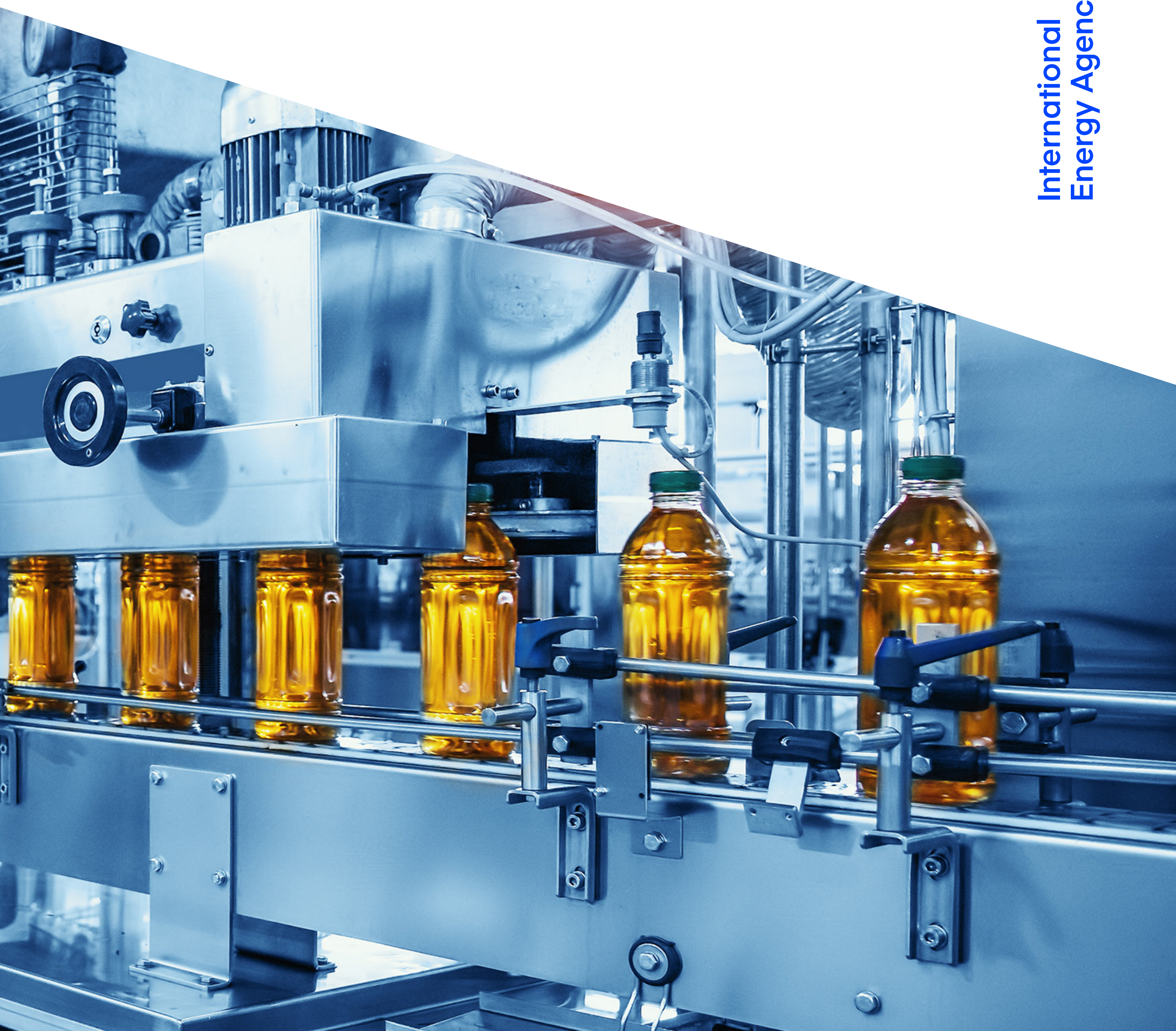
Renewables for Industry

Electrification of low-temperature heat and steam



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Abstract

Industry is responsible for 30% of global energy consumption, most of which is supplied by fossil fuels. The focus of industrial decarbonisation has largely been on the steel and cement sectors, but significant potential also exists in less energy-intensive sectors such as food and beverages, textiles, chemicals, paper, and other manufacturing activities. These sectors offer some of the most immediate and cost-effective opportunities for industrial decarbonisation and diversification of energy sources. Commercially available electric technologies – including heat pumps, electric boilers and resistance heaters – can meet most heat demand in these subsectors.

Widespread electrification of low-temperature heat and steam in industry, coupled with increasing deployment of renewable electricity supply, can deliver multiple benefits. In addition to reducing fossil fuel use and associated emissions, it can improve energy security by lowering exposure to volatile gas and oil prices and, when integrated with thermal storage, it can create demand flexibility that helps ensure a higher share of variable renewable generation.

This report explores how to expand the role of renewables in the industrial energy mix through electrification of low-temperature heat and steam. It focuses on the European Union, China and the Association of Southeast Asian Nations (ASEAN), examining their techno-economic potential and existing policy environments. Finally, the report proposes priority action areas for accelerating industrial heat electrification.

Acknowledgements, contributors and credits

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Executive summary

Electrification of heat can improve efficiency, help diversify industrial energy, and enhance energy security

A broad range of industries that depend primarily on low-temperature heat and steam processes represent roughly 70% of global industrial energy consumption. They span diverse manufacturing activities – from food and beverages to textiles, chemicals, transport equipment, wood products and paper. In 2023, these sectors emitted nearly 3 Gt of direct energy-related CO_2, accounting for half of all direct industrial emissions, although emissions have declined by around 8% since 2013.

Industrial energy use is largely in the form of heat and is increasingly being supplied from electricity. Over the past decade, global use of electricity for industrial heat has accelerated, with the People’s Republic of China (hereafter, “China”), India and the Association of Southeast Asian Nations (ASEAN) recording the largest increases. Despite differing industrial structures, all major economies have converged toward similar electricity shares for industrial heat of around 4–5%. Increased uptake is being driven by improving cost competitiveness, expanding technology availability and stronger policy signals, alongside the benefits of reducing exposure to volatile fossil fuel prices.

Renewables are rapidly transforming power systems around the world, leading to a higher share of renewables in the industrial mix via heat electrification. This linkage between industrial electricity demand and growing renewable generation is becoming an important driver of decarbonisation across industrial sectors. It contributes to greater system flexibility, strengthens energy security by reducing dependence on fossil fuel imports, and fosters economic growth, industrialisation and employment.

Low-temperature industrial heat and steam are ready for electrification, but market conditions are not yet in place

Improving energy efficiency is the foundational step in preparing for the electrification of low-temperature heat and steam. Energy efficiency measures lower overall heat demand, reduce losses and thereby enable smaller, more cost-effective electrification solutions. In many industrial facilities, basic optimisation such as recovering and effectively using waste heat, improving insulation, enhancing process control and plant-level thermal optimisation can deliver immediate reductions in fuel consumption at comparatively low cost. These measures not only cut emissions but also reduce the scale of investment required for electric heating technologies. Prioritising efficiency therefore maximises the impact of subsequent electrification efforts and strengthens the business case for switching from fossil fuels.

Industrial heat pumps and electric boilers are commercially available technologies for heat electrification but face several structural barriers. Large-scale industrial heat pumps are well established to deliver heat up to 150 °C, while electric boilers can generate steam up to 350 °C and pressure of around 70 bar. However, technology deployment has remained limited due to unfavourable electricity-to-gas price ratios, long grid connection lead times and the absence of clear policy frameworks. Supportive policies are only now gaining momentum, but stronger signals are still needed.

Thermal storage is the enabling technology that can connect low-cost variable renewable electricity supply with continuous industrial heat demand. Thermal storage systems can be built from low-cost, simple materials such as sand, cement and bricks and can store heat up to 1 000 °C. At around USD 15-20 per kWh, they are significantly cheaper than chemical batteries and don’t rely on global supply chains for critical minerals. Whilst the market for thermal energy storage for industrial applications is still developing, projects are emerging across multiple regions.

A set of drivers underpins momentum across world regions.

Electrifying industrial heat with renewables can enhance energy security in the European Union (EU). Electrification of industrial processes through heat pumps and e-boilers has the technical potential to reduce the EU’s industrial fossil fuel use by almost 3 000 PJ. Direct use of natural gas for industrial heat could be reduced by 35 bcm/yr, diversifying energy use and improving the continent’s energy security. Substituting natural gas and other fossil fuels with electricity at this scale would however imply around 600 TWh/yr of additional electricity demand, comparable to the combined annual electricity consumption of Germany and the Netherlands.

Industrial heat pumps are economically attractive compared to existing gas boilers in several EU member states. The range is, however, wide at 41-74 EUR/MWh, reflecting differences in electricity prices, and in approaches to energy taxation and network cost allocation among the examined countries. Electric boilers remain more expensive due to their lower efficiency, although they are increasingly finding markets in Northern Europe thanks to the region’s low electricity-to-gas price ratios and taxation that is favourable towards electrification. Adding thermal storage would enhance the cost competitiveness of e-boilers by reducing exposure to peak power prices, while improving operational flexibility and overall energy efficiency. Policy momentum for industrial heat electrification in the EU is building in the form of renewable heating targets and funding instruments but remains in early stages.

China is accelerating the electrification of industrial heat use through a range of policies. Electrification of low-temperature heat and steam has technical potential to reduce China's industrial fossil fuel use by almost 9 000 PJ. Direct natural gas use could be reduced by 48 bcm, reducing the country's strong import dependence. In parallel, realising the technical potential would increase electricity demand by 1700 TWh, which is comparable to the forecast growth in China's solar PV electricity generation between today and 2030.

Direct use of solar PV and wind, coupled with thermal storage, creates new opportunities for heat electrification in China. Connecting industrial consumers directly to captive renewable power generators (i.e., solar PV, wind onshore or hybrid) could almost halve heat electrification costs for steam from USD 70-100/MWh (grid-connected) to around USD 50/MWh in the examined provinces. Grid-connected industrial heat pumps are attractive today compared to natural gas boilers, but struggle while cheap domestic coal is available as a heat source.

China is accelerating industrial heat electrification through its carbon neutrality targets and through coordinating national and provincial policies. The 14th Five-Year Plan, sectoral energy efficiency plans, heat pump and electric boiler action plans, financial support programmes, and grid reforms provide strong support for deployment. However, many targeted policies still focus on energy-intensive industries, leaving an opportunity to expand their scope to all industrial sectors.

Industrial parks play a central role in the ASEAN industry landscape and could become drivers of heat electrification in the region. Regional visions and plans support renewables, energy efficiency, and green industrial hubs, yet still focus on energy-intensive sectors. Capital costs, grid constraints, and limited access to finance hinder deployment, particularly in manufacturing hubs such as Indonesia, Malaysia, Thailand and Viet Nam. Expanding policy and financial support to all industrial sectors, alongside targeted demonstration projects and electricity market reform, could accelerate deployment of heat pumps, electric boilers and thermal storage.

Policy priority areas to accelerate deployment

While several drivers exist, global policy momentum is increasing but remains in early stages. To help accelerate the electrification of industrial low-temperature heat and steam, the IEA recommends the following six priority actions:

1. **Elevate heat electrification into the policy agenda and integrate it into industrial roadmaps and targets** within broader energy goals, while keeping a

technology-open approach aiming at fostering a wide portfolio of possible pathways.

2. **Anticipate heat electrification in long-term grid planning** and **prioritise connection requests** with demand side flexibility to prevent capacity shortages and reduce project delays.
3. **Reform electricity taxes and levies** to level the playing field with fossil fuels and reward flexible industrial demand, possibly through lower network tariffs.
4. **Provide targeted early support for capital and operational costs** and enable innovative business models to accelerate the roll-out of heat electrification technologies.
5. **Enhance skills and workforce development** by expanding education and training programmes and certification schemes to meet the growing demand for industrial electrification expertise.
6. **Promote international collaboration on technical standard frameworks** to facilitate equipment interoperability, broader adoption of standards and achieve economies of scale

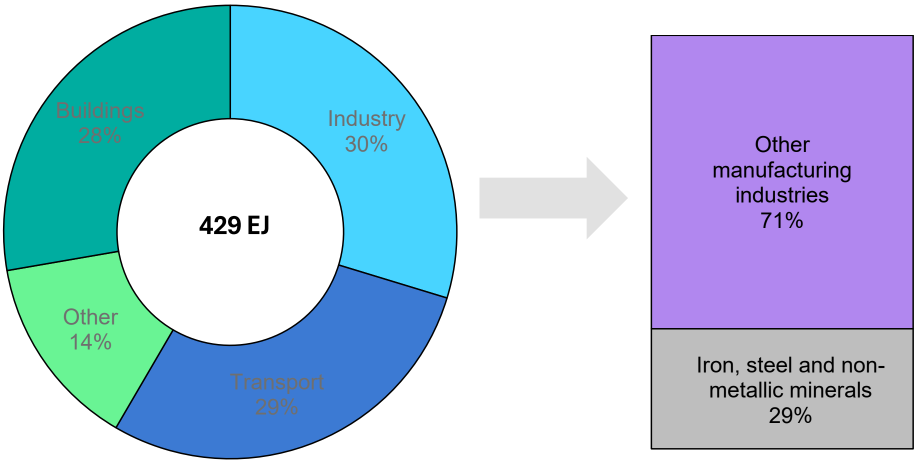
Chapter 1. Introduction

Industrial energy use

The industrial sector plays a vital role in shaping the global economy and our everyday lives. In 2024, it represented one-quarter of global gross domestic product (GDP) and is a key driver of economic growth and development. In the same year, it also employed one-quarter of the world's workforce, supporting millions of jobs across diverse skill sets and professions. Industry produces many essential tools and products that people rely on in their daily lives, from the packaging that protects and preserves food and beverages to the textiles used in clothing and furniture, and the cement that forms the foundation of homes, offices and public infrastructure.

The industrial sector is also a significant user of energy. It is responsible for 30% of global consumption, a share that has remained largely stable over the past decade, despite an increase in total industrial energy use from 116 exajoules (EJ) in 2012 to 129 EJ in 2023.

Figure 1.1 Global final energy consumption and share of industry energy consumption, 2023



Notes: EJ = exajoule. Buildings include residential, commercial and public service sectors. Other includes agriculture, forestry, fishing, final consumption not elsewhere specified and non-energy uses outside industry. Other manufacturing industries include mining and quarrying, construction, manufacturing, chemicals and petrochemicals, non-ferrous metals, transport equipment, machinery, food, beverages and tobacco, pulp, paper and printing, wood and wood products, textile and leather, and non-energy use in chemicals. Non-metallic minerals include cement, glass, ceramics and clay. Iron and steel energy consumption excludes energy use in blast furnaces and coke ovens.

Iron and steelmaking, along with the production of non-metallic minerals such as cement, glass or clay, are among those industrial subsectors that have an outsized impact on industrial energy use and emissions. Together they account for nearly 30% of total industrial energy demand (Figure 1.1). The remaining 70% is generally characterised by lower energy and carbon emissions intensities. The thermal energy demand in this segment is predominantly for low-temperature heat and steam.

Box 1.1 Electrification pathways and uses of heat covered in this report

This report focuses on electrification pathways that can displace fossil fuel use in the production of low-temperature heat and steam. The analysis concentrates especially on two technology families – industrial heat pumps and electric boilers – that are both mature and market ready for electrifying heat demand in the near term.

The report also explores electro-thermal energy storage (ETES) technologies that can shift grid electricity consumption from peak price periods to lower demand periods with lower prices, and that can alternatively provide a flexible, dispatchable heat supply from variable renewable energy sources such as wind and solar photovoltaic (PV) systems.

The report's scope does not include high-temperature processes, such as calcination, reforming and cracking. Although electrification options for these processes are advancing, their deployment conditions, equipment requirements and cost profiles differ substantially from low-temperature applications and are therefore not addressed in this report.

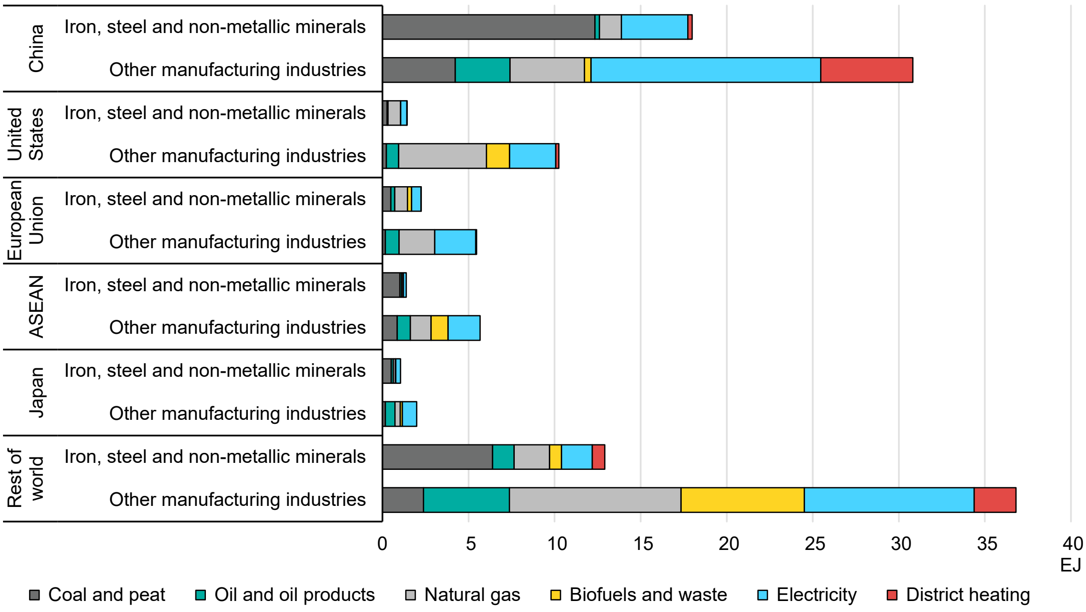
The report also excludes early stage or emerging technologies that have seen promising developments in recent years but are not yet at the level of market maturity suitable for broad industry uptake. The focus is instead on technologies with established supply chains, demonstrated industrial operation and clear pathways for short-term scale-up.

The report groups industries in accordance with process heat temperature requirements rather than in the conventional "hard-to-abate" or "light industry" categories. Iron, steel and non-metallic minerals are categorised as "high-temperature heat industries" that require very high heat for processes such as melting, calcining or sintering. "Other manufacturing industries" (textile, food, beverages, papermaking, etc.) typically rely on low-temperature heat and steam. This temperature-based grouping underpins the assessment of technology options and policy considerations throughout the report. Further methodological details are provided in Chapter 2.

Several abatement options are available for low-temperature heat and steam use, for example, electrical heating, solar thermal energy, geothermal energy and bioenergy (Box 1.2). However, fossil fuels remain the primary industrial energy source worldwide today, although energy mixes vary from one region to another. For examples, in China and the 11 member states forming the Association of Southeast Asian Nations (ASEAN), industrial energy use is dominated by coal. The use of coal is largely driven by abundant domestic resources that can provide heat to energy-intensive industries at low cost and with supply security advantages compared with other energy sources (Figure 1.2).

Industry in the European Union, on the other hand, is relatively gas dependent. At around 30%, the share of natural gas in overall industrial energy consumption in the European Union is closer to levels seen in major gas producing countries – the United States at 40% or the Russian Federation (hereafter "Russia") at 20%. In large gas-importing economies such as Japan or China, the share is less than 15%. This contrast reflects differences in supply conditions: liquified natural gas (LNG) imports would be more costly for both Japan and China whereas Europe, until recently, benefited from relatively cheap pipeline gas from Russia.

Figure 1.2 Energy use in the iron, steel and non-metallic mineral industries, and in other manufacturing industries, in major economies, 2023



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Notes: EJ = exajoule. Non-metallic minerals include cement, glass, ceramics and clay. Iron and steel energy consumption excludes energy use in blast furnaces and coke ovens. Other industries include mining and quarrying, construction, manufacturing, chemicals and petrochemicals, non-ferrous metals, transport equipment, machinery, food, beverages and tobacco, pulp, paper and printing, wood and wood products, textile and leather and non-energy use in chemicals.

In 2023, industry accounted for 18% of global direct energy-related CO_2 emissions, or just over 6 gigatonnes[1] (Gt) of CO_2, representing a 2% decline since 2013 (Figure 1.3). When including indirect energy-related CO_2 emissions from heat and electricity use, total energy-related CO_2 emissions more than double to approximately 12.5 Gt. In addition, process-related CO_2 emissions from the feedstock used to manufacture clinker in cement production can contribute approximately 60-70% of the total CO_2 emissions from this sector. These emissions are virtually unavoidable unless emerging solutions, such as material alternatives (lower clinker-to-cement ratio), or carbon capture and storage, are implemented at scale.

Just over half of direct energy-related industrial CO_2 emissions (around 3.3 Gt) stem from iron, steel and non-metallic minerals production, which includes cement, glass or clay, marking a 4% increase since 2013. China alone is responsible for more than half of these emissions. ASEAN, the European Union, Japan and the United States together contribute approximately 13% of CO_2 emissions in these sectors. These sectors rely on high-temperature heat to operate, for which few low-cost alternatives to fossil fuels exist. Similarly to cement, lowering process-related CO_2 emissions from iron ore reduction requires the large-scale deployment of emerging solutions, such as direct hydrogen reduction or carbon capture and storage. Indirect energy-related CO_2 emissions from heat and electricity use accounted for 1 Gt CO_2 in 2023, a 3% decline since 2013.

Other manufacturing sectors, including food, beverages, tobacco, textile and leather, rely on low-temperature heat and steam. In 2023, these sectors accounted for 3 Gt of direct energy-related CO_2 emissions, which is an 8% decline since 2013. China contributed around 30% of this total. However, indirect energy-related CO_2 emissions arising from purchased electricity and heat in these sectors were nearly double direct CO_2 emissions, and grew by 18% since 2013, which highlights the significant upstream carbon footprint embedded in the energy supply of these sectors.

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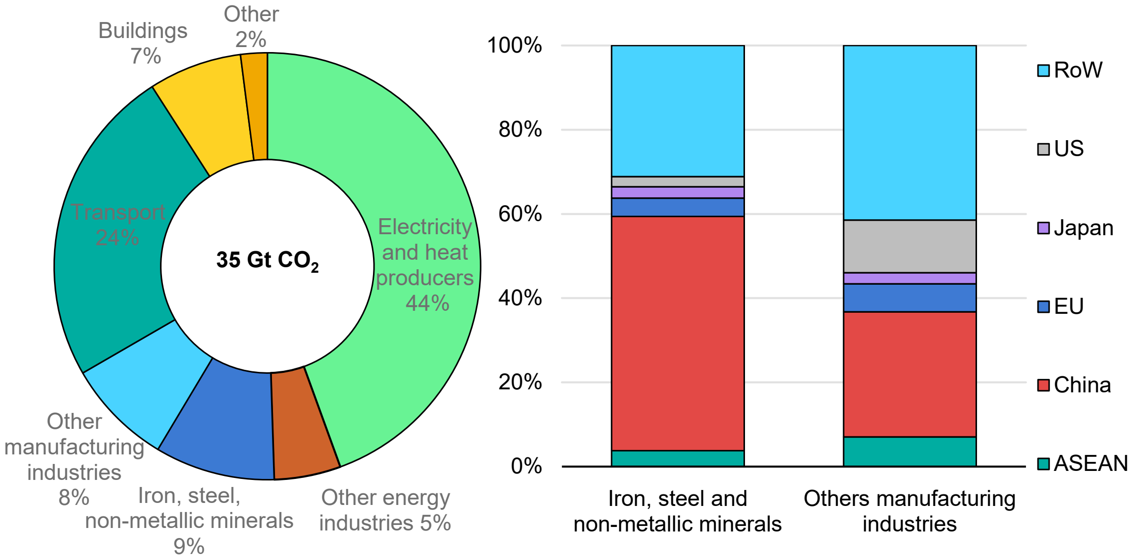
[1] The figure excludes emissions relating to blast furnaces and coke ovens.

Figure 1.3 Global direct energy-related CO_2 emissions by sector (left) and share of energy-related CO_2 emissions by country or region (right), 2023



Notes: Gt CO_2 = gigatonnes of carbon dioxide; RoW = Rest of world. Buildings include residential, commercial and public services. Other includes agriculture, forestry, fishing and final consumption not elsewhere specified. Non-metallic minerals include cement, glass, ceramics and clay. Other manufacturing industries include mining and quarrying, construction, manufacturing, chemicals and petrochemicals, non-ferrous metals, transport equipment, machinery, food, beverages and tobacco, pulp, paper and printing, wood and wood products, textile and leather and non-energy use in chemicals. The figure excludes emissions relating to blast furnaces and coke ovens, as well as indirect energy-related CO_2 emissions and process CO_2 emissions.

Box 1.2 Renewable energy options beyond electrification to decarbonise low-temperature heat and steam for industrial processes

While this report focuses on the opportunities that electrifying industrial heat offers for renewable electricity to penetrate the industrial energy mix, there are other renewable energy solutions that provide pathways to decarbonise industrial energy use, such as:

Solid bioenergy remains the dominant source of renewable heat for industry, particularly for low- to medium-industrial heat and steam. Biomass combustion is a technologically mature and widely used process in forest-based industries such as pulp mills or sawmills, where onsite by-products (e.g. black liquor, bark and sawdust) can be combusted to supply heat.

Biogases (biogas and biomethane) can supply heat for industrial processes. Biogas, derived from organic matter such as agricultural residues or biowaste, can be used locally for heat or can be co-fired in existing boilers. When upgraded to **biomethane** (i.e. to nearly 100% methane after removing CO_2 and other impurities) it can substitute for natural gas or be injected into gas grids for transport.

Industrial uptake of biogases remains limited, accounting for around 3% of total modern bioenergy production, which is equivalent to 1% of global natural gas demand. Their potential is growing, however, under supportive policies. Globally, nearly 1 trillion cubic metres of natural gas equivalent of biogases could be produced sustainably each year, using today's organic waste streams. This amount is equivalent to one-quarter of global natural gas demand today.

Geothermal energy offers continuous supply of low- and medium-temperature industrial heat (below 200 °C), particularly in the case of conventional direct-use systems. Conventional direct use relies on hydrothermal reservoirs, which are limited to geologically favourable regions. They are well established in buildings and agriculture, but also emerging in industrial applications, accounting for approximately 5% of direct geothermal use at the global level. Limitations preventing the adoption of geothermal use are largely associated with the high upfront costs of their deployment, insufficient policy support and site-specific constraints. **Next-generation geothermal** technologies aim to overcome geological limitations with advanced engineering. Current developments primarily focus on power generation, but these technologies could also provide industrial heat. Enhanced geothermal systems, which expand or create reservoirs through rock fracturing, and closed-loop geothermal systems, which circulate heat-transfer fluid through sealed wells in hot rock, could significantly broaden the availability of geothermal heat. The potential of these next-generation technologies is substantial: sedimentary aquifers located up to 5 km deep could theoretically supply up to 250 000 EJ of heat at temperatures above 90 °C and at levelised costs below USD 50/MWh.

Solar thermal technologies provide a renewable source of direct industrial heat, particularly in regions that are rich in solar irradiation. Temperature capability varies by collector type: air collectors, flat plate and evacuated-tube systems can deliver heat up to 100 °C, while concentrating collectors, such as parabolic troughs, can provide heat up to 500 °C, making solar thermal technologies suitable for low- and medium-temperature industrial processes. These systems are particularly effective for batch processes in food and beverages, textile or chemical sectors. Concentrating collectors are generally preferred for larger industrial sites, with breweries acting as a notable example of larger sites with an increased deployment of this type of solar technology.

