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REGULATORY ASSISTANCE PROJECT

Some like it hot: Moving industrial electrification from potential to practice

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Contents

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Figures

Tables

Executive summary

Europe cannot fully decarbonise without dramatically reducing industrial emissions, which are responsible for 20% of its greenhouse gas emissions. Cuts are not being made anywhere near swiftly enough to achieve a 90% reduction by 2040 and net zero by 2050, with levels of industrial emissions having fallen only 8% in the last decade. The main source of emissions from industry is the burning of fossil fuels for heat used in processes ranging from food processing and papermaking to the production of chemicals, steel and cement.

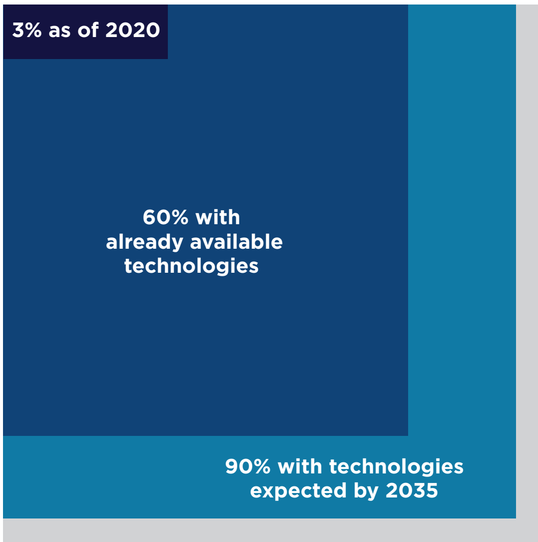
Electrification is emerging as the predominant strategy to decarbonise European industry. Only 3% of process heat was electrified as of 2020, but the potential is vast: 60% could be electrified today with commercially available technology, rising to 90% with technology expected to be mature by 2035 (see Figure ES 1).

Beyond reducing carbon emissions, electrification also offers the benefits of supporting the European clean tech industry, building on existing global leadership in areas such as large heat pump production; reducing Europe's dependence on fossil fuel imports; and improving efficiency and reducing pollution in the sector. Industrial electrification solutions are varied and versatile, leveraging technology options that can offer better productivity, process control, safety and flexibility than their fossil fuel counterparts.

Given this potential, why is the electrification of industry happening so slowly? The industrial sector comprises a great diversity of companies, products and processes, and they face many different barriers to electrification, some of them specific to certain processes. These barriers can be grouped into four categories:

- **Economic** — associated with investment and operating costs, risks and expected returns.
- **Infrastructure** — including the need for connections to the electricity grid that provide adequate capacity.
- **Knowledge** — of the available technologies and their suitability and benefits.
- **Technological** — in particular associated with high-temperature processes.

Figure ES 1. Current and potential electrification of industrial process heat in Europe



Source: RAP illustration based on Fraunhofer ISI. (2024). Direct electrification of industrial process heat: An assessment of technologies, potentials and future prospects for the EU. Agora Industry.

Accelerating industrial electrification in line with climate and energy goals will require a mix of approaches to comprehensively address these barriers. Policymakers have a number of tools and policy instruments available. In this report we organise them into five groups, each addressing a different need or type of barrier:

- **Define the course and set boundaries** through regulation, targets and standards.
- **Improve economic conditions** through energy and carbon pricing, fiscal incentives and targeted support.
- **Meet infrastructure needs** through grid planning and optimisation and providing access to value streams from flexibility markets.
- **Close the knowledge gap** by expanding information and supply chain integration.
- **Tackle technological barriers** by supporting research and development.

Decision-makers can design a combination of specific measures that best fits their context and goals, drawing on the policy tools in these five groups.

10-point action plan for industrial electrification in the EU

Decarbonising industry and improving economic competitiveness will be key priorities for the European Commission in the coming years, including through delivering the Clean Industrial Deal and a targeted Electrification Action Plan. The Regulatory Assistance Project offers the following 10-point action plan for the European Commission to promote industrial electrification by putting in place measures addressing five key needs or barriers.

Define the course and set boundaries

Include a clear focus on industrial electrification in the forthcoming EU Electrification Action Plan, to support delivery of the Clean Industrial Deal, with the help of a high-profile task force. The task force would develop ideas for advancing industrial electrification in Europe.

Set industry electrification targets in line with achieving 60% industrial electrification by 2050 and 90% economywide emissions reduction by 2040. The targets should be complemented with clear roadmaps for industrial subsectors and could be implemented as part of a new 'Electrification Directive.'

Set tighter standards on new industrial installations through the Industrial Emissions Directive. For example, these could include a 'zero-carbon' standard for lower-temperature installations (below 500 degrees Celsius) and energy efficiency standards for retrofitting industrial installations.

Improve economic conditions

Support Member States in creating a favourable climate for investments in industrial electrification. Provide guidance on rebalancing taxes and levies on electricity and fossil fuels and ways that Member States could provide financial support to industry.

Ensure state-aid guidelines do not pose a barrier to industrial electrification, by allowing operational support for direct electrification and by highlighting options in the guidance given to Member States.

Meet infrastructure needs

Fully consider industrial electrification in the implementation of the Action Plan for Grids. This includes requiring network planning in coordination with industrial users, setting network tariffs that incentivise better use of grid capacity, allowing cable pooling, and giving priority to flexible users.

Support improved access for industry to demand-side flexibility markets.

- Ensure swift and full implementation of the revised Energy Market Directive.
- Collect and consolidate data across all European countries on market barriers for demand-side resources, including indirect discrimination.
- Use gathered evidence to articulate and standardise best-practice principles to ensure markets actively facilitate all demand-side flexibility, including smaller-scale resources.
- Require proper consultation with demand-response providers, consumer groups and other newer stakeholders.

Close the knowledge gap

Launch a study on how electrification can drive industrial competitiveness in the EU. This will help decision-making on how to best target support measures and regulatory interventions and will raise awareness of the urgency of direct electrification.

Tackle technological barriers

Ensure EU funding programmes support industrial electrification, including through earmarked funds and improved funding accessibility.

Ensure adequate support for small and medium-sized enterprises through intermediaries and the sharing of good practices. Improve funding accessibility through project bundling, standardisation or reduced administrative requirements.

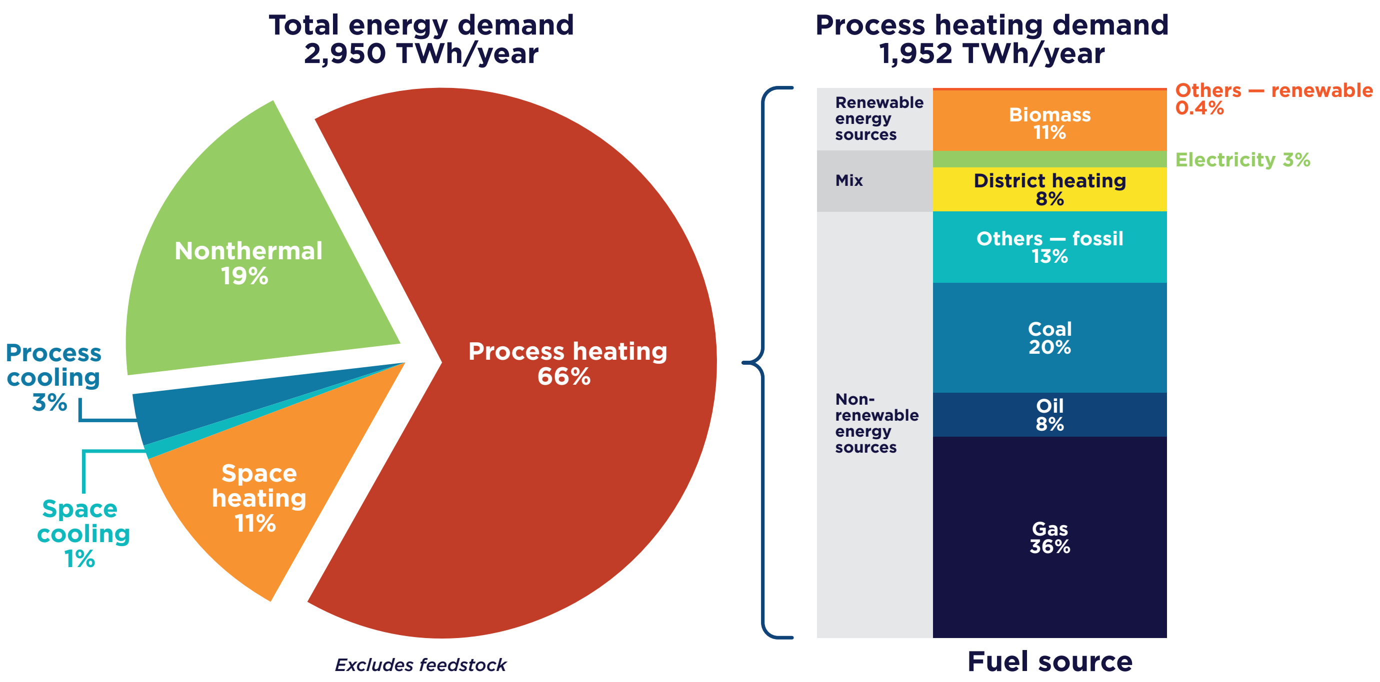
Introduction: Putting industry on the pathway to net zero

The decarbonisation of European industry is high on the agenda for the 2024-2029 European Commission: Its political guidelines[1] point to the delivery of a Clean Industrial Deal and an Industrial Decarbonisation Accelerator Act. In addition, the commissioner for energy and housing has been tasked with setting out an Electrification Action Plan with a focus on industry.[2]

And rightly so: Industry[3] is the third-largest energy user in the European Union (EU) after transport and households, amounting to 25% of total final demand.[4] It's also responsible for 20% of Europe's greenhouse gas emissions. Carbon and other emissions from industry remain stubbornly high and fell by a mere 8% over the last decade,[5] well short of what is needed to meet the EU's ambitious climate goals.

The majority of energy used in the sector is for heat in industrial processes, which is generated mainly by burning gas, coal and oil (see Figure 1).[6] This heavy reliance on fossil fuels makes process heat responsible for around 75% of industrial greenhouse gas emissions.

Figure 1. Industrial energy use and process heat sources in Europe



Source: de Boer, R., Marina, A., Zühlsdorf, B., Arpagaus, C., Bantle, M., Wik, V., Elmegaard, B., Corberán, J., & Benson, J. (2020). Strengthening Industrial Heat Pump Innovation. Decarbonizing Industrial Heat

1 von der Leyen, U. (2024, 18 July). *Europe's choice: Political guidelines for the next European Commission 2024-2029.* European Commission. https://commission.europa.eu/document/download/e6cd4328-673c-4e7a-8683-f63ffb2cf648_en?filename=Political%20Guidelines%202024-2029_EN.pdf

2 von der Leyen, U. (2024, 17 September). *Mission letter to Dan Jørgensen, commissioner-designate for energy and housing.* European Commission. https://commission.europa.eu/document/download/1c203799-0137-482e-bd18-4f6813535986_en?filename=Mission%20letter%20-%20JORGENSEN.pdf

3 Industry includes chemicals, steel, paper, food and beverage, ceramic and glass, machinery, cement, transport equipment, nonferrous metals, wood and textiles.

4 Eurostat. (2024a, 6 June). *Final energy consumption in industry — detailed statistics.* https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_industry_-_detailed_statistics

5 Eurostat. (2024b). *Greenhouse gas emissions by source sector* [Data set]. Retrieved 13 February 2024 from https://ec.europa.eu/eurostat/databrowser/view/env_air_gge/default/table?lang=en&category=env.env_air.env_air_ai

6 de Boer, R., Marina, A., Zühlsdorf, B., Arpagaus, C., Bantle, M., Wik, V., Elmegaard, B., Corberán, J., & Benson, J. (2020). *Strengthening industrial heat pump innovation. Decarbonizing industrial heat.* TNO. https://repository.tno.nl/SingleDoc?find=UID%206094902d-a680-4861-82d9-3bf6e31a4548

Electrification has the potential to play a large role in decarbonising European industry by enabling industrial facilities to efficiently use energy that increasingly comes from clean sources. More than two-thirds of electricity in the EU came from renewable energy or nuclear generation in 2023. As the grid continues to decarbonise, electrification could cut industrial carbon emissions by 78%, almost eliminating energy-related emissions, with feedstock use and chemical processes primarily responsible for the remainder.[7]

The critical role of electrification is also reflected in recent analysis by the European Commission of the pathways to meet the 2040 climate goal of reducing net greenhouse gas emissions by 90%. The analysis shows that to meet the climate and energy goals set in the European Green Deal, the share of electricity in final energy use economywide will need to almost double from 33% in 2022[8] to more than 60% in 2050.[9] International analysis comes to similar conclusions.[10]

The main area of focus for electrification in industry will need to be process heat because it plays such a major role in industrial energy use (66%) and currently is being generated largely (77%) by burning fossil fuels. Process heat is therefore a strong contributor to industrial carbon emissions and represents a huge untapped potential for reductions. There are, however, many barriers standing in the way of the widespread electrification of industrial energy use.

