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Electrifying Industrial Heating in China

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Executive Summary

The industrial sector in China accounts for roughly 65% of China's total primary energy use and 70% of its energy-related CO_2 emissions. As emissions from electricity generation decline, addressing thermal energy needs in the industrial sector, especially for process heating, will become a critical challenge in the pursuit of deep decarbonization of industry.

Heat represents two-thirds of all energy demand in the industrial sector, yet very little of this demand is met with 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.

In this report, we analyze the electrification potential for 14 industries in China (aluminum, container glass, ammonia, recycled plastic, beer, beet sugar, milk powder, wet corn milling, soybean oil, meat, steel, steel reheating, ethanol, and pulp and paper). We also analyzed the energy and CO_2 emissions impacts of electrification of boilers in Chinese industrial subsectors over time.

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

Table ES1 shows the change in CO_2 emissions after electrification of certain processes in those industries (assuming a 100 percent adoption rate, except for the steel industry). Negative values imply reduction in emissions. The baseline scenario assumes a net zero grid is achieved by 2060 according to China's current commitments under the Paris Agreement, whereas in the ambitious scenario, it is assumed that facilities will be able to procure renewable electricity for one third of their electricity needs in 2030, half by 2040, and all by 2050. In Table ES1, the 14 industries studied are listed in order from 1-14 based on estimated CO_2 emissions in 2050 (greatest to least), with columns describing the change in net CO_2 emissions after electrification in the baseline and ambitious scenarios across the study period. Plastic recycling, steel reheating processes, steel production, and the ammonia industry are the top four industries in terms of CO_2 emissions reduction potential from electrification.

Table ES1. Change in CO_2 emissions from electrification in China using electrified processes in fourteen industries.

No	Sectors	Change in sector's net CO_2 emissions after electrification in China - Baseline scenario (kt/year)			Change in sector's net CO_2 emissions after electrification in China - Ambitious scenario (kt/year)		
		2030	2040	2050	2030	2040	2050
1	Recycle plastic	-213,505	-254,510	-259,991	-180,455	-206,817	-197,888
2	Steel reheating	-68,781	-133,640	-183,471	-175,984	-230,999	-273,904
3	Steel H_2 DRI	-4,895	-72,010	-178,719	-9,257	-111,622	-252,306
4	Ammonia	8,857	-64,541	-146,334	-61,240	-138,675	-224,181
5	Paper	25,125	1,325	-22,034	-540	-24,367	-47,645
6	Aluminum	-182	-3,619	-9,520	-2,452	-7,392	-14,777
7	Soybean oil	-2,442	-5,175	-6,937	-5,124	-8,104	-9,614
8	Container glass	-1,287	-3,382	-5,393	-3,681	-5,778	-7,782
9	Beet sugar	-14	-2,474	-4,506	-2,777	-5,240	-7,066
10	Wet corn milling	2,339	-806	-3,640	-1,083	-4,294	-6,868
11	Beer	-956	-1,649	-2,460	-1,570	-2,338	-3,229
12	Ethanol	1,297	-220	-2,268	-190	-1,969	-4,271
13	Meat production	2,814	138	-2,255	-78	-2,776	-4,872
14	Milk powder	-337	-492	-636	-433	-608	-764

Note: For the steel sector, results are for the H_2-DRI production route relative to BF-BOF. We also modeled scrap-EAF vs. BF-BOF and electrolysis vs. BF-BOF, and those results are presented in section 3.11 below. For the plastics recycling sector, results are presented relative to production of virgin resin, as detailed in section 3.4. For ammonia production, it is unlikely that all electrolysis-based hydrogen production will be based on grid electricity – most will likely have dedicated renewable electricity supply, which would reduce the estimated increase in emissions.

This study also emphasizes the positive impact of electrification on reducing CO_2 emissions over the lifetime of the technology by calculating the cumulative change in CO_2 emissions from 2030 to 2050 (Figure ES1 and Figure ES2). Industrial electrification leads to a net decrease in CO_2 emissions over the lifetime of the technologies, assumed to span from 2030 to 2050. These figures indicate that, even if industrial electrification initially causes an increase in annual CO_2 emissions due to the high carbon intensity of China's electricity grid, the long-term effect of electrification will result in a net reduction of CO_2 emissions as China's grid decarbonizes. This demonstrates how industrial electrification contributes to China's carbon neutrality goal.

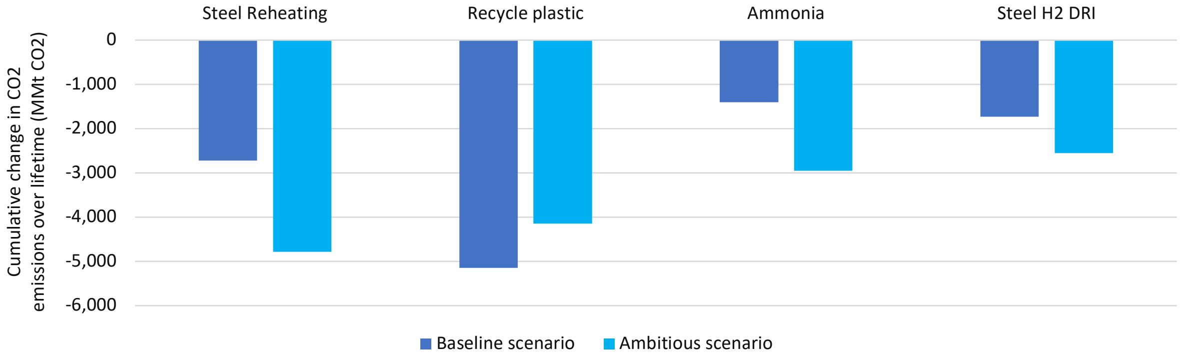

Figure ES1. Cumulative change in CO_2 emissions over the lifetime of electrified technologies over the period of 2030 - 2050 in four industries studied (Plastic recycling, steel reheating, steel and ammonia) (This is the technical potential assuming a 100% adoption rate, except for the steel industry, where we assumed a more gradual adoption rate of electrified technologies over the study period).

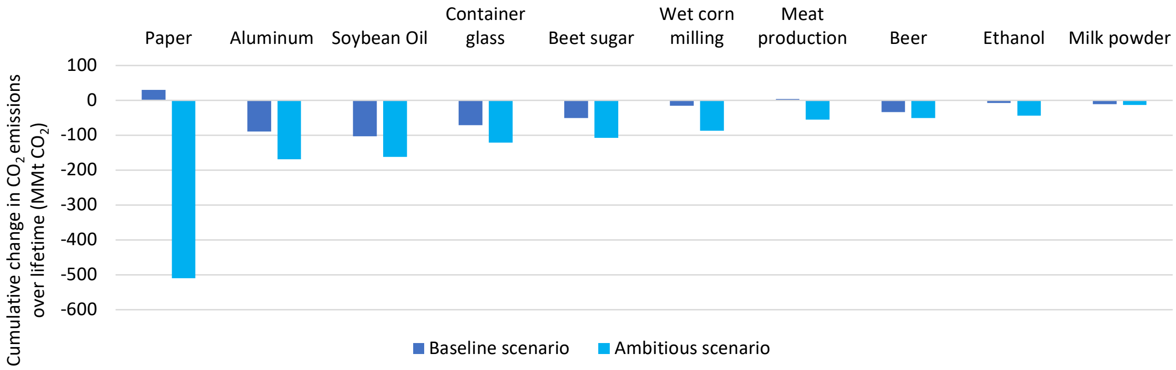

Figure ES2. Cumulative change in CO_2 emissions over lifetime of electrified technologies over the period of 2030 - 2050 in ten industries studied (Paper, aluminum, soybean oil, container glass, beet sugar, wet corn milling, beer, ethanol, meat processing, and milk powder) (This is the technical potential assuming 100% adoption rate. In the near term by 2030, the actual adoption rate will be low. Therefore, in sectors where there is a projected increase in CO_2 emissions in 2030, the actual increase will be very small).

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, fuel, and carbon price assumptions. Under the base case energy prices forecast, in many cases, the cost per unit of production for an electrified process is higher than that of the conventional process. For many industries, a scenario with 50% lower electricity prices in 2030 and 2050 compared to the base case forecast can substantially reduce the energy cost of the electrified production processes, making them more cost-competitive compared to the conventional processes. It should also be noted that our cost comparison focuses only on energy costs (with assumed prices on carbon in the future) and does not include capital cost and other potential cost advantages for electrified technologies (see the methodology section).

The study only considers several potential electrification solutions for each process and subsector, such as studying three alternative steel production routes relative to the blast furnace-blast oxygen furnace (BF-BOF) route – scrap-based EAF production, hydrogen-DRI production, and electrolysis-based steelmaking. Other applicable electrified heating technologies might currently exist or are under development, such as DRI-EAF steelmaking with hydrogen-rich gases. Furthermore, additional, yet unexplored, electrification potential may lie within the studied subsectors. Thus, this study's projected energy savings and CO_2 reduction potentials may represent an underestimate of total potential that full-scale industrial subsector electrification in China could achieve.

Mitigating emissions not only offers global benefits by mitigating climate change, but it also offers localized advantages. Industrial plants in China that employ fossil fuels onsite are significant contributors to air pollution, negatively impacting nearby urban areas. These urban communities are particularly susceptible to the adverse effects of this pollution. By transitioning to industrial electrification, China has an opportunity to reduce localized emissions significantly, directly improving the quality of life for the hundreds of millions of people residing in its cities.

The process of electrifying industrial operations in order to gain the related benefits calls for an all-encompassing strategy. Increasing the capacity for renewable electricity generation is a fundamental requirement to satisfy the industrial sector's large demand for clean energy. As the demand for electricity increases due to industrial electrification, there will be an increasing need for both technical and economic enhancements in China's electricity grid and energy market to ensure the energy transmission remains reliable and efficient.

Our analysis puts forth policy recommendations to expedite the electrification of industrial heating in China. One key recommendation is integrating electrification in industrial planning and decision-making, establishing industry-specific electrification roadmaps. The introduction of robust standards and regulations, such as green public procurement policies, is crucial for incentivizing industries to adopt cleaner technologies.

To boost the adoption of cutting-edge electrification technologies, we recommend promoting technology demonstrations, establishing pilot projects, and leveraging governmental resources such as the Five-Year Plan for Energy Technology Innovation. We also emphasize the need for financial incentives and grants to reduce upfront costs for manufacturers and encourage renewable electricity procurement. Workforce development is crucial to ensure that professionals are equipped to implement electrification technologies. Lastly, we suggest the development of Public-Private Partnerships to accelerate technology commercialization, facilitate technology transfer, and share the risk associated with investing in new electrified technologies.

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1 Introduction

China set an economy-wide target of peaking its carbon dioxide emissions before 2030 and reaching carbon neutrality before 2060 (CAT 2023). Meeting these goals will require a concentrated effort to develop and deploy clean technologies across sectors. In China's electric power sector, renewable energy installation rates are the highest in the world. Meanwhile, in China's transport sector, vehicle electrification is taking off. However, supportive policies for and investments in technology research and development for the industrial sector have lagged behind. Indeed, compared to other countries, China's industrial sector relies more on fossil fuels and less on electricity (Lu et al. 2022). Given the heavy concentration of China's energy use and emissions in the industrial sector, there is a huge need for commercialization and deployment of cleaner electrification 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 globally (IEA 2018a). However, only a fraction of this demand is met using renewable energy.

Despite the substantial energy demand and GHG emissions of industrial thermal operations, scalable, cost-effective mitigation solutions for thermal energy emissions are largely unavailable. This is in stark contrast to the transport and power sectors where renewable electricity, electric vehicles, and new mobility strategies have made significant strides over the past two decades.

Renewable thermal energy solutions, including electrification, encounter numerous technological, market, and policy barriers impeding their large-scale development and implementation, as detailed in our previous report (Hasanbeigi et al. 2021). Thermal energy faces unique challenges compared to renewable electricity. Industrial processes' thermal needs vary greatly and are often site- or sector-specific. Also, they require heat at diverse temperatures, necessitating different solutions for high- and low-temperature processes.

Many industrial thermal energy consumers have set ambitious, science-based emissions reduction targets, acknowledging the critical need to lower emissions from both electricity generation and thermal energy usage. However, meeting these individual and national emissions reduction targets will be challenging without further advancement 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 final energy demand is for heating, and about half of this heating demand 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, and few studies on wide-scale applications of industrial electrification technologies or their impacts in different sectors and geographies (Zuberi, Hasanbeigi, and Morrow 2022). 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, CO_2 emissions, and energy costs. Understanding which conventional processes could be electrified and how this impacts emissions and costs can help industrial facilities identify which of their processes may be suitable candidates for electrification. In addition, understanding the potential growth in industrial energy demand that will result from electrification can help utilities, grid operators, electricity regulators, electricity generators, and policymakers 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 China. 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, disproportion 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 China.

The report also estimates the energy and emissions savings from electrification of combustion boilers for ten industrial subsectors in China. The study estimates that electric boilers can reduce onsite energy demand by 28% in 2022, and potentially result in 1,156 PJ of annual onsite energy savings by replacing fossil fuel-fired boilers. While initial electrification could raise annual CO_2 emissions by about 28 $MtCO_2$ by 2030 due to increased electricity demand in our baseline scenario, more aggressive grid decarbonization in our ambitious scenario could lead to a significant reduction in emissions from 2030 onwards, reaching a decrease of 237-372 $MtCO_2$ per year in 2050 across scenarios. The most energy-intensive subsectors, such as the chemicals and steel industries, could see the most significant reductions under this ambitious scenario, although some sectors may experience near-term emissions increases due to China's highly carbon intensive grid. However, it is important to note that given that electrification decisions are made at the facility level, facilities that procure or generate on-site renewable electricity can realize emissions reductions from electrification immediately.

The report also considers the implications of industrial electrification on future electricity generation, transmission, and distribution in Chapter 5. 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 China's electricity grid infrastructure, which will already need to accommodate increasing electricity demand based on current projections. These grid impacts must be considered and addressed to ensure a smooth transition to electrification and realize emissions reductions.

Finally, the report offers eight 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, renewable energy siting, and workforce development.

2

Profile of Industrial Energy Use and Heat Consumption in China

Driven by population growth, rapid urbanization, and both domestic and external demand, China's industrial sector is the largest energy-consuming and CO_2-emitting sector in China. The industrial sector in China accounts for roughly 65% of China's total primary energy use and 70% of its energy-related CO_2 emissions (Figure 1) (Zhou et al. 2022)

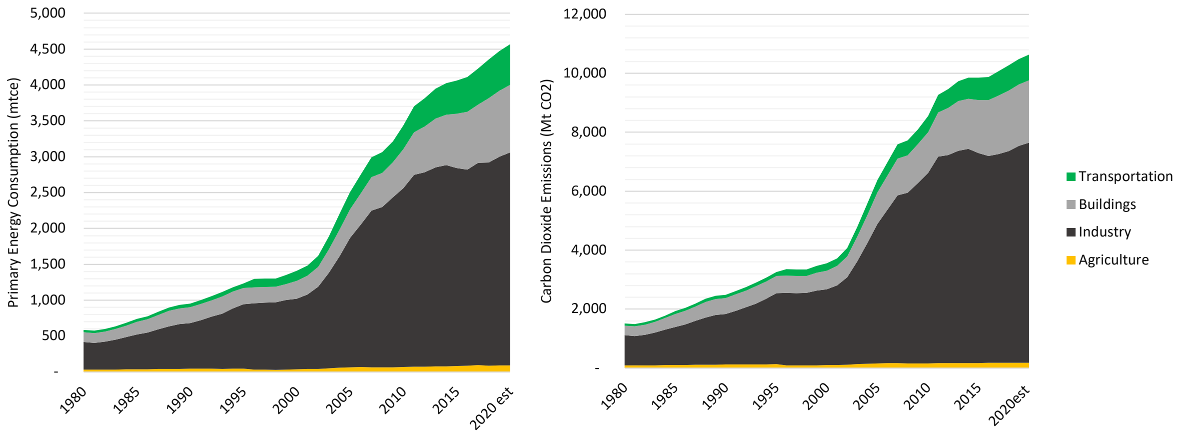


Figure 1. China's primary energy consumption (left) and energy-related CO_2 emissions (right) by end-use sector (1980-2020). Data source: Zhou et al. 2022.

The majority of the energy used in China's industrial sector is fossil fuels, with coal and coal products alone accounting for 48% of final industrial energy use (Lu et al. 2022). However, the share of direct use of coal sharply declined from 47% in 1980 to 19% in 2018. The decline of direct coal use was most significant in the last few years, due to China's increasingly stringent air pollution control policies. However, it is also noteworthy that the share of coke and coke products increased from 14% in 1980 to 28% in 2018. From 2010 to 2018, the share of coke and coke products stayed essentially the same (Figure 2). In addition, the share of natural gas increased from 3% in 2010 to 8% in 2018 while the share of electricity also increased from 17% in 2010 to 22% in 2018.

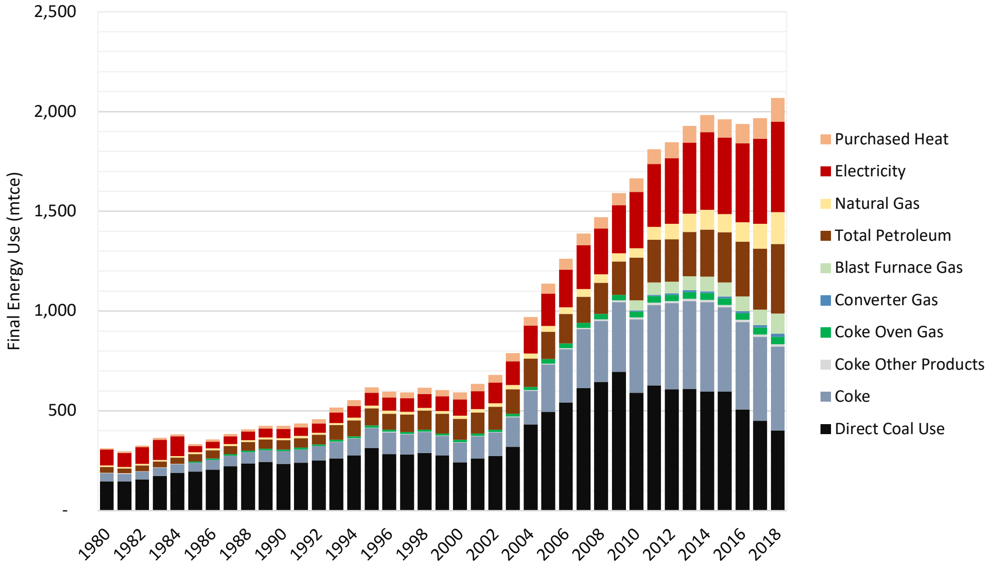


Figure 2. Manufacturing final energy use by energy source in China (1980-2018). Data source: Zhou et al. 2022.

Compared to other countries, China has one of the highest shares of fossil energy inputs into the industrial sector (Figure 3). About 72% of final industrial energy use is from coal, petroleum, and natural gas in China, while the share in other selected countries ranges from 51% (Germany) to 72% (Japan) (IEA, 2021; NBS, 2020).

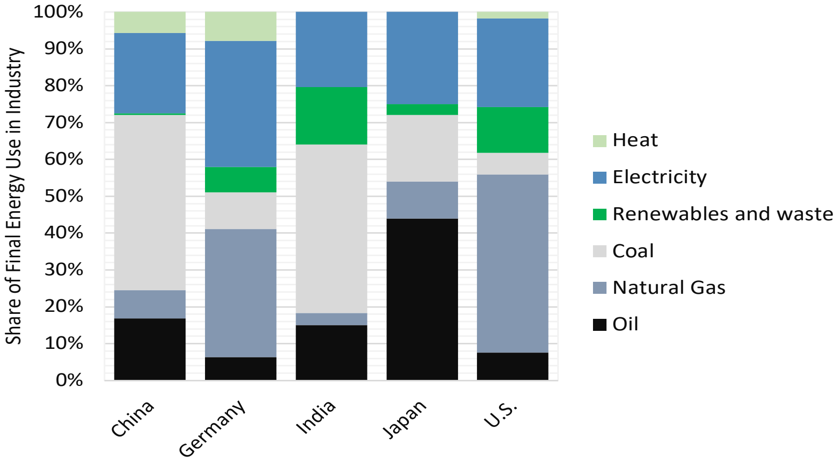


Figure 3: Final industrial energy use by source in selected countries (2018). Data source: Zhou et al. 2022.

Notes: 1) China energy data are from NBS (2020); energy data for other countries are from IEA (2021); 2) both data sets include non-energy use; 3) IEA (2021) defines "Renewables and waste" to include on-site "hydro, geothermal, solar, wind, and tide/wave/ ocean energy and the use of these energy forms for electricity and heat generation, as well as solid biofuels, liquid biofuels, biogases; industrial waste and municipal waste"; 4) "Electricity" refers to electricity purchased from the grid, which was generated via a mixture of renewable and non-renewable sources.

Since joining the World Trade Organization (WTO) in 2001, China has become the world's factory, producing a diverse variety of manufactured goods for both domestic and international consumers. However, in terms of energy use, the majority of China's manufacturing final energy use is in five manufacturing subsectors: ferrous metals, chemicals and chemical products, non-metallic minerals, petroleum refining and coking, and non-ferrous metals (Figure 4).

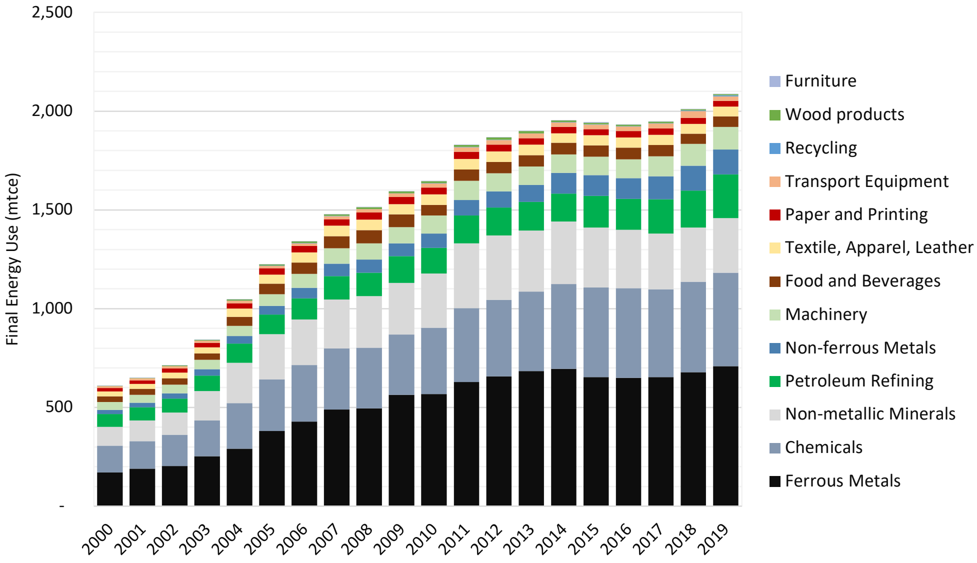


Figure 4: Manufacturing final energy use by subsector in China (2000-2019). Data source: Zhou et al., 2022.

These five subsectors accounted for 86% of total final energy use in China's industrial sector in 2019. Electricity represented between 7% and 16% of final energy use for these subsectors, excluding aluminum and non-ferrous metals, where electricity penetration reached 66%. For China's light industry, such as electronics, food and beverages, textiles, etc., the share of electricity in total final energy use is higher (Yu et al. 2022).

Process heating accounted for between 24% and 84% of final demand in China's top five most energy intensive industrial subsectors. Specifically, process heating systems accounted for 84%, 79%, 78%, 54%, and 24% of the final energy demand in China's cement, iron and steel, petroleum refining, chemicals, aluminum industries, respectively (Yu et al., 2022). Industrial process heating operations include drying, heat treating, curing and forming, calcining, and smelting. Process heating technologies can be grouped into four general categories based on the type of energy consumed: direct fuel-firing, steam-based, electric-based, and hybrid systems (which use a combination of energy types). In process heating, the material is heated by heat transfer from a heat source such as a flame, steam, hot gas, or an electrical heating element by conduction, convection, or radiation — or some combination of these. In practice, lower-temperature processes tend to use conduction or convection, whereas high-temperature processes rely primarily on radiative heat transfer. Energy use and heat losses from the system depend on process heating parameters, system design, operating practices, and other factors (ORNL 2017).

The electrification rate in China's heavy industry has been very low and was flat from 2000 to 2017 (NBS 2020, NBS 2021). When including electricity used for both process heating systems and non-process heating systems (e.g., machine drive systems, process cooling and refrigeration, electro-chemical systems, facility HVAC, and facility lighting), electricity only represented 7% of total final energy use in the petroleum refining and coking industry, 10% in ferrous metals, 15% in non-metallic minerals subsector, and 16% in chemicals. Electricity penetration is higher in non-ferrous metals subsector, reaching 66%.

Industrial heat demand in China's light industries, which account for about 14% of China's manufacturing energy use, typically requires low temperatures below 100°C or in the range of 150°C to 300°C. 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. As shown in Figure 5, the share of electricity in total final energy use in China's light industry is relatively high, especially in electronics, rubber plastics, and machinery industries. However, for other light industries, such as textiles, medicine manufacturing, and food, beverage and tobacco industry, their electrification rates are still relatively low. In 2018, the shares of electricity in food, beverages, and tobacco, medicine, and textiles were 30%, 32%, and 49%, respectively (NBS 2020).

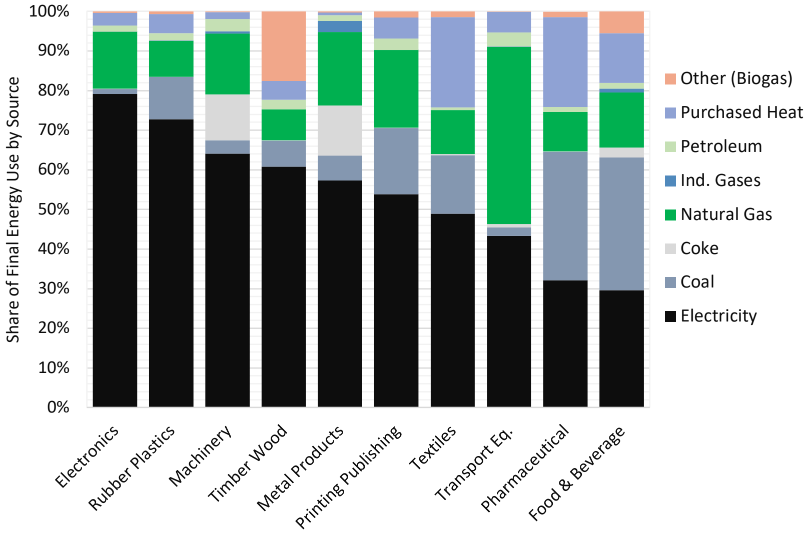


Figure 5: Final energy use by source in China’s light industry (2018). Data source: NBS 2020.

