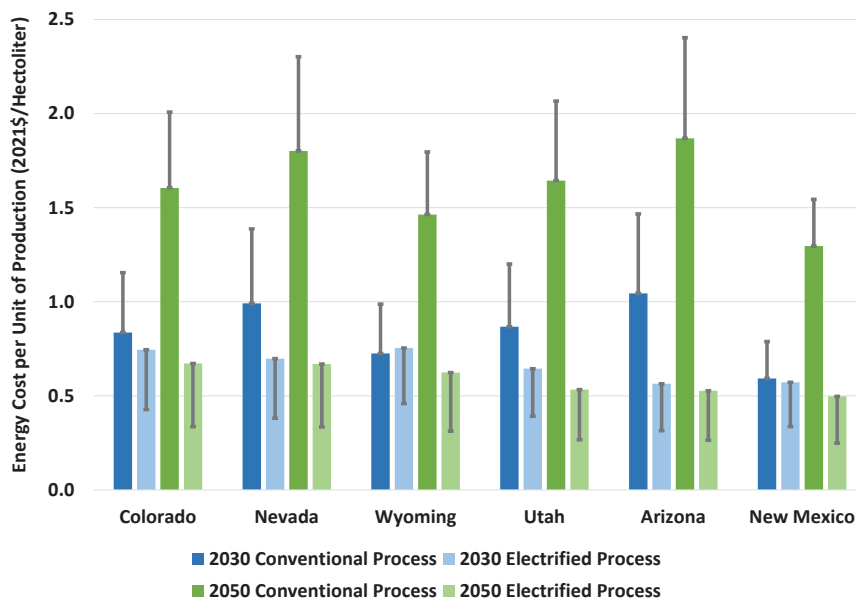


Figure 30. Energy cost per unit of production in the beer production industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast and the positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.



3.6. Beet sugar industry

Granulated white sugar, one of the most commonly used sweeteners, is derived from sugar cane and sugar beet plants, with the latter’s production being concentrated in Colorado and Wyoming among the southwest states. Despite the similar sugar content in beet and cane juices, differences in impurity levels (2.5% for beet juice and 5% for cane juice) necessitate distinct refining processes for each (Campos 2020). Meanwhile, bagasse, a by-product of sugar cane production, fuels cogeneration systems that produce heat and electricity for the sugar production process, sometimes generating surplus electricity for sale (Ensinas 2006). Since sugar from beet plants does not produce bagasse for fuel cogeneration, this study prioritized studying electrification of beet sugar production, given its high energy consumption within the food and beverage industry and high annual U.S. production (around 4.6 million tonnes) (U.S. DOE 2017b).

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

Table 10. Conventional and electric beet sugar 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
Conventional Steam Generator	153	778	Juice Diffusion	464	Heat Pump
Conventional Steam Generator			Juice Purification		Heat Pump
Conventional Steam Generator			Evaporation		Heat Pump
Conventional 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 that only two of the studied states, Colorado and Wyoming, have significant beet sugar production. Electrification will reduce the total final energy use for beet sugar production in Wyoming and Colorado (Figure 31). The energy savings increase over time is due to an assumed increase in beet sugar production up to 2050.

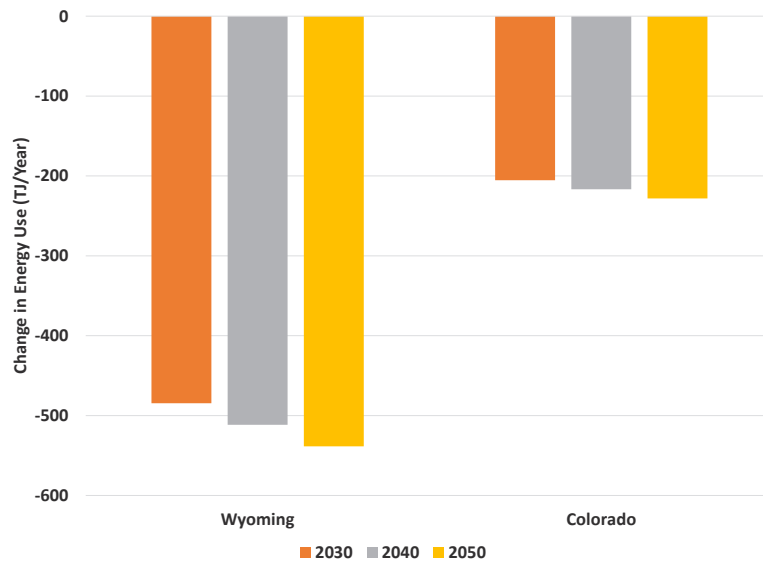


Figure 31. Change in the beet sugar industry's total final energy use after electrification (Technical potential assuming a 100% adoption rate)

Beet sugar production electrification could result in a near-term increase in CO₂ emissions in 2030 in Wyoming and Colorado (Figure 32), but as the electricity grid decarbonizes in these two states between 2030 and 2050, annual CO₂ emissions reductions from electrified beet sugar production will be realized in these states.

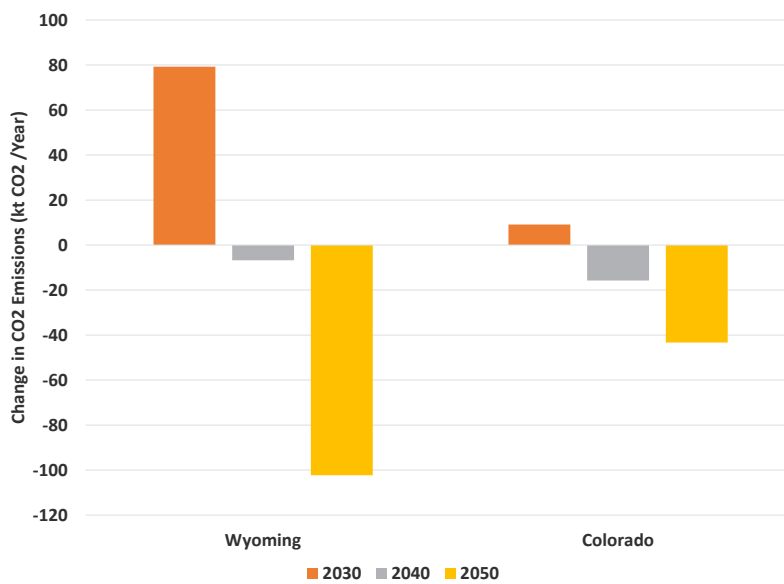


Figure 32. Change in the beet sugar industry's net CO₂ emissions after electrification - baseline scenario (technical potential assuming a 100% adoption rate)

If a zero-carbon grid is achieved earlier in Colorado according to the state policy scenario, the CO₂ emissions reduction potential in future years is higher (Figure 33) than the baseline scenario.

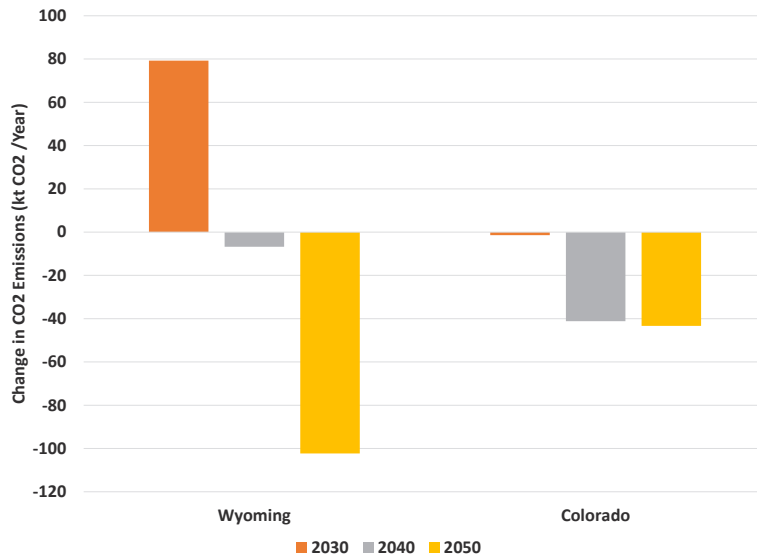


Figure 33. Change in the beet sugar industry’s net CO₂ emissions after electrification - state policy scenario (technical potential assuming a 100% adoption rate)

Figure 34 shows the effect of electrification on the total CO₂ emissions change from 2030 to 2050 for both the baseline and state policy scenarios. As seen in this figure, electrification can reduce CO₂ emissions by about 658 kilotons over the study period in Colorado based on the state policy scenario. Due to their differences in production levels and grid emission factors, our calculation shows different CO₂ savings during this period across Wyoming and Colorado.

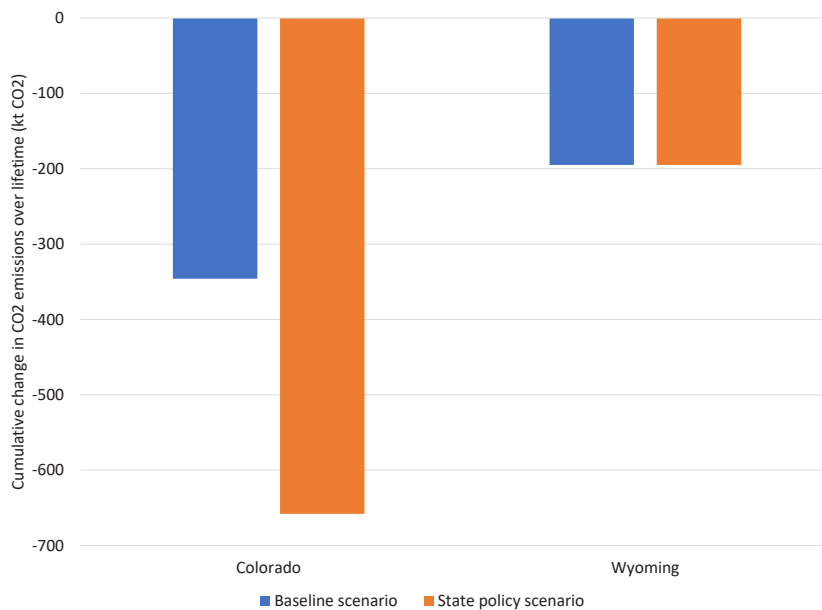


Figure 34. Cumulative change in CO₂ emissions in the beet sugar industry over the lifetime of electrification technologies, 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

Figure 35 shows that with the EIA electricity price forecast, the energy cost (in 2021\$) per unit of production (tonne of sugar) in 2030 for the electrified process in the beet sugar production industry is higher than that of the conventional process in Colorado and Wyoming.

It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified beet sugar process. We have provided sensitivity options with a lower renewable energy (RE) price forecast, which could make the energy price of the electrified process cost-competitive compared with the conventional process for both states even in 2030.

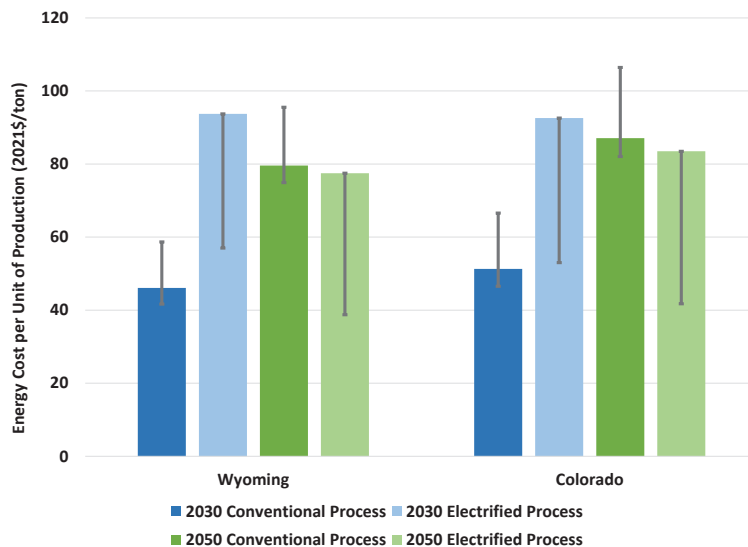


Figure 35. Energy cost per unit of production in the beet sugar industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast and the positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.

3.7. Milk powder industry

Dehydrating liquid milk using drying processes creates powdered milk or dried milk. Milk powder has a much longer shelf life 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 11 compares the energy intensity of the milk powder industry's conventional and electric processes.

Table 11. 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 Wyoming. Electrification can help to reduce the milk powder industry’s total final energy use (Figure 36). Arizona, Utah, and New Mexico are the states with largest energy savings potentials from switching to electrified milk powder production.

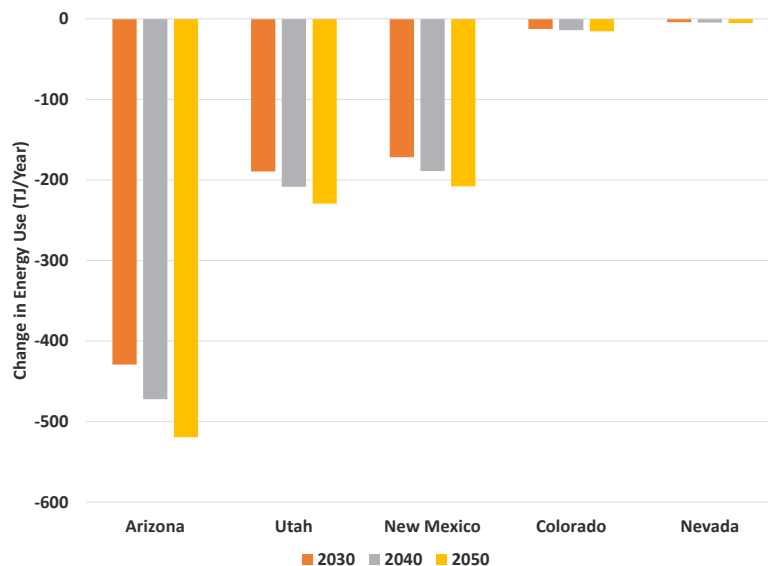


Figure 36. Change in the milk powder industry’s total final energy use after electrification (Technical potential assuming a 100% adoption rate)

CO₂ emissions

Milk powder process electrification can decrease CO₂ emissions in 2030 in all states studied that have milk powder production (Figure 37). Figure 38 shows the milk powder industry's change in net CO₂ emissions after electrification under our state policy scenario.

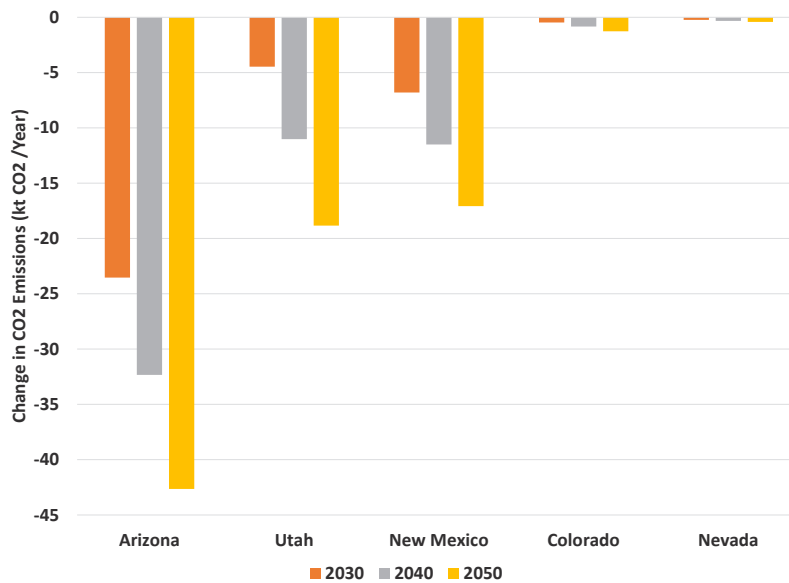


Figure 37. Change in the milk powder industry's net CO₂ emissions after electrification - baseline scenario (technical potential assuming a 100% adoption rate)

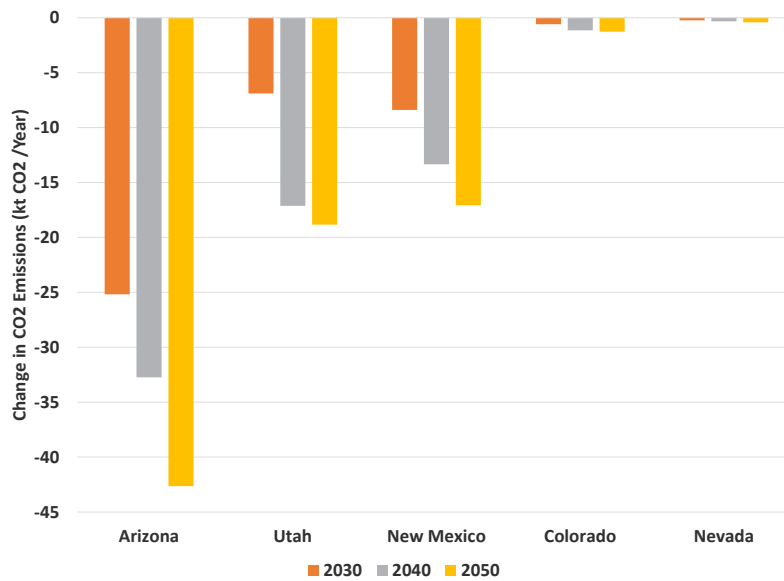


Figure 38. Change in the milk powder industry's net CO₂ emissions after electrification - state policy scenario (technical potential assuming a 100% adoption rate)

Figure 39 shows the effect of electrification on total CO₂ emissions change from 2030 to 2050 for both the baseline and state policy scenarios. As seen in this figure, electrification can reduce CO₂ emissions by a significant amount in New Mexico (273 kt), Utah (313 kt), and Arizona (700 kt) in the state policy scenario. Differences across state-level estimates are driven by variation in production rates and grid emission factors.