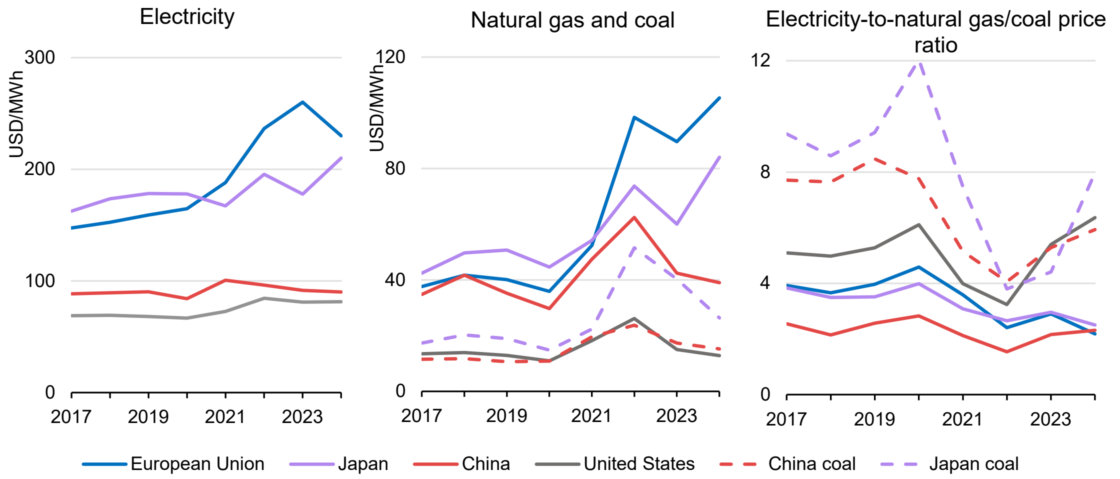
Global deployment of solar heat for industrial processes (SHIP) has been growing in recent years. In 2024, 125 megawatt thermal (MW_{th}) of new capacity was added to overall capacity, bringing the total to over 1 gigawatt thermal (GW_{th}) across 1 315 systems world wide, and covering more than 1.6 million m^2 of collector area. Several factors have hindered the expansion of SHIP, including weather dependence, high upfront costs and integration challenges, but innovative storage options and cascade use with other heat sources could enhance their efficiency and flexibility, and thus promote their more frequent use.

Industrial energy prices

Energy prices have a significant impact on industrial competitiveness and the potential attractiveness of available decarbonisation options. The highest average industrial end-user prices for both electricity and natural gas are in the European Union (Figure 1.4). Following Russia's war on Ukraine in 2022, the European Union also experienced the steepest increases in prices compared with the United States and China. Japan's prices remain significantly higher than those in the United States and China, although slightly below those in the European Union.

Despite recent decreases, average industrial electricity prices in the European Union remain more than 1.5 times higher than average industrial electricity prices in China and twice as high as those in the United States. Taxes and levies generally account for 30% of the electricity bill paid by the average industrial consumer in the European Union, a much higher level than the level in China, Japan and the United States.

Figure 1.4 Average industrial retail prices for electricity, natural gas and coal in major economies, 2017-2024



Note: USD/MWh = US dollar/megawatt hour. Average industrial retail electricity, gas and coal prices reflect all taxes, including recoverable taxes.

Sources: IEA (2025), IEA Energy Prices, accessed 3 December 2025; and IEA analysis based on data from Global Petrol Prices, [accessed 3 December 2025].

The European Union saw the most dramatic rise in natural gas prices between 2017 and 2023, surpassing Japan after 2020. This price rise was driven primarily by the global energy crisis and amplified by taxes. While China and the United States have seen prices return to near-2017 levels in 2024, gas prices in the European Union and Japan have remained high. In 2024, natural gas in the United States was in some cases around eight times cheaper than in the European Union, seven times cheaper than in Japan and three times cheaper than in China, giving industries in the United States a major cost advantage. In the European Union, taxes and levies make up 26% of the natural gas bill for the average industrial consumer, again a much higher share compared with other major economies.

In addition to differences between countries and regions, electricity prices also vary significantly across energy consumers in industry. Larger industrial consumers can access corporate power purchase agreements or can reduce price volatility by hedging portions of their electricity demand, allowing them to manage costs more effectively.

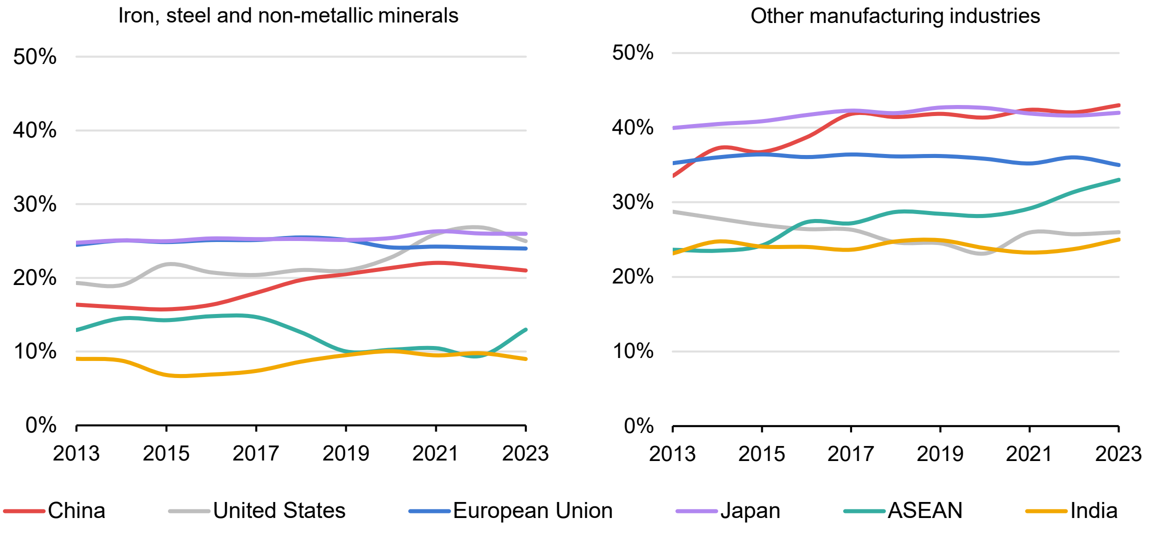
Electricity-to-gas price ratios, based on average retail industrial prices with important implications for electrifying process heat. In the European Union, this ratio dropped from the exceptionally high 4-5 range observed between 2017 and 2021 to around 2 in 2024, which signals a more favourable cost environment for electrified heat solutions. Japan's ratio declined from approximately 4 to 3 over the same period, while China remains close to 2, indicating moderate to favourable support conditions for industrial electrification. By contrast, the United States continues to exhibit a ratio near 6, reflecting persistently low industrial gas prices and offering relatively weak economic incentive to switch from gas-fired to electricity-based heat.

Industrial electricity use

Electricity is used to drive a range of industrial applications from pumps and compressors to electric motors and electric arc furnaces. Among the major producers of iron, steel and non-metallic minerals (e.g. cement, glass, clay), Japan has the highest share of electricity in total industrial energy consumption at 26%, followed closely by the United States at 25%, the European Union at 24% and China at 21% (Figure 1.5). The extent of industrial electricity use has seen the largest recent increases in China and the United States, particularly as a result of the expansion of industrial activity. The increased use of industrial electricity in the United States has also resulted from a parallel increase in scrap-based steelmaking using electric arc furnaces.

Among other manufacturing sectors that mainly rely on low-temperature heat and steam, the global average share of electricity use is much higher, at around 33%. China and Japan lead with 43% and 42%, respectively, with China showing the steadiest growth from 31% to 43% over the past decade, and ASEAN growth from 21% to 33%. These trends are in line with broader industrial capacity expansion and climate objectives. The European Union has largely stagnated at 35%, while the United States declined from 29% to 26%.

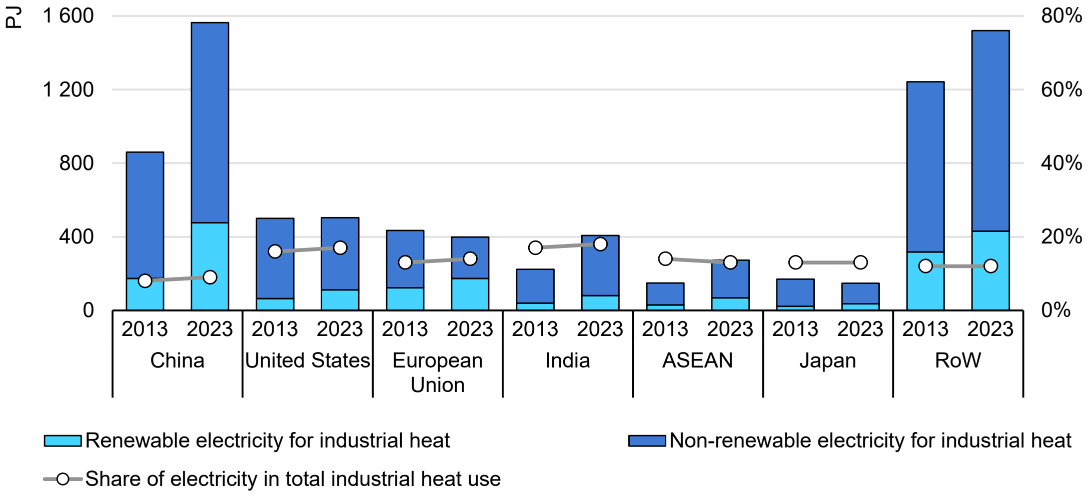
Figure 1.5 Use of electricity in the iron, steel and non-metallic mineral industries, and in other industries in major economies, 2013-2023



Notes: Non-metallic minerals include cement, glass, ceramics and clay. Other industries include mining and quarrying, construction, manufacturing, chemicals and petrochemicals, non-ferrous metals, transport equipment, machinery, food, beverages and tobacco, pulp, paper and printing, wood and wood products, textile and leather and non-energy use in chemicals.

Over the past decade, ASEAN, China and India have seen the largest increases in electricity use for industrial heat, while the European Union and Japan recorded declines (Figure 1.6). These trends reflect broader trends in total industrial energy consumption and production outputs in the different economies forming ASEAN, as well as in China and India. However, the share of electricity for industrial heat of total industrial electricity use remained largely unchanged across major economies. India (18%) and the United States (17%) had the highest shares, while China had the lowest at 9%. The use of renewable electricity to produce industrial heat was nevertheless rising across all major economies between 2013 and 2023. The European Union was leading with its share rising from 4% to 6%, while China and Japan, though increasing, rose more slowly from 2% to 3%.

Figure 1.6 Non-renewable and renewable electricity use for industrial heat and share of electricity in total industrial heat use in major economies, 2013 and 2023



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Note: PJ = petajoule.
Sources: IEA (2025) *Renewables 2025*, IEA (2025) *World Energy Outlook 2025*.

Case for the electrification of industrial heat

Renewables are rapidly transforming power systems worldwide. More than 3 000 gigawatts (GW) of renewable power capacity were installed between 2014 and 2024, and an additional 4 600 GW is forecast to be installed by 2030 as countries seek to improve their energy security, meet emission reduction targets and take advantage of cheaper electricity sources. The strong growth of renewables (and in the case of China, nuclear energy as well) in electricity generation has led to a rapid decline in the carbon intensity of power systems. In the European Union, grid carbon intensity fell from 312 grammes of CO_2 per kilowatt hour (gCO_2/kWh) in 2014 to 179 gCO_2/kWh in 2024. Over the same period, it declined from 683 gCO_2/kWh to 561 gCO_2/kWh in China, from 549 gCO_2/kWh to 444 gCO_2/kWh in Japan and from 486 gCO_2/kWh to 322 gCO_2/kWh in the United States.

One of the most immediate options for electrification in industry is the electrification of heat through the use of existing technologies, such as industrial heat pumps and electric boilers. These technologies are particularly well suited to provide low-temperature heat and steam, which together account for a large component of total industrial energy demand. Electrification also brings other benefits, for instance optimised energy management via automation and digitalisation.

Industrial heat pumps are valued for precise temperature control in sectors such as food and beverages, textiles and chemicals, as well as for applications that require both heating and cooling simultaneously, for example, those in the dairy industry.

The first wave of industrial heat electrification can already be observed in Northern Europe, where rapid growth in wind power and gradual phase-out of fossil fuels has lowered both wholesale electricity prices and the carbon intensity of the grids. This expansion has also increased price variability, creating frequent periods of very low-cost electricity during hours of sustained wind. District heating networks, although not industrial in nature, have been at the forefront of this transition, with large heat pumps and electric boilers having been installed and paired with hot-water storage to enable heat production during the cheapest hours (often at night) and buffer it for distribution during the day. The same logic would apply to industrial heat, particularly in the production of steam, but higher temperature storage technologies are required since hot-water systems are limited to around 150 °C (5 bar). As renewable capacity continues to expand across national grids, the combination of electrification and thermal storage offers a major new opportunity to decarbonise industrial heat.

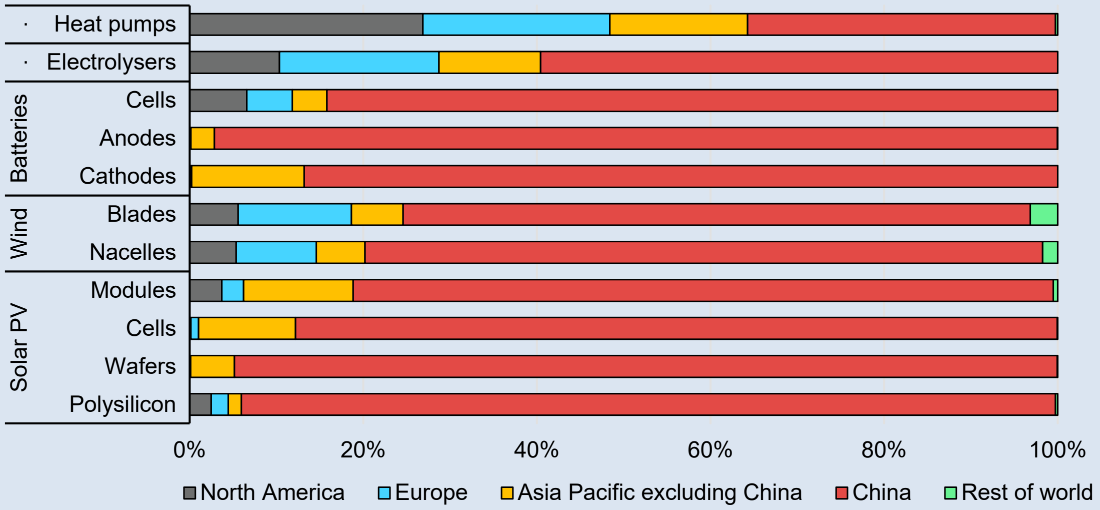
Unlocking this opportunity would mean overcoming several challenges. Although wind and solar PV are now the lowest cost sources of new electricity generation in most regions, use of grid electricity remains more expensive than direct use of fossil fuels in many markets, affecting the competitiveness of electrified heat solutions. Securing grid connections can also be a lengthy process – often taking several years – which adds uncertainty to investment decisions and also risks delaying deployment.

Box 1.3 Box 1.3: Heat pump with stable and resilient supply chains

The manufacturing capacity for heat pumps is more geographically diversified than for other major clean energy technologies. While supply chains for solar PV, batteries and key wind components remain highly concentrated, mostly in China, heat pump production is distributed across several mature industrial bases, including China, Europe, Japan, Korea and the United States. As a result, no single country holds a dominant share of global manufacturing capacity, which reduces exposure to geopolitical or trade-related disruptions and lowers the risk of supply bottlenecks. It also provides manufacturers and governments with greater flexibility to shift procurement across regions, enhancing the overall resilience of the heat pump supply chain.

In regions with established domestic production, this diversification also provides strategic advantages. The availability of domestically manufactured heat pumps can shorten delivery times, stabilise prices, support local employment and strengthen policy objectives aimed at accelerating electrification. It can also further enhance supply-chain resilience and energy security, particularly as demand for heat pumps continues to rise.

Heat pumps and installed manufacturing capacity by region, 2024



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Note: The forthcoming edition of IEA *Energy Technology Perspectives* will explore issues such as the outlook for global supply chains for selected energy technologies.

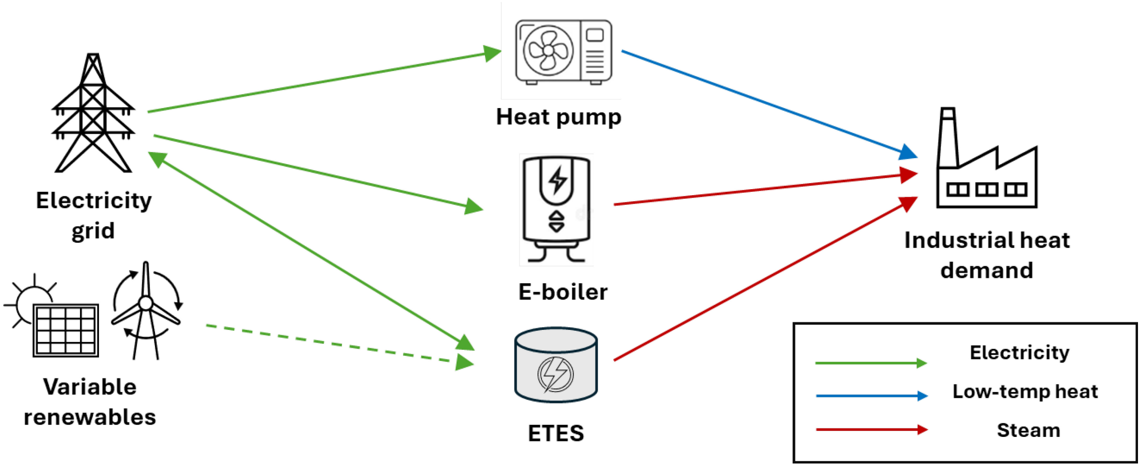
Source: IEA (2024), Energy Technology Perspectives.

Chapter 2. Electrification of heat

Overview

Heat is used across a wide range of industrial processes at different temperature levels. Examples of low-temperature applications include drying, vacuum distillation and pasteurisation. Steam can be used both directly and as a heat transfer medium, and is generally employed for the purpose of drying, evaporation, product heating and the stripping of impurities, in addition to being used as a reactive agent in chemical processes.

Figure 2.1 Electrification pathways for industrial heat considered in this report



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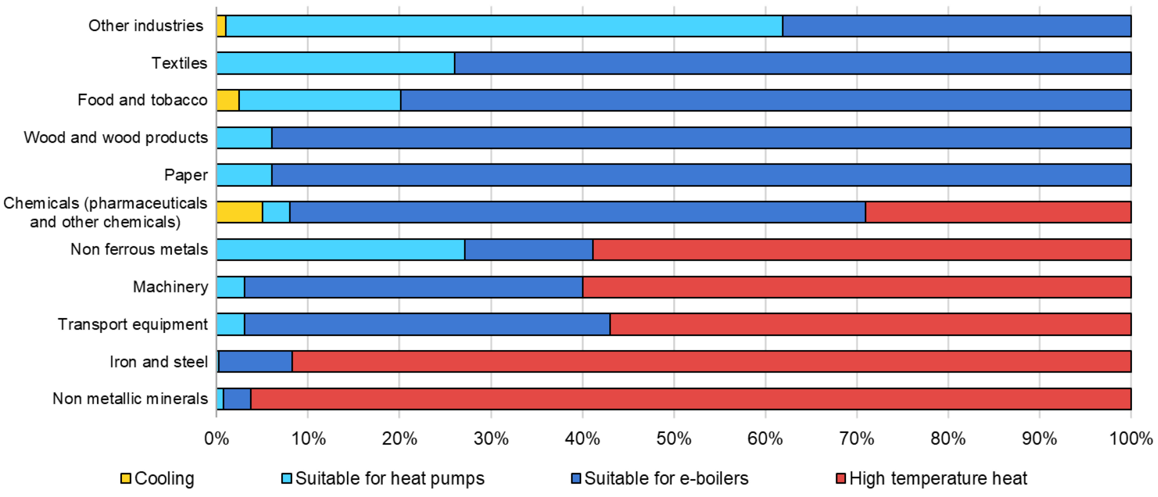
Notes: e-boiler = electric boiler; ETES = electro-thermal energy storage; Low-temp heat = low-temperature heat. The dashed line indicates variable electricity supply. When ETES is operated at a high enough temperature to produce superheated steam for turbines, it can also return part of the stored energy in the form of electricity as a co-product of heat.

Many industrial operations also require heat above 300 °C (and often exceeding 1 000 °C) for processes such as calcination, melting, sintering and cracking. At the other end of the thermal spectrum, cooling is also required for various processes, including condensation, gas drying, separation and chilling. The potential for electrifying industrial processes will depend not only on the temperature of process heat but also on factors associated with the site's existing energy mix, the balance between combustible by-products and steam demand, the level of energy efficiency and overall process configuration.

The temperature level at which industrial processes operate is nevertheless important as it will determine available decarbonisation opportunities, especially in the case of electrification. Heat pumps can be used for temperatures up to 150 °C while electric boilers can be used for temperatures up to 300 °C. For temperatures above 300 °C, heat is generally more difficult to electrify and typically requires a re-design of the core parts of the process. However, some scalable examples do exist, including plasma torches and electric arc ovens for specific applications.

Figure 2.2 shows how heat use is distributed in different industrial subsectors. In five sectors, more than half of the heat needs can be electrified with heat pumps and electric boilers (textile, food and beverages, wood and wood products, paper and printing, and other industries). Approximately another 40% of heat needs can be electrified in four additional sectors (chemicals, transport equipment, aluminium and machinery). Iron and steel, cement, ceramics and glass sectors are dominated by high-temperature heat requirements, and thus have more limited potential for immediate electrification.

Figure 2.2 Distribution of heat use in industrial subsectors of the European Union



Notes: Included are annual data from 14 manufacturing industries in EU member states. The food and tobacco category includes beverages.
Source: IEA analysis based on 2021 data from the Integrated Database of the European Energy System (IDEES) assembled by the European Commission Joint Research Centre, accessed May 2025.

Today, most of the industrial heat illustrated in the above figure is supplied through the burning of fossil fuels, with the notable exception of pulp making, where heat is largely supplied by the burning of biogenic by-products such as bark and black liquor. To a large extent, the chemicals sector similarly uses low-value combustible by-products, including liquefied petroleum gas and various off-gases, to meet part of its thermal needs. Substituting these fuels with electricity would not necessarily reduce emissions, since the by-products would still need to be disposed of through combustion.

Prioritising energy efficiency ahead of heat electrification

Improving the overall energy efficiency of an industrial site is a foundational step before designing and installing electrified replacement heating systems. Reducing heat demand at source lowers both the scale and complexity of subsequent electrification investments, improving economic viability and easing system integration. Efficiency improvements deliver multiple, reinforcing benefits, including reduced energy losses and associated emissions, lower process heat loads and temperature requirements, and avoidance of oversizing new electric heat equipment. They also reduce electricity demand and peak loads, which can significantly lower operational costs and, in many cases, reduce grid connection capacity requirements and associated connection delays.

Well-established technologies and operational practices offer substantial scope for efficiency gains. Across the light industry, energy efficiency measures could reduce fuel use by around 25% and electricity use by around 30%, although the achievable savings vary widely depending on site-specific factors.

The benefits of an efficiency-first approach are particularly pronounced in greenfield developments, where process design, layout and energy systems can be optimised from the outset. Programmes such as Ireland's SEAI EXEED Certified Grant Scheme illustrate this approach by placing energy efficiency design ahead of electrification and fuel switching. In one documented case, a distillery applying this methodology reduced its energy demand by around two-thirds compared with a conventional design. While such deep integration is often not feasible in existing facilities, the example highlights the scale of savings that can be achieved when efficiency considerations are embedded early in investment decisions.

For existing industrial sites, key opportunities include optimisation of heat exchanger networks, which can typically deliver energy savings in the range of 10–35%, depending on process complexity and temperature levels. Improvements in steam system maintenance, control and condensate recovery can reduce total site energy use by up to 15%. Enhancing insulation levels for pipes, vessels and equipment offers further low-cost savings potential; in the European Union alone, it is estimated that more than 5 million tonnes of oil equivalent per year are lost in low-temperature industrial applications due to missing or inadequate insulation.

Overall, placing energy efficiency at the centre of industrial decarbonisation strategies reduces costs, lowers technical barriers to electrification, and accelerates deployment. For policy makers and investors alike, an efficiency-first approach is a critical enabler of cost-effective industrial heat electrification.

Heat pumps

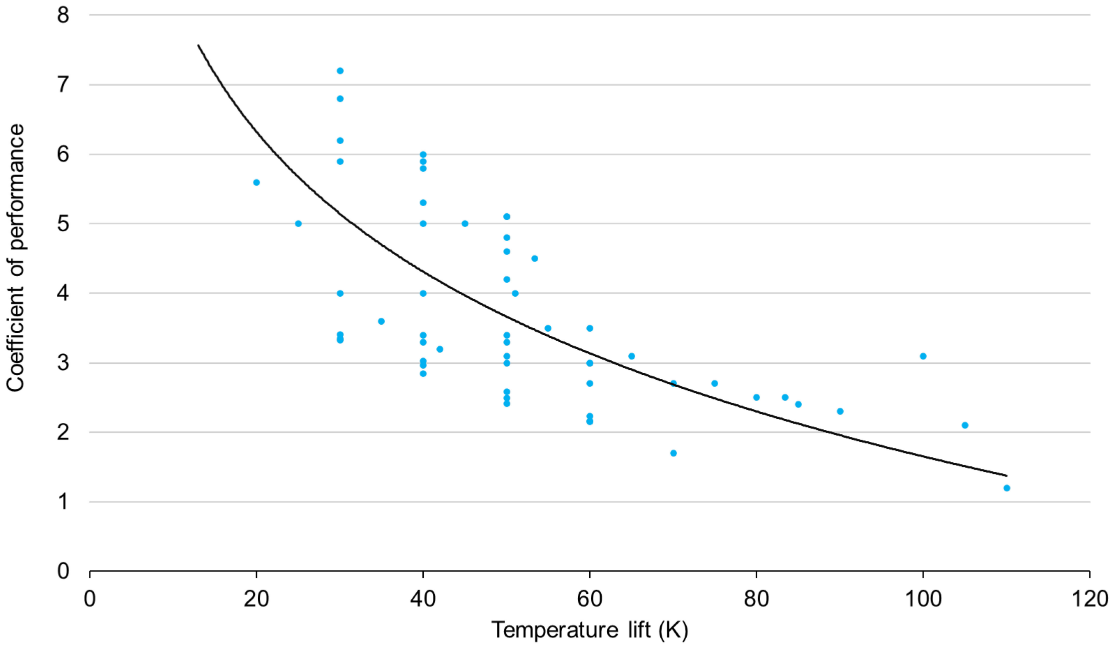
Global market trends

Industrial heat pumps today represent only a small fraction of installed heating equipment in industry at the global level, which is currently dominated by fossil fuel boilers and other electric heating alternatives. However, industrial heat pumps are gaining momentum in specific markets, including in Europe, where sales are growing rapidly, surpassing 2 500 units in 2022 (up from 600 in 2016), or in Japan where more than 6 000 systems were installed by 2020. In China, early examples include the Hongjitang brewery, which produces steam at 120 °C with a 200 kW heat pump, as well as a grain dryer built by the Chinese Academy of Sciences using a 650 kW heat pump to provide hot air at 70 °C. The world's largest heat pump today is located at the Katri Vala plant, which produces district heating and cooling in Helsinki (Finland). The plant was built in 2006 and can produce 165 MW of heat and 100 MW of cooling.