3 Electrification of Industrial Processes in China

3.0. Methodology

This chapter presents the results of our analysis of electrification potential in 14 industrial subsectors (Table 1) in China. 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 China.

Industries:
Table 1 shows China 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 China which are not included in this study since their electrification is particularly challenging due to several techno-economic barriers. In the case of the cement sector, process electrification is in the early stages of development and still faces challenges in meeting the high temperatures and heat transfer required in cement production. 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	Secondary Aluminum	8	Wet corn milling
2	Container glass	9	Soybean Oil
3	Ammonia	10	Meat Production
4	Recycle plastic	11	Steel production
5	Beer	12	Steel Reheating
6	Beet sugar	13	Ethanol
7	Milk powder	14	Pulp and paper

Analysis:
To conduct this bottom-up, systems- and technology-level electrification analysis for each industrial subsector, we followed four steps, as shown in Figure 6. 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. The detailed production processes for many of the sectors covered in this report can be found in our prior publications (e.g. Hasanbeigi et al. 2021). For newly added sectors in this report, we have included production diagrams.

Next, we did a high-level assessment of technology integration needs in each sector. Having the energy intensity of process heating technologies for both conventional and electrified processes, we then calculated the energy use, CO_2 emissions, energy cost, and electricity grid implications of electrification in each industry. For CO_2 emissions, we consider energy-related emissions associated with both fuel and electricity use.

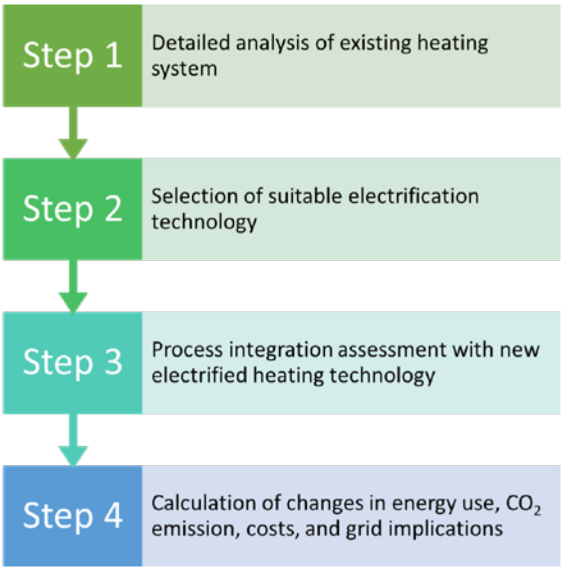


Figure 6. Methodology to estimate electrification potential in China's industrial subsectors.

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, CO_2 emissions, and energy cost implications of electrification in each industry. The electricity grid emissions factor and average unit price of fuel used in our analysis are shown below.

It should be noted that the changes in energy use and CO_2 emissions estimated for each subsector are the total technical potentials assuming a 100% adoption rate, except for the steel industry, which assumes a more gradual transition to electrified technologies. Actual industrial electrification technology adoption will be gradual and over time, and will depend on other factors such as renewable electricity availability, geographic location, etc.

For the energy intensity of processes and technologies used in our analysis, we kept the respective conventional and electrified intensities constant during the study period of 2021-2050. We did not take into account the technology learning curve and gradual improvement in technologies' energy performance (both for conventional and electrified technologies) in our analysis. This was primarily due to a lack of information for projections of energy performance improvement for the range of technologies considered in the analysis.

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

CO_2 emissions:
Two grid emissions factor scenarios are modeled through the analysis: A *baseline* scenario that assumes the national electricity grid achieves net zero emissions in 2060 and an *ambitious* scenario that aligns with achieving a zero-carbon grid by 2050. In the ambitious scenario, we assume that decarbonization is driven by procurement of renewable electricity in addition to grid decarbonization (one third of electricity from zero-carbon sources by 2030, half by 2040, and all by 2050). Additional details are included below.

The electricity grid emissions factor and average unit price of fuels and electricity for China used in our analysis are shown in Table 2.

Table 2. China electricity grid emissions factor and average unit price of energy (in final energy) used in our analysis.

	Unit	2021	2030	2040	2050
Emission factor for grid electricity in China – Baseline scenario	$kgCO_2/MWh$	614	472	315	157
Emission factor for grid electricity in China – Ambitious scenario	$kgCO_2/MWh$	614	315	158	0
Average unit price of electricity for industry in China	2021 US$/kWh	0.097	0.097	0.099	0.103
Average unit price of natural gas for industry in China	2021 US$/kWh	0.045*	0.026*	0.049	0.061
Average unit price of coke and coal for industry in China	2021 US$/kWh	0.012	0.014	0.014	0.014
Average unit price of LPG and fuels for industry in China	2021 US$/kWh	0.054	0.053	0.063	0.069

Note: The price of natural gas in China in 2021 increased substantially, but projections show that the price of natural gas will drop to pre-2021 levels by 2030, and then have a gradual increase over time through 2050.

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

In addition, renewable electricity prices could decrease more substantially than what we assumed in our Base Case price forecast scenario based on projections up to 2050, making electrification technologies more competitive. To address this issue, we added a sensitivity option with a lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the Base Case price forecast. The result of this sensitivity analysis is shown as negative error bars on cost figures.

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 international energy outlook/EIA projections). To address this issue, we added a sensitivity analysis with higher fuel price forecast that assumes 50% higher fuel prices compared with the Base Case price 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 a carbon price of $15, $30, and $50 per tonne of CO_2 in 2030, 2040, and 2050, respectively, based on current and projected carbon prices in China's national emissions trading system (Slater et al. 2021). We assume that the ETS will have full sectoral coverage over the timeline of the study. 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. However, it is very challenging to obtain credible estimates of capital costs for all the analyzed technologies. Generally, initial capital costs of new electrified technologies can be a barrier to their adoption, unless replacing conventional equipment that is already at the end of its 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.

Companies, government, and other stakeholders should also take into account the non-energy benefits of electrified industrial technologies. These include precise temperature control for consistent product quality; faster heating and cooling for improved throughput; advanced process control for optimized efficiency; enhanced safety mitigating risks of explosions or fires; reduced downtime due to fewer moving parts; improved energy efficiency lowering costs and potentially boosting productivity. Environmental benefits through reduced air pollutant emissions can enhance personnel health. Furthermore, easy integration with digital technologies like IoT, data analytics, and automation can improve product quality and productivity. Electrified technologies also provide scalability and flexibility for adaptive production capabilities, and they tend to produce less noise and vibration, promoting a better production environment.

3.1. Secondary aluminum industry

The aluminum production process can be divided into primary and secondary methods. Primary production involves transforming bauxite ore, obtained through mining, into aluminum oxide (Al_2O_3, also known as alumina). This transformation is achieved through the Bayer Process. Subsequently, alumina is converted into fresh aluminum using electroreduction via the Hall-Héroult Process (H.-G. Schwarz, in Encyclopedia of Energy, 2004).

Secondary production of aluminum involves the recycling of various industrial aluminum scraps. These can include internally rejected scrap, saw residues, or scrap aluminum contaminated with plastics, paints, or other metals. The industrial aluminum scrap is typically melted in a furnace at around 700-720 ℃. Contaminated aluminum, on the other hand, undergoes preheating on a bridge in a second furnace. This preheating is carried out using 800℃ air emanating from the first furnace (Keller, 1994). The resulting molten aluminum from both furnaces is then extracted for subsequent mixing and casting. It’s worth noting that the prevalent method of secondary aluminum production currently relies primarily on fuel gas-fired furnaces (Kortes, 2019).

China is currently the world’s largest primary aluminum producer. Secondary aluminum production in China is estimated to increase from 7 Mt in 2021 to 40 Mt in 2050 (Dai 2019). Since primary aluminum production is already an electrified process, this report focuses on electrification of furnaces used for the secondary aluminum production.

Induction coreless furnaces and single-shut induction furnaces are two major types of electric aluminum melting furnaces. A detailed explanation of conventional and electrified processes for the aluminum industry is provided in our previous report (Hasanbeigi et al. 2021). Table 3 compares the energy intensity of the secondary aluminum production industry's conventional and electric processes.

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

Conventional System	**Process Steps**	**All Electric System**
Tower Furnace		**Single-shot induction**
Melting		Melting
Holding		
Transfer and holding		
1,326	**Total Energy Intensity (kWh/tonne)**	**657**

Energy use

Figure 7 shows that electrification will significantly reduce the total final energy use for secondary aluminum production in China 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.

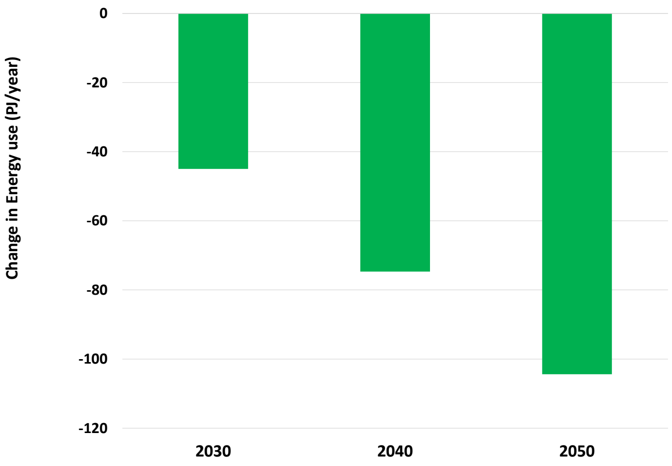


Figure 7. Change in the secondary aluminum industry's total final energy use after electrification (technical potential assuming 100% adoption rate)

CO_2 emissions

Electrification of secondary aluminum production has the potential to significantly reduce annual CO_2 emissions in China by 2050. This reduction in CO_2 emissions stems from the decreasing CO_2 emissions factor of the electricity grid, reflecting the ongoing process of grid decarbonization through 2050 in China.

Figure 8 presents the change in net CO_2 emissions from China's secondary aluminum industry post-electrification under both the baseline and ambitious scenarios. The implementation of electrification in secondary aluminum production could lead to a decline in CO_2 emissions by

2030 under both scenarios examined. However, under the ambitious scenario, the potential for CO_2 emissions reduction in future years (2030, 2040, and 2050) is markedly greater than the baseline scenario due to the assumption of a more rapid grid decarbonization.

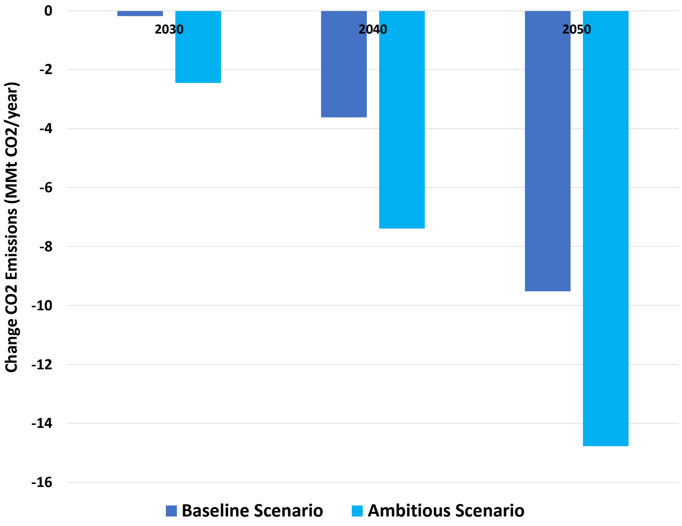


Figure 8. Change in the secondary aluminum industry's net CO_2 emissions after electrification - baseline and ambitious scenarios (technical potential assuming 100% adoption rate)

Figure 9 shows the cumulative change in CO_2 emissions in the secondary aluminum industry over the lifetime of electrified technologies over the period of 2030 – 2050 for both the baseline and ambitious scenarios.

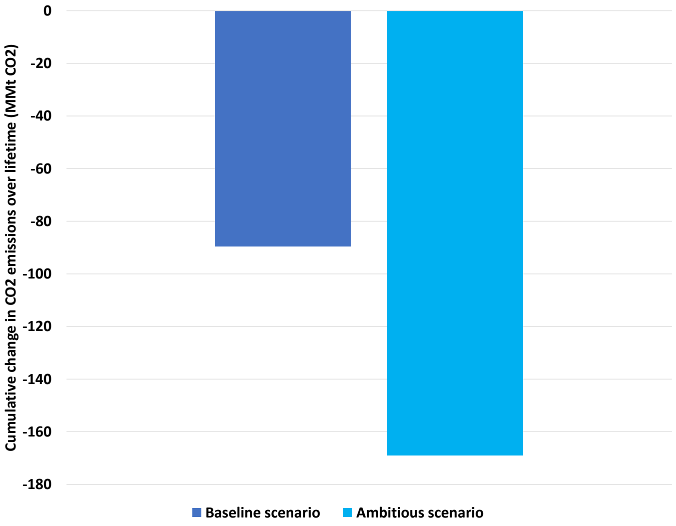


Figure 9. Cumulative change in CO_2 emissions in the secondary aluminum industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming 100% adoption rate)

Energy cost

Figure 10 shows that with the Base Case electricity price forecast (see section 2), the energy cost (in 2021$) per unit of production (tonne of secondary aluminum) in 2030 for the electrified process in the secondary aluminum industry is higher than that of the conventional process.

It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified secondary aluminum process. We have provided sensitivity options with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the Base Case price forecast in negative error bars and a higher fuel price forecast that assumes 50% higher fuel prices compared with the Base Case price forecast in positive error bars. Regarding these assumptions, the energy price of the electrified process could be cost-competitive compared with the conventional process in 2030.

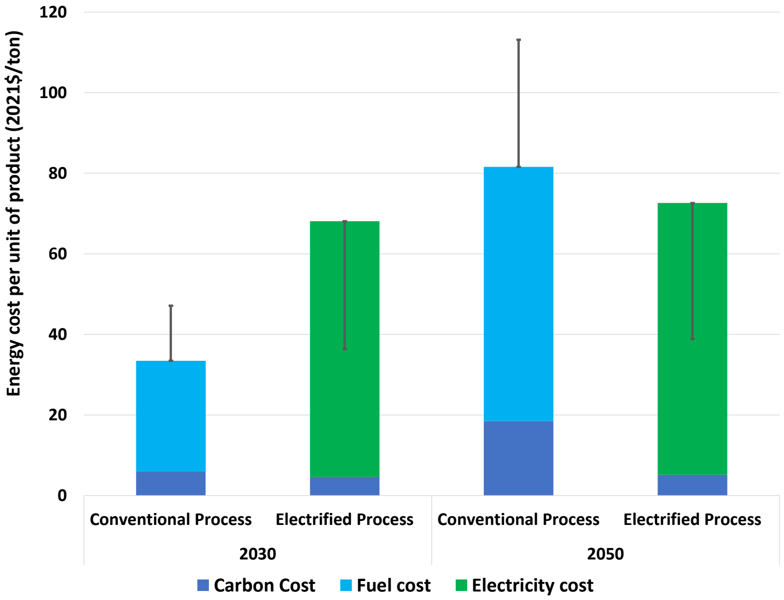


Figure 10. Energy cost per unit of production in the secondary aluminum industry
Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the Base Case price forecast and the positive error bars show the energy cost per unit of production assuming fuel price 50% higher than the Base Case price forecast.

3.2. Container glass industry

The glass industry manufactures a wide range of products used across various key sectors of China'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). The total quantity of container glass production in China is estimated to be approximately 17.9 Mt in 2021. Future production through 2050 is assumed to remain constant.

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 (authors' analysis based on US DOE 2017a and Beyond Zero Emissions 2019)

Conventional System	Process steps	All Electric System
Electrically-powered mixer/crusher	Mixing	Electrically-powered mixer/crusher
Gas-fired furnace	Melting	Electrically-powered glass melter
Forehearth and forming equipment	Conditioning & Forming	Electric forehearths
Gas-fired Annealing lehr	Post Forming (Annealing)	Electric Annealing lehr
1,612	Thermal demand (kWh/tonne)	-
458	Electricity demand (kWh/tonne)	1,308
2,069	Total Energy Intensity (kWh/tonne)	1,308

Energy use

Figure 11 shows energy savings from container glass production electrification across 2030-2050. The constant energy savings over time is because constant levels of container glass production are assumed up to 2050.

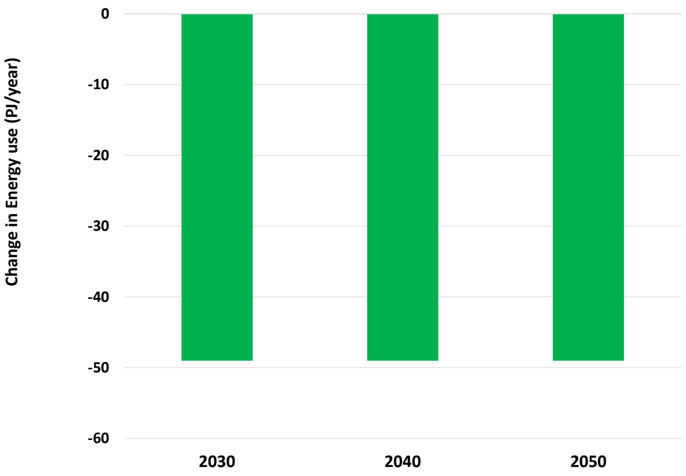


Figure 11. Change in the container glass industry's total final energy use after electrification
(Technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 12 shows the container glass industry's change in net CO_2 emissions after electrification. The container glass industry's electrification can result in a decrease in CO_2 emissions in 2030 in both scenarios. Under ambitious scenario, the CO_2 emissions reduction potential in China in years 2030 and 2040 is substantially higher than the baseline scenario because more rapid grid decarbonization is assumed.

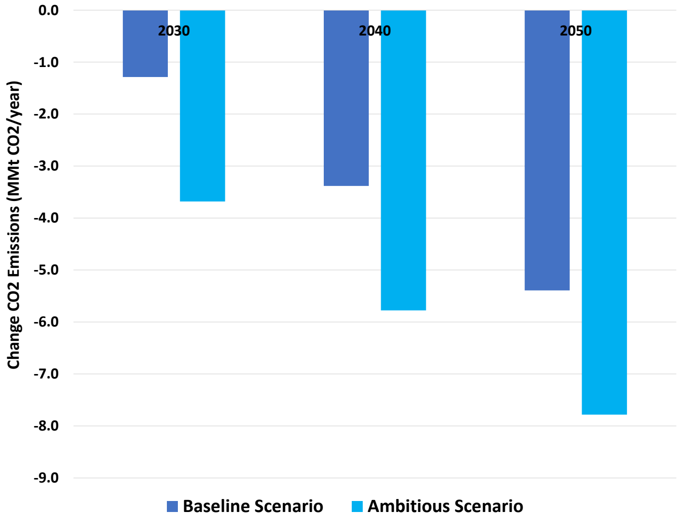


Figure 12. Change in the container glass industry's net CO_2 emissions after electrification - baseline scenario (technical potential assuming 100% adoption rate)

Figure 13 shows the cumulative change in CO_2 emissions in the container glass industry over lifetime of electrified technologies over the period of 2030 – 2050 for both baseline and ambitious scenarios. As seen in this figure, electrification can reduce CO_2 emissions by about 70 Mt during these twenty years under the baseline scenario and by more than 120 Mt under the ambitious scenario.

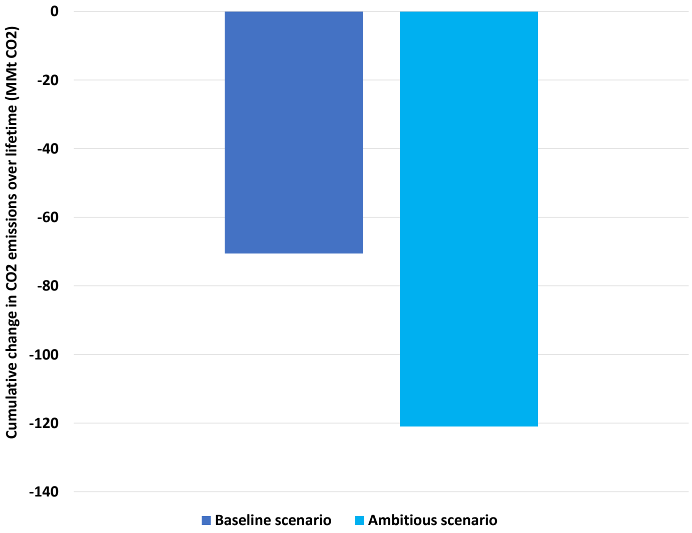


Figure 13. Cumulative change in CO_2 emissions in the Glass industry over lifetime of electrified technologies over the period of 2030 - 2050 (This is the technical potential assuming 100% adoption rate)

Energy cost
Figure 14 shows that with the Base Case electricity price forecast, the energy cost (in 2021$) per unit of production (tonne of glass) in 2030 for the electrified process in the container glass industry is higher than that of the conventional process.

It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified container glass process. We have provided sensitivity options with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the Base Case forecast in negative error bars and a higher fuel price forecast that assumes 50% higher fuel prices compared with the Base Case forecast in positive error bars. Regarding these assumptions, the energy price of the electrified process could be cost-competitive compared with the conventional process in 2030.

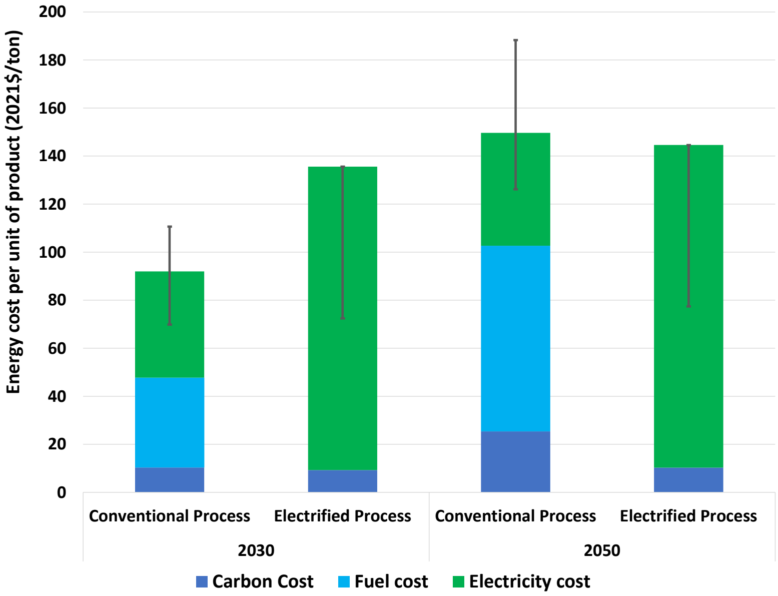


Figure 14. Energy cost per unit of production in the container glass industry
Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the Base Case forecast and the positive error bars show the energy cost per unit of production assuming fuel price 50% higher than the Base Case 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 have successfully developed processes that result in wider access to ammonia at highly reduced costs. China is one of the world's leading producers and consumers of ammonia. In 2021, China produced a total of approximately 51.2 million metric tons of ammonia (National Bureau of Statistics of China, 2022), primarily using coal as feedstock. Hence, in this study, we investigated the electrification of ammonia plants by employing coal as both the feedstock and energy source. Around 88% of ammonia manufactured globally is utilized for fertilizer production and the remainder is used to support formaldehyde production (AIChE 2016).

In the conventional coal gasification process, coal and limestone are initially obtained from the storage area, prepared (e.g., crushed, sized), then metered and mixed before being conveyed to the gasifier. As coal enters the gasifier, it undergoes drying through water vaporization and pyrolysis, resulting in the production of coke. Steam and oxygen are introduced into the gasifier, reacting with the char to predominantly generate carbon monoxide and carbon dioxide. These gasification reactions take place at high temperatures (around 700°C) and medium pressures (approximately 3–4 MPa), with gaseous products ascending countercurrent to the coal introduced in the gasifier.

The gas output from the gasification process is directed to two-stage high and low-temperature reactors, where the majority of carbon monoxide is converted into carbon dioxide and hydrogen. The gas, having undergone the water-gas shift reaction, then undergoes cooling through a series of heat exchangers, causing the condensation and removal of water present in the gas. The gas stream is routed to a CO_2 absorption system for the elimination of CO_2 and H_2S, with a Claus plant employed to recover sulfur from the H_2S-rich stream. The resulting gas stream, free from CO_2, is heated and sent to the methanation reactor, where residual carbon oxides are transformed into methane in the presence of catalysts.

Following a nitrogen wash that removes remaining impurities such as carbon monoxide and methane, the resulting gas is compressed and directed to the ammonia reactor—a horizontally oriented, intercooled converter. Here, hydrogen and nitrogen react at the correct stoichiometric ratio, yielding ammonia through a catalytic process (Intratec, 2019). In a fully electric process, hydrogen is derived via electrolysis.

A comprehensive explanation of the conventional and electrified processes within the ammonia industry can be found in our prior report (Hasanbeigi et al. 2021). Table 5 contrasts the energy intensity between the conventional and electric processes used in the ammonia industry.

Table 5. Conventional and electric ammonia production processes' energy intensities of (Adapted from Beyond Zero Emissions 2019)

Conventional System Process	Process steps	All Electric Process
Primary Reformer Feedstock	Using different process methods	Desalination
Gasification		Electrolysis
Shift-gas reactor		Air separation to acquire nitrogen
CO_2 Removal		Hydrogen and nitrogen reaction in Haber-Bosch process
Methanation		
Air separation to acquire nitrogen		
Ammonia Synthesis*		
Boiler **		
Turbine, Compressor, Others (Electrical)		
10,770	Thermal/feedstock demand (kWh/tonne)	-
1,230	Electricity demand (kWh/tonne)	9,494
12,000	**Total Energy Intensity (kWh/tonne)**	**9,494**

* Hydrogen and nitrogen are reacted at 450 C and 200 bar pressure over a catalyst to form ammonia.
** Ammonia synthesis produce waste heat, which is reused in the boilers.

Energy use

Electrification will significantly reduce the ammonia industry's total final energy use during the study period (Figure 15). The energy savings increase over time because an increase in ammonia production is assumed through 2050.

