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Authors

Sawe, Nik

Lu, Hongyou

Rissman, Jeffrey

et al.

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Nik Sawe[1], Hongyou Lu[2], Jeffrey Rissman[1], Zhiyu Tian[3], and Nan Zhou[2]

[1] Energy Innovation: Policy and Technology LLC
[2] Lawrence Berkeley National Laboratory
[3] Energy Research Institute of China

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Executive Summary

China's manufacturing sector generates 61% of the country's CO_2 emissions, nearly three-quarters of which is related to industrial process heating. To meet China's climate targets and attain a zero-carbon industrial sector, decarbonizing these industrial heating processes is a necessity. If China's electricity grid is similarly decarbonized, direct electrification is the most practical means of supplying this heat efficiently at the required scale.

In addition to reducing greenhouse gas emissions, industrial electrification would help reduce conventional pollution that was responsible for 1.85 million premature deaths in China in 2019, and it would improve China's energy security, as the country imported 85% of its petroleum products and crude oil as well as 46% of its natural gas in 2021. Direct electrification would also help Chinese firms avoid volatile fossil fuel prices and future carbon pricing costs, and ensure competitiveness when selling products to environmentally-conscious buyers and governments that may use carbon border adjustment mechanisms or similar efforts to encourage the procurement of cleaner materials.

Two electrified technologies stand out as means for China to decarbonize its industrial process heating: industrial heat pumps and thermal batteries. Heat pumps can be the most efficient and cost-effective method to supply clean, low-temperature heat for industrial processes. They can achieve efficiencies several times higher than other electrical technologies because they do not convert their input electricity into heat. Instead, heat pumps move heat from a low-temperature to a high-temperature area, operating much like a refrigerator or air conditioner. Industrial heat pumps can extract heat from a source (such as the air, ground, or waste heat from another industrial process) and output heat at temperatures up to 165 °C. Heat pumps that raise temperature by 40 to 60 °C typically have efficiencies of 300-400%. Notably, no other heating technology can generate heat at an efficiency beyond 100%; this exceptional efficiency makes heat pumps a particularly cost-effective electrification route.

For higher temperature processes, thermal batteries can provide up to 1,700 °C, making them a viable option for supporting over two-thirds of China's manufacturing sector's process heating needs. Thermal batteries contain thermal storage material with a high specific heat capacity that resists chemical breakdown at high temperatures. The storage material is enclosed in a highly insulated shell to minimize heat loss, losing as little as 1% a day in some systems. Electrical resistance heaters inside the battery convert their electricity to heat that is absorbed by the storage material and can then be extracted when the industrial facility is ready to use the heat.

The storage capability of thermal batteries means that they can provide steady-state heat in both on- and off-grid configurations. Off-grid batteries would be able to procure electricity at wholesale prices from dedicated renewables projects, smoothing over the variability of day-night cycles or lulls due to weather conditions. Similarly, for grid-connected batteries, energy can be purchased during the cheapest times of day and banked for future use. While many Chinese manufacturing firms are located in the eastern provinces where there may be limited land for creating new off-grid renewables projects, grid-connected thermal batteries offer firms and utilities the benefits of price-hunting and optimization. Additionally, by reducing industrial electricity demand when electricity is in short supply, direct electrification with thermal batteries could aid in grid regulation, help the grid integrate variable renewables, and cut peak demand, lowering the required grid-related capital costs of transitioning to clean industry.

Performing a techno-economic comparison of these two electrified heating technologies and their alternatives in China, we found that for temperatures under 100 °C, industrial heat pumps were the second-cheapest heating option with a levelized cost of \$38/MWh_{th} (¥260/MWh_{th}), remaining competitive with combined heat and power (CHP) variants and considerably cheaper than natural gas or electric boilers (Figure ES-1). While coal-fired boilers currently offer the lowest levelized cost of heat production, when incorporating a 2030 estimated carbon cost, industrial heat pumps become the lowest-cost option for low-temperature heat. For temperature ranges of 100-165 °C, industrial heat pumps cost about \$58/MWh_{th} (¥391/MWh_{th}), but are broadly competitive with natural gas, and may improve in terms of costs and efficiency with additional research and development. Industrial thermal batteries are costed in-between the two heat pump variants at \$46/MWh_{th} (¥314/MWh_{th}) and can support far higher temperatures.

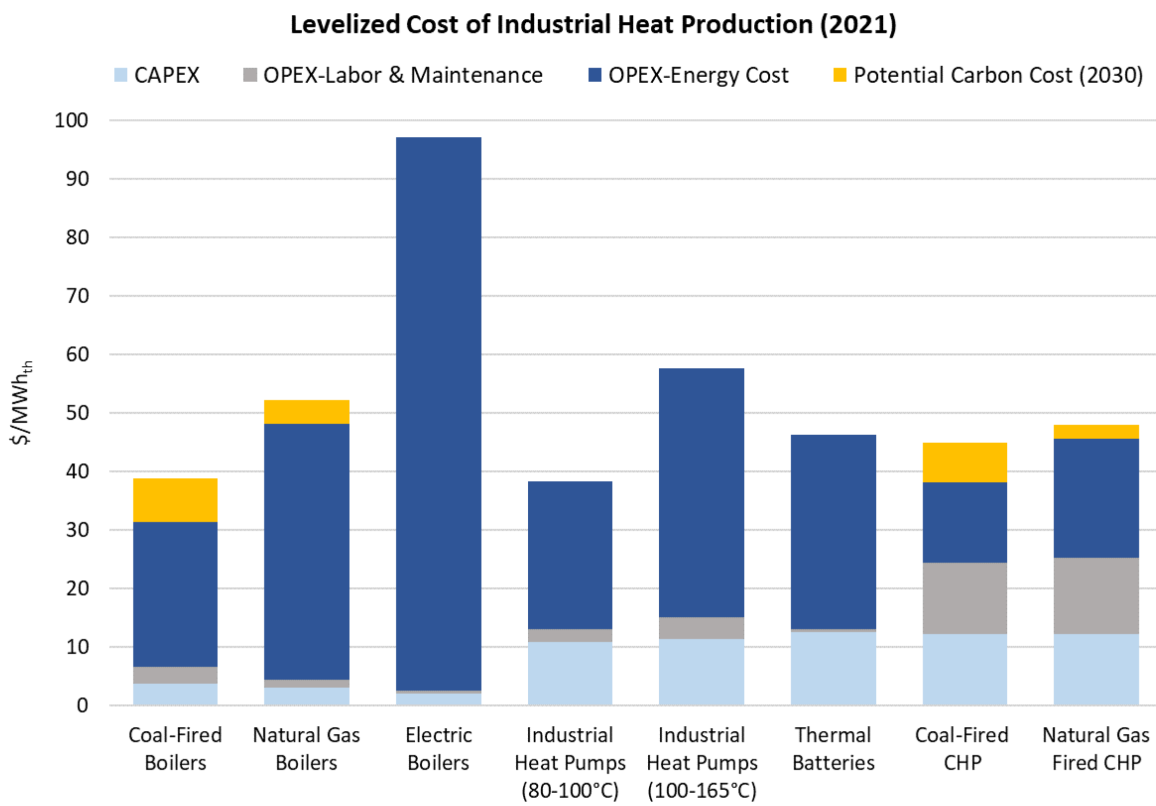

Figure ES-1. Total levelized cost incorporating capital expenditure, energy and non-energy operational expenditure, and forecast 2030 carbon pricing costs of various industrial heat production technologies

Notes: 1) An estimated carbon price for 2030 is added for coal and natural gas technologies to illustrate the cost comparison during the years when the equipment will operate, assuming that China's national ETS will expand from just the power sector to industrial sectors. The 2030 carbon cost is an estimate based on the *2022 China Carbon Pricing Survey,* a survey of about 500 industry stakeholders in China (Slater, Wang, and Li 2023). The cost used here is ¥130 yuan per tonne CO_2, or \$19.50/tCO_2. 2) Electrotechnologies, including electric boilers, industrial heat pumps, and thermal batteries, do not have additional carbon costs, as their energy source is electricity, which is covered by China's national ETS. Today's carbon prices are reflected in the electricity prices (X. Yang and Lin 2023). While the carbon price paid by electricity suppliers will be higher in 2030 than it is today, the carbon intensity of China's electric grid will be lower, and the cost of clean electricity generating technology may be lower as well, so there is no reason to assume final electricity prices will be higher in 2030 even after incorporating a higher carbon price. For this reason, we do not apply a potential carbon cost to electrotechnologies in this figure.

Relative to coal-fired technologies, heat pumps were found to achieve significant reductions in five pollutants (CO_2, NO_x, SO_x, PM_{10}, and $PM_{2.5}$) and thermal batteries in three pollutants (SO_x, PM_{10}, and $PM_{2.5}$), accounting for the pollutant emissions associated with the electricity they use. As China's grid increasingly shifts to zero-emissions electricity sources, electrified technologies' pollutant emissions will decline, ultimately reaching zero if China's grid becomes fully decarbonized.

Smart policy is necessary to overcome the barriers to industrial electrification in China. Fossil fuel prices are considerably lower in China than the cost of electricity for industrial energy buyers. Limited availability of electrified equipment, especially high-temperature industrial heat pumps and industrial thermal batteries, also presents a current hurdle. Additionally, upgrading and electrifying existing industrial equipment can be technically challenging, and doing so outside of the equipment's natural replacement cycle can incur additional costs.

Policymakers can incentivize the transition using equipment rebates, retooling grants, and access to low-interest financing mechanisms to offset the capital expenditures related to adopting these technologies. Enhancing existing energy-efficiency standards, emissions standards, and green public procurement programs can likewise encourage the transition to direct electrification. China's research laboratories, such as those operated by the Chinese Academy of Sciences, can collaborate with private industry on research and development (R&D) programs to move these early-stage technologies forward. Grant funding is not limited to supporting laboratory-scale R&D but can also fund pilot or demonstration plants that provide proof-of-concept and encourage industrial players to transition. Creating a competitive landscape between coal and electricity is also important and can be achieved by carbon pricing or by subsidizing the cost of clean electricity and the cost of upgrades to support electrification. Inter-provincial electricity trading and optimization of China's Green Electricity Certificate system can help facilitate access to clean electricity.

Direct electrification of industrial process heating in China has the potential to reduce greenhouse gas emissions immensely and would yield massive benefits to the country and the globe. While existing technologies offer a path forward, China must incentivize their adoption by creating a supportive environment for industrial decarbonization through the right policy approaches. Given the country's large industrial capacity, China has the potential to lead in clean industrial technology while achieving its climate targets.

Introduction

Industrial firms utilize heat for a variety of manufacturing purposes, such as melting metals, heat-treating parts, and driving chemical reactions. Globally, heat used in manufacturing accounts for around a quarter of final energy demand and a similar share of energy-related carbon dioxide (CO_2) emissions[1] (Figure 1), nearly 8 gigatons of CO_2 (8 $GtCO_2$). Therefore, decarbonizing industrial heat is a crucial aspect of reducing global greenhouse gas (GHG) emissions.

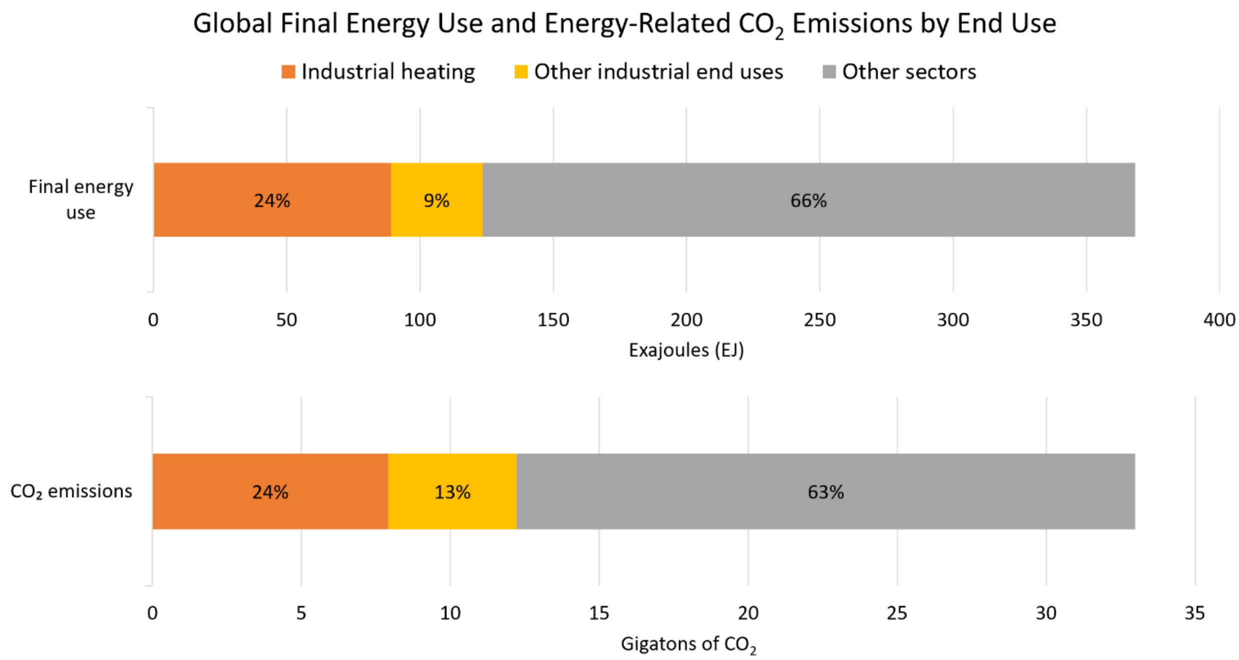

Figure 1. Contribution of industrial heat to global final energy use (in 2020) and energy-related CO_2 emissions (in 2021)
Sources: (International Energy Agency 2021a; Madeddu et al. 2020; International Energy Agency 2023b)
Note: In this figure, "industry" refers to manufacturing. Mining/drilling, refining, construction, and agriculture are included in the "Other sectors" category. "Final energy use" excludes feedstocks (fuels that are not combusted for energy but go into making products such as chemicals). "Energy-related CO_2 emissions" excludes CO_2 unrelated to fuel combustion, such as CO_2 from cement calcination and land use change. CO_2 emissions from purchased electricity or steam are assigned to the purchasing sector (industry or non-industry) and end use (heating or non-heating). "Other industrial end uses" is responsible for a larger share of CO_2 emissions than its share of final energy use because 65% of this energy consists of electricity, which is used more efficiently than combustible fuels but is associated with upstream CO_2 emissions from its production.

While industrial heating systems can employ a variety of energy sources, about 81% of global industrial heat comes from the burning of fossil fuels, including coal, petroleum products, and natural gas (BloombergNEF and WBCSD 2021). A further 10% of industrial heat is provided directly by electricity, and the last 9% comes from biomass and waste combustion (Lovins 2021; BloombergNEF and WBCSD

[1] Energy-related CO_2 excludes "process" CO_2 from non-energy sources, such as CO_2 from the calcination of limestone to form clinker, the main ingredient in cement.

2021). Therefore, the key challenge in decarbonizing industry is to shift from the use of fossil fuels to generate industrial heat to clean alternatives, such as direct electrification, clean hydrogen, bioenergy, or carbon capture.

Direct electrification, supplied with clean electricity[2] from cost-effective renewables (such as wind, solar, and hydroelectric power) has the potential to be the most promising option for most industrial heating needs. Electricity generation can be decarbonized using already-commercialized technology, and direct use of electricity is highly efficient in comparison to combustion processes. While approaches involving bioenergy, clean hydrogen, and carbon capture have roles to play in addressing a problem as large as decarbonizing global industry, direct electrification will be the most important lever in decarbonizing industrial heating.

When considering industrial heat needs, China stands out from all other countries. In 2020, fossil fuel combustion in Chinese industrial facilities accounted for 3.6 $GtCO_2$, 45% of the world's 8 $GtCO_2$ energy-related CO_2 emissions from industry (World Resources Institute 2022). Therefore, it is important to give special consideration to the technologies and policies that could most efficiently decarbonize industrial heat in China.

Industrial Heating in China

The manufacturing sector is the largest energy-consuming and CO_2-emitting sector in China. In 2021, it accounted for about 57% of all primary energy use and contributed 61% of total energy-related CO_2 emissions when emissions of purchased electricity and heat are attributed to purchasing sectors.[3]

China's manufacturing sector is dominated by five energy-intensive subsectors: ferrous metals, chemicals, non-metallic minerals, petroleum refining, and non-ferrous metals. In 2021, these five subsectors were responsible for 86% of China's total manufacturing energy use (Figure 2, top bar). Other manufacturing subsectors—such as machinery, food, and textiles—represented 14% of total manufacturing final energy use.

China's manufacturing sector relies heavily on fossil fuels. In 2021, approximately 70% of manufacturing final energy use came from coal, petroleum products, and natural gas consumed in industrial facilities (Figure 2, bottom bar). Electricity accounted for 24% of final manufacturing energy use (mostly used for non-heating purposes, such as operating electric motors). In addition, while China has added significant renewable power generation capacity in recent years, coal-fired power generation still remains the biggest source of electricity production, accounting for 67% of China's total electricity generation in 2021 (China Electricity Council 2022).

[2] Clean electricity refers to electricity generated without emitting greenhouse gases or conventional air pollutants.
[3] Energy consumption data are from the *2022 China Energy Statistical Yearbook* (NBS 2023a) and CO_2 emissions are calculated based on reported fuel consumption and CO_2 emission factors for fuels recommended by the Ministry of Ecology and Environment in China (MEE 2022).

