Agora Industry

STUDY

Direct electrification of industrial process heat

An assessment of technologies, potentials and future prospects for the EU

Fraunhofer ISI

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Preface

Dear reader,

Ensuring Europe's industrial transition while maintaining competitiveness is a top priority for the next EU policy cycle (2024–2029). Most prominent scenario pathways for climate neutrality feature the use of renewable electricity as a key strategy. This cuts greenhouse gas emissions and boosts energy security at the same time.

Thanks to rapid innovation, a broad range of electrification technologies in industry are already viable today and can address specific process needs in all sectors. Our new study shows that by 2035, direct electrification could also replace the vast majority of fossil fuels used to provide process heat for the production of industrial goods.

Opportunities for using green electricity directly from the grid as a means of accelerating the industrial transition have been underestimated compared with hydrogen and carbon capture and usage/storage. To boost electrification solutions, smart policies are needed across the value chain that help scale up industry's direct use of renewable electricity.

Our study assesses the potential of current and near-term electrification technologies to meet industrial heat demand, analyses barriers for deployment in Europe and provides first policy recommendations at the EU level to successfully reach climate targets and ensure industry's competitiveness.

We wish you pleasant reading!

Yours,

Frank Peter
Director, Agora Industry

Matthias Buck
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Key findings at a glance

1 **Achieving climate-neutral industry requires an efficient decarbonisation of industrial heat.** Three quarters of industrial CO_2 emissions result from burning fossil fuels that provide process heat for the production of industrial goods, such as chemicals, steel, paper, food and beverages. Process heat constitutes the single most significant energy use by industry.

2 **Direct electrification technologies expected to be available by 2035 could meet 90 percent of the energy demand not yet electrified by European industry.** Technologies readily available today, such as heat pumps and electric arc furnaces, could already deliver more than 60 percent of this demand. To tap into this potential, quickly ramping up technologies for the direct electrification of process heat at all temperature levels is key.

3 **A broad range of electrification technologies exists to meet specific process needs.** Heat pumps and electric boilers can already generate up to 200 and 500 degrees Celsius, respectively, for chemical processes. Electric arc furnaces are widely employed for steel production at 1 800 degrees. Technologies such as resistance heating, induction heating and electric steam crackers will become available in the coming years and cover all ranges, from 100 to 2 500 degrees.

4 **A targeted EU action plan is needed to address the economic and organisational barriers to direct electrification and ensure it is a key transition strategy for industry across Europe.** Major elements include establishing an industrial alliance to facilitate market introduction of technologies and setting deployment targets to enable investments. Funding schemes should explicitly support direct electrification projects, while regulators should integrate electrification in grid planning and allow industry easy grid access.

Content

List of abbreviations

Term	Explanation
ASK	Annular shaft kiln
BAT	Best available technology
BF/BOF	Blast furnace/basic oxygen furnace
CCU/S	Carbon capture and usage/storage
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Coefficient of performance
DRI	Direct reduces iron
EAF	Electric arc furnace
GHG	Greenhouse gas
GJ	Gigajoule
H_2	Hydrogen
IR	Infrared
kWh	Kilowatt hour
LRK	Long rotary kiln
MFSK	Mixed-feed shaft kiln
MOE	Molten oxide electrolysis
Mt	Megatonne
MW	Megawatt
MWh	Megawatt hour
PFRK	Parallel flow regenerative kiln
SEC	Specific energy consumption
t	Tonne
TCO	Total costs of ownership
TWh	Terawatt hour
UV	Ultraviolet

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1 Executive summary

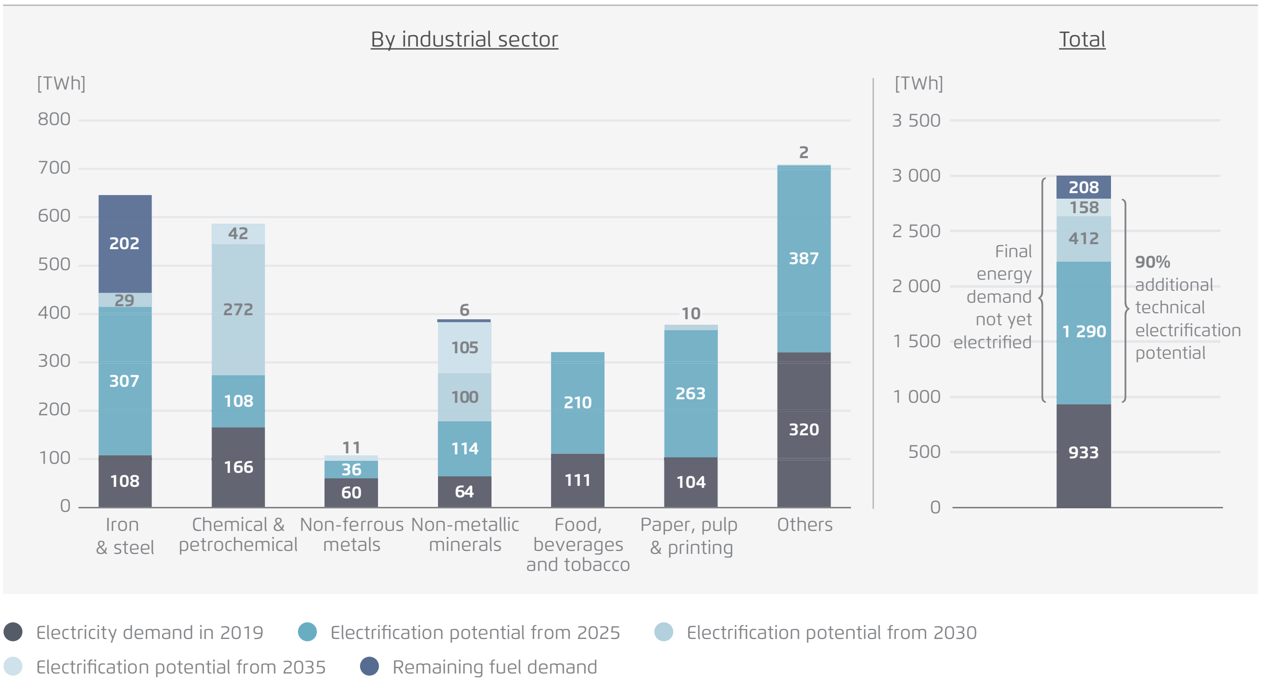
This study investigates the potential for direct electrification of industrial process heat in the EU-27 and considers technologies that are available today or expected to be available by 2035 at the latest, including electric boilers, heat pumps, resistance heating, induction heating, plasma heating, electric arc furnaces, shock-wave heating and thermal storage technologies. The electrification potential is calculated individually for seven industrial sectors and substantiated by an analysis of specific process heat requirements for 14 individual applications, assuming that increased efforts will be undertaken to develop electric heating technologies and the corresponding processes. This approach takes into account the considerable diversity of process heating types across the various industrial production processes. By matching these requirements with the capabilities of eight technologies, barriers and challenges to direct electrification have been identified and validated in stakeholder interviews.