This report focuses on the electrification of industrial process heat. In four sections, it sets out how to bridge the gap between current rates of electrification and what's possible:

- Section 1 provides an overview of the **potential for electrification** of industry, the **technologies** available to do so and the **benefits** of tapping into this potential.
- Section 2 looks at the most important **barriers** to industrial electrification in four categories: economic, infrastructure, knowledge and technological.
- Section 3 lays out a five-part menu of **policy options** that can be put in place to overcome the four types of barriers.
- Section 4 offers **10 concrete measures** the European Commission and national governments can take to support electrification.

Throughout the report, the authors highlight key takeaways and provide examples of electrification policy in action.

7 Madeddu, S., Ueckerdt, F., Pehl, M., Peterseim, J., Lord, M., Kumar, K.A., Krüger, C., & Luderer, G. (2020). The CO_2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat). *Environmental Research Letters, 15*(12): 124004. https://doi.org/10.1088/1748-9326/abbd02

8 Eurostat, 2024a.

9 European Commission. (2024). *Supplementary information: data for the graphs presented in the impact assessment* (SWD(2024) 63 final). https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en#documents

10 International Energy Agency. (2023). *A renewed pathway to net zero emissions.* Net zero roadmap: A global pathway to keep the 1.5 °C goal in reach. https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach/a-renewed-pathway-to-net-zero-emissions; International Energy Agency. (2021). *Net zero by 2050: A roadmap for the global energy sector.* https://www.iea.org/reports/net-zero-by-2050; Intergovernmental Panel on Climate Change. (2022). *Climate change 2022 — mitigation of climate change.* Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/9781009157926

Section 1: The potential for industrial electrification and its benefits

Key takeaways

- The potential for electrification is vast. Up to 78% of Europe's industrial energy use and 60% of its process heating demand can be electrified with existing technologies. It will be possible to electrify more than 90% of process heating when technologies under development enter the market by 2035 at the latest.
- There are many industrial electrification technology solutions for every sector's needs. The options range from mature and widely used technologies such as electric boilers, industrial heat pumps and resistance heating to novel technologies such as plasma torches and shock-wave heating.
- In addition to reducing carbon emissions, electrification brings many other benefits such as strategic independence from fossil fuel imports, improved efficiency and reduced pollution of other kinds.

Overall potential for electrification

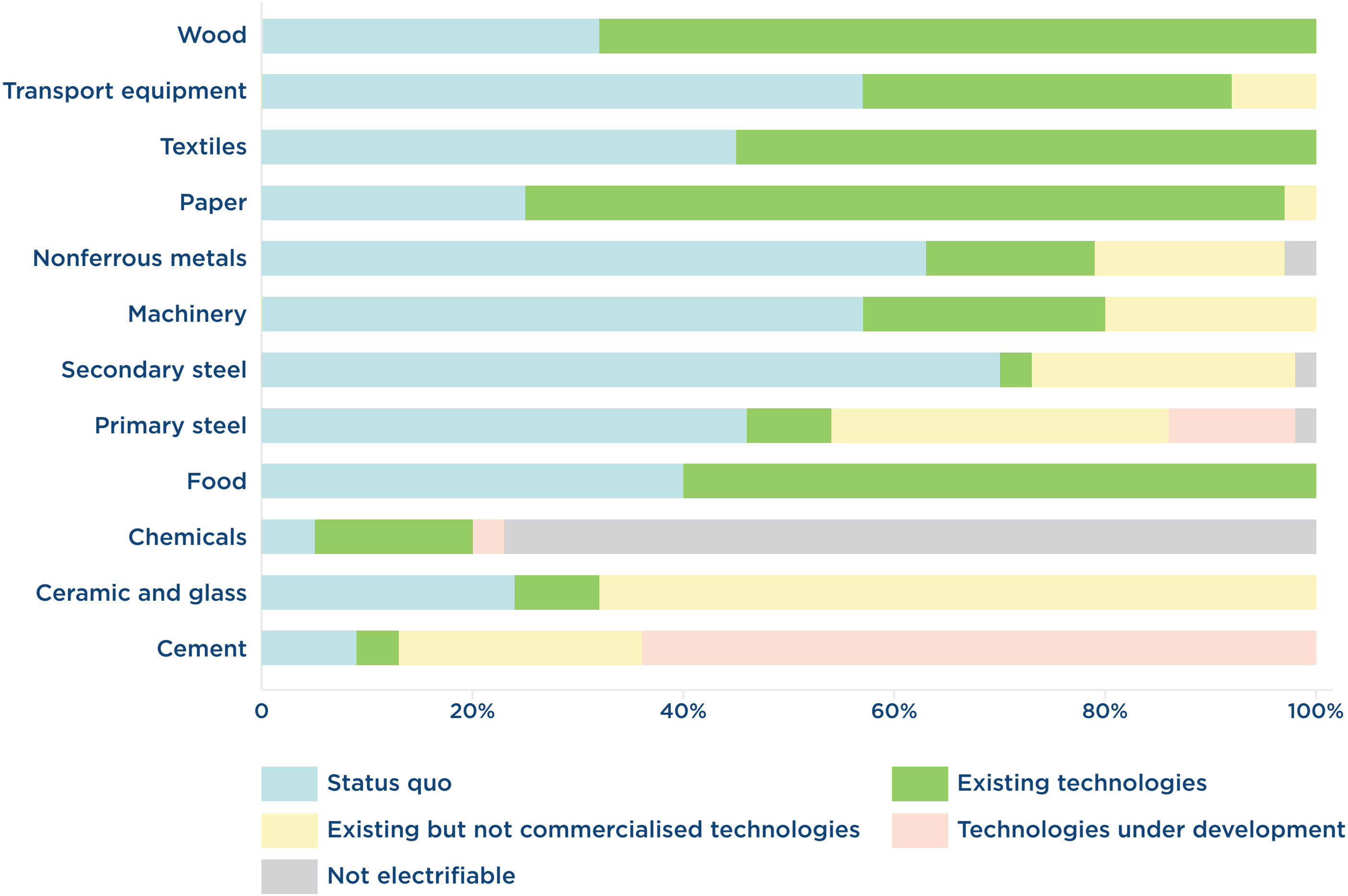
Currently, electricity provides one-third of final industrial energy use in Europe, mostly to power mechanical equipment and lighting. The potential for industrial electrification is significantly larger than what has been realised so far: Up to 78% of Europe's total industrial energy use could be electrified today with existing technologies.[11]

Figure 2 on the next page shows the potential for electrification in different industrial sectors.[12] Only the steel, other metals and chemicals sectors have fuel needs that, for now, cannot be met through electrification. These needs include non-energy use such as feedstocks, as well as final energy use applications where no electric technology exists or is under development.

Pixabay/yetanotheremailaddressaga

11 Madeddu et al., 2020.
12 Madeddu et al., 2020.

Figure 2. Overall electrification potential in EU industry



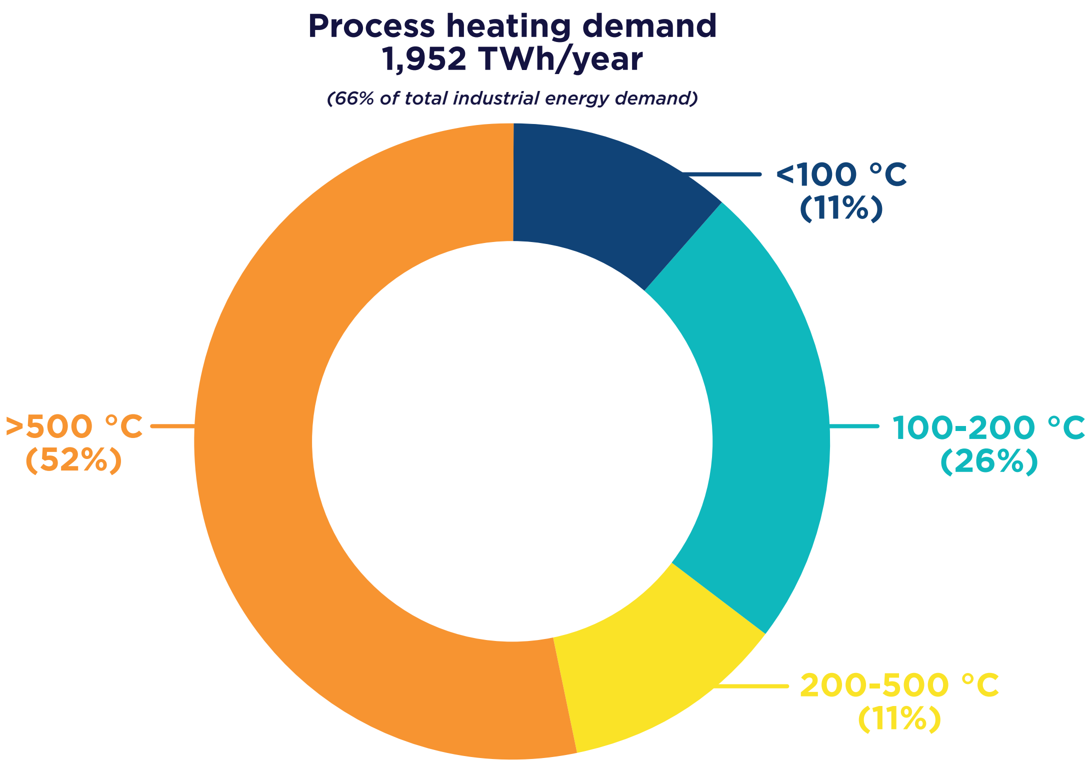
Data source: Madeddu, S., Ueckerdt, F., Pehl, M., Peterseim, J., Lord, M., Kumar, K.A., Krüger, C., & Luderer, G. (2020). The CO_2 Reduction Potential for the European Industry via Direct Electrification of Heat Supply (Power-to-Heat)

Process heating, as a subset of industrial energy use, also shows great potential for electrification. Around 60% could be electrified today with existing technologies, rising to 90% with technologies likely to become mature by 2035[13] — and yet, only 3% of industrial process heat in the EU was electrified by 2020.[14]

The potential for process heat electrification varies by sector and temperature needs and will continue to improve as new technologies come to market. Currently, 37% of process heat demand is for temperatures below 200 degrees Celsius, usually in the form of hot water and steam (see Figure 3).[15] This can be seen as 'low-hanging fruit' that can be electrified with renewable energy and highly efficient technologies such as heat pumps.[16] Demand for heat over 500 degrees (52%) also increasingly can be met through electrification using commercially available technologies, as discussed in the next subsection.

13 Fraunhofer ISI. (2024). *Direct electrification of industrial process heat: An assessment of technologies, potentials and future prospects for the EU.* Agora Industry. https://www.agora-industry.org/publications/direct-electrification-of-industrial-process-heat
14 de Boer et al., 2020.
15 de Boer et al., 2020.
16 Fraunhofer ISI, 2024.

Figure 3. Process heating demand in Europe by temperature range



Source: de Boer, R., Marina, A., Zühlsdorf, B., Arpagaus, C., Bantle, M., Wik, V., Elmegaard, B., Corberán, J., & Benson, J. (2020). Strengthening Industrial Heat Pump Innovation. Decarbonizing Industrial Heat

Technologies available to industry

Multiple solutions to electrify industrial process heat are available, ranging from mature and widely used technologies such as electric boilers, industrial heat pumps and resistance heating to novel technologies such as plasma torches and shock-wave heating. Table 1 on the next page offers more detail on the technologies themselves and their applications, benefits and suitability for different temperature ranges.[17]

Electrification of low- to mid-temperature processes is likely to be able to scale up faster than high-temperature processes. That's because solutions are readily available, upfront investment costs are smaller, and the energy savings — especially with heat pumps — can improve the business case better than for high-temperature processes. In particular, electric boiler deployment could be scaled up quickly, as this technology is a like-for-like exchange for existing fossil-fuel boilers and is highly versatile. But, given their lower efficiency than heat pumps, e-boilers preferably would be used for flexibility purposes and in combination with thermal storage. Integration of heat pumps can require more process adaptation, especially when redesigning installations for waste heat recovery.