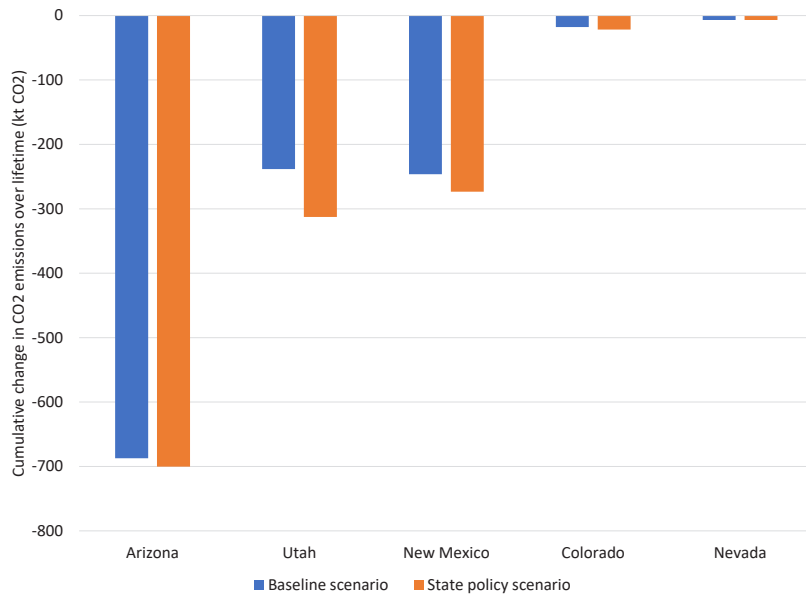


Figure 39. Cumulative change in CO₂ emissions in the milk powder industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

Figure 40 shows that with the EIA electricity price forecast, the energy cost (in 2021\$) per unit of production (tonne of milk powder) in 2030 for the electrified process in the milk powder production industry is lower than that of the conventional process in all studied states.

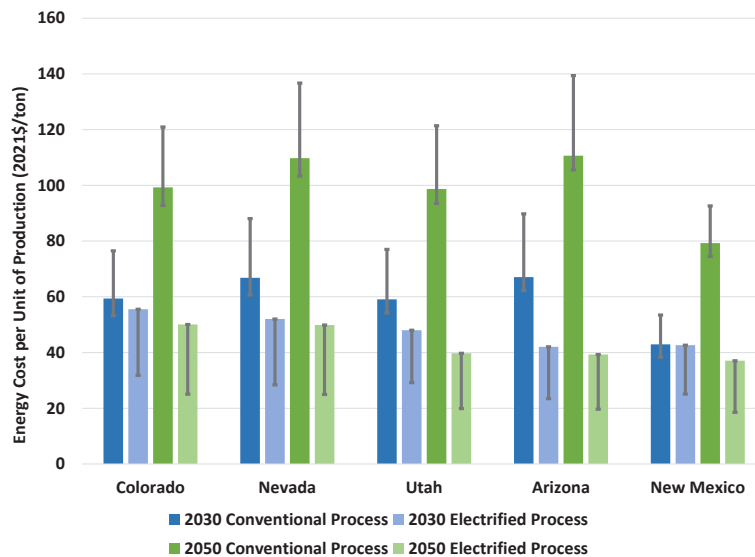


Figure 40. Energy cost per unit of production in the milk powder industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast and the positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.

3.8. Wet corn milling industry

Corn in the U.S. is commonly processed through two techniques: wet milling and dry milling. While ethanol is the main product of dry milling and a byproduct of wet milling, wet milling chiefly produces corn starch and edible corn oil, efficiently separating shelled corn and components for various uses (O'Brien and Woolverton 2009). This study concentrates on the wet corn milling process.

The U.S. has 25 corn refining plants and an additional four processing facilities. The corn refining industry contributed an estimated \$12 billion to manufacturing value added in 2018 (CRA 2019). In 2021, the U.S. wet corn milling industry's total output amounted to roughly 30 million tonnes, marking it one of the largest energy consumers within the food and beverage sector (US DOE 2017b, DOE/EIA, 2017). Of the southwest states, only Colorado and Utah have wet corn milling industries.

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



Table 12. 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 (1 st grind)	8	
	4	-	Germ recovery (2 nd 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

Figure 41 shows that for the two southwest states with wet corn milling, 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.

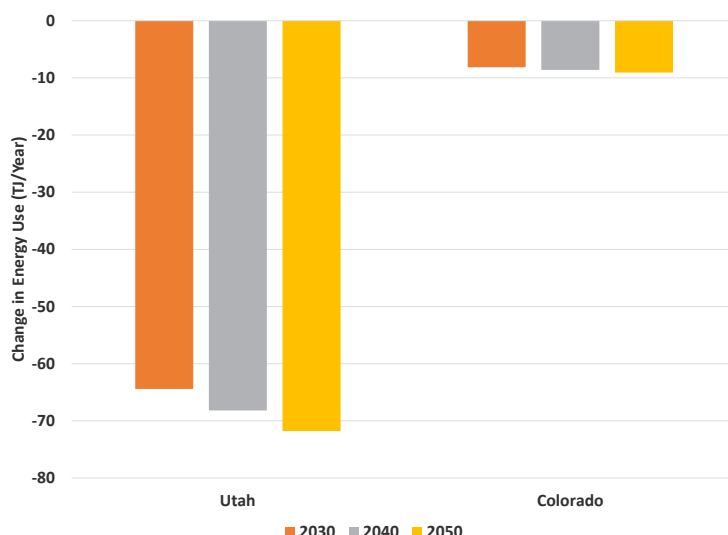


Figure 41. Change in the wet corn milling industry's total final energy use after electrification (technical potential assuming a 100% adoption rate)

CO₂ emissions

Figure 42 shows the wet corn milling industry's change in net CO₂ emissions after electrification under the baseline scenario. Wet corn milling electrification could result in an increase in CO₂ emissions in 2030 in Utah and Colorado. Electrification can help realize large annual CO₂ emissions reductions by 2050 in both states due to a decline in the electricity grid's CO₂ emissions factor between 2030 and 2050.

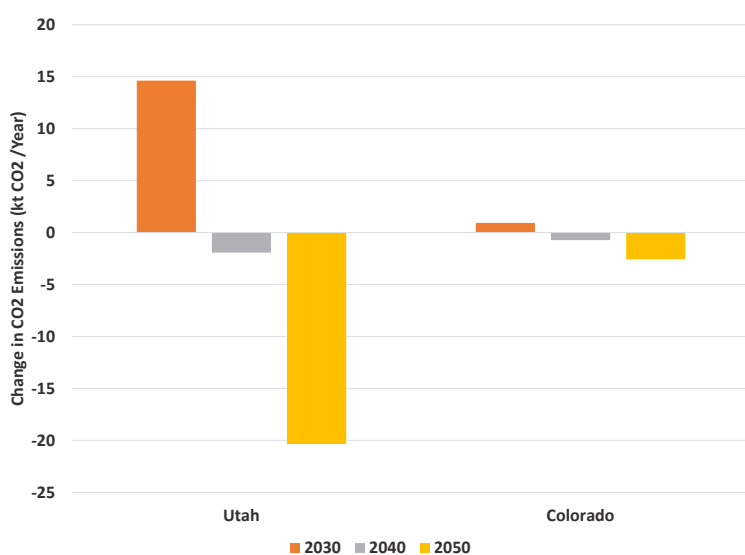


Figure 42. Change in the wet corn milling industry's net CO₂ emissions after electrification - baseline scenario (Technical potential assuming a 100% adoption rate)

Figure 43 shows the wet corn milling industry's change in net CO₂ emissions after electrification under the state policy scenario. The CO₂ emissions reductions potential in future years is substantially higher than the baseline scenario because more rapid grid decarbonization is assumed.

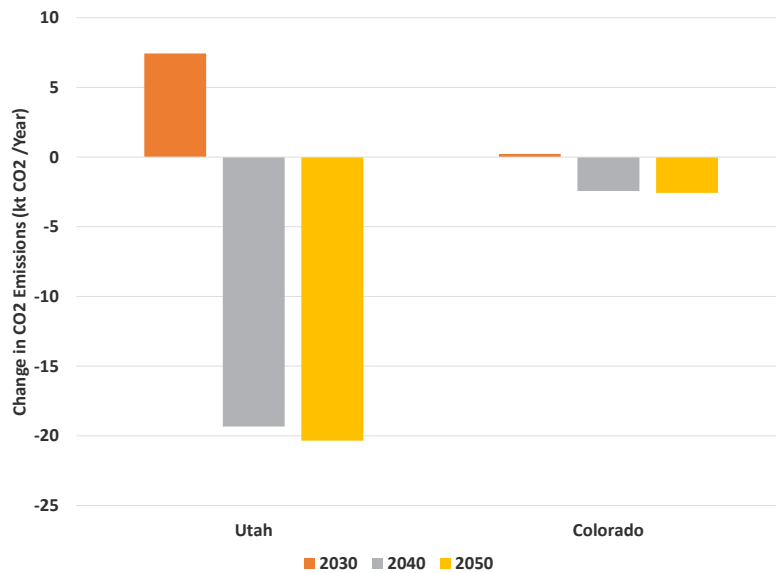


Figure 43. Change in the wet corn milling industry’s net CO₂ emissions after electrification - state policy scenario (technical potential assuming a 100% adoption rate)

Figure 44 shows the effect of electrification on total CO₂ emissions change from 2030 to 2050 for both the baseline and state policy scenarios. As seen in this figure, electrification can reduce CO₂ emissions by about 264 kilotons in Utah and about 37 kilotons in Colorado, based on the state policy scenario. Given the variations in production rates and grid emission factors across states, our calculations indicate different levels of CO₂ savings in Utah and Colorado during this period.

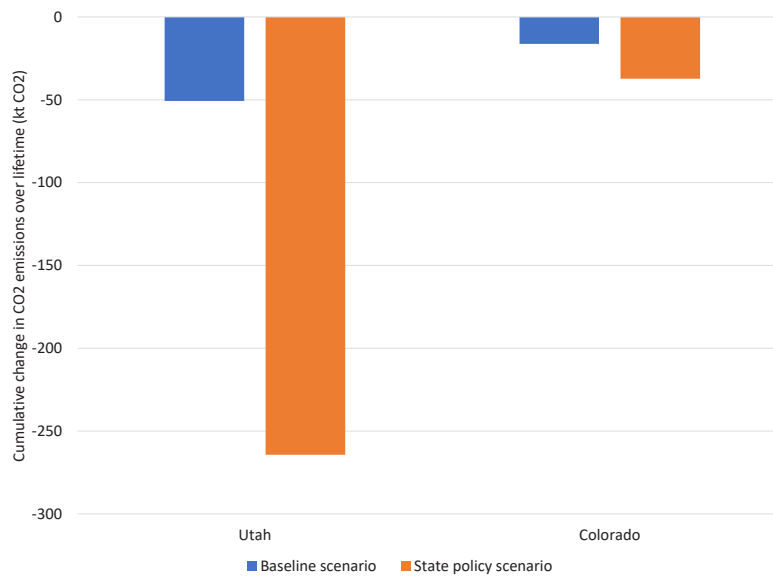


Figure 44. Cumulative change in CO₂ emissions in the wet corn milling industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

Figure 45 shows that with the EIA electricity price forecast, the energy cost (in 2021\$) per unit of production (tonne of wet corn) in 2030 for the electrified process in the wet corn milling industry is higher than that of the conventional process in Utah and Colorado. As with several other industries, it is clear that access to low-cost electricity can substantially reduce the

energy cost of the electrified wet corn milling process. The sensitivity analysis shown in Figure 45 indicates that the energy price of the electrified process could be cost-competitive compared with the conventional process in 2030 if electricity costs are lower than the EIA forecast.

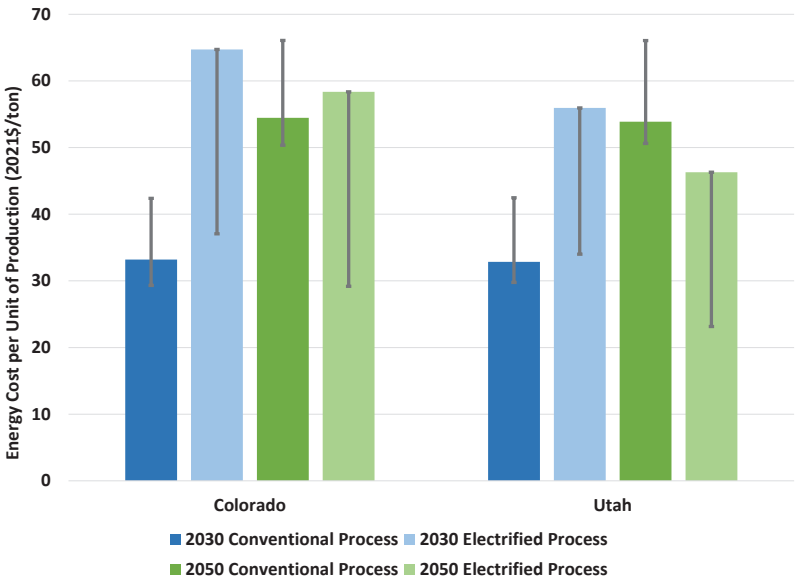


Figure 45. Energy cost per unit of production in the wet corn milling industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast and the positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.

3.9. Soybean oil industry

Extracted from soybean seeds, soybean oil is one of the most widely utilized natural oils worldwide, finding use in a multitude of applications such as nutritional supplements, cosmetics, food, and agriculture. The industry’s growth is fueled by the escalating demand for soybean meal in livestock feed, subsequently driving a significant surge in soybean oil production (EMR 2020). In 2019, the U.S. produced around 9.5 million tonnes of soybean oil (US DOE 2017b). It’s noteworthy that soybean oil production is one of the largest energy-consuming subsectors in the food and beverage industry (US DOE/EIA 2017). Within the southwest states, only Colorado and Utah host the soybean oil industry.

Our previous report provides a detailed explanation of the soybean oil industry’s conventional and electrified processes (Hasanbeigi et al. 2021). Table 13 compares the energy intensity of the soybean oil industry’s conventional and electric processes.

Table 13. 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 46 shows that electrification will reduce the soybean oil industry's total final energy use from 2030-2050. Colorado and Utah can both save a large amount of energy from switching to electrified soybean oil production processes.