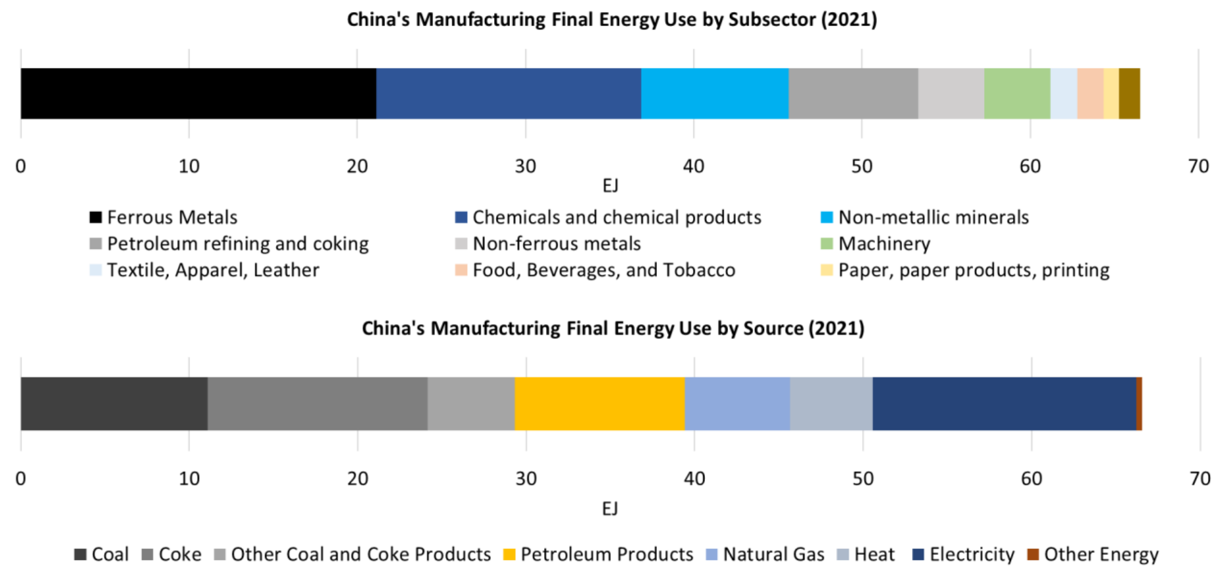

Figure 2. China's manufacturing final energy use by subsector and by source in 2021

Source: (NBS 2023a).

Notes: 1) "Others" include manufacturing of transport equipment, recycling, manufacturing of wood products, and manufacturing of furniture. 2) "Natural gas" also includes liquified natural gas. 3) "Other coal and coke products" include coke oven gas, blast furnace gas, converter gas, other coal gas, and other coking products. 4) "Other Energy" includes biomass, waste, geothermal, and other energy sources. EJ = exajoules or 10^{18} joules.

A majority of the final energy use in China's manufacturing sector is directed toward providing heat (e.g., heating, drying, calcination, distillation, etc.). In 2021, an estimated 73% of China's total manufacturing energy was consumed producing, supplying, and distributing industrial heat (Figure 3). Specifically, 62% of final energy use was for "process heating" and 11% of final energy use was attributed to "losses from onsite generation and distribution." Nearly 100% of the energy used to generate and supply industrial heat in China is from fossil fuels, such as coal, coke, their related products, and natural gas.

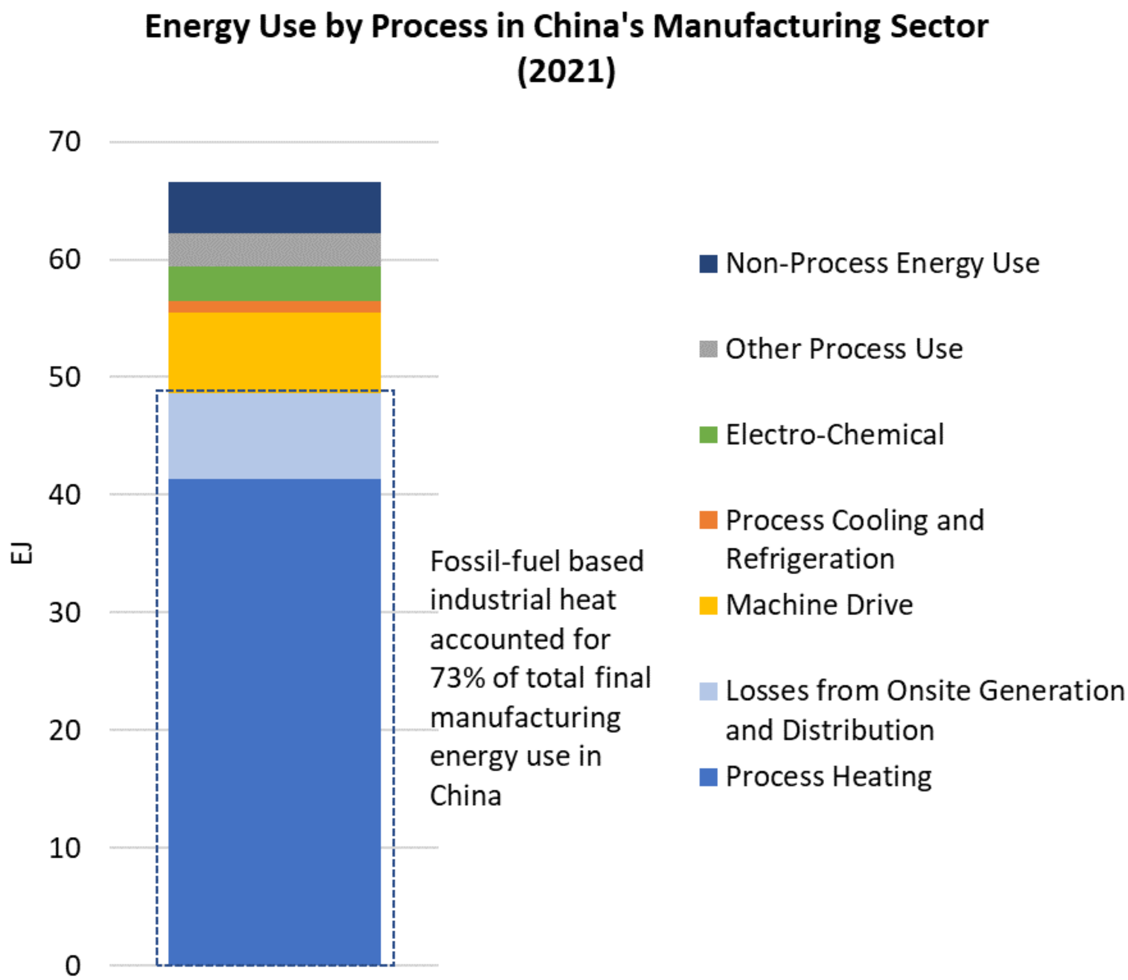

Figure 3. Energy use by process in China's manufacturing sector in 2021

Source: authors' estimation based on data from (NBS 2023a; U.S. Energy Information Administration 2021)
Notes: 1) Data presented here exclude feedstock use; 2) "Machine Drive" refers to systems such as electric motors, pumps, chillers, fans, and compressors; 3) "Other Process Use" refers to processes such as on-site product transfer using forklifts, cranes, and similar equipment, as well as oxidizers and other environmental/emission controls; 4) "Non-Process Energy Use" is dominated by heating, ventilation, and air conditioning (HVAC) systems that provide facilities with appropriate temperatures for working conditions but not the heating or cooling required by industrial processes. This category also includes facility lighting and energy (primarily electricity) use for offices, cafeterias, personal computers, printers, back-up or emergency generators, and wastewater treatment systems. 5) "Process Heating" includes all energy used in industrial cogeneration or combined heat and power (CHP) systems. EJ = exajoules or 10^{18} joules.

Different manufacturing processes have varying temperature requirements. As the industry sector seeks to decarbonize and electrify its energy use, the temperature requirements for industrial heat play an important role in selecting technologies. While the non-metallic minerals (e.g., cement and glass) and ferrous metals (e.g., iron and steel) industries require relatively high-temperature process heat, a number of manufacturing subsectors utilize heat at substantially lower temperatures (Figure 4). For example, 100% of the process heating required for the textiles industry is below 150 °C. More than 80%

of the process heating needed to make machinery (from purchased metal), as well as the processing and manufacturing of food, beverages, and tobacco, is in the range of 80-150°C. In the chemicals industry, 58% of the process heat demand is in the range of 80-150 °C, with another 14% in the range of 150-300 °C.

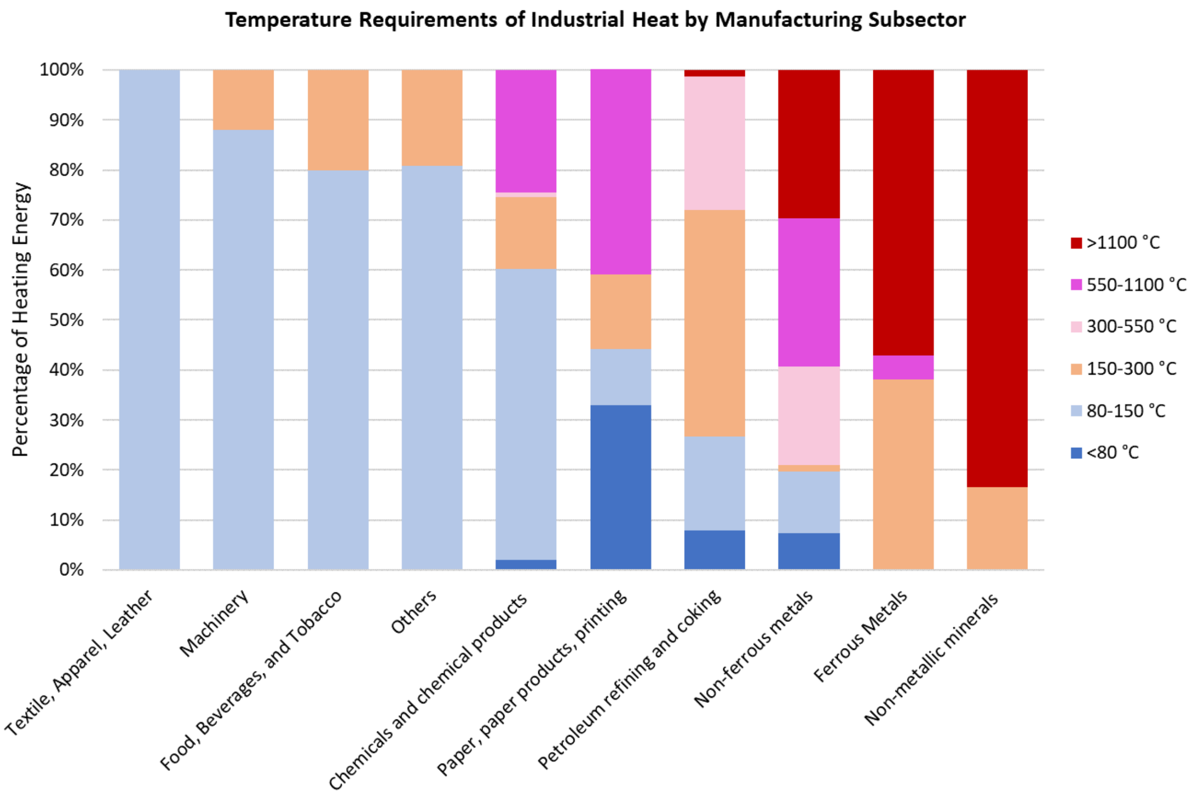

Figure 4. Temperature requirements of industrial heat by manufacturing sector
Sources: Rightor, Whitlock, and Elliott 2020; Rissman 2022.
Note: The "Others" category includes recycling facilities and the manufacturing of transport equipment, wood products, and furniture.

Very high temperature requirements are particular to certain industries, especially ferrous metals and non-metallic minerals (Figure 4). These are two of the three industries with the greatest *absolute* energy demand in China (Figure 5), so a significant fraction of China's industrial heat demand is at high temperatures. In total, around 90% of China's manufacturing heat demand is concentrated in just four industries (ferrous metals, chemicals, non-metallic minerals, and petroleum refining and coking), while all other industries (including food, textiles, machinery, etc.) make up the remaining 10%.

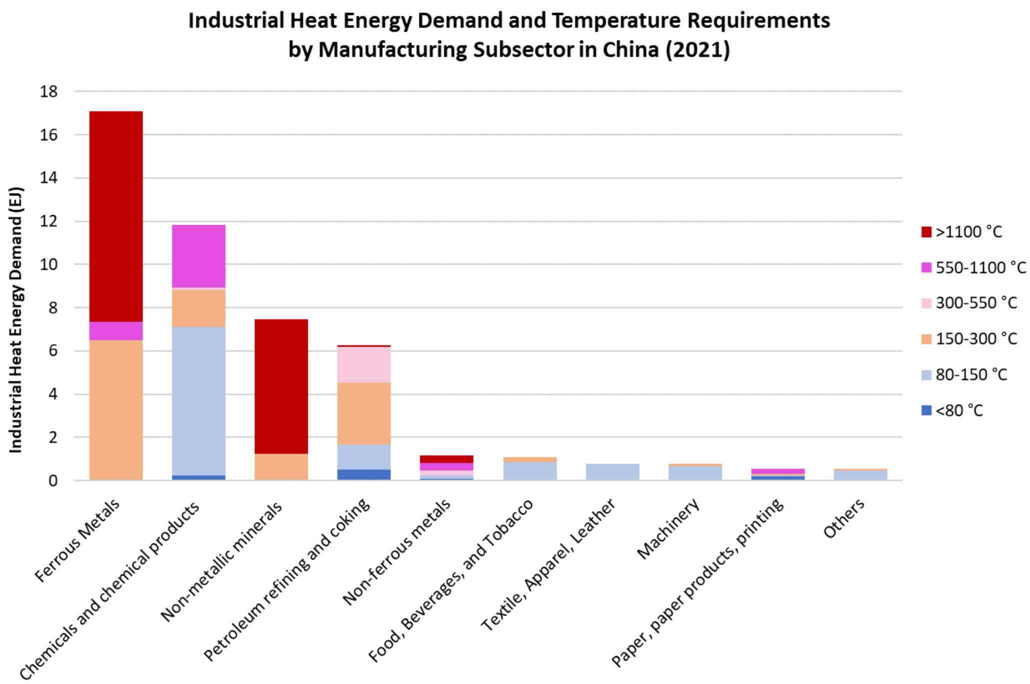

Figure 5. Process heat energy demand and temperature requirements by industry in China (2021)
Sources: (NBS 2022; Rissman 2022).
Note: The “Others” category includes recycling facilities and the manufacturing of transport equipment, wood products, and furniture.

Low-temperature industrial heat (below 150°C) accounted for 26% of total process heating demand in China’s manufacturing sector in 2021, while low-to-medium temperature heat (150-300°C) represented another 27% (Figure 6). Very high-temperature industrial heat (>1100°C) accounted for 34% of total industrial heat demand in China.

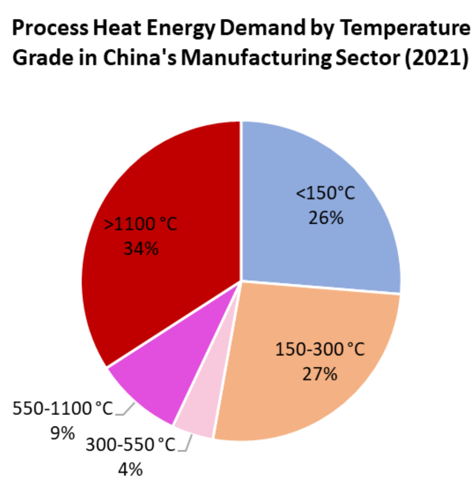

Figure 6. Process heat energy demand by temperature grade in China’s manufacturing sector (2021)
Sources: (NBS 2022; Rissman 2022)

It is worth noting that temperature requirements of industrial heat are a critical but not sole consideration when comparing electrification options. Industries that have very complex energy systems with integrated thermal and electrical energy demand, such as chemicals and petroleum refining, typically face the greatest electrification challenges (Deason et al. 2018). Industries with less complicated energy systems, such as the food, beverage, and textile industries, may be much easier to electrify.

Benefits of Industrial Electrification in China

Industrial firms switching from fossil fuel combustion to clean electricity has advantages for society and for the industrial firms themselves.

Emissions Reduction

Today, China's manufacturing sector is responsible for almost 61% of China's total energy-related CO_2 emissions (when emissions associated with electricity and heat production are allocated to the end-use sectors). This represents roughly 6.7 gigatons of CO_2 emissions ($GtCO_2$) (Figure 7), around 20% of global energy-related CO_2 emissions.

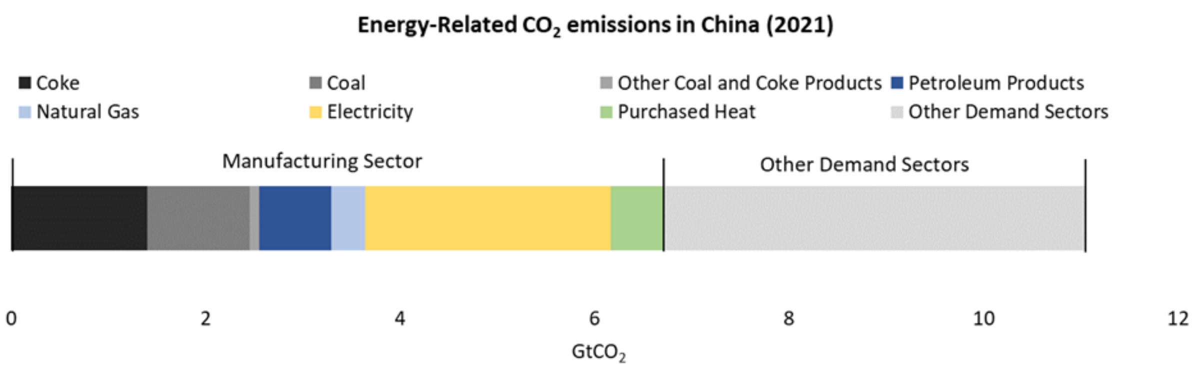

Figure 7. Energy-related CO_2 emissions in China (2021)
Sources: (NBS 2023a; IPCC 2006; NDRC 2015; MEE 2022)
Notes: 1) CO_2 emission factors for purchased heat and electricity are reported by China's National Development and Reform Commission (NDRC) and China's Ministry of Ecology and Environment (MEE), respectively (NDRC 2013; 2014; 2015; MEE 2022). 2) "Other Demand Sectors" include agriculture, construction, non-manufacturing industry (e.g., coal, oil, gas exploration and extraction), residential and commercial buildings, and transportation. 3) Emissions associated with electricity and heat production are allocated to the end-use sectors.