Technology considerations

Large-scale industrial heat pumps are a commercially available technology. Replacing a fuel boiler with a heat pump does not necessarily require major changes to core processes, although efficient integration can necessitate redesigns around the waste heat system, as well as upgrades to allow for connection to the grid. Heat delivery at 150 °C has already been implemented for multiple commercial applications. For higher temperatures up to 200 °C, heat pumps need special refrigerants and compressors, for which technologies are still in the early prototype stage.

Figure 2.3 Heat pump's coefficient of performance based on its temperature lift



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Notes: K = kelvin. Data collected as part of a literature review conducted in 2025.

The coefficient of performance (COP) is a measure of a heat pump's operational efficiency, expressing a ratio of the useful heating or cooling output to the electrical energy input. The COP is closely governed by temperature lift, or the difference between the heat pump's input and output temperatures. As shown in Figure 2.3, higher temperature lifts generally lead to lower COP. Incorporating internal heat exchangers or cascaded cycles can lead to improvements in the COP, although at an additional investment.

Heat pumps typically operate in a closed cycle, where a working fluid is compressed and expanded to change its temperature. Mechanical vapour recompression (MVR) devices, which operate in an open cycle, also exist and are sometimes referred to as open-cycle steam heat pumps. In the case of an MVR, the waste steam itself is compressed to raise its temperature. While heat pumps and MVR devices have some similarities, they are sufficiently different to be considered two distinct technologies.

For temperatures above 160 °C, MVRs have higher technical readiness levels (TRLs) compared with heat pumps. However, some examples exist of closed-cycle heat pumps, such as the HoegTemp ultra high-temperature heat pump and the HeatBooster Heaten, which are capable of reaching up to 250 °C and 200 °C, respectively, and have a TRL of 8 or 9.

Research is being undertaken to improve the heating capacity and temperature delivery of heat pumps. One of the more promising technologies is the steam generating heat pump (SGHP). Two such SGHPs are currently being developed by US companies: AtmosZero and Skyven Technologies. AtmosZero has developed an SGHP that leverages electricity and environmental heat to deliver steam with a higher efficiency than fossil fuel boilers. In June 2025, the company installed its first application at a brewing facility in Colorado. This SGHP is able to provide about 30-40% of the brewery's steam needs when running at full capacity. Skyven Technologies recently commissioned an SGHP demonstration project, Arcturus, at one of its facilities in Texas. This technology is capable of delivering 1 MWh of steam generated by the capture of waste heat. The company is currently installing the SGHP system at the ethanol plant, Western New York Energy, in New York.

Electric boilers

Global market trends

Electric boilers (e-boilers) are gaining prominence in industry thanks to their versatility and the simplicity of their installation. While their market share currently remains limited given their lack of economic competitiveness in comparison to fossil fuel alternatives, some successful examples of industrial e-boiler installations exist.

Since 2023, the forestry company, UPM, has started electrifying heat and steam production at its paper mills in Finland and Germany. In 2023, two 50 MW and 60 MW e-boilers were installed at the Tervasaari and Kaipola mills, respectively, and another eight natural gas boilers are to be replaced with e-boilers at the company's mills. The Alunorte alumina refinery located in Brazil also replaced coal fired boilers with two e-boilers that are able to produce 270 tonnes of steam per hour. These e-boilers were added alongside a previous e-boiler installed in 2022, having a capacity of 95 tonnes of steam per hour and consuming 60 MW of electricity.

Technical considerations

E-boilers can generate steam up to 350 °C and 70 bar, the most common types being resistance boilers and electrode boilers. Resistance boilers work on the basis of resistive elements that transfer heat to the water, while electrode boilers pass an electric current directly through water to evaporate. Electric resistance boilers typically have lower thermal capacities of up to 5 megawatt electrical (MW_e) while electrode boilers can have capacities between 3 MW_e and 70 MW_e.

Although e-boilers have a lower efficiency than heat pumps, they have a number of benefits over conventional fuel boilers. E-boilers do not produce combustion pollutants, have lower space requirements, require less frequent maintenance and can achieve faster ramp-up times. They also allow for more precise temperature control compared with fossil fuel boilers, which can translate to better product quality, particularly in the chemical sector. Moreover, e-boilers have a higher efficiency of 95-98% compared with the 70-85% efficiency (on a lower heating value basis) typical of combustion systems. However, condensing boilers can reach 92-95% efficiency.

High-temperature systems

Global market trends

Electricity can also be used to deliver high-temperature heat for industrial needs, for example, in the case of the ceramics, glass, machinery and transport equipment sectors. However, electrification is likely to advance slower in these areas as a result of technical challenges, such as scaling up, integrating process equipment and demonstrating proof of reliability. In the case of heavy industries, such as cement and iron, electric technologies continue to have a low maturity level and would need to be accompanied by fundamental changes in the set-up of industrial processes. New innovative concepts such as electric methane reformers are being developed with the objective of widening the application field.

Many activities are also being undertaken by the chemical industry to move towards electrifying steam crackers. For example, in 2024, three companies in Germany (BASF, SABIC and Linde) inaugurated the world's first demonstration plant for large-scale electric steam cracking furnaces. The demonstration plant, located in the BASF Verbund site in Ludwingshafen, aims to show that continuous olefin production is possible using electricity as a heat source. When accompanied by a low-emission electricity supply, the new technology can potentially reduce CO_2 emissions by more than 90% compared with technologies commonly used today. The project was granted EUR 14.8 million by the German Federal Ministry for Economic Affairs and Climate Action under its "Decarbonization in Industry" funding programme.

In 2021, Shell and Dow also signed a cooperation agreement for research into the electrification of steam cracker furnaces in petrochemical production. In 2019, six petrochemical companies in Flanders (Belgium), North Rhine-Westphalia (Germany) and the Netherlands created the Cracker of the Future consortium, to jointly investigate how naphtha or gas steam crackers could be heated using electricity instead of fossil fuels. A further example is the memorandum of understanding signed by CEMEX and Coolbrook in 2022 to test the Roto Dynamic Heater technology that aims to replace fossil fuel cement kilns with kilns that use electricity. In the ceramics sector, activities are also being undertaken to electrify high-temperature processes through the use of electric furnaces. For example, in one of the world's largest industrial projects to replace a gas fired kiln with an electric kiln using renewable energy, the Austrian company, Wienerberger, initiated the GreenBricks project in 2025 at its site in Uttendorf. This project follows the successful implementation of a similar technology in 2020, although on a much smaller scale, for the production of bricks at a Belgian plant in Kortemark.

Technical considerations

Electromagnetic heating technologies use radiation at different wavelengths to deliver heat, with examples including infrared, microwave and radio frequency heaters. Infrared heaters are mainly used to deliver very rapid heating of small surfaces and thin material, enabling faster processing times compared with gas furnaces. Some examples include heating and drying of surfaces, baking food, fixing coatings and drying paint in metallurgy. These heaters can deliver temperatures up to 2 200 ºC with an efficiency of 60-90%. Microwave and radio frequency heaters can also deliver temperatures up to 2 200 ºC with an efficiency of 50-85%. Microwave heaters ensure the rapid internal heating of large volumes, while radio frequency systems heat material more uniformly, with a higher depth of penetration. Microwave technologies are normally used in the food industry for cooking, sterilising and pasteurising food, as well as for drying processes in the wood, chemical, textile and other industries.

Electric arcs can deliver temperatures up to 2 000 ºC with an efficiency of up to 90%. They are commonly applied in metal processing, as well as in the steel sector and in hazardous waste disposal. The most common application of electric arc heating technologies is the electric arc furnace. Such furnaces can operate on a continuous basis, and are characterised by high thermal efficiency and fast melting rates. Induction heating technologies are also available for industrial applications in furnaces that can deliver temperatures up to 3 000 ºC, primarily for melting or heating metals. Induction heating systems have a high efficiency (up to 90%) since the heat is generated directly inside the material being heated, and there are no transfer losses.

Thermal energy storage systems

Global market trends

Thermal energy storage (TES) systems help to ensure that heat is available upon demand, whether it is for continuous industrial processes or for batch processes. While the TES market is still developing, several examples of projects can be cited from recent years. A description of selected projects is provided below.

Europe

In 2020, the Norwegian company, Energynest, in partnership with the fertiliser producer, Yara International, integrated a 4 MWh thermal battery directly connected to the steam grid of Yara's production facility in Porsgrunn (Norway). This renewable storage system provides increased flexibility to the plant by ensuring balanced local steam production and by reducing excess steam. In 2023, the Finnish food manufacturer, Herkkumaa Oy, deployed a 10 MWh thermal energy storage system to decarbonise its steam production, providing up to 2 000 MWh of steam annually and reducing energy costs by USD 140 000. Finland will also host the world's largest cavern TES facility, which is currently being built in Vantaa. The company building the facility, Varanto, began preparations for construction in 2024, with a completion date planned for 2028. The total thermal capacity of the seasonal storage will be 90 GWh, sufficient to heat a medium-sized Finnish town for as much as one year. Other projects include an aquifer thermal energy storage (ATES) project in the Netherlands. The latter project uses geological strata as the storage medium and groundwater as the heat transport fluid. Middenmeer was selected to host Europe's first high-temperature ATES system. In 2023, two Italian companies, Magaldi Group and Enel X partnered to decarbonise industrial processes at the Magaldi power plant, located at an industrial development area in Salerno (Italy). The plant was commissioned in September 2025. The sand battery at the plant has a storage capacity of about 7.5 MWh and is powered by a 2 MW solar PV plant, allowing continuous production of steam that meets about 15% of the company's thermal energy needs.

In 2023, PepsiCo's Kraftblock factory in the Netherlands replaced a 25 MW gas boiler with a TES that stores heat at 800 ºC (with a range of 350 ºC to 1 300 ºC), enabling a continuous renewable heat supply with a storage capacity of 70 MWh during the first phase of the project, and over 150 MWh of storage capacity in phase two. In addition to enabling cuts in costs by using surplus renewable power, the project also participates in grid balancing markets. In 2025, the Kyoto Group inaugurated the second European TES called the "Heatcube'' at the KALL Ingredients Factory in Tiszapüspöki (Hungary). This 56 MWh Heatcube will provide more than 30 GWh of process heat annually, replacing natural gas and reducing up to 8 000 tonnes of CO_2 emissions annually.

United States

In September 2025, the US company, Rondo, introduced the world's largest industrial heat battery into commercial service. The 100 MWh storage medium of the Rondo Heat Battery is manufactured from brick, and the battery is powered entirely by an onsite solar PV system. The plant delivers continuous, high-pressure steam to a fuel production facility in California, alongside traditional gas boilers. The battery can store heat at temperatures above 1 000 ºC and has a claimed efficiency of 97%. This project follows the installation of a commercial pilot project by Rondo in 2023 of brick storage at an ethanol plant in California. In early 2024, the world's largest concrete thermal energy storage pilot plant was tested at Alabama's Power's Ernest C. Gaston Electric Generating Plant. The storage pilot plant was developed by EPRI, in collaboration with Southern Company and Storworks. The system has a storage capacity of 10 MWh and uses heat generated from one of the gas plant's units to heat the concrete blocks.

Brazil

In 2022, Fortlev and Brenmiller Energy initiated a renewable energy TES system for plastic manufacturing in Anápolis (Brazil). The technology developed by Brenmiller Energy, the bGen TES, uses biomass to heat crushed rocks to more than 600 ºC in order to deliver hot air for water tank moulding machines at Forlev's fuel production facility. The 1 MWh biomass-powered thermal unit cuts fuel costs by more than 75%, while lowering greenhouse gas (GHG) emissions by approximately 800 metric tonnes/year.

Technical considerations

The most common approach to storing low-temperature heat is that of hot water tanks, which are widely used in combination with electric heating. The favourable properties of water make it a good option as a thermal storage medium, since it is cheap, easy to store and has a high specific heat capacity. Heat losses depend on the storage period, on the level of insulation of the tank, on the amount of heat stored in the tank (the number of cycles per year) and on the maximum operating temperature. If the tank is pressurised, hot water can store sensible heat up to around 150 °C (when pressurised under 5 bar).

When thermal storage needs exceed 150 °C, electro-thermal energy storage (ETES) systems can supply the needed steam and/or high-temperature industrial heat. ETES systems are made of solid material with robust thermal stability (e.g. sand, concrete, bricks, molten salt), enclosed in an insulating shell to minimise heat loss. Inside the storage, electrical resistance heaters convert the electricity to heat, which can be extracted at a later time by blowing gas through the storage material. Due to the use of cheap materials, the costs remain low at USD 10-15/kWh_{th}.

ETES systems can be used to minimise industrial electricity costs by avoiding charging during higher priced hours in the grid, or to buffer fluctuations in electricity supply from directly connected variable renewables. In some cases, if the heat is stored at a sufficiently high temperatures, it can be used to produce superheated steam for a turbine allowing co-production of electricity along with heat.

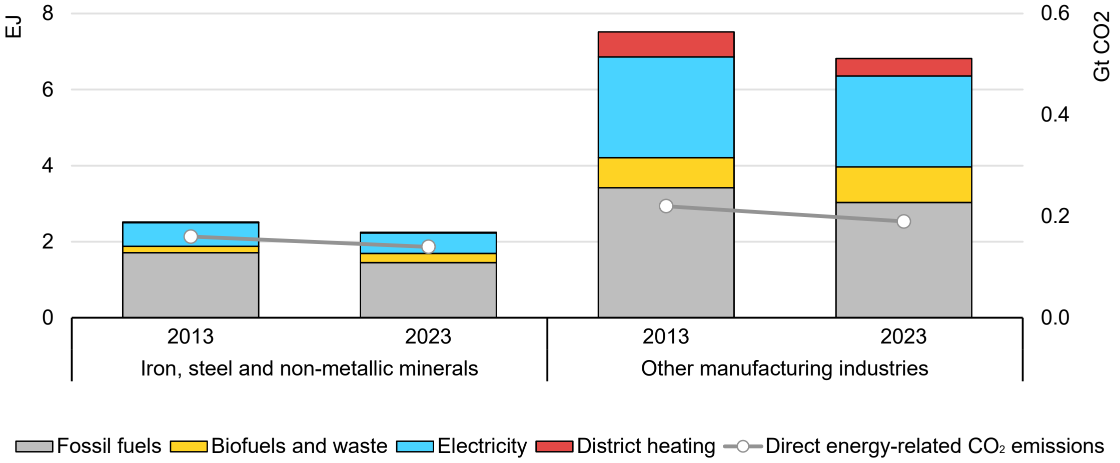
Chapter 3. Regional insights: European Union

State of play

The industrial sector plays an important role in the EU economy, contributing more than one-fifth of total GDP and providing millions of jobs across member states. Driven by high-value sectors such as machinery, vehicles, chemicals and pharmaceuticals, extra-EU[2] goods exports totalled around USD 2.6 trillion in 2024, capturing about 13% of export value in goods world wide, compared with 15% in China and 13% in the United States.

In 2023, industry accounted for approximately one-quarter of final energy use and around 15% of total direct energy-related CO_2 emissions in the European Union. When including indirect CO_2 emissions resulting from electricity and heat use, that share grew to 26%, making industrial decarbonisation essential to achieving the EU climate targets.

Figure 3.1 **Final energy consumption in industries and direct energy-related CO_2 emissions in the European Union, 2013 and 2023**



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Notes: EJ = Exajoule; Gt CO_2 = gigatonne of carbon dioxide. Non-metallic minerals include cement, glass, ceramics and clay. Iron and steel energy consumption excludes energy use in blast furnaces and coke ovens. Other industries include mining and quarrying, construction, manufacturing, chemicals and petrochemicals, non-ferrous metals, transport equipment, machinery, food, beverages and tobacco, pulp, paper and printing, wood and wood products, textile and leather and non-energy use. in chemicals. The figure excludes emissions relating to blast furnaces and coke ovens, as well as process emissions, and includes only direct energy-related CO_2 emissions.

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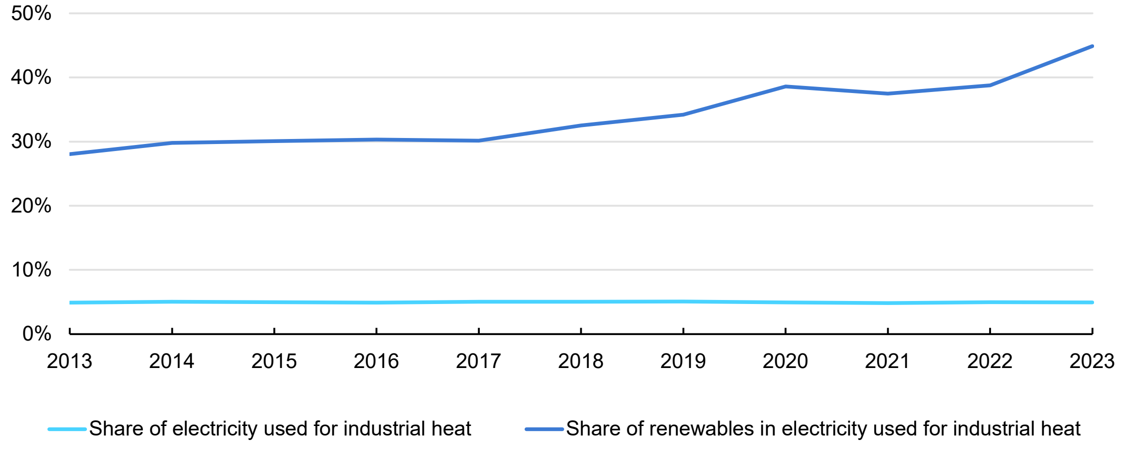
[2] Extra-EU trade refers to trade with non-EU countries, while intra-EU trade refers to trade between member states of the European Union.

Between 2013 and 2023, direct energy-related CO_2 emissions from EU industry fell by more than 0.04 Gt (or 13%) and indirect emissions declined by roughly another 0.03 Gt (or 13%). Industrial energy consumption declined by around 10% over the same period, signalling a clear reduction in the carbon intensity of industrial energy use. These declines were driven by a cleaner energy mix, with renewables gaining ground in electricity consumption and gradual fuel switching away from more carbon-intensive fossil fuels. The trend holds across subsectors such as iron, steel and non-metallic mineral industries, where energy use reduced by about 11% and emissions by 13%. Other industries cut their energy use by around 9% and emissions by 14%, suggesting even faster carbon-intensity improvements in sectors that can electrify more readily and can more quickly adopt efficiency measures.

These developments have been supported by regulatory pressure, which have led to a shift in consumer and investor preferences and to the implementation of broader structural trends, including reduced industrial output and ongoing de-industrialisation in parts of the European Union. Such structural trends further contributed to lowering energy demand. Progress over the period of 2013-2023 was nevertheless uneven, with periods of high energy prices and increased energy-security concerns, sometimes slowing fuel switching and temporarily increasing the reliance on carbon-intensive fuels.

In 2023, the EU industry consumed around 9 000 PJ of energy annually, which continued to be supplied to a large extent by the combustion of imported fossil fuels valued at around USD 56 billion. Electricity accounted for 32% of total industrial energy use, with five industries (chemicals and petrochemicals, food, beverages and tobacco, iron and steel, machinery, paper, and printing) consuming about three-quarters of all electricity. Higher electricity consumption in these industries largely results from production chains that rely heavily on electricity-driven operations, including grinding, mixing, pumping, refrigeration, drying and mechanical handling. Electricity-intensive processes in the iron and steel industries – including scrap melting in electric arc furnaces – further raise this demand. The share of electricity in total industrial heat remained stable at around 5% between 2013 and 2023, pointing to structural and economic barriers that continue to impede the electrification of industrial heat, and highlighting the need for stronger policy signals (see the Market and Policy section in this chapter). At the same time, the carbon intensity of electricity used for heat has fallen sharply, with the share of renewables rising from 28% in 2013 to 45% in 2023 (Figure 3.2).

Figure 3.2 **Share of electricity and of renewable electricity used for industrial heat in the European Union, 2013-2023**



Technical electrification potential

There is significant technical potential to shift industrial heat production away from fossil fuels and towards electrification in the EU. Complete to near-complete electrification of heat supply, with heat pumps and electric boilers, could be technically achieved in five sectors (food and tobacco, textiles and leather, paper and printing, wood and wood products and other industries), leading to a nearly 2 000 PJ potential reduction in fossil fuel-based heat demand (Figure 3.3). The chemical sector has the largest potential for electrification, with around 760 PJ (70%) of its heat use considered suitable for electrification using existing technologies.[3] In the remaining sectors, higher temperature requirements are likely to slow progress in electrification. The combined reduction potential for all these sectors is around 3 000 PJ, or 56% of total EU industry fossil fuel use for heat.

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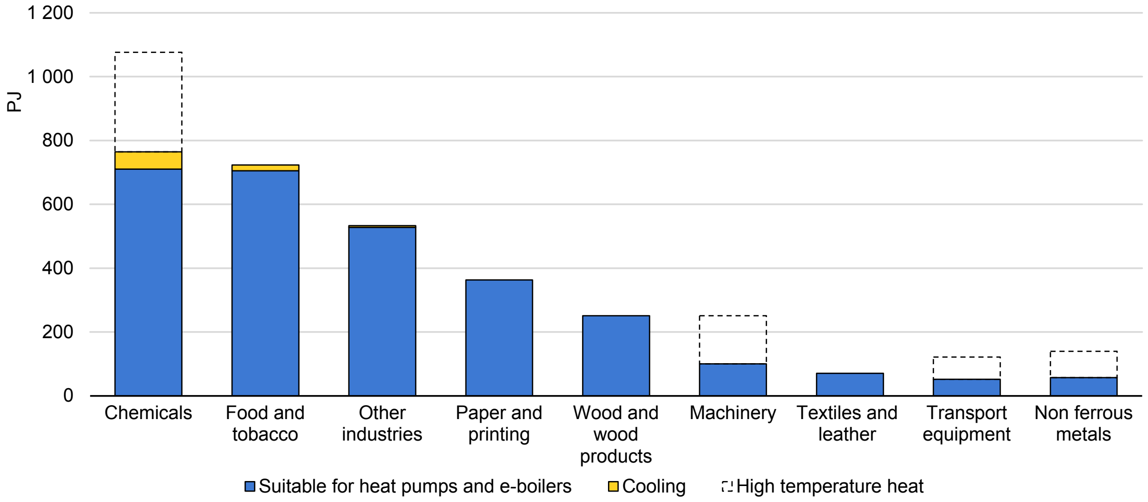
[3] Electrifying heat in the chemicals sector requires more careful consideration of heat integration and of the impacts relating to associated industrial processes.

Figure 3.3 **Technical potential for heat electrification in European industry sectors with commercially available technologies, 2023**



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Notes: PJ = petajoule; e-boilers = electric boilers. The food and tobacco category includes beverages.
Source: IEA (2025) World Energy Balances, accessed November 2025.

Electrification would thus lead to a significant reduction in the industrial use of fossil fuels. It would halve direct natural gas use for low-temperature and steam in manufacturing sectors excluding iron and steel and non-metallic minerals, equivalent to around 1 400 PJ or 35 billion cubic metres (bcm) per year, and it would reduce the consumption of other fossil fuels similarly by 1 500 PJ (approx. 60%). The reduction in demand for natural gas would have significant implications for Europe across several areas. A reduction in gas demand of 35 bcm is equal to about 8-9% of EU annual natural gas consumption, which would ease dependence on imports, lowering exposure to price volatility and supply disruptions. Moreover, reducing natural gas imports by 35 bcm would enable the European Union to further cut its remaining imports from Russia to only 15 bcm, or by 70% since the outbreak of Russia’s war on Ukraine. Imports from Russia had already fallen from 150 bcm to 50 bcm during this period. Total import volumes of natural gas into the European Union would thus fall by around 12%, reducing the annual import bill by about EUR 12-20 billion.[4]

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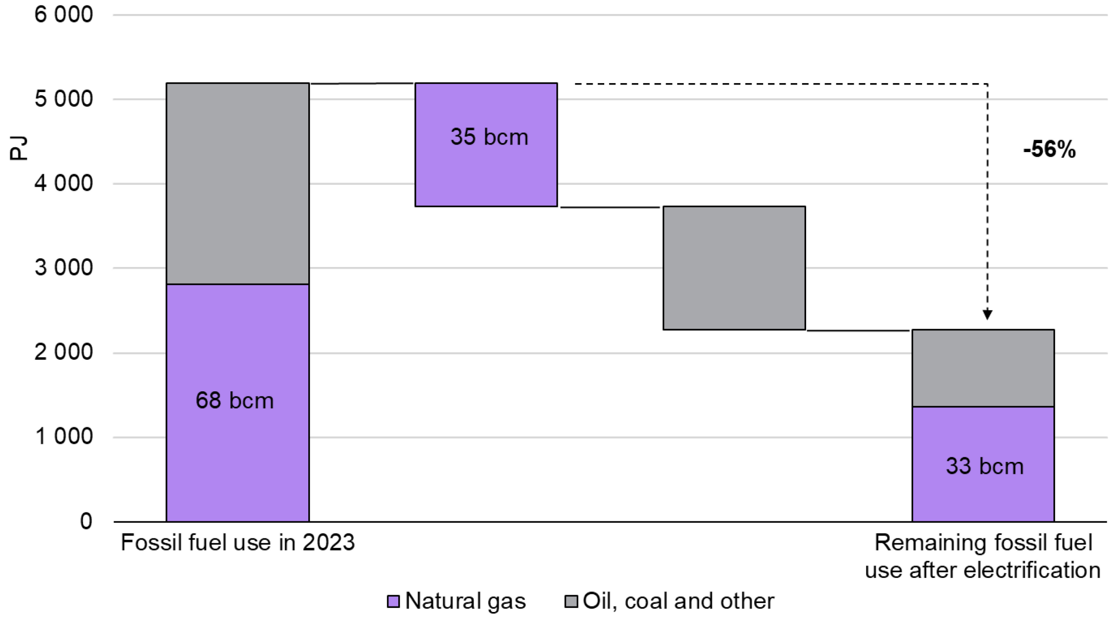
[4] Savings estimates are based on EUR 10-15/gigajoules (GJ).

Figure 3.4 **Impact on direct industrial fossil fuel demand in the European Union if the technical potential for electrifying steam and low-temperature heat was realised**



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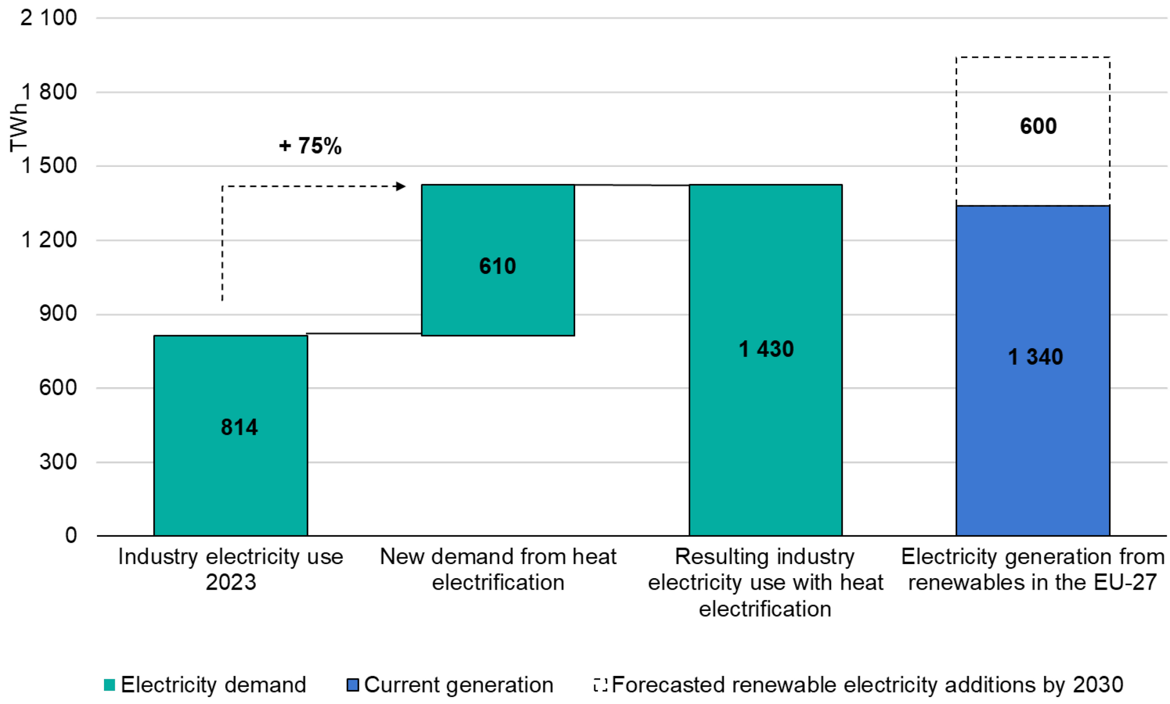
Note: PJ = petajoule; bcm = billion cubic metres.