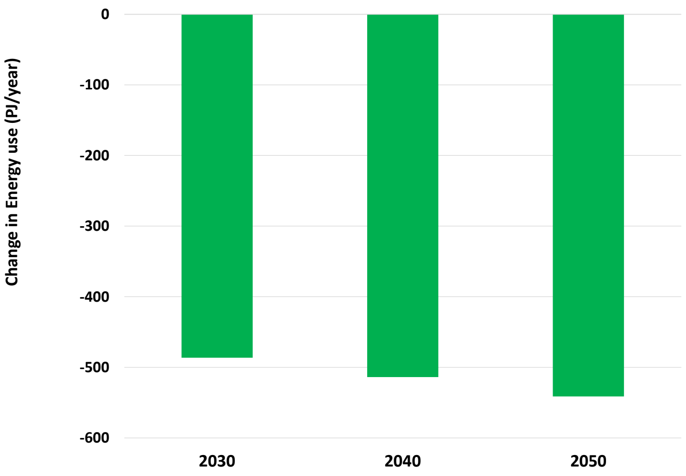


Figure 15. Change in the ammonia industry's total final energy use after electrification of coal-base plants. (Technical potential assuming 100% adoption rate)

CO_2 emissions

Ammonia production electrification through production of hydrogen by electrolysis would result in an increase in CO_2 emissions in 2030 in baseline scenario (Figure 16). Emissions reductions begin in baseline scenario in 2040 because of the decreasing grid CO_2 emissions factor.

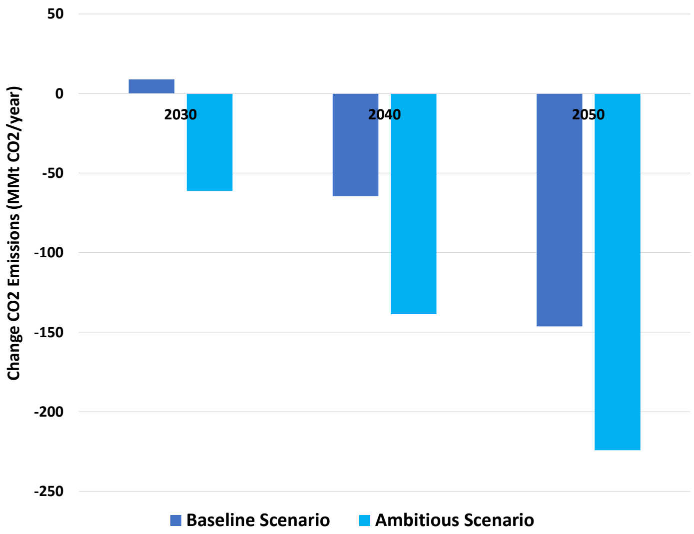


Figure 16. Change in ammonia industry's net CO_2 emissions after electrification of coal-base plants. (Technical potential assuming 100% adoption rate. In the near term by 2030, the actual adoption rate will be low. Therefore, in sectors where there is a projected increase in CO_2 emissions in 2030, the actual increase will be very small. In addition, it is unlikely that all electrolysis-based hydrogen production will be based on grid electricity – most will likely have dedicated renewable electricity supply, which would reduce the estimated increase in emissions.)

Figure 17 shows the cumulative change in CO_2 emissions in the ammonia production industry over the lifetime of electrified technologies over the period of 2030 – 2050 for both the baseline and ambitious scenarios. As seen in this figure, electrification will decrease CO_2 emissions by about 1,400 Mt during these twenty years in China under the baseline scenario. Electrification under the ambitious scenario can reduce CO_2 emissions by about 2,900 Mt during the study period in China's ammonia industry.

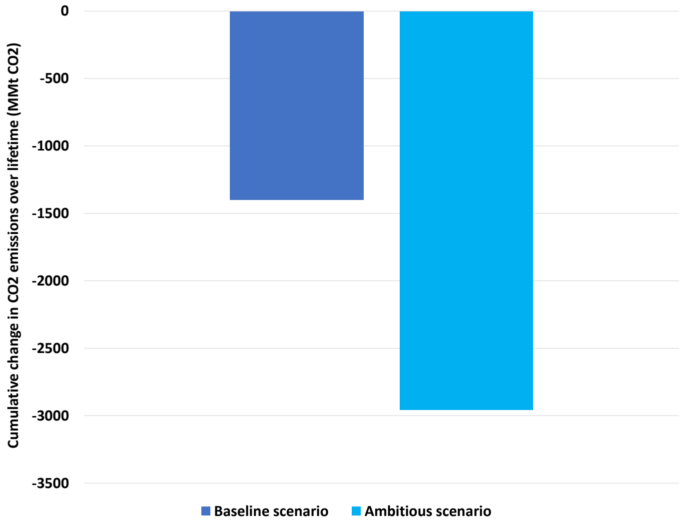


Figure 17. Cumulative change in CO_2 emissions in the ammonia industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming 100% adoption rate)

Energy cost

Figure 18 shows that with the Base Case electricity price forecast, the energy cost (in 2021$) per unit of production (tonne of ammonia) in 2030 for the electrified process in the ammonia industry is higher than that of the conventional process in China. It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified ammonia production process. We have provided sensitivity options with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the Base Case price forecast in negative error bars and a higher fuel price forecast that assumes 50% higher fuel prices compared with the Base Case price forecast in positive error bars.

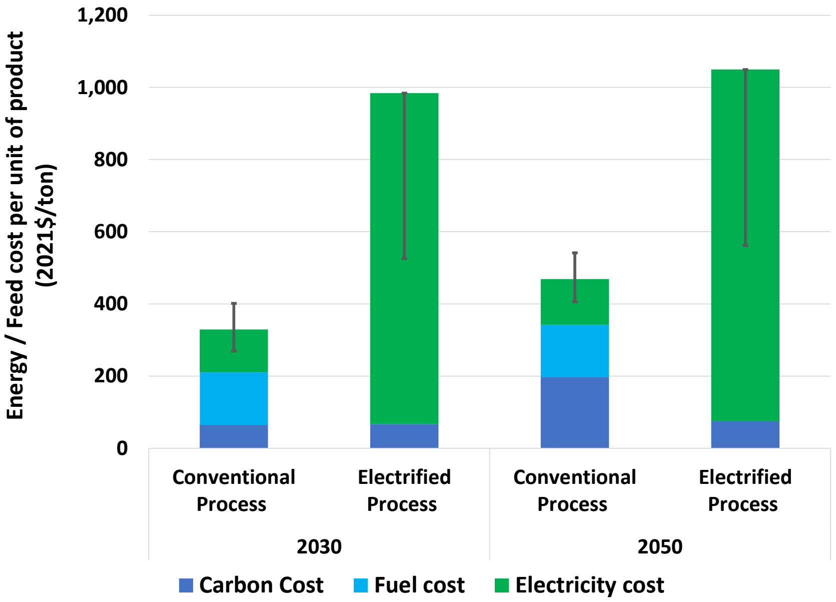


Figure 18. Energy cost per unit of production in the ammonia industry
Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the Base Case price forecast and the positive error bars show the energy cost per unit of production assuming fuel price 50% higher than the Base Case price forecast.

3.4. Plastic recycling industry

Plastics constitute an increasing share of municipal solid waste (MSW). Various types of plastics are incorporated in diverse MSW categories. The containers and packaging category predominantly consists of items like bags, packaging materials, polyethylene terephthalate (PET) bottles and jars, high-density polyethylene (HDPE) bottles, and other containers (EPA 2017).

The primary objectives of plastic recycling are to mitigate plastic pollution and to decrease the use of virgin materials in the production of plastic products. In 2021, China recycled an estimated 16 Mt of plastics (Wang, 2022).

Here, we compare the energy intensities of the electrified plastic recycling process and the traditional virgin resins production method in petrochemical plants. The energy- and emissions-saving potential of the electrified plastic recycling process is in addition to the other environmental benefits that plastic recycling delivers. It should be noted that virgin resins produced in petrochemical plants can be used in a wide range of low-to high-value applications while recycled plastics typically have applications in the low-value range. A detailed explanation of conventional and electrified processes for plastic manufacturing is provided in our previous report (Hasanbeigi et al. 2021). Tables 6 and 7 compares the energy intensities of the conventional and electric processes for plastic manufacturing.

Table 6. Original polymer production energy intensity (Used as plastic main raw materials) (Gervet, 2007).

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

Table 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

In Table 6, the displayed conventional energy intensity represents the average energy needed for the production of Polyethylene (PE), Polypropylene (PP), and Polyethylene Terephthalate (PET) using conventional methods.

Energy use

Figure 19 shows that using the electrified plastic recycling process will significantly reduce the total final energy use in plastic production compared to virgin resin production during the study period, up to 2050.

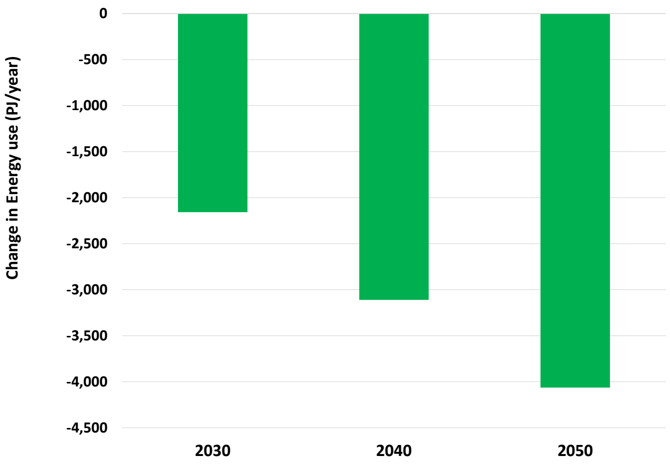


Figure 19. Change in the plastics industry's energy use using electric plastic recycling process
(Technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 20 shows the plastic industry's change in net CO_2 emissions after electrification under the baseline and ambitious scenarios. Because of the substantial energy savings from plastic production electrification (shown in Figure 19), electrification results in CO_2 emissions reductions in 2030. The decline in the CO_2 emissions reduction potential between 2030 and 2050 shown in Figure 20 results from a decline in the electricity grid's CO_2 emissions factor in this period: as the grid decarbonizes, virgin resin production emissions intensity will reduce, thereby reducing the difference between the conventional virgin resin process and the electrified recycled plastic process. Since the conventional process uses a considerable amount of electricity, under the ambitious scenario, the CO_2 emissions reduction potential is slightly lower than the baseline scenario.

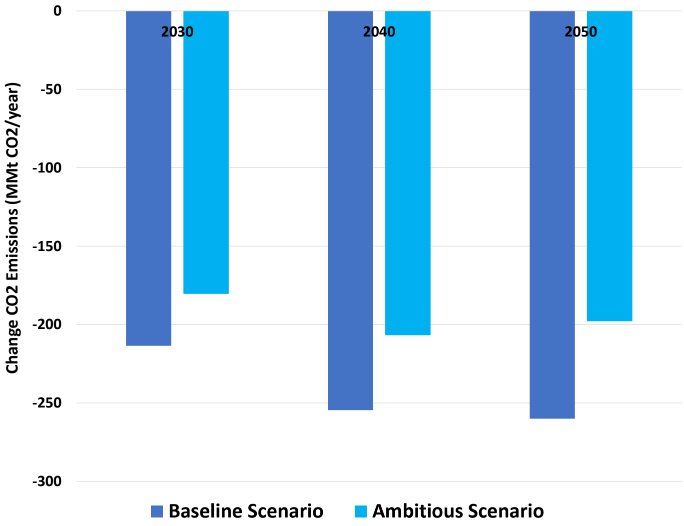


Figure 20. Change in the plastics industry's net CO_2 emissions using electric plastic recycling process. (Technical potential assuming 100% adoption rate)

Figure 21 shows the cumulative change in CO_2 emissions in the plastic recycling industry over the lifetime of electrified technologies over the period of 2030 – 2050 for both the baseline and ambitious scenarios. As seen in this figure, electrification can reduce CO_2 emissions by about 5100 Mt during these twenty years in China under the baseline scenario. Given that the conventional recycling process consumes a substantial amount of electricity, and the electrified process achieves over 95% energy savings (both in terms of electricity and fuel), the CO_2 emissions reduction potential under the ambitious scenario is marginally less than under the baseline scenario.

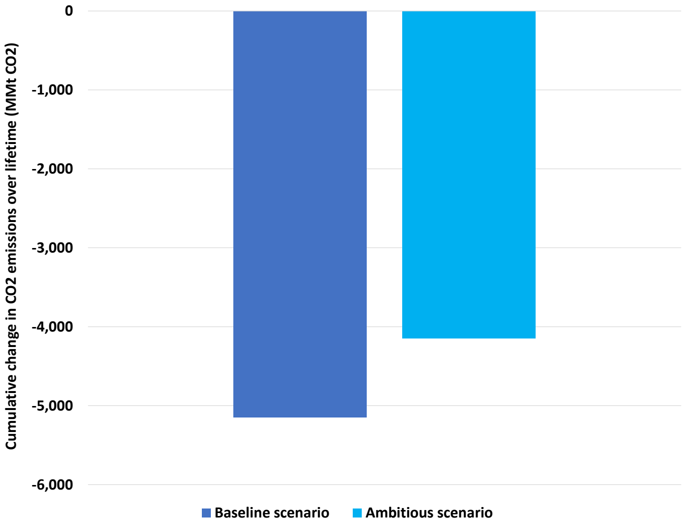


Figure 21. Cumulative change in CO_2 emissions in the plastic recycling industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming 100% adoption rate)

Energy cost

Figure 22 shows that the energy cost (in 2021$) per unit of production (tonne of plastic) in 2030 and 2050 for the electrified process in the recycling plastic industry is significantly lower than that of the conventional process. The main reason is that energy savings (for both electricity and fuel) in the electrified recycling process is more than 95%.

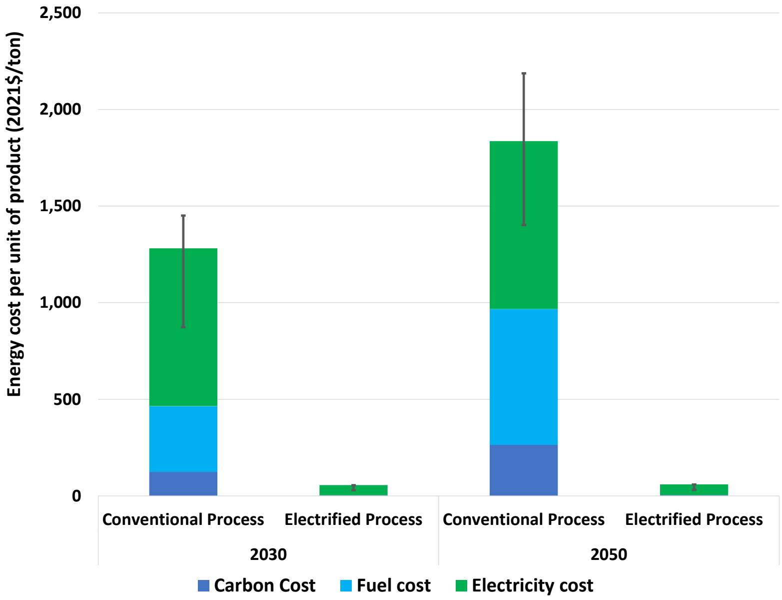


Figure 22. Energy cost per unit of production in the recycling plastic industry
Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the Base Case price forecast and the positive error bars show the energy cost per unit of production assuming fuel price 50% higher than the Base Case price forecast.

3.5. Beer industry

The total quantity of brewery production in China was estimated to be approximately 341 million hectoliters in 2021 (National Bureau of Statistics, 2022.) 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 varietals and temperature, yield a wide range of beer types and styles (Sánchez 2017). Heat pumps could be utilized to electrify the beer production process in four process stages. A detailed explanation of the beer industry's conventional and electrified processes is provided in our previous report (Hasanbeigi et al. 2021). Table 8 compares the energy intensity of beer production's conventional and electric processes, with the specifications of the required heat pumps listed in adjacent columns.

Table 8. Conventional and electric beer production processes' energy intensities (Beyond Zero Emissions 2019).

Conventional System	Process steps	All Electric Process	HP Output Temperature (Celsius)	Coefficient of Performance
Centralized Gas Boiler System	Mashing	Heat Pump 4	80	4
Centralized Gas Boiler System	Boiling	Heat Pump 1&2	110	1.8
Centralized Gas Boiler System	Pasteurization	Heat Pump 3	60	5
Centralized Gas Boiler System	Cleaning & Production Support	Heat Pump 4	80	4
36.3	Total Energy Intensity (kWh/hectoliter)	10.2		

Energy use

Beer production electrification will significantly reduce the total final energy use during the study period (Figure 23). The energy savings increase over time because an increase in production is assumed up to 2050.

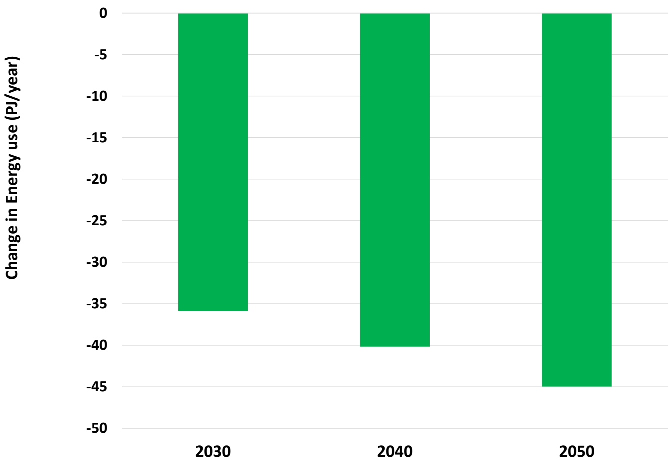


Figure 23. Change in the beer industry's total final energy use after electrification
(Technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 24 shows the beer industry's change in net CO_2 emissions after electrification under the baseline and ambitious scenarios. Beer production electrification results in a drop in CO_2 emissions in 2030. Electrification further reduces annual CO_2 emissions by 2050 because of grid decarbonization.

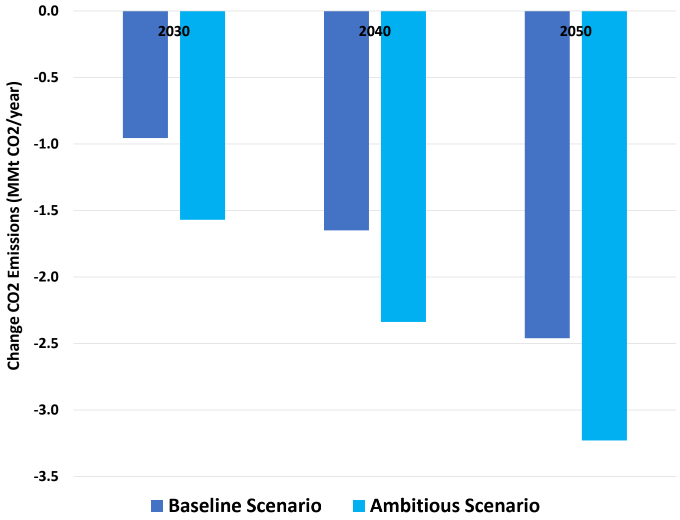


Figure 24. Change in the beer industry' net CO_2 emissions after electrification - baseline scenario (Technical potential assuming 100% adoption rate)

Figure 25 shows the cumulative change in CO_2 emissions in the beer industry over the lifetime of electrified technologies over the period of 2030 – 2050 for both baseline and ambitious scenarios. As seen in this figure, electrification can cumulatively reduce CO_2 emissions by about 30 and 50 Mt during these twenty years in China under the baseline and ambitious scenarios, respectively.

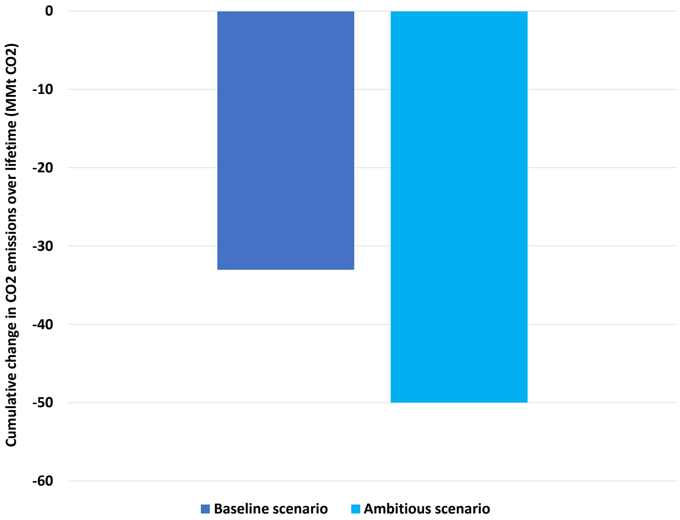


Figure 25. Cumulative change in CO_2 emissions in the beer industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming 100% adoption rate)

Energy cost

Figure 26 shows that with the Base Case electricity price forecast, the energy cost (in 2021$) per unit of production (hectoliter of beer) in 2030 for the electrified process in the beer production industry is a bit higher than that of the conventional process in China.

It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified beer process. We have provided sensitivity options with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the Base Case forecast in negative error bars and a higher fuel price forecast that assumes 50% higher fuel prices compared with the Base Case forecast in positive error bars. With these assumptions, the energy price of the electrified process could be cost-competitive compared with the conventional process even in 2030.

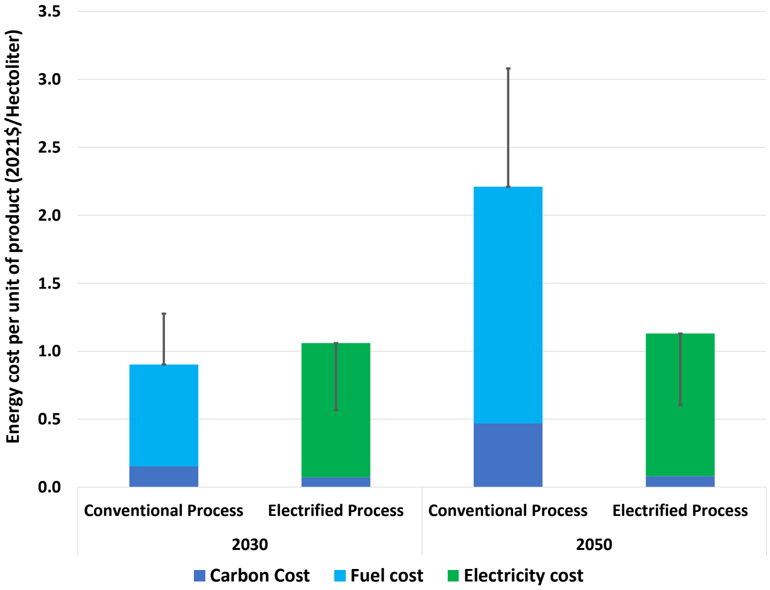


Figure 26. Energy cost per unit of production in the beer production industry
Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the Base Case price forecast and the positive error bars show the energy cost per unit of production assuming fuel price 50% higher than the Base Case price forecast.

3.6. Beet sugar industry

Granulated white sugar, a widely used sweetener, is derived from sugar cane and sugar beet plants. Commonly known as “table sugar,” it is one of the purest food products with purity levels reaching approximately 99.95%. Although the sugar content in beet and cane juices is roughly comparable, the impurity content varies, with about 2.5% found in beet juice and 5% in cane juice. The refining processes and chemicals used for cane and beet sugars differ, reflecting the variations in impurities and product compositions (Campos 2020).

Bagasse, a dry pulpy residue obtained as a by-product of the sugar cane sugar manufacturing process, is utilized as a fuel in cogeneration systems that provide heat and electricity for the sugar production process. Over the last few years, numerous sugar cane factories have produced excess electricity that can be sold to the grid, providing an additional revenue stream (Ensinas 2006). Therefore, sugar cane production electrification was deemed less likely and this study focuses on beet sugar production electrification. Total annual China beet sugar production is estimated to be around 14.3 million metric tonnes (National Bureau of Statistics 2022). It is also one of the food and beverage industry’s highest energy-consuming subsectors.

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

Table 9. Conventional and electric beet sugar production processes' energy intensities (Hasanbeigi et al. 2021)

Conventional System	Process steps	All Electric System
Conventional Steam Generator	Juice Diffusion	Heat Pump
Conventional Steam Generator	Juice Purification	Heat Pump
Conventional Steam Generator	Evaporation	Heat Pump
Conventual Steam Generator	Crystallization	Electric Steam Boiler
Direct Fuel Base Dryer	Pulp Drying	Electric Air Dryer
1,742	Thermal demand (kWh/tonne)	-
168	Electricity demand (kWh/tonne)	1,220
1,911	Total Energy Intensity (kWh/tonne)	1,220

Energy use

Electrification will reduce the total final energy use for beet sugar production in China (Figure 27). The energy savings is constant from 2030 to 2040 because of assume constant production, and energy savings drop in 2050 because projections show that production will decrease in 2050 (Zhao 2021).

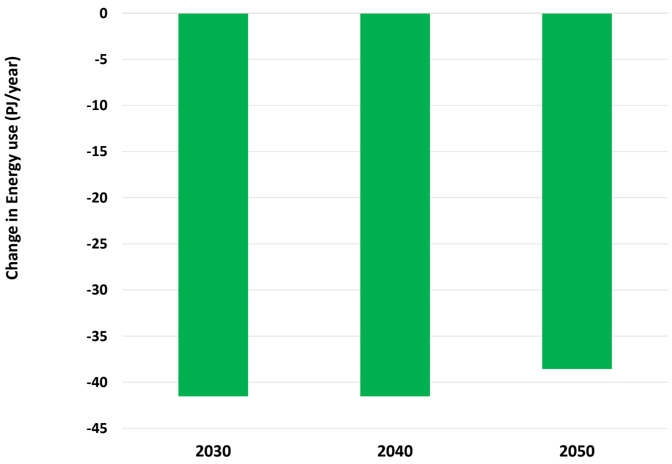


Figure 27. Change in the beet sugar industry's total final energy use after electrification (Technical potential assuming 100% adoption rate)

Beet sugar production electrification could result in decrease in CO_2 emissions in 2030 under both scenarios (Figure 28). As the electricity grid decarbonizes between 2030 and 2050, annual CO_2 emissions reductions from electrified beet sugar production are realized in 2040 and 2050.

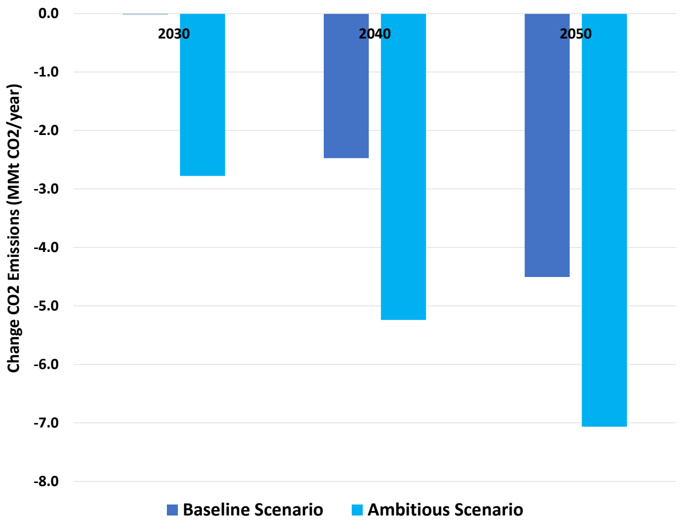


Figure 28. Change in the beet sugar industry's net CO_2 emissions after electrification. (technical potential assuming 100% adoption rate. In the near term by 2030, the actual adoption rate will be low. Therefore, in sectors where there is a projected increase in CO_2 emissions in 2030, the actual increase will be very small.)