Additionally, manufacturing is China's largest emitter of conventional pollution—such as particulates, nitrogen oxides, and sulfur oxides—which were responsible for 1.85 million premature deaths in China in 2019 (Q. Zhang et al. 2022). The air quality and health impacts from manufacturing industry are even more pronounced in densely populated cities and areas in China. Therefore, emissions from Chinese industry come with serious costs to the global climate and public health.

Electrification is a key strategy for cutting emissions from Chinese industry, supported by a rapid decarbonization of China's electrical grid and other mitigation strategies. Compared to onsite fossil-fuel based heat supply, the use of electricity for heating emits no GHGs or other pollution locally, allowing factories (which may be located in densely populated areas) to avoid adversely affecting nearby communities or contributing to climate change.

However, conventional pollutant and GHG emissions associated with electricity production are an important consideration. Although China is a leader in deploying renewable electricity technologies such as wind turbines and solar panels, two thirds of China's electricity still comes from fossil fuel combustion (China Electricity Council 2022). Therefore, it is important that industrial electrification be accompanied by a transition to a clean electricity grid if China is to achieve its 2060 carbon neutrality target (Sengupta 2020).[4]

Broadly speaking, it is easier to decarbonize electricity generation than to decarbonize industry. Clean electricity technologies (such as wind, solar, and hydroelectric power) are technologically mature and can be the cheapest sources of electricity if built in sufficiently sunny or windy locations and can be transmitted to electricity buyers cost-effectively. Additionally, researchers have identified viable pathways for China to cut emissions from its electric grid, such as a roadmap to 80% zero-carbon electricity by 2035 (Abhyankar et al. 2022), which would put China on a pathway to 100% clean electricity by (or well in advance of) its 2060 net-zero commitment. Similarly, Lawrence Berkeley National Laboratory's China Energy Outlook 2022 finds China's power sector must be fully decarbonized by 2045 in order to be on track to achieve its economy-wide carbon-neutrality goals (Zhou et al. 2022).

Finally, alternatives to electrification to cut emissions from industrial heat have their own challenges:

- **Combusting hydrogen** produced by electrolysis has no direct CO_2 emissions but requires twice as much clean electricity as simply creating heat from electricity directly due to combustion-related energy losses (for example, in hot exhaust gases and formed water vapor) as well as losses during hydrogen generation. Therefore, electrolytic hydrogen does not circumvent the need for clean electricity; rather, it makes that need more acute. It also produces nitrogen oxide (NO_X) emissions and requires capital expenditures on hydrogen electrolyzers and electricity or hydrogen transport infrastructure.
- **Bioenergy combustion** can be low-carbon, but most biomass today is not produced in a sustainable way and is not climate-neutral, bioenergy production competes with other land uses (such as agriculture for food production or the protection of biodiversity and ecosystems), solid biomass combustion emits large quantities of conventional (non-GHG) pollutants, and the total quantity of sustainably grown bioenergy will be too small to satisfy industrial needs on its own.

[4] Since 2010, China's non-fossil electricity generation has been increasing rapidly, growing 5.7% per year on average from 2010 to 2022, while the nation's total power generation increased an average of 3.4% per year during this period. By 2020, China's non-fossil power generation accounted for 34% of total generation, up from 20% in 2010. The share of thermal (mostly coal-fired) power decreased from 79% in 2010 to 66% by 2022. However, the absolute magnitude of thermal power generation in China grew by almost 76% over that period, largely due to newly added coal-fired capacity (China Electricity Council 2023).

Bioenergy should be directed first at applications that cannot be directly electrified, such as feedstocks for chemical production, and only secondarily toward industrial heating.

- **Carbon capture and sequestration** can prevent most of an industrial facility's CO_2 from reaching the atmosphere, but it: 1) increases the facility's energy demand to power the CO_2 capture, compression, and storage processes, 2) requires a suitable long-term underground CO_2 storage site nearby and a means of transporting the CO_2 to that site, 3) does not directly address conventional pollutant emissions, and 4) fails to address the upstream emissions associated with fossil fuel production, such as methane leakage from coal mines, which was responsible for over 20 million metric tons of China's 2022 methane emissions (International Energy Agency 2023a), equivalent to 560 $MtCO_2e$[5]; about 5% of China's total GHG emissions (World Resources Institute 2022). In addition, industrial facilities are widely dispersed across China, and many are small- to medium-sized enterprises. Developing the infrastructure to transport captured CO_2 to geological storage sites would be accompanied by high investment and operational costs.
- **Nuclear heat** (i.e., heat from a nuclear reactor) has been studied as an option for petrochemical industrial parks in Lianyungang City of Jiangsu Province (Jiangsu Provincial Department of Science and Technology 2022) and Maoming City of Guangdong Province (Jieman News 2023). However, it faces challenges such as high cost, limited scale, the fact that firms must locate near the reactor to utilize its heat, the need for safe handling of radioactive materials, and the long times required to plan and build nuclear reactors, which do not match well with the rapid timelines preferred by many manufacturing firms.

Given the potential benefits of direct electrification and the challenges faced by the alternatives, any viable pathway to decarbonize industrial heat and achieve China's 2060 carbon neutrality pledge would significantly involve direct electrification of industrial process heat.

Energy Efficiency

Electricity is used more efficiently than fossil fuels. For instance, in an engineering estimate of energy in an industrial furnace with an operating temperature of 1340°C and no combustion air preheating, over 55% of the energy in the fuel is lost heat in the exhaust gas stream and a further 10% is lost in the form of water vapor (United Nations Environment Programme 2006). Modern equipment that recovers and utilizes waste heat to preheat combustion air can reduce these losses by 32-65%, depending on the heat recovery technology employed (Mickey 2017). But electricity is still more efficient: it neither produces exhaust gases, nor does it form or contain water vapor, eliminating these important heat loss modes.[6] An electrical furnace similar to the example furnace above produces about 3.8 times more heat output per unit energy consumed by the furnace. This can help to reduce or overcome the price gap between electricity and fossil fuels.

Note that there exist more efficient combustion technologies. And combustion boilers with efficiencies over 90% have been demonstrated (IEA-ETSAP (Energy Technology Systems Analysis Program) 2010),

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[5] CO_{2e}, or CO_2 equivalent is a metric used to compare the global warming potential of a greenhouse gas to carbon dioxide (CO_2)

[6] Electricity does have losses in the transmission and distribution system, but these were only 5.9% in 2019 (China Electricity Council 2020).

though 70-79% efficiency is typical of fossil fueled boilers in China (United Nations Industrial Development Organization 2014). But at temperatures able to be served by industrial heat pumps (roughly up to 165 °C), the electrical alternative is more efficient as well. See the section “Industrial Heat Pumps” below for details.

Energy Security

Shifting to domestically produced clean electricity can improve China’s energy security. In 2021, China imported 7% of its coal, 46% of its natural gas, and 85% of its petroleum products and crude oil (NBS 2023a). In contrast, essentially all of China’s electricity is produced domestically. (In fact, mainland China is a net exporter of electricity to neighboring countries.) Shifting China’s industrial facilities to clean electricity, especially those facilities currently utilizing natural gas or petroleum, reduces China’s dependence on imported energy.

Additional Benefits to Industrial Firms

Industrial firms benefit from electrification in a variety of ways that are not captured in a simple cost comparison of electricity and fossil fuels. This can cause industrial firms to overlook some of the benefits of electrification and decline to pursue worthwhile electrification retrofits. These benefits include the following:

- Fossil fuel prices have historically been volatile, at the mercy of geopolitical events and changes in supply and demand in a global market. A reliable, domestic supply of clean electricity reduces exposure to fossil fuel price volatility, making costs more predictable for businesses.
- Firms using clean electricity may have an improved ability to sell their products to environmentally conscious buyers and to governments that aim to procure cleaner materials and products (such as steel) for use in government-funded buildings, infrastructure, etc.
- Switching to clean electricity positions a firm to avoid any present or future carbon pricing costs. China’s national emissions trading system, which currently covers only the power sector, is expected to expand to cover major industry categories (including iron and steel, aluminum, cement, chemicals, and pulp and paper) by 2025 (Busch 2022). Similarly, making products cleanly using renewable electricity can reduce their carbon footprints, making them more competitive in markets with carbon price border adjustments, such as the European Union.
- Switching to clean electricity and using efficient heating equipment also helps firms comply with any present or future standards, such as energy efficiency, GHG emissions, or conventional pollutant emissions standards. In addition, key areas in China, such as Beijing-Tianjin-Hebei and its surrounding areas, the Yangtze River Delta, and the Fenhe and Weihe Plain, are mandated by the central government to reduce coal consumption (in non-power generation) in order to mitigate local air pollution.
- Use of clean electricity reduces a firm’s need for cooling water, exhaust treatment (such as particulate filters), and cleaning and maintenance of combustion equipment. This also improves workplace health and safety.

Electrical Technologies for Industrial Heat

A variety of electrical technologies can produce heat for industrial processes (Table 1).[7]

Table 1: Electrical heating technologies, temperature ranges, and example industries

Electrical Heating Technology	Best Fit Temperature Range	Example Industries
Industrial heat pumps	Low	Food, textiles, wood products, chemicals
Dielectric heating (microwave and radio wave heating)	Low[(a)]	Food, textiles, plastic parts, wood
Infrared heating	Low – Med	Plastic products, wood products, coatings and adhesives, food
Electric resistance heating (with or without thermal storage)	Med – High	Glass, chemicals, plastic parts[(b)]
Electromagnetic induction	High	Iron and steel, nonferrous metals
Electric arcs / plasma torches	High	Iron and steel, metal parts
Lasers and electron beams	High	Metal parts, machinery, vehicles

Notes: (a) Although dielectric heating is capable of reaching extremely high temperatures, it is used overwhelmingly in low-temperature applications such as cooking food and drying materials, so it is classified as a low-temperature technology in this table. (b) Electric resistance is versatile and can be used to produce steam, heat furnaces or kilns, distill liquids, drive chemical reactions, etc. Although other technologies are better suited to to certain processes (such as induction or electric arcs for melting metals), most industries have at least some processes for which electric resistance is a reasonable fit.

The Techno-Economic Comparison section of this report (below) focuses on three specific electrical technologies: electric resistance boilers, industrial heat pumps, and thermal batteries—included in Table 1 as "Electric resistance heating (with or without thermal storage)—because these technologies have broad applicability across many industrial sub-sectors (including for steam generation) and can be readily compared to fossil fueled alternatives, such as natural gas- or coal-fired boilers and combined heat and power (CHP) systems. Other electrical technologies often have narrower applicability (such as lasers for cutting and welding metal parts, infrared heating for drying paint and coatings, or electric arcs for melting steel and cutting sheet metal).

While electrical resistance boilers are familiar, industrial heat pumps and thermal batteries are less well-known. Heat pumps and thermal batteries can reduce electricity costs for industrial firms relative to the other electrical technologies listed in Table 1. Heat pumps reduce costs by achieving extremely high energy efficiencies, while thermal batteries reduce costs by enabling firms to purchase particularly inexpensive electricity (i.e., during hours when the grid is over-supplied or from cheap off-grid wind and solar generation). This section describes industrial heat pumps and thermal batteries, including performance and efficiency information. Detailed cost and emissions comparisons appear in the subsequent section, Techno-Economic Comparison.

[7] There also exist electrical technologies that can replace heat with non-thermal processes in specific applications, such as electrolysis or ultraviolet curing of coatings.

Industrial Heat Pumps

Heat pumps can be the most efficient and cost-effective method to supply low-temperature heat for industrial processes. Heat pumps can achieve efficiencies several times higher than other electrical technologies because they do not convert their input electricity into heat. Instead, they move heat from a low-temperature to a high-temperature area, operating much like a refrigerator or air conditioner.

Industrial heat pumps can extract heat from a source (such as the air, ground, or waste heat from another industrial process) and output heat at temperatures up to 165 °C. The larger the temperature increase, the less efficient the heat pump. The efficiency of a heat pump is expressed as a coefficient of performance (COP), with a 100% conversion of electricity to heat equating to a COP of 1. One could imagine this 100% conversion as an idealized electric resistance heater. Heat pumps that raise the temperature by 40 to 60 °C frequently have a COP of 3 to 4, meaning they are three to four times as efficient as an idealized resistance heater. Even a heat pump configured to deliver an output temperature in the upper range of 165 °C—raising the heat by around 130 °C—has a COP of 1.5, 50% more energy efficient than the idealized resistance heater.

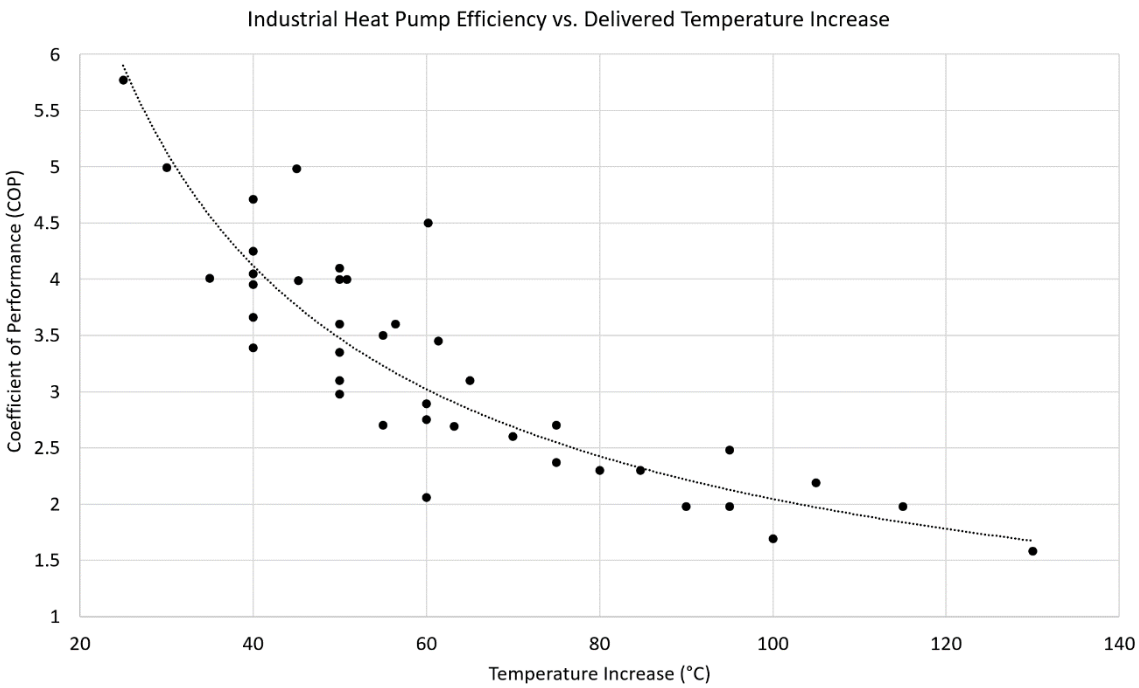

Figure 8. Heat pump efficiency (COP) for industrial heat pumps configured to deliver various levels of temperature increase

Notes: The data points show measured results from actual, commercially sold heat pumps configured to output heat with varying degrees of temperature rise. The dotted line is a theoretical curve fit.
Source: (Arpagaus et al. 2018)

The uniqueness of these efficiency gains cannot be overstated: no other electrical heating technology or fuel combustion method can generate heat at an efficiency over 100%. As such, for low-temperature heating, direct electrification via heat pumps can be a highly cost-effective route.

That said, there can be technical challenges related to upgrading industrial facilities to use heat pumps. Heat pumps typically are physically larger than steam boilers with equivalent heat output capacity, which might pose difficulties when retrofitting an existing facility with space constraints (International Energy Agency and Tsinghua University 2024). Additionally, the highest-capacity heat pumps today have a lower maximum power output (heat delivery per second) than the highest-capacity boilers (International Energy Agency and Tsinghua University 2024), though this can be addressed by evening out steam demand over time (so a lower maximum capacity is needed) and/or by utilizing two heat pumps whose output is modulated to follow changes in steam demand, which can save energy versus operating a single, large boiler.

The potential for industrial heat pumps to address the needs of China's industries is large. Approximately 7,000 PJ in 2021, or 13% of China's industrial non-electricity energy demand falls within the feasible temperature ranges for heat pumps (Figure 9). This finding is well-aligned with the estimate of researchers at the International Energy Agency and Tsinghua University, who found heat pumps could theoretically meet 15% of China's industrial heat demand, assuming heat pumps could deliver heat at up to 200 °C (versus a limit of 165 °C used in this report) (International Energy Agency and Tsinghua University 2024). The potential of industrial heat pumps will continue to increase as heat pump technology improves and China's industries transition from energy-intensive to less energy-intensive industries. Industries able to make effective use of heat pumps include food and beverages (drying, pasteurization, boiling, smoking), pulp and paper (drying, bleaching), metal products (pickling, degreasing, electroplating), plastic products (injection molding), textiles (coloring, drying, washing, bleaching), and wood products (drying, staining, gluing), as well as a wide range of other industries that require hot water or steam (Arpagaus et al. 2018).