Substituting natural gas and other fossil fuels with electricity at this scale would imply around 610-terawatt hour (TWh)/yr of additional electricity demand. This would represent 75% of current EU industrial electricity demand, which is roughly comparable to the total annual electricity consumption of Germany and the Netherlands combined. This level of electrification is also close to the projected growth (600 TWh) of EU renewable generation in 2025-2030**.** Given that the new demand would be largely met by new renewable capacity – currently the lowest-cost source of additional power generation in most parts of Europe – it could reduce total GHG emissions in the European Union by 8%, or around 190 million tonnes (Mt) CO_2 annually.

Using an additional 610 TWh of electricity to supply industrial heat in the European Union would entail new requirements on Europe's power grids. Both transmission and distribution networks would need to expand the size of connections to new locations that were formerly supplied by gas pipeline networks. Without adequate planning and investment in grid infrastructure, however, rising industrial electricity demand risks could create local bottlenecks, slow down electrification progress and increasing costs.

Figure 3.5 Impact on electricity demand in the European Union if the technical potential for electrifying steam and low-temperature heat were realised



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Box 3.1 Methodology for estimating the technical potential for electrification of low-temperature heat and steam in industry

The data used for this report on the use of industrial heat by industry subsectors and the temperature levels required in these subsectors are based on the Integrated Database of the European Energy System, assembled by the European Commission Joint Research Centre. The dataset provides detailed energy balances for all industry subsectors, including a breakdown of energy consumption, and the type of fuel used by specific processes and end uses. Fuels used as feedstock are excluded from energy consumption calculations.

Existing electricity use for heat purposes is first considered for each industrial subsector. The use of fossil fuel-based heat in the remaining processes is divided into three categories based on suitability for electrification: low temperature (suitable for heat pumps, generally below 150 °C), steam, and high temperature (indicatively >300 °C). These heat use profiles are then applied uniformly to all regions for each industrial subsector.

The impacts on reduced fossil fuel use and new demand for electricity are estimated by assuming the following average efficiencies: coal boilers 75% (lower heating value, LHV), natural gas boilers 85% (LHV), a coefficient of performance (COP) of 3 for industrial heat pumps, steam production from electricity 98% and cooling 75%.

In the case of China and ASEAN, data is lacking on the use of specific fuels in industrial unit processes. Therefore, when estimating the technical potential for electrifying low-temperature heat and steam in these regions, it was assumed that high-temperature needs are met by the combustion of natural gas, while a mix of fossil fuels – including coal – are used for processes requiring low-temperature heat and steam. All steam and low-temperature heat were generally considered suitable for electrification by electric boilers and heat pumps, whereas the electrification potential of higher temperature heat was deemed to be outside the scope of this report.

Data concerning energy use by industry associated with blast furnaces and coke ovens are excluded from the report. This approach has implications for the estimation of energy-related CO_2 emissions, since these processes represent a significant source of industrial fuel use and of carbon dioxide output.

Direct emissions (from onsite fuel consumption) are included in the calculation of the total energy-related CO_2 emissions, while indirect CO_2 emissions (from electricity and heat consumption) and process emissions are excluded.

Spatial analysis

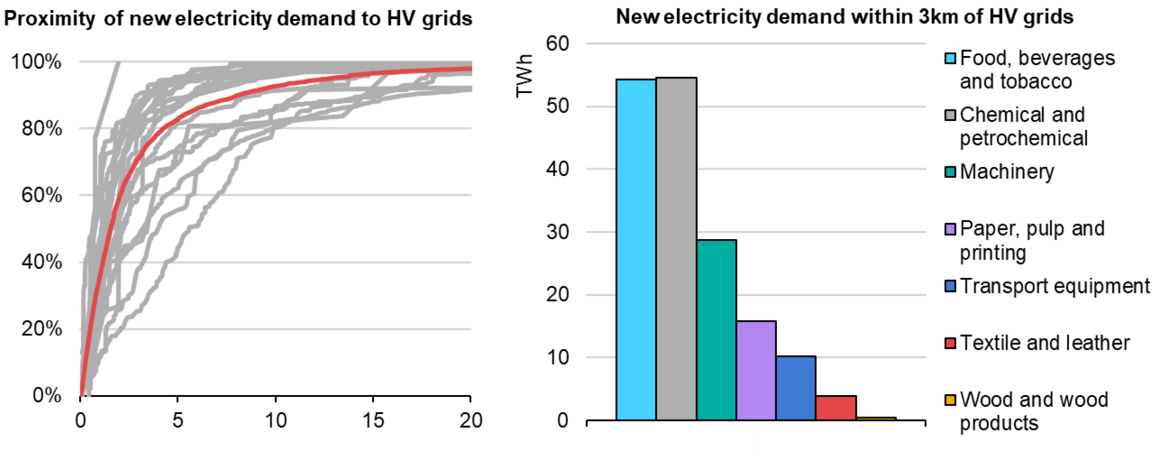
Heat electrification projects typically consist of three main components: permitting, construction and securing a grid connection. Lead times for industrial heat electrification projects vary in accordance with the geographical location and type of industrial plant. In Europe, a large-scale heat electrification project could take almost a decade to complete. While permitting can take only one to two years, and equipment delivery and installation often require a similar amount of time, the process of obtaining a grid connection is usually much longer and constitutes the main impediment for large-scale heat electrification projects in the European Union.

Historically, light industrial facilities have co-evolved alongside gas networks, with pipelines routed to meet demand, and plants often sited near available gas supply. While industrial sites are typically connected to electricity grids for lighting, ventilation and mechanical drives, these loads have been modest compared to the demand for thermal energy.

Small and medium-sized industrial consumers, with loads of up to around 5 MW, are generally connected at medium voltage levels from 10 to 20 thousand volts (kV). Larger facilities often require higher voltage connections. Very large consumers, exceeding 50-100 MW, such as steel or chemical plants, are typically connected at transmission voltages above 110 kV. The exact thresholds vary between countries and grid operators, depending on local network design and N-1 reliability requirements.

Increases in industrial electricity demand, such as through the electrification of process heat, can exceed the capacity of existing medium-voltage distribution networks. Meeting loads resulting from heat electrification may therefore require high-voltage connections to limit the current, reduce transmission losses and maintain voltage stability. It could also require the construction of a new substation or the expansion of an existing one. Costs associated with such grid reinforcements can significantly increase overall capital expenditure and reduce the financial attractiveness of a project.

Figure 3.6 **Proximity of existing natural gas demand to the high voltage grid (left) and potential new industrial electricity demand within 3 km of the high voltage grid (right)**

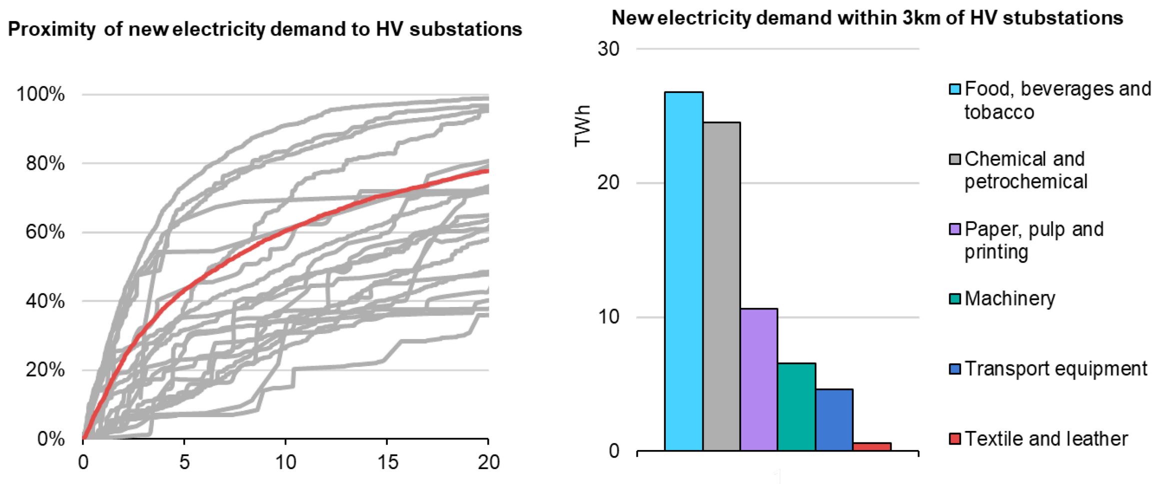


Sources: IEA analysis of industrial facilities based on data from the European Industrial Emissions Portal (2025), accessed November, 2025; industrial natural gas demand based on data from Eurostat Energy balances (2024), November, 2025; and existing grid topology based on data from Open Street Map, accessed November, 2025.

There is also the possibility that industrial sites are located in areas where the local grid infrastructure has not been designed to support large incremental loads or that the site is too far from the existing high-voltage grid infrastructure. The process of securing a grid connection can therefore be lengthy and complex. Typical approval and construction times for power lines vary greatly. Procuring a permit for, and constructing, a single extra-high-voltage overhead line (above 220 kV) could, for example, take 5 to 13 years in advanced economies, depending on the length of the line and on other factors. Additionally, transmission or distribution system operators usually perform a grid impact study to assess whether reinforcements, capacity upgrades or other infrastructure investments are required to accommodate the additional load, a process that can significantly delay project timelines.

To better understand the potential challenges, the proximity of new electricity demand arising from electrification of process heat in the target sectors was assessed for 22 EU member states[5] with respect to the existing high voltage grid (Figure 3.6) and high voltage substations (Figure 3.7). Country level results vary depending on the density of the HV grid and the size of the industrial base. On average, 70% of new demand arising from heat electrification would fall within 3 km of existing HV grids, representing around 55 TWh of annual electricity demand. Nearly all new loads would be within 20 km of an existing grid, but regional differences exist.

Figure 3.7 **Proximity of existing natural gas demand to high voltage substations (left) and potential new industrial electricity demand within 3 km of the high voltage substations (right)**



Sources: IEA analysis of industrial facilities based on data from the European Industrial Emissions Portal (2025), accessed November, 2025; industrial natural gas demand based on data from Eurostat Energy balances (2024), accessed November, 2025; and existing grid topology based on data from Open Street Map, accessed November, 2025.

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[5] Cyprus*, Greece, Malta, the Netherlands and Sweden were not included in the analysis due to data gaps.
* Note by the Republic of Türkiye The information in this document with reference to “Cyprus” relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Türkiye recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Türkiye shall preserve its position concerning the “Cyprus issue”. Note by all the European Union Member States of the OECD and the European Union The Republic of Cyprus is recognised by all members of the United Nations with the exception of Türkiye. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

When assessing the distance of new electricity demand to HV substations, on average only 30% of new demand falls within 3 km of existing HV substations. This indicates that although a large majority of new electricity demand in the examined countries is close to an existing high voltage (HV) transmission network, it is not necessarily close to an existing HV substation pointing to a need for new investments.

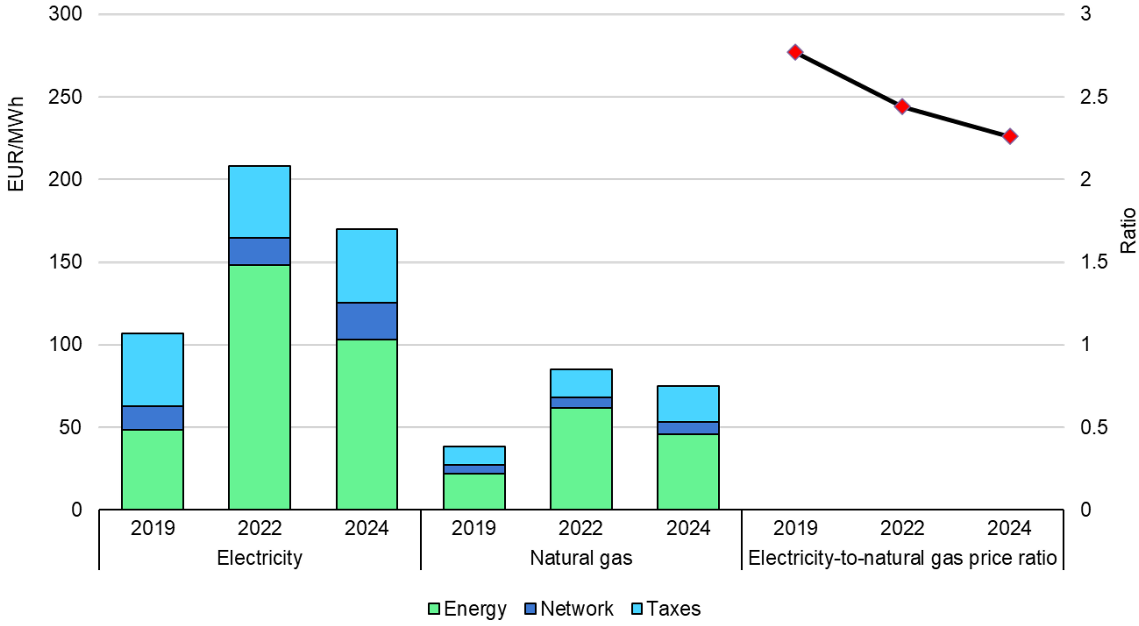
Cost analysis for focus countries

The levelised cost of heat (LCOH) is typically dominated by operating expenses, making the electricity-to-fuel price ratio the main indicator for the economic attractiveness of heat electrification. Generally, the ratio would need to be close to 1 to make electric boilers attractive as opposed to fuel-based boilers. For heat pumps – thanks to their high COP – the ratio can generally be higher. Electricity and natural gas prices for end users are composed of three main components: the energy, network charges, and taxes and levies. Policy levers to address these components are further discussed in the Market and Policy section of this chapter.

The energy component reflects the cost of purchasing electricity or natural gas on the wholesale market. In 2024, the average EU energy component for industrial consumers accounted for about 61% of the electricity price, up from 46% in 2019, with the only exceptions being Cyprus and Poland, where it decreased. For natural gas, the energy component reached 61%, up from 56% over the same period. These shares vary significantly, however, depending on the annual consumption level of industrial consumers. They also differ substantially across EU member states.

Network charges are regulated in most EU member states, and include transmission and distribution charges. For electricity, they also cover ancillary, balancing and metering service costs; while for natural gas, they include storage-related costs, system balancing, flexibility services and connection fees. The transmission-distribution split varies across EU member states and between electricity and gas systems, which reflects differences in network design, geography and the voltage or pressure levels that industrial plants require. In 2024, network charges accounted for around 13% of the electricity price for industrial consumers, slightly down from 14% in 2019, while for natural gas they averaged 9%, down from 15% over the same period. A small set of countries followed a different trend, with Finland, Germany, Spain and Sweden seeing an increase in the share of network charges; and Czechia, Estonia, Italy and Romania seeing an increase in the gas network share.

Figure 3.8 **Average electricity and natural gas retail price components and the electricity-to-gas price ratio for industrial consumers in the European Union, 2019, 2022 and 2024**



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Notes: Prices for industrial consumers are for consumption from 20 000 MWh to 69 999 MWh for electricity and for consumption from 10 000 GJ to 99 999 GJ for natural gas.

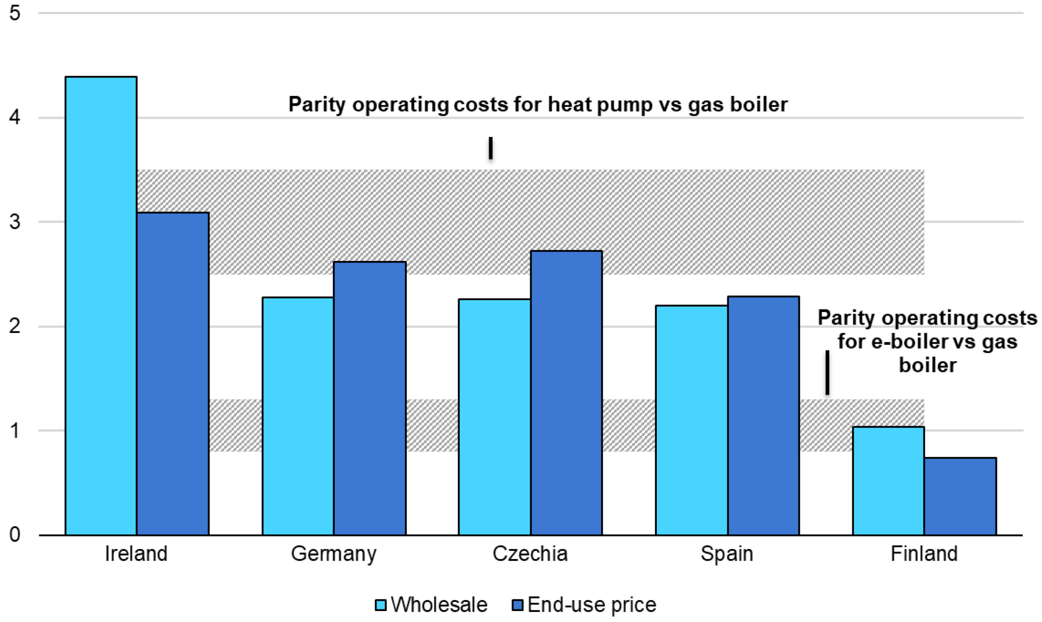
Source: IEA analysis based on electricity and natural gas prices from Eurostat, accessed December 2025.

Taxes and levies are regulated across EU member states and can vary significantly. They include renewable surcharges, excise duties, smart metering charges, and local or municipal energy taxes. The value-added tax (VAT), which is recoverable for industrial consumers, remains the largest single component, making up on average over 50% of both the electricity and gas tax components. Capacity market charges, where applied, are covered through tariffs and account for around 7% of total taxes. Only a handful of member states currently apply them, including Belgium, France, Germany, Poland, Portugal, the Slovak Republic (with the highest share at 13%) and Spain. Under the EU Energy Taxation Directive, excise duties on electricity must meet a minimum level of EUR 0.5/MWh, but EU member states retain the option to lower other electricity-related taxes to zero. In 2024, taxes and levies represented about 26% of the electricity price and 29% of the natural gas price for industrial consumers, with substantial variations across countries.

The following paragraphs present a cost analysis of industrial heat electrification in **Czechia, Finland, Germany, Ireland and Spain**. These countries represent a broad spectrum of electricity prices, carbon intensities and policy environments that demonstrate the potential pace and feasibility of industrial heat electrification across the European Union.

In 2024, the wholesale electricity-to-gas price ratio was over 3 in Ireland, representing one of the highest in Europe. If distribution costs and taxes are included, the ratio becomes less favourable for Czechia at 2.7 and for Germany at 2.6, but slightly more favourable for Ireland at 3.1. The attractiveness of electrification projects could be improved by reducing the electricity tax for industrial users from today's EUR 50/MWh in Czechia and EUR 65/MWh in Germany to EUR 0.5/MWh (the minimum EU level) as has already been done by some other member states.

Figure 3.9 **Electricity-to-gas price ratios for industrial users in selected EU member states, 2024**



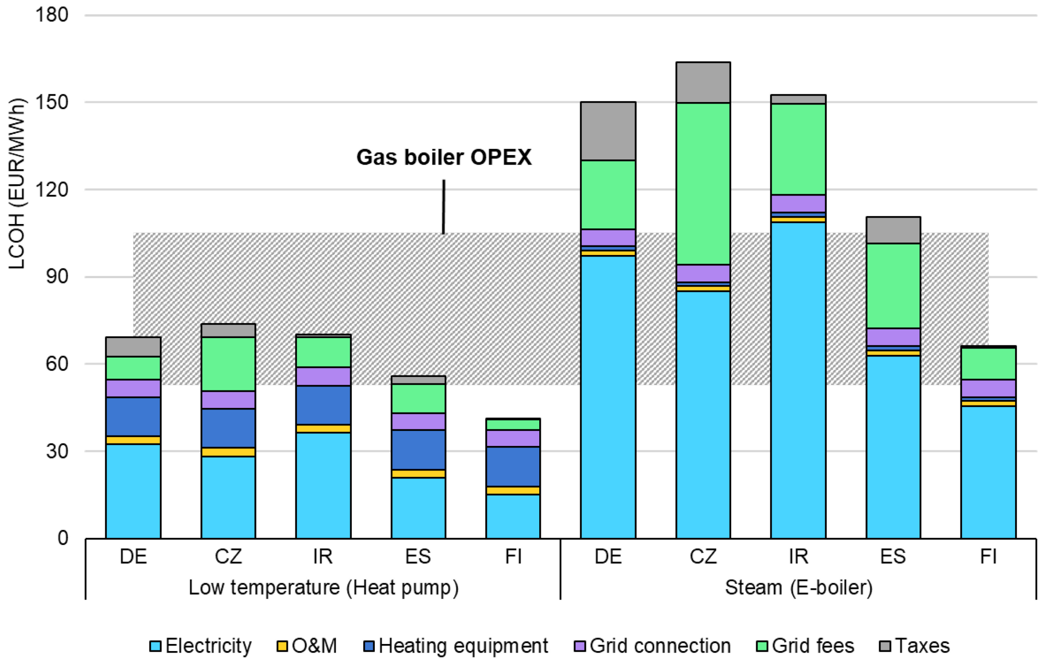
Notes: End-use price includes wholesale price, network charges and taxes and levies. Prices for industrial consumers are for consumption from 20 000 MWh to 69 999 MWh for electricity and for consumption from 10 000 GJ to 99 999 GJ for natural gas. Efficiency assumptions: gas boiler 85% (LHV), electric boiler 98%, heat pump coefficient of performance 3.

Source: IEA analysis based on data concerning electricity and natural gas prices from Eurostat, accessed November, 2025.

Detailed techno-economic analysis, based on an hourly dispatch model (Figure 3.10) indicates that grid-connected industrial heat pumps are already competitive against existing gas boilers in Finland with an LCOH of EUR 41/MWh and economically attractive in other examined EU member states. Adjusting taxation would provide strong further incentive for the installation of heat pumps in countries such as Czechia, Germany and Spain, where the LCOH range of heat pumps is EUR 56-74/MWh.

Although electric boilers are cheaper to install than heat pumps, their investment cost advantage is offset by lower efficiency and the consequent higher running costs. While steam can also be delivered through heat pumps, their COP is reduced because of the higher temperature lift. Among the EU member states examined, the cost of steam generation with an electric boiler was found to be attractive in Finland, where the LCOH of EUR 66/MWh falls within the rage of a gas boiler operating cost. With an LCOH of EUR 110-164/MWh, electric boilers are a significantly more expensive alternative in the other member states examined.

Figure 3.10 Levelised cost of heat from electricity, based on an hourly dispatch model, and from natural gas in selected EU member states, 2024



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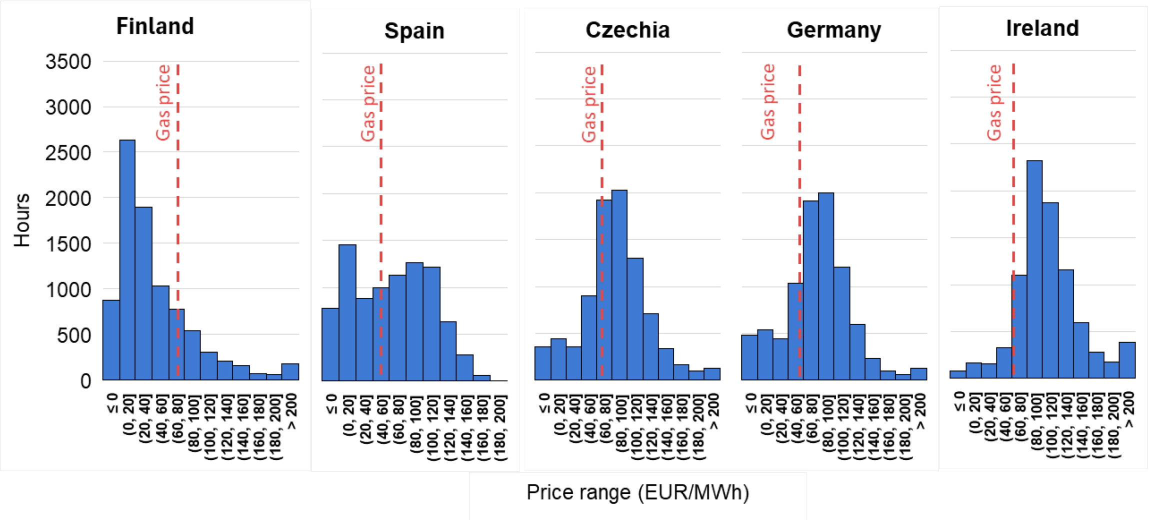
Notes: Competitiveness is compared against an existing gas boiler. The attractiveness of the electric heating system improves towards the end of the service life of the existing boiler, when investment in a new heating system becomes timely. Estimates are made on the basis of the following assumptions: process heat demand 3 MW, heat pump investment cost EUR 1 500/kW, electric boiler EUR150/kW$_{th}$, heat pump coefficient of performance 3, gas boiler efficiency 85% (LHV) and storage loss per hour 0.08%. Initial grid connection costs for the EU member states studied were: Czechia EUR 2 million, Finland EUR 2 million, Germany EUR 2 million, Ireland EUR 2.1 million and Spain EUR 2 million, with an annual capacity grid fee of: Finland EUR 12 000/MWh, Germany EUR 165 210/MW, Ireland EUR 1 902/MW; an annual consumption grid fee of: Czechia EUR 56/MWh, Finland EUR 9/MWh, Germany EUR 5/MWh, Ireland EUR 31/MWh and Spain EUR 29/MWh. Annual O&M costs of the electric boiler, heat pump and storage 5% of initial investment cost. Annual O&M costs for the gas boiler EUR 2.8/MWh of heat output. WACC 5% system lifetime 20 years. Electricity and gas prices are average annual prices (electricity consumption band IE and gas consumption band I3).

Source: Hourly dispatch model based on grid price data from Eurostat, accessed November, 2025.

Annual average electricity prices provide only a partial view of the underlying dynamics. Hourly price variability tends to grow with increasing shares of variable renewables in the power market, leading to an increasing number of hours when electricity is cheaper to use than natural gas. Among all of the EU member states examined, with the exception of Ireland, the cheapest 1 000 hours of electricity in a year were below the average natural gas price in 2024, although with significant variation from one member states to another. In Finland, for example, electricity was cheaper than natural gas for 6 000 hours in 2024.