Figure 29 shows the cumulative change in CO_2 emissions in the beet sugar industry over the lifetime of electrified technologies over the period of 2030 – 2050 for both baseline and ambitious scenarios. As seen in this figure, electrification can reduce CO_2 emissions by about 50 and 100 Mt during these twenty years in China under the baseline and ambitious scenarios, respectively.

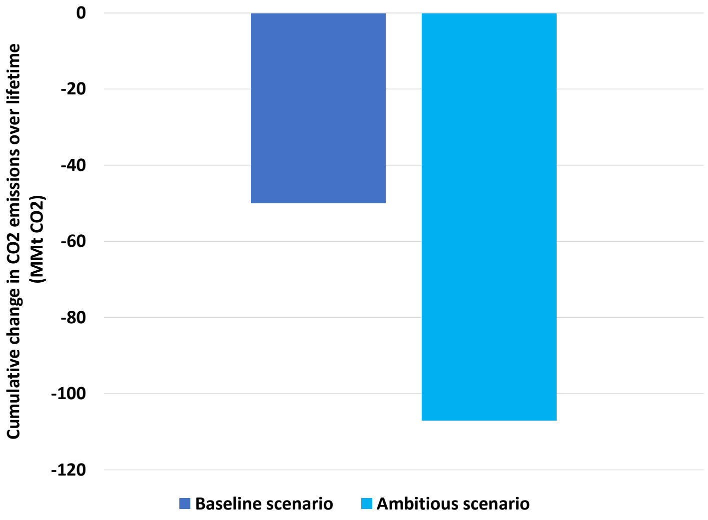


Figure 29. Cumulative change in CO_2 emissions in the beet sugar industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming 100% adoption rate)

Energy cost

Figure 30 shows that with the Base Case 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.

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 lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the Base Case forecast in negative error bars and a higher fuel price forecast that assumes 50% higher fuel prices compared with the Base Case forecast in positive error bars. Regarding these assumptions, the energy price of the electrified process could be cost-competitive compared with the conventional process even in 2030.

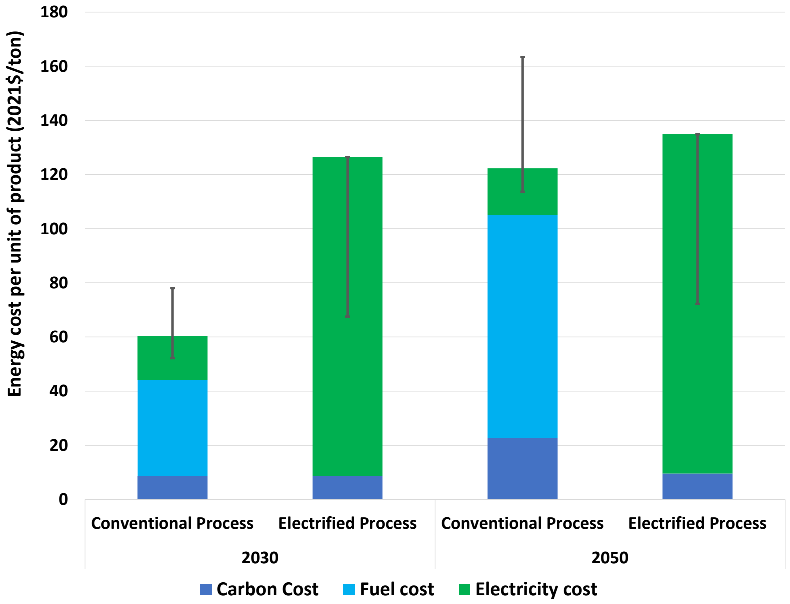


Figure 30. Energy cost per unit of production in the beet sugar industry
Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the Base Case forecast and the positive error bars show the energy cost per unit of production assuming fuel price 50% higher than the Base Case forecast.

3.7. Milk powder industry

Dehydrating liquid milk using drying processes creates powdered milk or dried milk. Milk preservation is one of the main reasons to dry it since milk powder has a much longer shelf life as compared to liquid milk and has no refrigeration requirements (Rotronic 2015). China is one the world's largest manufacturers of skim milk powder (SMP) or nonfat dry milk, with close to 1 Mt produced in 2021. 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 10 compares the energy intensity of the milk powder industry's conventional and electric processes.

Table 10. Conventional and electric milk powder production processes energy intensities (Beyond Zero Emissions 2018).

Conventional System	Process Steps	All Electric System
Centrifuge	Separation	Centrifuge
-	Reverse Osmosis	Reverse Osmosis Pump
Steam Boiler	Pre-Heating	Heat Pump 1
Mechanical and Thermal Vapor Recompression	Evaporation	Mechanical and Thermal Vapor Recompression
Steam Boiler	Drying	Heat Pump 2, Electric Air Heater
Fluidized Bed	Cooling	Fluidized Bed
1,951	Thermal demand (kWh/tonne)	-
218	Electricity demand (kWh/tonne)	762
2,169	Total Energy Intensity (kWh/tonne)	762

Energy use

Figure 31 shows that electrification will significantly reduce the total final energy use from milk powder production during the study period of 2030-2050. The electrification of milk powder production would reduce the total energy demand of the process, in spite of the projected increase in production between 2030 and 2050, and could lead to energy savings in excess of 7,000 TJ annually in 2050.

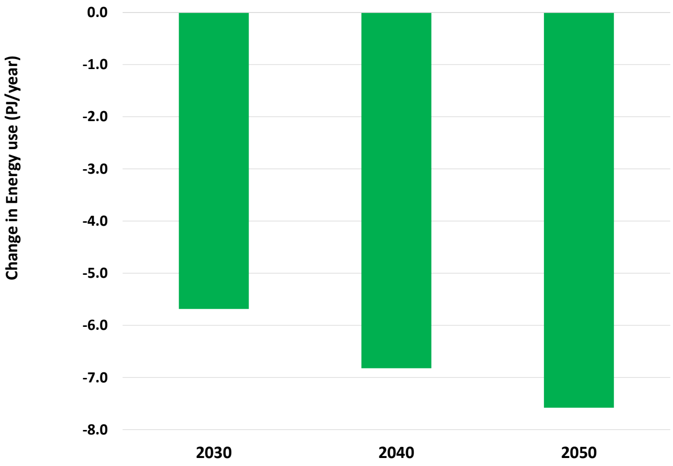


Figure 31. Change in the milk powder industry's total final energy use after electrification
(Technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 32 shows the milk powder industry's change in net CO_2 emissions after electrification under the baseline and ambitious scenarios. Milk powder production electrification results in a drop in CO_2 emissions in 2030. Electrification further reduces annual CO_2 emissions by 2050 because of grid decarbonization.

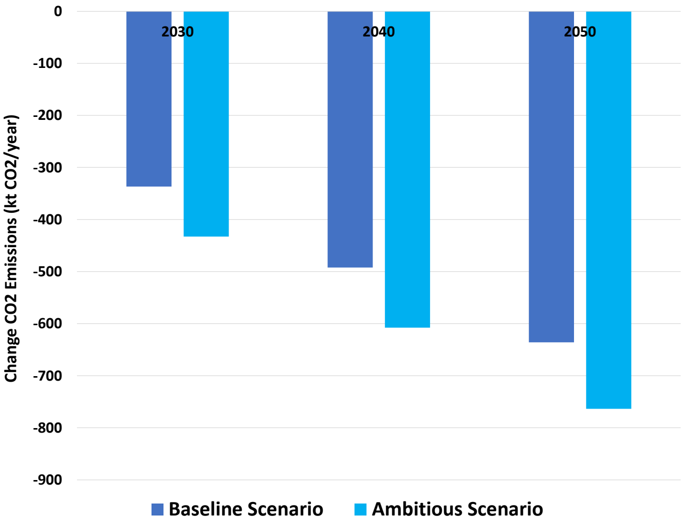


Figure 32. Change in the milk powder industry's net CO_2 emissions after electrification.
(technical potential assuming 100% adoption rate)

Figure 33 shows the cumulative change in CO_2 emissions in the milk powder industry over the lifetime of electrified technologies over the period of 2030 – 2050 for both baseline and ambitious scenarios. As seen in this figure, electrification can reduce CO_2 emissions by about 10.5 and 13 Mt during these twenty years in China under the baseline and ambitious scenarios, respectively.

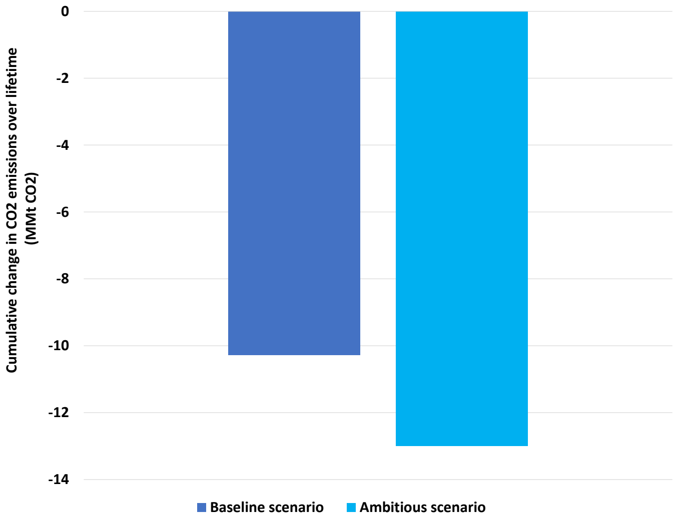


Figure 33. Cumulative change in CO_2 emissions in the milk powder industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming 100% adoption rate)

Energy cost

Figure 34 shows that with the Base Case electricity price forecast, the energy cost (in 2021$) per unit of production (tonne of sugar) in 2030 for the electrified process in the milk powder production industry is a bit higher than that of the conventional process.

It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified milk powder process. We have provided sensitivity options with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the Base Case forecast in negative error bars and a higher fuel price forecast that assumes 50% higher fuel prices compared with the Base Case forecast in positive error bars. Regarding these assumptions, the energy price of the electrified process could be cost-competitive compared with the conventional process even in 2030.

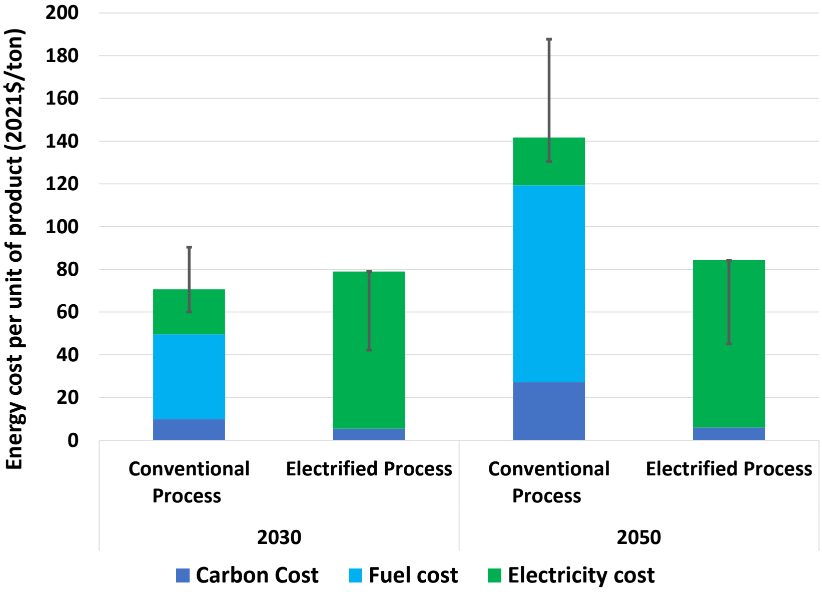


Figure 34. Energy cost per unit of production in the milk powder industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the Base Case forecast and the positive error bars show the energy cost per unit of production assuming fuel price 50% higher than the Base Case forecast.

3.8. Wet corn milling industry

In China, corn processing predominantly involves two techniques: wet milling and dry milling. The main product of the dry milling process is ethanol, whereas corn starch and edible corn oil are the primary products of the wet milling process. The wet milling process is efficient in separating corn components and parts for food and industrial use (O'Brien and Woolverton, 2009). This study centers on the wet corn milling process. In 2021, the total production output of China's wet corn milling industry was approximately 26 Mt (NBS, 2020).

A detailed explanation of the conventional and electrified wet corn milling processes is provided in our previous report (Hasanbeigi et al. 2021). Table 11 compares the energy intensity of the wet corn milling industry's conventional and electric processes.

Table 11. Conventional and electric wet corn milling production processes' energy intensities (Hasanbeigi et al. 2021)

Conventional System	Process Steps	All Electric System
	Corn Receiving	
Central Steam Systems	Steeping	Heat Pump @ 51 °C
Central Steam Systems	Steep water evaporation	Mechanical Vapor Recompression
	Germ recovery (1st grind)	
	Germ recovery (2nd grind)	
	Germ recovery (germ washing)	
Conventional Fluidized Bed Dryer	Germ dewatering and drying	Electrical Fluidized Bed Dryer
	Fiber recovery	
	Fiber dewatering	
	Protein (gluten) recovery	
Conventional Rotary Dryer	Gluten thickening and drying	Electrical Rotary Dryer
	Starch washing	
Conventional Rotary Dryer	Starch dewatering and drying	Electrical Rotary Dryer
Conventional Ring Dryer	Gluten feed dryer	Electrical Ring Dryer
971	Thermal demand (kWh/tonne)	-
128	Electricity demand (kWh/tonne)	888
1,099	Total Energy Intensity (kWh/tonne)	888

Energy use

Figure 35 shows that electrification will significantly reduce the wet corn milling industry's total final energy use during the study period in China. The energy savings change over time because wet corn milling production is expected to increase through 2040, then decrease by 2050 (Zhao 2021).

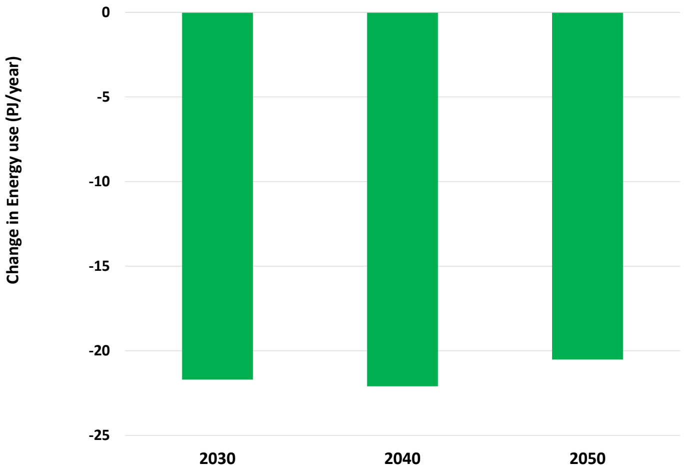


Figure 35. Change in the wet corn milling industry' total final energy use after electrification
(technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 36 shows the wet corn milling industry's change in net CO_2 emissions after electrification under the baseline and ambitious scenarios. Wet corn milling electrification could result in an increase in CO_2 emissions in 2030 in China in baseline scenario. Electrification can help realize large annual CO_2 emissions reductions by 2050 in both scenarios due to a decline in the electricity grid's CO_2 emissions factor between 2030 and 2050.

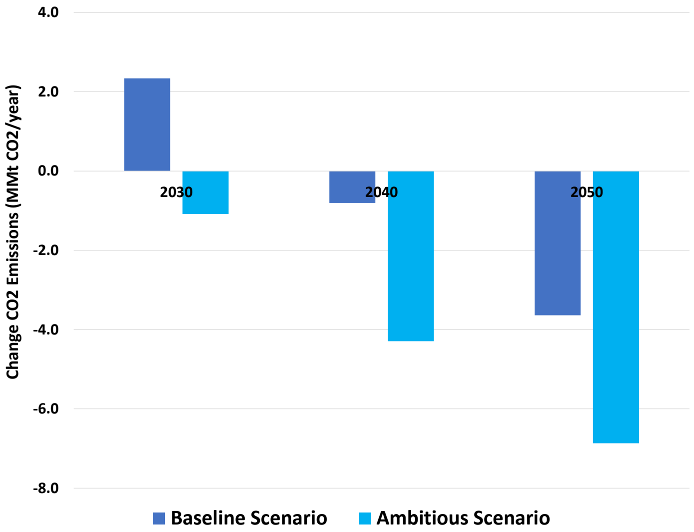


Figure 36. Change in the wet corn milling industry's net CO_2 emissions after electrification
(Technical potential assuming 100% adoption rate. In the near term by 2030, the actual adoption rate will be low. Therefore, in sectors where there is a projected increase in CO_2 emissions in 2030, the actual increase will be very small.)

Figure 37 shows the cumulative change in CO_2 emissions in the wet corn milling industry over lifetime of electrified technologies over the period of 2030 – 2050 for both the baseline and ambitious scenarios. As seen in this figure, electrification can reduce CO_2 emissions by about 15 and 90 Mt during these twenty years in China under the baseline and ambitious scenarios, respectively.

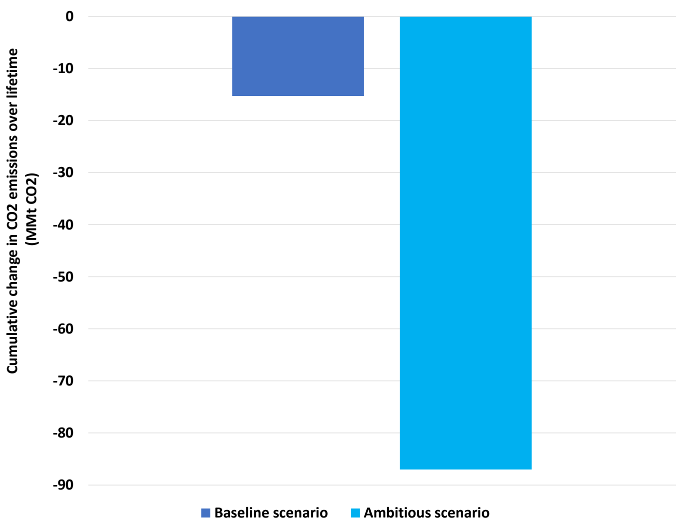


Figure 37. Cumulative change in CO_2 emissions in the wet corn milling industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming 100% adoption rate)

Energy cost

Figure 38 shows that with the Base Case 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.

It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified wet corn milling process. We have provided sensitivity options with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the Base Case forecast in negative error bars and a higher fuel price forecast that assumes 50% higher fuel prices compared with the Base Case forecast in positive error bars. Regarding these assumptions, the energy price of the electrified process could be cost-competitive compared with the conventional process even in 2030.

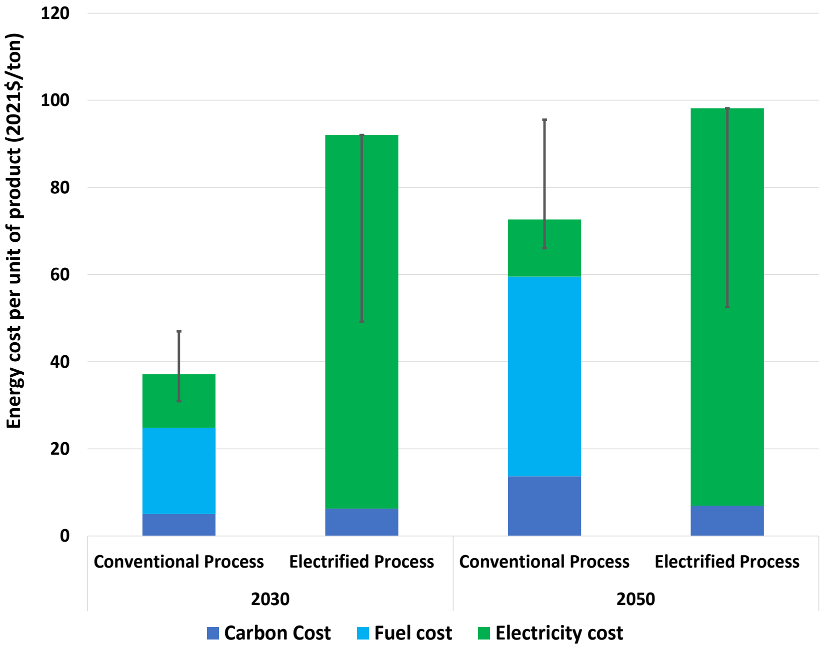


Figure 38. Energy cost per unit of production in the wet corn milling industry

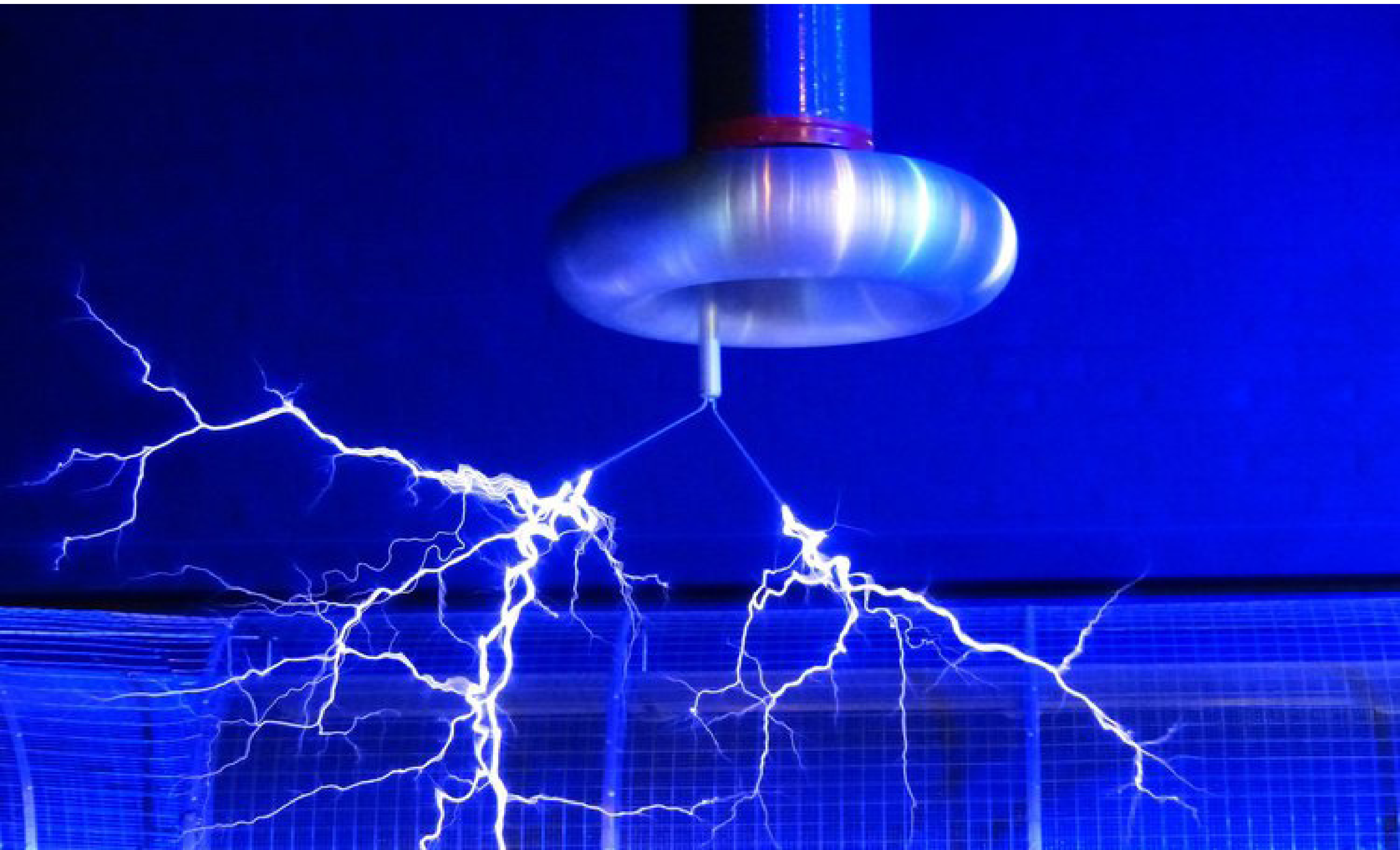
Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the Base Case forecast and the positive error bars show the energy cost per unit of production assuming fuel price 50% higher than the Base Case forecast.

3.9. Soybean oil industry

Soybean oil, extracted from soybean seeds, is among the world's most broadly used natural oils. It is used for a vast range of applications such as nutritional supplements, cosmetics, food, and agriculture. The industry is driven by the rising demand for soybean meal for livestock, resulting in a considerable increase in soybean oil production (EMR 2020). In 2021, China produced an estimated 17 Mt of soybean oil (Index Mundi 2021). Soybean oil production is also one of the food and beverage industry's largest energy-consuming subsectors. A detailed explanation of soybean oil industry's conventional and electrified processes is provided in our previous report (Hasanbeigi et al. 2021). Table 12 compares the energy intensity of the soybean oil industry's conventional and electric processes.

Table 12. Conventional and all-electric crude soybean oil production processes' energy consumption (Hasanbeigi et al. 2021)

Conventional System	Process steps	All Electric System
Conventional Steam Generator	Leaching	Heat Pump
Conventional Steam Generator	Evaporators	Electric Steam Boiler
Conventional Steam Generator		Indirect Resistive Heating
Conventional Steam Generator	Stripping	Electric Steam Boiler
Conventional Steam Generator	Desolventizer	Fluidized Bed Using Air/Nitrogen
Conventional Steam Generator	Tail gas stripper	
	Electrical devices	
1,966	Thermal demand (kWh/tonne)	-
138	Electricity demand (kWh/tonne)	1,049
2,103	Total Energy Intensity (kWh/tonne)	1,049



Energy use

Figure 39 shows that electrification will reduce the soybean oil industry's total final energy use during 2030-2050. Large energy savings potentials from switching to electrified soybean oil production processes are estimated for China. The energy savings change over time because soybean oil production is projected to peak in 2040 (Zhao 2021).