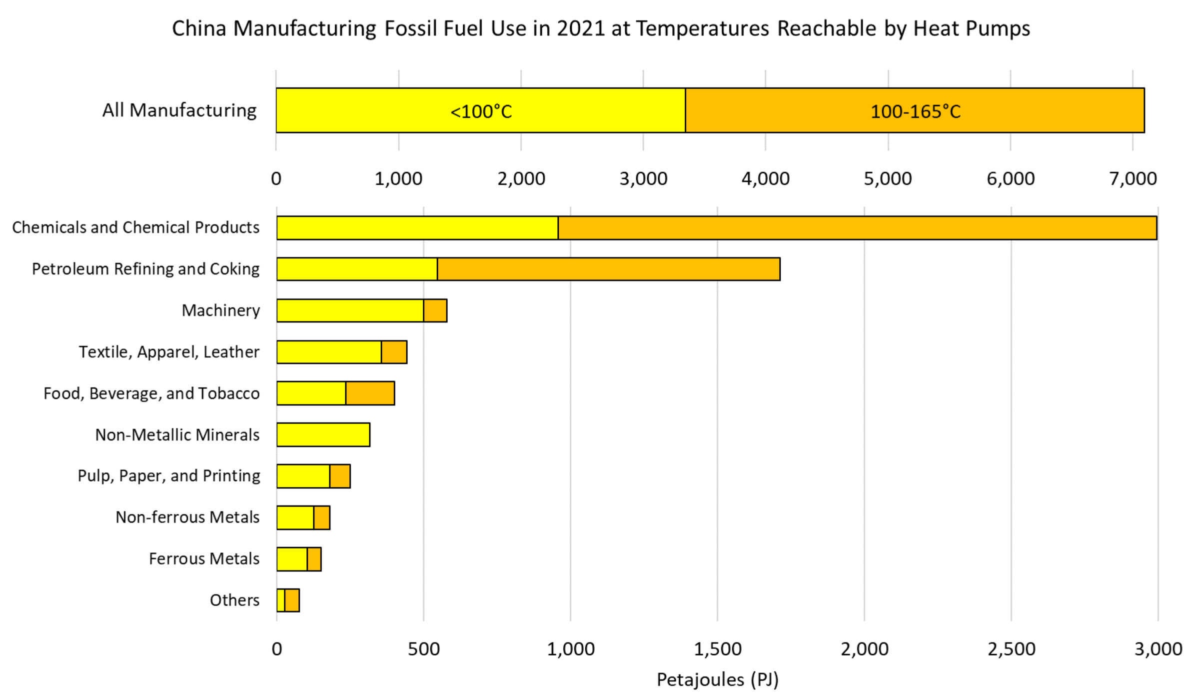

Figure 9: Heat demand in China's manufacturing industries at temperatures that can be served by industrial heat pumps (up to 165 °C)

Sources: (NBS 2023a; Madeddu et al. 2020)
Note: Assumes temperature demand between 100 °C and 400 °C is linearly distributed between those temperatures.

Commercial Status of Industrial Heat Pumps

The global market for heat pumps in 2021 ranged from $53-68 billion USD, primarily for water heating and HVAC systems. Industrial heat pumps comprise a much smaller share, from $0.6-1 billion USD, or around 2% of the market (Rissman 2022). Forty-seven manufacturers of heat pumps were identified in a 2022 study (Rissman 2022), including several Chinese firms that produce heat pumps intended for industrial use: Guangdong PHNIX Eco-energy Solution Ltd., Suzhou Vossli New Energy Equipment Co., and Zhengxu New Energy Equipment Technology.

Globally, most of the industrial heat pumps offered commercially top out at 90–100 °C. Several companies have brought heat pumps to market that output much higher temperatures, such as Kobelco Compressor Corporation of Japan (165 °C) and Viking Heating Engines of Norway (160 °C), but Kobelco no longer manufactures heat pumps and Viking has gone out of business. Several former Viking employees formed Heaten, which claims their HeatBooster industrial heat pump can produce temperatures up to 200 °C, a new record. Overall, the 100–200 °C temperature range has few competitors and a very large addressable market, making it a promising space for new market entrants.

A growing number of promising case studies showcase industrial heat pumps in use. In Davenport, Iowa, a Kraft foods plant utilizes an ammonia heat pump system to deliver hot water at 145 °C (Emerson 2012). An IEA report details a number of success stories, with heat pumps providing process heat for manufacturing chocolate and powdered milk, painting automobiles, and chromium plating of parts (International Energy Agency 2014). In China, heat pumps have been used by industrial firms in the making of rubber, tobacco, chemicals, salt, and crude oil, as well as for printing and dyeing (Jing Zhang et al. 2016).

Thermal Batteries

Most industrial heat demand is at temperatures too high to be provided by heat pumps. For these processes, thermal batteries are often a viable option. Thermal batteries, also known as heat batteries, convert electricity to heat and can store this energy for hours to days, releasing it when needed. They are capable of delivering heat at temperatures up to 1,700 °C (Rissman and Gimon 2023). In China, this is hot enough to meet at least two thirds of industrial heating demand (up to 1,100 °C, per Figure 6) plus a fraction of the heat demands over 1,100 °C. Thermal batteries are a viable option for most industrial heat needs, with the main exceptions being primary iron and steel (which requires a way to chemically reduce iron ore to metallic iron), precision applications like laser welding or plasma cutting, and applications that take advantage of special properties of electrical heating (such as radio waves' ability to penetrate materials and heat them evenly, inside and out).

Thermal batteries contain a large quantity of thermal storage material (such as brick (primarily silicon dioxide) or graphite) that has a high specific heat capacity and resists chemical breakdown at high temperatures. The storage material is enclosed in a highly insulated shell to minimize heat loss, losing as little as 1% a day in some systems (Rissman and Gimon 2023). Wires are connected to electrical resistance heaters inside the battery, which convert the electricity to heat that is absorbed by the storage material. When the industrial facility is ready to use the heat, it is extracted from the battery either by 1) pumping air or steam through the storage material, absorbing heat which is then used in an industrial process or heat exchanger, or 2) opening shutters in the battery's outer casing to transfer energy via emissions of infrared and visible light from the heated storage material (Figure 10). The process of storing heat in the battery and extracting it later is highly efficient, with round-trip efficiencies up to 95% (Rissman and Gimon 2023).

While other batteries, such as lithium-ion, also have the ability to store energy, thermal batteries have much lower capital costs per unit capacity. Industrial thermal batteries of the sort described here are a new technology only manufactured at small scale, so information about their capital costs is limited. But once thermal batteries are manufactured at large scale, they are estimated to cost only $27/kWh of capacity, compared to $150/kWh for lithium-ion batteries (Rissman and Gimon 2023; Henze 2022). This price advantage is due to their simpler components, including a lack of reliance on rare earth metals.

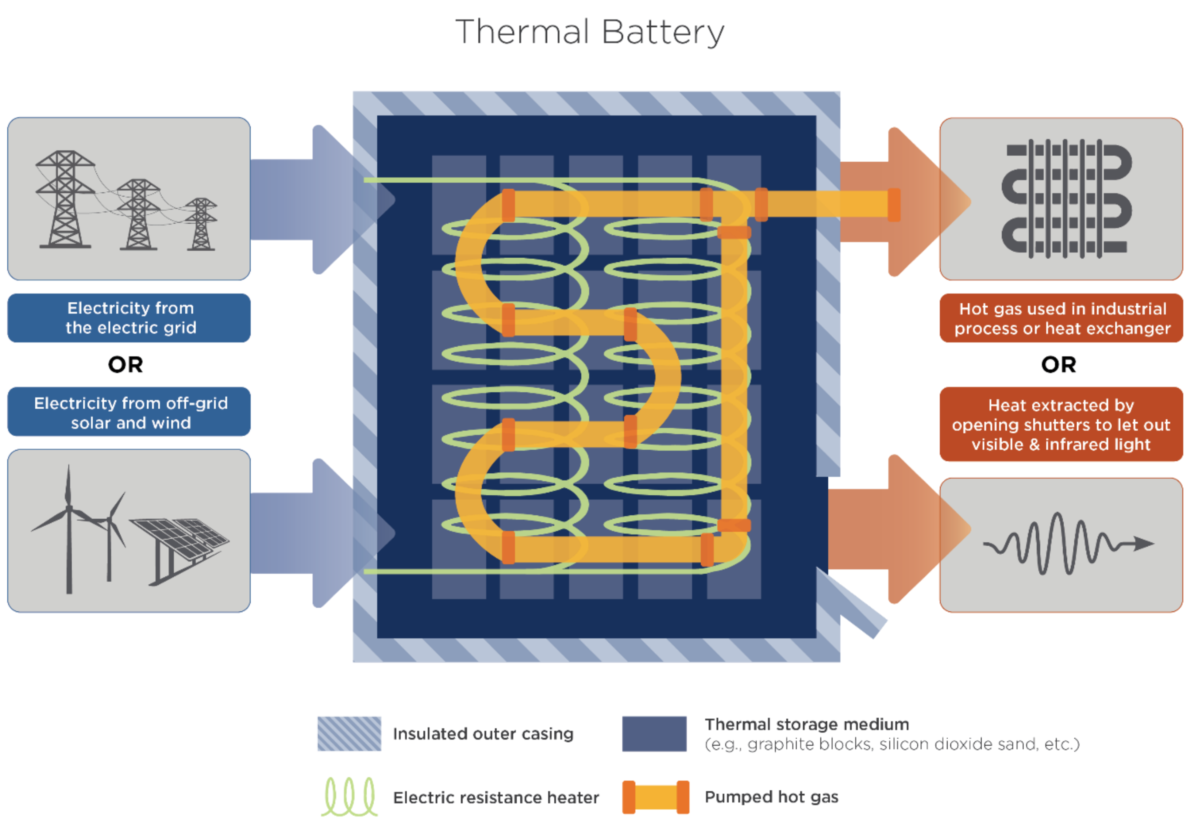

Figure 10. Diagram of an Industrial Thermal Battery
Source: (Rissman and Gimon 2023)

On or Off the Grid?

Industrial thermal batteries may be used profitably in off-grid or grid-connected configurations, but the benefits they provide are different in each case.

Some industrial facilities may be able to directly procure clean electricity without relying on a utility-controlled electric grid, such as by owning or purchasing power from a dedicated wind or solar farm in proximity to the facility. This electricity is much cheaper than buying electricity from the grid at retail prices, as the industrial facility need only pay the costs of generating the power, not costs to maintain grid infrastructure (such as extensive transmission and distribution lines), public benefits charges, or a profit margin for utilities. However, wind and solar power output varies over the day and year based on wind and sunlight availability. Most industrial facilities prefer to maintain reliable, known hours of operation, and some operate 24 hours per day to make the best use of their capital equipment and avoid equipment cool-down.

A thermal battery allows an industrial facility to store heat when there is excess renewable power available and to extract the heat during periods of low wind and solar production—essentially converting variable electricity into steady and reliable industrial heat. This off-grid approach has the benefit of low and predictable electricity costs that are insulated from potentially volatile grid pricing (which can be influenced by global gas and coal prices, utility policies and programs, congestion in transmission lines, etc.). In areas where the grid is unreliable, a thermal battery and off-grid generation may allow facilities to operate during grid outages, if they have a small amount of backup generation or electricity storage for their non-thermal needs. For firms with clean energy targets, an off-grid configuration makes it straightforward to certify their electricity came from sustainable sources, compared to purchasing electricity from the grid, where a firm's ability to do this may depend on the availability of renewable energy credits (RECs), also known as energy attribution certificates (EACs), from a given utility and whether the credits are vetted for additionality and accepted internationally. For more on China's credits, called "green certificates," see the Policy Options section below.

Many industrial facilities may be uninterested or unable to procure their own off-grid supply of renewable electricity. For instance, many Chinese manufacturing firms are located in the eastern provinces, where land and ability to add new renewable generation are often constrained. However, grid-connected thermal batteries may yet offer benefits by facilitating price-hunting and optimization. A utility's cost to generate and deliver electricity varies throughout the day based on changes in electricity supply, demand, and congestion in transmission and distribution lines. This variance is poised to grow as wind and solar become larger shares of utilities' portfolios, in line with China's grid decarbonization targets. Industrial facilities utilizing thermal batteries can pick and choose when they purchase and store large amounts of electricity, banking the energy as heat, and then utilizing it in their operations during times when electricity demand on the grid is highest (and thus at its most expensive). For data on intra-day (time-of-use) electricity price variance in China and its impact on thermal battery economics, see Figure 11 and associated discussion below.

Because grid-connected batteries draw on electricity during times of plenty while avoiding its use during times of high demand, they offer flexibility services and thus reliability to the grid. This creates an opportunity for utilities and industrial facilities to partner. A new rate class for thermal battery users could reflect the technology's lower cost to serve and encourage further optimization and grid utilization during low-demand times of use. Grid-connected batteries also benefit the grid by being able to reduce the net peak load, lessening the need for fuel-burning generation and infrastructure for transmission and distribution. If electricity is used to replace fossil fuels in industrial process heating, thermal batteries could theoretically shift most of the increased electricity demand to non-peak hours, dramatically lowering the required grid build-out and the capital cost of the transition to clean industry.

Thermal Battery Commercialization Status

Thermal energy storage has been commercially utilized for some time, most notably as molten salt energy storage (MSES), often used to store energy collected from concentrated solar-thermal power (CSP). As of 2022-2023, China had at least 14 operating CSP projects and another 30 CSP projects with thermal storage under construction (CSP Focus 2022; U.S. National Renewable Energy Laboratory 2023), illustrating China's experience with and interest in thermal storage technology. However, MSES systems differ from the thermal battery technologies described in this report. Molten salt is highly corrosive and difficult to work with, resulting in higher capital costs, and MSES systems generally store heat at up to around 600 °C (Reddy 2011), much lower than the 1,700 °C attainable by industrial thermal batteries. Therefore, MSES systems are generally better suited to storing energy at solar power plants, not providing heat to industrial facilities.

The thermal battery technologies described in this report are primarily at the pilot, demonstration, or early commercial stages. A worldwide overview of thermal energy storage system providers conducted by market research firm Solrico (Epp 2024) identified 32 companies offering a "new generation" of high-temperature storage technology, 28 of which target the industrial sector. 20 firms' technologies store thermal energy at over 565 °C, and 12 store energy at 1,000 °C or above. 19 store energy in solid materials that do not change phase, 7 use molten salt, 3 use phase change materials,[8] and 3 use other technologies. 18 firms are based in Europe, 11 in the United States, and one each in Australia, Canada, and Israel. 7 have commercial plants, 14 have demonstration plants, and 6 have pilot plants operating or under construction.[9] Two specific case studies follow.

Norwegian firm ENERGYNEST has performed pilots of their thermal battery at a fertilizer producer—directly connecting to their production facility's steam grid—and in a peer-reviewed pilot over twenty months at Masdar Institute Solar Platform in Abu Dhabi, UAE (Hoivik et al. 2019). The technology functioned as expected, with no indication of performance degradation or storage material breakdown, with long-term performance that matched predictions.

German startup Kraftblock installed thermal battery storage capable of supporting temperatures up to 1,300 °C in a PepsiCo production plant in the Netherlands (Southey 2023). The storage energy can be used up to two weeks later and allows PepsiCo to consistently source cheaper renewable energy from North Sea windfarms during nights and off-peak periods. In tandem with direct electrification of two of the site's thermal oil boilers, the facility was a first for both PepsiCo and Europe, achieving full decarbonization of a snack production plant.

[8] A phase change material stores energy through the process of transitioning to a liquid and releases it by solidifying. MSES systems involve a phase change (initially melting the salt), but the salt typically remains a liquid throughout the thermal charging and discharging process, and useful energy is stored as latent heat in the molten salt, so MSES is not considered a phase change storage technology.

[9] All of the figures cited here are taken from the PDF table accompanying the cited article. The numbers in the PDF table differ very slightly from those in the article. In our estimation, the PDF table is more authoritative.

Techno-Economic Comparison

Data inputs and assumptions

We conducted a comparative analysis of three electrified heating technologies and their alternatives, focused on China. In this analysis, we used China-based data wherever possible, complemented with adjusted international data when China-specific data were unavailable. Specifically, we used China's energy price data for industrial users of coal, natural gas, and electricity. Average energy price[10] for typical coal (5000 kcal/kg in lower heating value (LHV), as commonly reported in China) from 2019 to the second quarter of 2023 was used (NBS 2023b). Natural gas prices for industrial users in selected cities in 2022 were referenced (CEIC 2023), as well as reported electricity prices for industry (SASAC 2021). A summary of the energy prices used in this analysis is shown in Table 2.

Table 2. Energy prices for industrial users in China

Type	Yuan per unit	Yuan/MWh	USD/MWh	Year
Coal (5000 kcal/kg)	780.39 per metric ton	¥134	$20	Average from 2019 to Q2 2023
Natural Gas	3.76 per cubic meter	¥337	$50	2022
Electricity	0.64 per kWh	¥635	$94	2021

Sources: (NBS 2023b; CEIC 2023; SASAC 2021)
Note: 1 Yuan = 0.15 USD, the average exchange rate between 2019 and the second quarter of 2023. Source: https://www.macrotrends.net/2575/us-dollar-yuan-exchange-rate-historical-chart; "kcal" stands for kilocalories.

The energy efficiency and typical utilization rates of industrial boilers, CHP systems, and heat pumps are based on a combination of literature reporting from the U.S. (Zuberi, Hasanbeigi, and Morrow 2021; Rissman 2022), Europe (Agora Energiewende 2021), China (Shen et al. 2015; R. Liu et al. 2018), and Chinese national standards on industrial boiler energy efficiency.

Thermal battery capital costs levelized per unit of heat output are a function of the amount of thermal energy storage capacity (measured in hours the battery can deliver steady-state, useful heat) and maximum charging rate, which is determined by the size of input electrical equipment such as transformers and electric resistance heating coils. Maximum charging rate can be expressed as a multiple of the steady-state heat output rate. The thermal battery modeled in this study has a 24-hour heat capacity and a charging rate of 3.5 times its steady-state heat output rate. This configuration was found to offer the lowest levelized costs per unit heat output in a region with abundant wind and abundant solar resources (specifically, West Texas) (Rissman and Gimon 2023) and should be a representative battery configuration in any area of China that has good access to high-quality wind and high-quality solar power. (With poorer wind or solar resource access, more hours of storage and a

[10] National Bureau of Statistics (NBS) of China regularly reports and publishes the market prices of key means of production, such as coal, natural gas, and other materials. See one of the examples from August 2023: https://www.gov.cn/lianbo/bumen/202308/content_6898148.htm

higher charging rate—to enable the battery to fully charge in a smaller number of favorable hours—may be necessary, raising the levelized cost of heat from the battery.)