The technical potentials for direct electrification

Process heating today is the single largest energy use in the industrial sector, accounting for 47 percent of industrial energy demand and responsible for roughly three quarters of the CO_2 emissions generated by industry. Energy for process heating is predominately supplied by natural gas (35 percent), coal (27 percent) and other fossil fuels, while electricity (4 percent) and biomass (15 percent) account for low shares. Overall, fossil fuels account for about three quarters of the energy consumed by process heating.

Technical potentials for direct electrification in the EU-27 based on 2019 energy demands

→ Fig. 1



Fraunhofer ISI (2024)

The results of the study indicate **significant potential for the direct electrification** of process heat generation, which could meet 90 percent of the energy demand not yet electrified by European industry, if fully deployed (see Figure 1 and Section 4.3). This would contribute to a significant cut in carbon emissions due to the reduction in fossil fuel use, strengthening the sector's competitiveness and making a critical contribution to achieving EU climate targets. Solutions already exist to electrify a large part of process heat generation, potentially reducing fuel demand by 62 percent. Another 20 percent of the fuel demand could be electrified from 2030 onwards with technologies which are currently under development. For 8 percent of the fuel demand, electrification technologies might become available by 2035. This outlook presumes that the development of electric heating technologies will be pursued and encouraged by improved framework conditions. In all industry sectors, electrification technologies are available today. While sectors with low-temperature process heat demand like food or pulp and paper can be electrified to a very large extent using today's technologies, other sectors still have technical hurdles to overcome. Especially in sectors producing non-metallic minerals like cement, lime, glass or ceramics, further technology development and demonstration are needed to allow full electrification. In the steel industry a certain proportion of fuels is needed as a reducing agent in the production of primary steel, thereby limiting the electrification potentials in this sector.

The current state of direct electrification technologies

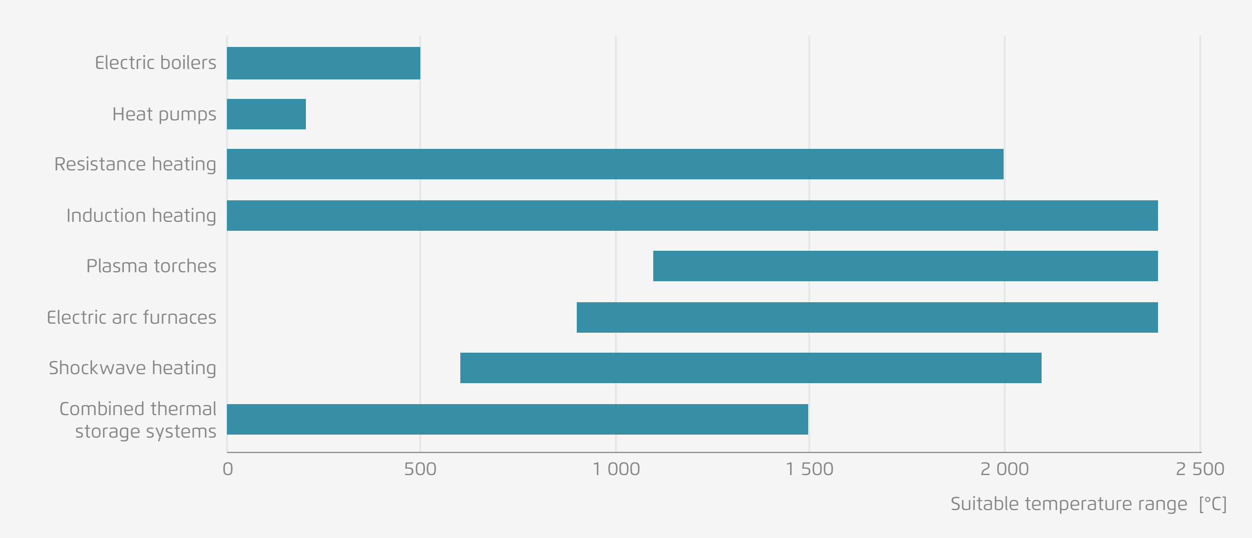
The investigated **direct electrification technologies** (Sections 3.1 and 3.3) demonstrate the capability to meet the temperature and capacity demands of a wide range of bottom-up investigated processes. Technology suppliers have ambitious plans for commercial-scale implementation, and it is advisable to closely monitor these developments. Electrification can be achieved by different technologies according to specific process needs.