Figure 3.11 Distribution of hourly electricity spot prices, and annual average natural gas prices for industrial consumers in selected EU member states, 2024



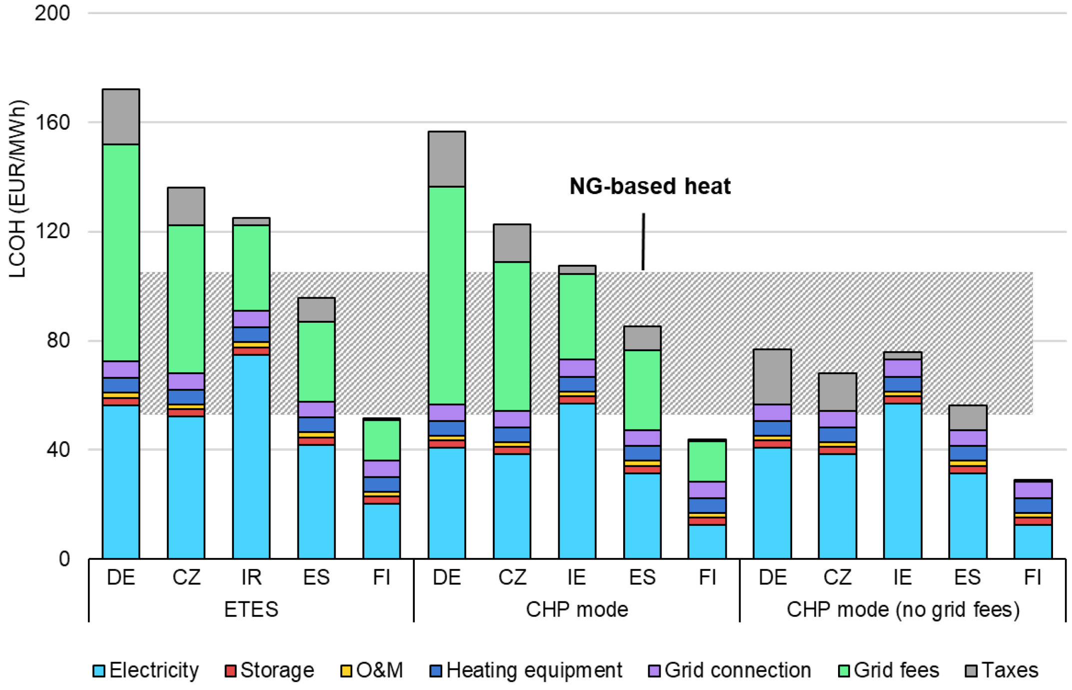
Notes: Natural gas prices exclude taxes and levies; electricity prices are spot market prices.
Sources: IEA analysis based on data from ENTSOE, accessed May, 2025 and Eurostat, accessed May, 2025.

An electric heating system can take advantage of price fluctuations when integrated with thermal storage. An **electro-thermal energy storage (ETES)** system allows to deliver continuous steam supply while avoiding electricity use during peak price periods, thereby reducing energy costs. In all examined EU member states except for Germany, ETES systems produced steam at a lower cost than electric boilers. Proper optimisation of the storage size depends on the pricing structure of grid connections and network fees, considered individually in Figure 3.12. Compared with an electric boiler, an ETES system requires a significantly larger electricity connection to enable rapid charging of storage during the lowest priced hours of the day. If connection and grid charges are sensitive to electric load, as is the case in Germany, adding thermal storage can substantially increase fixed costs, offsetting savings from lower electricity prices.

An ETES system can also be operated in **combined heat and power (CHP)** mode, co-producing electricity and steam. When the heat is stored at a sufficiently high temperature, it enables the production of superheated steam with high enough parameters (temperature and pressure) for electricity generation. The steam is first expanded in a turbine to generate electricity, after which steam is extracted at a lower temperature and pressure to meet process heat demands. In this case, the production of electricity is not individually optimised, but rather is a continuous co-product of heat.

Compared with the steam-only mode, CHP configuration lowers the levelised cost of heat (LCOH) in all examined EU member states. The reduction in LCOH is about 15% for Finland and Ireland, about 10% for Czechia, Germany and Spain. Despite these reductions, electrically produced steam remains significantly more expensive than steam from gas boilers in Czechia, Germany and Ireland. In Spain, CHP mode can decrease costs within the range of the natural gas-based alternative, while in Finland the CHP mode makes electrically produced steam competitive even at the lower end of natural gas prices.

Figure 3.12 Levelised cost of heat for an ETES system, based on an hourly dispatch model, under varying assumptions in selected EU member states, 2024



Notes: CHP = combined heat and power; O&M = operation and maintenance. Estimates are made on the basis of the following assumptions: process heat demand 3 megawatt (MW), gas boiler efficiency 85% (LHV), electrical efficiency of a co-generation turbine 17%, storage losses per hour 0.08%, maximum storage charge rate 9 MW. Capital costs are: heating equipment: EUR150/kW$_{th}$, storage EUR 15/kWh, cogeneration: EUR 900/kW$_{th}$, grid connection USD 1 000 000 per MW, operations and maintenance USD 2/MWh (heating equipment). Initial grid connection costs were: Czechia: EUR 2 million, Finland: EUR 2 million, Germany: EUR 2 million, and Spain EUR 2 million. O&M for gas boiler EUR 2.8/MWh, weighted average cost of capital 5%, economic life 20 years. Electricity and gas prices are average annual prices (electricity consumption band IE and gas consumption band I3).

Source: Electricity and gas prices based on data from Eurostat, accessed November, 2025.

In addition to generating electricity for industrial self-consumption, a CHP configuration could also sell electricity back to the grid, and in some cases could provide similar services than stationary battery energy storage systems or hydrogen storage systems based on electrolysers and fuels cells.

To avoid double charging network tariffs (i.e. paying for both the charging and the subsequent injection into the grid), several countries have introduced exemptions or partial waivers for battery energy storage systems. National implementation in the European Union varies, with some countries exempting storage input provided that stored energy is later exported, while others apply tariffs only on net consumption.

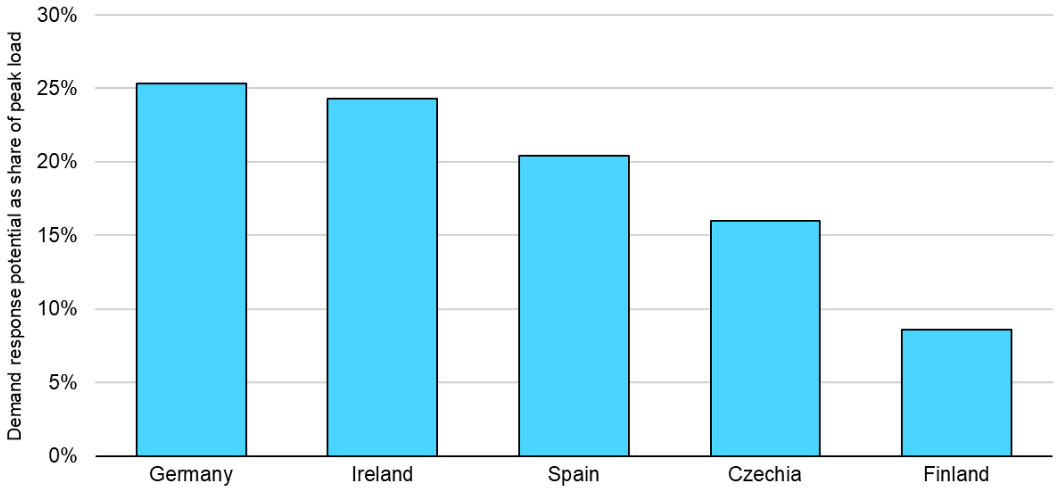
Like battery energy storage systems, hydrogen electrolysers can, in principle, provide grid services that include frequency regulation, demand response and congestion management. They do so by adjusting their electricity consumption in real time. Some member states are beginning to recognise the value that electrolysers can offer and are exploring differentiated tariff frameworks. For example, Germany's Energy Industry Act allows for reduced network charges for "controlled electrolyser" projects that provide system services, while France and Spain have included in draft hydrogen strategies the possibility of partial exemptions or reduced tariffs for electrolysers providing balancing or congestion relief.

If ETES systems were similarly recognised for their flexibility services and exempted from grid fees, their economic attractiveness would increase significantly. Among all the examined member states, the LCOH decreases markedly when grid fees are eliminated. The impact of such exemptions is particularly strong in Germany and Czechia, where the LCOH falls by 51% and 45%, respectively, as grid fees represent a major share of total costs. In Finland, eliminating grid fees makes the CHP mode more economically attractive than gas-based heat. In Spain, costs decrease close to the lower end of the natural gas-based alternative, while for the remaining countries, removing grid fees brings LCOH within the range of natural gas-based heat.

Contribution to system flexibility

One of the benefits accompanying the electrification of industrial heat is the potential to provide demand-side flexibility services for the electricity grid. Although the primary motivation for ETES systems is to minimise electricity costs, avoiding the use of electricity during peak price periods also supports system stability by reducing demand during congestion and critical periods. A canned food factory in Finland that uses a 10 MW ETES system to decarbonise steam production for food processing, serves as an example. The factory can flexibly adjust charging and discharging in accordance with the grid operator, enabling it to take part in demand-response programmes and to generate additional revenue.

Figure 3.13 Technical potential to provide electricity demand flexibility via industrial electro-thermal energy storage as a share of peak demand in selected EU member states, 2024



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Notes: The assumption is that the entire technical potential for electrifying low-temperature heat and steam demand in the EU industry sector would be implemented and supported by an electro-thermal energy storage system.

Already today, electrically driven industrial batch processes like crushing and milling are increasingly scheduled to run during periods of low electricity prices. However, thermal storage has the potential to make industrial consumers more flexible users of electricity. If the technical electrification potential of low-temperature heat and steam would be fully integrated with thermal storage, the resulting increase in demand flexibility would be considerable. For example, the size of the demand response opportunity for Germany would represent up to 25% of its peak load in 2024. This potential would be similar for Ireland and be around 8%-11% for the rest of the countries examined.

Market and policy

Both EU-level and national policy frameworks are increasingly converging to drive industrial electrification through a coordinated mix of regulatory, fiscal and market instruments. By reducing industry’s reliance on fossil fuel imports and promoting renewable energy use, these measures aim to create a framework that supports investment in low-emission technologies. On the demand side, industrial policies that include efficiency and emissions standards, along with dedicated support schemes, are encouraging the uptake of electric boilers, heat pumps and other electrification solutions. On the supply side, renewable energy targets, carbon pricing and market integration reforms are resulting in an expansion of the supply of renewable electricity to meet new demand.

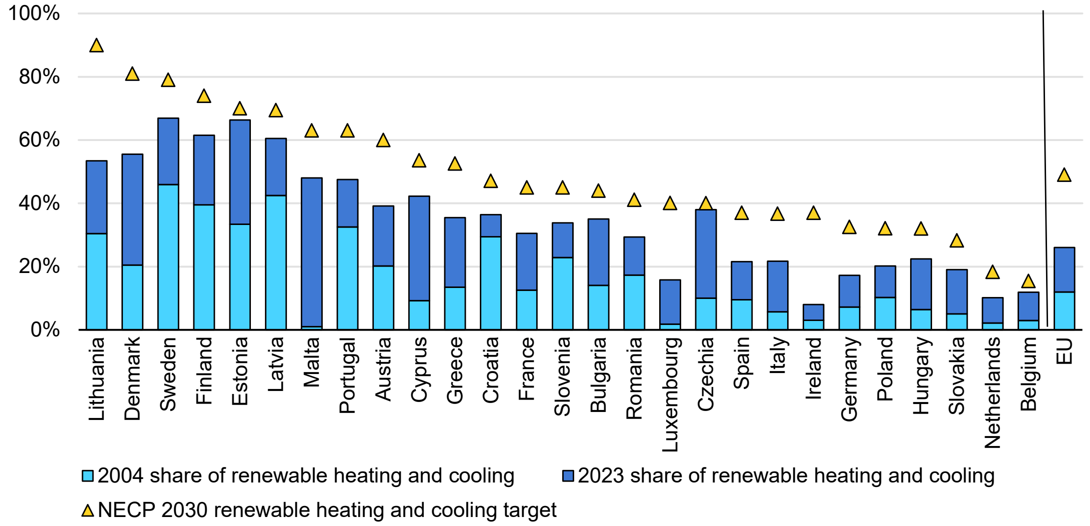
Policies and targets: following indicative annual increases of 0.8 percentage points between 2021 and 2025, in 2026 the EU Renewable Energy Directive set mandatory annual increases of 1.1 percentage points in renewable heat and cooling for member states, with a higher, though indicative, target of 1.6 percentage points for industry. Compliance with mandatory targets is monitored by the European Commission through national reporting, and persistent underperformance can trigger infringement procedures under EU law. The EU Clean Industrial Deal (February 2025) further strengthens the above directive through an economy-wide electrification target of 32%, while a proposed amendment to the European Climate Law, which includes an industrial electrification benchmark of 48% by 2040 and 62% by 2050, is designed to help reach 2040 carbon emissions reduction targets. These initiatives reflect the level of political and industrial consensus around the electrification of industrial processes, particularly for low-temperature heat and steam processes.

Complementary EU initiatives reinforce these ambitions. The Action Plan for Affordable Energy for All Europeans includes a range of policy reforms to promote price stability, investment mobilisation, grid reinforcements and demand-side flexibility. These policy reforms will be followed by an EU Electrification Action Plan and a new Heating and Cooling Strategy, both of which are to be released in early 2026, and are expected to translate high-level targets into operational measures.

The revised Industrial and Livestock Rearing Emissions Directive (IED 2.0) covers more than 37 000 industrial installations and strengthens pollution control requirements through binding “best available techniques”. It also requires that large plants prepare transformation plans for decarbonisation and resource efficiency. In addition, it mandates streamlined, digital permitting across all member states by 2035 and introduces binding energy-efficiency parameters within those operating permits.

At the national level, the National Energy and Climate Plans (NECPs) for 2021-2030 require member states to define specific targets and measures for renewable heating and cooling in line with the obligations set by the EU legislation. These 2024 plans vary in their ambitions, with frontrunners (Estonia, Latvia, Sweden) already exceeding 60% renewable heating and cooling shares, while others (Ireland, Germany, Luxembourg) are planning a substantial scale-up. From October 2025, the requirements for local heating plans, which map demand, renewable potential and waste-heat opportunities, introduce a more spatially integrated approach to energy planning. Integrating these plans into NECPs can help better align national and local planning.

Figure 3.14 **Share of renewables in heating and cooling for EU member states, 2004 and 2023; and 2030 targets of National Energy and Climate Plans**



Notes: NECP = National Energy and Climate Plans (EU). Austria has set a legislative target. Targets based on WEM (with existing measures) are used by Denmark, Estonia, Finland, France, Germany and the Netherlands. The remaining countries' targets are based on WAM (with additional measures).

Sources: IEA analysis based on data from Eurostat, accessed [3 December 2025]; and EU National Energy and Climate Plans, accessed [3 December 2025].

Financial support and competitive electricity prices are key enablers for industrial heat electrification. At the EU level, relaxed state aid rules and the EUR 100 billion Innovation Fund to be overseen by Industrial Decarbonisation Bank will help reduce investment risks through grants, tax advantages and loan guarantees. The first EUR 1 billion auction for industrial process heat decarbonisation, launched in December 2025, targets industrial processes from 100 °C to above 400 °C to support electrification, geothermal and solar thermal solutions, as well as waste-heat recovery. Its design includes storage, demand side response and other flexibility solutions to be priced into bids and allow higher support levels. At the national level, initiatives such as the Netherlands' SDE++ scheme, Germany's Carbon Contracts for Difference, or France's PACTE Industrie and France 2030 complement EU measures with targeted grants, contracts for difference, debt financing and tax incentives to accelerate the deployment of industrial heat electrification projects.

In 2024, industrial electricity prices declined from their record 2023 levels, with the EU average at around USD 260/MWh. They nevertheless remain roughly 1.5 times higher than in 2019, which continues to weigh heavily on production levels and industrial competitiveness. Policy makers are increasingly recognising the pressure that elevated industrial electricity prices place on industry and have begun addressing them through three levers: the energy component, network charges, and taxes and levies.

As low-cost renewables expand, supported by EU market reform that combines spot pricing with long-term contracts such as power purchase agreements and carbon contracts for difference, the cost for the energy component – today accounting for over half of industrial electricity bills – is expected to fall. This dual-market approach not only reinforces merit order effects but also improves price predictability for industrial consumers. Spain stands out as a leading example with renewables making up a growing share of electricity generation. In 2024, its wholesale electricity prices averaged around USD 70/MWh, placing it among the lowest in the European Union (outperformed only by Nordic countries), and its industry benefited from electricity costs nearly 21% below the EU average.

Network charges, representing about 20% of electricity bills in industry, have become a key policy focus. The European Commission's July 2025 Communication calls for cost-reflective pricing based on peak demand, flexibility and grid location to incentivise grid-friendly behaviour, optimise grid infrastructure use and reduce long-term grid expansion costs. Industrial consumers are increasingly exposed to dynamic, time-based, and capacity-based tariffs, as well as incentives for flexible connections and energy storage (mostly batteries). Denmark, the Netherlands, Norway and Sweden have pioneered schemes to reward flexibility and lower charges. Early lessons from Sweden have revealed some challenges, with several pilot initiatives showing that even well-intentioned designs may create unintended disincentives and suboptimal outcomes, such as limited profitability, high technical or administrative costs or short-term contracts. Germany has taken measures to begin cutting network charges in 2026 through subsidies to four transmission operators and through regulatory reforms that integrate storage and batteries. Such measures will also allow for the implementation of dynamic, time-based and capacity-based tariffs, along with a redistribution of grid costs more evenly between electricity producers and consumers. The impact on wholesale electricity prices remains uncertain and will depend on the extent of implementation and on market response.

Electro-thermal energy storage (ETES) can enhance grid integration by shifting heat production to off-peak hours, thus easing grid congestion. Some countries waive network charges for electrochemical batteries. ETES systems generally do not benefit from similar treatment. Adopting a technology-neutral approach would allow for the diversification of grid services. Practical experiences in Denmark, Finland and Germany show that integrating ETES into district heating can absorb excess renewable power, reduce curtailment, stabilise the grid and lower fossil-based back-up needs. For non-energy-intensive industries, some regional suppliers in Germany are piloting time-based network charges that include flexibility benefits from ETES systems, which result in cost savings.

Electricity taxation and levies for industry are shifting from bill-based levies to general budget financing, enabling targeted support for industrial electrification without distorting electricity prices for other consumers. In practice, only a few countries have applied such measures. Finland provides reduced electricity tax rates for industrial users, while Ireland links tax relief to the share of renewable electricity consumed by industrial users. In 2022, Germany removed its renewable energy levy from the electricity price (which is mostly a legacy of the past repaying expensive feed-in-tariff for early stage solar PV). Under its electricity price package for manufacturing companies, Germany also extended temporary measures to reduce electricity taxes for the manufacturing sector to the EU minimum in an effort to strengthen industrial competitiveness beyond 2025. These measures are currently pending European Commission approval under state-aid rules. At the EU level, the EU Energy Tax Directive revision seeks to align energy taxation with carbon content, creating renewable incentives across the European Union, although no binding agreement exists to date.

Electricity market and grid access conditions remain key barriers to the pace and costs of industrial electrification. Some of the more persistent barriers include particularly lengthy grid connection queues and complex permitting processes, which continue to limit investment and deployment. To address these barriers, the European Union and its member states are moving towards more flexible and technology-neutral approaches to grid management. The recommendations of the EU Agency for the Cooperation of Energy Regulators on the high-voltage direct current network code (December 2024) propose to shorten connecting procedures for demand-side projects. A newly proposed European Grids Package and Energy Highway initiative (December 2025) aim to strengthen demand-side integration by streamlining connection and permitting processes, enable grid investments for industrial electrification and promote demand-side flexibility as a key resource for ten-year network development plans. Other emerging, novel approaches at the national level include Italy’s digitalisation of project permitting and the Netherlands' use of flexible connection contracts to allow large electricity users and generators to obtain grid access more quickly by accepting limits on operation during peak hours.

Technology and enabling platforms: The important role of heat electrification technologies such as industrial heat pumps, electric boilers and thermal storage systems, as well as the value of further developing these technologies, has been recognised through financial and policy backing. Examples of such financial and policy backing include Horizon Europe, LIFE-Clean Energy Transition, the Innovation Fund, the European Innovation Centre for Industrial Transformation and Emissions and the Strategic Energy Technology Plan. Financial schemes are also supporting the integration of renewable and waste-heat sources, which permits platforms such as the Heat Pump Accelerator Platform to further complement the above efforts by fostering technology deployment, workforce skills, supply chain capacities and grid integration for the effective electrification of industrial heat.

Table 3.1 Examples of recent policy developments relating to the electrification of industrial low-temperature heat and steam

Policy area	Date	Development
Policies and targets	**European Union**	
	September 2023	The Energy Efficiency Directive sets a binding target for EU member states to reduce final energy consumption by 11.7% by 2030 (compared with 2020), supported by annual energy savings targets of 1.3% (2024-2025), 1.5% (2026-2027) and 1.9% (2028-2030).
	October 2023	The Renewable Energy Directive sets a binding target for EU member states for renewable heating and cooling (as of 2026) at 1.1 percentage points annually, alongside indicative targets for industry at 1.6 percentage points.
	August 2024	The Industrial and Livestock Rearing Emissions Directive (IED 2.0) tightens pollution control requirements through binding “best available techniques” and obliges large installations to prepare transformation plans for decarbonisation and resource efficiency. It also requires streamlined and digital permitting in all EU member states by 2035 and introduces binding energy-efficiency parameters in permits.
	February 2025	The Clean Industrial Deal introduces a 32% cross-economy electrification target for 2030.
	February 2025	The Action Plan for Affordable Energy for All Europeans aims to stabilise prices, expand clean power supply, strengthen grids, foster flexibility and mobilise investment.
	July 2025	The proposal for an amendment to the European Climate Law sets an industrial electrification target of 48% by 2040 and of 62% by 2050.
	Q1/2026	The Electrification Action Plan and Heating and Cooling Strategy are currently undergoing public consultation.
Financial support	**European Union**	
	June 2025	The Clean Industrial Deal State Aid Framework expanded eligible categories for aid, including renewable heating and cooling in industry, through grants, tax incentives and de-risking mechanisms.
	December 2025	The Innovation Fund’s first EUR 1-billion heat auction for industrial process heat decarbonisation was launched in December 2025.
	Q4/2025	The European Commission established recommendations on tax incentives to lower capital costs for industrial decarbonisation (including electrification and clean heat) through accelerated depreciation, targeted tax credits and predictable, state-aid-aligned incentives to improve investment certainty.

Policy area	Date	Development
	Member states	
	2024	Approved state aid dedicated to industrial decarbonisation, including initiatives in Austria, Finland, France, Germany and the Netherlands, have taken the form of direct grants or investment grants and carbon contracts for difference.
	Since December 2020	The Netherlands’ SDE++ scheme on low-carbon heat is supporting the deployment of industrial heat pumps and electric boilers.
	Since June 2023	Germany’s carbon contracts for difference provide support by covering the additional costs of switching to low-carbon production processes, including electrification.
	Since 2018	France’s PACTE Industrie and France 2030 programmes provide industrial consumers with investment and operation support, as well as training.
Electricity market and competitive prices	**European Union**	
	Since July 2021	The EU Energy Tax Directive revision aims to align energy taxes with carbon content, providing incentive for the use of renewables and renewable electricity.
	May 2024	Electricity market design reform has introduced improved access to power purchase agreements.
	December 2024	The EU Agency for the Cooperation of Energy Regulators recommended that the high-voltage direct current network code be amended to facilitate grid connection for industrial consumers.
	October 2025	The Energy Efficiency Directive requires member states to develop local heating plans as of October 2025 and promotes cascade heating in district heating (including waste heat recovery from industrial processes).
	July 2025	The EU Communication on network charges addresses peak demand, flexibility and grid location, allowing industrial consumers that shift consumption to off-peak times, use energy flexibly or optimise location-based usage can reduce their grid charges.
	December 2025	The proposed European Grids Package aims to strengthen demand-side integration by streamlining connection and permitting processes, enabling anticipatory grid investments for industrial electrification and promoting demand-side flexibility as a key resource for ten-year network development plans.
	Member states	
	November 2024	The Netherlands’ Authority for Consumers and Markets initiated a broad set of measures to unlock unused grid capacity, introducing flexible grid connection contracts that allow flexible loads to have priority access.
	December 2024	Italy is simplifying and digitalising grid connections and decentralising project approvals to speed up electricity access for industry.
	May 2025	Germany’s government adopted more cost-reflective electricity network charges and stronger price signals for flexibility, and has proposed reducing the electricity tax.

Policy area	Date	Development
	European Union	
Technology and enabling platforms	Since April 2023	The Heat Pump Accelerator Platform promotes the accelerated roll-out of heat pumps in buildings, industry and district heating, providing information on industrial heat pumps, grid integration, skills and supply chains, and financing aspects.
	2020-2027	Horizon Europe Cluster 5 (on climate, energy and mobility) and Cluster 4 (on digital, industry and space) focus on innovating and demonstrating industrial heat technologies.
	2020-2027	The LIFE-Clean Energy Transition sub-programme has several calls for proposals concerning industry and skills.
	Since 2007	The Strategic Energy Technology Plan promotes activities relating to energy efficiency in industry, which include electrification of industrial heat. The European Technology and Innovation Platform focuses on renewable heating and cooling, including in industry.
	Since 2024	The European Innovation Centre for Industrial Transformation and Emissions identifies, assesses and promotes mature and cost-effective innovations to support industrial decarbonisation and transformation under the Industrial and Livestock Rearing Emissions Directive (IED 2.0).

Chapter 4. Regional insights: China and selected provinces

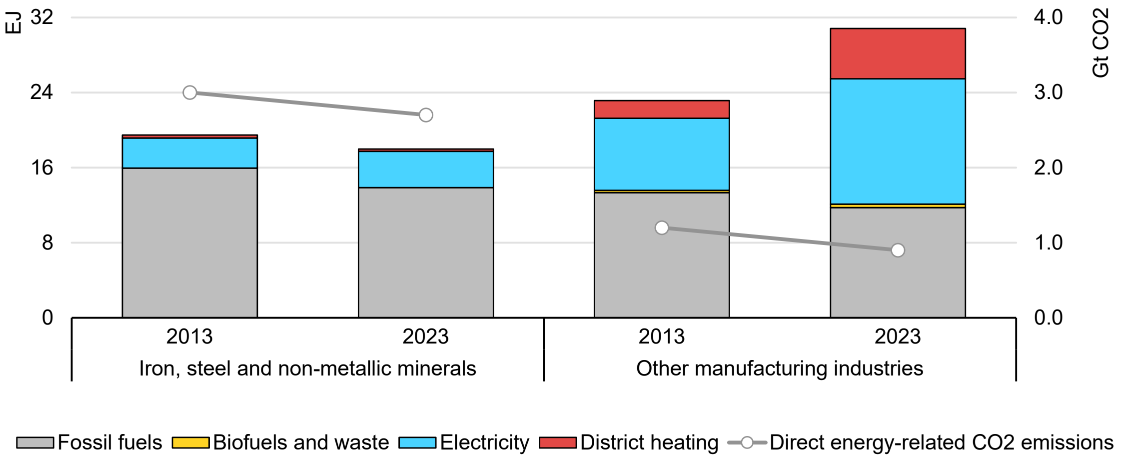
State of play

China's industrial sector contributes 37% to the country's total GDP and is responsible for about one-third of total employment, reflecting its central role in the economy. China is the world's largest exporter of manufactured goods and services, with merchandise exports reaching around USD 3.6 trillion in 2024, capturing roughly 15% of global goods export value.