17 Fraunhofer ISI, 2024; Rightor, E., Whitlock, A., & Elliott, R. (2020). *Beneficial electrification in industry.* American Council for an Energy-Efficient Economy. https://www.aceee.org/research-report/ie2002

Table 1. Electrification offers many technologies for different sectors' needs

Technology	Description	Maximum temperatures (degrees Celsius) Now	By 2030
Industrial heat pump	Commercially available, with growing installation rates across Europe. Highly efficient for lower-temperature heating in all sectors. Can be coupled with a waste heat source to increase efficiency and/or achieve higher temperature lifts cost-effectively. *Example uses: hot water and steam generation in paper, food and chemical industries*	165	>200
Electric boiler	Widely established alternative to fossil-fuel boilers and combined heat and power generation. Versatile, easy to install. Potential for higher temperatures than heat pumps but less efficient. *Example use: steam generation in paper, food and chemical industries*	500	500
Shock-wave heating	Commercial launch expected in 2025 for industrial applications at medium to high temperatures. *Example uses: cement and chemical industries*	700-1,000	1,500
Combined thermal storage	Currently used at a small scale in industry. Frequently uses resistance heating to generate heat for storage, such as in bricks or salt. Can reach higher temperatures than water-based storage.	1,000	1,500
Electric arc furnace	Mature technology providing high-temperature heat for steel production from scrap and melting metals. Substantial energy savings compared with steel production from primary material.	1,800	1,800
Resistance heating	Broadly applicable for medium to high temperatures. Efficient but has a high power requirement. Offers precise temperature control, rapid heating and low maintenance cost. *Example uses: storage, calcination, production of aluminium and glass*	1,850	2,000
Induction heating	Established solution for high-temperature heat. Less efficient than resistance heating. *Example use: metal production*	3,000	3,000
Plasma torch	Innovative alternative to fossil-fuel burners but less efficient. *Example uses: cutting/welding/melting metal, in future for cement and clinker industries*	5,000	5,000

Sources: Based on Fraunhofer ISI. (2024). Direct Electrification of Industrial Process Heat: An Assessment of Technologies, Potentials and Future Prospects for the EU; and Rightor, E., Whitlock, A., & Elliott, R. (2020). Beneficial Electrification in Industry

The food and beverage, paper and chemical industries are prime candidates for accelerated electrification. In addition, a broad variety of non-energy-intensive industries, ranging from textiles to wood products and mining, have significant low-temperature heat demand and can be quick wins for electrification.[18] These sectors include small- and medium-sized enterprises, requiring action by more stakeholders to achieve large-scale deployment (see Section 2 on barriers).

In addition to electric end-use technologies, thermal storage increasingly plays an important role as an enabler of the electrification of heat. Thermal storage allows facilities to store lower-cost electricity to be used during periods of higher electricity costs and helps with managing the electricity system.

18 Fraunhofer ISI, 2024.

Thermal storage: Baseload heat from variable sources

Energy storage is key to ensuring that supply can reliably meet demand, as production and use of energy do not always overlap in time. As we phase out fossil fuels and integrate more variable sources such as wind and solar into our energy systems, the need for storage increases. Thermal energy storage, or storing energy as heat, can make an important contribution to meeting this need, as it is generally cheaper and enables longer storage than electric energy storage. The International Renewable Energy Agency expects global installed capacity of thermal storage to triple from 234 GWh in 2019 to more than 800 GWh by 2030.[19]

There are different thermal storage technologies and media, including water, bricks, ceramics, sand, rocks and metals. Important criteria for choosing the medium include affordability, accessibility and environmental attributes, as well as the ability to meet the targeted temperature and operating requirements. Currently, most thermal storage systems are water based, but increasingly systems using other media are becoming commercially available. For short durations of hours or days, heat can be stored in water in pipes and small insulated tanks (low to medium temperatures) or in bricks in a container (high temperatures). Larger tanks in the ground, boreholes and aquifers can be used to store heat for both short and longer periods (days to months).

A complete thermal storage system for industrial electrification consists of the storage vessel combined with electrified heat generation — such as a heat pump, electric boiler or resistive heaters — and heat delivery equipment (e.g., steam pipes, compressors, heat exchangers).

Benefits of decarbonising industry through electrification

If done well, electrification is a winning strategy for a) tackling emissions in the industrial sector, b) supporting European strategic independence, c) harnessing unused clean heat, d) reducing pollution, e) unlocking wider power system benefits, and f) improving industrial processes and their associated benefits. Speeding up electrification will require improving the current regulatory and enabling framework, since incumbent technologies persist in many locations because they cost less to operate.

Cutting carbon emissions and boosting energy efficiency

Using lower-carbon electricity instead of carbon-intensive fossil fuels reduces emissions. Over two-thirds of European electricity generation in 2023 was from low-carbon sources (renewables and nuclear), and the carbon intensity of electricity continues to decline.[20] Electrified end uses mostly have higher efficiency than combustion technologies, meaning that electrification will lead to emissions reductions through primary energy savings.[21] This efficiency increase can offset the efficiency loss of generating electricity from fossil fuels, meaning that electrification reduces emissions even in countries with high-carbon electricity.

19 International Renewable Energy Agency. (2020). *Innovation outlook: thermal energy storage.* https://www.irena.org/publications/2020/Nov/Innovation-outlook-Thermal-energy-storage
20 Ember. (2024). *European electricity review 2024.* https://ember-energy.org/latest-insights/european-electricity-review-2024/
21 Rosenow, J., & Eyre, N. (2022). Reinventing energy efficiency for net zero. *Energy Research & Social Science, 90*: 102602. https://doi.org/10.1016/J.ERSS.2022.102602

Supporting European strategic independence

Electrification of industrial heat is not only beneficial from a climate perspective but will also enhance Europe's strategic independence. Gas and coal imports could be significantly reduced, replaced with locally available electricity from renewable sources. Moreover, due to the much-increased energy efficiency of electrification solutions, it would not be necessary to replace the entirety of industrial fossil energy use.

A strong push for industrial heat electrification also supports the expansion of Europe's clean tech industry, in line with the goals of the Net-Zero Industry Act. For example, many of the world's producers of industrial heat pumps, a key electrification technology, are in Europe and would benefit from increased demand for their products, which would result in multiple macroeconomic benefits for the European economy.[22]

Harnessing unused ambient, geothermal and waste heat

Electrification of industrial heat can enable the use of vast amounts of ambient, geothermal and waste heat. Ambient heat — the heat naturally present in the air, water and ground — and geothermal heat deep below the Earth's surface can be effectively used by industrial heat pumps, particularly for low- and mid-temperature processes. Waste heat already present at or near industrial sites can be reused, frequently in connection with heat pumps, reducing overall heat demand. The waste heat potential is estimated at around 300 TWh per year,[23] which could cover around one-third of total process heat demand below 500 degrees Celsius.

By preventing or reducing on-site fuel combustion, electrified processes avoid the release of pollutants like nitrogen and sulphur oxides and particulate matter, thus benefitting the health of workers and neighbouring communities.

Reducing local pollution

Industrial electrification can deliver significant reductions in local pollution. By preventing or reducing the need for on-site fuel combustion, electrified processes avoid the release of pollutants like nitrogen and sulphur oxides and particulate matter, thus improving local air quality and benefitting the health of workers and people in neighbouring communities. In some cases, it may also be easier and cheaper to obtain permits for electric heating solutions than for combustion-based heating in areas with high pollution levels or close to protected nature conservation areas. This is already the case in the Netherlands, where enforcement of the EU Habitat and Water Framework directives[24] has put limits on new economic activities that cause nitrogen deposition, including on-site fossil fuel combustion.[25]

22 Arpagaus, C. (2023a, 22 February). *High-temperature heat pumps for industrial applications — new developments and products for supply temperatures above 100 °C* [Webinar slides]. Australian Alliance for Energy Productivity. https://022fdef7-26ea-4db0-a396-ec438d3c7851.filesusr.com/ugd/c1ceb4_4c566f4ba92f4db4a7ee45a2ec951ff3.pdf

23 Papapetrou, M., Kosmadakis, G., Cipollina, A., La Commare, U., & Micale, G. (2018, 25 June). Industrial waste heat: estimation of the technically available resource in the EU per industrial sector, temperature level and country. *Applied Thermal Engineering*, *138*: 207-216. https://doi.org/10.1016/j.applthermaleng.2018.04.043

24 European Commission. (2024). *The Habitats Directive*. https://environment.ec.europa.eu/topics/nature-and-biodiversity/habitats-directive_en; European Commission. (2024). *Water Framework Directive*. https://environment.ec.europa.eu/topics/water/water-framework-directive_en

25 Stokstad, E. (2019, 6 December). Nitrogen crisis threatens Dutch environment—and economy. *Science, 366*(6470): 1180-1181. https://doi.org/10.1126/science.366.6470.1180

Producing system benefits through increased flexibility

Industrial electrification can increase the penetration of renewable electricity and support the balancing of power systems by providing flexibility services.[26] The size of industrial electrical loads, in total and per user, means that electrification could play a significant role in providing demand response — for example, increasing heat production when plenty of low-cost renewable electricity is available and reducing production at times of high electricity consumption and low renewable electricity generation.[27] Thermal energy storage is a key technology, as the storage of heat for later use will allow heat production to ramp down temporarily to reduce electricity demand. Coupled with smart management systems, industrial installations with thermal storage can provide for the growing need for flexibility in the renewables-based electricity system. At the same time, they can benefit from cost savings (provided that tariffs accurately reflect system costs) and generate revenue from offering flexibility services to the market.

Improvements to process and product

Industrial electrification solutions can leverage a wide range of technological and physical principles, making them more versatile than their fossil fuel-based counterparts. For example, microwave heating for drying processes gives better control, faster processing and reduced waste compared with combustion-based technologies, improving plant efficiency and productivity.[28] Although process and product benefits will be specific for each industrial site and application, frequently found benefits include easier installation, improved worker safety, faster and more controllable processing (heating, drying, cooling), and improved opportunities for automation and flexible use. Such non-energy benefits have been shown to increase the return on investment in process heat electrification solutions.

26 Strategy&. (2021). *Unlocking industrial demand side response.* TenneT. https://netztransparenz.tennet.eu/fileadmin/user_upload/Company/News/Dutch/2021/Unlocking_industrial_Demand_Side_Response.pdf

27 Johnson, A., Fraser, A., & York, D. (2024). *Enabling industrial flexibility: aligning industrial consumer and grid benefits.* American Council for an Energy-Efficient Economy. https://www.aceee.org/white-paper/2024/02/enabling-industrial-demand-flexibility-aligning-industrial-consumer-and-grid