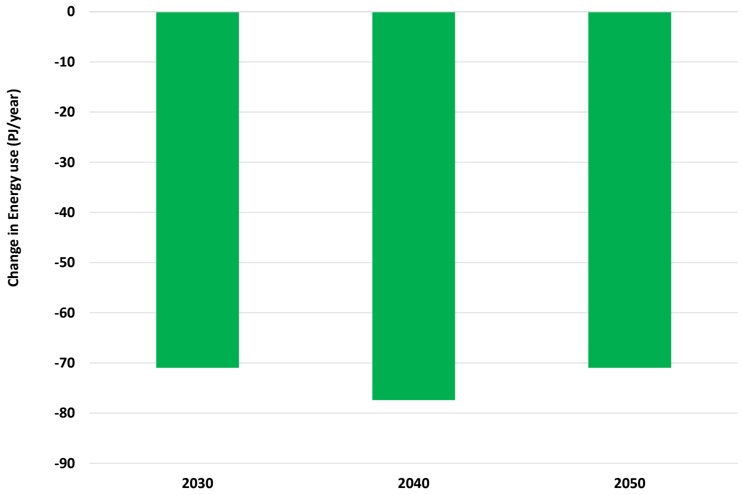


Figure 39. Change in the soybean oil industry's total final energy use after electrification
(technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 40 shows the change in the soybean oil industry's net CO_2 emissions after electrification under the baseline and ambitious scenario. Soybean oil production electrification results in a drop in CO_2 emissions in 2030. Electrification further reduces annual CO_2 emissions by 2050 because of grid decarbonization.

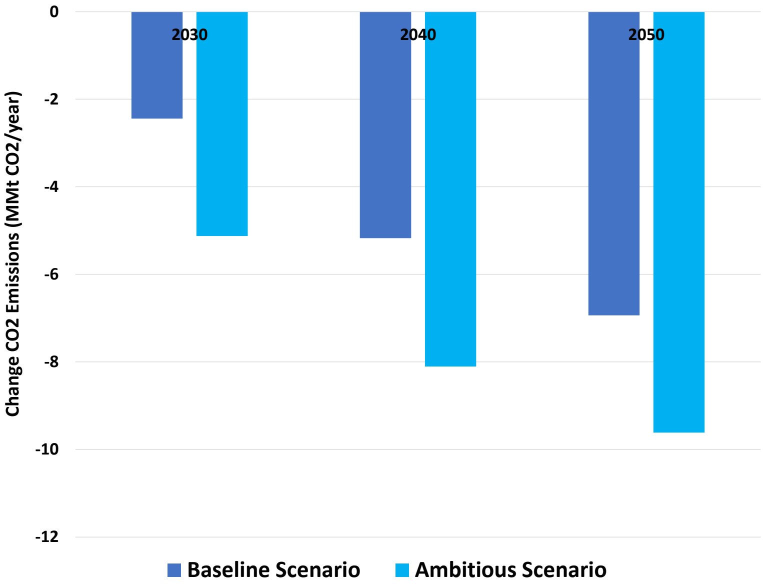


Figure 40. Change in the soybean oil industry's net CO_2 emissions after electrification
(technical potential assuming 100% adoption rate)

Figure 41 shows the cumulative change in CO_2 emissions in the soybean oil industry over the lifetime of electrified technologies over the period of 2030 – 2050 for both baseline and ambitious scenarios. As seen in this figure, electrification can reduce CO_2 emissions by more than 100 and 160 Mt during these twenty years in China under baseline and ambitious scenarios, respectively.

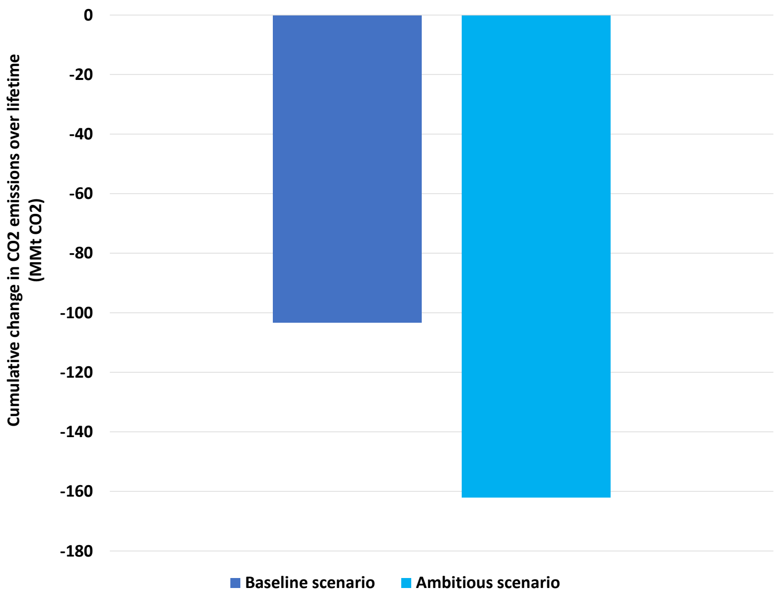


Figure 41. Cumulative change in CO_2 emissions in the soybean oil industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming 100% adoption rate)

Energy cost

Figure 42 shows that with the Base Case electricity price forecast, the energy cost (in 2021$) per unit of production (tonne of soybean oil) in 2030 for the electrified process in the soybean oil industry is higher than that of the conventional process in China.

It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified soybean oil production process. We have provided sensitivity options with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the Base Case forecast in negative error bars and a higher fuel price forecast that assumes 50% higher fuel prices compared with the Base Case 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 China in 2030.

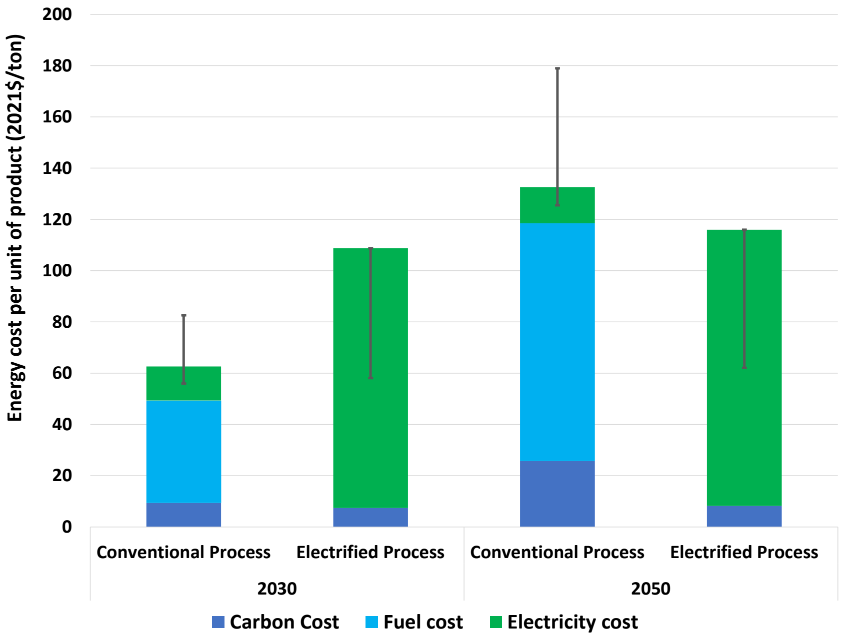


Figure 42. Energy cost per unit of production in the soybean oil industry
Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the Base Case forecast and the positive error bars show the energy cost per unit of production assuming fuel price 50% higher than the Base Case forecast.

3.10. Meat production industry

Total beef production in China is estimated to be 76.4 million metric tonnes in 2021 (NBS, 2021). China also processes other kinds of meats, such as ham, sausage, bacon, hot dogs, jerky, and sauces made with those products. When meat is processed, it is transformed through curing, fermenting, smoking, or salting in order to boost flavor and shelf life.

Food preservation techniques have relied heavily on heat in diverse forms and levels to destroy microorganisms and extend shelf life. The meat-processing industry consists of establishments primarily engaged in the slaughtering of different animal species, such as cattle, hogs, sheep, lambs, or calves, to obtain meat to be sold or to be used on the same premises for different purposes. Processing meat involves slaughtering animals, cutting the meat, inspecting it to ensure that it is safe for consumption, packaging it, processing it into other products such as sausage or lunch meats, delivering it to stores, and selling it to customers. The meat-processing industry is distinct from the meat-packing sector. It involves transforming raw meat into marketable products that are safe and appealing for consumption (E. Ortega-Rivas, 2014).

For meat processing, various process lines are employed depending on the desired final products. Key steps in red meat production include blood processing, chilling/refrigeration, dressing and cutting, processing methods like curing, smoking, and cooking, and packaging. Figure 43 illustrates the process of sausage cooking as an example.

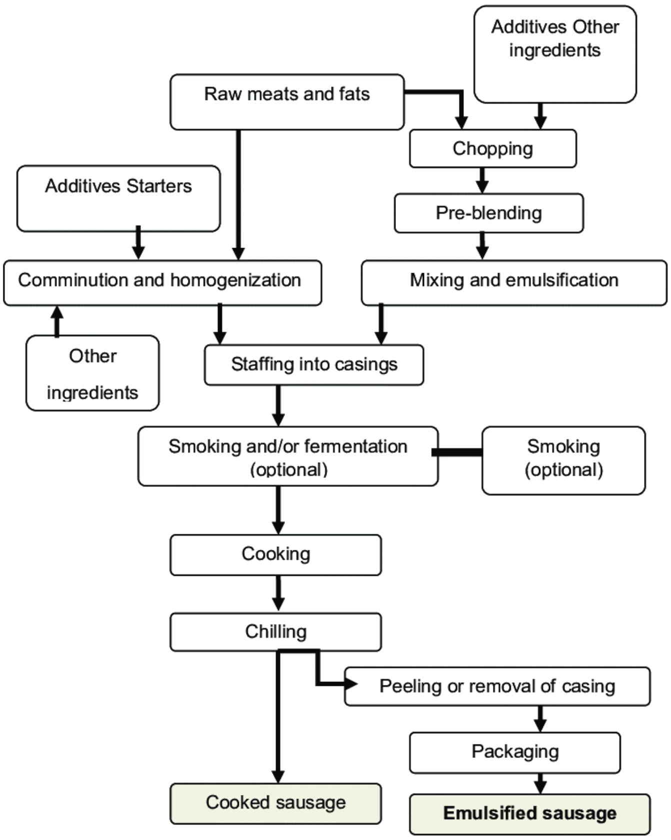


Figure 43. Cooked sausage production diagram (Mladenoska, 2017)

The heat-required processes, including curing, smoking, and cooking conventionally done by using steam-heated or direct-fired ovens. Electric curing equipment and meat processing ovens using electric heat resistance, plasma technology, and other electrical heating methods are available now. Electric heating is able to achieve temperatures quickly. In food preparation, that means less time wasted waiting for ovens and grills to heat up. This increases efficiency, reducing wasted costs and offering faster product delivery. Electricity also has minimal energy waste. Virtually no energy is lost, so the operational costs are lower, and there is less of an environmental impact (Alkanan 2021). Table 13 compares the energy consumption of conventional and electrified processes for red meat production.

Table 13. Energy intensities of conventional (Bandwidth 2017) and electric red meat production processes.

Conventional System	Process Steps	All Electric System
Blood Processing		Blood Processing
Chilling/Refrigeration		Chilling/Refrigeration
Dressing and cutting		Dressing and cutting
Processing		Processing
Packaging		Packaging
228	Thermal demand (kWh/tonne)	-
585	Electricity demand (kWh/tonne)	789
813	Total Energy Intensity (kWh/tonne)	789

Energy use

Figure 44 shows that electrification will reduce the meat processing industry's total final energy use during 2030-2050. Large energy savings potentials from switching to electrified meat production processes are estimated for China. The energy savings change over time because a change in processed meat production is projected up to 2050. (Zhao 2021)

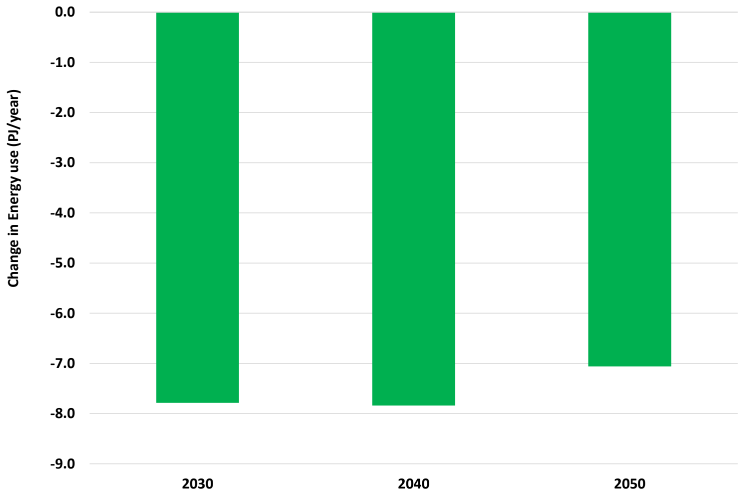


Figure 44. Change in the meat processing industry's total final energy use after electrification (Technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 45 shows the meat processing industry's change in net CO_2 emissions after electrification under the baseline and ambitious scenarios. Meat process electrification could result in an increase in CO_2 emissions in 2030 in China. Electrification can help realize large annual CO_2 emissions reductions by 2050 in both scenarios due to a decline in the electricity grid's CO_2 emissions factor between 2030 and 2050.

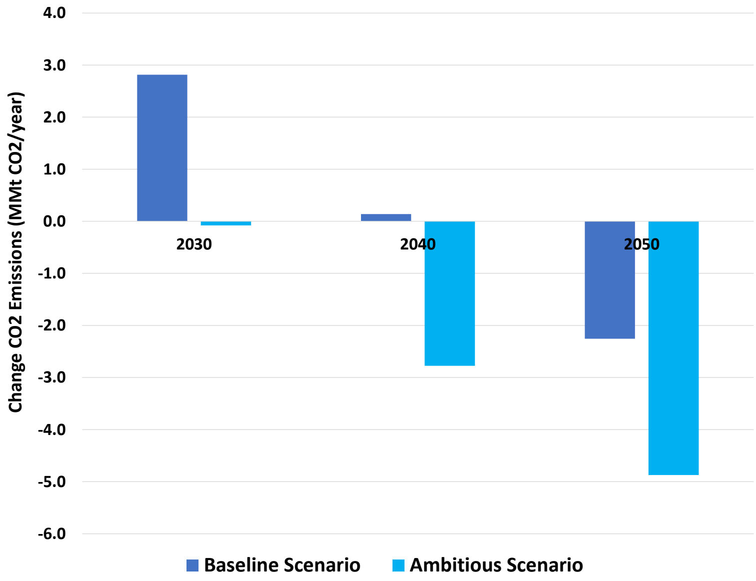


Figure 45. Change in the meat processing industry's net CO_2 emissions after electrification
(technical potential assuming 100% adoption rate. In the near term by 2030, the actual adoption rate will be low. Therefore, in sectors where there is a projected increase in CO_2 emissions in 2030, the actual increase will be very small.)

Figure 46 shows the cumulative change in CO_2 emissions in the meat processing industry over lifetime of electrified technologies over the period of 2030 – 2050 for both baseline and ambitious scenarios. As seen in this figure, electrification can increase CO_2 emissions by about 5 Mt during these twenty years under baseline scenario and reduce more than 55 Mt under ambitious scenario, Due to their differences in grid emission factors.

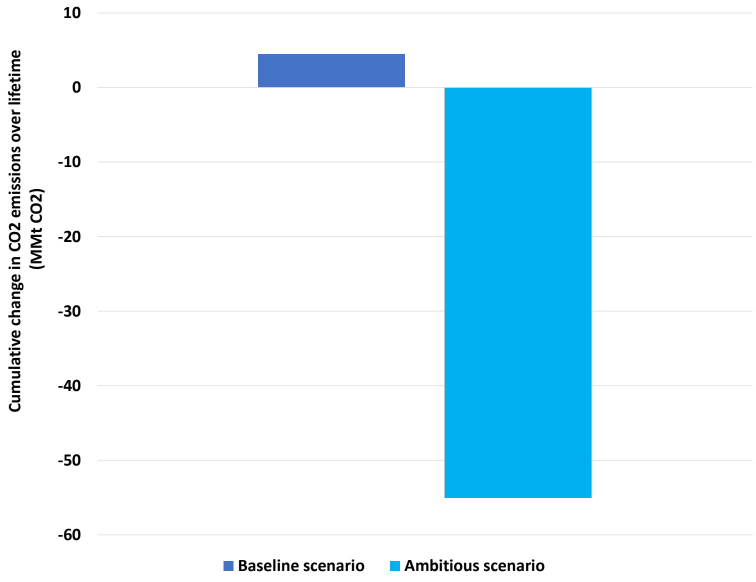


Figure 46. Cumulative change in CO_2 emissions in the meat processing industry over lifetime of electrified technologies over the period of 2030 - 2050
(This is the technical potential assuming 100% adoption rate)

Energy cost

Figure 47 shows that with the Base Case electricity price forecast, the energy cost (in 2021$) per unit of production (tonne of proceeded meat) in 2030 for the electrified process in the meat processing industry is higher than that of the conventional process.

It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified meat processing. We have provided sensitivity options with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the Base Case forecast in negative error bars and a higher fuel price forecast that assumes 50% higher fuel prices compared with the Base Case forecast in positive error bars. Regarding these assumptions, the energy price of the electrified process could be cost-competitive compared with the conventional process in 2030.

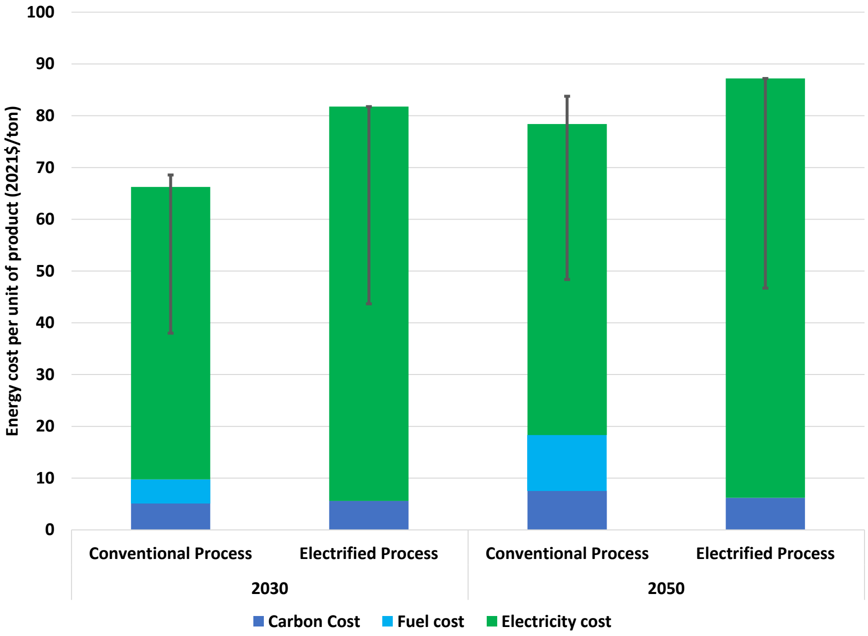


Figure 47. Energy cost per unit of production in the meat processing industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the Base Case forecast and the positive error bars show the energy cost per unit of production assuming fuel price 50% higher than the Base Case forecast.

3.11. Steel production industry

China's steel industry produced 1,033 Mt of crude steel in 2021: 89% was produced by primary steelmaking plants using blast furnace-basic oxygen furnaces (BF-BOF), and 11% was produced by electric arc furnaces (EAFs), which mainly use steel scrap (USGS 2020).

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

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

Table 14. Conventional and (mostly) electric steelmaking processes' energy intensities

Steel Production Types	Process Steps	Thermal Demand (kWh/tonne)	Electrical Demand (kWh/tonne)	Total Energy (kWh/tonne)
BF-BOF Steel Production	Sintering/Palletization Coke Making Blast Furnace Basic Oxygen Furnace Casting, Rolling, and Finishing	5,250	642	5,892
Scrap-EAF Steel Production	EAF Casting, Rolling, and Finishing	667	710	1,377
H_2 DRI-EAF Steel Production	H_2 Production DRI Production EAF Casting, Rolling, and Finishing	667	3,500	4,167
Steel Production by Electrolysis	Electrolysis of Iron Ore Casting, Rolling, and Finishing	556	3,300	3,856

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

Table 15 presents the assumption of steel industry electrification adoption rates up to 2050 assumed in this study. Given the large share of steel produced by the BF-BOF route in China, we assumed more gradual adoption rates of EAF steelmaking by 2030.

Table 15: Steel production share by each route as % of total steel produced in China up to 2050.

	2030	2040	2050
Scrap-EAF	20%	40%	60%
Steel-H_2 DRI	1%	10%	20%
Steel-Electrolysis	0%	1%	2%

Energy use

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

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

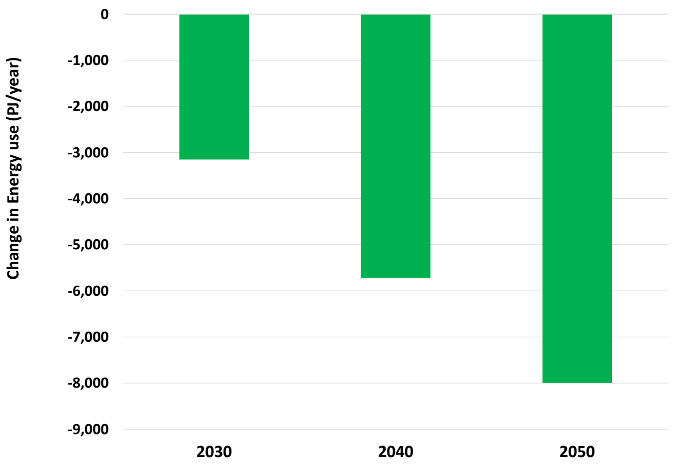


Figure 48. Change in the steel industry's total final energy use after electrification using Scrap-EAF technology (Based on Table 15 adoption rates)

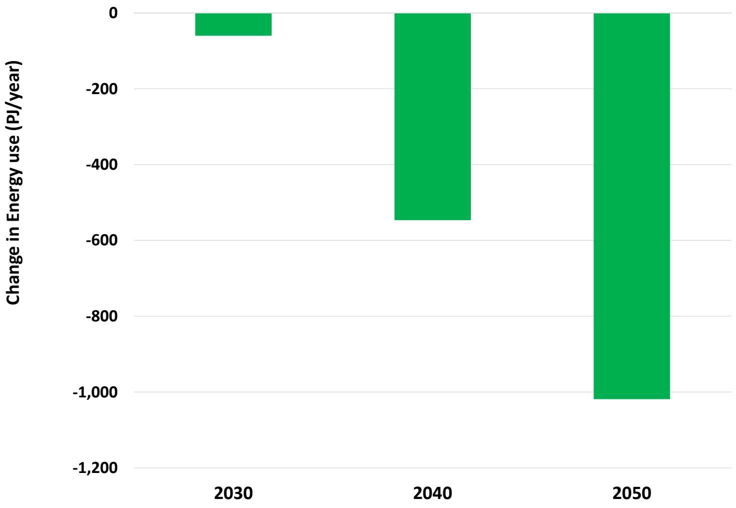


Figure 49. Change in the steel industry's total final energy use after electrification using H_2 DRI-EAF technology (Based on Table 15 adoption rates)

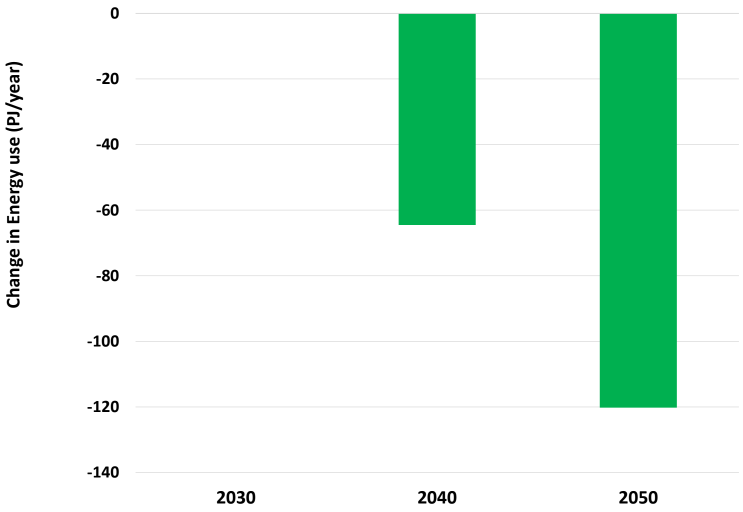


Figure 50. Change in the steel industry's total final energy use after electrification using electrolysis technology (Based on Table 15 adoption rates)

CO_2 emissions

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

The H_2 DRI-EAF and electrolysis process routes result in relatively smaller total energy savings, since the majority of energy used in H_2 DRI-EAF and electrolysis is electricity (for H_2 production needed in H_2 DRI and electrolysis process in the electrolysis of iron ore), and as a result their CO_2 emissions reductions are also less than those that can be achieved by switched to scrap-EAF production in 2050. If a zero-carbon grid is achieved earlier (under the ambitious scenario), the CO_2 emissions reduction potential in future years (2030, 2040, and 2050) is larger than the baseline scenario for H_2 DRI-EAF and electrolysis technologies.