Between 2013 and 2023, industry accounted for nearly half of China's final energy consumption and just over 30% of direct energy-related CO_2 emissions, a share that rose to more than 60% when including indirect energy-related CO_2 emissions resulting from electricity and heat use. Over this same period, direct industrial energy-related CO_2 emissions increased by almost 0.04 Gt (Figure 4.1).

Subsector trends revealed stark contrasts. In the iron, steel and non-metallic mineral industries, energy use fell by roughly 8%, while direct emissions declined by only 2%, indicating limited improvements in carbon intensity and underlining the continued reliance on fossil fuels. In other industries, energy consumption surged by about 33%, yet direct energy emissions fell by 27%, suggesting a dramatic reduction in carbon intensity, likely driven by fuel switching, electrification and the adoption of low-emission production technologies. However, this apparent decoupling of energy use and direct emissions is partly misleading. The doubling of energy-related CO_2 emissions in these industries, contributing nearly 1 Gt of total industrial emissions, demonstrates that much of the additional electricity emanates largely from China's coal-based grid, limiting the overall greenhouse gas emission savings from electrification. Indirect emissions from the iron, steel and non-metallic minerals sectors remained broadly stable, consistent with their smaller energy consumption changes. Reducing industrial CO_2 emissions will thus be essential to meet China's ambitious dual carbon targets – to peak carbon emissions by 2030 and to achieve carbon neutrality by 2060.

Figure 4.1 Final energy consumption in industry and CO_2 emissions in China, 2013 and 2023



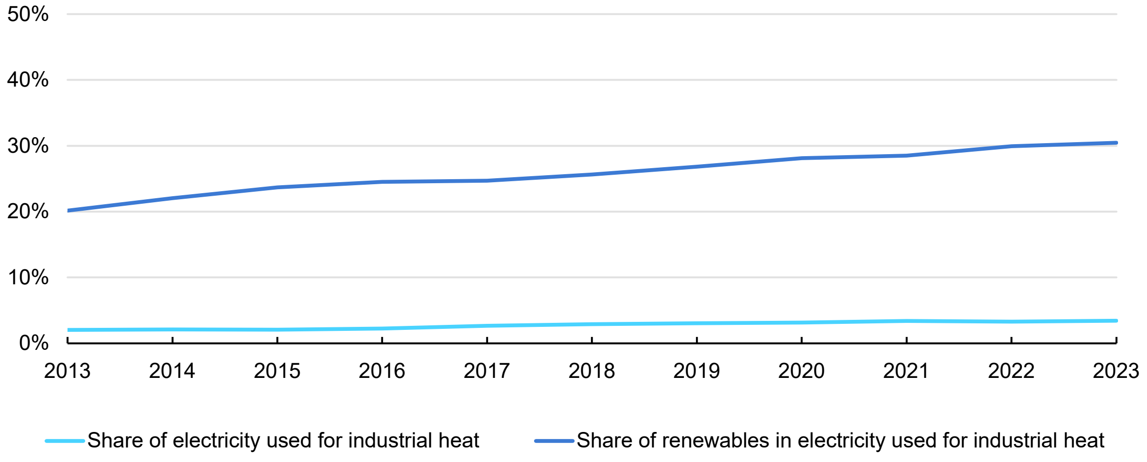
IEA. CC BY 4.0.

Notes: EJ = Exajoule; Gt CO_2 = gigatonne of carbon dioxide. Non-metallic minerals include cement, glass, ceramics and clay. Iron and steel energy consumption excludes energy use in blast furnaces and coke ovens. Other industries include mining and quarrying, construction, manufacturing, chemicals and petrochemicals, non-ferrous metals, transport equipment, machinery, food, beverages and tobacco, pulp, paper, and printing, wood and wood products, textile and leather and non-energy use in chemicals. The figure excludes emissions relating to blast furnaces and coke ovens, process emissions and indirect energy-related CO_2 emissions resulting from electricity and heat use.

China's 2023 industrial energy use was approximately 48 000 PJ, still largely supplied by the combustion of fossil fuels, and more specifically domestic coal. Electricity accounted for 34% of total industrial energy consumption. Five sectors: chemicals and petrochemicals; iron and steel; machinery; non-ferrous metals (such as aluminium or copper); and non-metallic minerals (such as cement, glass or clay) consume over three-quarters of all industrial electricity. High industrial energy consumption in these sectors results from their core production processes and auxiliary systems being inherently electricity-intensive, with electricity often serving as the primary energy input for melting, electrochemical refining, grinding and motor-driven operations.

Electricity used for heat represented only 3% of all industrial heat use in China, a share that remained largely stable over the past decade, reflecting structural and economic barriers to the electrification of industrial heat, including the continued availability of cheap coal. Despite the slow growth of electrified heat, the carbon intensity of electricity used for heat has fallen sharply, with the share of renewables rising from 20% in 2013 to 30% in 2023 (Figure 4.2).

Figure 4.2 **Share of electricity and of renewable electricity used for industrial heat in China, 2013-2023**



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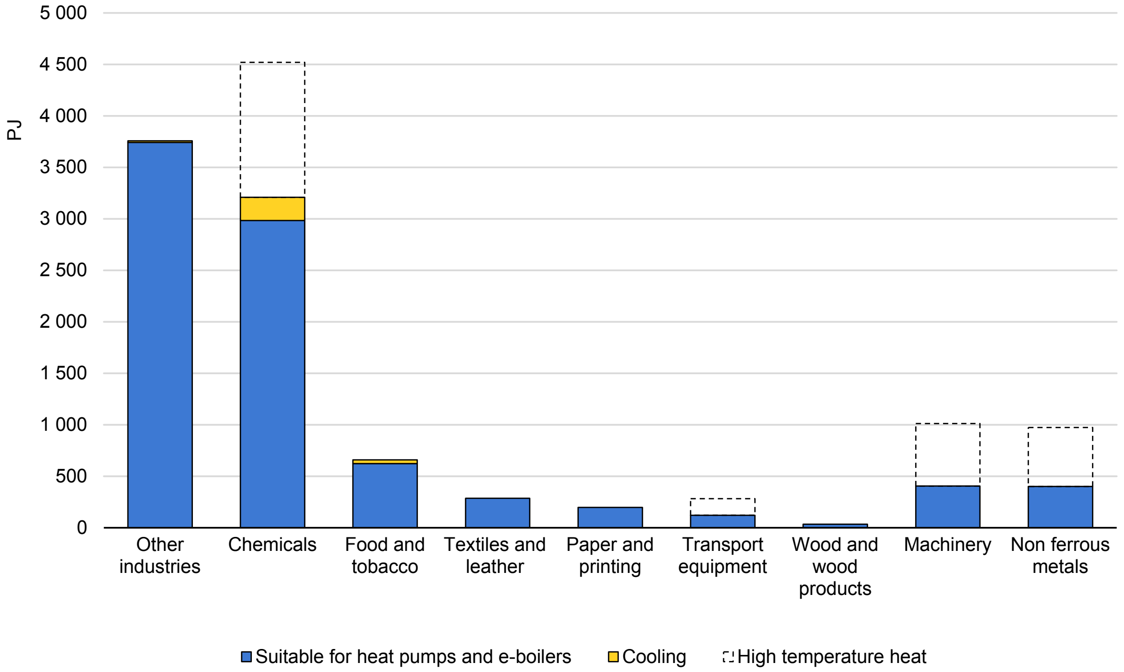
Technical electrification potential

The technical potential to shift industrial heat production away from fossil fuels and towards electrification in China is substantial. Complete to near-complete electrification of the heat supply with heat pumps and electric boilers could be technically achieved in five sectors (food and beverages, textile, paper and printing, wood and wood products, and other industries), representing a 4 900 PJ reduction potential in fossil fuel use. In addition, almost three quarters of heat demand (3 200 PJ) in the chemical sector could be technically electrified with commercial technologies, and approx. 920 PJ (40%) for machinery, transport equipment and non-ferrous metals. The combined reduction potential for all these sectors is 9 000 PJ, or 35% of total China industry fossil fuel use for heat (see Box 3.1 for an explanation of the methodology). In the remaining sectors, higher temperature requirements are likely to slow progress in electrification.

Figure 4.3 **Technical potential for heat electrification in Chinese industry sectors using commercially available technologies, 2023**



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Notes: e-boilers = electric boilers; PJ = petajoule. The Food and tobacco category includes beverages.
Source: IEA (2025), World Energy Balances, accessed November 2025.

Currently, total fossil fuel use in Chinese industry is 25 500 PJ, of which 22% is natural gas, while the remainder is mostly coal and oil. Direct natural gas use could be cut by 48 bcm per year (by 36%), which would ease the country's dependence on natural gas imports, and lower exposure to price fluctuations and supply disruptions. Import volumes of natural gas to China would fall by 30%, reducing annual import expenditure by around USD 720 billion.[6]

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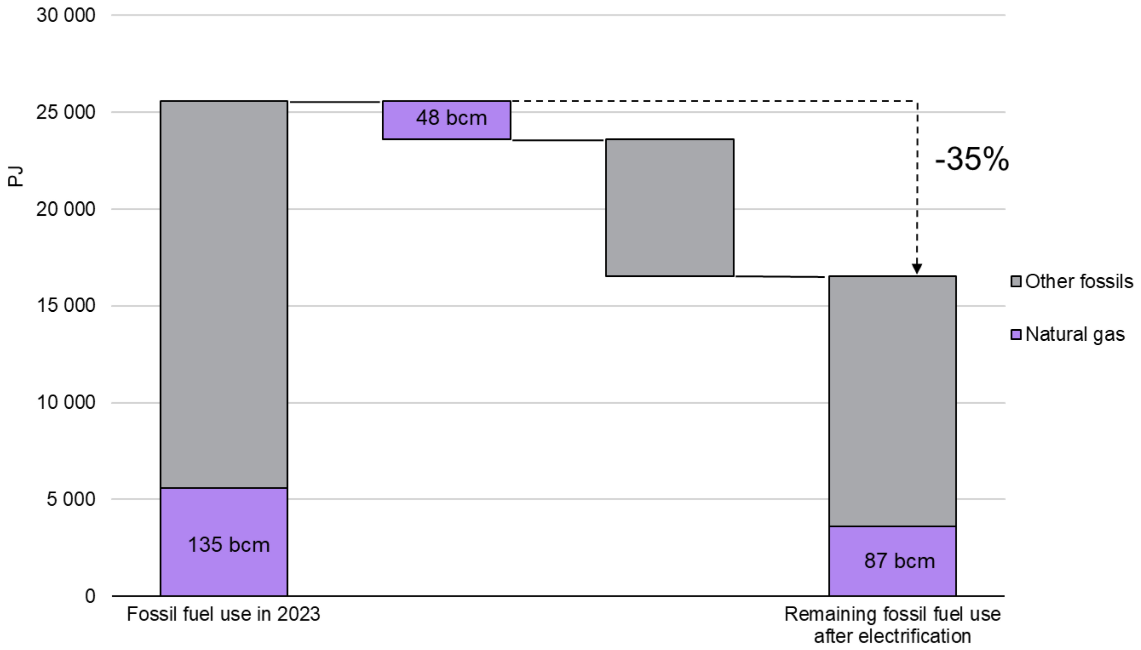
[6] Savings estimates are based on USD 10-15/GJ.

Figure 4.4 **Impact on direct industrial fossil fuel demand in China if the technical potential for electrifying steam and low-temperature heat were realised**



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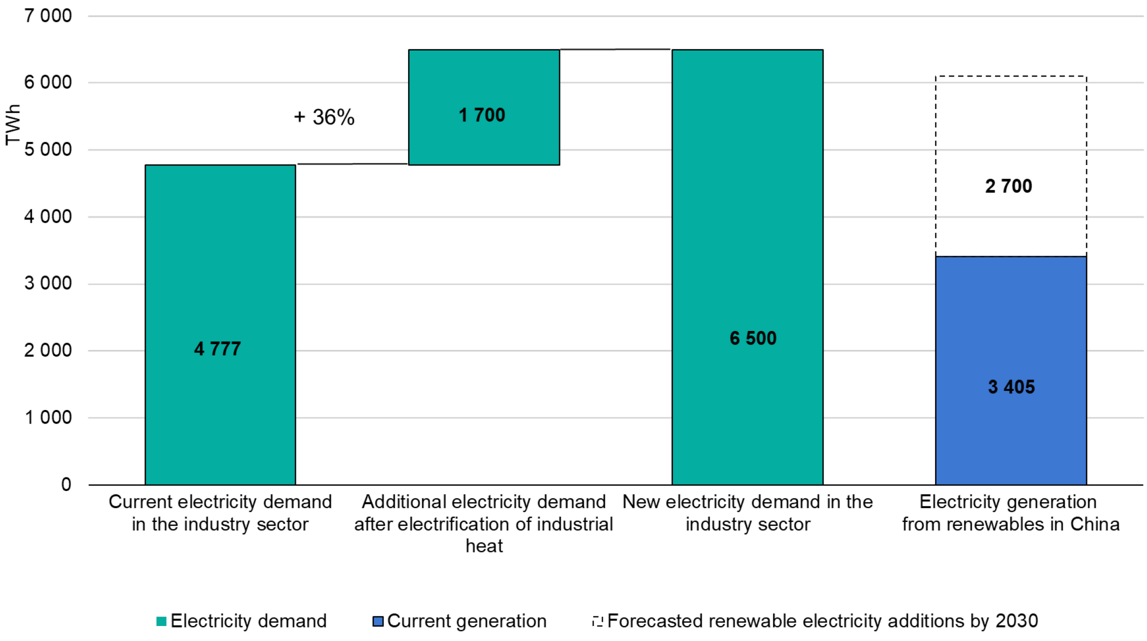
Note: PJ = petajoule; bcm = billion cubic metres.

A broad transition of the industry sector to heat electrification would increase electricity demand by 1 700 TWh (36%) from 4 800 TWh to 6 500 TWh, which is comparable to the forecast growth in China's solar PV electricity generation between today and 2030. The additional electricity demand would represent 63% of the projected growth (2 700 TWh) of China's renewable generation from 2025 to 2030. If the increased electricity demand were primarily met by new renewable energy sources, emissions from the industrial sector could be reduced by 600 Mt CO_2 per year.

Figure 4.5 Impact on electricity demand in China if the technical potential for electrifying steam and low-temperature heat were realised



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Note: TWh = terawatt hour.

Cost analysis

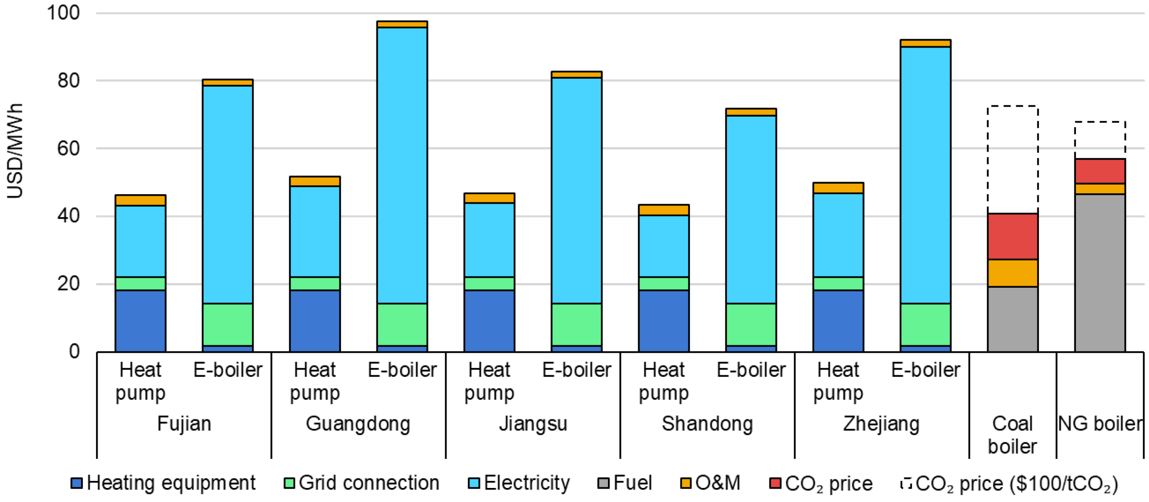
The levelised cost of electrified heat is analysed on the basis of electricity prices for industrial consumers in five major Chinese provinces: **Fujian, Guangdong, Jiangsu, Shandong** and **Zhejiang** in 2023.

In China, industrial electricity prices were previously set by the government for each province based on coal benchmark prices. However, the provinces have long included time-of-use elements such as peak, flat and valley pricing to shape demand. Three-segment tariffs are used for industrial consumers in Jiangsu and Guangdong, for example, and five-segment tariffs have more recently been adopted in Shandong or Hebei, which provide pre-defined variations. Industrial consumers thus faced differentiated prices across time bands but not real-time or market-reflective pricing. China’s ongoing electricity market reforms will increase industrial exposure to wholesale prices and allow industrial consumers to take more advantage of cost-saving opportunities through bilateral power purchase agreements between large consumers and renewable energy producers. As of mid-December 2025 only 21 provinces had issued auction rules while fewer completed auction rounds (see the Market and Policy section in this chapter).

The reference system for industrial heat supply is domestic coal, with coal boiler operating costs at USD 40/MWh under the current industrial CO_2 price of

USD 13/t CO_2. Natural gas boilers account for about 22% of the industrial heat supply and use largely imported liquified natural gas, with operating costs at around USD 57/MWh under the current industrial CO_2 price. The results of a techno-economic analysis indicate that the levelised cost of heat for heat pumps in selected Chinese provinces is USD 40-50/MWh. Grid-based heat pumps would therefore require a carbon price of about USD 20-30/t CO_2 to breakeven with coal boilers in heat supply. However, heat pumps would clearly have lower costs than gas boilers using imported LNG.

Figure 4.6 **Comparison of the levelised cost of low-temperature heat and steam for industry using electricity, coal or natural gas, in selected Chinese provinces, 2023**



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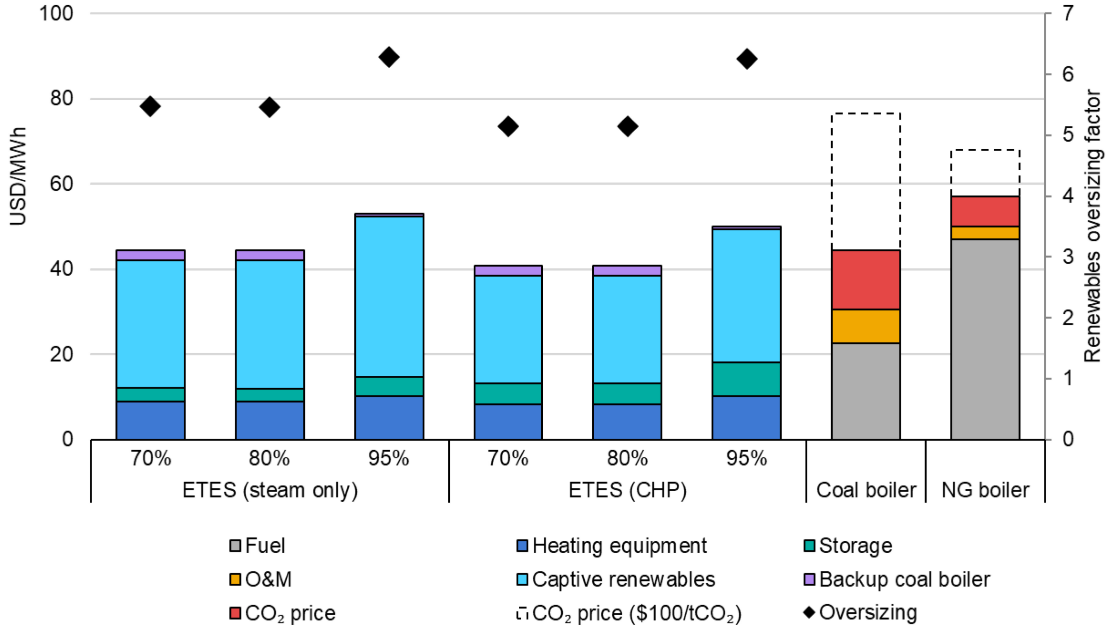
Notes: Estimates are made on the basis of the following financial assumptions: WACC 8%, economic life 20 years, coal price USD 100/tonne, natural gas price USD 15/GJ (liquified natural gas), CO_2 price USD 13/t CO_2 (default) and USD 100/tCO_2 (high). Assumptions for process parameters are: heat demand 3 MW and annual availability 8 000 hours/year. Efficiencies (in LHV) are: coal boiler 75%, gas boiler 85%, heat pump coefficient of performance 3; electric boiler 98%. Capital costs are: heat pump USD 1 500/kW_{th}, electric boiler USD 150/kW_{th}, grid connection USD 1 000 000 per MW, O&M USD 2/MWh (electric boiler), USD 3/MWh (heat pump and NG boiler), USD 8/MWh (coal boiler). CYN/USD conversion rate (2023).Urostat.

Compared with heat pumps, electric boilers have markedly higher costs, around USD 70–100/MWh, representing roughly 2.5 to 3.5 times the cost of coal-based steam, depending on the province. The carbon price would need to be above USD 100/t CO_2 to make electricity-based steam production competitive against coal in several provinces.

One possible way to reduce heat electrification costs in China would be to connect industrial consumers directly to renewable power generators such as solar PV, onshore wind or a hybrid system consisting of an optimised mix of both solar and wind. In such a case, industrial end users would directly benefit from the low cost of renewables and could use thermal storage to buffer daily variation in supply.

Figure 4.7 Comparison of the levelised cost of low-temperature heat and steam for industry using captive solar PV and wind in China, 2023



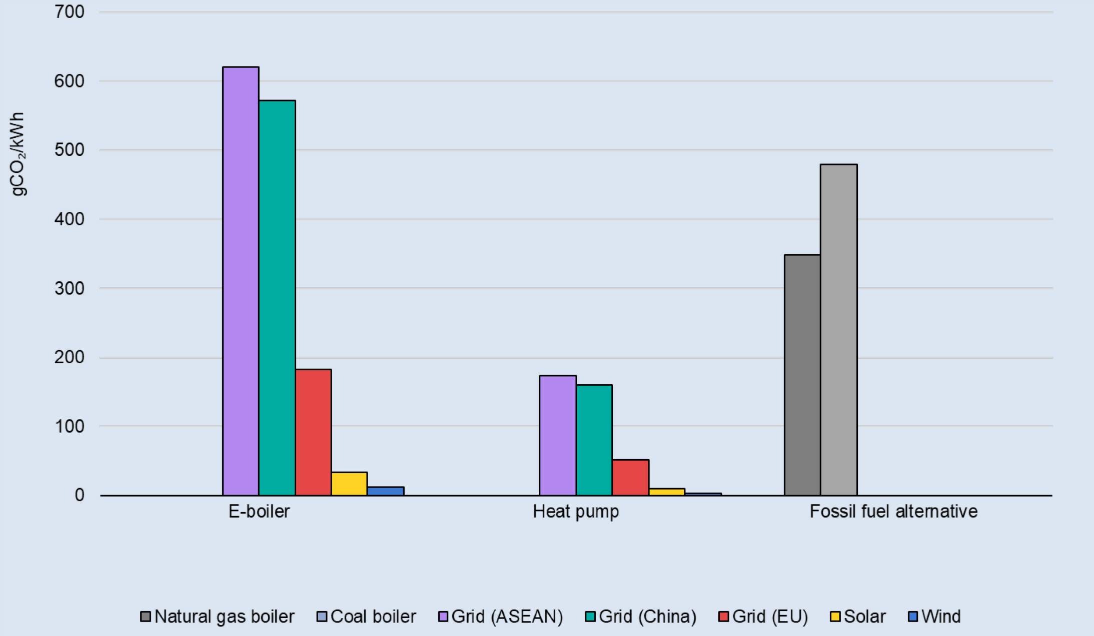
Notes: CHP = combined heat and power; ETES = electro-thermal energy storage; Estimates are made on the basis of the following financial assumptions: weighted average cost of capital 8%, economic life 20 years, coal price USD 100/tonne, back-up fuel price USD 15/MWh, electricity price USD 56/MWh, CO_2 price USD 13/t CO_2 (default) and USD 100/t CO_2 (high). Assumptions on process parameters are: heat demand 3 MW, annual availability 8000 hours/year. Efficiencies in lower heating value (LHV) are: coal boiler 75%, gas boiler 85%, heat pump coefficient of performance 3, electric boiler 98%. Capital costs are: electric boiler USD 150/kW_{th}, storage USD 16 /kWh, cogeneration: 900/kW_{th},, operations and maintenance USD 2/MWh (heating equipment), USD 3/MWh (heat pump and natural gas boiler), USD 8/MWh (coal boiler), ETES O&M: USD 2/MWh. Storage size: 20 hours, electrical efficiency of the back-pressure turbine 17%, thermal storage investment USD 16/kWh, storage losses per hour 0.08%, grid electricity price USD 80/MWh.

The cost of delivering a continuous supply of steam from a captive hybrid solar PV and wind installation in China was assessed based on local data on wind speeds and solar irradiation. Electro-thermal energy storage (ETES) was equipped with a back-up grid connection used in the case of extended periods of low generation from renewables. The share of annual steam demand covered by the captive renewables through an ETES system was calculated for an 70%, 80% and 95% contribution, with the remaining electricity supply coming from the grid. For all cases, two different ETES configurations were considered: a steam-only system, which provides steam for industrial use, and a combined heat and power (CHP) system that also co-produces electricity for self-consumption. The levelised costs for the steam-only system are fairly stable at USD 45/MWh across the studied range, while running the system in CHP mode reduces these costs to around USD 40/MWh. Compared with fully grid-based systems, captive renewables help to nearly halve the cost of steam from USD 70-100/MWh to around USD 50/MWh.

Box 4.1 Impact of the electricity source on the GHG emissions of heat pumps and electric boilers

The greenhouse gas (GHG) emissions associated with electric heating depend closely on the carbon intensity of the electricity used. When electricity is sourced from wind and solar PV power plants, the emissions from the heat produced are in the range of 12-34 gCO_2/kWh in the case of electric steam boilers and 3-9 gCO_2/kWh in the case of low-temperature heat pumps, or around 90-95% lower than emissions from the fossil fuels that they replace.

GHG emissions relating to the production of heat by electricity source



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Notes: gCO_2/kWh = grammes of carbon dioxide per kilowatt hour. Estimates are made on the basis of the following efficiency assumptions: heat pump coefficient of performance 3; e-boiler 98%, gas boiler 85% (LHV) and coal boiler 75% (LHV). Coal boilers are heat-only. In larger industrial facilities, coal boilers can be operated in a combined heat and power mode. Embodied emissions of renewable power are included.

Using grid electricity can lead to situations where electric heating leads to higher emissions than heat produced by the burning of fossil fuels. For example, electric boilers using average 2024 grid emissions from ASEAN (608 gCO_2/kWh) and from China (560 gCO_2/kWh) would lead to 16-23% higher emissions compared with a coal-fired steam boiler. In order for a grid-connected electric boiler to have lower emissions than a coal boiler, the carbon intensity of the grid should be lower than 440 gCO_2/kWh. However, given the high coefficient of performance of heat pumps, the emission intensity of low-temperature heat using average grid emissions from ASEAN and China would remain amongst three times lower than that of coal.

When electric heating is integrated with thermal storage, the CO_2 intensity of the used electricity can be lower than the average annual grid intensity. Thermal storage is often charged when electricity prices are low, which is associated with large production from wind and solar PV (i.e. times of low grid carbon intensity). By contrast, when electricity prices are high, an industrial facility is encouraged to use heat from thermal storage – thereby avoiding use of electricity with high emissions and again reducing the average CO_2 emissions associated with heat production.