Resistance heating (Section 3.1.3) is a versatile technology that can be applied to many processes, but integrating it into existing production plants, especially brownfield installations, poses ongoing challenges that require adaptations. An important limitation is the necessary energy density that might require large surface areas. The technology that is expected to be developed would aim to overcome challenges in high-capacity, high-temperature applications (up to 2 000 °C) like cement sintering and hot steel rolling. **Induction heating** (Section 3.1.4) has potential in metal processing, where it is already used in specific applications today. **Plasma technology** (Section 3.1.5) is emerging as a promising alternative for high-temperature (up to 3 000 °C) processes due to its ease of integration into existing furnaces. However, current restrictions such as the low lifetime of plasma torches and lower efficiency compared to gas-fired furnaces limit the short-term applicability of this technology. **Novel technologies** like shock-wave heating (Section 3.1.7) also have the potential to enhance the attractiveness and applicability of direct electrification, especially in high-capacity, high-temperature processes. These and other technologies are likely to improve in the coming decade and broaden the applicability of electrification even in challenging areas. **Electric boilers and heat pumps** (Sections 3.1.1 and 3.1.2) are highly suitable for electrification in low- to medium-temperature applications where hot water or steam are needed. Technologies are mature and proven in industrial use. Heat pumps, particularly when employed at suitable temperatures, offer significant efficiency gains in the paper, food and also chemical industries.

Adapting production processes can help overcome technological limitations and enable direct electrification. For example, by directly electrifying the lower temperature stages of clinker production or using longer paper machines for drying in paper production, the required temperature can be lowered, facilitating the use of direct electric heating technologies. However, these changes come with economic challenges, especially when existing installations are involved.

Potential development of suitable temperature range of electric heating technologies until 2035

→ Fig. 2



Fraunhofer ISI (2024)

In general, direct electric heating technologies offer higher **efficiency** than fuel-based technologies, with the potential exception of plasma torches, though the latter require further development, and their efficiency is dictated by application-specific properties. It is worth noting that more energy-efficient solutions are often more difficult to integrate into existing processes than less energy-efficient options (e.g. heat pump versus electric boiler). As a rule of thumb, the lower the process temperature is, the higher will be the efficiency potentials that can be achieved by switching to direct electrification. Though the system-wide effects of the competition between direct and indirect electrification were not the focus of this study, Section 4.4 does indicate the potential final energy demand differences.

The applicability of direct electrification by industrial sector

An evaluation of **industrial sectors** revealed the highly heterogeneous nature of their activities and their wide range of temperature demands and installed capacities. Focusing on specific applications with significant heat demand and greenhouse gas emissions allows the potential of direct electrification technologies to be assessed. Of the 33 applications evaluated, 14 were fully quantified, covering a substantial portion of the high-temperature process heat demand.

The **iron and steel sector** (Section 4.1.1) heavily depends on coal for the reduction of iron ore to obtain metallic iron and for metallurgical reasons such as impurity control and adjustment of desired steel properties. With technologies expected to be available by 2035, the direct electrification of iron production faces severe limitations; though hydrogen will likely play a major role in future iron production, the subsequent process of steelmaking is expected to be highly electrified. Furthermore, the first steps in the processing of steel intermediate products (reheating for rolled products) are highly energy intensive, with the result that concepts involving resistance heating elements have their limitations when it comes to integrating them into existing installations. Full direct electrification would require the technology to be improved and/or rolling lines to be more fundamentally redesigned. The **chemical industry** (Section 4.1.2), which is transitioning towards climate neutrality, faces significant challenges due to its reliance on fossil energy carriers as feedstock. The chemical industry offers significant potential for direct electrification, especially in electrified steam cracking and steam production, and could see considerable efficiency gains, especially if heat pumps were employed at suitable temperatures. Nonetheless, huge demand for feedstocks will remain, necessitating alternative solutions to electrification. In the **non-ferrous metals sector** (Section 4.1.3), electricity already accounts for a significant share of energy use, including primary aluminium production and non-ferrous metals processing in electric furnaces. A substantial proportion of the remaining fossil fuel use supplies temperatures below 500 °C and should, generally speaking, be possible to electrify (at least in part). Even at high temperatures, induction and resistance heating constitute more efficient alternatives to fossil heating and are proven technologies in this sector. Challenges remain in the **non-metallic minerals sector** (Section 4.1.4) due to the high capacities and temperatures of the furnaces (e.g. rotary kiln in cement clinker production). Achieving full electrification of important high-capacity furnaces will continue to pose a challenge in the coming years, and the sector's efficiency gains through electrification will rely heavily on technological developments. Technologies like resistance heating, plasma heating and shock-wave heating could play a major role.

Steam plays a vital role in various sectors, particularly in the paper, chemicals and food industries. Steam generation using electric boilers and heat pumps offers great potential for the early direct electrification of low- to medium-temperature applications, with heat pumps entailing considerable efficiency advantages over gas-fired boilers.

The findings indicate that most processes offer a lot of potential for direct electrification, though its success will not depend solely on the electric heating technology used. It will also require furnaces and corresponding processes to be developed that can replace optimised fossil-fired processes while ensuring product quality. In many cases, direct electrification will necessitate the fairly substantial redesign of the furnaces used. Therefore, new technology developments might also involve plug-in solutions for high temperature supply such as shock-wave or plasma heating.

Based on the **findings on the technical level**, we recommend closely monitoring the developments of technology suppliers' plans for commercial-scale implementation. Additionally, investing in the development of direct electrification technologies that are tailored to the specific needs of each sector and application is crucial. The adaptation of processes should be encouraged to overcome technological limitations, and sector-specific potentials and barriers should be taken into consideration when implementing direct electrification technologies. Encouraging the adoption of heat pumps for steam and hot water supply can lead to significant efficiency gains. Exploring the potential of waste heat utilisation, particularly for heat pump technologies, is important to leverage the full efficiency improvement potentials by decreasing temperature lifts. Lastly, emphasising the importance of furnace development and corresponding process adaptations is vital to ensure successful direct electrification, considering the specific requirements of each industry.

The role of hydrogen and its derivatives

Direct electrification is not the only option for decarbonising fossil fuel-fired process heating: one important alternative is the use of climate-neutral synthetic gases or fuels. The most widely discussed of these is **hydrogen**, which – if available in large quantities – has the technical potential to provide climate-neutral process heating in most applications (Fleiter et al. 2023b). When comparing direct electrification with hydrogen use or other forms of indirect electrification, both the end-user perspective and the effects on the overall energy system need to be considered. While this kind of systemic comparison is beyond the scope of this study, some relevant aspects of indirect electrification were identified in the stakeholder dialogue and in the existing literature (in particular on the energy-system level).