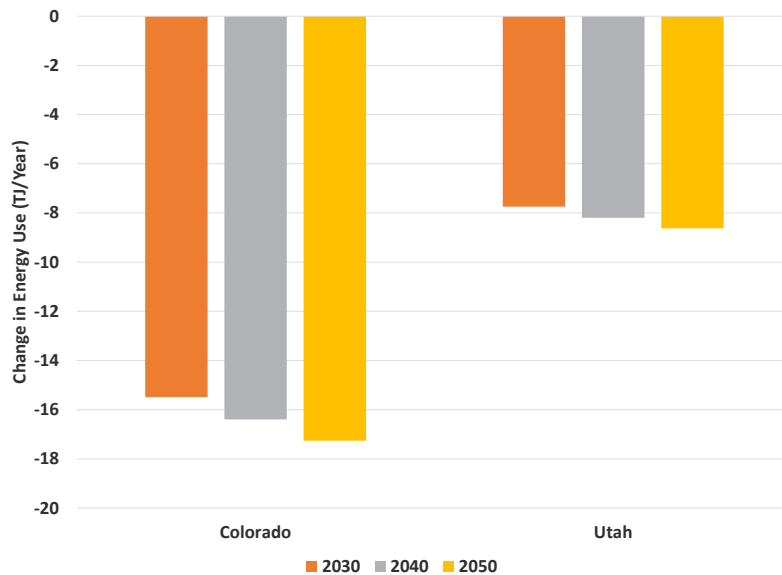


Figure 46. Change in the soybean oil industry's total final energy use after electrification (technical potential assuming a 100% adoption rate)

CO₂ emissions

Figure 47 shows the change in the soybean oil industry's net CO₂ emissions after electrification under the baseline scenario. Soybean oil production electrification could result in CO₂ emissions increases in 2030 in Utah because of its relatively higher grid emissions factor compared with that of another soybean oil producing state.

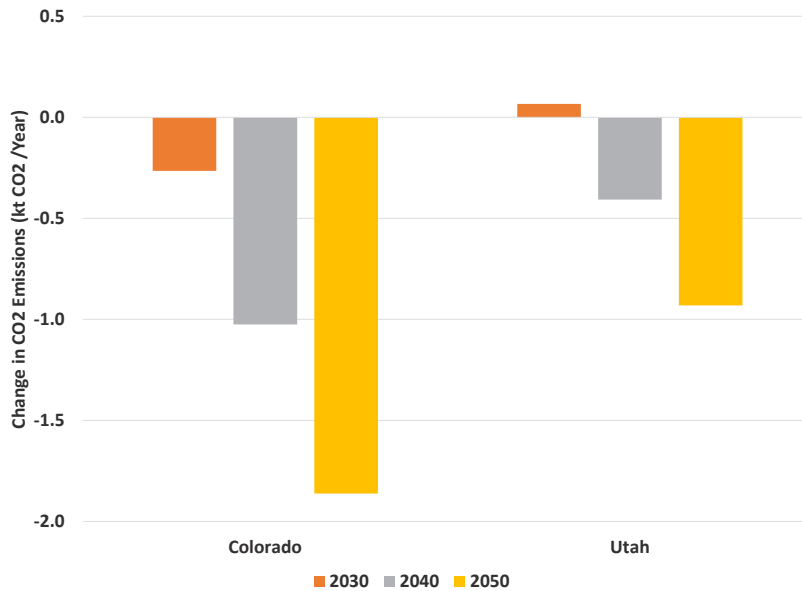


Figure 47. Change in the soybean oil industry's net CO₂ emissions after electrification - baseline scenario (technical potential assuming a 100% adoption rate)

Figure 48 shows the soybean oil industry's change in net CO₂ emissions after electrification under the state policy scenario. Under this scenario, the CO₂ emissions reductions potential in future years (2030, 2040, and 2050) is substantially higher than in the baseline scenario because more rapid grid decarbonization is assumed under the state policy scenario.

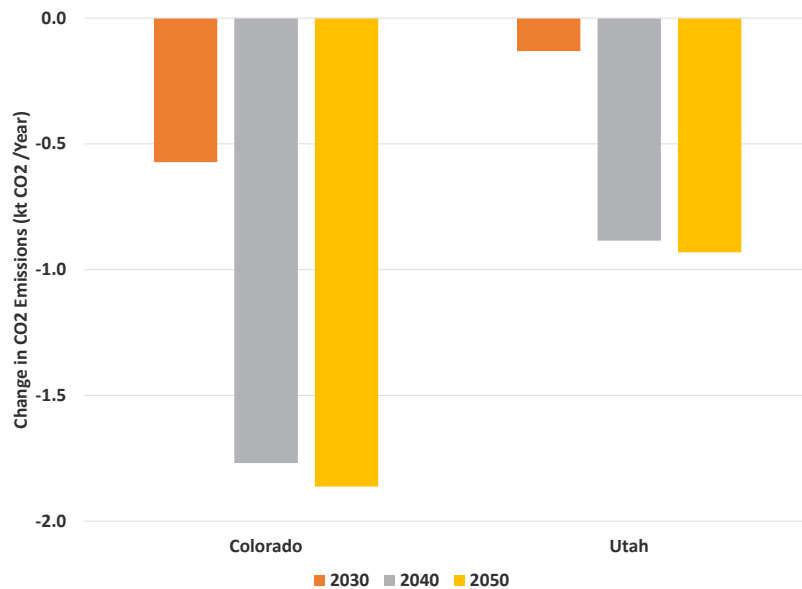


Figure 48. Change in the soybean oil industry's net CO₂ emissions after electrification - state policy scenario (technical potential assuming a 100% adoption rate)

Figure 49 shows the effect of electrification on total CO₂ emissions change from 2030 to 2050 under the baseline and state policy scenarios. As seen in this figure, electrification can reduce CO₂ emissions by about 31 kilotons during these twenty years in Colorado and 15 kilotons in Utah, based on the state policy scenario. Each state has different production levels and grid emission factors, which drive differences in the estimates.

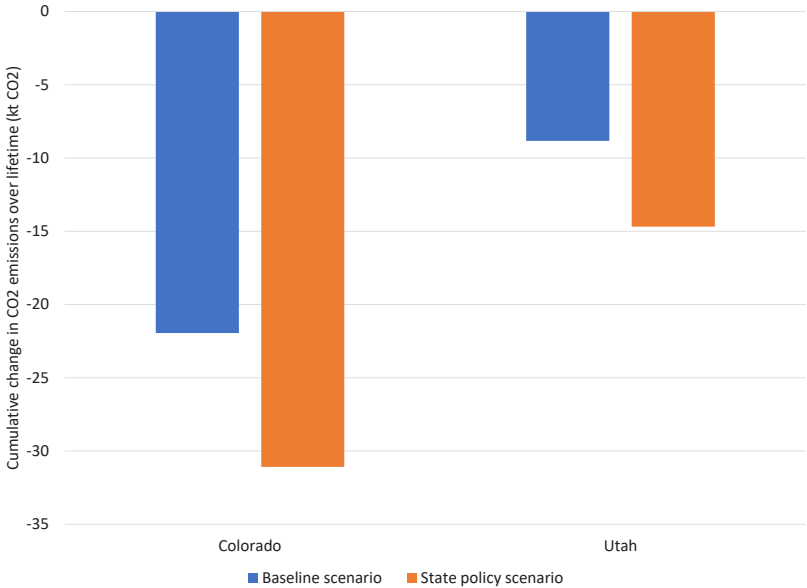


Figure 49. Cumulative change in CO₂ emissions in the soybean oil industry over the lifetime of electrified technologies over the period of 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

Based on the Energy Information Administration’s (EIA) electricity price forecast presented in Figure 50, the per-unit energy cost for the electrified soybean oil production process is anticipated to be higher than the conventional method in Colorado and Utah by 2030. However, with access to lower-cost electricity, the energy cost could significantly decrease. We’ve included sensitivity options reflecting a 50% decrease in electricity prices and a 50% increase in natural gas prices compared to EIA forecasts, as shown in the negative and positive error bars respectively. Given these factors, the electrified process may become cost-competitive with the conventional process in both states by 2030.

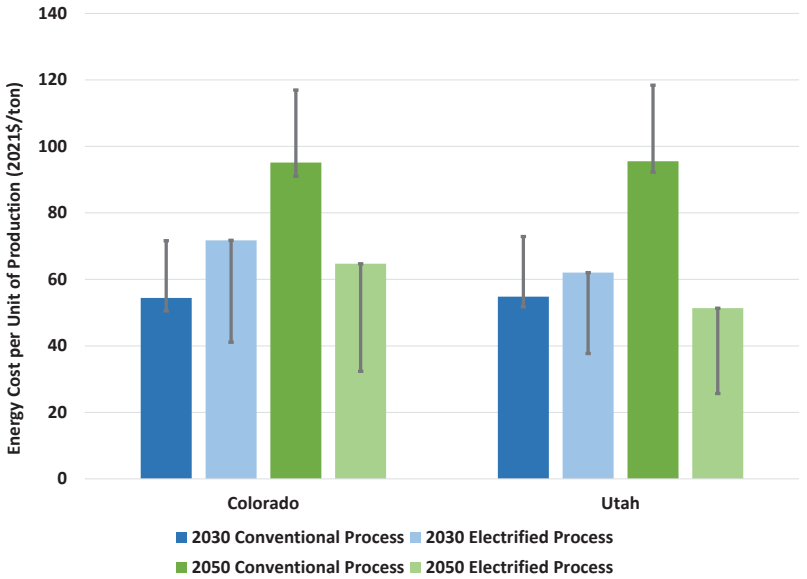


Figure 50. Energy cost per unit of production in the soybean oil industry
 Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast and the positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.

3.10. Meat production industry

The United States consumes more beef than any other country in the world. Total U.S. beef production was estimated at 27.17 billion pounds in 2022, a slight decrease from the previous year, maintaining a generally stable trend over the last two decades (Statista 2021). The meat-processing industry transforms raw meats—including beef, pork, and lamb—into various products like ham, sausage, and bacon through techniques such as curing, fermenting, smoking, or salting, thereby enhancing flavor and longevity. The industry’s key processes encompass slaughtering, meat cutting, safety inspection, packaging, further processing into items like sausages, distribution, and sales (E Ortega-Rivas, 2014).

Different process lines are used in meat processing, determined by the desired end products. Essential stages include blood processing, chilling/refrigeration, dressing and cutting, further processing such as curing and smoking, and packaging. Figure 51 shows the schematic of sausage production as an example.

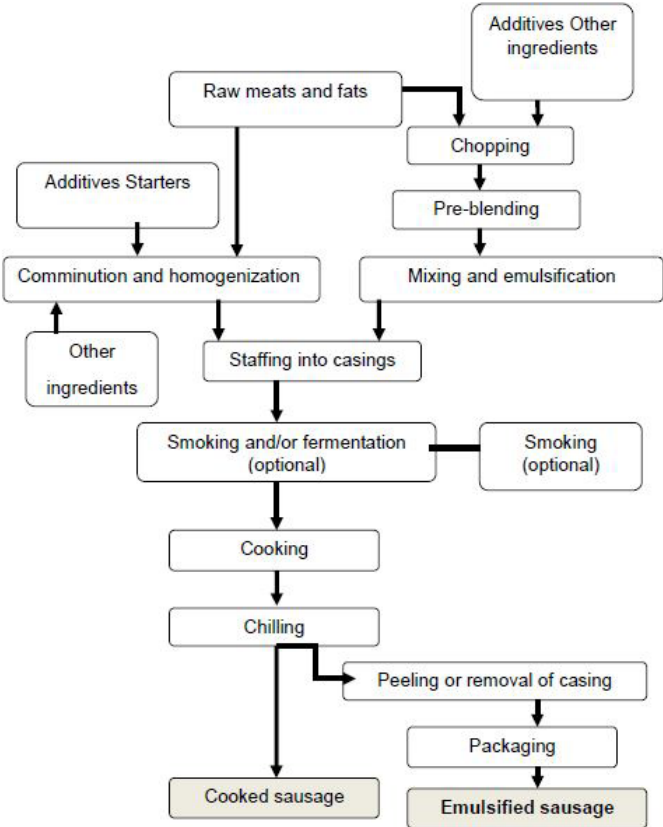


Figure 51. Cooked sausage production diagram (Mladenoska, 2017)

Conventionally, processes requiring heat, like curing and smoking, have employed steam-heated or direct-fired ovens. However, there is now a shift towards electric heating equipment that utilizes electric heat resistance, plasma technology, and other electrical methods. This transition brings about quicker heating, operational cost savings, increased efficiency, and a reduced environmental footprint (Zina T. Alkanan, Ammar Altemimi 2021). Energy consumption comparisons between conventional and electrified processes for red meat production are presented in Table 14.

Table 14. Energy intensities of conventional (Bandwidth 2017) and electric red meat production processes.

Conventional System Process		Process Steps	All Electric Process
Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)
52	-	Blood Processing	52
303	-	Chilling/Refrigeration	303
117	-	Dressing and cutting	117
-	207	Processing	185
60	-	Packaging	60
532	207	Subtotal	717
739		Total Energy	717

Energy use

Electrification can help to reduce the meat processing industry’s total final energy use (Figure 52). Utah and Arizona are the states with largest energy savings potentials from switching to electrified meat processing.

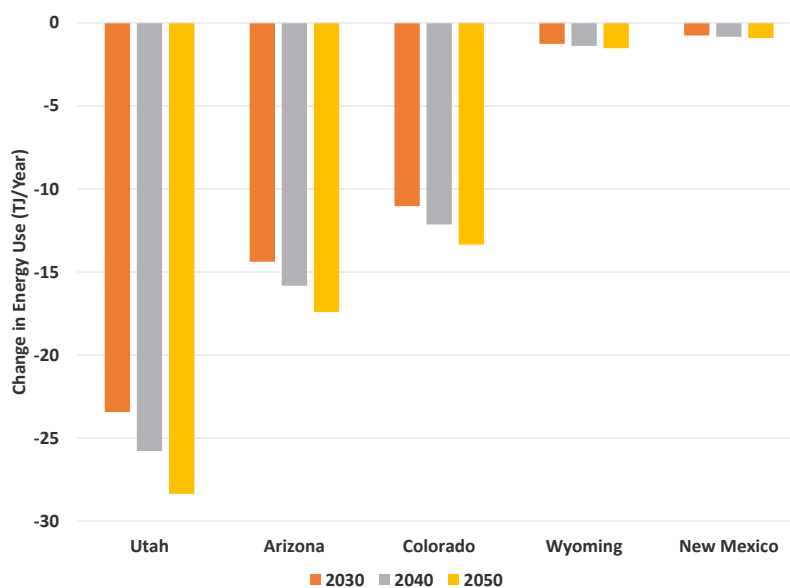


Figure 52. Change in the meat processing industry’s total final energy use after electrification (Technical potential assuming a 100% adoption rate)

CO₂ emissions

Meat process electrification can decrease CO₂ emissions in 2050 in all states under the baseline scenario (Figure 53). Figure 54 shows the meat processing industry’s change in net CO₂ emissions after electrification under our state policy scenario,

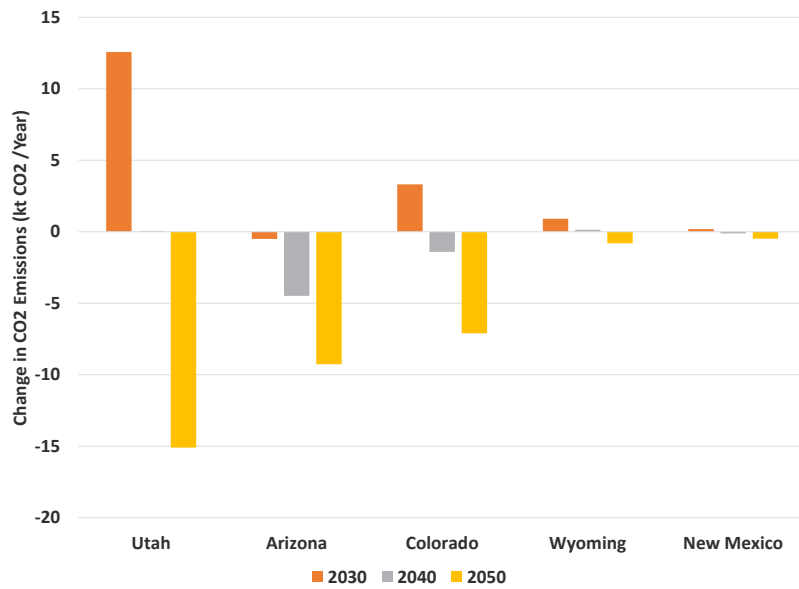


Figure 53. Change in the meat processing industry’s net CO₂ emissions after electrification - baseline scenario (technical potential assuming a 100% adoption rate)