Industrial facilities can also procure electricity through power purchase agreements (PPAs), by signing a contract directly with a producer of low-emission electricity. Such PPAs can take the form of either a physical PPA, where contractual partners are located on the same grid and in the same bidding area, or they can take the form of a financial PPA, where the contracting parties are located and/or operating on different grids and even in different countries. PPAs can offer several advantages to each party. For clean electricity developers, PPAs bring the revenue certainty needed to secure investment in the plant. For an industrial facility looking to electrify its heat production, engaging in a PPA allows for long-term price certainty, in addition to offering a pathway to procure low-emission electricity when connected to a high-emission grid.

Market and policy

Chinese heating strategies and policies originally prioritised air quality improvements but have since evolved to target low-carbon heating solutions. In 2020, China set ambitious dual carbon targets to peak carbon emissions by 2030 and to achieve carbon neutrality by 2060. These targets have been outlined in detail in sectoral action plans, including a dedicated industry plan.

Policies and targets are essential tools for elevating this issue on the energy agenda. China's 14th Five-Year Plan (2021-2025) established an overarching framework with broad implications for industry: prioritising the electrification of end-use sectors, using non-fossil fuel energy and ensuring better coordination of generation, demand and storage. The 2022 action plan on boosting industrial energy efficiency reinforces these priorities with sector-specific measures.

China and its provinces have been pursuing a comprehensive industrial decarbonisation strategy. The 2022 policy on the transition of the light industry set the direction for a more efficient and sustainable sector. It was followed by a plan for digital transformation, which promotes the integration of digital and low-emission technologies in this sector. Policy recommendations in 2025 encourage industrial consumers to invest in their own onsite renewable power generation facilities.

Building on this foundation, the years 2024 and 2025 marked a more systemic shift towards the decarbonisation of heavy industry. Two comprehensive roadmaps, one on accelerating green manufacturing and another on large-scale equipment upgrades in key energy sectors, set clear investment and policy directions. Renewable and decarbonised energy measures now mainly target energy-intensive industries (iron and steel, cement, polysilicon, aluminium) supported by provincial renewable electricity consumption mandates (July 2025). These mandates require that industry source 25% to 70% of its power from renewables in 2025-2026. The mandates are monitored through provincial reviews and backed by trading in green electricity certificates.

The national Emission Trading Scheme similarly covers energy-intensive industries and power. The August 2025 policy signals a major shift, with a move from intensity-based allocation to absolute emission caps by 2027, expanding coverage to sectors such as chemicals, glass and paper, and planning to gradually introduce allowance auctioning from 2030 to strengthen the carbon price signal.

Complementing these measures, the heat pump action plan and boiler action plan signal a policy push to electrify industrial heat and heat for buildings. These plans target industrial park applications, encourage retrofits and the adoption of advanced heat pumps and electric boilers. They also require provinces to integrate plans into regional heating strategies, calling for public investment, financial support and infrastructure planning to facilitate large-scale deployment.

All of the above priorities are expected to feature more prominently in the upcoming 15th Five-Year Plan (2026-2030), which is to be formally released in March 2026.

Financial support and competitive electricity prices are key enablers for industrial heat electrification to reduce high upfront and operating (energy) costs.

The central government's Equipment Upgrade Programme and the People's Bank of China guidelines to strengthen financial support for new industrialization work together to lower capital costs for industrial electrification by mobilising substantial treasury bond funds and easing access to concessional loans. This integrated framework combines grants, loan facilitation and regulatory support to strategically de-risk electrification investments in heat pumps, electric boilers and thermal storage. The Zero-Carbon Industrial Parks initiative complements this framework by promoting integrated low-emission power, heating, cooling and storage in industrial parks so as to enhance energy system flexibility.

At the provincial level, the Shandong Green Development Fund (a pilot financed by the Asian Development Bank, KFW and the Green Climate Fund) leverages public and private capital to reduce upfront risks and to accelerate industrial projects tailored to Shandong's industrial profile.

In terms of operating (energy) costs, China's industrial electricity prices were previously set by the government for each province based on coal benchmark prices. However, provinces have long included time-of-use elements such as peak, flat and valley pricing to shape demand. Three-segment tariffs are used for industrial consumers in Jiangsu and Guangdong, for example, and five-segment tariffs have more recently been adopted in Shandong or Hebei, which provide pre-defined variations. Industrial consumers thus face differentiated prices across time bands but not real-time or market-reflective pricing. China's ongoing electricity market reforms will increase industrial exposure to wholesale prices and allow industrial consumers to take more advantage of cost-saving opportunities through bilateral power purchase agreements between large consumers and renewable energy producers.

Since June 2025, all new wind and solar projects in China must bid in provincial competitive auctions for contracts for difference, ending previously administratively set power purchase tariffs as part of the market reform (under Document 136). The reform requires wind and solar developers to sell their output directly in provincial wholesale markets. However, as of mid-December 2025, only 21 provinces have issued auction rules, while fewer completed auction rounds. In provinces where continuous wholesale market operations already began, negative price hours (when allowed) have been increasing during mid-day hours while growing price volatility within regulatory ceiling and floor price settings.

Energy supply is the largest component of the final electricity price, accounting for around 60% of the total, with the rest divided between network charges (~30%), system operation and line losses (~5%), as well as government levies and charges (~5%). In the case of network charges, provinces with high industrial electricity demand and significant coal and renewable generation (Hebei, Shanxi and Guangdong) apply two-part tariffs that combine fixed capacity charges with variable consumption charges to encourage more predictable grid use. Smaller industrial consumers are typically billed on the basis of a variable consumption rate (prevalent in urbanised provinces such as Beijing, Shanghai, Jilin or Hubei). However, 2023 regulatory reforms allow these smaller industrial consumers to opt for two-part pricing.

Electricity market and grid access conditions remain key barriers to the pace and costs of industrial electrification. The Chinese government has issued guidelines to streamline grid connection for new capacity, including in the case of industrial electrification projects. Measures include simplifying connection approvals for capacities below 10 MW, ensuring that planning is coordinated between industrial parks and grid operators, and supporting integrated source-grid-load storage projects where electrified heat and thermal storage contribute to flexible demand management.

The increased exposure to price signals creates incentives for demand-side flexibility and storage investments. While the recent reforms removed requirements to combine renewable projects with a storage component at the national level, in practice, provinces are taking different approaches, with Yunnan or Guizhou keeping the requirement while Shandong is eliminating it. Despite these changes, the government is nevertheless encouraging industry to participate in ancillary services and capacity markets in the case of electrified heat and storage, and some provinces (Shandong or Jiangsu) are piloting differentiated tariffs and compensation schemes for flexible loads. Wholesale markets, however, have very narrow ceiling and floor prices, which may limit storage investment opportunities.

Regardless of the clear policy direction to treat electrified industrial heat and thermal storage as flexible grid assets, practical implementation varies depending on local grid capacity, and compensation also remains unclear across provinces.

Technology innovation: the Chinese government systematically mobilises public co-funding for research, pilot and demonstration projects in alignment with its Five-Year Plans. Within this framework, targeted R&D programmes have supported the advancement of high-efficiency heat pumps, electric boilers and thermal storage technologies. The 2022 Energy Technology Innovation Five-Year Plan marked a shift in China's policy priorities, placing a larger focus on technology innovation, including electrification, grid reform and energy storage. The 2025 heat pump action plan also underlines the importance of advancing heat pump efficiency.

China's 2023 programme to fund demonstration projects for green and low-carbon technologies is designed to accelerate technology maturity through targeted state intervention. The programme offers a suite of incentives, including direct financial and fiscal support, expedited administrative approvals, improved access to technology and talent resources, preferential treatment in government procurement and long-term support from local authorities. Nearly 150 projects have been selected through this programme, with the first batch of selected projects released in April 2024 and the second batch in April 2025. However, to date none of the projects address industrial electrification of low-temperature heat and steam.

Table 4.1 Examples of recent policy developments relating to the electrification of industrial low-temperature heat and steam

Policy area	Date	Development
Policies and targets	**Central level**	
	March 2021	The 14th Five-Year Plan (2021-2025) guides China's social and economic development for a five-year period, and includes guidance for industry.
	June 2022	The Industrial Energy Efficiency Improvement Action Plan reinforces the priorities of the 14th Five-Year Plan with sector-specific measures.
	June 2022	Guidance on Promoting High-Quality Development of Light Industry outlines the directions for transforming the sector towards greater efficiency, innovation and sustainability.
	August 2022	The Carbon Peaking Implementation Plan in the Industrial Sector provides a sector-specific implementation plan for dual carbon strategies.
	December 2023	The Action Plan for Green, Low-Carbon and High-Quality Development of Boilers promotes cleaner, more efficient industrial heat systems.
	February 2024	Guidance provided on Accelerating the Green Development of the Manufacturing Industry sets goals for the sector for 2030. These goals focus on energy efficiency, renewables, electrification of end-uses, and circular, digitalised systems.
	August 2024	The action plan to promote large-scale equipment renewals in the energy sector outlines measures to upgrade equipment in key areas of the energy sector so as to enhance efficiency, for example, through the transformation of coal-fired power generation units.
	October 2024	The New Renewable Energy Action Plan aims not only to boost renewable energy generation but also renewable energy consumption across all sectors, including for industrial electrification.
	March 2025	The Implementation Plan for the Digital Transformation of Light Industry promotes the integration of digital and low-emission technologies in this sector.
	April 2025	The Action Plan for Promoting the High-quality Development of the Heat Pump Industry is designed to accelerate the electrification of industrial and district heat.
	May 2025	The Notice Related to the Orderly Promotion of the Direct Development of Green Power encourages industrial consumers to invest in their own dedicated renewable energy supply.
	July 2025	Renewable electricity consumption mandates were introduced for energy-intensive industries for 2025 and 2026, at 25% and 70%, respectively. These goals are monitored through provincial reviews and supported by the trading of green electricity certificates.
	August 2025	An updated Emission Trading System provides guidelines on the transition to absolute caps and expands the scope of the Emission Trading System.

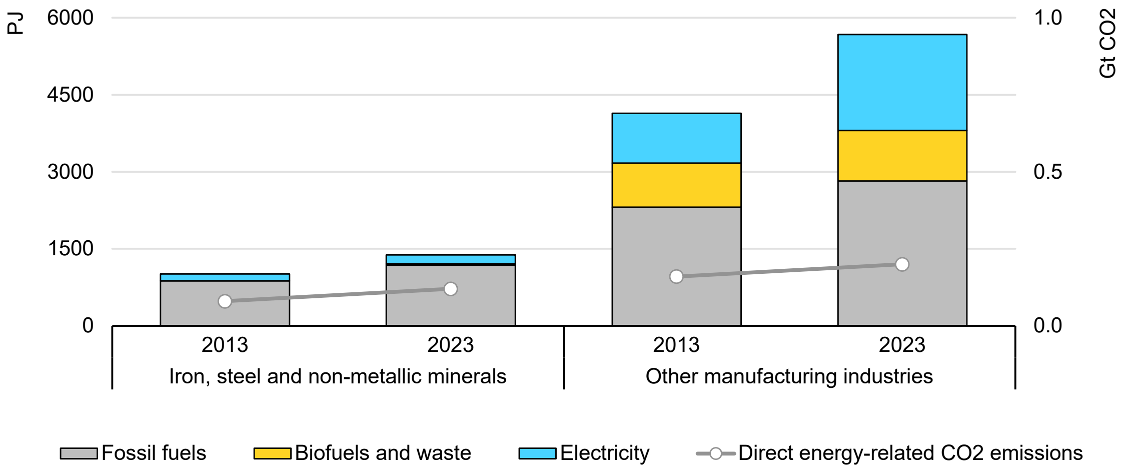
Policy area	Date	Development
Financial support	**Central level**	
	May 2023	Price document 526 sets provincial grid transmission and distribution tariffs for electricity, including for industrial consumers.
	February 2025	Document 136 introduces market-based pricing for new wind and solar power, replacing fixed tariffs.
	February 2025	The equipment upgrade programme (the “Two-New” policies) provides financial support to consumers and industry for large-scale equipment upgrades.
	July 2025	The Zero-Carbon Industrial Parks initiative is designed to accelerate the transformation of these parks through the use of low-emission energy, and heat and storage solutions.
	August 2025	The People’s Bank of China and six other government agencies released financial guidelines on promoting financial support for new industrialisation to mobilise access to bonds, concessional loans, equity and insurance.
	Provincial level	
	Since August 2020	The Shandong Green Development Fund (financed by the Asian Development Bank, KFW and the Green Climate Fund) leverages public and private capital to reduce upfront risks and accelerate industrial projects.
Electricity market and grid access	**Central level**	
	March 2021	Guidance on the integration of power sources, grids, loads and storage, as well as the development of multi-energy complementarity outlines a systemic approach to a flexible power system by coordinating generation, transmission, demand and storage.
	March 2023	Guidance on the high-quality development of distribution grids is designed to prepare the distribution grid for new market participation, which includes streamlining grid connections to new demand projects.
	September 2025	The Action Plan for Large Scale Construction of New Energy Storage (2025-2027) provides guidance on scaling up storage deployment, and supporting the integration of electrified heat and storage (including thermal storage) to contribute to flexible demand management.
Technology innovation	**Central level**	
	April 2022	The Energy Technology Innovation Five-Year Plan (2021-2025) sets priorities for developing new energy technologies, including in the area of storage.
	August 2023	The Implementation Plan for Demonstration Projects for Green and Low-Carbon Advanced Technologies will provide selected demonstration projects with direct government support, including preferential land pre-approvals, energy-efficiency reviews and environmental assessments. Two batches (in April 2024 and April 2025) have so far resulted in the selection of nearly 150 projects, none of which focus on industrial electrification of low-temperature heat or steam to date.

Chapter 5. Spotlight: ASEAN region

State of play

The industry sector accounts for around 36% of the ASEAN GDP and has been a key driver of rising energy demand. Over the past decade, energy consumption in the industry sector increased by nearly 40% with growth across all major fuels. Coal demand rose by around 60%, largely driven by the expansion of cement, iron and steel production. Over the same period, natural gas use grew by almost 40%, while electricity consumption nearly doubled. These changes can be attributed to ASEAN's rising standards of living and growing population, as well as deepening integration into global manufacturing value chains for goods ranging from food and beverages to textiles and consumer electronics. Electricity and natural gas use are typically more intensive in these sectors.

Figure 5.1. **Final energy consumption in ASEAN industries and direct energy-related CO_2 emissions, 2013 and 2023**



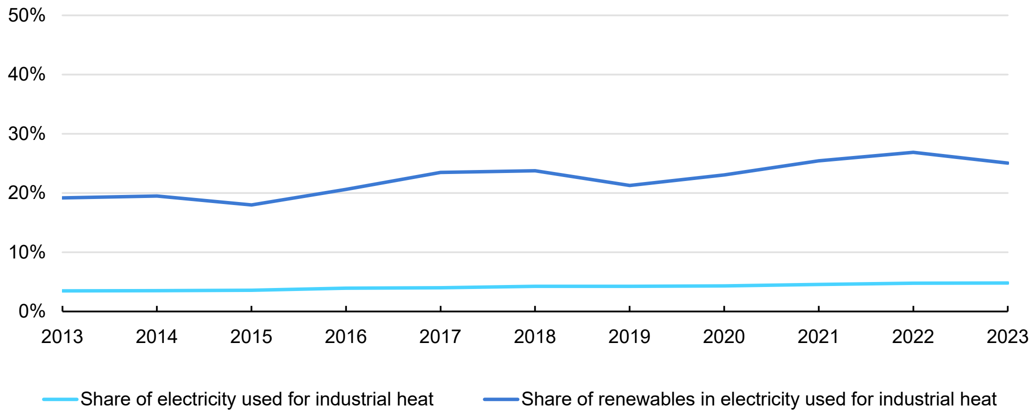
Notes: Gt CO_2 = gigatonne of carbon dioxide; PJ = petajoule. Non-metallic minerals include cement, glass, ceramics and clay. Iron and steel energy consumption excludes energy use in blast furnaces and coke ovens. Other manufacturing industries include mining and quarrying, construction, manufacturing, chemicals and petrochemicals, non-ferrous metals, transport equipment, machinery, food, beverages and tobacco, pulp, paper and printing, wood and wood products, textile and leather and non-energy use in chemicals. The figure excludes emissions relating to blast furnaces and coke ovens, as well as process emissions and indirect energy-related CO_2 emissions from electricity and heat.

In 2023, the industry sector accounted for 37% of total final energy consumption in the ASEAN region. It generated around 19% of the region's direct energy-related CO_2 emissions, a share that rose to more than 40% when including indirect energy-related CO_2 emissions resulting from electricity and heat use. Between 2013 and 2023, direct industrial energy-related CO_2 emissions increased by 0.08 Gt (Figure 5.1).

In 2023, total energy use in the ASEAN industry was approximately 7 000 PJ per year, which is expected to continue rising, driven by growing output in energy-intensive industries such as iron, steel and chemicals, as well as expansions in other manufacturing industries (such as automotive production). Energy-intensive industries account for roughly 64% of industrial energy use, relying heavily on coal (56%) to meet heat demand. Non-energy-intensive sectors primarily depend on bioenergy (40%) and electricity (33%). The overall industrial energy mix varies across the region, with countries such as Indonesia and Viet Nam relying on their large domestic coal resources, while industry in Thailand and Malaysia is fuelled by a more balanced mix, with higher shares of natural gas and renewables.

Electricity accounted for 29% of total industrial energy consumption. Five sectors, chemicals and petrochemicals, food, beverages and tobacco, iron and steel, machinery and non-metallic minerals (such as cement, glass or clay) consumed nearly 90% of all industrial electricity. Their core production processes and auxiliary systems rely heavily on electricity driven operations, including grinding, mixing, refrigeration, drying, electrochemical refining and other motor driven operations.

Figure 5.2. **Share of electricity and of renewable electricity used for industrial heat in ASEAN, 2013-2023**



IEA. CC BY 4.0.

In 2023, electricity used for heat represented 5% of total heat generation, increasing from 3% in 2013, and reflecting slow progress in the electrification of industrial heat. This slow progress largely results from structural and economic barriers, including the continued availability of cheap coal. At the same time, the share of renewables in the electricity used for heat increased from 19% in 2013 to 27% in 2022 but decreased to 25% in 2023 (Figure 5.2).

Technical electrification potential

The ASEAN industry sector consumes 7 000 PJ of energy in total, of which 4 100 PJ is from fossil fuels and approximately 2 000 PJ is in the form of electricity, while the remainder is from other sources (biofuels and renewables). About 60% of industrial heat is used at temperatures above 400 ºC, while the remaining 2 400 PJ (41%) is used at below 400 ºC and could technically be electrified to a large extent.

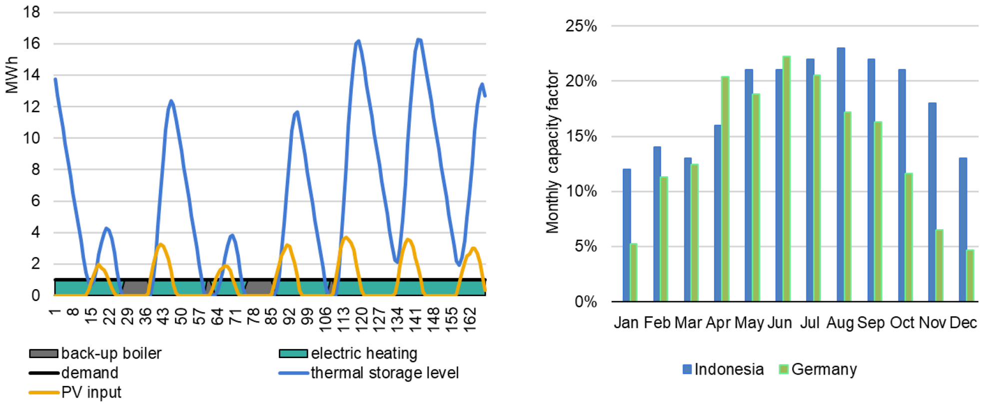
Resulting new demand for electricity from heat electrification would be between 300-400 TWh depending on the mix of heat pumps. This amount is two to three times higher than the expected 160 TWh growth of renewable electricity generation in the ASEAN region during 2025-2030.

Cost analysis

The ASEAN region is endowed with significant solar resources, with annual capacity factors reaching 20%. The region’s combined technical potential for utility-scale solar PV, and onshore and offshore wind exceeds 20 terawatts – roughly 55 times the current regional generation capacity from all sources. The quality of the resource varies by country and by geography, but the ASEAN region is comparable to northern Australia and parts of India in this regard. Given that the region lies close to the equator, it also has one of the lowest seasonal variations in solar irradiation, leading to consistent daily demand patterns. The lowest monthly capacity factors are around 13%, which is high compared with Europe, where capacity factors can drop below 5% during the winter months.

The strong solar resources in the ASEAN region offer opportunities for using electrically powered heating supplied by captive solar PV installations, for example, through rooftop systems on factory buildings. Integrating thermal storage would result in a stable supply of heat (for plants operating in three shifts), while a back-up boiler could cover extended periods of low solar availability. Brownfield installations can repurpose existing boilers as back-up systems.

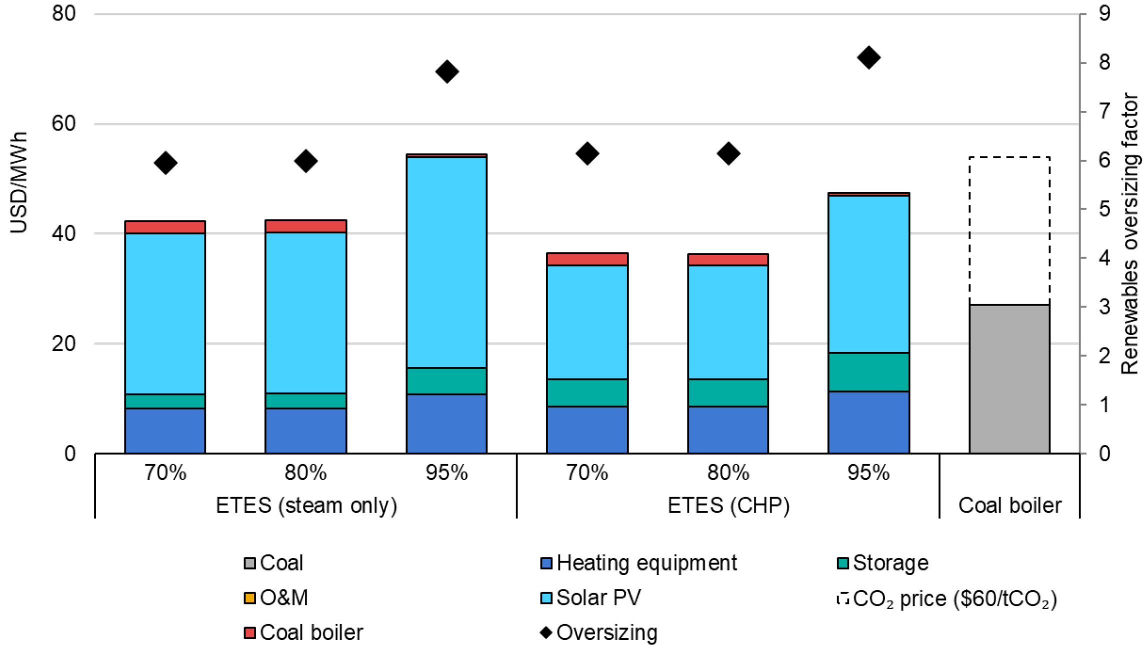
Figure 5.3. Hourly operation of a solar PV-based electro-thermal energy storage system with a back-up boiler in Indonesia (left); and monthly solar PV capacity factors for Indonesia and Germany (right)



Source: IEA analysis based on weather data from Renewables ninja, accessed October, 2025.

The cost of delivering a continuous supply of steam from a captive solar PV installation was assessed using an hourly optimisation model for the ASEAN region. Electric heating is integrated with thermal energy storage and supported by a back-up boiler that operates during longer periods of low solar irradiation. The fossil fuel boiler is assumed to already exist at the factory site, so no additional investment cost is included. The model analyses three scenarios for the share of annual steam demand covered by the solar PV-based ETES system: 70%, 80% and 95%. Achieving 100% coverage would significantly increase costs. A back-up boiler therefore offers a cost-efficient way to fully meet steam demand while still achieving a substantial reduction in fossil fuel use for heat supply. Two different ETES configurations are considered: a steam-only system, which provides steam for industrial use, and a combined heat and power (CHP) system, which also generates electricity for self-consumption, thereby reducing reliance on grid electricity.

Figure 5.4. Comparison of the levelised cost of heat using steam only or combined heat and power mode against a coal boiler in ASEAN, 2024



IEA CC BY 4.0.

Notes: Estimates are made on the basis of the following assumptions: continuous heat demand 3 MW, storage size 20 hours, electrical efficiency of the back-pressure turbine 17%, thermal energy storage investment USD 16/kWh, storage losses per hour 0.08%, back-up boiler efficiency 75% (LHV), coal price USD 100/tonne, O&M; USD 2 MWh (ETES), USD 8/MWh (coal). A USD 30/MWh was assumed for the ground-mounted projects with the lowest bid prices in Malaysia's LSS 5+ solar PV auction, which resulted in an average price of around USD 34/MWh. WACC 8%, economic life 20 years. Capital costs are: heating equipment: USD 163/kW_{th}, storage USD 16/kWh, steam turbine: USD 900/kW_{th}, grid connection USD 1 000 000 per MW.

The reference system for industrial heat supply in the ASEAN region is domestic coal, with boiler operating costs around USD 30/MWh, and without established CO_2 pricing. In comparison, the levelised cost of heat for a system based on captive solar PV is in the range of USD 40-55/MWh for the steam-only and USD 35-50/MWh for the CHP configuration. A carbon price of about USD 45/tCO_2 would be needed for a system producing combined heat and power, while around USD 60/tCO_2 would be needed for the steam-only configuration.

Box 5.1 Industrial parks as enablers of industrial heat electrification in ASEAN

Industrial parks play a central role in the ASEAN industry landscape, hosting a large share of manufacturing activity and receiving a significant amount of foreign direct investment. More than a thousand industrial parks and special economic zones are scattered across the region, including large-scale clusters such as the Viet Nam–

Singapore Industrial Park, Thailand's Eastern Seaboard Industrial Estate, Malaysia's Penang Free Industrial Zone, and Indonesia's Jababeka Industrial Estate and Batamindo Industrial Park. These parks are at the centre of industrial energy demand and infrastructure, making them natural focal points for coordinated decarbonisation efforts.

Electrifying industrial heat within industrial parks can leverage economies of scale and shared infrastructure. Common grid connections, renewable electricity supply and thermal storage facilities can be planned at the park level, lowering specific capital costs and enhancing overall system efficiency. Some parks are already installing large-scale rooftop solar PV systems and providing onsite renewable electricity to multiple users. These parks can also invest in oversized PV systems to maximise renewable power use during daylight hours, directing surplus generation that would otherwise be curtailed to thermal storage. The co-location of industries can also create opportunities for cascading heat use, waste heat recovery and thermal networks.

With appropriate planning, industrial parks can integrate onsite renewable generation, such as captive power projects, and balance electricity demand through shared energy management systems. Industrial parks can also serve as demonstration hubs for electrification technologies and workforce training, as well as examples for the wider roll-out of replicable models.