China's industrial boilers generally have small capacity and rely heavily on coal. More than 90% of the industrial boilers have a steam delivery capacity of less than 35 metric tons/hour, and about 70% of total industrial boilers have a capacity between 2 and 7 tons/hour. The average capacity of industrial boilers in China is about 4 tons/hour, and more than 65% of China's industrial boilers used coal (China Special Equipment Inspection and Research Institute, China National Institute of Standardization, and Lawrence Berkeley National Laboratory 2017).

There is some uncertainty regarding typical fossil fueled boiler efficiencies in China. In 2014, the United Nations Industrial Development Organization found that the typical efficiencies of industrial boilers in China were 70-79% (United Nations Industrial Development Organization 2014). In 2015, the China Special Equipment Inspection and Research Institute tested more than 2,000 smaller-capacity industrial boilers (delivering less than 10 tons/hour) and found typical efficiencies of 80-81% (China Special Equipment Inspection and Research Institute, China National Institute of Standardization, and Lawrence Berkeley National Laboratory 2017). The 2020 Chinese national standard on industrial boiler energy efficiency (GB 24500-2020) indicated that smaller coal-fired boilers (less than 20 tons/hour) have a thermal energy efficiency of 80%, as measured in LHV.[11] For natural gas boilers, which tend to be more efficient than coal-fired boilers, a thermal energy efficiency of 92% was used in this analysis based on the latest Chinese standard (State Administration for Market Regulation and Standardization Administration of China 2021).[12] Electric boiler energy efficiency is assumed to be 99% (Table 3).

Industrial heat pump efficiency (coefficient of performance; COP) varies by the temperature ranges that it can supply, as shown earlier in Figure 8. In this analysis, calculations with lower-temperature industrial heat pumps (80-100 °C) use an average COP of 3.7 while low-to-medium temperature industrial heat pumps (100-165 °C) use an average COP of 2.2.

An average utilization rate of 70% and a total lifetime of 20 years for all technologies were also employed in the analyses.

Table 3. Efficiency/COP and utilization rates of industrial heat technologies

Type	Efficiency (LHV)	Coefficient of Performance (COP)
Coal-fired boilers	80%	
Natural gas boilers	92%	
Electric boilers	99%	
Industrial heat pumps (80-100 °C)		3.7
Industrial heat pumps (100-165 °C)		2.2
Thermal batteries	95%	
Coal-fired CHP	87%	
Natural gas-fired CHP	90%	

[11] LHV is the standard used in reporting energy content of fuels and energy efficiencies in China. LHV assumes the water vapor in the exhaust is not condensed to recover its latent heat.

[12] These efficiency figures, based on standards for newly sold equipment, are best suited to a forward-looking analysis, i.e., comparing the purchase of a new coal or gas boiler to a new electric alternative. Replacing an older, inefficient coal or gas boiler with an electric alternative would achieve larger energy savings.

Sources: Zuberi, Hasanbeigi, and Morrow 2021; Rissman 2022; Agora Energiewende 2021; Shen et al. 2015; Liu et al. 2018; China Special Equipment Inspection and Research Institute, China National Institute of Standardization, and Lawrence Berkeley National Laboratory 2017; State Administration for Market Regulation and Standardization Administration of China 2021.
Note: LHV = lower heating value; COP = coefficient of performance; CHP = combined heat and power. The higher-temperature heat pump's COP of 2.2 corresponds to a 90-degree increase in temperature in Figure 8, which implies a heat source temperature of 10–75 °C. This encompasses room-temperature heat sources. The lower-temperature heat pump's COP of 3.7 corresponds to a 45-degree increase in temperature in Figure 8, which implies a heat source temperature of 45–65 °C. This is achievable if the heat source is warmed by waste heat from another industrial machine in the plant.

Information on China-specific capital costs and non-energy operating costs (labor and maintenance) for these heating technologies are more challenging to find. This study used capital and non-energy operating costs reported by Agora (Agora Energiewende 2021) for Germany, but the costs were adjusted for China based on available studies on this topic (Han, Shen, and Zhang 2017; M. Yang and Dixon 2012).

In addition, we used a China-specific energy content for fuels (in LHV), as reported in the China Energy Statistical Yearbook (NBS 2022), and CO_2 emissions factors for fuels reported by the IPCC (IPCC 2006). These energy content and emissions factors are those used in China's domestic GHG emissions inventories (MEE 2022). Similarly, China's domestic GHG inventory uses an emissions intensity for grid electricity of 0.581 tCO_2/MWh in 2021 (MEE 2022), which was also adopted for this analysis.

China launched its national carbon emissions trading scheme (ETS) in July 2021 after local ETS pilots that began in 2013. Currently, the national ETS only covers the power sector, but it is expected to expand to cover other sectors, such as the iron and steel, cement, and electrolytic aluminum industries. In 2022, the average carbon price in China was ¥55.3 yuan/tCO_2 ($8.3 USD/$tCO_2$) (Economic Daily (China) 2023). According to the *2022 China Carbon Pricing Survey*, which surveyed about 500 industry stakeholders in China, the carbon price in China is expected to increase to ¥87 yuan/tCO_2 ($13 USD/$tCO_2$) by 2025 and ¥130 yuan/$tCO_2$ ($19.5 USD/$tCO_2$) by 2030 (Slater, Wang, and Li 2023). We use the 2030 value in our analysis, as this is well within the operating lifetime of new industrial equipment, so prudent facility managers should consider these carbon costs when deciding which type of equipment to purchase today.

Daily Electricity Variance for Thermal Batteries

Over the course of the day, grid electricity prices in China vary, with some hours offering a discount relative to the typical or "flat" electricity pricing. Conversely, in "peak" and "super peak" hours, electricity is more expensive than during hours with "flat" pricing. Figure 11 shows China's intraday price ratios for industrial electricity buyers in 2022, which vary by province, by month of the year, and sometimes by other factors.


Industrial Electricity Price Ratios and Hours per Day at Each Price Tier in China in 2022
Deep Valley
Valley
Flat
Peak
Super Peak
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
Guangdong, July-Sept
Guangdong, other months
Jiangsu, large ind., Jul-Aug
Jiangsu, large ind., Dec-Jan
Jiangsu, other ind. & mths
Shandong, Dec-Jan
Shandong, June-Aug
Shandong, other months
Shanxi, Dec-Jan, July-Aug
Shanxi, other months
Zhejiang, lrg ind, Win, Sum
Zhejiang, lrg ind, oth mths
Zhejiang, general industry
Henan, Dec-Jan
Henan, July-Aug
Henan, other months
Anhui
Jibei, June-Aug
Jibei, Nov-Jan
Jibei, other months
Hebei, June-Aug
Hebei, Dec-Feb
Hebei, other months
Sichuan, July-Aug, Dec-Jan
Sichuan, other months
Chongqing, Dec-Ja, Jul-Au
Chongqing, other months
Tianjin, Dec, July-Aug
Tianjin, other months
Hunan, Dec-Jan, July-Sept
Hunan, other months
Hubei, Dec-Jan, July-Aug
Hubei, other months
Jiangxi, Dec-Jan
Jiangxi, July-Sept
Jiangxi, other months
Shanghai, 2PT, July-Aug
Shanghai, 2PT, Sept
Shanghai, 2PT, Dec-Jan
Shanghai, 2PT, othr mnths
Shanghai, 1PT

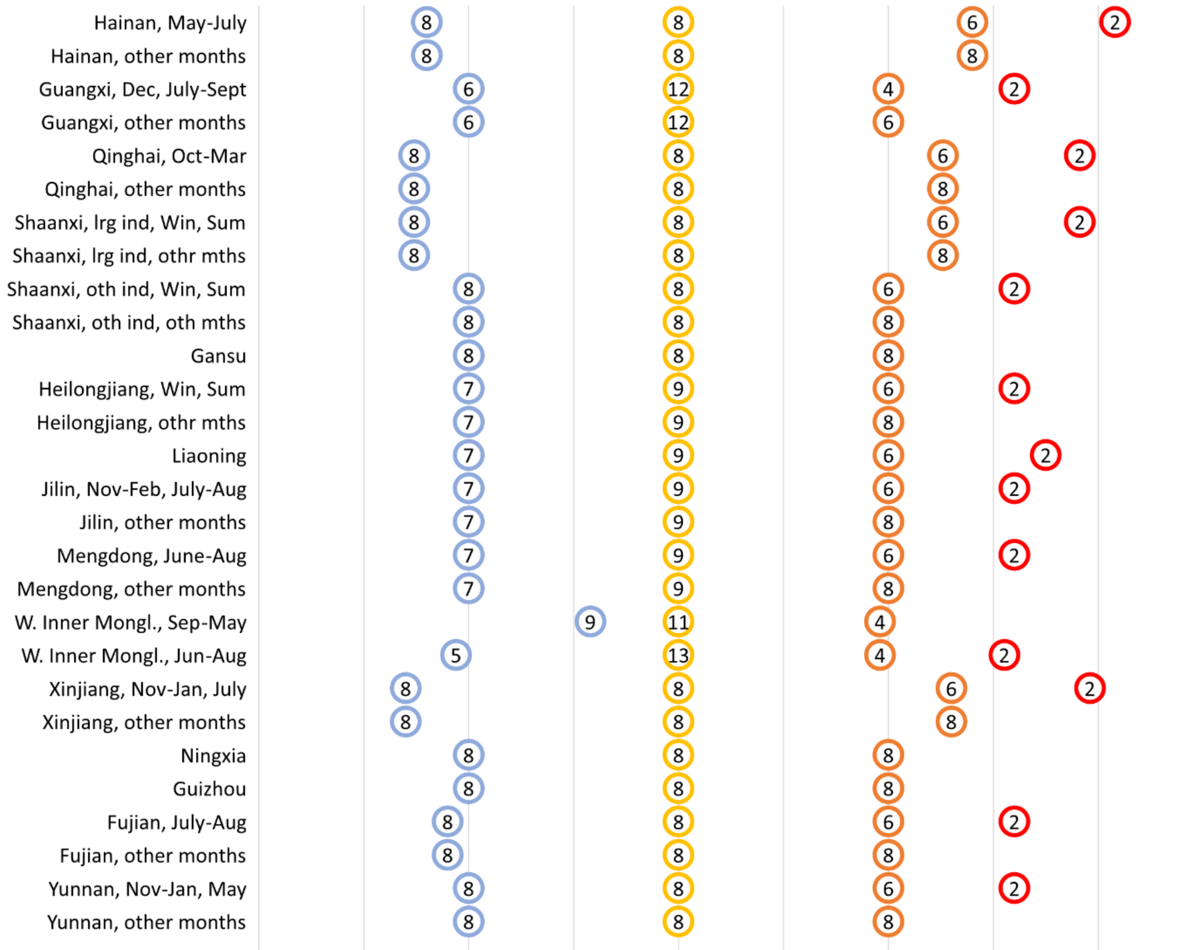

Figure 11: Intraday electricity price variance for industrial electricity buyers in China in 2022
Source: (Polaris Sales Network 2023)
Notes: The values along the X-axis indicate the ratio in electricity price in each hour relative to the "flat"-priced hours, which always have a ratio of 1. The colors of the circles indicate whether the electricity price is in a deep valley (large discount), valley (discount), flat (typical), peak (high), or super peak (very high). The numbers inside each circle indicate the number of hours per day that electricity prices are in that price regime. In Shanghai's rows, "2PT" refers to "two-part tariff" and "1PT" refers to "one-part tariff," two methods of electricity billing.

As discussed above, thermal batteries can be grid-connected or off-grid. For purposes of this analysis, we assume the thermal battery is grid-connected and charges in the hours when electricity is inexpensive ("valley" and "deep valley" pricing) and discharges in other hours, enabling the industrial firm to avoid buying electricity at flat, peak, or super peak rates. The thermal battery we model is located in Guangdong or Shandong provinces, China's two most populous provinces and, also, two of the provinces with the greatest daily electricity price variance, a trait that makes thermal batteries more cost-effective. (For these reasons, Guangdong or Shandong provinces are likely places for some of the earliest thermal battery deployments.) As a result, industrial firms using a thermal battery are able to purchase grid electricity at 34% of the cost that would be faced by a firm that must buy electricity evenly in every hour (as is the case for the modeled electrical resistance boiler and heat pump technologies).

Findings

Cost Comparison

A comparison of the levelized cost of various industrial heat technologies (Figure 12)—including capital expenditures (CAPEX), energy expenditures (based on the prices shown in Table 2, inclusive of taxes on purchased energy), and non-energy operational expenditures (OPEX) such as labor and maintenance, and an expected potential carbon cost for 2030 —indicates that for temperatures under 100 °C, industrial heat pumps are highly competitive with CHP variants and considerably cheaper than natural gas or electric boilers in China. Specifically, as shown in Table 4, lower-temperature industrial heat pumps have a levelized cost of \$38/MWh$_{th}$ (¥260/MWh$_{th}$), which is 15% lower than coal-fired CHP, 20% lower than natural gas-fired CHP, 27% cheaper than heat produced using natural gas boilers, and 60% cheaper than heat from electric boilers.

Without policy or other market interventions (e.g., without considering a future carbon cost), coal-fired boilers in China presently offer the lowest levelized cost of heat production. However, when a 2030 estimated carbon cost is considered (¥130 yuan per tonne CO_2, or \$19.5/tCO_2), lower-temperature industrial heat pumps will be the lowest-cost option to provide low-temperature industrial heating. It is also possible that by 2030, China might increase the taxes charged on purchases of coal or natural gas (in addition to explicit carbon pricing), but this possibility is not considered in Figure 12.

For industrial heat from 100-165 °C, the levelized cost of heat production using industrial heat pumps is about \$58/MWh$_{th}$ (¥391/MWh$_{th}$), about 50% more than heat pumps operating in the 80-100 °C range, largely due to heat pumps' lower efficiency when delivering greater temperature increases (Figure 8). Heat produced from high-temperature industrial heat pumps is 10% and 20% more costly than heat from natural gas boilers and natural gas-fired CHP, respectively, so heat pumps could be competitive with natural gas at these temperature ranges, particularly because high-temperature industrial heat pump prices may come down and efficiency may improve with additional research, development, and manufacturing scale-up.

Our findings regarding heat pump costs agree with those of the International Energy Agency and Tsinghua University, who found that an industrial heat pump with a COP of 3—in between the COP values of the two heat pump variants in this report (2.2 and 3.7; see Table 3)—had a cost of \$40/MWh$_{th}$ (International Energy Agency and Tsinghua University 2024), in between the estimated costs of the two heat pump variants in Figure 12.

Industrial thermal batteries can meet heat needs at temperatures far higher than heat pumps at a cost of \$46/MWh$_{th}$ (¥314/MWh$_{th}$), in between the two heat pump variants.[13] Thermal batteries are competitive with the two natural gas-fired technologies.

Note that the costs in Figure 12 do not account for the public health harms caused by fossil fuel use such as premature deaths due to particulate emissions. Comprehensive monetization of climate damages

[13] The levelized cost figure is based on projected capital costs for thermal batteries if manufactured at large scale (Rissman and Gimon 2023), as the technology is currently in demonstration or early commercial stages without well-established, publicly available capital costs. It also assumes the thermal battery will be in a location with abundant wind and solar resources that cause significant fluctuations in electricity price, which thermal batteries rely on to achieve their savings.

from GHG emissions are also not shown (except for consideration of an explicit ¥130 per tonne CO_2 carbon price, which may not be high enough to fully encompass the value of all climate harms). Additionally, equipment that burns coal is required to meet stringent standards for impacts on local air quality, which involves both upfront capital and ongoing operating costs for exhaust treatment, which are not shown in Figure 12. Therefore, Figure 12 understates the benefits of non-fossil technologies.