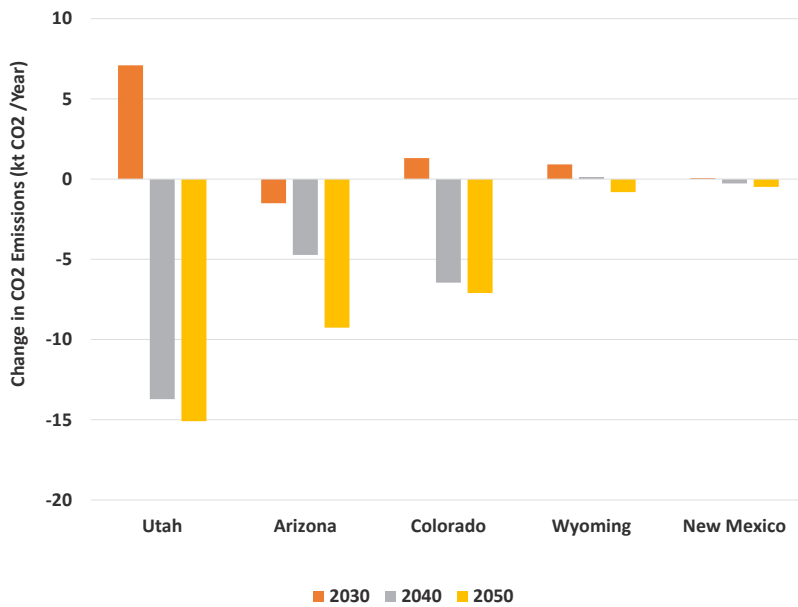


Figure 54. Change in the meat processing industry’s net CO₂ emissions after electrification - state policy scenario (technical potential assuming a 100% adoption rate)

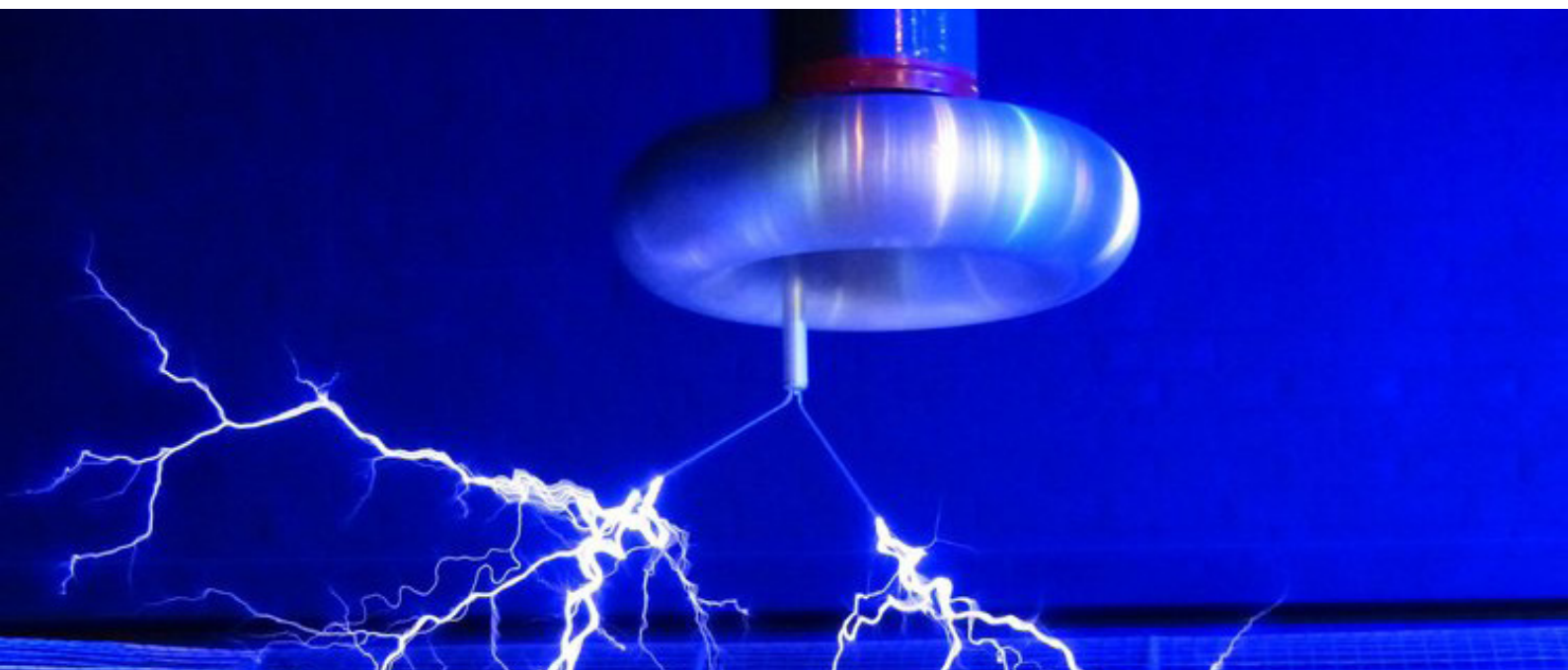


Figure 55 shows the effect of electrification on total CO₂ emissions change from 2030 to 2050 between the baseline and state policy scenarios. Due to their differences in production rate and grid emission factors, our calculation shows that Utah has the most savings (about 180 kilotons) and New Mexico has the least CO₂ savings (around 5 kilotons) during this period under the state policy scenario.

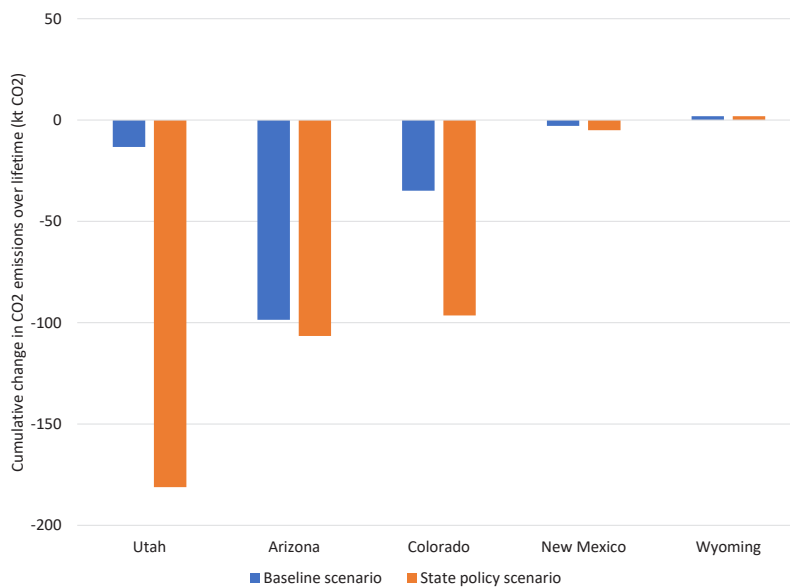


Figure 55. Cumulative change in CO₂ emissions in the meat processing industry over the lifetime of electrified technologies over the period of 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

As depicted in Figure 56, when observing the Energy Information Administration’s (EIA) electricity price projections, the cost of energy in terms of 2021 dollars per tonne of processed meat for the electrified method in the meat processing industry in 2030 appears higher than that of conventional methods in all studied states. However, when we account for access to affordable electricity, the cost of electrified meat processing can be substantially trimmed, leading to a more cost-effective operation. To illustrate the impact of potential future changes, we have provided sensitivity analyses showing scenarios of 50% lower electricity prices and 50% higher natural gas prices, relative to EIA forecasts.

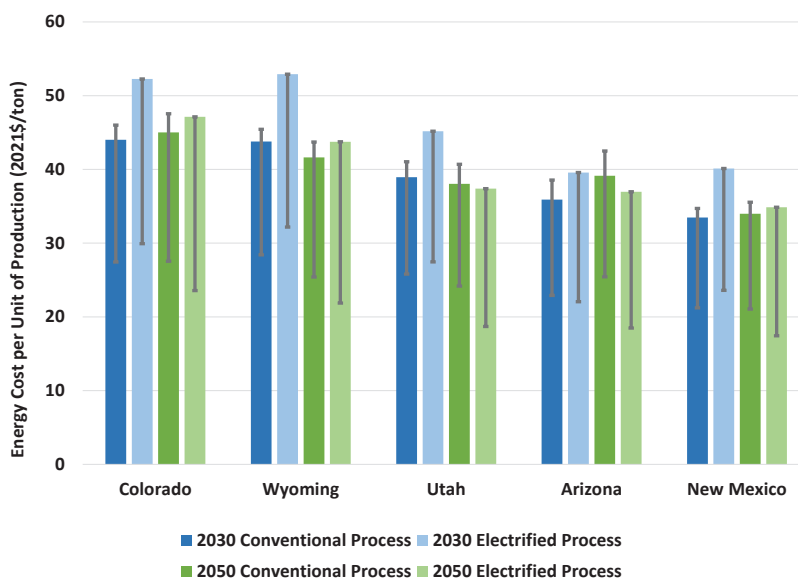


Figure 56. Energy cost per unit of production in the meat processing industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast and the positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.

3.11. Cheese production industry

In the United States, the dairy industry consists in large part of the production of over 300 cheese varieties, predominantly from cow’s milk. Data from 2020 indicates that total U.S. cheese production rose 2% from 2016, reaching 6.2 million tons. Notably, Wisconsin led the nation with 1.6 million tons of cheese produced in 2019, while Colorado’s production was around 21,400 tons (Statista, 2022).

The remarkable variety of cheeses is determined by factors such as milkfat, solids nonfat, and water proportions, the strains of bacteria used, and specific processing steps. Figure 57 presents a generalized process for cheese production, though certain types of cheese may require additional steps, like specific resting/aging times or repeated procedures (Wastra et al., 2006). In this process, raw milk is initially standardized through centrifugation to achieve a specific milk fat level. For some cheeses requiring higher solids nonfat content, ultrafiltration is used to remove water during standardization, and other concentrated dairy ingredients may be added. The standardized milk is then pasteurized and transferred to a cheese vat, where rennet, enzymes, and/or bacterial cultures are added according to the cheese type.

In the U.S., it is common for natural colors to be added to cheeses like cheddar, Colby, and gouda. The mixture undergoes cooking to facilitate the creation of cheese curds, and additional cooking stages can “age” the cheese to reach desired flavor and characteristics. Following cooking, the curds are separated from the liquid whey, a byproduct of cheesemaking, and pressed into solid blocks. Some cheeses, such as mozzarella, undergo stretching for a “stringy” texture. Finally, the cheese is packaged, aged, and stored (Wastra et al., 2006).

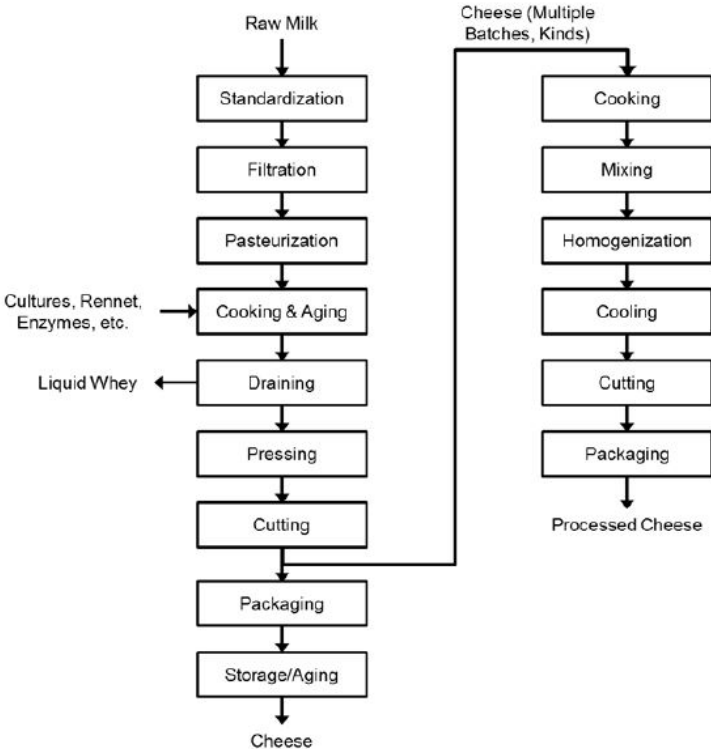


Figure 57. Process diagram for generic cheese production (LBNL, 2011)

Various technologies have been evaluated as alternatives to conventional heating for pasteurization and sterilization of foods. Ohmic heating of food products, achieved by the passage of an alternating current through food, has emerged as a potential technology with comparable performance and several advantages. Although the ohmic heating process has better retention of nutritional quality, high energy efficiency, etc., higher cost input limits its commercial use on a larger scale. Foods containing fats and oils cannot be processed with ohmic heating because of a lack of electrical conductivity (Zina T. Alkanan, 2021).

Electric heaters have become the ideal choice for pasteurization, especially in preheating. The smooth temperature curve and rapid heating capabilities of electricity make for the ideal preheater. In addition, electricity provides higher efficiency through much greater accuracy and control. The electric heaters deliver more precise temperatures, and pair well with thermocouples and regulators. Intelligent, automated digital control panels allow for reliable and accurate pasteurization heater operation (Wattco. 2022). Table 15 compares the energy consumption of conventional and electrified processes for cheese production.

Table 15. Energy intensities of conventional and electric cheese production processes (Bandwidth 2017)

Conventional System Process		Process Steps	All Electric Process
Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)
544	-	Motors, Pumps	544
115	-	Make Vat	115
-	60	Cooking Pasteurization1	53
-	47	Cooking Pasteurization2	42
659	106	Subtotal	754
756		Total Energy	754

Energy use

Electrification can help to reduce the cheese processing industry’s total final energy use (Figure 58). Utah, New Mexico, and Arizona are the states with largest energy savings potentials from switching to electrified cheese production.

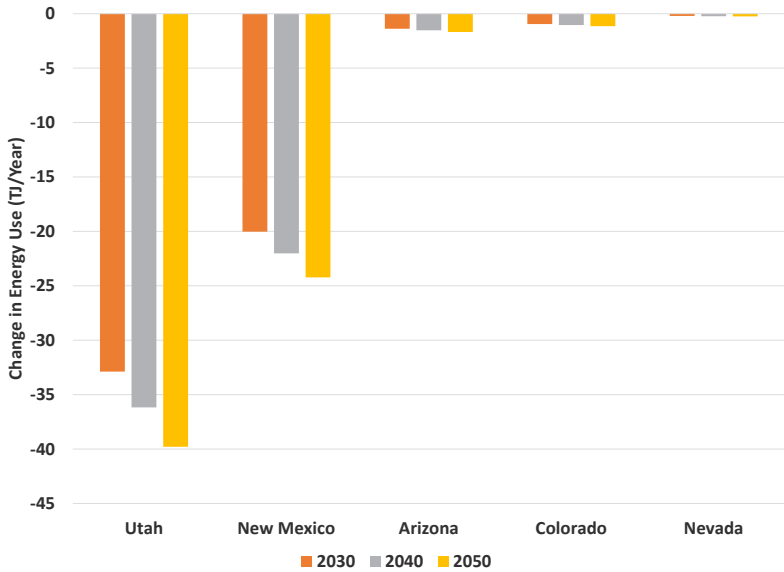


Figure 58. Change in the cheese processing industry’s total final energy use after electrification (Technical potential assuming a 100% adoption rate)

CO₂ emissions

Cheese production electrification can decrease CO₂ emissions in 2050 in all states, although there may be a near-term rise of emissions in 2030 in our baseline scenario without rapid grid decarbonization (Figure 59). Figure 60 shows the cheese production industry’s change in net CO₂ emissions after electrification under our state policy scenario.