28 Rightor et al., 2020.

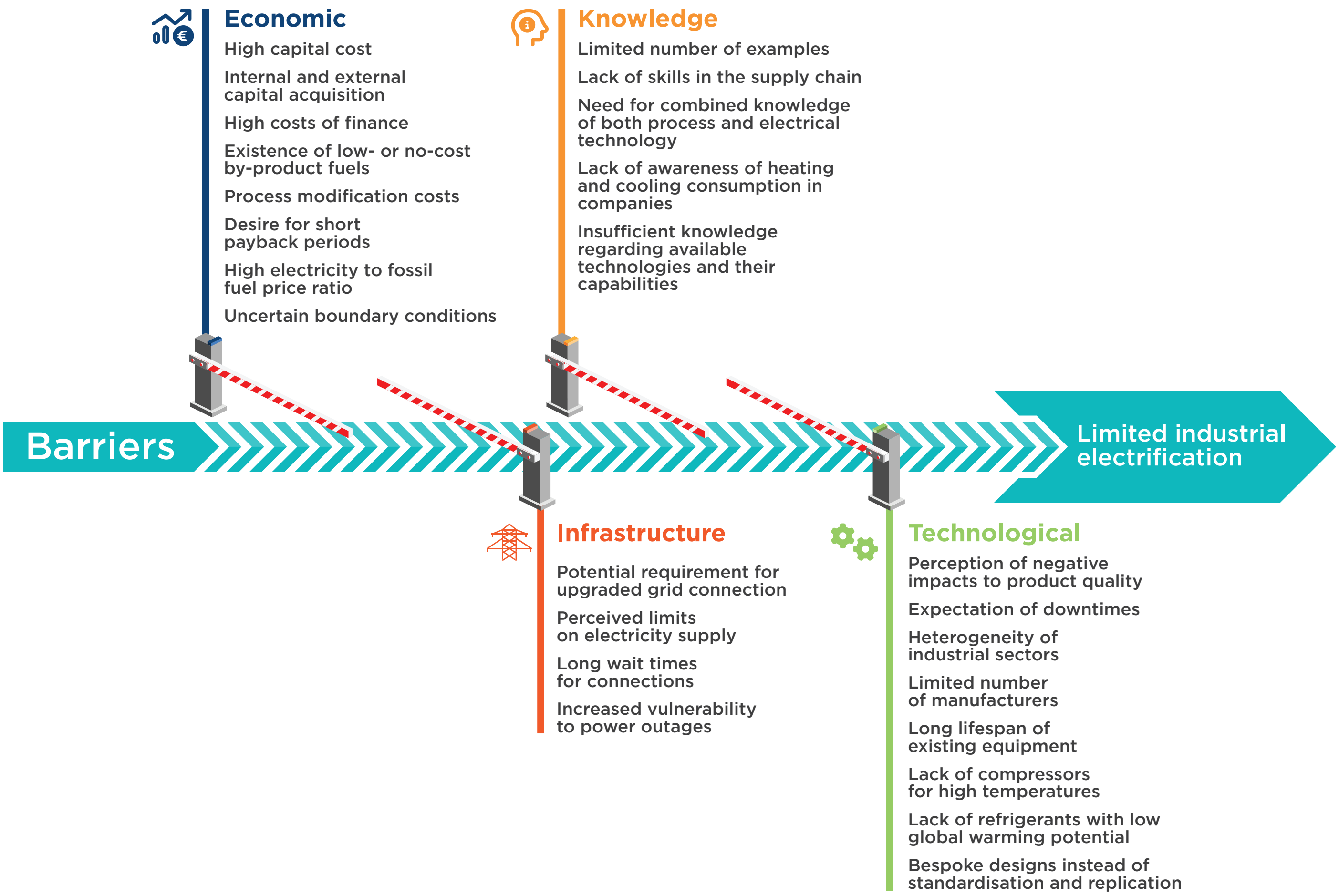
Section 2: What is holding back industrial electrification?

Key takeaways

- Multiple economic, infrastructure, knowledge and technological barriers are holding back industrial electrification.
- Barriers are particularly significant for retrofitting existing facilities, where electrification is more complex.
- The multitude of barriers suggests that a policy mix will be needed to address them comprehensively.

The barriers to industrial electrification can be grouped into four categories: economic, infrastructure, knowledge and technological (illustrated in Figure 4). Given the large variability in industrial processes, many of the barriers apply only in specific cases (see the Annex for more detail).

Figure 4. Barriers to industrial electrification



Because many industries are highly sensitive to costs due to competitive pressures and profit expectations, **economic barriers** are among the most frequently mentioned in literature and by experts surveyed during research for this report. For one thing, there is the high capital expenditure needed to buy new equipment and adapt processes when making the switch. At the same time, high electricity prices compared with fossil fuels can limit operational cost savings. Add to these factors expectations of very short payback times, increased capital costs due to recent higher interest rates, and uncertainty on future fuel and carbon prices and demand for industrial products, and it's clear that economic conditions are a key barrier to capital-intensive investments in electrification.

Electrification relies on supporting **infrastructure**. As renewable electricity generation and electrification of energy use pick up in Europe, electricity grid congestion is becoming an increasingly pressing issue in many areas. Industrial installations can face long waiting times for new connections, uncertainty about the potential to upgrade existing connections and doubts about the supply of electricity. Even in cases where there are not necessarily grid or supply issues, uncertainty about future availability of grid capacity hinders the shift to electrification.

Knowledge barriers also hinder progress. Even though many electrification technologies are mature and commercially available, there is still a lack of awareness among both industrial heat users and energy advisors on the available technologies, their capabilities, their benefits and the business case behind them.

Finally, the biggest **technological barriers** are related to higher-temperature processes. Although many innovative solutions for high-temperature processes exist (see the Annex for details), commercial readiness is lower than in heating solutions for low- and mid-temperature processes. Another frequently mentioned barrier is the lack of standardisation in design, limiting replication opportunities and increasing the cost of investment and construction time.

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Electrifying heat processes: Retrofitting vs. new build

It is important to distinguish between retrofitting existing installations and constructing new ones. In the simplest cases, existing fossil fuel-based heaters can be replaced with electrified equivalents with minimal impact to the manufacturing process — for example, swapping a gas boiler for an electric boiler.

In more complex cases, electrification can happen only with more substantial modifications to the manufacturing process, potentially requiring changes to the site layout or even to which feedstock inputs can be used. Electrification of steelmaking is a good example of this: Traditional steelmaking via blast furnaces uses virgin iron as input, whereas electric arc furnaces are fed a mix of recycled steel and direct reduced iron which has been processed from ore.

Generally, electrifying industrial processes in new-build facilities is easier than retrofitting existing installations. New facilities can be built in locations with low electricity prices, good grid availability and supportive regulatory frameworks, and installation and site design can be optimised for electrification. In Europe, however, it is likely that the majority of industry will have to electrify through retrofitting and in some cases early retirement of existing equipment due to the high maturity of industry, highly integrated supply chains, and limited availability of new sites.

Challenges for retrofitting

- Higher upfront costs due to, for example, site layout changes and potential earlier write-off of replaced installations.
- Potential loss of revenue due to downtime during implementation of the retrofit.
- Need for planning. Electrification is likely to involve a system change, rather than an equipment change, usually requiring the services of design experts.
- Space constraints.
- Grid availability at the current connection point.
- Process integration constraints.
- Labour force impacts. Electrified installations likely require a different skill set and/or less labour.

Opportunities for retrofitting

- When equipment reaches its end of life, it's likely cheaper to retrofit than to develop a new site, as some of the infrastructure and administrative requirements usually are already in place.
- High cost-effectiveness due to the hybrid use of heaters. Existing fossil-fuel heaters could be used in parallel with, or as backup for, new electrified installations. For example, electric boilers — possibly coupled with thermal energy storage — could run only when electricity prices are low or when using renewable electricity generated on site, minimising operating costs.

Section 3: Designing a policy mix for industrial electrification

Key takeaways

- The menu of policy options to support industrial electrification is long and varied.
- Combining policies is key to driving industrial electrification.
- Few countries have implemented ambitious electrification policies, and the existing EU framework has room for improvement.

Although industrial decarbonisation is increasingly on the agenda at both the EU and national level, only a few countries have put in place targeted measures to support electrification. The size of the challenge requires more action and more urgency.

A mix of policies (illustrated in Figure 5 on the next page) is needed to promote industrial electrification and tackle the multiple and diverse barriers industry faces. A targeted strategy for industrial electrification needs to include, for example, elements of regulation and standards, pricing, taxation, subsidy provision, voluntary agreements, information provision, value chain development, and support for research and development. We present these policy options in four groups that respond to the four types of barriers identified in Figure 4, with an additional group of policy tools dedicated to defining political ambition and boundaries.[29] For each group of policy options, we also offer real-world examples of their application.

kaband/Shutterstock.com

29 Examples of policies in place at both the EU and national level in this section were gathered through an expert survey, literature study and an analysis of EU Member State national climate and energy plans.

Figure 5. Policy instruments for accelerating industrial electrification

Define the course and set boundaries

Regulation, targets and standards

A range of regulatory tools is available for policymakers to set a clear direction of travel with backstops. These tools provide certainty on future expectations for industrial stakeholders and their supply chains. Voluntary agreements and targets can raise urgency among all stakeholders, while binding targets can ensure governments or industrial actors achieve specified decarbonisation and electrification goals. Phaseout dates for fossil fuel use, or technology/process use or replacement, provide clear boundaries.

Regulatory instruments can play an important role in driving electrification by, for example, setting up a system of standards, certification and labelling for low-carbon industrial products so purchasers can be certain of what they are buying. Such a low-carbon product standard could then also be used in green procurement by governments to drive demand for low-carbon industrial products. Efficiency and emissions standards could also be set for new equipment or the construction of greenfield installations.

Examples: Regulation, targets and standards

The **Renewable Energy Directive** requires Member States to increase the share of renewable heat by 1.6 percentage points per year between 2021 and 2030. Electrification of industrial heat can make a considerable contribution to meeting these targets.

The **Energy Efficiency Directive** sets obligatory annual energy savings targets (final energy) for Member States. For 2024-2025 the target is 1.3%, for 2026-2027 the target is 1.5%, and from 2028 the target is 1.9% per year. The directive also requires large enterprises to undertake energy savings audits and identify cost-effective energy savings measures. Electrification of industrial energy use can deliver significant primary and final energy savings.

EU taxonomy for sustainable activities: The EU has developed the 'green taxonomy' to promote sustainable finance and to direct investment to economic activities supporting the EU's climate, energy and Green Deal targets.[30] The taxonomy is a voluntary classification system that defines the criteria for economic activities that are in line with environmental objectives. It indirectly supports industrial electrification projects if they meet a certain emissions standard. The taxonomy includes a lifetime average emissions threshold of 100 grams of carbon dioxide per kWh for electricity and heat generation, which gas boilers and combined heat and power plants without carbon capture and storage are unlikely to meet.[31] Investments that meet the criteria can be labelled as 'green/environmentally friendly,' potentially meaning they receive a premium from investors. In future, however, the taxonomy could be used for more than simply labelling. For example, public banks and investors such as the European Investment Bank could use it to prioritise investments, or the European Commission to decide on the approval of state aid.

Industrial Emissions Directive: The Industrial Emissions Directive regulates pollutant emissions from industrial installations. It covers around 50,000 installations responsible for 20% of the EU's air and water pollution and 40% of its greenhouse gas emissions. The impact from this regulatory instrument, however, is unclear and could potentially also promote marginal improvements in fossil fuel-based technology, hindering electrification.

The state of California has implemented zero-emissions standards for nitrogen oxide emissions from commercial ovens, boilers, water heaters and process heaters, promoting a switch to electrification.[32]

China has launched an 'industrial equipment upgrading plan' to reduce energy consumption and emissions. The plan provides fiscal and financial support for upgrades related to energy savings, emissions reductions, smart controls and digitalisation, and safety. This includes industrial electrification, with the electrification of steel, chemicals and construction material being specifically targeted.[33]

Energy efficiency obligation schemes

An energy efficiency obligation scheme (EEOS) is a regulatory mechanism that places a quantitative obligation on energy suppliers, retailers and/or other parties to deliver a specific amount of energy or carbon emissions savings.[34] Many different EEOSs have been implemented across the globe, and there is broad evidence that well-designed EEOSs[35] can deliver significant and cost-effective energy savings. As electrification of heat leads to energy savings, EEOSs can be used to support electrification in industry.

30 Schütze, F., & Stede, J. (2021). The EU sustainable finance taxonomy and its contribution to climate neutrality. *Journal of Sustainable Finance & Investment, 14*(1): 128-160. https://doi.org/10.1080/20430795.2021.2006129

31 Environmental Coalition on Standards. (2021). *7 key points about the EU taxonomy's 100g emissions threshold.* https://ecostandard.org/wp-content/uploads/2021/12/EUTaxonomy_100g_7points.pdf

32 South Coast Air Quality Management District. (2024). *Proposed Amended Rule 1146.2.* https://www.aqmd.gov/home/rules-compliance/rules/scaqmd-rule-book/proposed-rules/rule-1146-2

33 State Council of the People's Republic of China. (2024). *Notice of the State Council on issuing the 2024-2025 Energy Conservation and Carbon Reduction Action Plan.* https://www.gov.cn/zhengce/content/202405/content_6954322.htm

34 Environmental Coalition on Standards, 2021.

35 Lees, E., & Bayer, E. (2016). *Toolkit for energy efficiency obligations.* Regulatory Assistance Project. https://www.raponline.org/knowledge-center/toolkit-for-energy-efficiency-obligations/; and ENSMOV. (2020). *Snapshot of energy efficiency obligation schemes in Europe (as of end 2019).* Institute for European Energy and Climate Policy. https://ieecp.org/publications/snapshot-of-energy-efficiency-obligation-schemes-in-europe-as-of-end-2019/

Examples: Energy efficiency obligation schemes

The EU **Energy Efficiency Directive** requires Member States to put in place an EEOS, or alternative measures, to achieve their annual energy savings targets. Thirteen Member States have opted to put in place EEOSs.