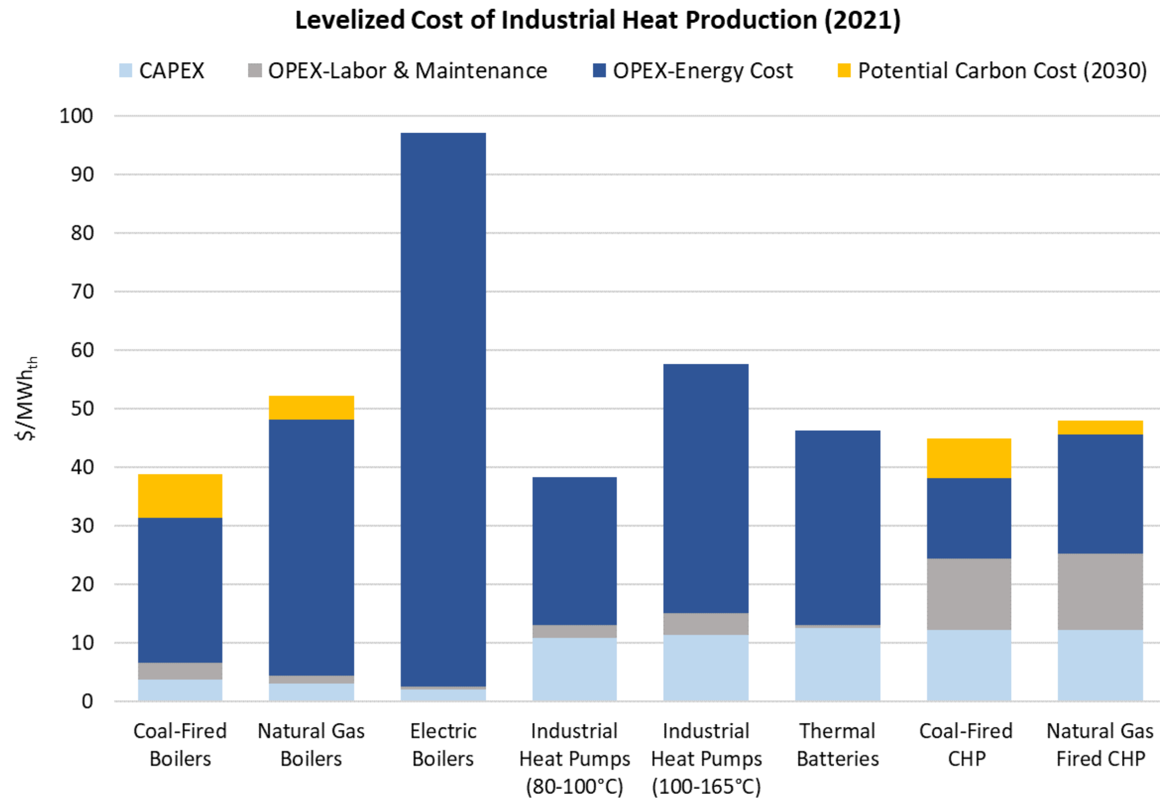

Figure 12. Total levelized cost incorporating capital expenditure, energy and non-energy operational expenditure, and forecast 2030 carbon pricing costs of various industrial heat production technologies

Notes: 1) An estimated carbon price for 2030 is added for coal and natural gas technologies to illustrate the cost comparison during the years when the equipment will operate, assuming that China's national ETS will expand from just the power sector to industrial sectors. The 2030 carbon cost is an estimate based on the *2022 China Carbon Pricing Survey,* a survey of about 500 industry stakeholders in China (Slater, Wang, and Li 2023). The cost used here is ¥130 yuan per tonne CO_2, or \$19.5/tCO_2. 2) Electrotechnologies, including electric boilers, industrial heat pumps, and thermal batteries, do not have additional carbon costs, as their energy source is electricity, which is covered by China's national ETS. Today's carbon prices are reflected in the electricity prices (X. Yang and Lin 2023). While the carbon price paid by electricity suppliers will be higher in 2030 than it is today, the carbon intensity of China's electric grid will be lower, and the cost of clean electricity generating technology may be lower as well, so there is no reason to assume final electricity prices will be higher in 2030 even after incorporating a higher carbon price. For this reason, we do not apply a potential carbon cost to electrotechnologies in this figure.

Table 4. Cost comparison of heat production technologies in China

	Coal-Fired Boilers	Natural Gas Boilers	Electric Boilers	Industrial Heat Pumps (80-100°C)	Industrial Heat Pumps (100-165°C)	Thermal Batteries	Coal-Fired CHP	Natural Gas Fired CHP
Values in ¥/MWh$_{th}$								
CAPEX	¥25	¥21	¥14	¥74	¥77	¥85	¥83	¥83
OPEX – Energy	¥168	¥297	¥641	¥172	¥289	¥224	¥93	¥138
OPEX – Labor & maintenance	¥20	¥10	¥4	¥15	¥26	¥4	¥83	¥89
Potential Carbon Cost (2030)	¥51	¥28					¥46	¥15
Levelized Cost	**¥264**	**¥355**	**¥659**	**¥260**	**¥391**	**¥314**	**¥305**	**¥325**
Values in $/MWh$_{th}$								
CAPEX	$4	$3	$2	$11	$11	$13	$12	$12
OPEX – Energy	$25	$44	$95	$25	$43	$33	$14	$20
OPEX – Labor & maintenance	$3	$1	$1	$2	$4	$1	$12	$13
Potential Carbon Cost (2030)	$8	$4					$7	$2
Levelized Cost	**$39**	**$52**	**$97**	**$38**	**$58**	**$46**	**$45**	**$48**

Notes: 1) CAPEX includes purchase, installation, and integration. 2) For electricity, assumes carbon prices are reflected in electricity prices (X. Yang and Lin 2023). See note 2 in Figure 12 for more details. 3) Thermal battery OPEX is assumed to be similar to electric boiler OPEX, as no data on maintenance costs for thermal batteries are available, and they use similar components to electric boilers (electric resistance heating and a pump).

Energy Consumption

Industrial heat pumps are much more energy efficient than all other heat-producing technologies included in this analysis. For instance, lower-temperature industrial heat pumps use only 20% as much energy as coal-fired boilers per unit of heat produced (Figure 13). Higher-temperature industrial heat pumps only consume one-third as much final energy as coal-fired boilers to produce the same amount of heat. Even compared to other alternatives, such as CHP systems, electric boilers, and thermal batteries, industrial heat pumps are still significantly more efficient in delivering heat.

The efficiency differences between non-heat pump technologies are small but generally favor electrical technologies due to the better efficiency of electrical resistance versus combustion. At higher temperatures and in applications without waste heat recovery (boilers often re-use hot condensate and may preheat feed water using hot exhaust gases), the efficiency advantage of electric resistance versus combustion would be more pronounced.

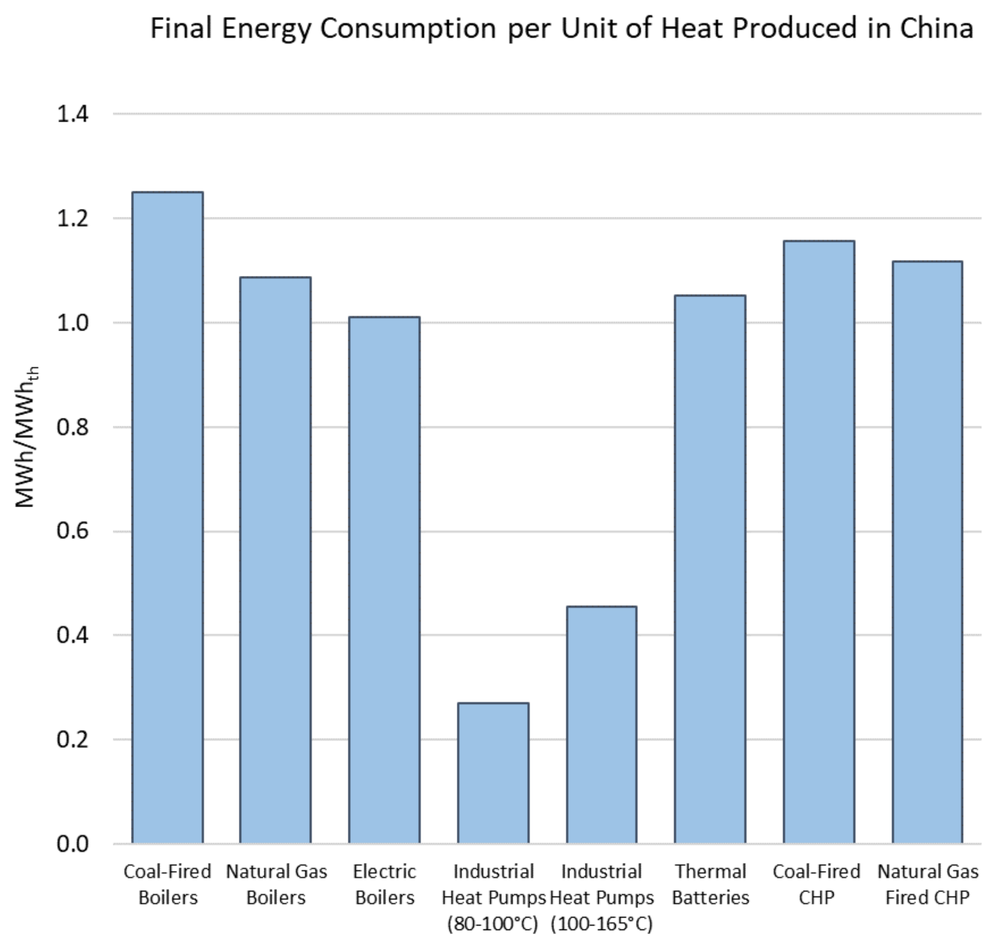

Figure 13. Final energy consumption per unit of heat using industrial heat pumps and alternative technologies

Note: the energy inputs can be either thermal (in units such as MWh$_{th}$) or electric (in units such as MWh$_{e}$). For this reason, we used MWh/MWh$_{th}$ as the unit and indicator to assess final energy intensity per unit of heat production.

CO_2 Emissions

In terms of CO_2 emissions, industrial heat pumps are one of the least carbon-intensive options for heat production in China. As shown in Figure 14, CO_2 emissions from lower-temperature (80-100 °C) industrial heat pumps are 26%, 60%, and 73% lower than natural gas, coal, and electric boilers, respectively. Compared to coal-fired CHP systems, lower-temperature industrial heat pumps have 53% less CO_2 emissions when emissions from the generation of electricity to power the heat pump are included. For higher-temperature (100-165 °C) industrial heat pumps, CO_2 emissions per unit of heat are 21%, 33% and 55% lower than coal-fired CHP units, coal-fired boilers, and electric boilers, respectively.

As noted above, this analysis uses China's 2021 grid emission factor (0.581 tCO_2/MWh) to calculate the CO_2 emission intensity of heat production for all electric technologies.[14] This is why electric boilers and thermal batteries are the highest-emission technologies appearing in Figure 14. Thermal batteries have slightly higher emissions intensity than electric boilers because they have heat losses while storing thermal energy, whereas a boiler uses the heat it generates immediately. Also, we assumed the electricity produced from CHP units would reduce the need to purchase electricity from the grid, so the direct emissions of the CHP technologies are partially offset by avoided emissions from not consuming grid electricity. Natural gas CHP units, given their ability to offset CO_2 emissions from China's coal-heavy grid and natural gas's lower CO_2 intensity relative to coal, were the lowest-CO_2-emission-intensity option for industrial heat production in China in 2021. However, this will no longer hold true as China's grid becomes decarbonized.

[14] Grid emissions factors vary across China's regions and provinces. For instance, while the average share of renewable electricity consumption is 31%, at least six provinces already have shares above 50%. A future, provincial-level analysis could provide insight into the emissions intensities of the technologies highlighted in this report when installed in specific locations.

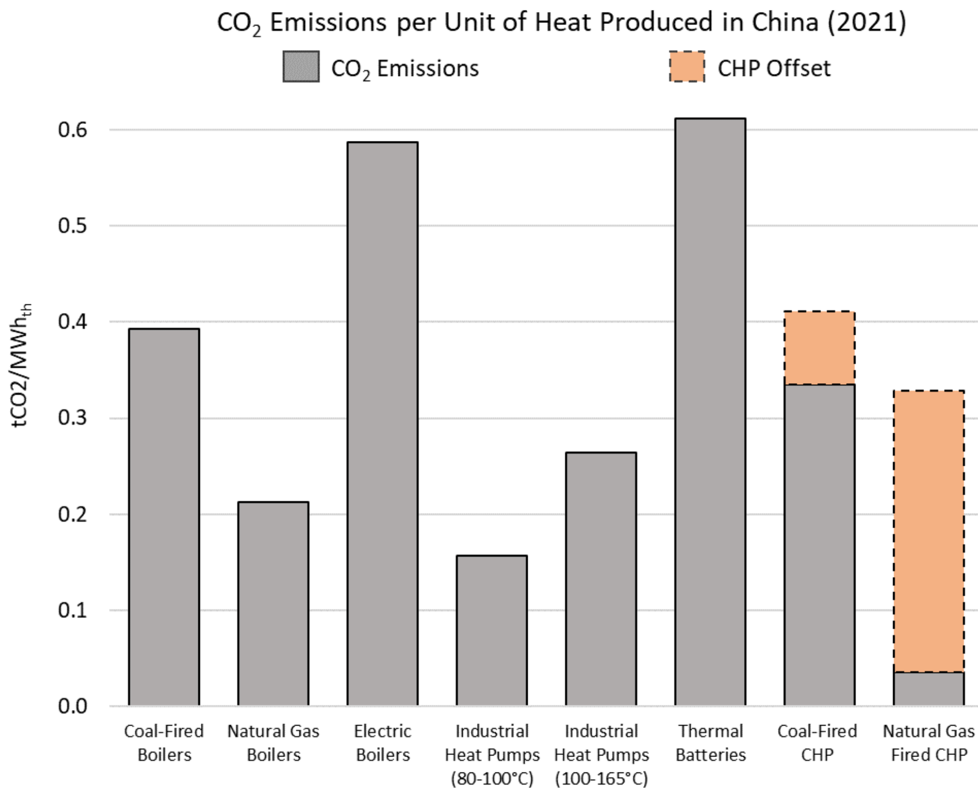

Figure 14. CO_2 emissions per unit of heat produced in various technologies in China (2021)
Notes: 1) based on China's grid emission factor of 2021; 2) considering offsetting grid CO_2 emissions due to electricity generation onsite in CHP units.

To achieve China's carbon neutrality goals, studies show that China's power sector needs to reach zero or negative emissions before 2050 (Yu et al. 2022).[15] Assuming China achieves its target, China's grid emissions factor in 2050 will be zero. As a result, industrial heat pumps, thermal batteries, and electric boilers will have no CO_2 emissions (Figure 15). Simultaneously, CHP units will no longer offset CO_2 emissions from the electric grid, so their emissions intensities will be higher than in 2021. This result highlights the fact that in order to decarbonize industrial heat production via electrification, it is critical to decarbonize the power sector in China.

[15] Additionally, China has targets for years sooner than 2050. The *14th Five-Year Plan of Modern Energy System Planning* predicts the share of non-fossil power generation will increase to around 39% by 2025, and the *Energy Production and Consumption Revolution Strategy* set a goal of 50% of non-fossil power generation by 2030. As of 2022, the share of non-fossil power generation was 34% (China Electricity Council 2022).

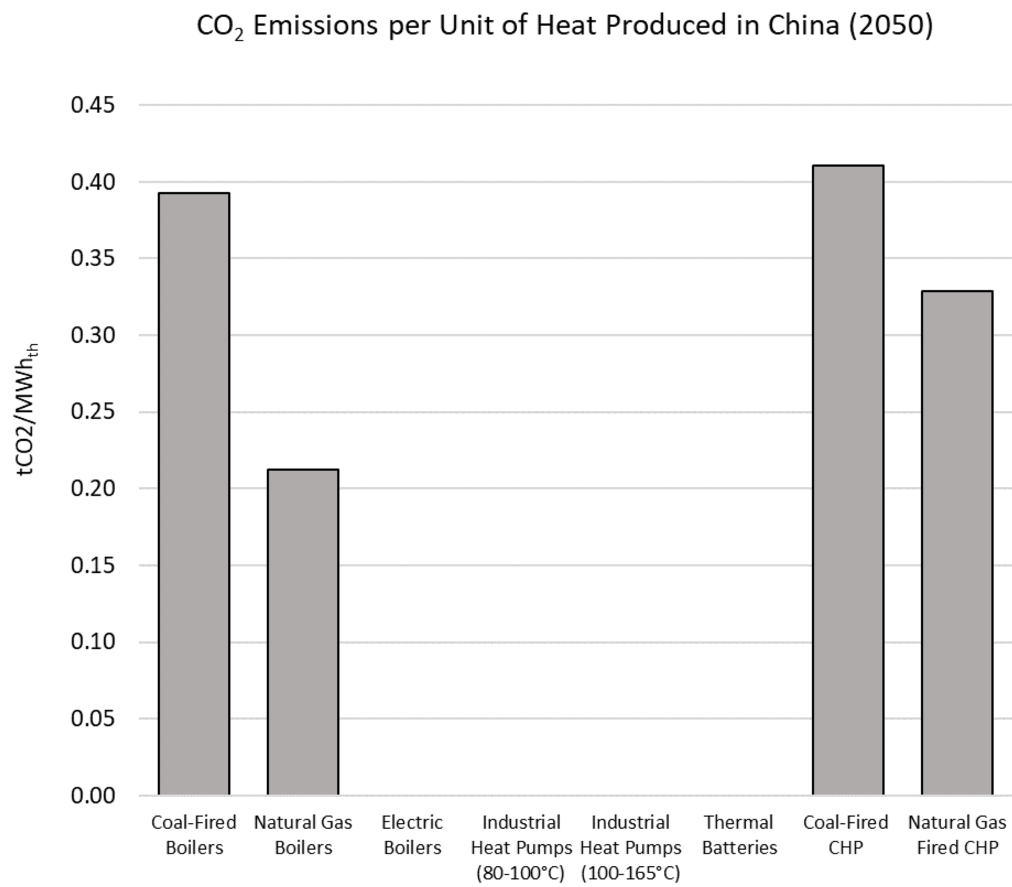

Figure 15. CO_2 emissions per unit of heat produced in various technologies in China (2050)
Note: This figure assumes China's electric grid is fully decarbonized by 2050.

Conventional Pollutant Emissions

In addition to greenhouse gases, fossil fuel combustion emits conventional pollutants such as nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter ten micrometers or less in diameter (PM_{10}), and particulate matter 2.5 micrometers or less in diameter ($PM_{2.5}$). These pollutants cause health problems such as lung disease, asthma, heart attacks, and premature death. In 2021, electrical technologies have lower pollutant emissions than coal-fired boilers and coal-fired CHP, but higher pollutant emissions than natural gas technologies, which is reflective of the mix of electricity sources on China's grid (Figure 16). In 2050, assuming China meets its targets, the grid will be decarbonized, and electrical heating technology will therefore not cause conventional pollutant emissions (Figure 17).