Stakeholder interviews revealed that indirect electrification methods such as the use of synthetic natural gas or hydrogen are perceived to have several benefits from an end-user perspective. One notable argument is that it reduces the urgency to make significant changes to the final energy consumption patterns. More specifically, indirect electrification is seen as a less disruptive option than direct electrification in terms of transforming the overall energy use (Fleiter et al. 2023b). While direct electrification requires infrastructure to be adjusted on-site and, in many cases, entire process heat installations to be replaced (see Section 5.3), switching from natural gas to hydrogen may – from the end-user perspective – merely involve the exchange of burners and fuel lines. On the other hand, long-term operation at industrial scale with hydrogen has not yet been proven for most processes. Additionally, the future large-scale availability of climate-neutral hydrogen at the individual production sites is still perceived as being highly uncertain, thereby impeding proper planning and investment decisions – particularly as this still requires the construction of new infrastructure or the repurposing of existing natural gas pipelines.

A further important factor regarding the competition between direct electrification and the use of hydrogen (or derivatives) is the **efficiency of heat supply**. Estimating the total electricity demand for varying levels of direct electrification versus hydrogen use underlines the need for differentiation and prioritisation (see Section 4.4, Figure 31). Particularly in the **hard-to-electrify applications** in high-temperature steel and minerals processing, efficiency gains from electrification are not significant by comparison with hydrogen use. In this context, a site-specific assessment and comparison of alternatives is required, and advantages like the ease of integration into existing processes need to be considered. Furthermore, a hybrid approach combining electrification and hydrogen use in applications without immediate access to full direct electrification (clinker burning, steel reheating) may enable a shift away from fossils, allow the on-site infrastructure to be modernised and give access to more electrification options in the future. In such cases the use of hydrogen might help allow barriers to direct electrification to be overcome, while at the same time not significantly increasing the electricity demand compared to full electrification. On the other hand, there is also huge potential on the **"easy-to-electrify"** side, where electrification can entail substantial efficiency gains when compared to hydrogen use. This is particularly the case in steam and hot water generation when heat pumps are applied.

However, **further research** is needed to compare options more systematically, including factors such as technology maturity, ease of implementation and compatibility with existing installations. The systemic effects of indirect electrification also require much more detailed investigation, including the additional effort involved in infrastructure and energy transformation. Assuming efficiency for hydrogen production can only be the first step, ultimately the costs for hydrogen generation will determine its competitiveness. These costs will also depend on the role played by hydrogen in the energy system, where full sector coupling can take advantage of benefits such as seasonal storage and integration of wind and solar generation.

The barriers to and challenges for direct electrification

Realising the potential of direct electrification may be prevented or slowed down by a number of **barriers** (see Section 5). These can be grouped according to technical, economic and organisational aspects. Given the technology development assumed in this study, the **technical barriers** (primarily relating to energy density and the temperature range of the individual technologies) are expected to be overcome by 2035 (Section 5.1). **Economic barriers** include the price difference between electricity and natural gas (the prevalent fossil fuel) and the additional capital required for the fast replacement of process heat installations (Section 5.2). In addition, a diverse set of **organisational barriers** hinder the widespread application of direct electrification and may continue to do so in the future if left unaddressed (Section 5.3): infrastructures on site and in the immediate vicinity favour fossil technologies – the prime example being the on-site capacity of electricity supply, which in many cases will need to be expanded substantially to satisfy the demand generated by full direct electrification. Following the same line of reasoning, the existing process heat installations often have lifetimes of several decades and replacing them may involve deep interventions in the entire production process. In such cases, the windows of opportunity for electrification are rare. Finally, a lack of knowledge about the available (and potential future) direct electrification technologies and how they compete with indirect electrification, not to mention about the latter's general availability, contribute to a high level of uncertainty. This uncertainty also extends to grid connection and extension and to security of supply, paralysing decision makers.

These barriers do not apply equally to all applications and technologies: many applications can already be directly electrified today as technologies are mature and available. Especially in the low-temperature range in which heat pumps operate with high efficiency, economic challenges can already be overcome. Applications in this area are the most likely candidates for early electrification, including first and foremost the generation of steam, e.g. in paper production, the food industry and various chemical processes. The next group involves medium- to high-temperature applications that can be at least partially directly electrified and addressed by existing technologies (resistance heating, induction), though still entail some not insignificant economic challenges (e.g. glass production, chemical processes, some steel processing steps). The highest requirements in terms of energy density and temperature (e.g. clinker burning, reheating of steel) can be met by technologies that are still in the process of being upscaled (plasma torches, shock-wave heating).

Overcoming barriers to accelerate electrification

The results of the study show that available technologies would allow a high degree of electrification and that many technical barriers could be overcome in the coming decade, but that organisational and market barriers are preventing the large-scale roll-out of electrification. Overcoming such barriers and directing technological learning should be a focus for policy makers in order to facilitate a climate-neutral production system. Most importantly, this requires climate-neutral electricity to be made available in large quantities and at competitive prices for industrial consumers. Mitigating (perceived) risks by demonstrating technologies under industrial conditions can facilitate the market entry of electrification in specific applications. It is essential to demonstrate that electrified processes work reliably at industrial scale in continuous long-term operation and have no detrimental effect on product quality. In the short term, the regulatory framework should allow or even support partial electrification as hybrid systems enable technology learning and further strengthen the market via a pull effect. Though the technical challenges can be overcome, active support to scale up direct electrification technologies is vital, especially during the demonstration and commercialisation phases of concepts that push the technical boundaries of electrification (in terms of energy density or temperature range) or that extend its use to new processes and materials (metals, non-metallic minerals, some high-temperature chemical processes).