In 2023, **Italy** classified interventions supporting the electrification of heat production as eligible for the country's EEOS ('white certificates'), including thermal energy production plants, heat recovery component installations, mechanical heat recompression systems, chillers and heat pumps.[36]

In 2024, **France** added a deemed savings method for industrial heat pumps to its EEOS, making it easier to claim savings from their installation.[37]

Improve economic conditions

Carbon pricing

Putting a price on carbon increases the cost of using carbon-intensive fuels such as oil, gas and coal. This can incentivise electrification and energy savings. As electrification of production processes leads to primary energy savings in almost all cases, a carbon price reduces the cost of electrification relative to fossil fuel use even in countries where the electricity mix is relatively high-carbon.

Two principal carbon pricing methods exist: direct carbon taxation, and cap and trade (with or without minimum and maximum prices). Although carbon pricing is an important tool for incentivising change, it is often not sufficient to ensure decarbonisation at scale (unless prices are very high) and needs to be embedded in an integrated policy approach to overcome the diverse barriers to electrification.[38]

Examples: Carbon pricing

EU Emissions Trading System (ETS I): The EU ETS I sets a cap on carbon emissions, requires the purchase of carbon allowances to cover emissions included in the system, and allows the trading of allowances. It covers energy production (electricity and heat), civil aviation, shipping (phase-in from 2024) and energy-intensive industry sectors (large facilities with an input power capacity over 20 MW).[39] Specific industries currently receive free allowances because they're at risk of carbon leakage (the likelihood that production and thus emissions would shift to countries with less stringent standards). These industries include many with high electrification potential such as paper and pulp, chemicals, and parts of food and organic material processing.[40] Over time, these free allocations are being phased out.

EU ETS II: In January 2027 (or 2028 in case of exceptionally high energy prices) the EU's new emissions trading system, EU ETS II, for transport, buildings and small energy and industry installations will start.[41] For industry[42] the scheme will apply to all fossil fuel-burning installations that are not already covered by ETS I

36 Gestore Servizi Energetici [Italian Energy Agency]. (2024). *Certificati bianchi [White certificates].* https://www.gse.it/servizi-per-te/efficienza-energetica/certificati-bianchi/tee-per-la-car

37 Association Technique Energie Environnement [Technical Association for Energy and the Environment]. (2024). *CLUB C2E: Certificats d'économies d'énergie [Energy saving certificates].* https://atee.fr/efficacite-energetique/club-c2e/fiches-doperations-standardisees/industrie#os

38 Thomas, S., Sunderland, L., & Santini, M. (2021). *Pricing is just the icing: The role of carbon pricing in a comprehensive policy framework to decarbonise the EU buildings sector.* Regulatory Assistance Project. https://www.raponline.org/knowledge-center/pricing-just-icing-role-carbon-pricing-comprehensive-policy-framework-decarbonise-eu-buildings-sector/

39 LIFE Emissions Trading Extra. (2024). *EU ETS 101: A beginner's guide to the EU's Emissions Trading System.* https://carbonmarketwatch.org/publications/eu-ets-101-a-beginners-guide-to-the-eus-emissions-trading-system-2024-update/

40 European Commission. (n.d.). *Free allocation.* https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/free-allocation_en

41 European Commission. (n.d.). *ETS2: buildings, road transport and additional sectors.* https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/ets2-buildings-road-transport-and-additional-sectors_en

42 CRF category 1.A.2 as defined in the 2006 International Panel on Climate Change Guidelines for National Greenhouse Gas Inventories.

Examples: Carbon pricing (con't.)

(less than 20 MW input power). Between 8,000 and 11,000 installations will be covered, with an expected 56% using gas, 24% coal and 20% oil.[43] The impact of ETS II on fossil fuel prices is still uncertain. At the European Commission's target auction price of €45 per tonne of carbon dioxide, the price of fossil gas would increase by about 0.9 euro cents per kWh (before taxes).[44] Several studies expect much higher prices in the range of €100-300 per tonne. As emissions in ETS II sectors will need to reduce five times faster than historic reduction rates to meet the cap, a higher price range is likely.[45]

Carbon Border Adjustment Mechanism (CBAM): The Carbon Border Adjustment Mechanism will put a price on carbon-intensive goods that are imported into the EU from 2026. The aim is to reduce the risk of carbon leakage in selected industrial sectors and replace the provision of free allowances, while at the same time driving the adoption of carbon pricing and clean production in non-EU countries.[46] CBAM is likely to drive up the cost of carbon-intensive products and commodities in the EU[47] — including imported fossil fuels and imported electricity from fossil generation — and increase incentives to decarbonise production in the EU as free allowances are phased out.[48] CBAM could thus provide an additional incentive for electrification.

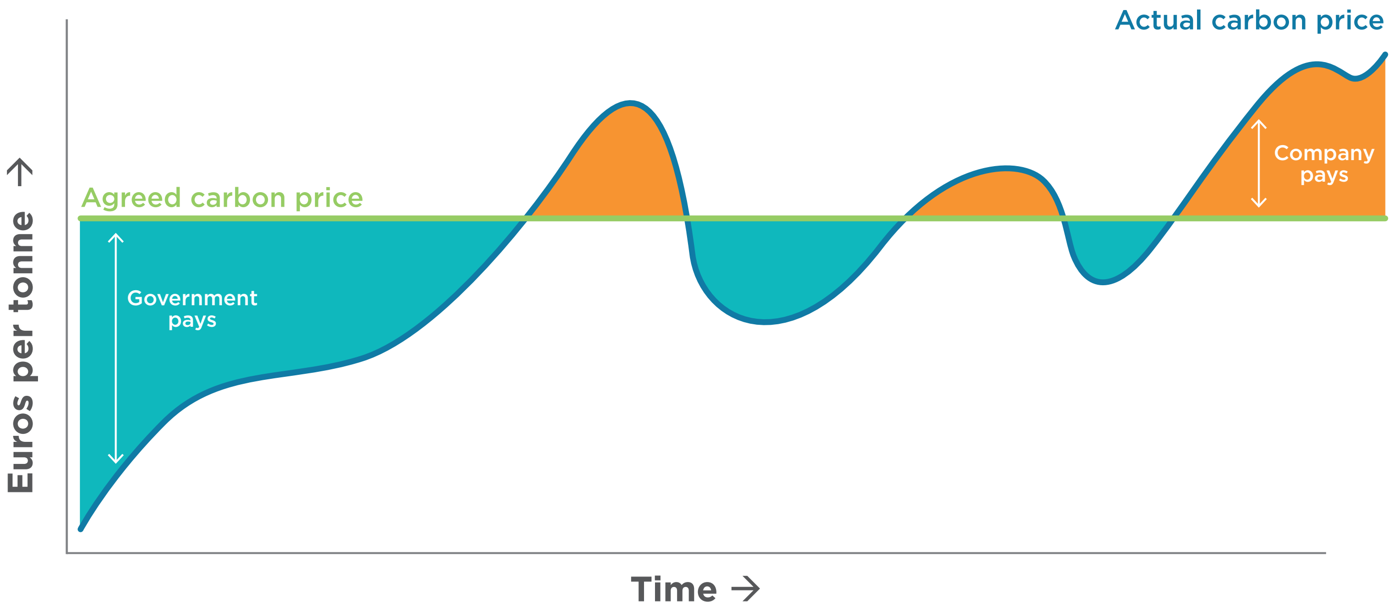
National carbon taxes: Many Member States have put in place national carbon pricing. For example, Sweden and Finland have had carbon taxes in place since the 1990s, including for several industrial and manufacturing sectors.[49] Particularly heavy industry has often received partial or full exemptions in most national pricing systems, but several Member States — including Finland, Estonia, Slovenia and the Netherlands — have put in place an additional carbon price for industry.[50] For example, the Netherlands introduced a tax in 2021 that targets emissions from industrial installations above an EU benchmark level of the top-performing 10%.[51]

Carbon contracts for difference

The introduction of carbon markets has created an additional risk for industries: potential losses from selling or buying carbon allowances as the carbon price fluctuates. Carbon contracts for difference aim to address the risk of uncertainty of future carbon prices. The instrument secures the revenue from carbon savings, resulting in lower overall emissions mitigation costs.[52] This is how it works: In a carbon contract for difference, the government or other institution enters into a delivery contract with an industry partner agreeing on a fixed carbon price (strike price) for the duration of the contract. If the actual carbon price (reference price) drops below the strike price, the company receives compensation to make up the difference — hence, a contract for difference. In a 'two-sided' carbon contract, companies will return revenue to the government in case the reference price is higher than the strike price (as illustrated in Figure 6 on the next page). This shares the risk between taxpayers and industry. At the same time, it creates an incentive for governments to steer towards a high carbon price, as this reduces the cost of the subsidy.

43 Simon, F. (2024, 24 April). *Briefing: Who are the small industrial emitters covered by the EU's ETS2?* Carbon Pulse. https://carbon-pulse.com/280782/
44 Agora Energiewende & Agora Verkehrswende. (2023). *Der CO2-Preis für Gebäude und Verkehr. Ein Konzept für den Übergang vom nationalen zum EU-Emissionshandel [The CO2 price for buildings and transport. A concept for the transition from national to EU emissions trading].* https://www.agora-energiewende.de/publikationen/der-co2-preis-fuer-gebaeude-und-verkehr
45 Graichen, J., & Ludig, S. (2024). *Supply and demand in the ETS 2.* German Environment Agency. https://www.umweltbundesamt.de/en/publikationen/supply-demand-in-the-ets-2
46 Overland, I., & Huda, M.S. (2022, 9 September). Climate clubs and carbon border adjustments: a review. *Environmental Research Letters, 17*(9). https://iopscience.iop.org/article/10.1088/1748-9326/ac8da8
47 Belletti, E., Han., N., & Pérez, I. (2023). *Playing by new rules: How the CBAM will change the world.* Wood Mackenzie. https://www.woodmac.com/horizons/how-the-cbam-will-change-the-world/
48 Bellora, C., & Fontagné, L. (2023, July). EU in search of a carbon border adjustment mechanism. *Energy Economics, 123.* https://www.sciencedirect.com/science/article/abs/pii/S0140988323001718
49 European Environmental Bureau. (2021). *A carbon pricing blueprint for the EU.* https://eeb.org/library/a-carbon-pricing-blueprint-for-the-eu/
50 de Bruyn, S., de Vries, M., Juijn, D., & Jongsma, C. (2022). *Speeding up the decarbonisation of European industry: Assessment of national and EU policy options.* CE Delft. https://cedelft.eu/publications/speeding-up-the-decarbonisation-of-european-industry/
51 Koelemeijer, R., van Hout, M., Ooms, E., van Dam, D., & Koole, G. (2024). *Analyse Tarief CO2-Heffing Industrie — tariefstudie 2024 [Analysis of CO2 levy rate for industry — rate study 2024].* Planbureau voor de Leefomgeving [PBL Netherlands Environmental Assessment Agency]. https://www.pbl.nl/publicaties/analyse-tarief-co2-heffing-industrie-tariefstudie-2024
52 Richstein, J.C., & Neuhoff, K. (2022, 19 August). Carbon contracts-for-difference: How to de-risk innovative investments for a low-carbon industry? *iScience, 25*(8): 104700. https://doi.org/10.1016/j.isci.2022.104700

Figure 6. Two-sided carbon contract for difference



Examples: Carbon contracts for difference

The Netherlands' SDE++ operational subsidy supports investments in low-carbon technologies by subsidising the difference between the market price and a benchmarked cost price for each technology. The scheme operates as a type of one-sided carbon contract for difference. There is a project-specific floor price insuring projects against low prices, but there is no payback to the government in the case of high prices. Budget has been reserved for low- and high-temperature heat electrification and power-to-fuel in 2023 and 2024.[53]

Germany launched a **'climate protection contract'** scheme in 2024 to support industry investments in low-carbon production processes.[54] Similar to the SDE++, the scheme subsidises the difference in operating cost between low-carbon and fossil fuel-based installations over a period of 15 years. Subsidies are auctioned according to the criteria of subsidy efficiency and relative emissions reduction of the project. The scheme incorporates elements from a two-sided contract for difference, as companies will have to return revenue to the government when prices drop below the agreed price.