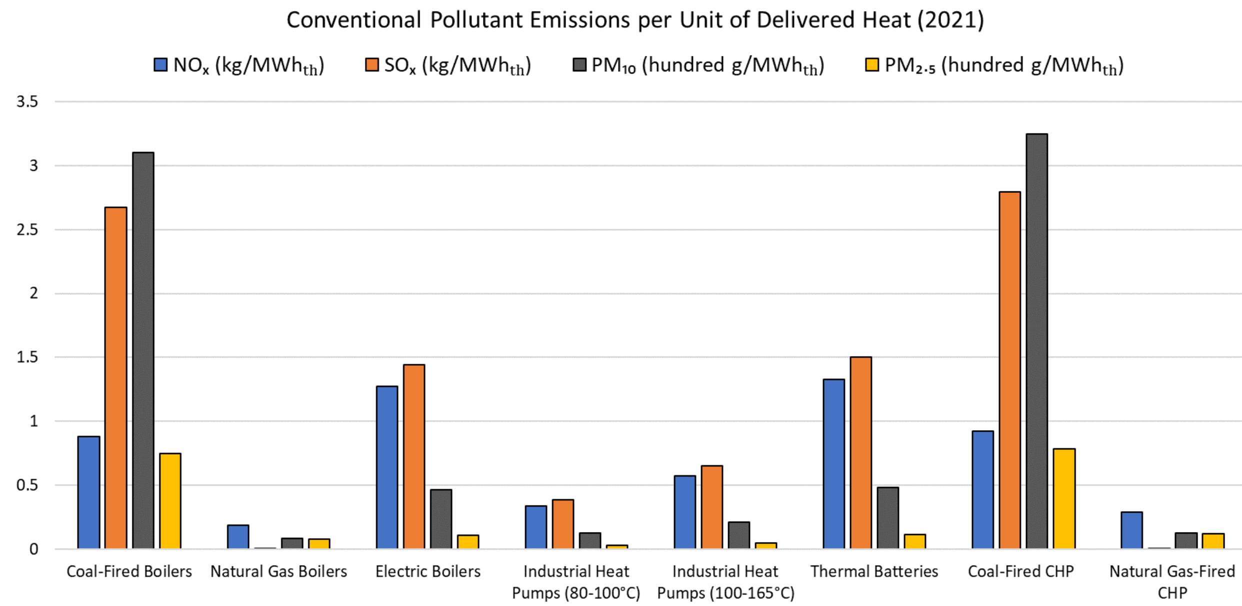

Figure 16: Conventional pollutant emissions per unit of delivered heat in China in 2021

Note: This figure does not include a "CHP Offset," as Figure 14 does for CO_2, because conventional air pollutants affect the local area around the industrial facility, so pollutant reductions at an electric power plant cannot be assumed to be equivalent to reductions at the industrial facility. However, if a CHP offset were shown, it would reduce coal-fired CHP NO_x by 18%, SO_x by 7%, PM_{10} by 2%, and $PM_{2.5}$ by 2%. The emissions intensities of natural gas-fired CHP would be negative (-0.34, -0.72, and -0.11 for NO_x, SO_x, and PM_{10} respectively), since utilizing natural gas-fired CHP would have been cleaner than using electricity from China's grid in 2021 for these three pollutants, while natural gas-fired CHP for $PM_{2.5}$ would have been positive 0.06 hundred g/MWh_{th}, a 47% offset.

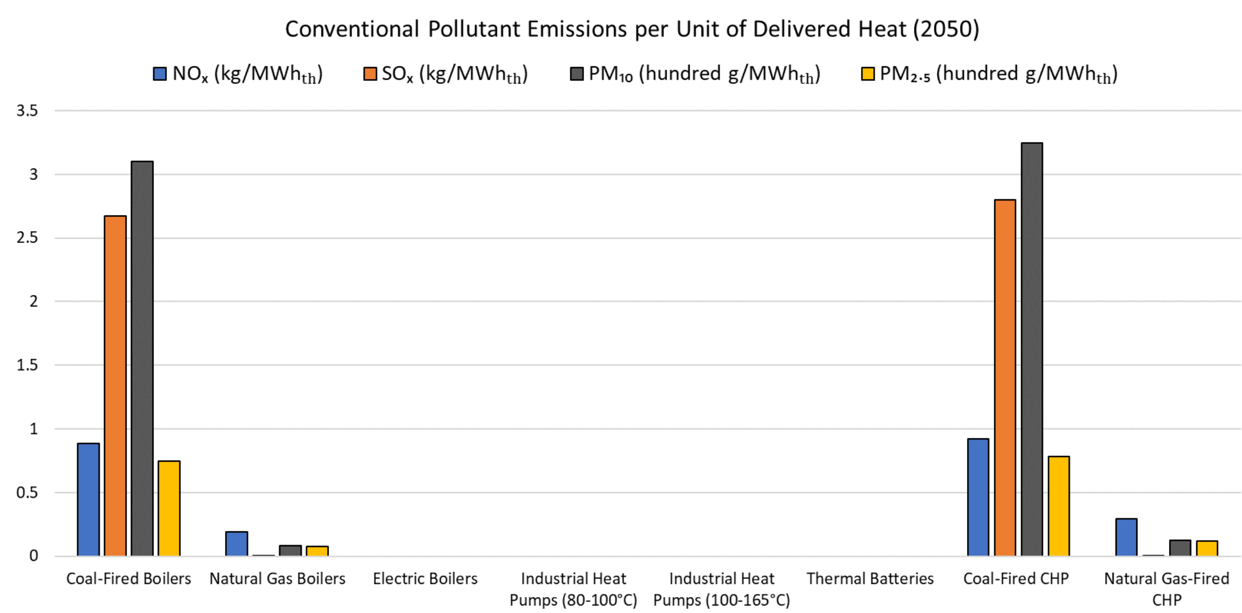

Figure 17: Conventional pollutant emissions per unit of delivered heat in China in 2050

Note: This figure assumes China's electric grid is fully decarbonized by 2050.

Summary of Findings

Overall, the analysis shows that industrial heat pumps and thermal batteries can be highly competitive in China based on their levelized costs of heat production. When disregarding carbon pricing, lower-temperature industrial heat pumps already have the second-lowest cost among the analyzed alternatives, after coal-fired boilers. But when considering near-future carbon costs, lower-temperature industrial heat pumps are the cheapest technology. Thermal batteries and higher-temperature industrial heat pumps are costlier but still broadly competitive with fossil technologies, especially when carbon cost, environmental constraints, and local renewable resources are considered.

Industrial heat pumps' high energy efficiency can save 50-80% of total final energy use compared to all other technologies considered in this analysis. Thermal batteries only save a modest amount of energy relative to fossil alternatives, but they allow energy to be purchased at times when the grid has surplus electricity, limiting the impact of industrial electricity demand on the need for new grid infrastructure or generation capacity. In terms of CO_2 emissions, natural gas CHP units have the lowest emissions in 2021 when considering their ability to offset purchases of grid electricity, but all electric technologies will achieve zero emissions (and CHP technologies' emissions intensities will rise) as China's grid decarbonizes, making electric technologies the best long-term solution for decarbonizing industrial heating, in line with China's national emissions targets.

Barriers and Policy Options

Barriers to Industrial Clean Electrification in China

There are two principal barriers to the broad adoption of clean electricity for industrial heating in China: the price difference between renewable electricity and fossil fuels (particularly coal) and limited availability of electrified options for some types of industrial equipment.

In addition, it is essential to shift the electricity sector to zero-carbon sources such as wind, solar, geothermal, hydroelectric, and nuclear power (while also growing electricity output and upgrading power grid capacity to meet increased industrial electricity demand). Growing and decarbonizing the electricity sector are beyond the scope of this paper, but roadmaps have been produced by researchers, including the International Energy Agency (International Energy Agency 2021b), Energy Foundation China (Yu et al. 2022), Abhyankar et al. (Abhyankar et al. 2022), RMI (Chen et al. 2023), China Electricity Council (China Electricity Council 2021), State Grid Energy Research Institute (B. Liu 2023), and the Chinese Academy of Engineering (Shu et al. 2021). Therefore, this paper focuses on the two principal barriers to industrial electrification mentioned above.

Energy Prices

Per unit energy, fossil fuel prices in China are lower than the cost of electricity. For industrial energy buyers, coal costs around 134 yuan/MWh ($19.8/MWh), compared to 337 yuan/MWh ($49.6/MWh) for natural gas and 635 yuan/MWh ($93.6/MWh) for electricity (Figure 18). In part, the high price of electricity for industry in China is due to the fact that industrial electricity buyers are charged around 40% more on average than residential electricity buyers to help subsidize the cost of electricity for everyday consumers (Energy Innovation LLC and Institute for Global Decarbonization Progress 2024). (In the U.S. and Europe, industrial electricity rates are lower than residential electricity rates, reflecting the fact that industries buy power in bulk and have a lower cost to serve per unit of electricity delivered.) This surcharge on industrial electricity customers is a disincentive to industrial electrification.

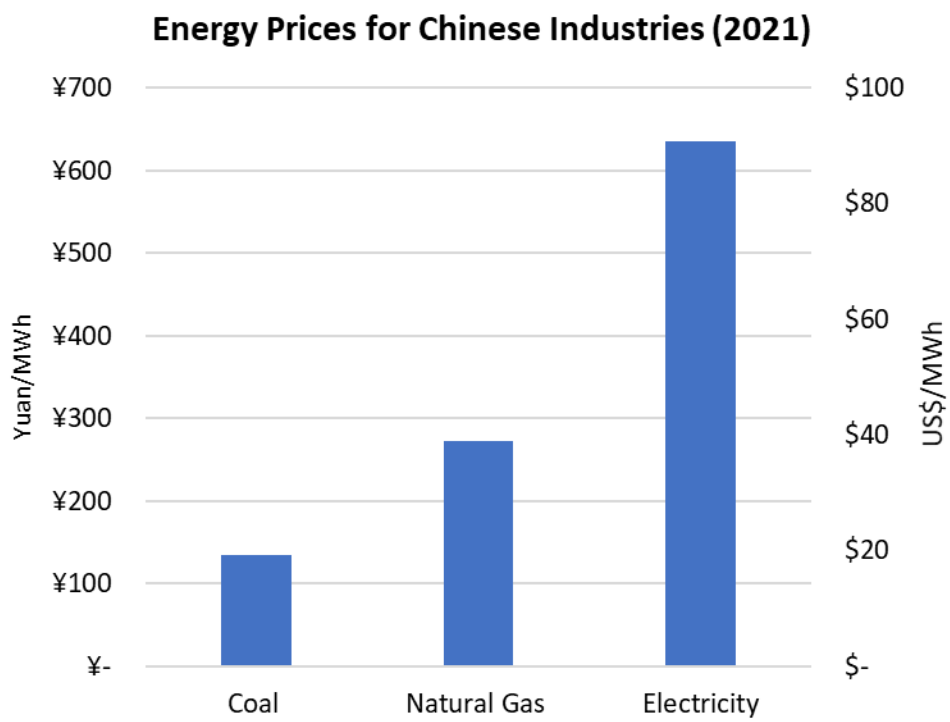

Figure 18. Prices for industrial energy buyers in China
Sources: NBS 2023; CEIC 2023; SASAC 2021.
Notes: Figure depicts average pricing. Electricity price can fluctuate significantly throughout the day. For such "peak" and "valley" pricing, see Figure 11.

Coal and coal products are the most commonly used fuels for industrial process heating in China (Error! Reference source not found.), and coal costs just one fifth as much as electricity per unit energy. Electricity is used more efficiently than coal to provide industrial heating (for instance, Table 3 compares 80%-efficient coal-fired boilers to nearly 100%-efficient electric boilers), but this is often not sufficient to overcome the large cost gap between coal and electricity. But as we have discussed, two electrical technologies offer greater-than-usual savings: heat pumps and thermal batteries.

Heat pumps can be several times more efficient than an electric resistance heater, so they can narrow the cost gap considerably more than other electrical technologies. For example, a heat pump with a coefficient of 3.75 (i.e., 375% efficiency) is five times more efficient than a 75%-efficient coal-fired boiler, making the two technologies largely equivalent in terms of energy cost per unit of heat delivered.

Thermal batteries have an efficiency of around 95%, in line with most other electrical technologies. They achieve their exceptional cost savings by allowing industrial firms to purchase electricity in the hours when it is the cheapest and avoid purchasing electricity when it is most expensive. In China, the electricity cost for industrial buyers varies throughout the day and by province or city. In many provinces, electricity in the lowest-cost hours costs just 30-40% of the average electricity price in the same location (Figure 11). For example, if a 60%-efficient coal-fired steam system is replaced with a 95%-efficient thermal battery that also reduces the facility's average electricity costs by 60%, the fuel costs per unit energy are almost equal.

Other electrified technologies (such as electric resistance heaters without thermal storage, infrared heaters, electromagnetic induction, dielectric heating, lasers, etc.) are not efficient enough to close the price gap on their own. Even heat pumps and thermal batteries can only close the price gap in certain conditions (such as when a heat pump is configured to deliver a small temperature increase, or when a thermal battery is in a province that has large hourly electricity price fluctuations and passes these fluctuations through to industrial customers). Usually, coal maintains at least a small price advantage.

Therefore, government policy is crucial to help make electrified technologies cheaper to operate than coal-fired technologies. This can take the form of incentives to make clean electricity less expensive, carbon pricing or other policies to make coal more expensive, or energy efficiency or emissions standards that require better environmental performance. Additionally, coal combustion emits conventional (non-GHG) pollutants that cause health harms, and standards that strictly limit this pollution can increase the cost of coal power by requiring coal power plants to install and use better exhaust treatment technologies.

Electrified Equipment Availability

Due in part to the energy price barrier discussed above, demand for electrified versions of some industrial technologies has been limited. While it is possible to buy electrified boilers and industrial heat pumps, thermal batteries are very new, and electrified equivalents of some technologies (such as electric heating for steam crackers or cement kilns) are still in the research stage. Even a commercial technology, such as high-temperature industrial heat pumps, may today be manufactured in small quantities, so heat pump manufacturers would need to ramp up production to meet the large demand that could come from electrifying industrial heat in China.

As a result of limited adoption, industrial facilities in China have limited awareness of the benefits and potential that can be provided by industrial heat pumps. Information on commercialized industrial heat pumps is not widely available. Their performance and key characteristics (heat production, energy consumption, stability, space requirements) need to be validated and widely shared. Applications of industrial heat pumps in different industrial sectors and processes need to be presented to industrial facilities as relevant case studies. (For some examples, see the Commercial Status of Industrial Heat Pumps section above.) Much the same is true of thermal batteries, which are at an even earlier stage of commercial adoption.

Again, there is a role for government policy here, to encourage demand for these technologies and to give manufacturers certainty that the demand will be sustained for many years (so they feel comfortable investing in new production lines and factories to build electrified industrial equipment). As more equipment is made per year, the cost per unit will decline due to returns-to-scale and learning-by-doing, which has the potential to drive additional demand. Therefore, policy can initiate a virtuous cycle that gradually ratchets down technology costs and increases market demand.

Other Technical Barriers

Adoption of electrified heating technologies faces several other challenges. First, replacing fossil fuels with electricity may require the industrial facilities to significantly change their current electrical/thermal energy systems. It would require optimization and matching between heat demand and heat sources across different sizes, locations, and timing (at the day and/or season scale). The more integrated systems a facility has, the more challenging it may be to directly electrify the facility's heating demand using drop-in technologies.

Second, upgrading the existing industrial heating systems not only requires investment into new manufacturing equipment but also may require expansion of existing electrical infrastructure, either onsite, outside of the facility, or both. A facility may require more transformers, switch gears, electrical panels, and wires to support the growth in electricity demand from newly added electrified heating systems. A facility often will need to work with a local utility to perform these upgrades.

Third, industrial facilities are often risk-averse, due to concerns about process disruption, the need for staff retraining, and uncertainty regarding new technologies' long-term reliability or maintenance needs.

Fourth, industrial equipment typically has a long lifetime, and much of it currently relies on fossil fuels for heat production. Therefore, waiting until existing equipment wears out before replacing it with electrified equipment can significantly slow industrial electrification.

Policies for Industrial Electrification

Financial Incentives for Novel Technologies (CAPEX)

Although electricity costs are the main barrier, the cost of purchasing and installing new, electrified industrial equipment can also be a hurdle for industrial firms. **Equipment rebates** can lower the cost of new capital equipment that meets certain efficiency or emissions intensity thresholds. These incentives can be adjusted to reflect the performance of the equipment: the size of the rebate can be based on the degree to which the equipment's environmental performance surpasses the threshold. Equipment manufacturers can apply for these rebates and must submit test results to prove their equipment meets the required performance thresholds; the government can test products to independently verify the manufacturers' submissions if time and funding permit.[16]

Similarly, **retooling grants** can provide similar financial support for qualifying businesses to adopt new technologies by helping them to cover the costs of installing the new equipment (and temporarily halting production during the installation process). Government may place restrictions on the types of firms and activities that are eligible for retooling grants, such as requiring the installed equipment meet emissions benchmarks or requiring firms to provide a specified number of well-paid jobs in local communities. Other countries have instituted such programs. For instance,in March 2024, the U.S. Office of Clean Energy Demonstrations awarded over $6 billion to 33 industrial decarbonization projects,

[16] An extra incentive can be offered if clean equipment is replacing fossil fuel-burning equipment at least five to ten years before the fossil-burning equipment would otherwise have been replaced (i.e., in the absence of the extra incentive), on condition that the fossil fuel-burning equipment be verifiably destroyed (not sold to any buyer, whether within or outside of China). The government can structure this as a scrappage program in which the government purchases the old equipment and sends it to be melted down and turned into recycled steel.

many of which involved retooling existing facilities, and all came with significant community benefits, worker protections, and jobs (U.S. Department of Energy 2024).