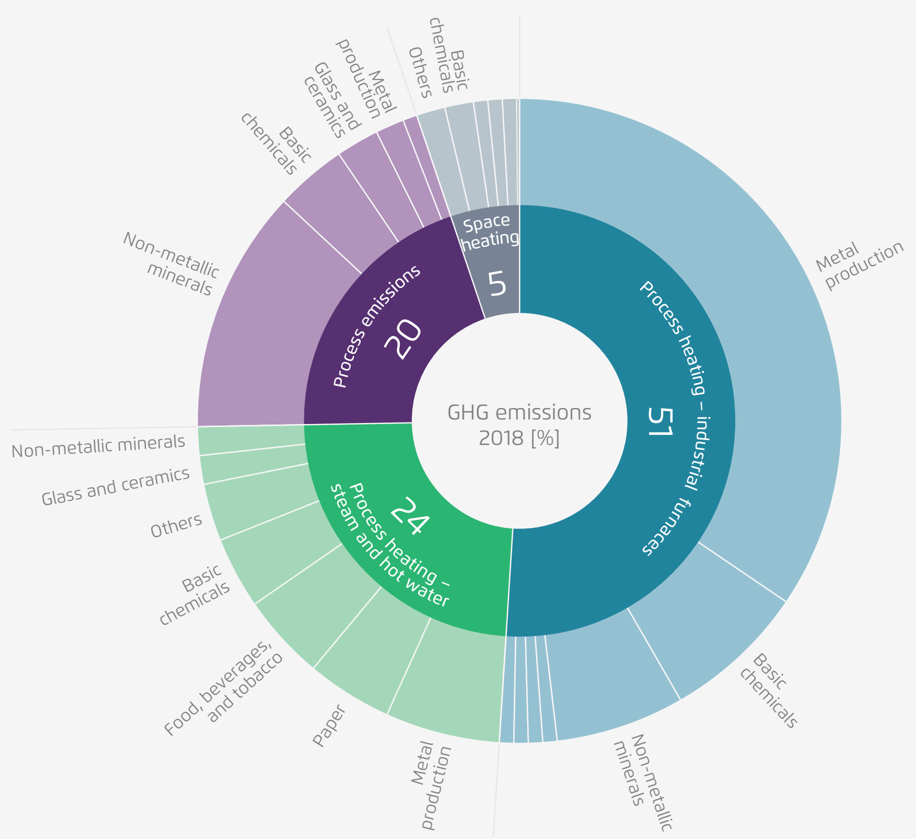
2 Introduction, scope and method

2.1 Background: status quo of process heating in European industry

Today, process heating is the largest energy use in industry and the main source of greenhouse gas (GHG) emissions. Roughly three quarters of overall GHG emissions from industry are related to the combustion of fossil fuels for process heating (see Figure 3). In this context, metal production is the most important sector due to its high demand for coal. Other sectors such as basic chemicals, non-metallic minerals (e.g. glass and cement) or paper production also contribute substantially to overall GHG emissions from process heating.

The total energy demand from industry in the EU-27 accounted for about 4 000 TWh in 2019, including final energy plus feedstock. Of this total, nearly one half – about 1 860 TWh – was used for process heating, making this the single most important energy use in industry (see Figure 4) (Rehfeldt et al. 2017; Fleiter

Approximate structure of GHG emissions in the European industry sector, 2018 → Fig. 3



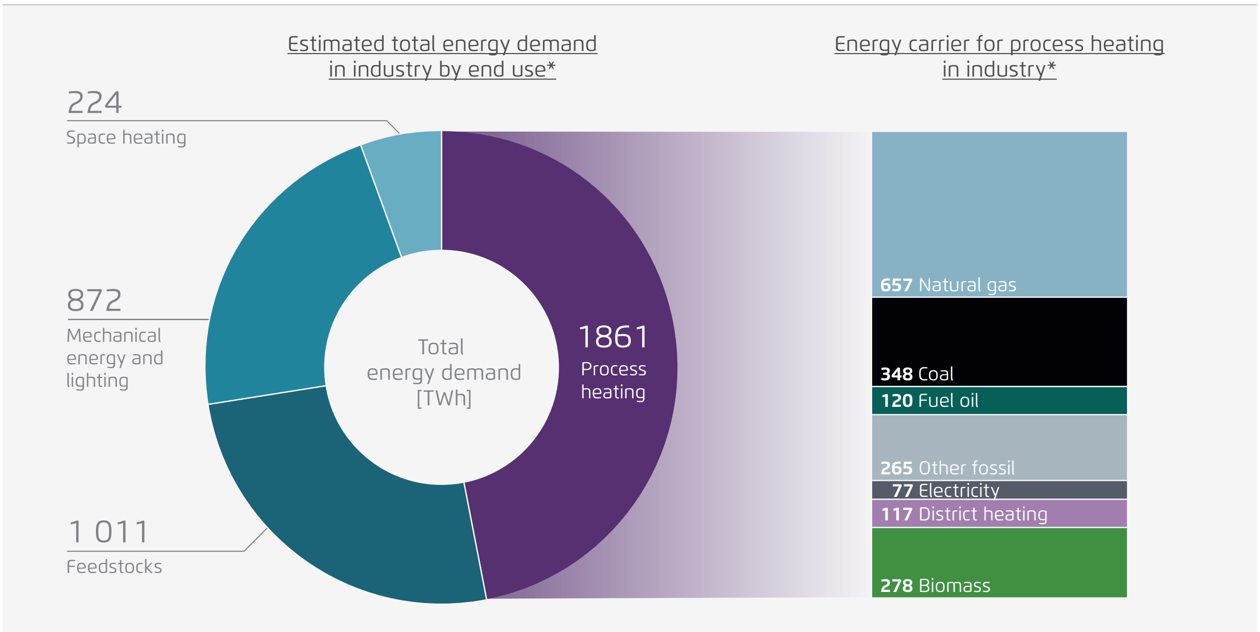
Fraunhofer ISI (2024), based on National Inventory Reports, extended with Germany-based model data from Fraunhofer ISI.