European Union state aid: In the EU, financial support to business is forbidden unless approved by the European Commission. The rules on state aid govern the approval process and thus strongly influence the possibility and design of support schemes. As part of the European Green Deal, the guidelines on state aid for climate, environmental protection and energy have been improved to align with the EU's net-zero target. The guidelines are not, however, in line with a phaseout of fossil fuels in heat. Needed improvements include a simplified application process, increased support limits for clean tech production, increased conditionality for investments in fossil gas, and extended rules to cover gas infrastructure decommissioning.[55]

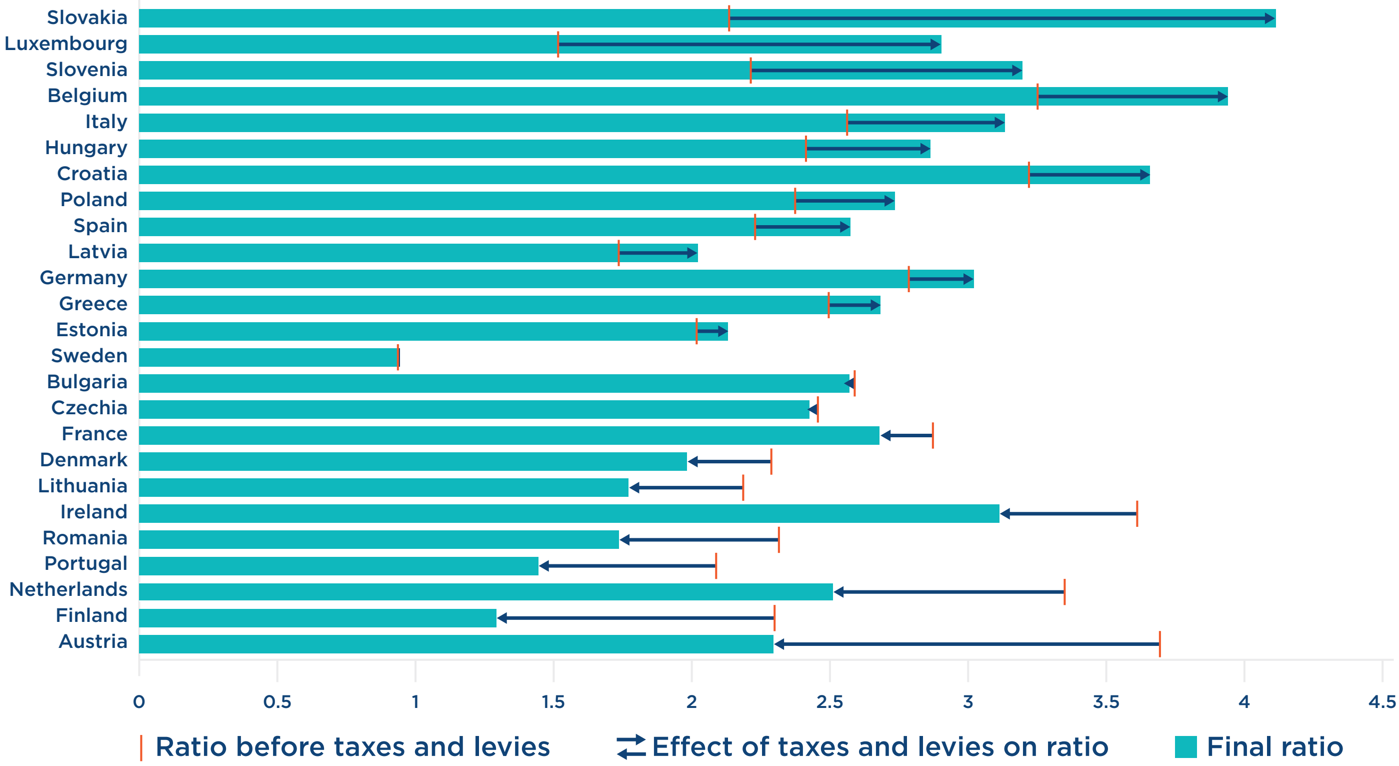
53 Planbureau voor de Leefomgeving [PBL Netherlands Environmental Assessment Agency]. (2023). *Wijzigingsnotitie SDE++ 2024 [Amendment note SDE++ 2024]*. https://www.pbl.nl/uploads/default/downloads/pbl-2023-wijzigingsnotitie-sde-plus-plus-2024-5034.pdf
54 German Federal Ministry for Economic Affairs and Climate Action. (n.d.). *Carbon contracts for difference*. https://www.klimaschutzvertraege.info
55 Graf, A., & Buck, M. (2024). *EU policies for climate neutrality in the decisive decade: 20 initiatives to advance solidarity, competitiveness and sovereignty.* Agora Energiewende. https://www.agora-energiewende.org/publications/eu-policies-for-climate-neutrality-in-the-decisive-decade-full-report

Aligning tariffs, taxes and levies with electrification

The cost of electricity is a key factor in industrial electrification. In most EU countries electricity is taxed at a higher rate than fossil fuels, and renewable energy support levies are often put on electricity and not gas or oil.[56] Lowering taxes and levies on electricity used for industrial heat, shifting them towards fossil fuels, or shifting levies towards the public budget can reduce the operational cost of electrified end uses relative to fossil-fuel combustion alternatives.

Figure 7 shows how taxes and levies can increase or decrease the electricity to gas price ratio for average size industrial consumers in European countries.[57] The higher the ratio, the less economic electrification costs are when compared with using gas instead.

Figure 7. Ratio of electricity to gas price for industrial users in Europe, 2023



Data source: Eurostat. (2024). Energy Statistics — Prices of Natural Gas and Electricity

56 Rosenow, J., Thomas, S., Gibb, D., Baetens, R., De Brouwer, A., & Cornillie, J. (2022). *Levelling the playing field: Aligning heating energy taxes and levies in Europe with climate goals.* Regulatory Assistance Project. https://www.raponline.org/knowledge-center/aligning-heating-energy-taxes-levies-europe-climate-goals/

57 Eurostat. (2024c). *Energy statistics — prices of natural gas and electricity* [Data set]. https://ec.europa.eu/eurostat/web/energy/database

Examples: Aligning tariffs, taxes and levies with electrification

Finland has recognised the key importance of electrification in industry and is politically committed to ensuring competitive electricity prices.[58] The country has addressed the imbalance between electricity and gas prices by significantly reducing tax for electricity used in manufacturing and industrial heat pumps and implementing a national carbon price to raise the cost of fossil fuel use. Without taxes and levies electricity is 2.3 times the cost of gas per unit, while after taxes and levies this ratio drops to 1.3. Although many countries will not have Finland's favourable renewable and low-carbon energy supply, and correspondingly lower base electricity prices, its fiscal approach can be copied in all contexts.

The Netherlands ended a levy on gas and electricity tariffs that had raised money for renewable energy investments and instead funded these investments from the general budget. It also put in place a slight shift in tax from electricity to gas for small and medium-sized enterprises.[59]

Grants, loans and fiscal incentives

Because industrial electrification usually requires significant capital expenditure, government grants and loans can be useful ways to increase deployment. Grants directly reduce investment costs, while government-backed loans with lower interest rates reduce the cost of capital. Fiscal incentives can also support electrification in industry; examples include allowing companies to deduct electrification-related investment from their taxes (tax allowance/credit), and giving rebates of taxes paid related to electrification investments.

Examples: Grants, loans and fiscal incentives

France offers tax deductions for investments in clean technology production capacity, including large heat pumps.

Italy has approved a €6.3 billion package known as Transition 5.0 to enhance the energy efficiency of its factories.[60] The subsidy is provided as a tax rebate and requires investments to be completed by December 2025. This package is expected to be highly effective in encouraging companies to install solar panels, heat pumps and thermal storage systems. The subsidies have a broad scope; however, they are specifically designed to incentivise high energy savings (greater than 15%) in medium-sized installations (with an investment cost of less than €2.5 million).

The **United States** has put in place a comprehensive fiscal support programme under the header of the Inflation Reduction Act. In addition to several tax credits supporting investment, its Industrial Demonstrations programme has awarded grant support to several large electrification demonstration projects in the chemical, steel, food and beverage, glass and manufacturing industries.[61]

58 Ministry of Economic Affairs and Employment of Finland. (2024). *Finland's integrated national energy and climate plan update.* http://urn.fi/URN:ISBN:978-952-327-527-0

59 Belastingdienst [Dutch Tax Service]. (2024). *Tabellen tarieven voor milieubelasting [Tables of rates for environmental tax].* https://www.belastingdienst.nl/wps/wcm/connect/bldcontentnl/belastingdienst/zakelijk/overige_belastingen/belastingen_op_milieugrondslag/tarieven_milieubelastingen/tabellen_tarieven_milieubelastingen

60 Italian Government, Presidency of the Council of Ministers. (n.d.). *Transition 5.0: Implementation of production processes to an efficient and sustainable energy model.* ItaliaDomani. https://www.italiadomani.gov.it/content/sogei-ng/it/en/Interventi/investimenti/transizione-5-0.html

61 U.S. Department of Energy, Office of Clean Energy Demonstrations. (n.d.). *Industrial demonstrations program selected and awarded projects.* https://www.energy.gov/oced/industrial-demonstrations-program-selected-and-awarded-projects

Meet infrastructure needs

Grid planning and optimisation

Electrification of large industrial heat loads depends on there being sufficient grid capacity and renewable generation. Grids have long development lead times, which could hinder industrial electrification. Planning that considers the needs of both new and existing industrial processes can help to overcome this barrier to electrification.[62]

For new industrial plant, decisions on location are based on many factors beyond energy, including existing grid capacity. An assessment of existing capacity should consider not only firm but also flexible options. Flexible options consider the flexible electricity use capabilities of the industrial process, on-site renewables and storage as a portfolio of resources to be aligned with the capacity of the grid, opening more options to integrate new loads without reinforcing the grid. Other factors that can facilitate grid connection for new electrified industrial facilities include coordinated development and zoning to identify areas of good renewable energy generation, land availability and alignment with expected demand. Grid planning can also be integrated with heat planning that identifies, among other things, sources of water heat and hydrogen infrastructure.

Grids have long development lead times. Planning that considers the needs of both new and existing industrial processes can help to overcome this barrier to electrification.

To enable the electrification of existing plant, a higher-capacity grid connection may be necessary. Where grid capacity is constrained, there are a number of approaches to better utilise existing capacity including, where appropriate, shared or nonfirm connections, congestion management platforms and user engagement. Improved allocation of remaining capacity in grid queues can also facilitate connection for priority projects. This can include competitive allocation of grid capacities as an alternative to the first-come, first-served approach that largely dominates.

Examples: Grid planning and optimisation

EU Action Plan for Grids: In November 2023 the European Commission released an EU grid action plan, which aims to address the main challenges in expanding, digitalising and better using EU electricity transmission and distribution grids.[63] It aims to unlock the estimated €584 billion investment that is needed. The action plan focuses on implementation of projects of common interest; long-term planning; regulatory incentives to accommodate increased renewables and electrification; enhanced transparency and better-aligned network tariffs to improve grid usage; improved access to finance; faster permitting; and improved and more secure grid supply chains.

62 Pató, Z. (2024). *RIP first come, first served.* Regulatory Assistance Project. https://www.raponline.org/toolkit/rip-first-come-first-served/
63 European Commission. (2023, 27 November). *Commission sets out actions to accelerate the roll-out of electricity grids* [Press release]. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_6044

Reforming network tariffs to incentivise flexibility

One way to reduce electricity prices for industrial end users and encourage them to electrify their operations is to minimise network costs through better and smarter regulation.

Network costs currently account for 8%-12% of industrial electricity prices in the EU, on average,[64] and are projected to rise given the need to build out the grid. The required investment may translate into average additional network costs of 1.5 to 2 euro cents per kWh.[65] At 2023 prices, this would increase the share of network charges to 16%-19%.

Regulation can minimise these costs in different ways. Currently, a significant part of network costs is recovered through fixed charges based on the capacity of a grid connection rather than the volume of electricity consumed. The rationale is that network costs primarily stem from capital investments, and therefore fixed or peak-demand fees better reflect these costs. Fixed network fees are often based on the maximum capacity of the connection and an implicit assumption that the capacity of the connection to the grid will be used to the maximum 24/7. In reality, industrial electricity customers will not always use the same amount of electricity and will also not consume close to the maximum capacity of their connection.