Government can also make capital expenditures more manageable **by improving access to low-interest loans, bonds, and other financing mechanisms** when the funds are used to purchase electrified equipment and retrofit facilities. This can be more flexible and cost-effective when the government partners with private lenders, whether through aggregation (pooling multiple smaller industrial projects together to increase scale and diversify risk), co-lending to share the risks and profits of a loan, implementing loan loss reserves or guarantees that reduce private lenders' exposure in the event that the loan is not repaid, or selling tax-exempt bonds to raise money for industrial electrification projects. These are lower-cost options for the government than rebates or tax credits, as the loans are repaid with interest. Green banks, such as the Connecticut Green Bank (the oldest green bank in the United States), demonstrate how government or a quasi-governmental entity can use many of these tools to unlock financing for energy-saving and clean energy projects.(Connecticut Green Bank 2024)

Energy Efficiency and Emissions Standards

Setting standards on GHG emissions and energy efficiency are further avenues to facilitate industrial decarbonization. Standards remove the lowest-performing products from the market, ensuring that all newly sold equipment achieves a certain, minimum level of environmental performance. To drive continuing innovation, standards should become more stringent over time, rather than remaining a static benchmark. The best practice is to build an improvement mechanism into the standards at the outset, such as determining that the 50th percentile of products on the market every 3 years becomes the new minimum performance threshold for the upcoming 3 year period. This ensures that standards do not have to be routinely re-evaluated and debated, while giving industrial firms transparency about how standards are set and what to expect in the years to come. (The standards can be written to tighten more slowly, or to stop tightening, as the efficiency range among products on the market becomes narrow as products approach practical or thermodynamic efficiency limits.)

Some standards can apply to specific pieces of equipment, such as the efficiency of converting electricity into useful heat. A more flexible approach is to apply standards to an entire industrial facility, specifying how much electricity or emissions can be emitted per product produced. This is generally easiest for commodity products like specific chemicals. For non-commodities, facilities can report their current energy use and associated emissions and develop a tailored plan for improvement relative to this baseline, or to a historical average in cases where data for prior years are available.

While typical standards determine which products can be sold on the market (to any buyer), **green public procurement (GPP) programs** can establish an emissions intensity standard specifically for government-purchased goods. Because governments purchase large volumes of industrial products to support buildings and infrastructure, they are major buyers of many heat-incentive goods such as steel, concrete, and glass. Procurement by China's central government totaled around $0.5 trillion in 2019, or over $2 trillion when including procurement by state-owned enterprises (Schonberg 2021). Also, GPP standards need not apply only to government-owned facilities but can be extended to any projects that accept government funding or subsidies as a condition of that support. Thus, enacting standards on government purchases still creates a large market for clean industrial products and may be more politically feasible than enforcing them across the market as a whole. This creates a protected starter market for clean industrial technologies, enabling them to scale up and drive down costs.

China launched its first GPP program in 2006, and today there is a complicated landscape of GPP programs and requirements across many levels of government: central, provincial, county, and municipal (Denjean et al. 2015). This provides a robust policy infrastructure that can be used to promote industrial electrification, e.g., by including electrified production as a criterion that governments use when deciding what to purchase under existing GPP programs.

Research and Development Support

Promoting early-stage technologies through support for research and development (R&D) is a critical way to accelerate foundational advancements and bring technologies from the laboratory to the marketplace. For instance, investment in solar photovoltaic research in the 1970s in what would later become the U.S.'s National Renewable Energy Laboratory was crucial in fostering declining costs that would allow the solar industry to eventually flourish globally (Rissman 2024). Government laboratories such as those operated by the Chinese Academy of Sciences could provide an ideal home for ongoing research to optimize and scale industrial electrification technologies, and research to increase the energy efficiency and the ease of integration of electrified industrial technologies could be added to the Ministry of Science and Technology's key project list.

Government laboratories are most effective not when they operate in isolation but when they **partner with academic institutions and private firms**. Partnerships enable access to a broader range of expertise and help ensure that research projects are informed by private firms' knowledge of the market, such as the specific needs of industrial firms. In some partnerships, private firms can also provide cost-sharing support in exchange for intellectual property (IP) ownership or favorable IP licensing terms. For example, the U.S. Department of Energy established Innovation Hubs that brought together government, academic, and private sector partners to develop technologies to solve specific decarbonization challenges (Cho 2021). Similarly, China has advocated for an innovation model that integrates R&D in industry, higher education, and the broader research community (产学研一体化).

Hybrid models with quasi-independent research organizations also exist, such as Germany's Frauenhofer-Gesellschaft, a network of seventy-six applied research institutes that receive approximately 30% of their revenue from federal and state governments and engage in contract research for the remainder. This has yielded a number of advancements in green hydrogen, bioplastics, and hydrogen-to-methanol technologies (Rissman 2024).

Government grants can also **incentivize investment in specific technologies** in independent organizations; in 2019, such grants fueled 44% of basic research and 33% of applied research in the U.S. (U.S. National Science Foundation 2022). Governments should target these grants at research projects aiming to develop and refine industrial electrification technologies, including industrial heat pumps and thermal batteries.

Beyond the laboratory stage, governments can help **fund pilot or demonstration plants** that utilize innovative industrial heating decarbonization technologies through cost-sharing arrangements, which help private firms demonstrate the performance and competitiveness of new technologies at larger scale. At the laboratory stage, it can be appropriate for government to fund 100% of the research costs, in some cases. But as a technology matures and grows to the point where pilot or demonstration plants are being built, cost-sharing (rather than the government funding the entirety of the project) helps to optimize the use of government resources by only supporting technologies that private firms believe have market potential and are willing to help fund.

Exemptions from Shut-Down Orders

In some parts of China, the government requires industrial firms to cease operations on days when air quality is worse than specific threshold levels (Lee 2023). The government could provide waivers for industries operating with a minimum percentage of electric heating equipment to allow them to continue operating on high-pollution days.

Education of Industrial Firms

Electrified industrial heating technologies, especially newer options such as industrial heat pumps and thermal batteries, are not yet well-known in China. Improving industrial firms' familiarity with direct electrification options for industrial heat is critical to adoption. To that end, **national education campaigns on electrified technologies, catalogues, guidebooks, and case studies** should all be employed to help decision-makers at industrial firms understand the relevant options, benefits, and challenges. This will enable them to make thoughtful decisions about when to transition to electrical heating, what types of equipment to use, what electrical infrastructure upgrades their facilities might require, etc. Education can often be handled by industrial trade groups once a technology is sufficiently widespread. For instance, the China Heat Pump Alliance (CHPA) and China Energy Conservation Association (CECA) provide educational materials about heat pumps and run an annual conference. A similar association might play a role in educating firms about thermal batteries or other electrified technologies.

Fostering Price Parity Between Coal and Electricity (OPEX)

Along with equipment availability, the most important barrier to industrial electrification is the fact that electricity costs significantly more than fossil fuels per unit energy (Figure 18). This cost gap can be partially closed via highly efficient electrical technologies (such as industrial heat pumps) or by selectively buying electricity in low-priced hours (Figure 11) and storing it in thermal batteries. However, even after accounting for these technical benefits, electricity generally remains more expensive than coal absent policy support. Therefore, policy measures to help foster price parity between coal and electricity are powerful tools to accelerate clean technology adoption.

One approach is to **subsidize the cost of clean electricity purchased by industrial firms**. This can spur the deployment of clean electricity generation capacity and electrified industrial equipment, but it does not incentivize improvements in energy efficiency, as the subsidy provides no credit for reducing energy consumption. A more flexible approach is to subsidize the production of output products, if those products were produced exclusively using clean energy. This incentivizes manufacturers not only to switch to clean energy but also to reduce the energy intensity of their production processes. Output-based incentives involve more regulatory complexity than subsidies for clean electricity, so they work best for commodity products (such as steel or methanol), where the quantity of output is easy to measure and the produced material is comparable across different manufacturing facilities and companies. Complexity can be further reduced by establishing internationally-accepted guidelines that industrial firms can use to measure the carbon intensity of their products, enabling firms to measure and report their emissions intensity only once, and these data can be used both domestically (e.g., to qualify for output-based subsidies) and internationally (e.g., to export products to a region with a carbon border adjustment mechanism, such as the EU).

Another aspect of electricity cost is the investment required to upgrade the power lines, transformers, and other equipment delivering electricity to industrial facilities. Government can provide subsidies to **reduce the cost of these upgrades**, or they may simply instruct utilities to reduce their fees for electrical service upgrades, especially when government directly controls the utility and can provide guidance and financial support to the utility as needed.

Carbon pricing can also encourage direct electrification of industrial heating technologies. China's nationwide emissions trading system (ETS), in operation since July 2021, currently only covers power plants and should be expanded to cover industrial facilities, especially the five top-emitting industries: ferrous metals, chemicals, non-metallic minerals, refining and coking, and non-ferrous metals (Error! Reference source not found.).

Ultimately, the goal of a carbon pricing system is to cause industrial firms to switch to cleaner processes, not for firms to pay the carbon fee and continue using dirty processes. However, if the carbon price is low, it may be cheaper to pay the carbon price rather than to switch to clean processes. Government can address this using a "carbon contract for difference," an agreement between the government and a manufacturer who uses low- or no-carbon processes. Any difference between the manufacturer's GHG emissions abatement costs and the carbon price is paid by the government, effectively closing any potential cost gap between firms that comply by cutting emissions and firms that comply by paying the carbon price. Rather than negotiating contracts with specific manufacturers (which can be complex, costly, and give manufacturers and incentive to inflate their clean production costs), government can run a "**reverse auction**," taking bids where manufacturers compete to offer a type of good (such as steel or cement) to government-funded projects at the lowest possible price while using exclusively clean production methods. The government then sets the "carbon contract for difference" value that applies to *all* manufacturers on the basis of the lowest (winning) bid in the reverse auction. This helps ensure the government does not overpay for clean products and avoids the regulatory complexity of assessing individual firms' financial and environmental performance and establishing firm-specific contracts.

Policies to Facilitate Access to Clean Electricity

For industrial electrification to contribute to China's climate targets, the electricity used by industrial firms must be produced without CO_2 emissions. Therefore, to accompany the policies that facilitate the adoption of electrified heating technologies, it is also necessary to enact policies that help industrial firms access clean electricity. (Policies to help decarbonize China's grid more generally are also helpful but are beyond the scope of this paper.)

Expand Inter-Provincial Electricity Trading

Today, there is very little trading of electricity between provinces in China. In 2022, inter-provincial electricity trades made up 12% of electricity sales (Y. Zhang et al. 2023), and most of these trades were based on long-term contracts, not dynamic supply-and-demand signals that can aid in grid balancing or integration of variable renewables (Howe 2023).

China has surplus renewable energy in certain western and north-western provinces, where there is substantial installed renewable capacity but fewer urban centers and industrial facilities. In 2022, eight provinces and administrative regions (Gansu, Guizhou, Inner Mongolia, Ningxia, Shaanxi, Qinghai, Xinjiang, and Yunnan) made up 43% and 48% of China's operating wind and solar capacity respectively (Global Energy Monitor, n.d.-b; n.d.-a) but accounted less than 12% of China's gross domestic product (National Bureau of Statistics of China 2022). Most manufacturing is in eastern provinces, where there is little surplus renewable electricity available to purchase. Renewable electricity generated in eastern provinces is often needed to fill policy-mandated quotas, such as renewable portfolio standards (RPS), and therefore is not available to be procured by specific industrial firms using power purchase agreements—or would not represent additional GHG abatement if so procured.

To expand electricity trading and help get clean electricity from areas of surplus to areas with large numbers of industrial facilities, China needs to **expand physical electricity transmission infrastructure and set up inter-provincial regulation and "spot" power markets**—i.e., power trading that is responsive to supply and demand, with timelines typically ranging from day-ahead to less than 60 minutes before delivery (KYOS Energy Consulting 2023). China has begun taking strides in this direction. In 2023, China launched a pilot inter-provincial spot power trading program and aims to build a national power spot market by 2030 (Howe 2023).

Utilize Best Practices for China's Green Energy Certificate System

To determine compliance with laws requiring renewable electricity provision or use (such as China's RPS or ETS), it is necessary to track the amount of renewable energy generated. In many countries, including China, this tracking is accomplished using market-tradable renewable energy certificates (RECs). Different countries have slightly different versions of RECs; China's variant is called the Green Electricity Certificate (GEC).

A key challenge in developing a RECs system is to avoid double-counting, i.e., not letting the same renewable energy be counted multiple times to satisfy requirements. Historically, China has allowed several different types of incentives to be offered for the same electricity. For instance, a renewable electricity generator may receive GECs and also participate in a carbon offset market based on the same electricity generation (RE100 2020).[17] Until reforms to the GEC program in 2023, some renewable power producers were able to "unbundle" the GEC from the produced electricity, sell the GEC to a firm that to enable it to meet its clean electricity use requirements, then sell the actual electricity to grid companies that would count the electricity toward China's RPS requirements, another example of double-counting (Fishman 2023).[18]

[17] In some cases, renewable electricity generators received a feed-in tariff subsidy in addition to the certificates, though this is no longer allowed for projects receiving GECs (Fishman 2023).

[18] These are not the only challenges facing China's RECs system. For instance, when estimating the environmental benefits of clean electricity, regulators assume the clean electricity displaces grid average electricity, based on an annual average grid emissions factor. But when a large share of clean electricity is already being dispatched, displacing grid electricity with clean electricity has lower emissions benefits. A more accurate way to estimate benefits would be to time match when the renewable electricity is dispatched with the grid's emissions intensity in that same hour.

RE100, a consortium of hundreds of international companies, establishes centralized guidelines for whether RECs are qualified for use by their member companies (RE100 2020)., RE100 found that the GEC certificates on their own do not meet international standards for additionality and avoidance of double-counting. The consortium determined that in order for the use of clean energy to be recognized outside of China, a GEC user must retire all certificates and other "environmental and social" instruments issued for the renewable power, ensuring that none were sold off, transferred, or claimed elsewhere (RE100 2020). This work-around was not always practical or cost-effective, making it difficult for Chinese firms to secure international recognition of their use of clean electricity.

International recognition is important for several reasons. First, some international firms that purchase parts or materials from China have corporate commitments to decarbonize their supply chains, or they wish to sell to buyers that have such requirements. Second, Chinese exporters unable to prove their products were made cleanly may be subject to carbon-based border fees under policies such as the European Union's Carbon Border Adjustment Mechanism. Carbon-based border taxes are also under discussion in the United States. Third, sales to governments or for government-funded projects may need to comply with green public procurement rules. Only internationally recognized RECs count for these purposes.

Some countries use RECs managed by an international body, such as International Renewable Energy Certificates (I-RECs) and Tradable Instruments for Global Renewables (TIGRs), rather than devising their own REC systems and criteria. Some Chinese renewable projects have issued I-RECs and TIGRs, catering to multinational companies (Fishman 2023). However, fearing a loss of control over the program and its requirements, the Chinese government passed a law specifying that GECs shall be the only type of instrument used to track renewable energy in China, and the use of other certificates, such as I-RECs, shall be phased out (Jeff Zhang and Wang 2023). This move also prevented provincial and local officials from devising and launching their own, competing certificate schemes.

Avoiding a profusion of different types of RECs is a good thing, as this can ensure clean power is measured based on uniform criteria throughout the country, and it may reduce the opportunities for double-counting. But China's choice to standardize on the GEC makes it crucial that the GEC be robustly designed and internationally accepted. China should ensure that GEC criteria are fully compatible with international standards. It may be necessary to require that renewable energy producers choose a single incentive (such as participating in carbon markets or receiving a GEC certificate) for each unit of electricity they generate, to avoid double-counting.

One complication is that in 2023, China relaunched its voluntary carbon market after a six-year hiatus. This program uses tradable China Certified Emission Reduction (CCER) certificates. It may be beneficial to consolidate the GEC and CCER programs, e.g., to use GECs rather than CCERs in the carbon markets (Jeff Zhang and Wang 2023). This will require coordination, as the programs are run by different ministries. GECs are issued by the China National Energy Administration while CCERs are handled by the Ministry of Ecology and Environment.

Phase Out Industrial Fossil-Based On-Site Electricity Generation

Industrial firms in China have about 153 GW thermal power generation capacity, accounting for 13% of China's total thermal power generation capacity as of 2018. More than 97% of the self-generation capacity in industry relies on coal (China Electricity Council 2019). For these facilities, switching to electricity-using equipment may worsen emissions, if they produce more on-site electricity by burning more fossil fuels. It is important for these facilities to instead purchase their electricity from the grid, which already has a roughly 30% share of renewable electricity (annual average) and is set to decarbonize further in line with China's national targets (discussed above). Most industrial firms will not be able to have large quantities of renewable generation on-site, so replacing self-generation with grid electricity is the best option for these facilities.

Conclusion

China's manufacturing sector accounts for 61% of the country's CO_2 emissions, almost three quarters of which is associated with industrial process heating. Therefore, meeting China's climate targets necessitates decarbonizing China's industrial heating processes. If supported by a rapidly decarbonizing electrical grid, direct electrification can be the most practical and energy-efficient way to supply this heat at the scale demanded by China. Fortunately, electrified technologies can deliver heat across the wide range of temperatures needed by different industries. Industrial heat pumps can offer unparalleled efficiency in lower temperature ranges (under 165 °C), making them well-suited to food, beverage, textile, and other industries. Much of the higher-temperature range can be served by thermal batteries, which are capable of delivering heat up to 1,700 °C. When used in tandem with expanded renewables deployment in on- and off-grid configurations, thermal batteries can dramatically cut the cost of electricity, helping to close the price gap between electricity and coal. When grid-connected, they also can help balance the grid by taking up electricity in hours when it is abundant and by not purchasing electricity in hours when it is scarce.

Policy interventions will be necessary to promote the deployment of these technologies. Approaches include support for research and development, education of industrial firms, mechanisms to foster price parity between coal and electricity, financial incentives for clean production, and energy efficiency and emissions standards. Policymakers should prioritize electrification of industrial facilities where it would bring the largest benefits, such as in areas where the electric grid is more decarbonized, in areas suffering from impacts of local pollutants, and in areas with local targets for low-carbon development. Within specific industries, policymakers can prioritize electrification of certain types of equipment based on the technological maturity and affordability of electrified versions of that equipment. Additionally, Chinese policymakers can use targeted electricity sector reforms to make it easier for industrial firms to procure clean electricity, such as expanding inter-provincial electricity trading in spot markets and aligning China's Green Electricity Certificates with international best practices.

While the challenges ahead are complex and multi-faceted, China's large and modern industrial capacity means that China has the potential to become both the largest manufacturer and the largest user of electrified industrial heating equipment. With the right policy approaches, China can become a leader in clean industrial technology and achieve its climate targets.

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