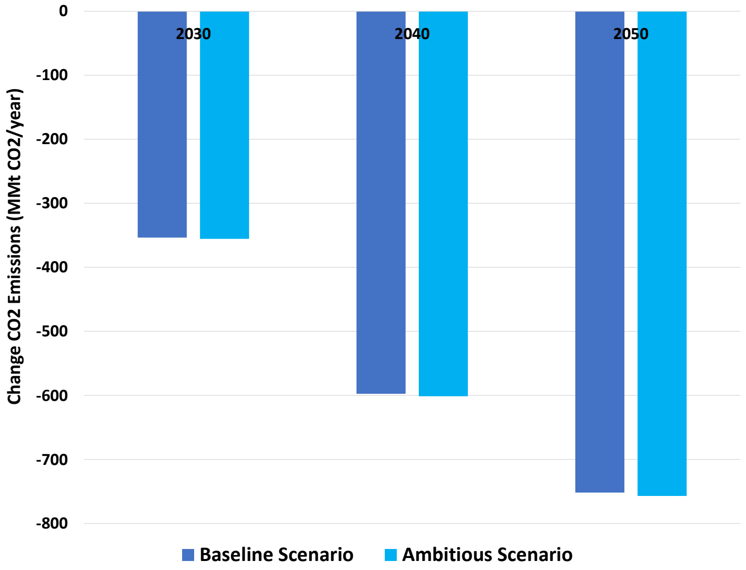


Figure 51. Change in the steel industry's net CO_2 emissions after electrification using Scrap-EAF technology (Based on Table 15 adoption rates)

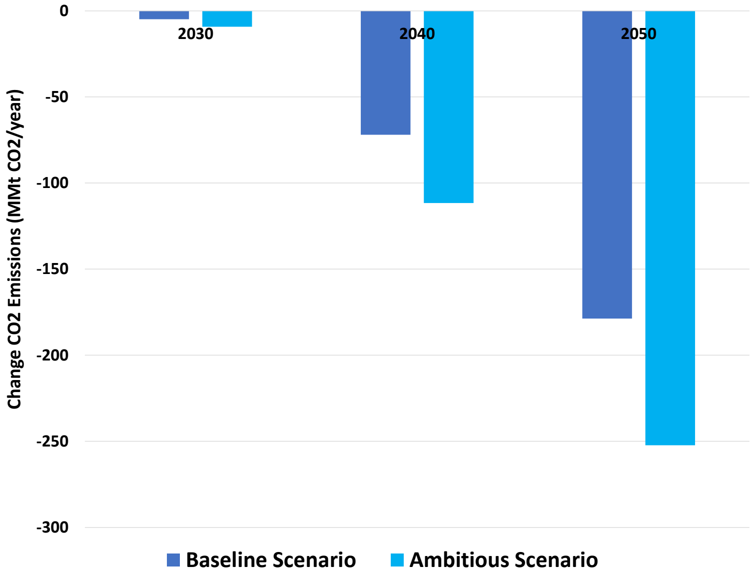


Figure 52. Change in the steel industry's net CO_2 emissions after electrification using H_2 DRI-EAF technology (Based on Table 15 adoption rates)

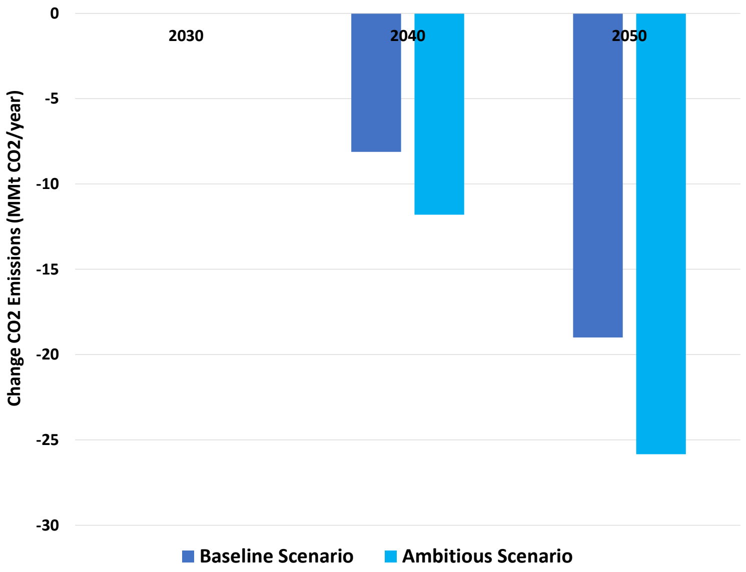


Figure 53. Change in the steel industry's net CO_2 emissions after electrification using electrolysis technology (Based on Table 15 adoption rates)

Figure 54 shows the cumulative change in CO_2 emissions in the steel industry over lifetime of electrified technologies over the period of 2030 – 2050 for both baseline and ambitious scenarios for all three Scrap-EAF, H_2 DRI-EAF and electrolysis technologies.

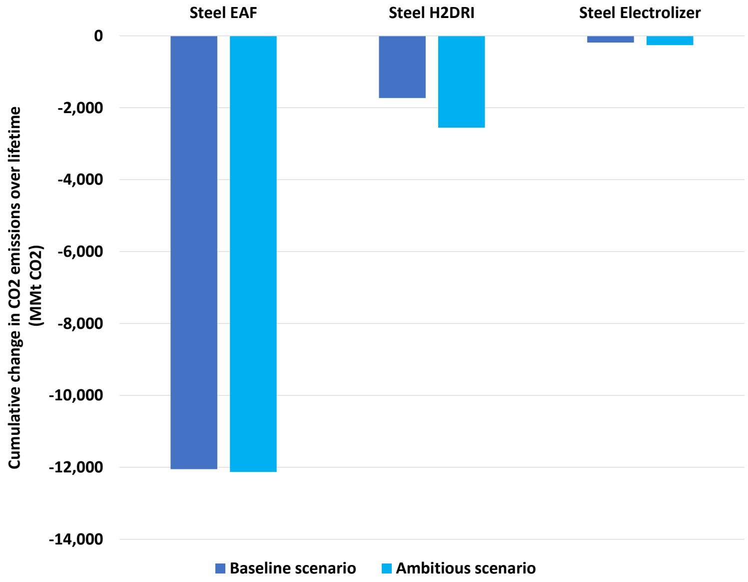


Figure 54. Cumulative change in CO_2 emissions in the steel industry over lifetime of electrified technologies over the period of 2030 - 2050 (Based on Table 15 adoption rates)

Energy cost

Figure 55 shows the energy cost per unit of production (tonne of steel) for the BF-BOF route and three electrified steel technologies. Compared with BF-BOF steel production, under the scenario with the Base Case electricity price forecast, the energy cost per unit of product is substantially lower for Scrap-EAF technology and significantly higher for the H_2 DRI-EAF and electrolysis technologies in 2030. The Scrap-EAF has a lower energy cost than BF-BOF steelmaking and the other two electrified processes mainly because Scrap-EAF has substantially lower energy demand (Figure 48) than the other processes.

Under the Lower RE electricity price and higher fuel price forecast, both H_2 DRI-EAF and electrolysis technologies have a lower energy cost per unit of production compared with the BF-BOF steel production in 2050.

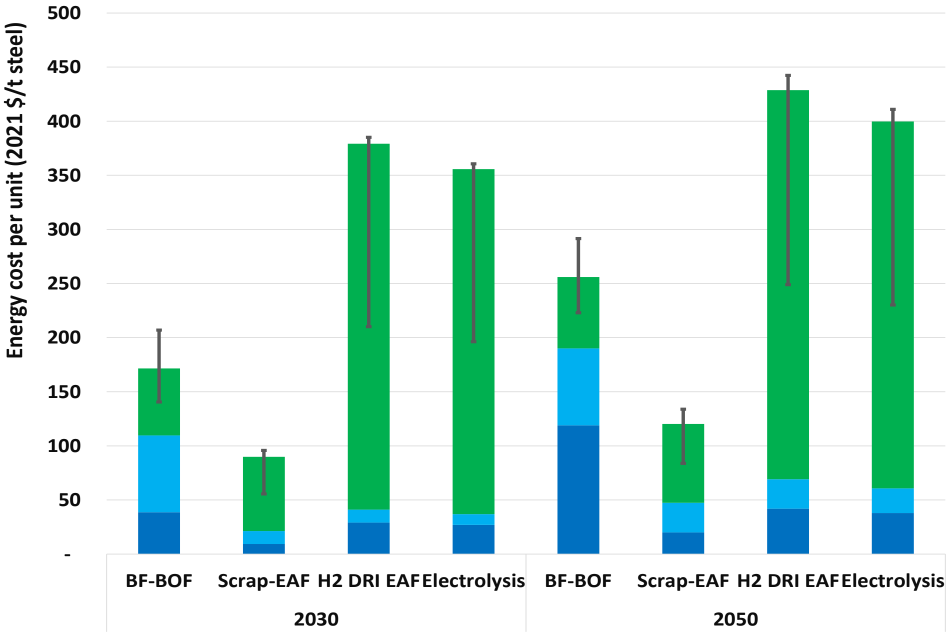


Figure 55. Energy cost per unit of production in the steel industry for conventional and three electrified steel technologies

3.12. Steel reheating process

China was the largest producer of steel globally in 2021 (Hasanbeigi, 2022). Reheating furnaces are the 2nd largest user of energy in steel plants (Vavra, 2021). In 2021, China total steel reheating volume was estimated to be around 1002 million metric tonnes (Statista, 2021).

Reheating furnaces are used in hot rolling mills to heat still billets, blooms, or slabs to temperatures of approximately 1,200°C. At these temperatures, the steel becomes suitable for plastic deformation and requires eight to ten times less forming force than cold-rolled steel. The process in the reheating furnace is continuous, in which the steel is charged at the furnace entrance, is heated, and discharged at the end of the furnace. Convection within the furnace, as well as radiation from the burner and furnace walls, provide the primary method of heat transfer to the steel (Satyendra, 2013), (Schmitz et al., 2021).

These types of plants harness electric heating elements, controlled by a Modular Power Controller, on the chamber walls and door for reheating power. They operate at a maximum temperature of approximately 1,200°C, and a vertically-oriented fan installed in the vault maintains excellent temperature uniformity. The furnace structure typically includes a quadrangular or rectangular muffle, a guillotine door, a fixed hearth, a flat vault, an electric reheating system (heating elements), and electric control equipment.

In addition, Electric Furnaces with resistance heating elements progressively for every industrial process, and more operators have considered replacing oil and gas heating with electrical equipment. The advantages of electric furnaces are a consequence of the development of electric heating technology. Resistance heating furnaces have low installation costs and are highly energy efficient with minimum waste heat while providing a quieter working atmosphere, closer temperature control, and more even heating throughout the furnace chamber than fuel-fired furnaces. In comparison to combustion heating furnaces, they avoid combustion products or flame impingements and are unrequired of storage or piping of flammable fuels. The later mentioned results in space savings and lower insurance premiums. Other appreciable benefits are a cooler plant environment without flue stacks and exhaust hoods, leading to a cleaner system, free from pollution.

The preheating furnace transport system is designed in the same way as the existing walking beam furnace to obtain the same production rate and ensure that the skids do not leave skid marks on the slab. It is a fast and gentle transportation system. However, this is energy-consuming since the skids are water-cooled, where 10 – 15% of the total energy input in the existing walking beam furnace is lost to the cooling water. As the proposed preheating furnace is operated at a lower temperature than existing walking beam furnaces, the skids take less damage from heat. Therefore, it is possible to lower the cooling rate in the skids, resulting in less heat loss and leading to a more efficient furnace. Also, for further studies, it is substantial to investigate whether water cooling is necessary, for instance, if better insulation is considered. Table 16 compares the energy intensities of conventional and electric steel reheating furnace (Gfelti, 2021).

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

Conventional System	Process Steps	All Electric System
Gas-Fired Reheating Furnace Energy Intensity	Hot Rolling	Electric Reheating Furnace Energy Intensity
917	Total Energy Intensity (kWh/tonne)	647

Energy use

Electrification can help to reduce the steel reheating furnace's total final energy use (Figure 56). The energy savings reduce over time because a drop in steel production is assumed up to 2050.

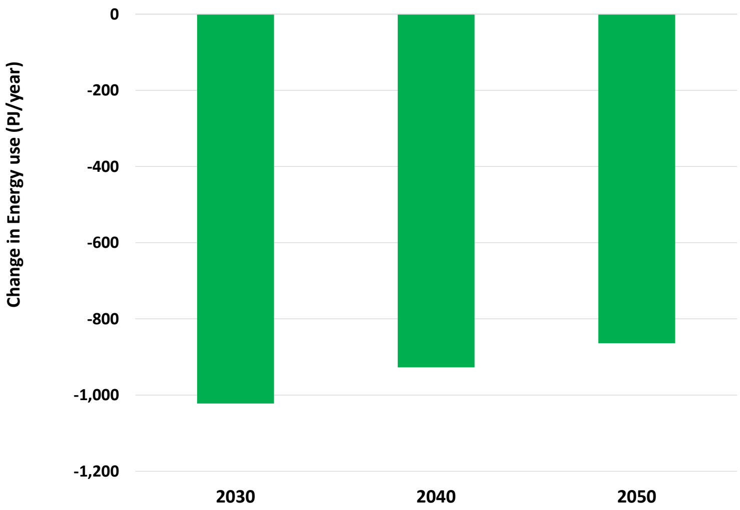


Figure 56. Change in the steel reheating furnace's total final energy use after electrification (Technical potential assuming 100% adoption rate)

CO_2 emissions

Steel reheating furnace electrification can decrease CO_2 emissions in 2030, 2040, and 2050 in China under the baseline and the ambitious scenario (Figure 57).

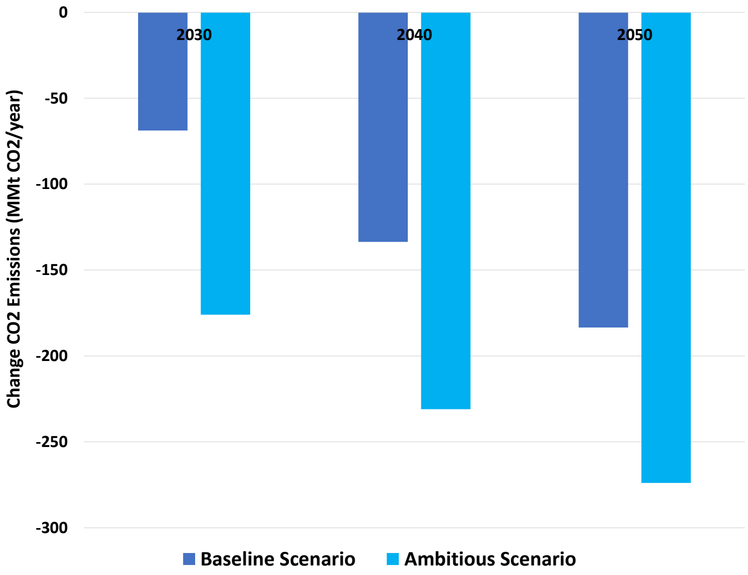


Figure 57. Change in steel reheating furnaces' net CO_2 emissions after electrification (technical potential assuming 100% adoption rate)

Figure 58 shows the cumulative change in CO_2 emissions in the steel reheating process over the lifetime of electrified technologies over the period of 2030 – 2050 for both the baseline and ambitious scenarios. As seen in this figure, electrification can reduce CO_2 emissions by about 2600 and 4800 Mt during these twenty years in China under the baseline and ambitious scenarios.

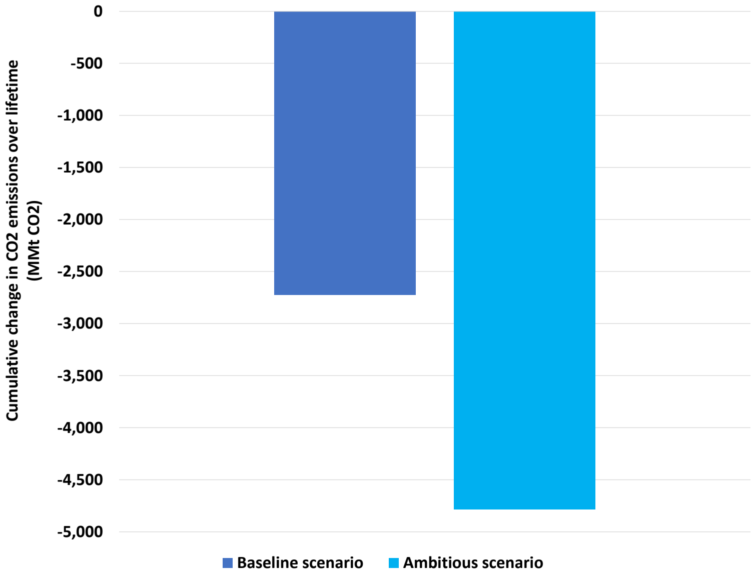


Figure 58. Cumulative change in CO_2 emissions in the steel reheating industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming 100% adoption rate)

Energy cost

Figure 59 shows that with the Base Case electricity price forecast, the energy cost (in 2021$) per unit of production (tonne of steel) in 2030 for the electrified process in the steel reheating industry is higher than that of the conventional process.

It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified steel reheating process. We have provided sensitivity options with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the Base Case forecast in negative error bars and a higher fuel price forecast that assumes 50% higher fuel prices compared with the Base Case forecast in positive error bars. Regarding these assumptions, the energy price of the electrified process could be cost-competitive compared with the conventional process in 2050.

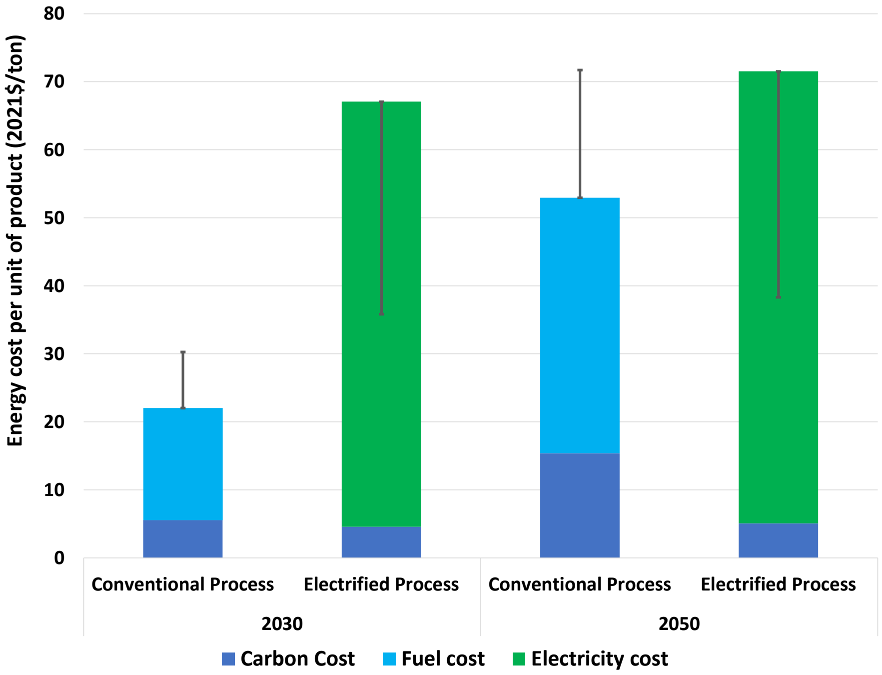


Figure 59. Energy cost per unit of production in the steel reheating process.
Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the Base Case forecast and the positive error bars show the energy cost per unit of production assuming fuel price 50% higher than the Base Case forecast.

3.13. Ethanol production

Ethanol is an alternative fuel most commonly made from corn. It is also made from cellulosic feedstocks, such as crop residues and wood—though this is not as common. 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. (DOE 2020). In 2021, China total ethanol production volume was estimated to be around 3 Mt. (Statista, 2023).

A typical process flow diagram for a corn ethanol refinery is shown in Figure 60. Corn consisting of 75% starch (dry mass basis) and 15% moisture, is input into the refinery and sent through a hammer mill. The resulting flour is mixed with recycled process water and sterilized before undergoing saccharification and fermentation to convert the starch to ethanol and CO_2. The CO_2 is removed and the ethanol mixture (containing 14 wt% ethanol) is sent to distillation to bring the mixture to 91 wt% ethanol. Due to the presence of the ethanol/water azeotrope, the remaining water is separated out using a molecular sieve. The pure ethanol stream (100 wt%) is then mixed with denaturant (up to ~4.7 wt% gasoline), before it leaves the refinery as final product.

The undissolved solids are separated out with the remaining water at the bottom of the column. This slurry, known as stillage, is sent to a centrifuge for the start of the drying process. The overflow is sent to a three-effect vacuum evaporation section which uses the heat of condensation from distillation to drive off a portion of the remaining water and return it to the process. The resulting syrup is combined with the centrifuge underflow and sent to the drum dryer to dry the distillers' grains and solids (DDGS) to 9 wt% moisture to prevent it from rotting. Available fuels are used as the fuel source for steam production and drying of distiller's grains.

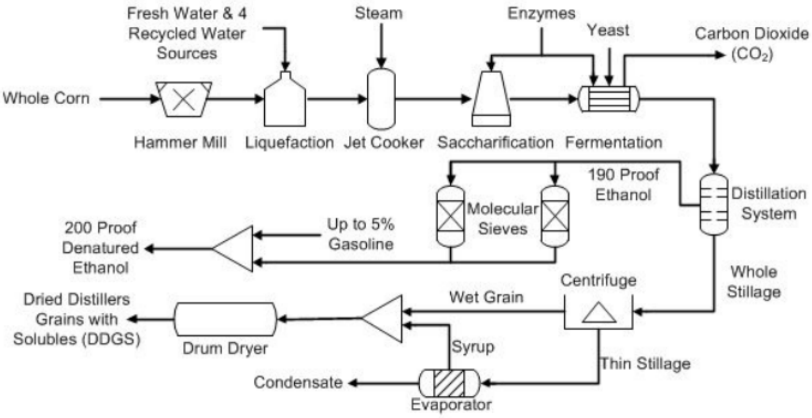


Figure 60. Schematic of modelled corn ethanol dry mill process for pure (anhydrous) ethanol production. (Howard A. 2015)

Thermal energy use is defined as the energy required to produce steam for the beer column reboiler, the stripping column reboiler, liquefaction section and molecular sieve pre-heating, and the energy required in the DDGS natural gas (or other fuels) fired dryer. (Howard A.2015)

Since the most important heat consumption in the ethanol production process is in the form of steam, the simplest and most accessible way to electrify the process is to use electric steam boilers. Table 17 compares the energy intensities of conventional and electric ethanol production.

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

Conventional System	Process Steps	All Electric System
	Mill	
Conventional Gas Fired	Beer Column Reboiler	Resistance heating/Electrical boiler
Conventional Gas Fired	Stripper Column Reboiler	Resistance heating/Electrical boiler
Conventional Gas Fired	Liquefaction Section	Resistance heating/Electrical boiler
Conventional Gas Fired	Molecular sieve pre-heating	Resistance heating/Electrical boiler
Conventional Gas Fired	DDGS natural gas fired dryer	Resistance heating/Electrical boiler
2,970	Thermal demand (kWh/tonne)	-
297	Electricity demand (kWh/tonne)	2,954
3,267	Total Energy Intensity (kWh/tonne)	2,954

Energy use

Figure 61 shows that electrification will reduce the ethanol industry's total final energy use during 2030-2050. Large energy savings potentials from switching to electrified ethanol production processes is estimated for China.

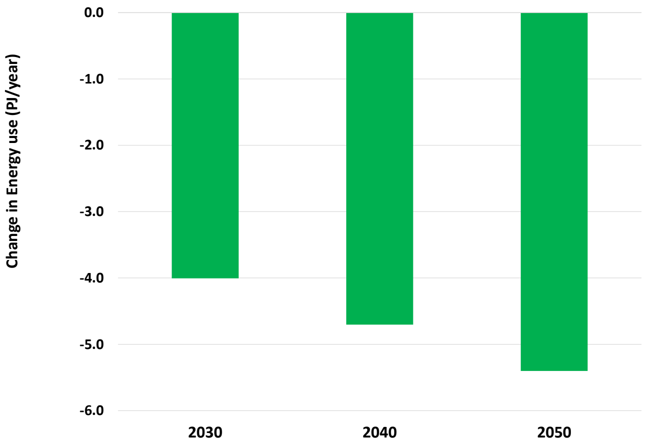


Figure 61. Change in the ethanol industry's total final energy use after electrification (technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 62 shows the ethanol industry's change in net CO_2 emissions after electrification under the baseline and ambitious scenarios. Ethanol production electrification results in an increase in CO_2 emissions in 2030. Electrification further reduces annual CO_2 emissions by 2050 because of grid decarbonization.

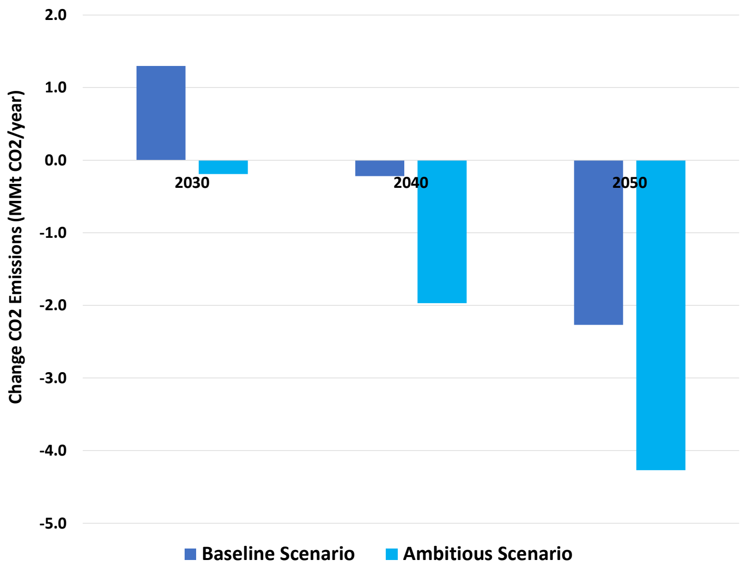


Figure 62. Change in the ethanol industry's net CO_2 emissions after electrification
(technical potential assuming 100% adoption rate. In the near term by 2030, the actual adoption rate will be low. Therefore, in sectors where there is a projected increase in CO_2 emissions in 2030, the actual increase will be very small.)

Figure 63 shows the cumulative change in CO_2 emissions in the ethanol production over the lifetime of electrified technologies over the period of 2030 – 2050 for both the baseline and ambitious scenarios. As seen in this figure, electrification can reduce CO_2 emissions by about 7 and 44 Mt during these twenty years in China under the baseline and ambitious scenarios, respectively.

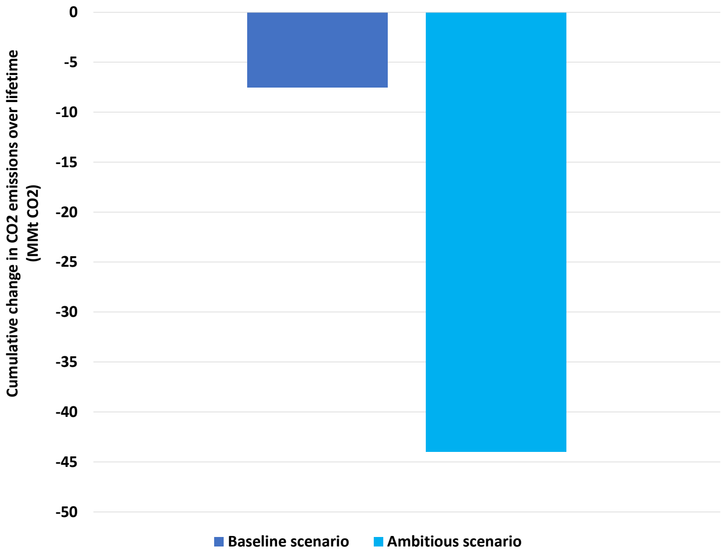


Figure 63. Cumulative change in CO_2 emissions in the ethanol industry over the lifetime of electrified technologies, 2030 - 2050 (This is the technical potential assuming 100% adoption rate)

Energy cost

Figure 64 shows that with the Base Case electricity price forecast, the energy cost (in 2021$) per unit of production (tonne of ethanol) in 2030 for the electrified process in the ethanol industry is higher than that of the conventional process.