Historically, large industrial consumers even received discounts for maintaining a constant electricity demand, as in Germany, for example. Such regulation originated when power generation was centralised, with electricity supplied primarily by large power plants. At that time, the goal was to maintain a steady load on the grid to optimise efficiency and minimise fluctuations. However, with today's increasing reliance on variable renewable energy sources, such as wind and solar, this traditional model has quickly become out of date. Such pricing models disincentivise and penalise flexibility.

To incentivise industrial customers to offer flexibility to the grid, current network tariffs need to be reformed. In fact, EU regulations already mandate that network fees must be cost-reflective and nondiscriminatory. As the energy mix shifts to more variable renewable energy, cost reflectivity requires dynamic, time-varying network fees, which are not yet universally adopted across Europe.

64 Eurostat. (2024d). *Electricity prices components for non-household consumers — annual data (from 2007 onwards).* https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205_c/default/table?lang=en&category=nrg.nrg_price.nrg_pc

65 McWillams, B., Sgaravatti, G., Tagliapietra, S., & Zachmann, G. (2024, 11 January). *Europe's under-the-radar industrial policy: intervention in electricity pricing.* Bruegel. https://www.bruegel.org/policy-brief/europes-under-radar-industrial-policy-intervention-electricity-pricing

Incentives for distributed energy resource flexibility

Behind-the-meter distributed energy resources (local generation) and heat or energy storage can increase the types and times of electricity demand flexibility that an industrial plant can offer. Behind-the-meter resources can also reduce the capacity requirement for firm grid connection, enabling electrified industrial loads to be integrated into the grid more quickly, where there is grid scarcity. Information, evidence of the value to be gained, and alignment of existing incentives with flexibility goals are tools to promote investment in distributed energy resources at the same time as electrification.[66]

Market access for demand flexibility

Nondiscriminatory market access for demand-side flexibility is essential to ensure that active industrial customers are fairly rewarded for the value they create in the system, whether they participate directly or via an aggregator.[67] Ensuring access to fair rewards provides an additional incentive to electrify processes and helps minimise total system costs. Solutions like demand reduction and demand-side flexibility are often cheaper than supply-side solutions to meet system needs (such as balancing, resource adequacy and grid services) and user needs. Ensuring market access for demand flexibility allows this resource to compete. Specifically for industry, it can also address grid capacity and connection barriers and incentivise installation of thermal energy storage, which has further system benefits of flexibility and efficiency.

The industrial sector has a history of engaging in contracts that include interruptability for a reduced tariff. This is an early and blunt form of demand response. Electrified industrial processes combined with on-site generation and storage can enable operators to realise the value of their flexibility through scaling up and down energy use, while avoiding the risk of supply interruption and the associated loss of output and economic disadvantage.

Examples: Market access for demand flexibility

At the EU level the Electricity Market Directive and Regulation govern demand-side flexibility. Implementation and potential support measures are left to Member State governments and regulators. Member States are required by the Electricity Market Directive to undertake flexibility assessments and set national targets for non-fossil-fuel flexibility, including the specific contributions of demand response and energy storage. System operators must also offer flexible connection options that can be an interim measure pending grid reinforcement.

Examples of countries with mature flexibility markets include France, Great Britain, Germany, the Netherlands and Sweden. That said, this does not mean there are no barriers in these countries; for example, in Germany access for demand-side flexibility at the distribution system operator level is limited.[68]

66 Regulatory Assistance Project. (2024). *Incentivising network innovation*. Power System Blueprint. https://blueprint.raponline.org/incentivising-network-innovation/

67 Regulatory Assistance Project. (2024). *Market access for demand-side flexibility*. Power System Blueprint. https://blueprint.raponline.org/market-access-for-demand-side-flexibility/

68 For a full overview, see: Murley, L., & Ferris, J. (2024). *2023 market monitor for demand side flexibility*. LCP Delta; smartEn. https://www.lcp.com/en/insights/publications/5th-edition-of-the-market-monitor-for-demand-side-flexibility

Close the knowledge gap

Information provision

Providing more and better information to raise awareness on electrification solutions and their benefits is key in driving electrification in industry. Our analysis of barriers found that awareness of technological options for electrification and government support programmes can be limited, because electrification of industrial heat is a novel solution in many sectors. Moreover, especially for light industry, many diverse companies will be involved, including small and medium-sized enterprises with limited resources. It will likely require additional efforts to reach these companies. To provide clarity on future industry decarbonisation pathways, governments can develop sector-specific roadmaps together with industry.[69] Another approach is to provide engineering assistance to companies interested in electrification.[70]

Cooperation within value chains

Scaling up the deployment of electrification solutions can benefit from value chain cooperation, both in the production process of electrification solutions and in the value chains with potential to electrify. Because the value chains for industrial products can be long — with products produced by one company serving as input for another — changes in the production process and product outcomes affect other players in the chain. In addition, for industries grouped in clusters, there can be significant benefits from close cooperation on decarbonisation — for example, from shared grid use, optimisation of renewable energy self-consumption and water use, and heat and cold exchange.[71] Governments can provide the platform for increased value chain cooperation, bringing companies together to encourage synergies, developing common goals and targets (a sectoral roadmap), sharing data and solutions, and co-developing policy approaches. A value chain approach should also support standardisation of electrification solutions to facilitate easier integration into production processes.

Examples: Cooperation within value chains

The Netherlands designed a policy package for industrial decarbonisation based on setting a carbon price combined with significant financial support for the deployment of decarbonisation solutions. This was done through extensive stakeholder consultation, including collaborative design of decarbonisation scenarios,[72] and was part of a larger sectorwide climate agreement.[73]

Switzerland combines a strict regulatory approach with voluntary sector-specific agreements on emissions reductions, coupled with financial support for implementation.[74]

As part of its ambitious policy to achieve net zero by 2045, the government of **Sweden** worked together with the steel, cement and petroleum industries to develop decarbonisation roadmaps.[75]

69 See, for example: UK Government. (2015). *Industrial decarbonisation and energy efficiency roadmaps to 2050*. https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050

70 Eisen, J., & Johnson, A. (2023). *Enabling strategic energy management (SEM) to support U.S. decarbonization*. American Council for an Energy-Efficient Economy. https://www.aceee.org/white-paper/2023/07/enabling-sem-to-support-us-decarbonization

71 Baldassarre, B., Schepers, M., Bocken, N., Cuppen, E., Korevaar, G., & Calabretta, G. (2019, 10 April). Industrial symbiosis: towards a design process for eco-industrial clusters by integrating circular economy and industrial ecology perspectives. *Journal of Cleaner Production*, *216*: 446-460. https://doi.org/10.1016/j.jclepro.2019.01.091; Sovacool, B.K., Geels, F.W., & Iskandarova, M. (2022, 10 November). Industrial clusters for deep decarbonization. *Science*, *378*(6620): 601-604. https://doi.org/10.1126/science.add0402

72 Anderson, B., Cammeraat, E., Dechezleprêtre, A., Dressler, L., Gonne, N., Lalanne, G., Guilhoto, J.M., & Konstantinos, T. (2023, March). Designing policy packages for a climate-neutral industry: a case study from the Netherlands. *Ecological Economics*, *205*: 107720. https://doi.org/10.1016/j.ecolecon.2022.107720

73 Fumagalli, E., & Akerboom, S. (2019). Dutch climate and energy policy: targets and progress for 2020 and 2030. *Economics and Policy of Energy and the Environment*. https://doi.org/10.3280/EFE2019-001008

74 Zuberi, M.J.S., Santoro, M., Eberle, A., Bhadbhade, N., Sulzer, S., Wellig, B., & Patel, M.K. (2020, February). A detailed review on current status of energy efficiency improvement in the Swiss industry sector. *Energy Policy*, *137*: 111162. https://doi.org/10.1016/j.enpol.2019.111162

75 Brodén Gyberg, V., & Lövbrand, E. (2022, 9 February). Catalyzing industrial decarbonization: the promissory legitimacy of fossil-free Sweden. *Oxford Open Climate Change*, *2*(1), kgac004. https://doi.org/10.1093/oxfclm/kgac004

Tackle technological barriers

Research and development

For sectors and applications where electrification is not yet a mature technology, additional research and development funding will be needed to support technological development, build confidence in electrification solutions through pilot projects, build supply chains and support pilot retrofit projects. Specific focus should be on standardising electrification solutions and how to easily integrate them into industrial processes to scale up deployment.

Examples: Research and development

At the EU level, the Horizon and LIFE programmes provide general support to research and development, including for industrial electrification technologies.

Several countries have put in place dedicated research and development programmes for industrial decarbonisation, including electrification. For example:

- In 2024 **Germany** put in place a €2 billion support scheme for industrial decarbonisation — the Federal Fund for Industry and Climate Action [Bundesförderung Industrie und Klimaschutz, or BIK] — under which research and development will also be eligible for support.[76]
- **The Netherlands** has a dedicated research and development programme to support electrification of high-temperature heat and industrial flexibility (MOOI: Industrie).[77]
- In the **United States**, the Department of Energy has launched the Industrial Heat Shot programme to support the development of cost-effective industrial heat decarbonisation technologies.[78]

76 Competence Centre on Climate Change Mitigation in Energy-Intensive Industries. (2024). *Funding programmes: Federal fund for industry and climate action*. https://www.klimaschutz-industrie.de/en/funding/
77 Rijksdienst voor Ondernemend Nederland [Netherlands Enterprise Agency]. (2024, 5 September). *MOOI: Industrie*. https://www.rvo.nl/subsidies-financiering/missiegedreven-onderzoek-ontwikkeling-en-innovatie/industrie
78 U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. (2024). *Industrial Heat Shot*. https://www.energy.gov/eere/industrial-heat-shot

Section 4: Policy recommendations

Key takeaways

- ❑ To address the multiple barriers that exist, the European Commission should consider launching an industrial electrification action plan.
- ❑ A combination of ambitious carbon pricing and regulation could motivate industry to electrify eventually, but not as quickly as needed, and would face political hurdles.
- ❑ Only an integrated package of policy measures complemented by electrification targets and fossil fuel phaseout dates can drive industrial electrification with the scale and urgency needed to meet climate and energy goals.

Accelerating the electrification of industrial energy use, and especially process heat, is key in achieving Europe's climate, renewable energy and strategic independence goals. Electrification significantly reduces emissions through a combination of energy savings and the low (and continuously improving) carbon intensity of Europe's electricity. It enables the use of a huge potential amount of ambient, geothermal and waste heat, using highly efficient solutions such as heat pumps, thereby supporting the achievement of the EU's renewable energy and heat targets under the Green Deal. If coupled with smart control systems and thermal storage, industrial electrification can support increased integration of renewable electricity into the grid through flexibility services. Combined, these benefits would significantly reduce demand for fossil fuels, in particular imports, thereby improving Europe's strategic independence.

However, despite these multiple benefits, industry is wary of investing in electrification due to the range of barriers discussed in this report. A coordinated policy approach at both the EU and national level is needed.

Moreover, only an integrated package of policy measures can drive industrial electrification with the scale and urgency needed to meet climate and energy goals. In the long term, sufficiently high carbon pricing, combined with electrification targets and fossil fuel phaseout dates, would provide the necessary incentives and conditions for a shift from fossil fuels to electricity and low-carbon fuels. In the short and medium term, however, this framework would do little to address economic, knowledge, infrastructure and technological barriers. In addition, there are political hurdles in the way of achieving a sufficiently high carbon price and robust regulatory framework.

The European Commission is currently in the unique position of being able to address the multiple barriers holding back industrial electrification through its Electrification Action Plan, which can be embedded in an ambitious heating and cooling decarbonisation strategy for Europe. At the national level, governments should develop targeted strategies for industrial electrification with a specific focus on the considerable potential for electrification of lower and mid-temperature process heat.

10-point action plan for industrial electrification in the EU

Decarbonising industry and improving economic competitiveness will be key priorities for the European Commission in the coming years, including through delivering the Clean Industrial Deal and a targeted Electrification Action Plan. The Regulatory Assistance Project offers the following 10-point action plan for the European Commission to promote industrial electrification by putting in place measures addressing five key needs or barriers.

Define the course and set boundaries

Include a clear focus on industrial electrification in the forthcoming EU Electrification Action Plan, to support delivery of the Clean Industrial Deal, with the help of a high-profile task force. The task force would develop ideas for advancing industrial electrification in Europe.

Set industry electrification targets in line with achieving 60% industrial electrification by 2050 and 90% economywide emissions reduction by 2040. The targets should be complemented with clear roadmaps for industrial subsectors and could be implemented as part of a new 'Electrification Directive.'