Market and policy

The ASEAN Community Vision 2045 (May 2025) establishes a strategic framework for regional cooperation, positioning industrial and energy transformation as central to climate and economic resilience in the ASEAN region. It calls for the development of green industrial hubs, regional carbon-neutrality strategies and cross-border clean energy infrastructure. It envisions a staged energy transition towards electrification, energy efficiency and clean hydrogen, particularly in key sectors such as iron and steel, cement and chemicals. The document reaffirms the collective objective of carbon neutrality by 2050, with all countries forming the ASEAN region (except the Philippines and Timor-Leste) setting net-zero or carbon neutrality targets for 2050 or 2060.

Policies and targets are essential tools for elevating this issue on the energy agenda. The ASEAN Plan of Action for Energy Cooperation (2026-2030) (2025) together with the ASEAN Renewable Energy Long-Term Roadmap (2025) build on earlier plans and outline seven programme areas that include the ASEAN power grid, renewable energy and energy efficiency. The plan presents measures within these areas to expand the cost-effective deployment of renewables in the industrial sector and to accelerate the adoption of sector-specific high-efficiency equipment and technologies that will support industrial decarbonisation. However, it primarily frames electrification in the context of transport decarbonisation rather than industrial process heat.

The limited focus on industrial heat electrification does not fully reflect the evolving needs of key manufacturing centres. Malaysia, Indonesia, Thailand and Viet Nam host global hubs for higher-value industries, including pharmaceuticals, food and beverages, electronics, and textiles and apparel. These hubs, while less energy-intensive, are highly sensitive to the quality, reliability and cost predictability of power. Such challenges present real barriers to competitiveness, and local renewable energy could help mitigate these challenges.

Financial support plays a crucial role in enabling industrial heat electrification in ASEAN countries as it helps to reduce high upfront capital requirement costs. These costs are further amplified by the high cost of capital in emerging economies, often nearly twice the global average, and by associated operating costs. ASEAN countries face significant gaps in terms of market-enabling policies and regulatory frameworks, which includes a lack of de-risking instruments, co-financing mechanisms for early-stage projects and mandatory industrial emissions-reduction targets.

Supportive measures, where they exist, focus on incentivising renewable energy investments and energy efficiency improvements rather than on industrial projects.

Industries, and particularly those that are reliant on low-temperature heat and steam, face multiple barriers with respect to the adoption of heat pumps and electric boilers at scale. These barriers include limited access to capital, high grid electricity prices, fossil fuel subsidies, limited access to technology providers, grid infrastructure issues and a shortage of skilled labour. Much of the support provided to these sectors emanates from private sector initiatives and philanthropic sources, but often in an ad hoc manner. For example, Viet Nam's textile and apparel industry benefited from targeted funding to electrify its heat demand with the installation of heat pumps.

While sustainable finance products are slowly becoming available, industry uptake is at times hampered by impediments to accessing these products. Malaysia has pioneered green sukuk (Islamic financial certificates similar to bonds), which provide accessible financing for large-scale renewable energy and energy efficiency projects. The scope of these sukuk was recently broadened to allow companies across various sectors access to financing for their transition to low-emission operations. Malaysia's Green Investment Tax Incentives extend beyond renewable generation to include projects deploying green technologies or delivering green services.

Both Viet Nam and Indonesia have leveraged Just Energy Transition Partnerships in collaboration with multilateral climate finance solutions, which offer concessional loans and risk mitigation instruments to help decarbonise and potentially electrify industrial heat. Indonesia has also established the integrated Green Industry Service Company platform (August 2025) to accelerate industrial decarbonisation. This platform provides a suite of services, including technical assistance, resource efficiency assessments, calculations of emissions footprints and aid for access to green finance initiatives.

The ASEAN Centre for Energy, in partnership with the Korea Development Bank and the Green Climate Fund, is piloting an industrial energy efficiency programme in Indonesia, which provides a package of innovative solutions, including financial de-risking mechanisms, new energy service business models, assistance with the development of a supportive regulatory framework and targeted technical assistance. The programme is intended to serve as a scalable model for replication in other ASEAN member states.

Singapore’s sovereign wealth fund, Temasek, has taken a strategic role in investing in power and energy-intensive sectors in particular. However, it has yet to finance decarbonisation of industry relying on low-temperature heat and steam in the ASEAN region, despite having invested in the installation of heat pumps within buildings in Europe.

The Technology Introduction Support Framework within the Asia Zero Emission Community is a regional platform led by Japan involving 11 regional members. Its primary aim is to advance technology transfers, policy coordination and the financing of innovative low-carbon projects, as well as the development of green industrial supply chains. However, its current activities place substantial emphasis on the development of renewable power, hydrogen, ammonia and carbon capture and storage, with comparatively limited focus on decarbonisation options relating to non-energy-intensive industries.

The Asian Development Bank supports industry through funding frameworks and project preparation facilities aimed at unlocking private sector investment in industry. However, such efforts currently focus on energy-intensive industries.

Electricity prices across ASEAN countries are generally higher than those involving onsite generation with coal or gas. In addition, electricity prices in most ASEAN countries remain regulated, with the exception of Singapore and the Philippines. These latter two countries have established more liberalised electricity markets with competitive retail sectors, enabling multiple private generators and retailers to operate and facilitate corporate power purchase agreements and market-driven pricing. However, regulated markets are evolving towards more dynamic pricing structures with increased cost transparency, particularly in terms of how network and capacity charges are allocated. Corporate power purchase agreements and a new two-part electricity tariff pilot programme for industrial customers (October 2025) in Viet Nam, for example, introduce explicit capacity charges and time-of-use tariffs, which could incentivise the demand side, as well as the deployment of storage options, particularly in industrial parks.

Malaysia is moving even faster on tariff unbundling. The 2025 tariff reform divides the tariff bill into four components: generation, capacity, network and retail charges, with the aim of aligning price signals with system constraints and of rewarding demand flexibility. The State Electricity Company (PLN) in Indonesia, by contrast, maintains administratively stable industrial tariffs, with limited visibility into the network and capacity cost drivers. While it may shield the industry from short-term volatility, such tariffs obscure the economic argument for shifting to renewables or storage solutions. The core challenge across these markets is aligning electricity pricing with decarbonisation objectives, and aligning tariff structures and network charges so that they reflect system costs and benefits.

Renewable electricity market and grid access conditions remain key barriers to the pace and costs of industrial electrification. Industrial decarbonisation across the ASEAN region depends to a large extent on the availability of renewable electricity and the ability of industrial parks to reliably access this electricity. While Viet Nam, Malaysia and Indonesia are all expanding solar and wind capacity, the electrification potential is limited by grid integration, dispatch flexibility and policy frameworks that reduce investment risk.

Viet Nam has made significant advances in policy clarity and market liberalisation. The revised Power Development Plan VIII (PDP8) (April 2025) and the 2024 Electricity Law introduced a structural shift towards the optimisation of grid planning for renewables and enabled direct corporate participation in the power market. Ceiling tariffs for new solar projects (USD 38-52/MWh without storage) have introduced the cheapest prices in Southeast Asia, and rapid renewable capacity additions are already displacing coal and liquified natural gas. Investor confidence, however, has been undermined by retroactive reductions of feed-in tariffs for nearly 200 wind and solar projects, leading to delayed payments and defaults, and threatening USD 13 billion in committed capital. Industrial parks could assist in implementing the transition by aggregating industrial energy demand, integrating utility-scale renewables with storage (currently mostly battery storage) and offering bundled, direct or virtual power purchase agreements.

Malaysia's industrial electrification has progressed along the lines of measures outlined in the National Energy Transition Roadmap (September 2023), with a structured renewable energy procurement mechanism that includes feed-in tariffs, net-energy metering, large-scale solar projects and the Corporate Green Power Programme. The latter programme is designed to reduce transaction risks and facilitate participation of the private sector. Industrial parks are beginning to leverage these mechanisms by combining rooftop solar projects and battery energy storage systems to secure a reliable, low-emission energy supply, supported by fiscal incentives such as the Green Investment Tax Allowance. As is the case in Viet Nam, the main constraint is grid flexibility, with no priority dispatch, inflexible transmission and non-transparent tariff structures. Malaysia's policy challenge is therefore to combine generation incentives with integration and storage solutions.

Indonesia's industrial decarbonisation remains burdened by its relatively young coal-based generation fleet. The 2025–2034 Power Development Plan (June 2025) however targets 42.6 GW of renewable capacity and 10.3 GW of energy storage (more explicitly, battery storage and pumped-storage hydropower). The government has introduced reforms in this regard, including streamlined procurement processes, a new ceiling tariff system to replace cost-based tariffs, and targeted incentives for priority sectors. Despite such advances, independent and industrial generators still face barriers to connect projects to the grid or sell renewable power. Industrial parks and special economic zones are beginning to adopt renewables, often with battery storage, supported by fiscal incentives, including a 10-20 year 100% income tax exemption for special economic zones.

In Singapore, flexible industrial electrification is already rewarded through a mature demand response market administered by the Energy Market Authority. Industrial consumers can offer load reductions during price spikes or periods of grid stress, and could also receive direct payments through market-based mechanisms. The participation of large industrial facilities in demand-response markets demonstrates that electrified, digitally metered industrial loads can capture recurring financial value while supporting grid reliability.

The Philippines is also moving in this direction, but it remains in the early stages of developing comparable incentives. Its Interruptible Load Programme, for example, provides compensation for demand reduction, and forthcoming demand-side bidding in the wholesale electricity spot market aims to allow industrial loads to participate as dispatchable resources. Regulatory measures, including expanded smart metering requirements and lower contestability thresholds, are strengthening the enabling environment, but commercial pathways for monetising industrial flexibility are not yet as mature as those in Singapore.

Regional initiatives, such as the ASEAN power grid, launched by the World Bank, the Asian Development Bank and ASEAN, could improve system reliability over time and enable cross-border balancing with variable renewables.

Technology Innovation: the Economic Research Institute for ASEAN and East Asia, and the ASEAN Centre for Energy launched the ASEAN Low-Carbon Energy Technologies Roadmap, which focuses primarily on hydrogen and ammonia. To date, visibility remains limited in terms of whether other technologies or sectors will be covered in the future.

Chapter 6. Conclusions and priorities for action

Electrifying low-temperature heat and steam in industry offers some of the most immediate and cost-effective opportunities for diversification of energy sources and industrial decarbonisation. In several markets, electricity-based heat is already approaching or achieving cost parity with fossil fuel alternatives. Yet despite technical readiness, deployment remains slow due to structural barriers that include long lead times for grid connections, unfavourable electricity taxation and the absence of clear policy frameworks supporting the transition towards heat decarbonisation.

Realising the potential of electrification in these sectors of industry would require policies that combine clear deployment targets, fiscal and tariff reforms, and coordinated planning between actors both in industry and in energy systems. The IEA recommends six priority actions to accelerate the electrification of low-temperature heat and steam for industrial uses:

Priority 1: Elevate heat electrification into the policy agenda and integrate it into industrial roadmaps and targets

Challenge: Despite growing recognition of the importance of industrial electrification for energy security, decarbonisation and for competitiveness, most countries still lack clear and ambitious targets and long-term roadmaps to guide the electrification of industrial heat processes, particularly for low-temperature heat and steam applications. Countries often view industrial electrification only as a decarbonisation measure, rather than a strategic lever for diversification and the wider transformation of the energy system. As a result, industrial electrification tends to receive lower policy priority than measures targeting renewable power generation or end-use efficiency.

Yet when implemented effectively, industrial electrification can help to advance several objectives that are high on policy makers' agendas. It strengthens energy security by reducing dependence on fossil fuel imports and exposure to volatile global oil and gas markets. It also creates new electricity demand that facilitates the integration of higher shares of variable renewables through increased demand response capabilities. The lack of recognition and forward planning for these broader system benefits risk slowing progress on industrial decarbonisation, resulting in missed opportunities to enhance resilience and accelerate the clean energy transition.

Policy response: Policy makers should elevate electrification of industrial heat higher in the policy agenda and integrate it into national energy and grid planning, recognising its contributions to energy security, renewables integration and system flexibility, as well as to economic growth, industrialisation and employment. Governments can then translate the technical potential for industrial heat electrification into explicit targets for renewable heat and include those in industrial roadmaps that define the roles of electricity, thermal storage and waste heat, as well as their contribution to decarbonisation objectives.. Roadmaps would specify technology pathways, deployment timelines and integration strategies, aligning these targets with updated nationally determined contributions.

Selected examples: The European Union has included industrial decarbonisation in its mandatory renewable heating and cooling targets starting in 2026, along with indicative targets for the use of renewables in industry under the recast Renewable Energy Directive (RED III). These targets are measured as annual increases. The EU Clean Industrial Deal reinforces this approach by introducing an economy-wide electrification target, paving the way for the European Union's proposed industrial electrification 2040 and 2050 benchmark under the European Climate Law.

China has also established renewable electricity consumption mandates (July 2025) for heavy industry, which are monitored through provincial reviews and backed by a trading system that involves the exchange of green electricity certificates. These measures have been complemented by the heat pump action plan and boiler action plan, both of which signalled a coordinated policy push to electrify industrial heat and heat for buildings.

Priority 2: Anticipate industrial electrification in grid planning and prioritise connection requests with demand side flexibility

Challenge: Obtaining a grid connection is a major obstacle for industries seeking to electrify their heat supply. Despite the level of maturity of electrification technologies and their degree of availability, many industrial sites face multi-year delays to obtain new or upgraded sufficiently large grid connections. Such delays are incompatible with typical investment horizons and often lead to industrial users postponing or abandoning electrification projects that would otherwise have been technically feasible and economically attractive.

The challenge is particularly acute for electro-thermal storage systems. While these systems can enhance operational flexibility and cost efficiency, they also significantly increase the required connection capacity, with industries seeking to charge storage rapidly during the lowest priced hours of the day to minimise energy costs.

Policy response: As part of future electricity system development, grid planning and connection procedures need to anticipate the roll-out of electrification for industrial heat. Incorporating projected industrial demand into long-term grid expansion plans can help prevent capacity shortages and avoid the connection delays that currently constrain new projects. Although thermal storage increases the required connection size, it can also reduce overall grid stress by shifting electricity use to periods of low demand and low prices. If countries were to recognise this potential for flexibility, they could then introduce preferential treatment for projects that demonstrate demand-side management capabilities, for example, by allowing them to obtain grid connections faster or at lower cost. Such an approach would essentially reward flexibility, while simultaneously accelerating electrification and supporting a more resilient and efficient power system.

Selected policy examples: In the Netherlands, grid operators have introduced a prioritisation framework to address growing grid congestion. Instead of following a strict “first-come, first-served” approach, connection requests are now ranked on the basis of their contribution to alleviating congestion. Projects that can reduce their electricity use during peak hours or shift electricity use to non-peak hours, through demand-side management or the integration of thermal storage, for example, are given preferential access to the grid. This approach is particularly beneficial for industrial projects that pair heat electrification with thermal storage.

The Chinese government has issued guidelines to streamline grid connection for new capacity, including for industrial electrification projects. Measures include simplifying connection approvals for capacities below 10 MW, coordinated planning between industrial parks and grid operators and support for integrated projects involving source-grid-load-storage, where electrified heat and thermal storage contribute to flexible demand management.

In Southeast Asia, the ASEAN Power Grid initiative supports industrial electrification by strengthening cross-border electricity trade and enabling access to more affordable, reliable and renewable power, thereby reducing risks for industries seeking to electrify heat processes.

Priority 3: Reform energy taxation and levies for industrial users and provide lower network tariffs for flexible demand

Challenge: In many countries, fossil fuels that are used for industrial heat production are taxed at significantly lower rates than electricity – representing a legacy tax structure designed to protect energy-intensive industries. Such tax structures have today become a major distortion in the current decarbonisation context. Electricity used for heat is still subject to multiple levies and network charges, several of which were originally introduced to finance renewable energy support schemes. As a result, electric boilers and heat pumps face higher effective energy costs than fossil fuel boilers, even when electricity is supplied from renewable sources. This imbalance undermines the economic case for electrification and impedes the replacement of fossil fuels in industrial heat supply. It also discourages investment in electric technologies that are otherwise technically proven and increasingly competitive on a total-cost basis, when taxes and levies are neutral.

Policy response: Reforming energy taxation and levies is essential to create a level playing field between fossil fuels and electricity in industrial heat supply. Several countries have already taken steps to reduce or remove electricity taxes for industrial users as part of broader efforts to accelerate electrification. Such measures lower operating costs for electric boilers and heat pumps and improve investment confidence in low-emission technologies.

Equally important is the design of network tariffs, which can strongly influence the competitiveness of electrification. Some countries are introducing lower or more dynamic grid fees for industrial users that demonstrate demand-side flexibility. Examples include consumption adjustments in response to price signals, load shifting to off-peak hours, or use of thermal storage to avoid demand during system peaks. Such differentiated tariffs recognise the system value of flexibility and help to reduce congestion and defer costly grid reinforcements. Countries that reward flexible operation are in effect making electrification projects more economically attractive. They are also supporting grid stability and the integration of variable renewables.

Selected policy examples: To address growing grid congestion, the transmission system operator in the Netherlands has introduced flexible connection contracts that allocate capacity on the basis of off-peak usage. Under this scheme, large electricity users and generators can obtain grid access more quickly by accepting limits on operation during peak hours. The approach makes use of capacity (estimated at 9.1 GW, or more than 40% of the country’s current peak electricity demand) that remains unused outside peak periods. By tapping into off-peak capacity, the system operator can expand connection availability without immediate large-scale grid reinforcements. Denmark has introduced something similar with dynamic tariffs to incentivise industrial and other consumers to adjust their power consumption in response to real-time grid signals, thereby freeing up grid capacity during peak periods.

A notable trend in electricity taxes and levies for industry is the shift from electricity bill surcharges to general budget financing. This approach allows for targeted support for industrial electrification, while at the same time minimising distortion in electricity prices for other consumers. Germany, for example, has moved its renewable levy to a state-managed fund. Finland also provides reduced electricity tax rates for industrial users to enhance competitiveness, while Ireland ties tax relief directly to the share of renewable electricity consumed by industrial users.

In Southeast Asia, Singapore and the Philippines have developed demand response programmes, with different levels of maturity, as a means of rewarding flexible industrial electrification.

Priority 4: Provide targeted support for capital and operating costs and enable business model innovation to accelerate the roll-out of heat electrification technologies

Challenge: Industrial electrification often stalls as a result of the substantial upfront capital requirements, particularly for retrofits. Costs extend beyond new equipment and include process integration, production line modifications and grid connection upgrades. With tight profit margins and uncertainties concerning electricity prices, carbon pricing and long-term policy stability, many companies delay or scale down investment. The challenge is not only about implementing pilot or demonstration projects, but also about accelerating the large-scale roll-out of such projects. Financial hurdles are even more acute for first movers, who are forced to contend with the early-stage risks without a guaranteed competitive advantage.

Policy response: Policy makers can implement targeted policy support mechanisms to overcome high upfront capital requirements and mobilise private finance, thus contributing to the large-scale roll-out of industrial electrification. Governments could expand their support for capital and operating costs in the form of grants and concessional finance or carbon contracts for difference that can reduce initial investment risk. Tax incentives or rebates that directly lower overall project costs could also be used. Innovative business models such as the Energy-as-a-Service or Heat-as-a-Service models, along with heat pump performance contracts, could further de-risk investments and reduce payback periods. Moreover, increased governmental support for demonstration and pilot projects would help accelerate real-world performance data. It would also help to generate critical lessons on technology performance, regulatory barriers and business models, thus reducing investment uncertainty and risks.

Well-designed and sustainable finance taxonomies can act as a critical enabler for industrial electrification by clearly defining eligible low-carbon investments, lowering due diligence costs for financiers and improving access to capital through reduced risk premiums. Embedding all of these mechanisms in national industrial decarbonisation strategies would provide the long-term clarity and financial certainty needed for first movers.

Selected examples: In the European Union, coordinated EU and national-level instruments support the deployment of heat pumps, electric boilers and thermal storage. These instruments include relaxed state aid rules, auctions for industrial process heat decarbonisation under Innovation Fund, and national schemes in France, Germany and the Netherlands. The EU Sustainable Finance Taxonomy also explicitly classifies the manufacture and installation of heat pumps as eligible green activities, with criteria such as global warming potential limits and minimum efficiency thresholds. These initiatives help channel cheaper, lower-cost and low-emission capital into industrial electrification and de-risk investments.

China has mirrored this approach through equipment upgrade programmes, financial guidelines and treasury-backed concessional loans. Initiatives such as Zero-Carbon Industrial Parks integrate power, heat, cooling and storage at the level of an industrial park to enhance operational and investment flexibility. China's Green Bond Endorsed Project Catalogue (2021) supports clean-heating and energy-efficient investments, enabling heat pumps and other electrified heating projects to qualify for green finance labelling. Although the criteria are less technology-specific than those of the European Union, the framework nonetheless broadens access to lower-cost capital and supports the scale-up of industrial electrification. In Singapore, the Industrial Transformation programme under the Financing Asia's Transition Partnership initiative provides debt financing to industries seeking to decarbonise industrial processes.

Priority 5: Enhance skills and workforce capacity for industrial electrification

Challenge: While the technologies needed to electrify low-temperature industrial heat are mature, they have yet to be installed on a large scale. At present, only a limited number of service providers specialise in installing and maintaining electric boilers, heat pumps and related systems in industrial settings. A rapid scale-up will therefore require a significant expansion of qualified contractors, engineers and technicians. This need for skills extends not only to external service providers but also to employees within industry, particularly in small and medium enterprises. Employees will need to acquire the skills to operate and maintain these systems. Although these technologies are not inherently complex, their installation and operation require professionals with electrical backgrounds and appropriate certification, skills that many workers currently engaged in fuel-based heat systems do not necessarily possess.

Policy response: Policy makers and industry will need to take proactive steps in an effort to ensure that the workforce is ready to support the large-scale deployment of electric heating technologies. Integrating the subject of electrified heat systems into vocational and technical education programmes will be a first step, as would updating certification schemes to cover industrial applications. Supporting targeted retraining will also be important, not only for employees currently specialised in fossil fuel-based systems but also for public sector staff who will need to effectively engage with industrial players, and to apply and monitor regulations. For employees in industry, short-term targeted measures such as government-supported energy audits could help bridge knowledge gaps and build internal capacity. Partnerships between industry, training institutions and public agencies can help align curricula with real project needs and accelerate the creation of qualified service providers.

Selected examples: Several international initiatives demonstrate how workforce readiness can be strategically embedded into industrial energy transition planning, and how such planning could be easily replicated. For example, the European Battery Academy coordinates training initiatives to ensure the immediate roll-out of high-quality training across the European Union. EU Net-Zero Industry Academies (established through the Net-Zero Industry Act) are aiming to train thousands of people over a 3-year period, with approximately 100 000 people trained per academy. These academies offer training on solar energy, wind and hydrogen, as well as on raw material, with courses on heat pumps and other technologies forthcoming. National programmes in France and Germany integrate vocational retraining directly into heat transition policies, although retraining currently focuses primarily on heat in buildings. The UK Industrial Decarbonisation Skills Partnership similarly links clean energy incentives to apprenticeship and certification requirements, ensuring that labour supply grows in step with technology deployment. Support schemes for audits, such as those in Finland and Ireland, can also help in the short term to bridge knowledge gaps and build internal capacity.

In Asia, Japan’s Green Transformation Strategy and Singapore’s Green Skills Accelerator fund targeted reskilling on electrified industrial energy systems. Thailand’s 4.0 policy and Cambodia’s National Energy Efficiency Policy include incentives for training and capacity building. In Cambodia’s case, these efforts are specifically targeting the industrial sector, focusing on enhancing skills in efficient energy management and the deployment of advanced energy technologies. These examples demonstrate that aligning training, certification and investment frameworks under a coordinated policy umbrella is critical to avoid future skills bottlenecks and to enable the rapid roll-out of industrial electrification technologies.

Priority 6: Promote international collaboration on technical standards frameworks

Challenge: The absence of interoperable international technical standards and frameworks for industrial-scale heat pumps, electric boilers and energy storage systems (including electro-thermal energy storage, waste or excess heat storage) has clear consequences in terms of both the production and the deployment of such technologies. The lack of widely agreed performance metrics for industrial heat pumps (e.g. standardised definitions of coefficients of performance) limits the capacity for comparability, knowledge sharing and the large-scale integration of performance metrics into industrial processes. While residential and commercial heat pumps benefit from relatively mature and aligned standards, industrial-scale applications are currently governed by fragmented, sector-specific and often incompatible frameworks. Such fragmentation leads to increased certification costs, limits interoperability and poses constraints on market scale. Over-harmonisation, on the other hand, could mean imposing uniform technical templates that ignore process diversity and stifle innovation. A coordinated international approach is therefore important to align performance, safety and the interoperability of frameworks, while preserving flexibility for process-specific adaptation and technology evolution.

Policy response: It is important for policy makers, standardisation bodies and industry to pursue collaboration on industrial electrification frameworks. International organisations (e.g. the International Organization for Standardization, International Electrotechnical Commission, International Energy Agency Technology Collaboration Programmes) can help align core safety, performance and interoperability principles for industrial-scale heat pumps, electric boilers and thermal storage, while maintaining flexibility for process- and sector-specific adaptation. Establishing mutual recognition of testing and certification schemes, as well as joint demonstration and benchmarking initiatives, would then lower compliance costs and accelerate the technology transfer. Embedding these efforts into trade, industry and climate cooperation agendas could lead to predictable, cross-border market conditions that de-risk private investment and scale up industrial electrification world wide.

Selected examples: Emerging precedents from other sectors demonstrate that collaboration on technical and policy frameworks, rather than prescriptive-based standardisation, can accelerate industrial-scale decarbonisation. For example, the EU CertifHy platform for renewable hydrogen and the ISO/TC 265 framework for carbon capture and storage both illustrate how coordinated definitions, certification and monitoring can unlock investment without constraining technology choice. Similarly, the IEC 61850 for smart grids and Best Available Techniques mandated by the EU Industrial Emissions Directive show the effectiveness of interoperability and performance-based harmonisation.

In Southeast Asia, the ASEAN Sectoral Mutual Recognition Arrangements for energy equipment can provide a practical foundation for extending regional certification and compliance frameworks to industrial-scale heat pumps, electric boilers and electro-thermal energy storage. These experiences demonstrate that aligning testing, certification and data-exchange frameworks across jurisdictions offers the most viable path to scale up industrial electrification.

Annex

Abbreviations

ASEAN	Association of Southeast Asian Nations
bcm	billion cubic metres
CAPEX	Capital expenditure
CHP	Combined heat and power
CO_2	Carbon dioxide
COP	Coefficient of performance
CYN	Chinese Yuan
E-boiler	Electric boiler
EJ	Exajoule
ETES	Electro-thermal energy storage
EU	European Union
GDP	Gross Domestic Product
GHG	Green House Gas
GIZ	German Agency for International Cooperation
Gt	Gigatonnes
GW	Gigawatt
GWh	Gigawatt hour
HV	High voltage
km	kilometres
kV	thousand volts
kWh	kilowatt hour
LCOH	Levelised cost of heat
LNG	Liquified natural gas
Mt	Million tonnes
MVR	Mechanical vapour recompression
MW	Megawatt
MWh	Megawatt hour
NG	Natural gas
O&M	Operation and maintenance
PJ	Petajoule
PPA	Power purchase agreements
PV	Photovoltaic
SGHP	Steam generating heat pump
SHIP	Solar heat for industrial processes
TES	Thermal energy storage
TRL	Technical readiness levels
TW	Terawatt
TWh	Terawatt hour

UK	United Kingdom
USD	United States Dollar
VAT	Value-added tax

See the IEA glossary for a further explanation of many of the terms used in this report.

International Energy Agency (IEA)

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