et al. 2023a)[1]. In addition, process heating today is still supplied mainly by fossil fuels. Most sectors and processes use large quantities of natural gas, as it was available at low costs in the past and brings many advantages, such as simple handling, high energy density and good process control. Coal also still plays an important role in areas where it is technically necessary, such as in oxygen steel production, or where the lower costs of coal are more important. Fuel oil as a source of process heating has been continuously phased out over the past decades and supplies a relatively small proportion today. Other fossil fuels such as waste or blast furnace gas play more specific roles in individual industry sectors. Overall, all industrial sectors nowadays are highly dependent on fossil fuels to provide process heating. More specifically, fossil fuels account for about 75 percent of the overall energy use for process heating in the EU-27. Biomass plays a certain role, mainly in sectors such as pulp and paper in which biogenic production residues can be used. Direct electrification only plays a marginal role in a number of specific processes where it offers substantial advantages such as efficiency gains or ease of process handling. The overall share of electricity is small and currently accounts for less than 5 percent of total process heat demand. A recent study shows untapped efficiency potentials for industrial processes (Meyer et al. 2023).

Looking beyond the highly aggregated energy balance reveals a considerable diversity in process heating patterns across the different industrial sectors and processes. Temperatures, heat densities, process operation, installation capacities and applicable technologies differ across the various processes used in industry. The bulk of energy demand for process heating is concentrated in the basic materials industries such as iron and steel, chemicals and non-metallic minerals. These sectors not only consume the lion's share of the energy for process heating; they also require the highest temperatures, typically of more than 1 000 °C, as well as very high energy densities. Process heat in these sectors is provided by highly specialised large-scale furnaces and kilns that

1 The method of estimating EU-wide process heat demand by energy carrier and industrial sector is described in Rehfeldt et al. 2018 and integrated into the FORECAST model. The figures presented here take into account the updated activity data and energy balances based on Fleiter et al. (2023a).

Energy demand of process heating and its energy sources in the EU → Fig. 4



(Fleiter et al., 2023a), FORECAST model. Note: * in 2019 in the EU-27 countries.

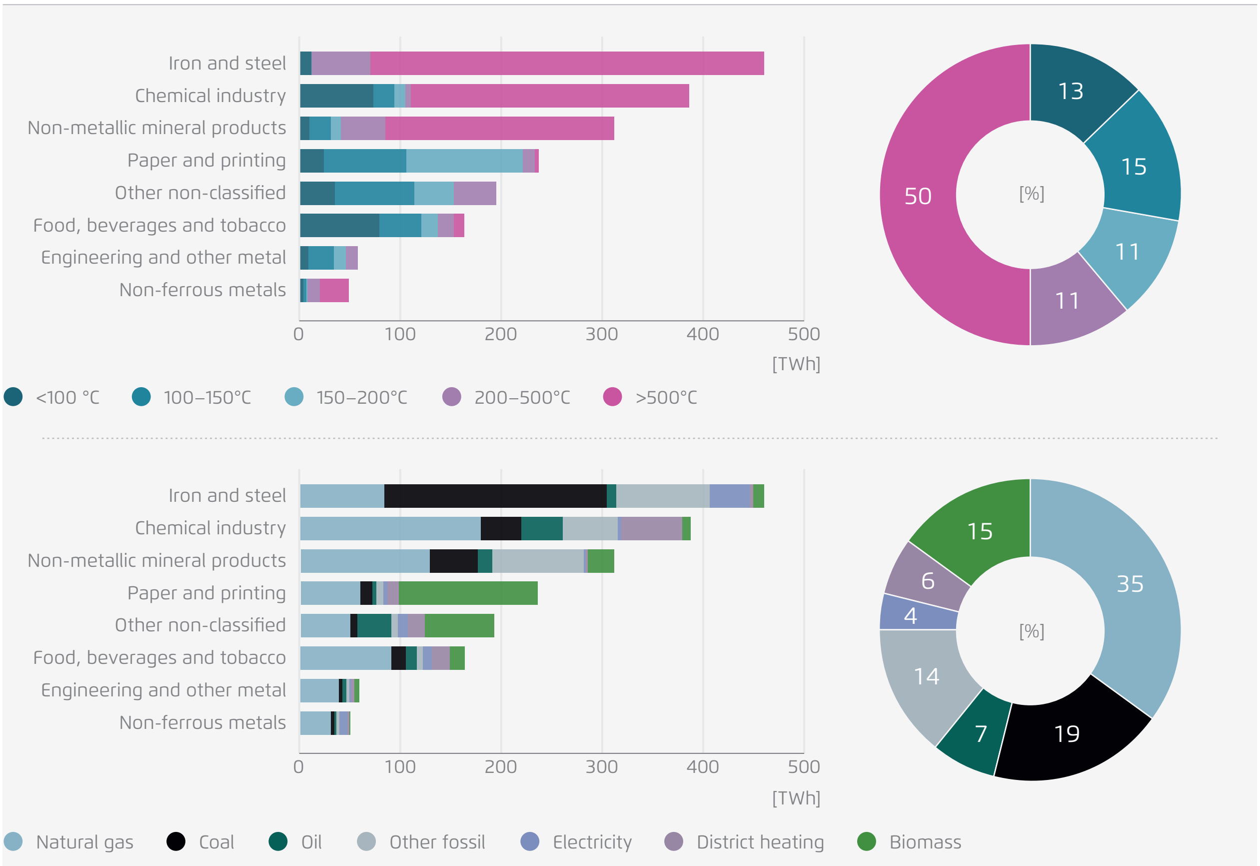
have been optimised over decades and are typically operated continuously, with only short downtimes for major maintenance cycles[2]. Natural gas and coal dominate the fuel mix, and electricity has for the most part not been considered for most processes on account of its higher price compared to natural gas or coal. Assessing future electrification potentials requires specific analyses of individual applications and their related furnaces.