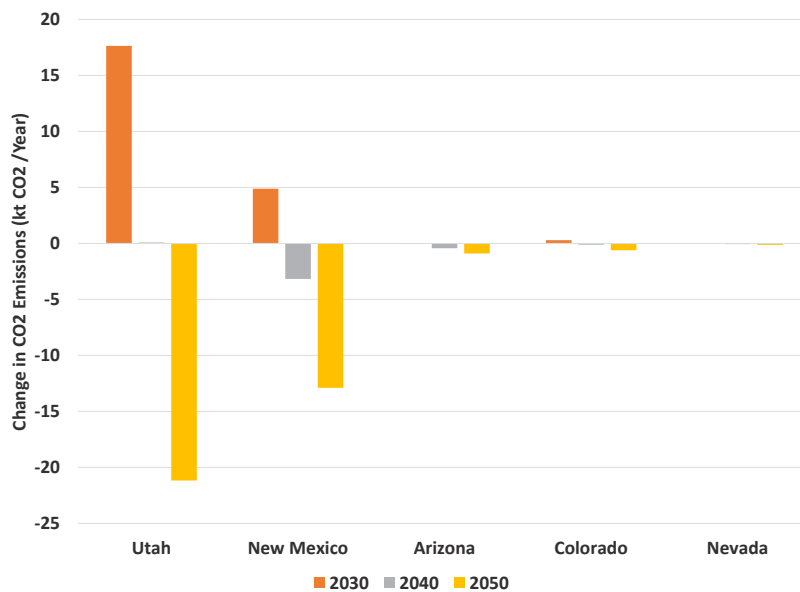


Figure 59. Change in the cheese production industry’s net CO₂ emissions after electrification - baseline scenario (technical potential assuming a 100% adoption rate)

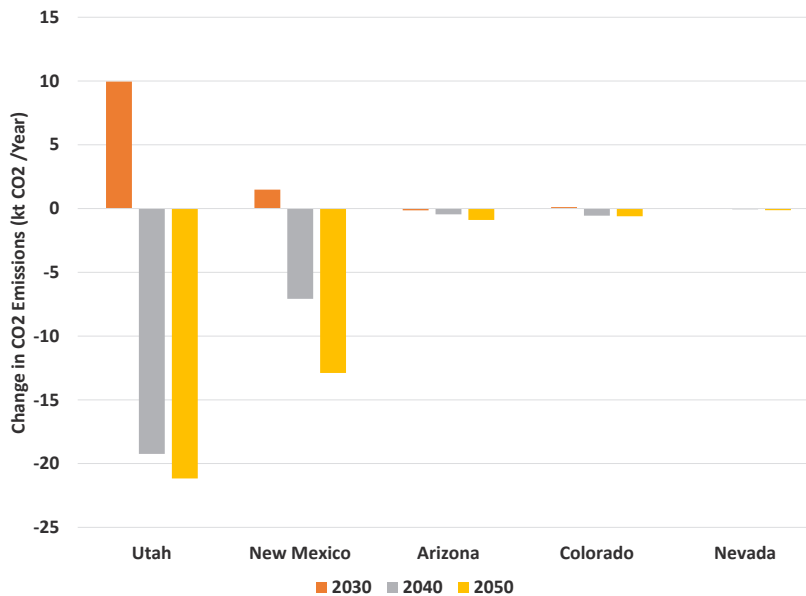


Figure 60. Change in the cheese production industry’s net CO₂ emissions after electrification - state policy scenario (technical potential assuming a 100% adoption rate)

Figure 61 shows the effect of electrification on total CO₂ emissions change from 2030 to 2050 between baseline and state policy scenarios. As seen in this figure, electrification can reduce CO₂ emissions by about 134 kilotons during these twenty years in New Mexico and over 254 kilotons in Utah based on state policy scenario.

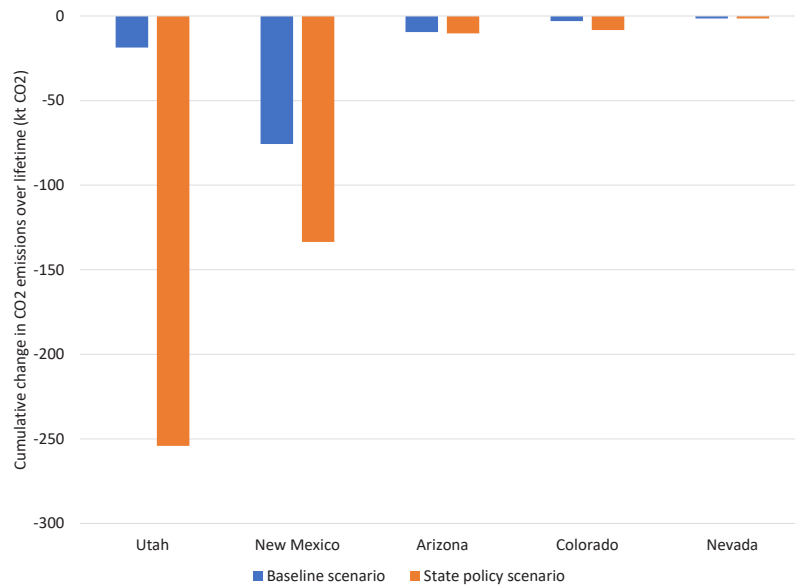


Figure 61. Cumulative change in CO₂ emissions in the cheese production industry over the lifetime of electrified technologies over the period of 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

As displayed in Figure 62, the anticipated energy cost per unit of cheese production (in 2021\$) in 2030 is projected to be higher for electrified processes than conventional methods across all studied states, using the EIA electricity price forecast. However, the accessibility of inexpensive electricity could significantly curtail these energy costs, as demonstrated by the error bars.

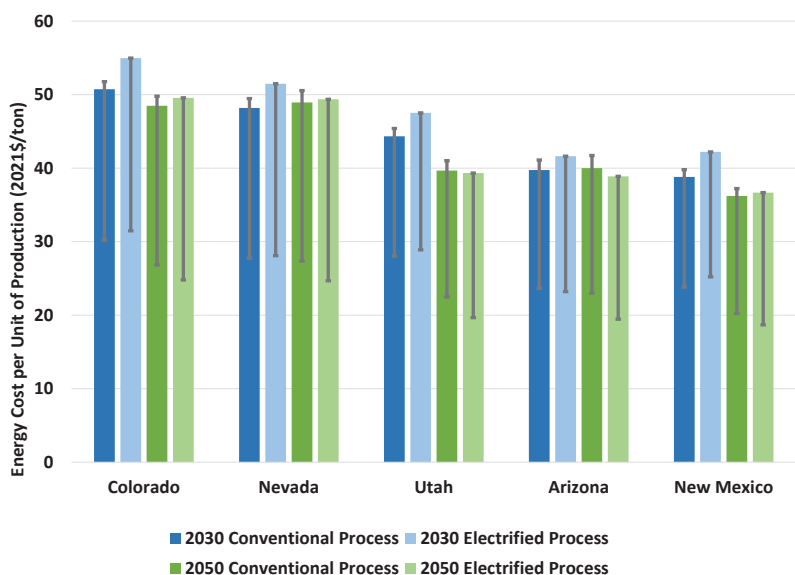


Figure 62. Energy cost per unit of production in the cheese production industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast and the positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.

3.12. Steel reheating

Globally, iron and steel industries account for 7% of global greenhouse gas (GHG) emissions and 11% of global CO₂ emissions. The U.S. was ranked as the 4th largest producer of steel worldwide in 2017. Reheating furnaces, integral to steel hot rolling mills, produce roughly 0.98 tons CO₂eq/ton of hot-rolled structural steel sections and are the second largest energy consumers in steel plants. These furnaces are used to heat steel billets, blooms, or slabs to approximately 1,200°C, making the steel amenable to plastic deformation, which requires eight to ten times less forming force than cold-rolled steel. The process is continuous, with steel being charged, heated, and discharged in succession. The heat transfer to the steel primarily occurs through convection within the furnace and radiation from the burner and furnace walls.

The reheating power in such furnaces is typically provided by electric heating elements applied to the furnace’s walls. These electrically heated furnaces are characterized by excellent temperature uniformity, achieved through a vertical fan in the vault. Furnace components include a quadrangular or rectangular muffle, a guillotine door, a fixed hearth, a flat vault, electric heating elements, and electric control equipment.

Electric furnaces with resistance heating elements are becoming increasingly prevalent, offering various advantages including low installation costs, high energy efficiency, quieter operation, precise temperature control, and even heating throughout the chamber. Compared to combustion heating furnaces, they don’t produce combustion products or flame impingements and don’t require storage or piping of flammable fuels, which translates into space savings and lower insurance premiums. Furthermore, they create a cleaner, cooler plant environment, contributing to reduced pollution.

Despite their efficiency, these furnaces can be energy-intensive due to their water-cooled transportation system. However, with a preheating furnace operating at a lower temperature than existing walking beam furnaces, it is possible to reduce the cooling rate, leading to less heat loss and a more efficient furnace. Table 16 provides a comparison of the energy intensities of conventional and electric steel reheating furnaces.

Table 16. Energy intensities of conventional and electric steel reheating furnaces (Gfelti, 2021)

Conventional System Processes	Process Steps	All Electric Processes
Gas-Fired Reheating Furnace Energy Intensity (kWh/tonne)		Electric Reheating Furnace Energy Intensity (kWh/tonne)
833		Hot Rolling

Energy use

Electrification can help to reduce the total final energy use in steel reheating furnaces (Figure 63). Among the states studied, Colorado is the state with largest energy savings potential from switching to electrified reheating furnaces.

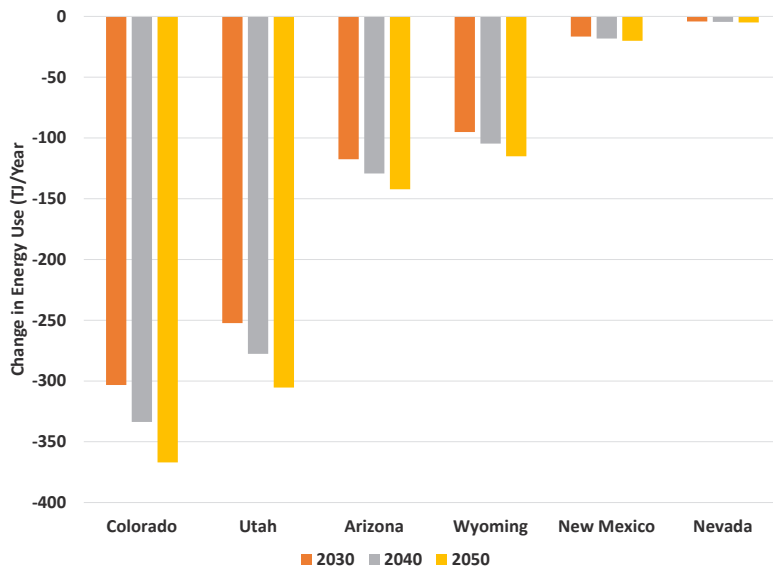


Figure 63. Change in the steel reheating furnace industry's total final energy use after electrification (Technical potential assuming a 100% adoption rate)

CO₂ emissions

Steel reheating furnace electrification can decrease CO₂ emissions in 2050 in all states, though near term emissions may increase in Colorado, Utah, and Wyoming due to still-high grid emissions factors in 2030 (Figure 64). Figure 65 shows the steel reheating change in net CO₂ emissions after electrification under our state policy scenario.

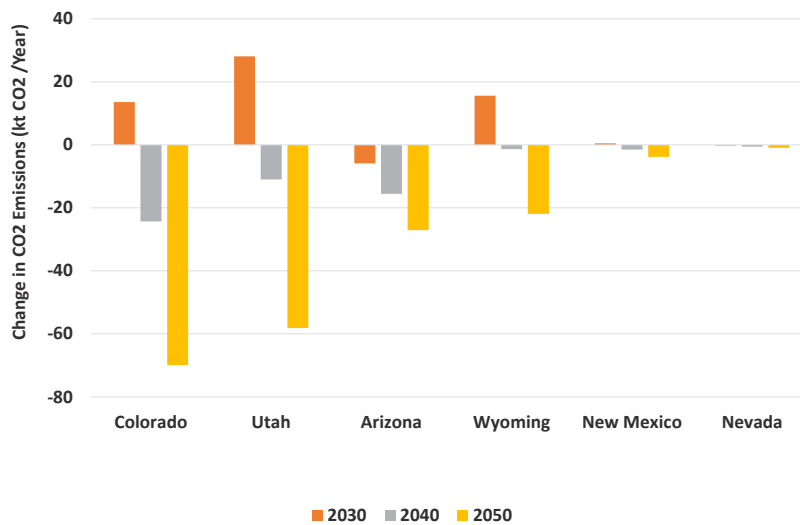


Figure 64. Change in the Steel reheating furnace's net CO₂ emissions after electrification - baseline scenario (technical potential assuming a 100% adoption rate)

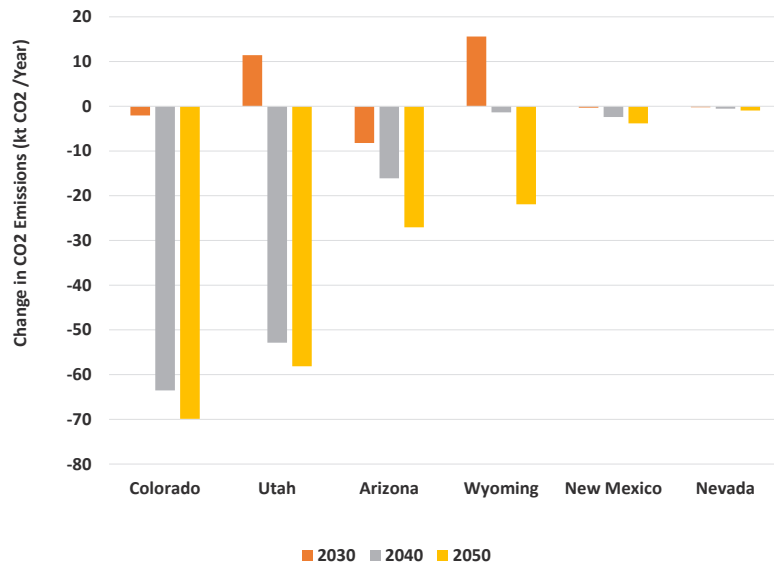


Figure 65. Change in the Steel reheating furnace’s net CO₂ emissions after electrification - state policy scenario (technical potential assuming a 100% adoption rate)

Figure 66 shows the effect of electrification on total CO₂ emissions change from 2030 to 2050 for both baseline and state policy scenarios. Due to their differences in production rate and grid emission factors, our calculation shows that Colorado has the most and Nevada has the least CO₂ savings during this period.

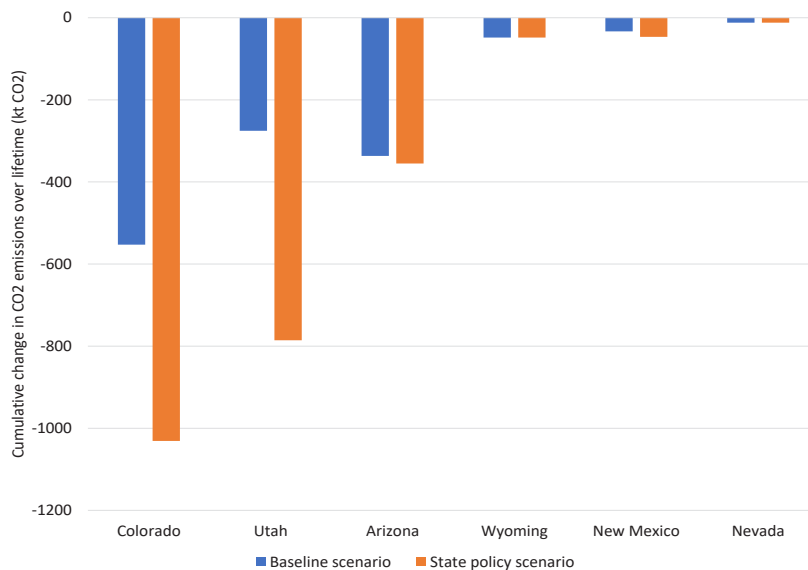


Figure 66. Cumulative change in CO₂ emissions in the steel reheating industry over the lifetime of electrified technologies over the period of 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

Figure 67 reveals that, based on the EIA’s 2021 electricity price forecast, the per-tonne cost of electrified steel reheating in 2030 is higher than its conventional counterpart in all analyzed states. However, affordability could be achieved with access to low-cost electricity and changes in energy prices. If electricity prices drop by 50% and natural gas prices rise by 50% compared to the EIA’s forecast, electrified steel reheating could compete with the conventional process in Nevada, Utah, Colorado and Arizona by 2030, and Wyoming, and New Mexico by 2050.