It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified ethanol production process. We have provided sensitivity options with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the Base Case forecast in negative error bars and a higher fuel price forecast that assumes 50% higher fuel prices compared with the Base Case forecast in positive error bars. Regarding these assumptions, the energy price of the electrified process could be cost-competitive compared with the conventional process in 2050.

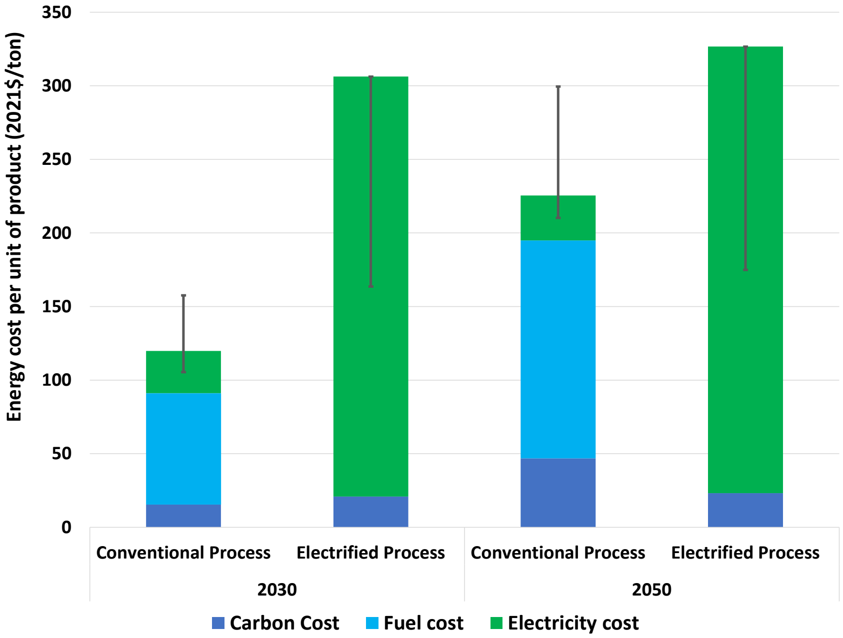


Figure 64. Energy cost per unit of production in the ethanol production industry
Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the Base Case forecast and the positive error bars show the energy cost per unit of production assuming fuel price 50% higher than the Base Case forecast.

3.14. Pulp and paper industry

In 2021, the total paper and cardboard production across the globe was around 419 million metric tonnes. China, the U.S., and Japan are the top paper manufacturing nations (Garside 2020). The pulp and paper industry is comprised of pulp mills, mills dedicated to manufacturing paper and paperboard, and integrated mills that process pulp as well as manufacture paper. In 2021, the total pulp, paper, and paperboard production in China were close to 127 million metric tonnes (National Bureau of Statistics 2022).

A detailed explanation of conventional and electrified processes for the pulp and paper industry is provided in our previous report (Hasanbeigi et al. 2021). Table 18 compares the energy intensity of the pulp and paper industry's conventional and electric processes.

Table 18. Conventional and electric pulp and paper production processes' energy intensities (Our analysis based on Brueske et al. 2015)

Conventional System	Process steps	Process Using Electric Dryer
Liquor Evaporator	Liquor Evaporation	Liquor Evaporator
Pulp machine	Pulping Chemical Preparation	Pulp machine
Cooking machine	Wood Cooking	Cooking machine
Conventional bleaching plant	Bleaching	Conventional bleaching plant
Steam/fuel-based dryer	Paper Drying	Infrared dryer
Paper making machine	Paper Machine Wet End	Paper making machine
4,738	Thermal demand (kWh/tonne)	3,294
790	Electricity demand (kWh/tonne)	2,075
5,528	**Total Energy Intensity (kWh/tonne)**	**5,369**

Energy use

Figure 65 shows that electrification will significantly reduce the total final energy use for pulp and paper in China during the study period. The similar reduction in annual saving potential between 2030-2050 is due to an assumed similar paper production during this period and the same energy efficiency of electrified process over time.

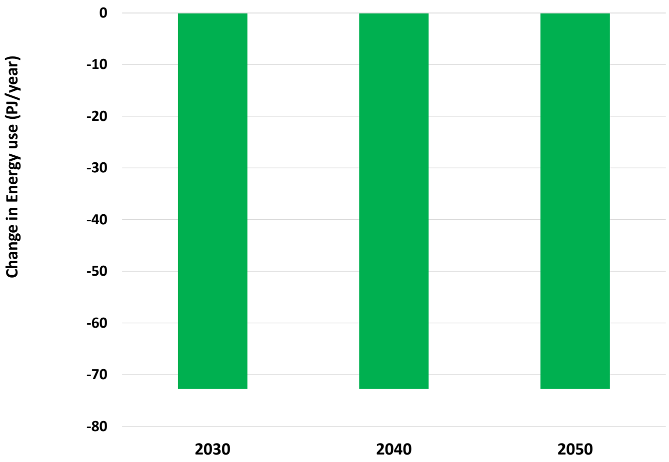


Figure 65. Change in the pulp and paper industry's total final energy use after electrification (technical potential assuming 100% adoption rate)

CO_2 emissions

Figure 66 shows the pulp and paper industry's change in net CO_2 emissions after electrification under the baseline and ambitious scenarios. The industry's electrification would result in an increase in CO_2 emissions in 2030 in China. Although biomass makes up a large share of fuel used in the paper industry in some countries, because biomass is a by-product of the pulping process (US DOE 2019), in China, there is no reported biomass fuel use for pulp and paper production (IEA 2022). This is because China's pulp and paper industry primarily uses imported pulp, and domestically produced pulp is mainly from recycled paper, overall limiting availability of biomass residue for the industry. If China's pulp and paper industry uses biomass in the future, carbon and cost benefits could change dramatically. This would also be affected by standards on carbon accounting for biomass under the GHG protocol, under which biomass waste material is currently considered carbon neutral, although the protocol is undergoing revision.

Electrification can help realize annual CO_2 emissions reductions in China in 2050 under the baseline scenario and in 2030 under the ambitious scenario. This substantial reduction in CO_2 emissions is the consequence of a decline in the electricity grid's CO_2 emissions factors.

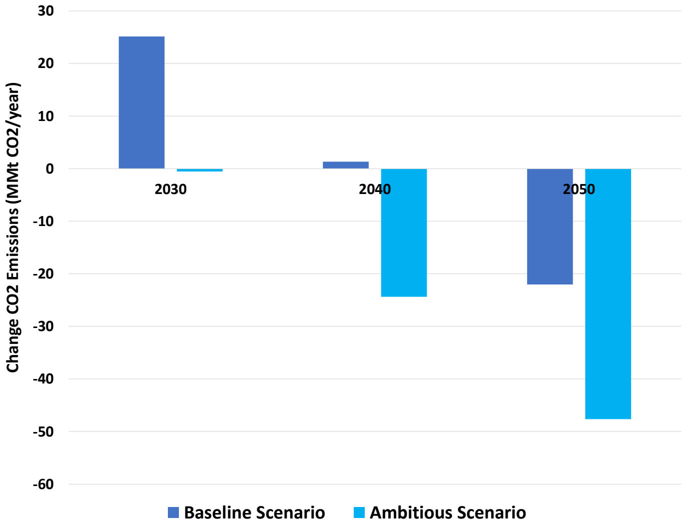


Figure 66. Change in the pulp and paper industry's net CO_2 emissions after electrification
(Technical potential assuming 100% adoption rate. In the near term by 2030, the actual adoption rate will be low. Therefore, in sectors where there is a projected increase in CO_2 emissions in 2030, the actual increase will be very small.)

Figure 67 shows the cumulative change in CO_2 emissions in the pulp and paper industry over the lifetime of electrified technologies over the period of 2030 – 2050 for both the baseline and ambitious scenarios. As seen in this figure, electrification can increase CO_2 emissions by about 20 Mt during these twenty years under the baseline scenario and reduce more than 500 Mt under the ambitious scenario, due to their differences in grid emission factors.

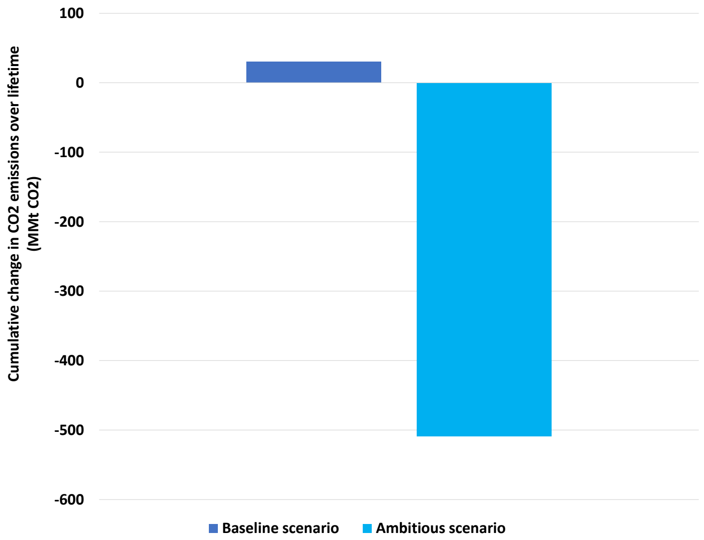


Figure 67. Cumulative change in CO_2 emissions in the pulp and paper industry over the lifetime of electrified technologies, 2030 - 2050

(This is the technical potential assuming 100% adoption rate. In the near term by 2030, the actual adoption rate will be low. Therefore, in sectors where there is a projected increase in CO_2 emissions in 2030, the actual increase will be very small.)

Energy cost

Figure 68 shows that with the Base Case electricity price forecast, the energy cost (in 2021$) per unit of production (tonne of hydrogen) in 2030 for the electrified process in the pulp and paper production industry is higher than that of the conventional process.

It is clear that access to low-cost electricity can substantially reduce the energy cost of the electrified pulp and paper production process. We have provided sensitivity options with lower renewable energy (RE) price forecast that assumes 50% lower electricity prices compared with the Base Case forecast in negative error bars and a higher fuel price forecast that assumes 50% higher fuel prices compared with the Base Case forecast in positive error bars. Regarding these assumptions, the energy price of the electrified process could be cost-competitive compared with the conventional process even in 2030.

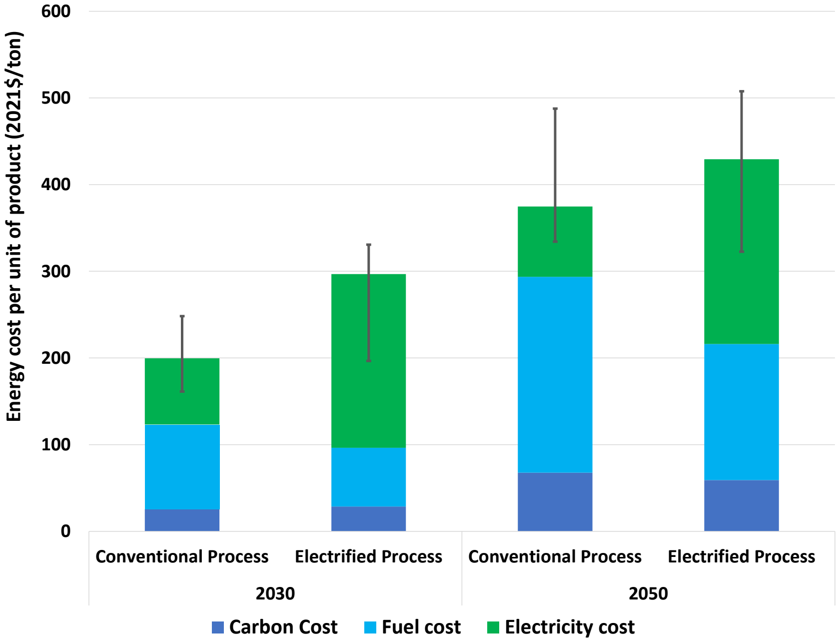


Figure 68. Energy cost per unit of production in the pulp and paper industry

Note: The negative error bars show the energy cost per unit of production assuming an electricity price 50% lower than the Base Case forecast and the positive error bars show the energy cost per unit of production assuming fuel price 50% higher than the Base Case forecast.

3.15. Total energy savings and CO_2 emissions reduction potential

This section presents the total energy savings and CO_2 emissions reduction potentials that can be achieved in China from electrification of 12 of the 14 industrial subsectors included in this study.

The cumulative energy savings and CO2 emission reductions illustrated in this section exclude the ammonia, and plastic recycling industries. This exclusion is due to ammonia industry undergoing indirect electrification, primarily through the production of hydrogen via electrolysis using electricity. In the ammonia industry, hydrogen serves as a feedstock rather than an energy source. Our study contrasts the mechanical electrified plastic recycling process with the conventional method of virgin resin production in petrochemical plants. This disparity between plastic recycling and primary resin production contributes to significant energy savings, which could have outsized influence on the overall savings results..

Figure 69 shows that electrification will significantly reduce industrial total final energy use in China. Total energy saved in these 12 industrial subsectors after electrification is about 1400 and 2300 PJ for 2030 and 2050 respectively. For context, every 10 PJ of energy can power around 260,000 US households per year.

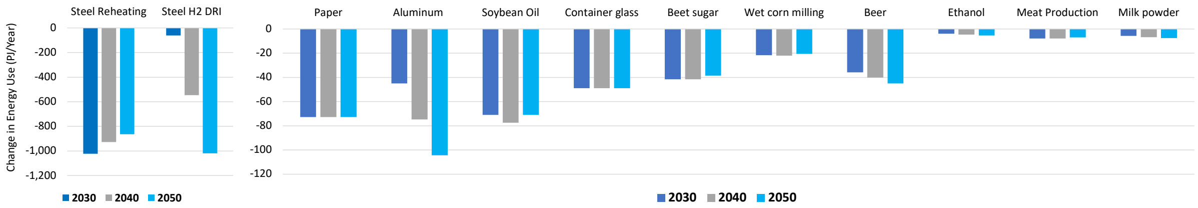


Figure 69. Change in industrial energy use using electrified processes in twelve industries studied (Excludes ammonia, hydrogen, methanol and plastic recycling industries, technical potential assuming 100% adoption rate, except for the steel industry)

Figure 70 shows the change in industrial net CO_2 emissions after electrifying the twelve industries under the baseline scenario. Electrifying these twelve industries could result in CO_2 emissions being reduced by about 47 and 421 Mt in 2030 and 2050 respectively. For context, reducing annual CO_2 emissions by 1 million tones is equal to taking about 217,000 internal combustion engine passenger cars off the road.

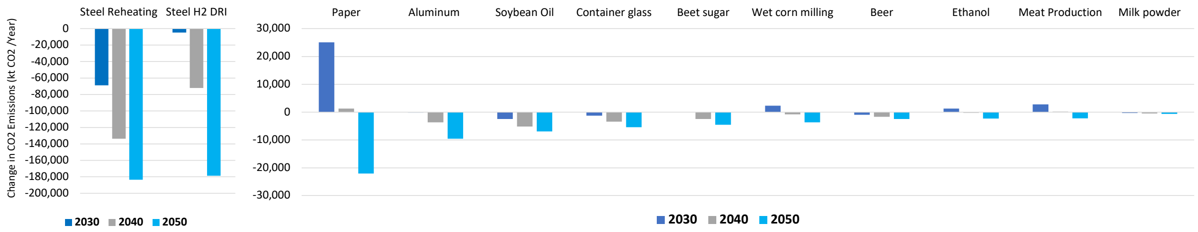


Figure 70. Change in industrial net CO2 emissions using electrified processes in twelve industries studied (excludes ammonia and plastic recycling industries - baseline scenario, technical potential assuming 100% adoption rate, except for the steel industry. In the near term by 2030, the actual adoption rate will be low. Therefore, in sectors where there is a projected increase in CO2 emissions in 2030, the actual increase will be very small.

Figure 71 shows the change in industrial net CO_2 emissions after electrifying the twelve industries under the ambitious scenario. Electrifying these twelve industries could result in CO_2 emissions being reduced by about 203 and 633 Mt in 2030 and 2050 respectively.

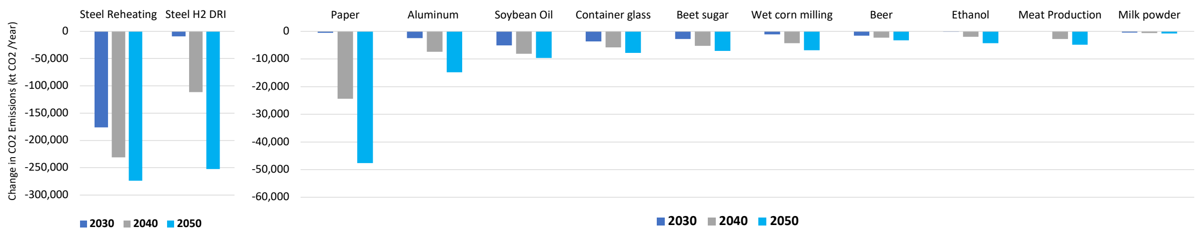


Figure 71. Change in industrial net CO2 emissions using electrified processes in twelve industries studied - Ambitious scenario. (excludes ammonia, and plastic recycling industries, technical potential assuming 100% adoption rate, except for the steel industry. In the near term by 2030, the actual adoption rate will be low. Therefore, in sectors where there is a projected increase in CO_2 emissions in 2030, the actual increase will be very small.)

In addition, total CO_2 emissions savings from 2030 to 2050 were calculated for China under both the baseline and ambitious scenarios. Figure 72 shows considerable cumulative CO_2 savings during this period.

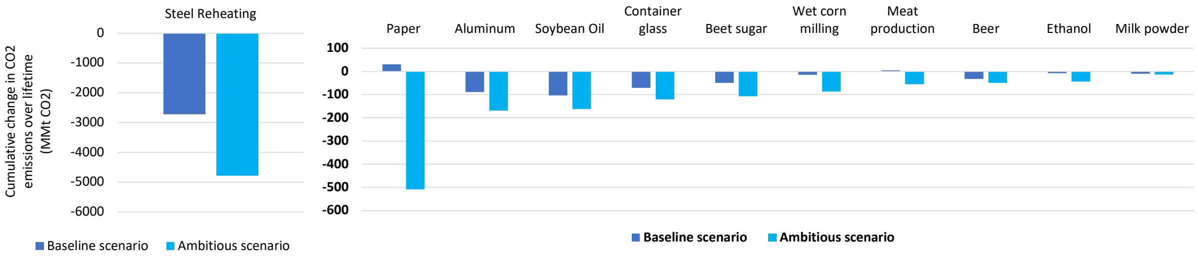


Figure 72. Cumulative change in CO_2 emissions over lifetime of electrified technologies over the period of 2030 - 2050 in twelve industries studied (all except ammonia, and plastic recycling) (This is the technical potential assuming 100% adoption rate, except for the steel industry. In the near term by 2030, the actual adoption rate will be low. Therefore, in sectors where there is a projected increase in CO_2 emissions in 2030, the actual increase will be very small.)

4 Electrification of Boilers in Chinese Industries

Steam boilers are an important technology for delivering energy in industrial settings, primarily responsible for converting water into steam. This steam carries substantial energy, widely used to regulate temperatures and pressures in industrial processes, dry products, separate contaminants, and more. Boilers can consume a significant amount of energy in the industrial and manufacturing sectors. The U.S., for instance, sees nearly 75% of its total final energy demand in the manufacturing sector used for thermal processes, with about 17% of that energy consumed by conventional boilers for steam generation (Hasanbeigi et al. 2021).

Two prevalent combustion boiler types in industry are water-tube and fire-tube boilers. Contrastingly, electric boilers, which are more efficient (achieving up to 99% efficiency), still hold a small market share, despite being a mature technolgoy. These electric boilers function either as electric resistance boilers, where an electrically heated element transfers heat to water, or as electrode boilers, where electric current directly heats the water. Electric boilers offer advantages like reduced air pollution, quicker ramp-up times, and overall efficiency gains.

The primary challenge for wider electric boiler adoption has been economic. As renewable electricity prices drop and the push for decarbonization intensifies, electrification of boilers may become more attractive. Transitioning to electric boilers can significantly reduce CO_2 emissions, especially when the electricity is sourced from renewables, making it a crucial step towards meeting climate goals. This section analyzes the energy use, emissions impacts, and cost implications of switching from conventional to electric boilers in Chinese industry.

Energy use

This section assesses the impacts of specifically electrifying combustion-based steam boilers in several Chinese industrial subsectors. Using the weighted average efficiencies of combustion boilers (which range from 64% to 83% across the sectors studied), sectoral useful energy demand (defined as the energy output of an energy conversion equipment; calculated as the product of combustion boilers' energy demand and boiler efficiencies) can be determined (see Zuberi et al. 2021 for additional notes on methodology). The efficiency of an electric boiler is assumed 99%, which is used to estimate the potential electricity consumption in electric boilers. Figures 73 and 74 show the comparison of current onsite energy demand in combustion boilers, and potential electricity use in electric boilers in Chinese industry in 2022. The comparison shows that electric boilers can reduce the boiler onsite energy demand by 28% in across China's industrial sectors in the base year.

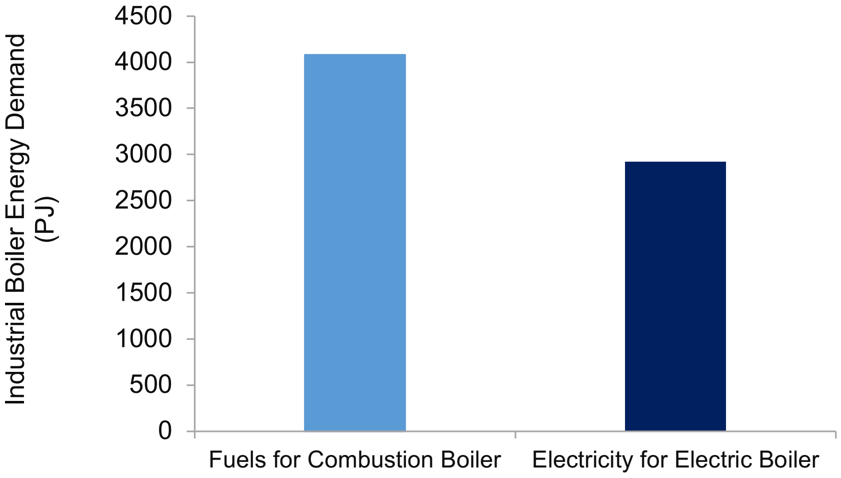


Figure 73. Estimated annual energy demand in combustion and electric boilers in Chinese manufacturing in 2022.

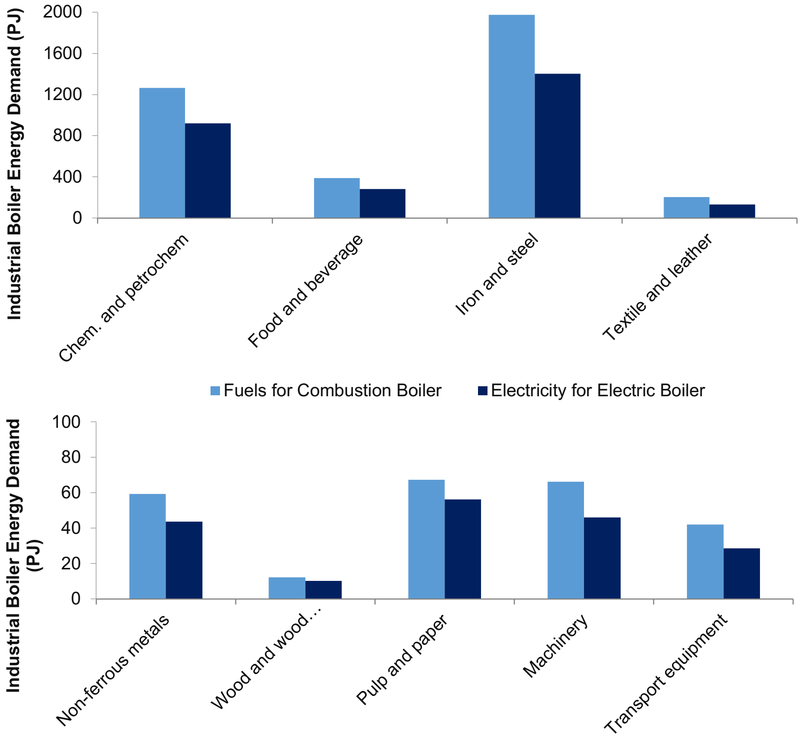


Figure 74. Estimated annual energy demand in combustion and electric boilers in the top four most energy-intensive (top) and the remaining (bottom) Chinese industrial sectors in 2022.

Note: The non-metallic minerals sector generally does not utilize steam from boilers and is not included in this analysis.

CO_2 emissions

Figures 75 and 76 show that electrification could significantly reduce boiler energy demand for steam generation in China's industrial sector and its sub-sectors during the period 2030-2050 (negative values in the figure represent energy savings). Approximately 1,156 PJ of annual onsite energy demand in overall Chinese manufacturing can be saved if the existing fossil fuel-fired boiler capacity is electrified in the base year. This is equal to roughly 28% of the total energy demand in Chinese industrial combustion boilers. Since the boiler energy demand is projected to increase slightly in the future, the annual savings potential is estimated at 1200 PJ in 2050 as also shown in Figure 75. It must be noted that the change in energy demand (Figure 76) and CO_2 emissions (see later) estimated for each Chinese industrial sector are the technical potentials assuming an adoption rate of 100%. However, the actual adoption of electric boilers in Chinese manufacturing will be gradual and over time.

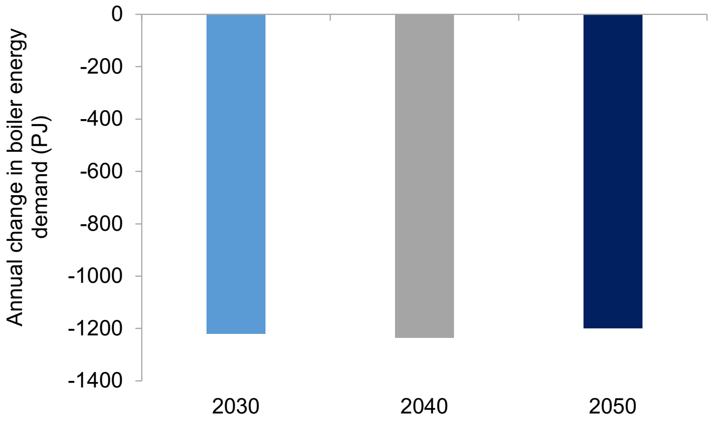


Figure 75. Potential change in boiler annual energy demand in Chinese manufacturing after electrification, 2030-2050.