Other sectors, such as paper and printing or food, beverages and tobacco, show a different pattern. Though they also feature high overall process heat demands, they use heat at lower temperature levels, mostly below 200 °C in the form of steam or hot water. Steam generation technologies are more homogenous and comparable across industries and processes. While the lower temperature level potentially makes them more suitable for the use of renewables or electricity, steam generation today is mainly provided by natural gas. Biomass plays a certain role here, however, e.g. in the pulp and paper industry, as well as in the "other" category that includes various sectors such as wood processing. To assess electrification potentials, it is possible to extrapolate from the individual steam applications to the entire area of steam and hot water generation. Temperature and steam pressure are the main parameters to consider.

2 Major installations typically show 8 300+ yearly full-load hours, with only some weeks of downtime for maintenance purposes.

Estimated total final energy demand for process heating in 2019 by temperature and energy carrier in the EU-27 countries

→ Fig. 5



Fraunhofer ISI (2024), based on FORECAST model

2.2 Objectives

The industrial sector faces highly specific challenges when it comes to decarbonising its energy use. Fossil fuels, which are used to provide process heat for a broad range of industrial applications, are the main source of greenhouse gas (GHG) emissions in EU industry. While the goal of decarbonising this process heat by 2050 is clear, several technologies and transformation pathways are under discussion. Their attractiveness from societal, individual-economy and ecological perspectives varies and the resulting transformation pathways can at the same time be mutually exclusive. The best way to reach climate targets is thus the subject of political discussion and strongly influenced by interest groups. One contentious issue in this discussion is the use of direct electrification as opposed to indirect electrification via hydrogen (or its derivatives). Direct electrification is favoured for its higher systemic efficiency and general role as a crucial decarbonisation strategy, while indirect electrification offers solutions for specific applications in the chemical and steel industry (Lübbers et al. 2022) and can be an attractive option for processes that use natural gas today because it requires relatively little in the way of changes at the production site. The extent to which indirect electrification should be used beyond these applications, especially for the production of process heat, is currently being debated. The technical and economic capabilities of direct electrification technologies to supply process heat are one main aspect of this discussion.

In this study, we assess the technical potential for direct electrification to supply process heat to European industry. Our aim is to inform the discussion by estimating the potential for the direct electrification of process heat across several industrial processes. Both available and emerging direct electrification technologies are identified and described. This analysis is complemented by an assessment of sectors, processes and applications to encompass a broad range of technical and economic requirements – from steam demand in paper production and food industries to high-temperature process heat in metal processing furnaces. Practical insights into technology implementation and ways of overcoming barriers are included via stakeholder engagement. The study thus increases knowledge about the technological options for direct electrification, their technology readiness, expected market entry, cost effectiveness and usability in existing installations and transforming applications. It estimates the electrification potentials of process heat generation across the European Union and important industrial subsectors and processes, and analyses the barriers that need to be addressed to tap into that potential. Based on these insights, recommendations are formulated with a view to supporting communication to policy makers on the national and European levels.

The study focuses on the end-use perspective. System-wide aspects such as the efficiencies of entire value chains (e.g. of hydrogen production), infrastructure extension and generation capacities are not part of its scope – assuming that they do not directly affect the technology options on-site.

2.3 Technologies within scope

The primary objective of this study is to assess the potential for the electrification of process heat with a view to contributing to a carbon-neutral future. This involves a thorough examination of available and emerging heating technologies, focusing particularly on those properties that enable or restrict their use in existing industrial processes. These include temperature ranges, power requirements and applicability in existing installations. By comprehensively exploring various technology options, this study aims to identify the most promising technologies for achieving electrified heat generation and to suggest actions to enable their implementation.

In order to estimate their policy-relevant electrification potential, the expected market availability and diffusion of the selected technologies are very important. In this study, technologies with an expected market entry at full industrial scale by 2035 or earlier are considered. We therefore assume that these technologies will have the opportunity to reach the market shares necessary to impact decarbonisation efforts by 2050. They include not only available technologies – industrial heat pumps, electric boilers, resistance heating, induction heating, and plasma torches – but also emerging technologies such as shock-wave heating and combinations of process heat generation and storage. The electric heating technologies considered in this study are listed in Table 1. Other electric heating technologies such as dielectric heating, infrared heating, direct electrolysis of iron production, electron beams and ultra-violet light are not among the technologies selected, either because they are not expected to be relevant before 2035 (direct electrolysis) or apply only to niche applications (lasers, ultraviolet), or because they merely represent alternatives to the considered technologies (dielectric and infrared) without extending the electrification potential. Their potential for additional electrification and efficiency improvements may be investigated in subsequent analyses.

List of considered direct electrification technologies → Table 1

	Industrial heat pumps
	Electric boilers
	Resistance heating
	Induction heating
	Plasma torches
	Electric arc furnace
	Shock-wave heating
	Combined thermal storage systems

Fraunhofer ISI (2024), Agora Energiewende (2024)

2.4 Applications and sectors within scope

The dominant use of fossil fuels to supply process heat is complemented by their use as feedstock and reducing agent in chemical reactions. These uses are not investigated in this study, because these parts of the applications – with the exception of the electrolysis of iron ore – cannot be directly electrified. For example, the use of natural gas in the production of ammonia – where natural gas is converted into a synthesis gas comprising hydrogen and carbon monoxide – involves inserting hydrogen into the final product (NH_3). Thus, while the required process heat may be supplied directly by electricity, the hydrogen itself relies on indirect electrification for decarbonisation.

The focus of this study is on the provision of process heat for industrial applications and sectors in which a switch to direct electrification is possible in principle. This includes two major areas: low- to mid-temperature process heat, often supplied in the form of steam (temperatures between 100 and 250 °C degrees[3], which is most relevant in the chemical sector, pulp and paper and food production), and high-temperature process heat applied in furnaces (temperatures above 500 °C and up to and beyond 1 500 °C, most relevant in the chemical, metal and non-metallic mineral industry). However, the solutions for process heat electrification and feedstock use interact on a system-wide level (e.g. infrastructures). Energy system scenarios and policy designs usually consider both in integrated approaches. The results of this study also need to be considered in this context; this may be done in subsequent analyses.