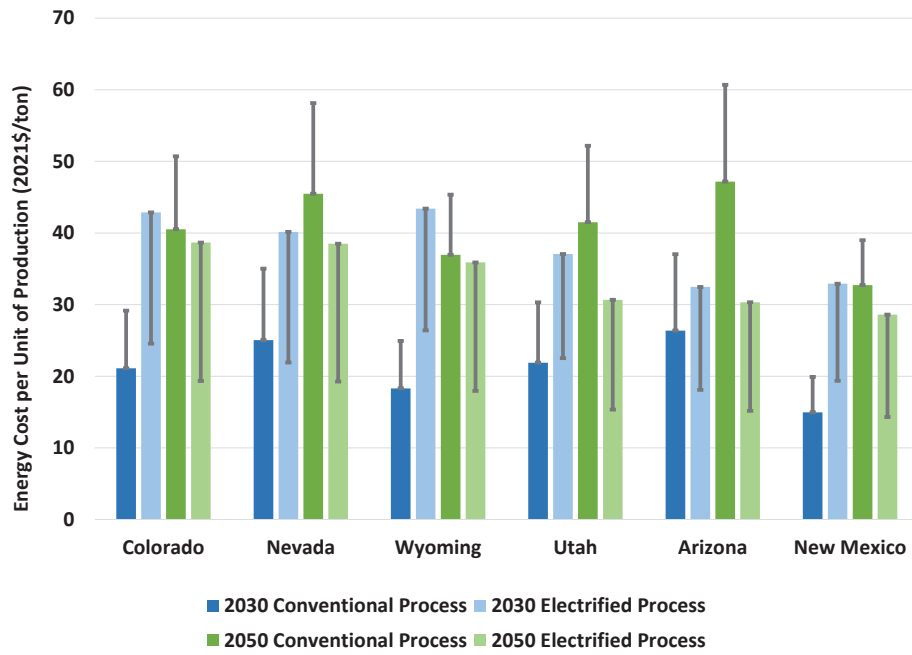


Figure 67. Energy cost per unit of production in the steel reheating process.

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast and the positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.



made from cellulosic feedstocks, such as crop residues and wood—though this is not as common. U.S. ethanol plants are concentrated in the Midwest because of the proximity to corn production. Plants outside the Midwest typically receive corn by rail or use other feedstocks and are located near large population centers. The production method of ethanol depends on the type of feedstock used. The process is shorter for starch- or sugar-based feedstocks than with cellulosic feedstocks. Most ethanol in the United States is produced from starch-based crops by dry- or wet-mill processing. Nearly 90% of ethanol plants are dry mills due to lower capital costs (DOE, 2020). Among the southwest states, only Colorado and Arizona have an ethanol industry.

Figure 68 illustrates a typical corn ethanol refinery process. Corn is milled, mixed with water, sterilized, then fermented to convert starch into ethanol and CO₂. The ethanol mixture is distilled and dehydrated using a molecular sieve, yielding pure ethanol. This ethanol is combined with a denaturant and leaves the refinery as the final product. Unprocessed solids and remaining water are separated into a substance known as stillage, which undergoes a drying process. Natural gas is used to produce steam for various process steps and drying distiller's grains.

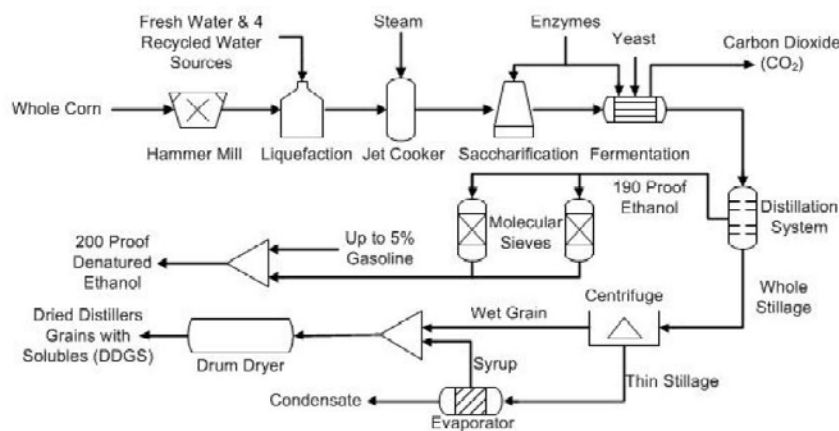


Figure 68. Schematic of modelled corn ethanol dry mill process for pure (anhydrous) ethanol production. (Howard A. 2015)

Since steam production is the main energy consumer in ethanol production, one approach to electrify the process is by using electric steam boilers. Table 17 compares the energy intensities of conventional and electric ethanol production methods.

Table 17. Energy intensities of conventional and electric ethanol production.

Conventional System Process		Process equipment	All Electric Process
Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)		Electrical Demand (kWh/tonne)
270	2700	Mill	2686
		Beer Column Reboiler	
		Stripper Column Reboiler	
		Liquefaction Section	
		Molecular sieve pre-heating	
		DDGS natural gas fired dryer	
		Subtotal	
2970	Total Energy	2686	

Energy use

Figure 69 shows that electrification will reduce the ethanol industry's total final energy use from 2030-2050. Both Colorado and Arizona have large energy savings potentials from switching to electrified ethanol production processes.

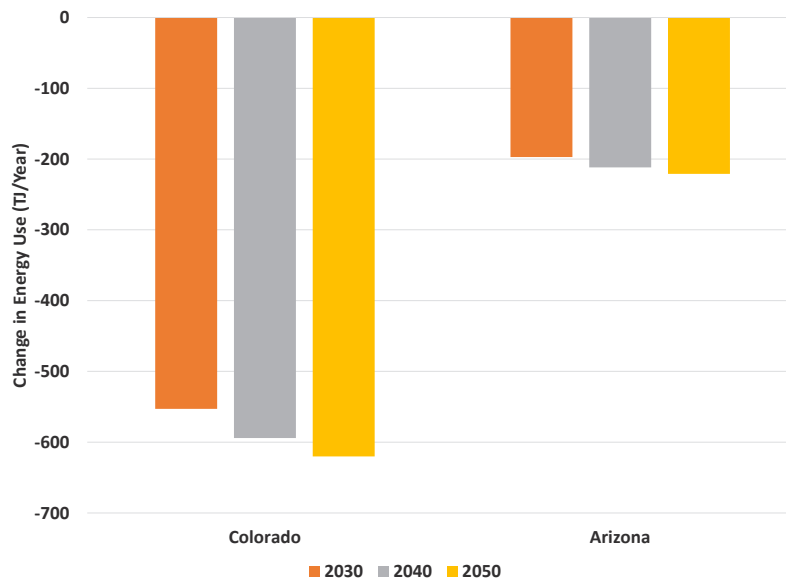


Figure 69. Change in the ethanol industry's total final energy use after electrification (technical potential assuming a 100% adoption rate)

CO₂ emissions

Figure 70 shows the change in the ethanol industry's net CO₂ emissions after electrification under the baseline scenario. Ethanol production electrification could result in CO₂ emissions increases in 2030 in Colorado because of its relatively higher grid emissions factor compared with that of Arizona, but both states see emissions decreases under the baseline scenario in 2040 and 2050.

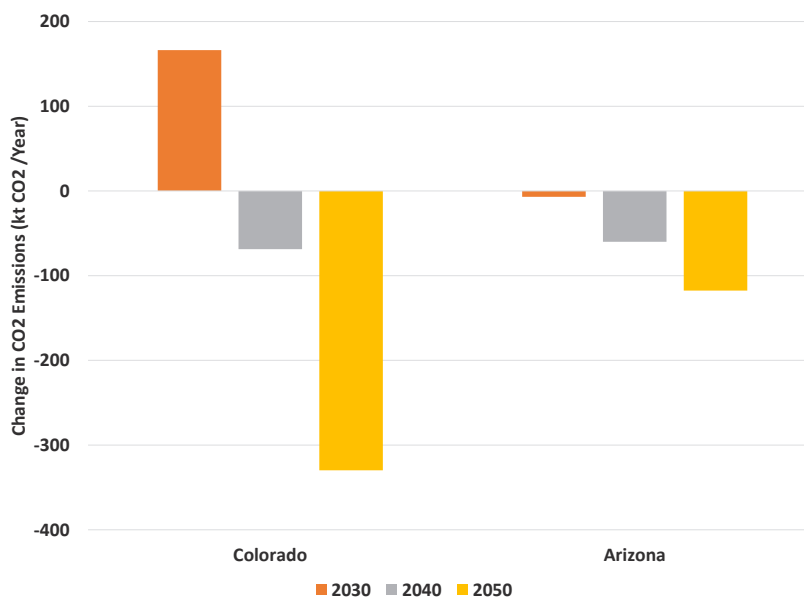


Figure 70. Change in the ethanol industry's net CO₂ emissions after electrification - baseline scenario (technical potential assuming a 100% adoption rate)

Figure 71 shows that under the state policy scenario, the CO₂ emissions reduction potential increases more than the baseline scenario because more rapid grid decarbonization is assumed under the state policy scenario.

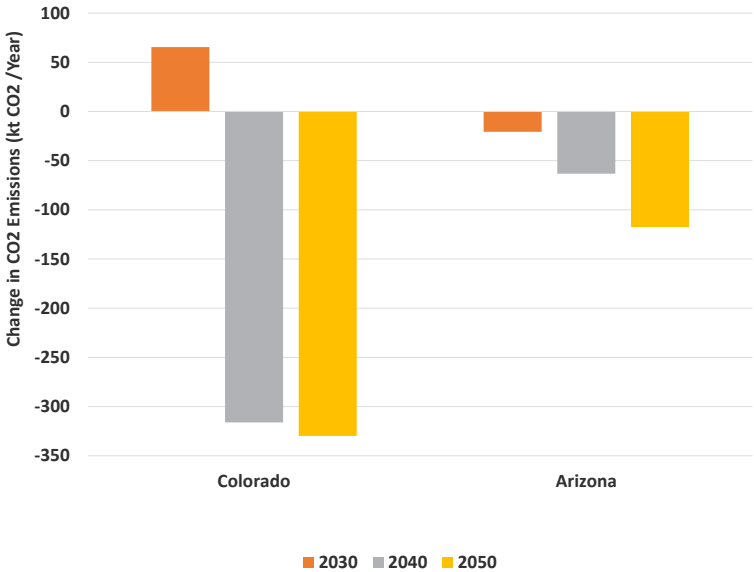


Figure 71. Change in the ethanol industry’s net CO₂ emissions after electrification - state policy scenario (technical potential assuming a 100% adoption rate)

Figure 72 shows the effect of electrification on total CO₂ emissions change from 2030 to 2050 for both baseline and state policy scenarios. As seen in this figure, electrification can reduce CO₂ emissions by about 4,615 kilotons during these twenty years in Colorado based on state policy scenario. Due to differences in production rate and grid emission factors, Arizona has less reduction in emissions.

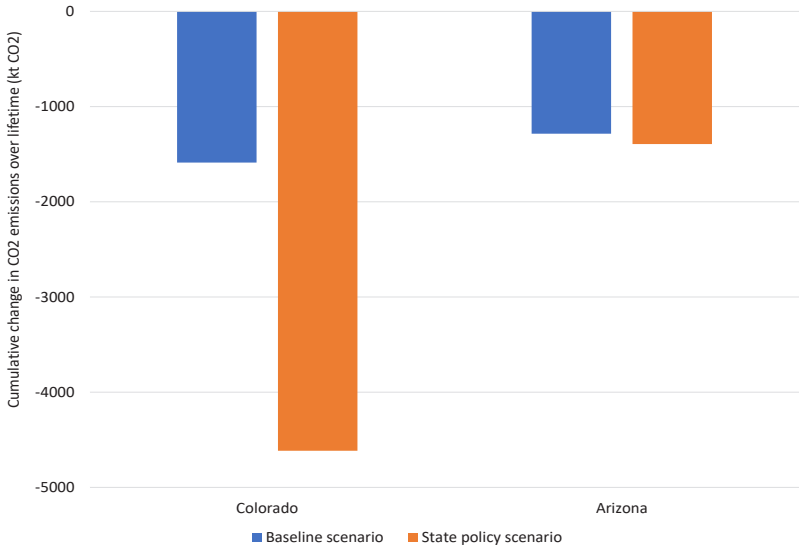


Figure 72. Cumulative change in CO₂ emissions in the ethanol industry over the lifetime of electrified technologies over the period of 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

As Figure 73 illustrates, the EIA's projected electricity costs suggest a higher per-unit energy cost (in 2021\$) for the electrified ethanol production process compared to the conventional process in Colorado and Arizona by 2030. Yet, the prospect of affordable electricity could drastically diminish these energy costs. This is demonstrated through our sensitivity analysis, which indicates that by 2030, the electrified production process could feasibly compete with traditional methods in both states.

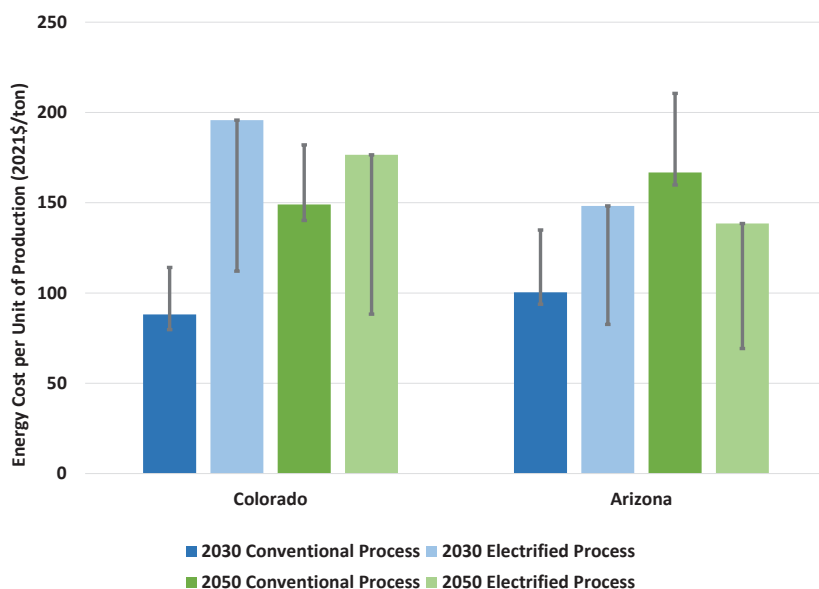


Figure 73. Energy cost per unit of production in the ethanol production industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast and the positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.

3.14. Hydrogen production

The U.S. produces approximately 10 Mt of hydrogen per year, mostly for the petroleum refining, ammonia, and the chemical industry. Currently, over 95 percent of U.S. hydrogen is produced in steam methane reforming (SMR) plants. Given that SMR hydrogen production produces about ten times as much CO₂ as it does hydrogen (by weight), this is a highly emissions-intensive industry. In the U.S., current hydrogen production generates 100 Mt of CO₂ equivalent per year (U.S. DOE, 2022b).

In SMR plants, high-temperature steam (700°C–1,000°C) is used to produce hydrogen from a methane source, such as natural gas. Methane reacts with steam under 3–25 bar pressure (1 bar = 14.5 psi) in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. Steam reforming is endothermic—that is, heat must be supplied to the process for the reaction to proceed. Steam reforming can also be used to produce hydrogen from other fuels, such as ethanol, propane, or even gasoline. (U.S. DOE, 2022b).

Electrolysis is a promising option for carbon-free hydrogen production from renewable and nuclear resources. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer. Electrolyzers can range in size from small, appliance-size equipment that is well-suited for small-scale distributed hydrogen production to large-scale, central production facilities that could be tied directly to renewable or other non-greenhouse-gas-emitting forms of electricity production. A typical process flow diagram for an electrolyzing process is shown in Figure 74. (U.S. DOE, 2022b).