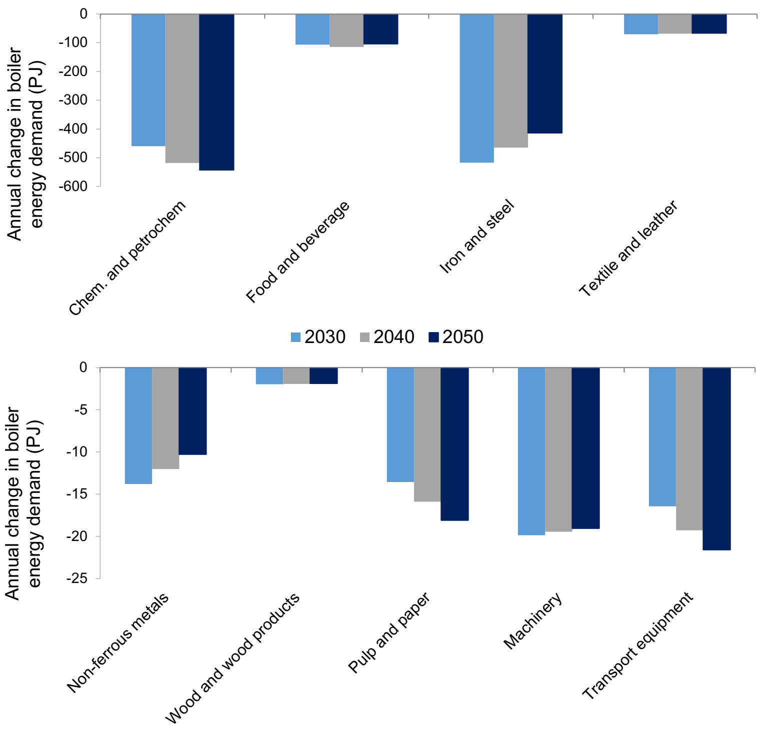


Figure 76. Potential change in boiler annual energy demand after electrification in the top four (top) and the remaining (bottom) Chinese industrial sectors, 2030-2050.

The electrification of combustion boilers in all of China's industrial sectors could initially lead to an increase in annual CO_2 emissions by around 28 $MtCO_2$ from the base year to 2030 in our baseline scenario, due to increased electricity demand from China's carbon-intensive grid. However, in our ambitious scenario that projects increased procurement of renewable electricity and net-zero electricity by 2050, the annual change in emissions is negative in 2030. Boiler electrification is projected to result in 237-372 $MtCO_2$ per year reduction in CO_2 emissions in 2050 across scenarios, as shown in Figure 77.

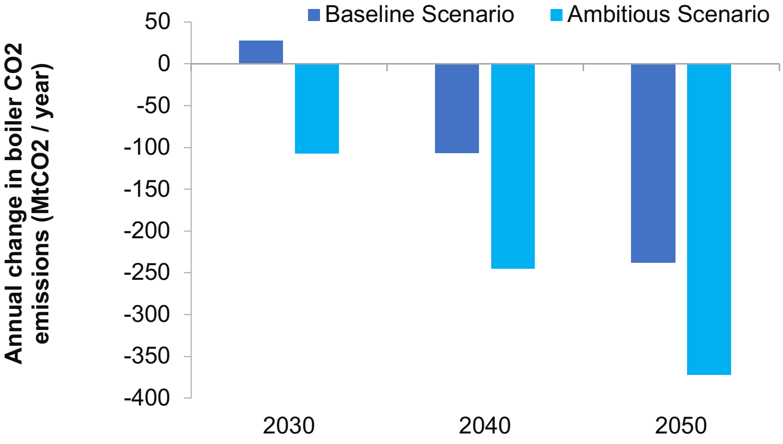


Figure 77. Potential change in boiler's annual CO_2 emissions after electrification in different Chinese industrial sectors, 2030-2050 (This is the technical potential assuming 100% adoption rate. In the near term by 2030, the actual adoption rate will be low. Therefore, in sectors where there is a projected increase in CO2 emissions in 2030, the actual increase will be very small.)

Figure 78 presents the potential change in boiler CO_2 emissions in different Chinese industrial subsectors from 2030-2050. For the most energy-intensive subsectors, annual emissions reductions can reach 167 $MtCO_2$ in the chemicals subsector and 133 $MtCO_2$ in the steel sector under the ambitious scenario. Some subsectors see near-term increases in emissions in 2030 due to the carbon intensity of China's electric grid in the baseline scenario.

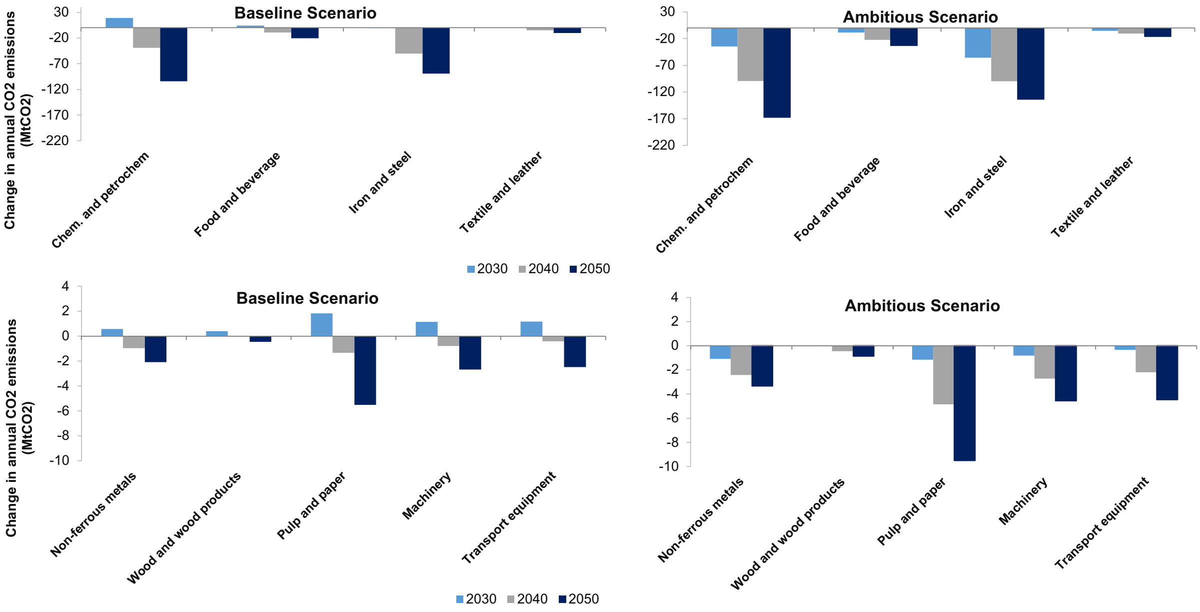


Figure 78. Potential change in boiler's annual CO_2 emissions after electrification in different Chinese industrial subsectors, 2030-2050 (This is the technical potential assuming 100% adoption rate. In the near term by 2030, the actual adoption rate will be low. Therefore, in sectors where there is a projected increase in CO_2 emissions in 2030, the actual increase will be very small). The top row of graphs presents results for the four most energy intensive subsectors, while the bottom row of graphs presents results for the five least energy intensive subsectors. The left column of graphs presents results from the baseline scenario, while the right column presents results from the ambitious scenario.

Energy cost

In China, the energy cost per ton of steam production for the electrified boiler process is nearly three times higher than the conventional process in 2030. However, taking into account China's carbon pricing policy, in 2050, the energy cost per ton of steam production is only about 15% higher for the electrified process compared to the conventional process under our ambitious scenario. The availability of lower-cost electricity can reduce the energy cost of the electrified industrial steam boilers, as shown in Figure 88 with error bars, potentially bringing the electrified process into line with the conventional process per ton of steam by 2050, especially if projected fuel costs also increase.

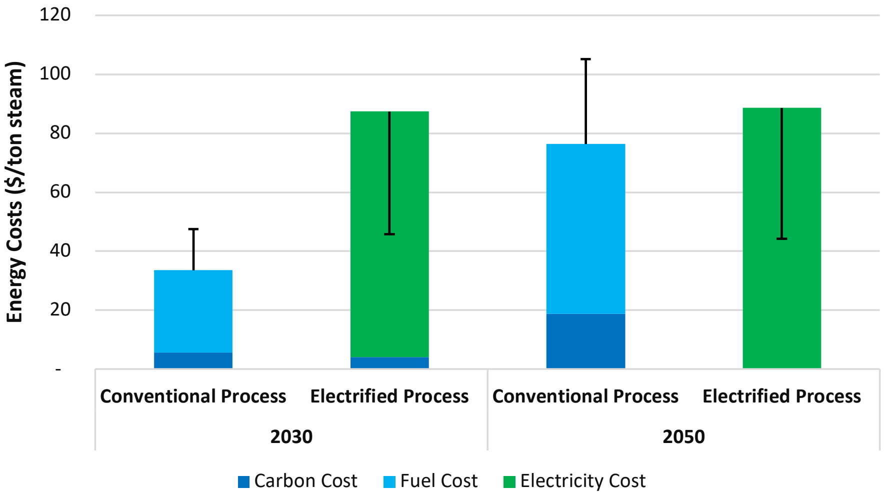


Figure 79: Energy cost per ton of steam in China's industrial steam boilers, 2030 vs. 2050

Note: The error bar shows the energy cost per unit of production when the unit price of electricity is reduced by 50 percent and when the cost of fuel increases by 50% Carbon costs are zero in 2050 for the electrified process based on our assumption that zero-carbon electricity is used by 2050 in the ambitious scenario.

When looking sector by sector, it is clear that for some sectors, electrification will be relatively less costly in terms of energy costs per ton of steam by 2050, especially when taking into account carbon costs under our ambitious scenario (Figure 80). A lower electricity price in 2050 relative to current price projections would make the overall energy costs of boiler electrification competitive with conventional boilers, with some sectors having more favorable break-even points, such as machinery, textiles, and transport equipment. Also, it should be noted that we did not consider capital or operation and maintenance cost of boilers. In general, electric boilers are cheaper than conventional fuel-fired boilers.

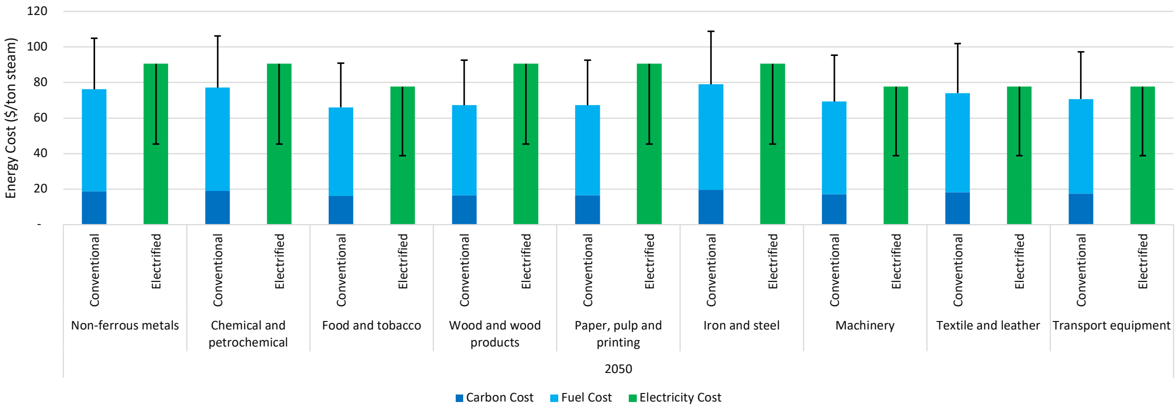


Figure 80: Energy cost per ton of steam in China's industrial steam boilers in 2050

Note: The error bars show the energy cost per unit of production when the unit price of electricity is reduced by 50 percent and when the cost of fuel increases by 50% Carbon costs are zero in 2050 for the electrified process based on our assumption that zero-carbon electricity is used by 2050 in the ambitious scenario.

It should be noted that the adoption of electric boilers possesses several co-benefits besides CO_2 abatement, including the elimination of combustion-related air pollutants, lower space requirements, less frequent maintenance, etc. However, techno-economic quantification of these co-benefits is outside the scope of this report.

5 Industrial Electrification's Impact on the Electricity Grid

Industrial electrification has the potential to reduce emissions across industrial subsectors and around the country, but China's coal-heavy electricity power generation poses challenges to realizing these reductions. Key challenges to decarbonizing China's grid include economic and technical issues facing the integration of renewable energy, energy security as a policy priority, and power market reform. Further decarbonization of China's grid will provide clean electricity for an increasingly electrified industrial sector and contribute to meeting the nation's emissions reduction goals.

5.1. China's electricity grid

China's electricity grid is the largest in the world. The majority of China's electricity comes from coal-fired power plants. In 2021, coal-fired power plants provided 62.6% of China's electricity generation, while 16% came from hydropower, 8% from wind, 4.8% from nuclear, 4% from solar, and 2% from biomass (Sandalow et al. 2022).

Electricity generation from renewable resources has increased over time while electricity from coal has remained fairly stable, with a slight decline from 2020 to 2021 due to the initial effects of the COVID-19 pandemic. Nevertheless, China continues to install new coal-fired power capacity, with more than 25 GW of capacity added in 2021. This additional installed capacity is in part meant to balance renewable energy, which is also being installed at rapid rates in China. At the same time, coal remains a favored energy source due to its domestic abundance and low cost, political preferences, and path dependency (Springer et al. 2022).

On the renewables side, China continues to install more renewable energy capacity each year than any other country, with 43% of global renewable energy capacity in 2021 added in China alone (Sandalow et al. 2022). Under China's 14th Five Year Plan for Renewable Energy, released in 2022, China set a target to reach 18% non-hydro renewable electricity generation by 2025, and 33% including hydropower. China also set a target to reach 1,200 GW of installed wind and solar capacity by 2030, but is already on track to meet this target five years ahead of schedule. As of the end of 2022, China had reached 392 GW of operating solar installed capacity with an annual growth rate of 22% and 365 GW of operating wind installed capacity with an annual growth rate of 9% (Figure 81) (Mei et al. 2023). Feed-in tariffs that have incentivized renewable energy in the past are gradually being phased out, although other types of policy and market incentives remain (Jaghory 2022).

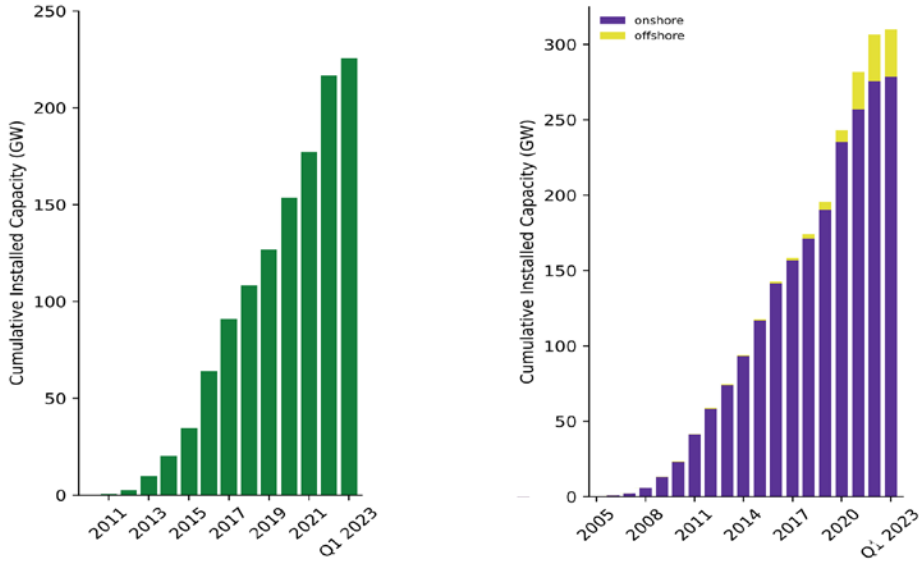


Figure 81: China's cumulative installed operating utility-scale solar capacity (left) and wind capacity (right) by year. Source: Mei et al. 2023

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. China's grid has faced major and unprecedented challenges in reliability in the past several years, when rebounding electricity demand in the wake of the COVID-19 pandemic clashed with electricity supply shortfalls, triggered by incidents such as drought-induced hydropower shortages and shocks to coal prices. Additional pressure will be placed on the grid system as multiple sectors, including transportation and buildings in addition to industry, move to electrify to access renewable resources and reduce their emissions.

In some provinces, there are high rates of curtailment of wind and solar energy. Further investment in transmission infrastructure can ensure more renewable energy is integrated into the grid, with the ability to generate and use renewable energy locally being the best option to reduce curtailment. In addition, China's highly regulated electricity markets historically gave preference to coal-fired power generation, even when wind and solar power was being generated at zero marginal cost (Sandalow et al. 2022).

In conclusion, China's move towards industrial electrification has the potential to significantly reduce greenhouse gas emissions, but only if it is paired with a broader transition towards cleaner electricity generation. Research has demonstrated that China can reach an 80% carbon-free electricity system by 2035 if wind and solar generation capacity reach 3,000 GW by then (Abhyankar et al. 2022) (Figure 82). This is a significant scale-up even relative to China's likelihood of achieving 1,200 GW of installed wind and solar capacity by 2025, involving not only technological challenges but also economic, policy, and institutional challenges.

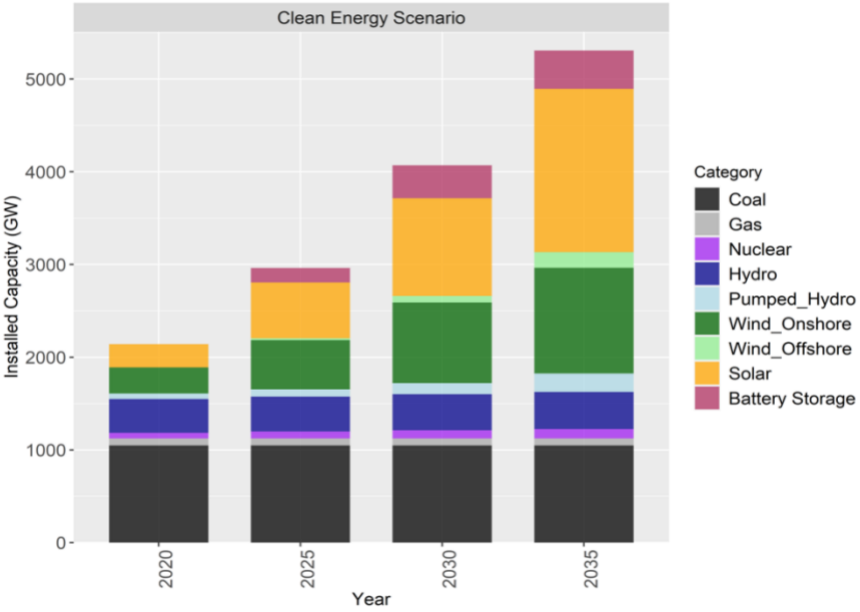


Figure 82: Installed capacity by energy type in a scenario to generate 80% carbon-free electricity by 2035 in China. Source: Abhyankar et al. 2022

5.2. Industrial electrification's electricity grid impacts

The analysis results clearly show that in the industrial sectors studied, electrification results in a reduction in the total annual final energy use. While electrification decreases net final energy demand due to the higher efficiency of electrified technologies, the demand for electricity naturally increases. Figure 83 shows that electrifying twelve industries result in an increase in annual electricity load after industrial electrification.

To fully electrify the twelve industries (except ammonia and recycled plastic) included in this study with the processes described in this report, an additional 620 GW of power generation capacity in 2050. For comparison, China aims to install 3,000 GW of generating capacity by 2025. To estimate the impacts of additional load, we assumed all the additional load is coming from clean renewable energy sources. We further assumed that that two-third of this additional load is coming from solar power and one-third from wind power.

Utilities, policymakers, industry, and other stakeholders should pay attention to this potential increased demand for renewable electricity, and the associated need for more renewable electricity generation, additional energy storage, demand response programs, and transmission and distribution system expansion. 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.

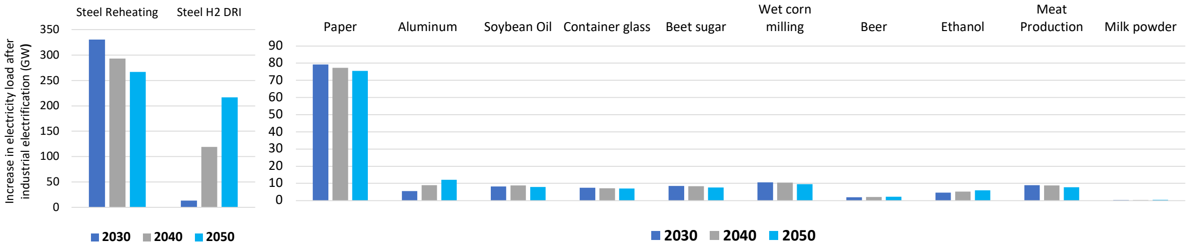


Figure 83. Increase in electricity load after industrial electrification in 2030-2050 (GW)
(assuming 100% adoption rate, except for the steel industry)

6 Recommendations and Policy Implications

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 eight most impactful changes that would support increased industrial electrification. These changes will require numerous actors to work together to solve significant challenges in renewable electricity generation and transmission, technology development and deployment, and workforce development.

Establish industry-specific electrification roadmaps.
A one-size-fits-all approach will not be successful given the varied heat demand and profile and constraints across different sectors. Therefore, it is recommended to develop industry-specific roadmaps for the electrification of industrial heating, outlining a clear path towards electrification. These roadmaps should consider the specific needs, capacities, and potential for electrification within each industry, with a focus on industries that are energy-intensive and heavily reliant on fossil fuels. By doing so, businesses in these sectors can have a clearer understanding of their pathway to electrification, the milestones they need to reach, and the specific technologies and practices they can adopt to realize these goals. The government, in turn, can also gain insights into the unique challenges and barriers faced by these sectors and devise appropriate supportive policies.

Integrate electrification in industrial planning and decision making.
China can take significant strides towards electrification of industrial heating by embedding electrification in the planning and decision-making processes of its industries. It is crucial for the government to work in collaboration with private firms to incorporate clean energy goals into their long-term business strategy. To promote this, China could establish policy mechanisms requiring or incentivizing industry-wide strategic electrification planning. This could involve mandatory clean energy targets for industries or the integration of clean energy targets into the assessment of industry performance. Such mechanisms can send a clear signal to the market, creating greater certainty for industries to invest in electrification technologies.

Establish robust standards and regulations.
The Chinese government should consider implementing stringent standards and regulations that encourage the use of electrification technologies. These could take the form of energy efficiency standards, emission caps, or mandatory usage of certain electrification technologies in specific industrial processes. Regulations to phase out the most energy-intensive and carbon-emitting technologies should continue to be introduced and strengthened. The standards should be dynamic, keeping pace with the advancements in technology and decreasing costs of electrification solutions. The introduction of such policies could pressurize industries to adopt cleaner technologies and could be complemented with financial incentives for early and ambitious adopters.

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

Though provinces and city-level governments might not directly conduct research and development for electrification technologies, they can facilitate technology demonstrations and deployments. For example, in Hebei province, the Hebei Iron and Steel group is undertaking a pilot DRI project and planning future hydrogen DRI pilots for greener steel production, with encouragement from the provincial government (Hasanbeigi et al. 2023). At the national level, China can also establish pilot projects or incentive programs to advance electrification technologies. Moreover, Chinese companies and regulators can seek opportunities to leverage government resources in support of industrial electrification. For example, China has a Five-Year Plan for Energy Technology Innovation and a Five-Year Plan for a Modern Energy System, both of which call for more R&D funding to various clean energy technologies. The Chinese government has also developed guidance funds to support private sector innovation, including for clean energy.

Numerous 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 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. This is a particular issue for adoption of electric boilers, since capital costs for equipment replacement are dwarfed by energy costs over the lifetime of the technology.

Thus, financial incentives to overcome increased operating costs (i.e. energy costs) for electrified technologies are important. By leveraging government financial and technical support, provincial regulators and manufacturers may be able to reduce costs, particularly for pilot or demonstration projects. Grants for adopting electrified technologies would diminish manufacturers' upfront and expected lifetime costs and incentivize change. Grants could be awarded for pilot projects to encourage early adoption and demonstrate success. Given China's ongoing power sector reform, there also needs to be consideration of electricity procurement for major industrial facilities that are undergoing electrification, and how to incentivize purchase of renewable electricity.

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. It will also be important to help companies understand the potential impacts of China's emissions trading system on fuel prices, future cost declines in renewable electricity, and variations in local energy prices, all of which can impact the favorability of electrification.

Facilitate cross-sectoral collaboration for electrification.
Achieving large-scale industrial electrification requires collaboration between various stakeholders in the energy and industrial sectors, including collaboration across different industrial subsectors and collaboration between industry and other economic sectors (such as the electric power sector). The government can play a critical role in fostering this collaboration by establishing platforms for knowledge sharing and partnership between industry players, power companies, technology providers, researchers, and policy makers. Such platforms could facilitate the exchange of best practices, promote the co-development and adoption of electrification technologies, and help align interests and coordinate actions among stakeholders.

Develop Public-Private Partnerships (PPPs).
The government could facilitate the formation of Public-Private Partnerships (PPPs) for the research, development, and deployment of advanced electrification technologies. Under PPP arrangements, the government can provide financial support, policy incentives, and a platform for collaboration, while businesses can bring technical expertise, resources, and market insights. Such partnerships can help in risk sharing, accelerating technology commercialization, and facilitating technology transfer. In the long run, these collaborations could contribute to reducing the cost of electrification technologies and speeding up their adoption in the industry.

Develop and expand the workforce.
Workers and contractors employed in China's industrial facilities may require training on new electrification technologies, encompassing installation, operation, and maintenance procedures. China can leverage its educational programs to offer training on existing electrified technologies and ensure that the future workforce is well-prepared to develop and implement innovative solutions. Chinese governmental departments, such as those handling education, energy, public utilities, and economic development, should collaborate to gather input on the development of educational programs. Engaging with utility companies, trade associations, educators, and students will prove invaluable in guaranteeing that training programs align with both current and future industry needs.

Moreover, workforce development initiatives should focus on establishing partnerships with communities that may be affected by fossil fuel phaseout as China transitions away from a coal-based economy. By collectively creating pertinent educational and training programs, China can ensure these communities participate equitably in the clean energy economy. Furthermore, by cultivating robust relationships between educational institutions and the private sector, China can ensure that emerging professionals are ready to face the challenges and opportunities presented by industrial electrification, thereby promoting employment opportunities in high-value industries.

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