Set tighter standards on new industrial installations through the Industrial Emissions Directive. For example, these could include a 'zero-carbon' standard for lower-temperature installations (below 500 degrees Celsius) and energy efficiency standards for retrofitting industrial installations.

Improve economic conditions

Support Member States in creating a favourable climate for investments in industrial electrification. Provide guidance on rebalancing taxes and levies on electricity and fossil fuels and ways that Member States could provide financial support to industry.

Ensure state-aid guidelines do not pose a barrier to industrial electrification, by allowing operational support for direct electrification and by highlighting options in the guidance given to Member States.

Meet infrastructure needs

Fully consider industrial electrification in the implementation of the Action Plan for Grids. This includes requiring network planning in coordination with industrial users, setting network tariffs that incentivise better use of grid capacity, allowing cable pooling, and giving priority to flexible users.

Support improved access for industry to demand-side flexibility markets.

- Ensure swift and full implementation of the revised Energy Market Directive.
- Collect and consolidate data across all European countries on market barriers for demand-side resources, including indirect discrimination.
- Use gathered evidence to articulate and standardise best-practice principles to ensure markets actively facilitate all demand-side flexibility, including smaller-scale resources.
- Require proper consultation with demand-response providers, consumer groups and other newer stakeholders.

Close the knowledge gap

Launch a study on how electrification can drive industrial competitiveness in the EU. This will help decision-making on how to best target support measures and regulatory interventions and will raise awareness of the urgency of direct electrification.

Tackle technological barriers

Ensure EU funding programmes support industrial electrification, including through earmarked funds and improved funding accessibility.

Ensure adequate support for small and medium-sized enterprises through intermediaries and the sharing of good practices. Improve funding accessibility through project bundling, standardisation or reduced administrative requirements.

Annex

Heat electrification solutions

Well-established alternatives to fossil fuel-burning equipment include industrial heat pumps and resistive heating. More specialised technologies to produce very high temperatures have been available for decades, and more are emerging each year.

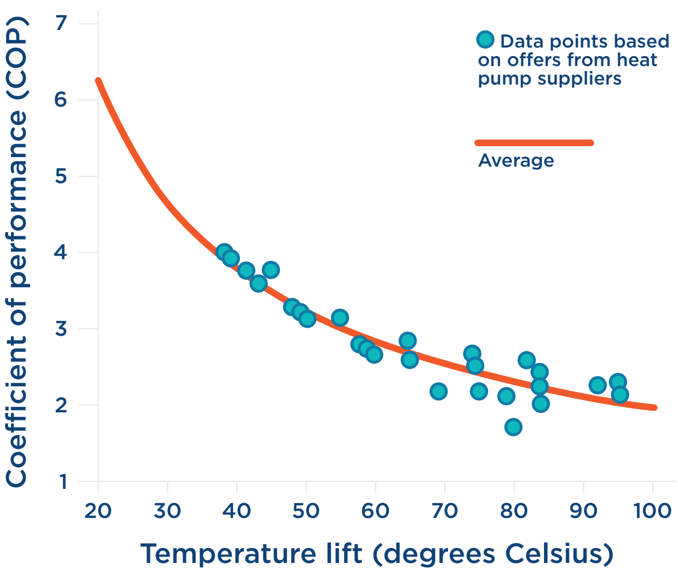
Industrial heat pumps

Heat pumps are highly efficient at generating heat. Their efficiency is measured using the 'coefficient of performance' (COP), the ratio between the heat output and the electricity input. Industrial heat pumps frequently achieve COPs of 2 to 4, equivalent to an efficiency of 200%-400%. This means that for every unit of electricity used to drive the heat pump, it generates two to four units of heat. With these high efficiencies, heat pumps offer energy savings of 50%-80% versus heating with fossil fuels.[79]

The efficiency of a heat pump depends strongly on the 'temperature lift,' the difference between the input and output temperature.[80] A COP of 2.5 or higher is generally attainable for temperature lifts of no more than 75 degrees Celsius, whereas a temperature lift of up to 100 °C can be delivered by a COP of around 2 (see Figure 8).[81]

Multiple suppliers are offering or developing industrial heat pumps that target temperatures up to 280 °C,[82] or possibly even as high as 400 °C.[83] This makes them particularly useful in the food and drink sector, the chemical industry, and pulp and paper manufacturing.

Figure 8. Efficiency curve for industrial steam-generating heat pumps



Source: Arpagaus, C., Bless, F., & Bertsch, S. (2022). Techno-Economic Analysis of Steam Generating Heat Pumps for Integration Into Distillation Processes

To achieve a high COP while delivering heat at such high temperatures, industrial heat pumps must use waste heat of a sufficient temperature to minimise the necessary temperature lift. In some cases, if process vapour — generally steam — can be directly recycled, a special type of industrial heat pump known as mechanical vapour recompression can be used. These devices use electrically driven compressors to pressurise and heat vapour to the required level.

Some industrial heat pump suppliers focus on applications without waste-heat recovery. Although their heat pumps have a lower COP than is attainable with waste-heat recovery, they hold promise for greater standardisation and consequently reduced cost, as well as for greater applicability, since air-source heat pumps

79 Arpagaus, C., Bless, F., & Bertsch, S. (2022). *Techno-economic analysis of steam generating heat pumps for integration into distillation processes.* International Institute of Refrigeration. http://dx.doi.org/10.18462/iir.gl2022.0029
80 That is, the temperature of the heat source and that at which heat is delivered to the process.
81 Arpagaus et al., 2022.
82 Arpagaus, 2023a.
83 Arpagaus, C. (2023b, 22 February). *2023 high-temperature heat pumps update with Dr. Cordin Arpagaus* [Webinar]. Australian Alliance for Energy Productivity. https://www.a2ep.org.au/post/webinar-2023-high-temperature-heat-pumps-update-with-dr-cordin-arpagaus-22-february

can be deployed where waste heat is not available. Moreover, these heat pumps will still be much more efficient than fossil fuel-based technologies. Less efficient yet cheaper industrial heat pumps could be a worthwhile compromise in applications where reducing upfront investment is valued more than the ongoing energy savings, as can be the case with processes operated with low capacity factors.

Resistive heating

Due to its relative simplicity and established track record, resistive heating underpins many of the best-known solutions for industrial electrification, including immersion and electrode boilers and electric resistance ovens, heaters and furnaces, and is generally at the core of thermal energy storage solutions. A distinction is made between indirect and direct resistive heating.

- Indirect resistive heating is carried out by passing an electric current through a metal wire or other resistive element, causing it to heat up. The heat can then be delivered to the materials via convective heat transfer using a working fluid (most often air, steam or thermal oil), via conductive heat transfer if the process materials are in direct physical contact with the hot wire, or, in certain cases, via radiative heat transfer.

- Direct resistive heating instead works by applying an electric potential difference to the process materials themselves, causing an electricity flow that heats them directly.

Electrification solutions for very high temperatures

It is often argued that the high temperatures encountered in the cement, ceramics, metals

Table 2. Electric technologies under development for high-temperature industrial heat

Industrial process	Temperature (degrees Celsius)	Examples of electrification solutions
Glass melting in furnaces	1,500	• Electric furnaces by Electroglass, HORN Glass Industries and Fives
Clinker calcination and sintering for cement manufacturing	1,100-1,450	• Electric Arc Calciner by SaltX Technology • Electrochemical processing by Sublime Systems and Chement • Existing electric arc steel furnaces by Cambridge Electric Cement • Shock-wave-based RotoDynamic Heater by Coolbrook • High-temperature thermal energy storage by Electrified Thermal Solutions
Alumina calcination	1,050-1,100	• Indirectly heated electric calciner by Calix • Electric calciner pilot by Alcoa
Melting of ferrous and nonferrous metals	1,000-1,300	• Induction furnaces for melting steel, copper, gold, silver and other metals by Topcast, Electroheat Induction and Inductotherm Corp.
Steam cracking for olefins production	800-1,000	• Shock-wave-based RotoDynamic Reactor by Coolbrook • e.Furnace by T.EN • Rotary Olefin Cracker by T.EN and Siemens Energy • E-cracker pilots — one by Shell, Dow, TNO and ISPT, and another by Linde, BASF and SABIC
Iron ore reduction	800-1,000	• Molten ore electrolysis by Boston Metal • Electroreduction by Element Zero • Electrochemical-hydrometallurgical processing by Electra
Miscellaneous furnaces	Up to 1,900	• Microwave furnaces by Linn High Temp and Enerzi

Sources: Author research, industry interviews and public project announcements and chemical industries are hard to decarbonise or electrify. Higher-temperature processes are not, however, intrinsically out of reach for electrification. Commercially mature solutions such as electric arc furnaces commonly used in steelmaking reach 1,800 °C. Similarly, induction furnaces for reheating metals at well over 1,000 °C have been operated for decades. Many of the technologies described earlier in Table 1 can reach similar or higher temperatures. In addition, new solutions that leverage a variety of electrification technologies to tackle some of the highest-temperature industrial processes are emerging every year. Indeed, numerous innovative solutions for the electrification of high-temperature industrial heat are under development, as summarised in Table 2.

Barriers to industrial electrification

This section provides a more detailed overview of the barriers to industrial electrification that are summarised in Figure 4.

Economic barriers

- High capital costs: New equipment is often associated with significant upfront investment costs.
- High electricity to fossil fuel price ratio: If electricity prices are significantly higher than fossil fuel prices, the relative operational costs are higher. This is often driven by policy and regulation — for example, taxation and levies attributed to electricity.
- Process modification costs: Apart from the expenses associated with acquiring new equipment and making upgrades, electrifying an industrial thermal process may necessitate additional modifications to other processes. In some industries, plants run continuously for several years (plant turnaround), leaving limited space for process modification.
- Companies expect short payback periods, typically of two to three years. However, for long-term energy supply technologies like steam-generating heat pumps, longer payback periods of four to six years seem to be acceptable.
- Internal and external capital acquisition: Large companies can face internal competition between investment projects, while small and medium-size enterprises can face barriers in acquiring capital from external providers, for reasons such as the limited track record of electrification projects (low risk acceptance).
- Long lifespan of existing equipment (sunk costs): Some core components of industrial facilities last 30 to 60 years. Early retirement would lead to stranded assets.
- Uncertain boundary conditions: End users face uncertainties in the boundary conditions (such as gas, electricity and carbon prices) that dictate the viability of the business case.
- Existence of low- or no-cost by-product fuels: In some industries (e.g., forestry products, waste processes, petrochemicals, iron and steel), processes result in by-products that are used as fuel on site to prevent disposal costs.
- There is no incentive for utilities and other energy suppliers to support electrification projects that reduce primary energy demand, as this will reduce their sales.

Infrastructure barriers

- The potential need to upgrade the electrical grid connection: Substantial increase in the electrical load may require an upgrade of the existing connection to the grid, with potential high investment costs, higher network fees, long lead times for permitting and planning, and multistakeholder coordination.

- Increased vulnerability to power outages: With a higher share of an industrial facility's energy use being electricity, it could become more exposed to power outages unless coupled with suitable energy storage solutions.
- Perceived or real limits on the decarbonised electricity supply and grid connection availability in a user's region.

Knowledge barriers

- Lack of knowledge: There is insufficient knowledge regarding the available electrification technologies and their capabilities.
- Need for combined knowledge: Integrating heat pumps into industrial processes requires understanding of both the process itself and heat pumps. This combined knowledge often does not exist.
- Within companies there is a lack of detailed understanding of heating and cooling requirements or consumption.
- Lack of skills in the supply chain: There are a limited number of companies with the skills to support industry with electrification, as well as a lack of electrical engineers and installers.
- Inertia: There are unrealistic expectations that low-cost hydrogen and biofuels will become available at scale.

Technological barriers

- Limited number of manufacturers: Although more than 50 high-temperature heat pump products are available on the market, there are still few manufacturers of heat pump solutions designed for higher-temperature applications.
- Limited demonstration examples: There have been few instances to showcase and validate the reliability of emerging heat pump technology in an industrial setting, resulting in perceived risks due to the lack of a long track record.
- A lack of available compressors for high temperatures and refrigerants with low global warming potential and zero ozone depletion potential.
- Bespoke designs instead of standardisation and replication of installations and potential difficulty/uncertainty over process integration (physical space and process adaptation).
- Heterogeneity of industrial sectors: Industry is composed of diverse sectors, technologies and processes, making standardisation challenging.
- Perception of negative impacts to product quality where precise temperature profiles are required.
- Expectation of significant operational disruption for site conversion (downtime).

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