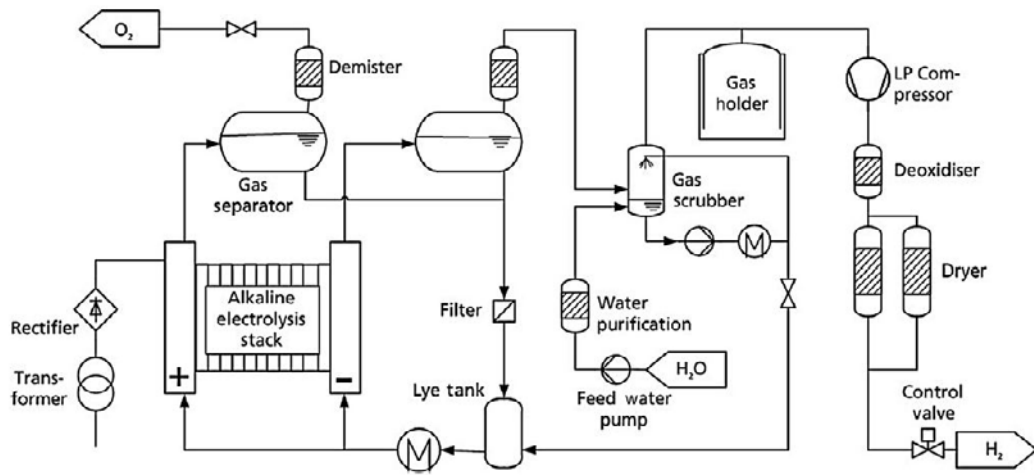


Figure 74: A typical process flow diagram for an electrolyzing process (Smolinka.2015)

Table 18 compares the energy intensities of hydrogen production via the SMR process vs. the water electrolyzing process.

Table 18. Energy intensities of conventional and electric hydrogen production.

	Hydrogen production process	Electrical Demand (kWh/tonne)	Thermal Demand (kWh/tonne)
Conventional process	Steam methane reforming	570	45,800
Electrified Process	Water electrolyzing	50,000	-

Note: The thermal demand of SMR process includes both of fuel requirements and equivalent natural gas feed thermal capacity.

Energy use

Hydrogen production electrification will significantly increase the total final energy use during the study period (Figure 75). The energy consumption increases for all states over time because total energy intensity increases with replacing conventional processes with electrified ones.

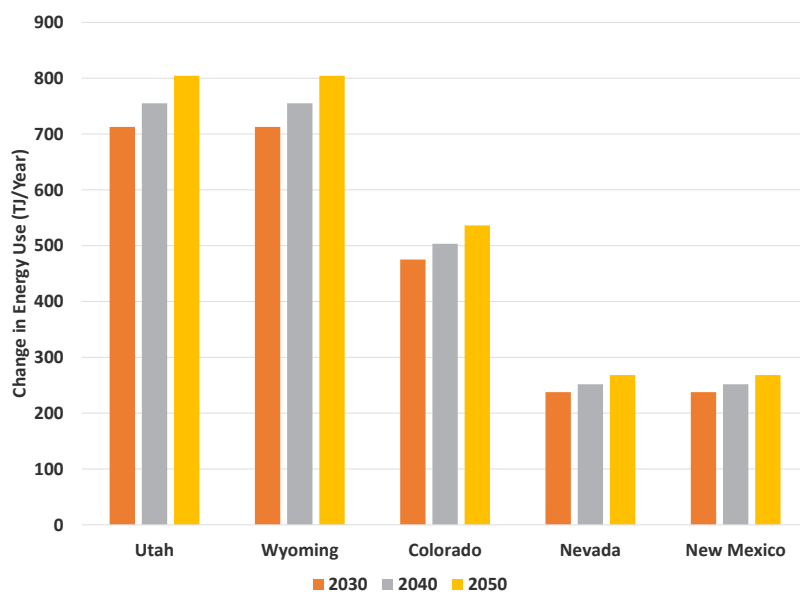


Figure 75. Change in the hydrogen production industry's total final energy use after electrification (Technical potential assuming a 100% adoption rate)

Figure 76 shows the hydrogen production industry’s change in net CO₂ emissions after electrification under the baseline scenario. Hydrogen production electrification results in an increase in CO₂ emissions in 2030 in all states studied except Nevada. Electrification reduces annual CO₂ emissions by 2050 in all states because of grid decarbonization. Producing hydrogen via electrolysis using carbon-intensive grid electricity may result in increase CO₂ emissions initially. However, it should be noted that in majority of cases around the world, renewable electricity (not carbon-intensive grid electricity) is proposed to be used in electrolysis process to produce green hydrogen.

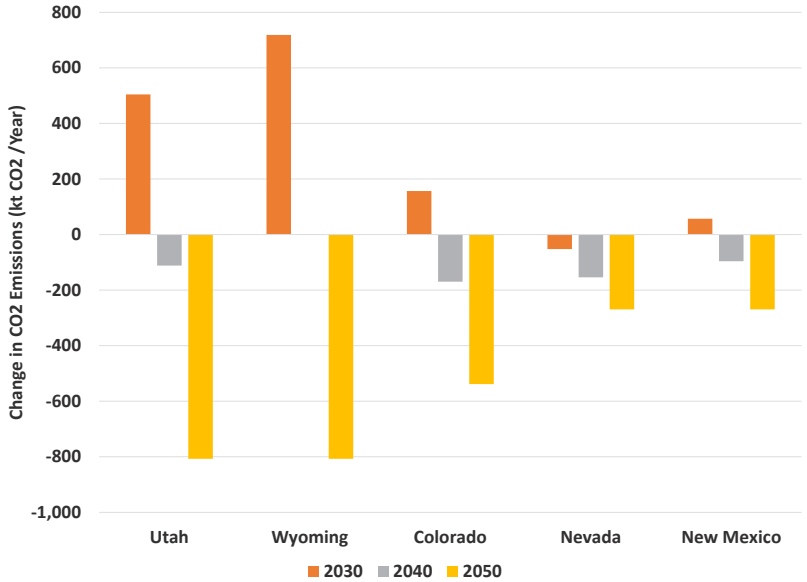


Figure 76. Change in the hydrogen production industry’ net CO₂ emissions after electrification - baseline scenario (Technical potential assuming a 100% adoption rate)

Figure 77 shows that under state policy scenario, the CO₂ emissions reduction potential increase more than the baseline scenario because more rapid grid decarbonization is assumed under the state policy scenario.

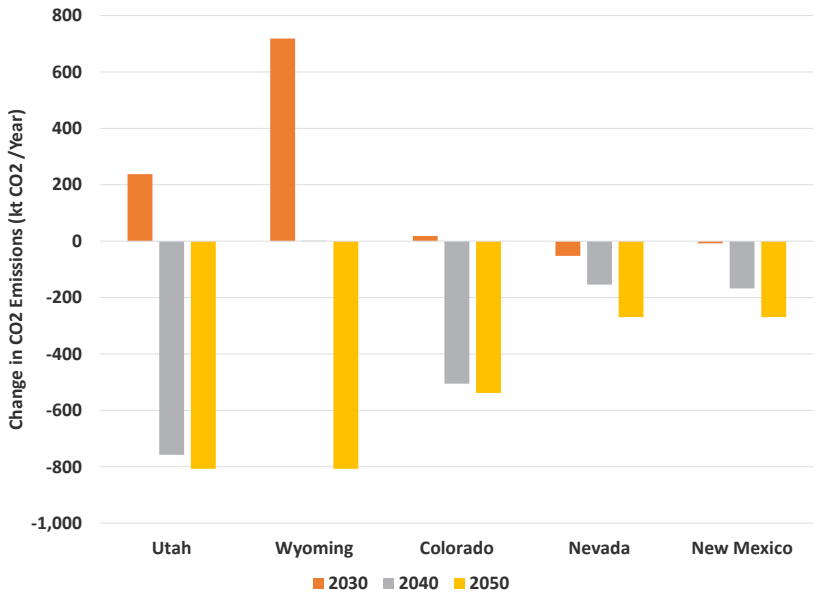


Figure 77. Change in the hydrogen production industry’s net CO₂ emissions after electrification - state policy scenario (technical potential assuming a 100% adoption rate)

Figure 78 shows the effect of electrification on total CO₂ emissions change from 2030 to 2050 for both baseline and state policy scenarios. Due to their differences in production levels and grid emission factors, our calculation shows that Utah has the most and Wyoming has the least CO₂ savings during this period.

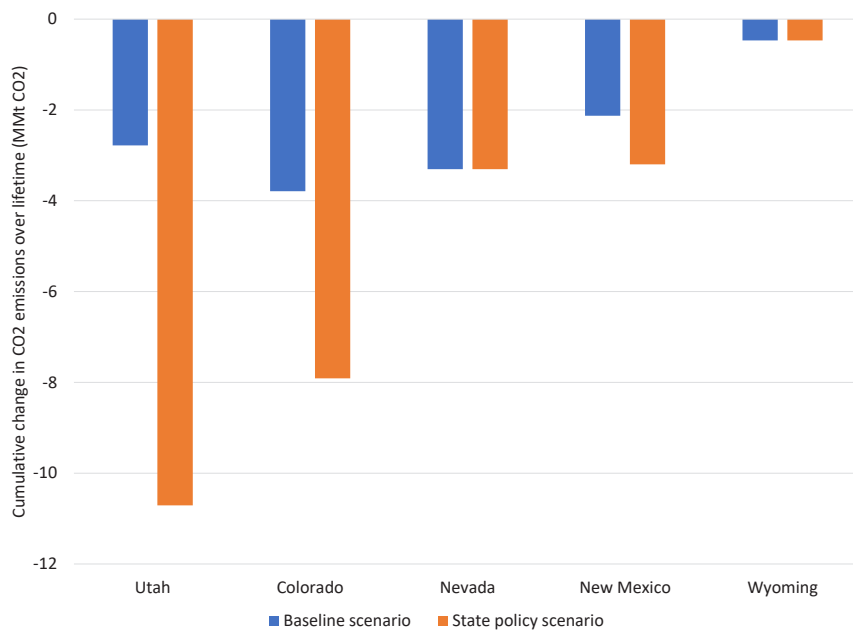


Figure 78. Cumulative change in CO₂ emissions in the hydrogen industry over the lifetime of electrified technologies over the period of 2030 - 2050 (This is the technical potential assuming a 100% adoption rate)

Energy cost

Figure 79 shows that with the EIA electricity price forecast, the energy cost (in 2021\$) per unit of production (tonne of hydrogen) in 2030 for the electrified process in the hydrogen production industry is higher than that of the conventional process in all studied states. It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified hydrogen production process. We have provided sensitivity options with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the EIA forecast in negative error bars and a higher natural gas price forecast that assumes 50% higher natural gas prices compared with the EIA forecast in positive error bars. Regarding these assumptions, the energy price of the electrified process could be cost-competitive compared with the conventional process for all states in 2050.

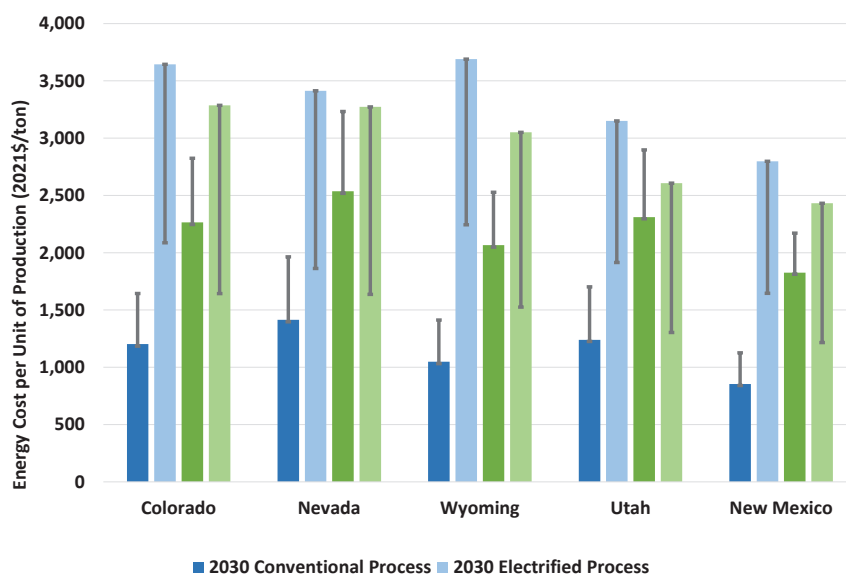


Figure 79. Energy cost per unit of production in the hydrogen production industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the EIA forecast and the positive error bars show the energy cost per unit of production assuming a natural gas price 50% higher than the EIA forecast.

3.15. Total energy savings and CO₂ emissions reduction potential

This section presents the total energy savings and CO₂ emissions reduction potentials that can be achieved in all six states from electrification of 11 of the 14 industrial subsectors included in this study.

The total energy savings and CO₂ emissions reduction presented in this section do not include the ammonia, hydrogen, and plastic recycling industries. This is because the electrification of the ammonia and hydrogen industries is indirect electrification through hydrogen production by an electrolysis process that uses electricity. Hydrogen is used as a feedstock and not as energy in the ammonia industries. Lastly, because this study compares the mechanical electrified plastic recycling process with the traditional method of producing virgin resins in petrochemical plants, the difference between plastic recycling and primary resin production inherently results in substantially high energy savings that can distort the combined savings results.

Figure 80 shows that taken together, electrification in the studied industries will significantly reduce industrial total final energy use in all states studied. Colorado and Arizona are the states with the largest energy savings potentials from electrifying the eleven industries included in this study (excluding ammonia, hydrogen, and plastic recycling industries for the reasons explained above). For context, every 10,000 TJ of energy can power around 260,000 US households per year.

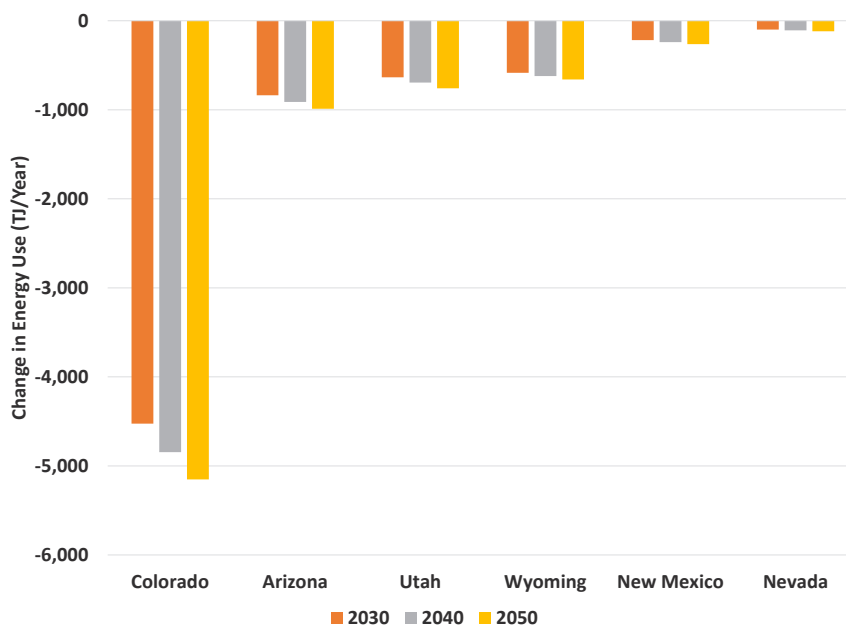


Figure 80. Change in industrial energy use using electrified processes in eleven industries studied (Excludes ammonia, hydrogen, and plastic recycling industries, technical potential assuming a 100% adoption rate)

Figure 81 shows the change in industrial net CO₂ emissions after electrifying the eleven industries under the baseline scenario. Electrifying these eleven industries could result in CO₂ emissions increases in 2030 in all states studied except Arizona and Nevada in these states, the relatively lower 2030 grid emissions factors (see Figure 3) help to achieve CO₂ emissions reduction in 2030. For context, reducing annual CO₂ emissions by 1,000 kt is equal to taking about 217,000 internal combustion engine passenger cars off the road.

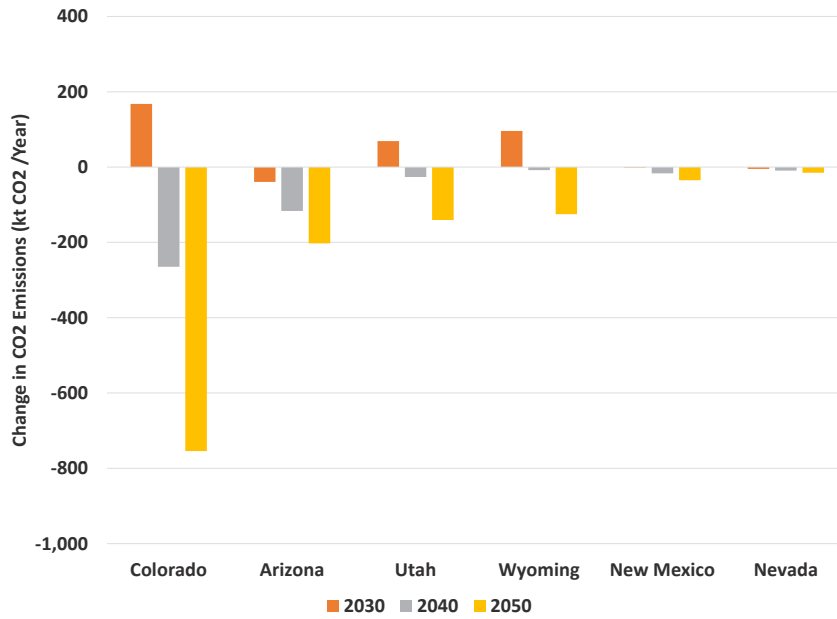


Figure 81. Change in industrial net CO₂ emissions using electrified processes in eleven industries studied (excludes ammonia, hydrogen, and plastic recycling industries - baseline scenario, technical potential assuming a 100% adoption rate)

Figure 82 shows the change in industrial net CO₂ emissions after electrifying these eleven industries under the state policy scenario. This scenario shows a higher CO₂ emissions reduction potential in future years than the baseline scenario in all studied states (except for Wyoming and Nevada) because more rapid grid decarbonization is assumed under the state policy scenario.

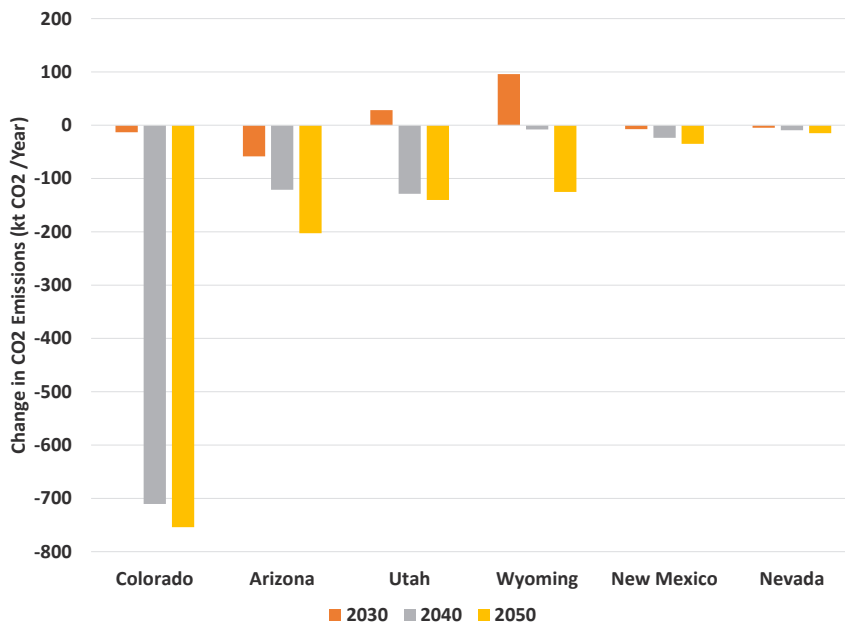


Figure 82. Change in industrial net CO₂ emissions using electrified processes in eleven industries studied - state policy scenario (excludes ammonia, hydrogen, and plastic recycling industries; technical potential assuming a 100% adoption rate)

In addition, total CO₂ emissions savings over the lifetime of electrified technologies from 2030 to 2050 were calculated for all studied states and both baseline and state policy scenarios. Figure 83 shows considerable cumulative CO₂ saving during this period. As seen in this figure, because of differences in industries, amount of production, and the differences in the grid emission factors, Colorado has the largest and Nevada has the smallest cumulative CO₂ emissions savings.

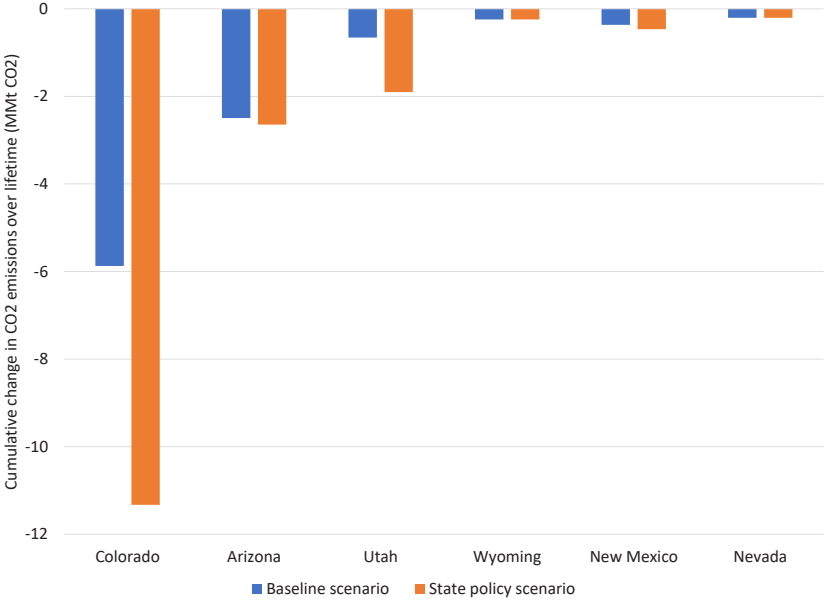


Figure 83. Cumulative change in CO₂ emissions over the lifetime of electrified technologies over the period of 2030 - 2050 in eleven industries studied (all except ammonia, hydrogen, and plastic recycling) (This is the technical potential assuming a 100% adoption rate).



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 5, 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 that will continue to be complicated by trends towards more distributed generation resources, renewable resources, and electrification continue in the face of challenges to reliability from aging infrastructure and more frequent and severe weather impacts. 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, 137).

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, 137). 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 14 of the industrial sectors studied, electrification results in a reduction in the total annual final energy use. The exception is Hydrogen 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 84 shows that electrifying eleven industries results in an increase in annual electricity consumption (GWh/year). This translates into an increase in electricity load after industrial electrification (MW), as shown in Figure 85.

For example, to fully electrify the eleven industries (except ammonia, recycled plastic, and hydrogen) included in this study with the processes described in this report, Colorado would need an additional 1.2 GW, Arizona an additional 0.3 GW, and Utah an additional 0.2 GW of power generation capacity in 2050. For comparison, in 2021, the U.S. has 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 two-thirds 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.

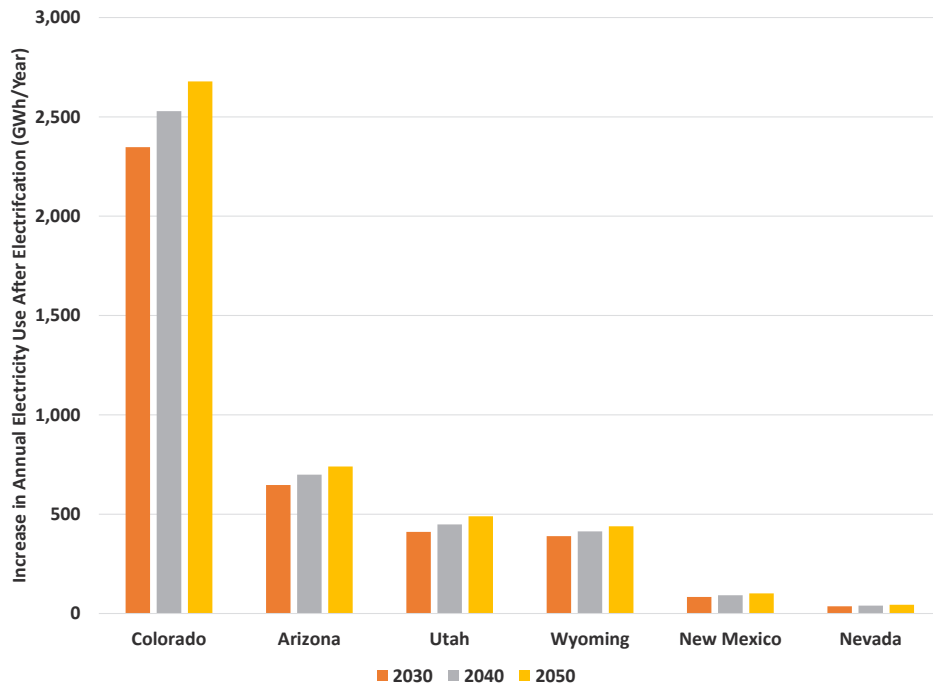


Figure 84. Increase in annual electricity consumption after industrial electrification in 2030-2050 (GWh/year) (assuming a 100% adoption rate)

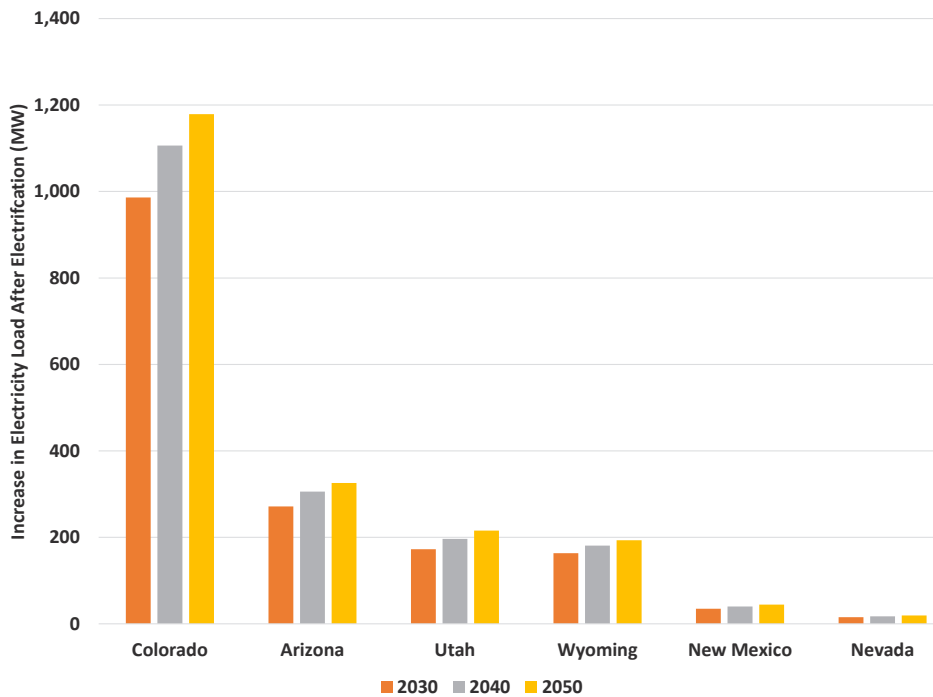


Figure 85. Increase in electricity load after industrial electrification in 2030-2050 (MW) (assuming a 100% adoption rate)

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 technology development and deployment, workforce development, and in some states, renewable electricity generation and transmission.

Promote demonstrations of cutting-edge electrification technologies and innovative applications of existing technologies.

Though states might not directly conduct research and development for electrification technologies, they can facilitate technology demonstrations and deployments. States can establish pilot projects or incentive programs to advance electrification technologies.

Moreover, states can seek opportunities to leverage federal resources in support of industrial electrification. For instance, the 2021 Infrastructure Investment and Jobs Act allocates \$500 million to the Industrial Emissions Reduction Technology Development Program, which offers grants, contracts, cooperative agreements, and demonstration projects focused on emissions reduction in heavy industry through alternative heat generation pathways, including electrification. States can work to access these resources or assist manufacturers in applying for funds directly.

Many technologies discussed in this report are commercially available and prepared for deployment. When an off-the-shelf solution is not feasible, industrial firms can collaborate with original equipment manufacturers to develop and fine-tune electrified technologies tailored to their specific processes and applications.

Encourage electrification through financial incentives.

Energy prices can fluctuate considerably between states or even counties, making cost comparisons per unit of production highly sensitive to energy unit prices. The EIA predicts that electricity prices in 2050 will be somewhat higher than today, although renewable electricity prices are expected to decline, potentially faster than anticipated. This could make electrification technologies more competitive against traditional fossil fuel-based technologies. This analysis considers costs using both EIA-forecasted prices and prices 50% lower.

Furthermore, natural gas and other fossil fuel prices might rise more than projected, particularly if the U.S. introduces carbon pricing policies. Energy costs represent a small fraction of total manufacturing costs for most industrial subsectors, except in cases like cement and steel industries where energy accounts for 30-40% of total manufacturing costs. In sectors with lower energy costs, a small or moderate increase in energy cost per unit of product due to electrification will minimally impact the final product's price. However, energy-intensive industries typically have low margins and operate in a highly competitive global market, making them sensitive to energy cost increases. Therefore, suitable policy measures should be implemented to address this issue.

By leveraging federal financial, technical, or program support, states and manufacturers may be able to reduce costs, particularly for pilot or demonstration projects. States may also create their own policies and programs to lower electrification technology adoption costs, such as tax incentives, reduced permitting costs, or rate-based utility infrastructure upgrade costs.

Grants for adopting electrified technologies would diminish manufacturers' upfront costs and incentivize change. Grants could be awarded for pilot projects to encourage early adoption and demonstrate success. The structure of utility rates can also promote electrification. Electricity rates and ratemaking differ across states, requiring tailored approaches for each state.

Lastly, financiers need more information about electrification technologies and their advantages. Those who could finance electrified technologies may not be aware of industrial electrification's benefits or companies' interest in pursuing it to reduce energy use and emissions. A better understanding of the capabilities of industrial electrification technologies and the need for additional investment and support can improve policy and investment decisions.

Develop and expand the workforce.

Employees and contractors working at industrial facilities may need training on new electrification technologies, including installation, operation, and maintenance procedures. The U.S. DOE can support training programs associated with these technologies through its various grant programs. States can also leverage their educational programs across technical schools and universities to provide training on existing electrified technologies and ensure that the future workforce is well-equipped to develop and implement the next generation of innovations.

States should collaborate across various agencies and offices, such as education, higher education, energy, public utility commissions, and economic development, to gather input on educational program development. Engaging with utilities, trade associations, teachers, and students will also be valuable in ensuring that training programs are aligned with current and future industry needs.

Furthermore, workforce development initiatives should focus on establishing partnerships with underserved communities. By working together to create relevant educational and training programs, states can help guarantee that these communities can participate equitably in the clean energy economy. This approach will not only enhance workforce diversity but also contribute to addressing historical and systemic injustices in access to education and well-paying jobs.

In addition to formal education, states can promote apprenticeship and mentorship programs that provide hands-on experience and practical knowledge in the field of industrial electrification. These programs can help bridge the gap between theoretical knowledge and real-world applications, enabling a smooth transition for workers entering the industry. Moreover, by fostering strong relationships between educational institutions and the private sector, states can ensure that emerging professionals are well-prepared for the challenges and opportunities presented by industrial electrification.

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, potentially avoiding 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. 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.

In conclusion the electrification of industrial heating is a key step to help us keep global warming below 2 degrees C. This transition presents a great opportunity to replace the substantial share of carbon-intensive fossil fuel heat generation in the industrial sector with cleaner, renewable electricity. As we aim for this transformative change in the U.S., a collaborative approach is needed by industrial companies, electrification technology developers and service providers, U.S. DOE, utilities, grid operators, policymakers, and other stakeholders. Many industrial electrification technologies are commercially available today and are ready for deployment.



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Appendices

Appendix 1. States grid emission factors (kg CO₂/MWh) (US EPA 2023)

State	Baseline Scenario				State policy Scenario			
	2021	2030	2040	2050	2021	2030	2040	2050
Arizona	329	211	105	0	329	181	99	0
Colorado	551	353	176	0	551	276	0	0
Nevada	324	207	104	0	324	207	104	0
New Mexico	514	329	164	0	514	257	89	0
Utah	707	452	226	0	707	354	0	0
Wyoming	831	532	266	0	831	532	266	0