2.5 Method

For the purposes of this study, we define specific terminology to refer to the investigated objects and concepts. **Direct electrification** describes process

3 Though higher temperatures of steam use (e.g. 400–500 °C) exist, the huge majority of applications work below 250 °C.

heat generation involving the immediate use of electricity (e.g. without an intermediate product such as electricity-based hydrogen or synthetic fuel). **Technologies** are (based on the terms used in Fleiter et al. 2023b) general concepts of direct electrification such as resistance heating, plasma torches or heat pumps. **Industrial sectors** are classifications of broad activities based on raw material or final product groups (e.g. iron and steel, non-ferrous metals) according to the classification systems (e.g. NACE 2.0) used in energy balances or greenhouse gas inventories. **Applications** are more specific uses of process heat for which specific technical and economic requirements and conditions can be identified (e.g. heat treatment furnaces in steel processing, steam generation for paper drying).

The method used in this study involves investigating selected applications[4] and describing their process heat demand (especially in terms of capacity and temperature level). On this basis, the process heat demand of their respective industrial sectors is extrapolated (see Section 2.5.1) and matched with the capabilities of direct electrification technologies. This allows the direct electrification potential of industrial process heat using existing (available by 2020–2025) and expected (available by 2035) technologies to be calculated. These timeframes have been selected as a means of distinguishing between technologies that are available today or will be in the near future (2020–2025) and those needing additional but limited research and development (2035). In particular, it sets them apart from technologies that are expected to require extensive research (expected availability after 2035) and thus risk lacking the time required for upscaling and diffusion in actual applications. The calculations are based on the energy demand in the European Union (EU-27) in 2019.

The information and assumptions about technologies and applications are substantiated by expert interviews with **manufacturers** and **users** of process heating technologies (see Section 2.5.2).

4 To a high degree based on previous work done by Fleiter et al. 2023b and Agora Energiewende 2023 and supplemented by expert interviews.

2.5.1 Calculation of electrification potentials

Based on the in-depth assessments of state-of-the-art electrification technologies and technological readiness levels by 2035 (see Section 3), the overall electrification potential for industrial heat in EU-27 industry is assessed.

The calculation of electrification potentials follows a **combined bottom-up/top-down** approach. The **bottom-up calculation** uses detailed information on the energy intensity and process heat requirements of individual applications (i.e. temperature profile of heat demand, specific energy consumption, conventional technologies, physical production amounts) based on previous work and literature (e.g. Fleiter et al. 2023b; Agora Energiewende 2023). In total, 14 applications (plus three that are exemplary of the entire steam range) from seven industrial sectors are quantified in this manner (see Section 4.1), covering approx. 80 percent (of which approx. 40 percent is steam) of European process heat demand (compare Figure 25). This includes making special assumptions about the entire range of steam demand: we consider three investigated applications (paper drying, milk powder production and steam supply in chemical parks) sufficient to cover all relevant steam users. These applications span most of the usual range of steam temperatures (100 °C– 400 °C) and pressures (3–40 bar, in rare cases higher) – we assume that all steam use can be addressed with the range of technologies able to supply these example applications.

The **top-down calculation** closes the gap between the bottom-up sum and statistical values (Eurostat Energy Balance 2019). For this purpose, we assume that the remaining process heat demand for each industrial sector is similar to representative processes. For the sectors which are not covered, we assume that the same requirements apply as to the demand covered in the bottom-up calculation (see Section 4.2). These assumptions are an approximation and simplify actual heterogeneity in favour of the research design's feasibility. The challenges and barriers to direct electrification incurred by the properties and requirements of individual applications not included in the bottom-up calculation may be underestimated. Special care has been taken to identify the most relevant and representative applications per sector in order to limit this risk.

2.5.2 Stakeholder involvement

Stakeholder involvement consisted both of expert interviews that were conducted between July and September 2023 and a multi-stakeholder workshop in August 2023.

In total, 12 expert interviews with technology users and manufacturers, mainly from Germany but also from other European countries and the United States, were conducted, of which seven were with representatives of technology/process heat users, four were with technology manufacturers and one was with an energy consultant. The interviews covered a wide range of industries, including glass (1), pulp and paper (1), chemicals and pharmaceuticals (2), cement and concrete (1), metals and steel (1), and food processing (2). The remaining four interviews were based on cross-industry expertise. The interviews were semi-structured along an indicative questionnaire (Appendix) and lasted about one hour each.

The results of the interviews and the preliminary results of the study were presented to experts from the interviews and additional stakeholders in a two-hour (hybrid) workshop in August 2023. In total, 28 external stakeholders participated in the workshop in August 2023. The participating experts confirmed the presented preliminary results; additional comments and information received have been incorporated into the final results.

The interviews were especially helpful when it came to validating information from literature research and previous projects, identifying and confirming practical barriers and discussing how to overcome these in order to foster diffusion and actual implementation. We thank all contributing experts for their involvement.

3 Technology assessment

The following sections describe the selected technologies and assess their capabilities, potential applications and inherent challenges. The fact sheets relating to the individual technologies indicate their current status and expected development – under the assumption that further research and development will take place and further economically viable use cases will be created.

This section is divided into an introduction of the technologies included in this study and a very brief presentation of those technologies that are considered out of scope. The main criterion for this selection is the expected impact of the individual technology by 2035 – in particular, whether market readiness can be expected by 2035 and whether the technology increases the potential for the direct electrification of process heat. On the basis of these criteria, electric boilers, heat pumps, resistance heating (especially in the context of industrial furnaces), induction, plasma torches, electric arc furnaces and shock-wave heating are included – as is the combination of resistance heating with thermal storage systems. Dielectric, ultraviolet and infrared heating are considered to be alternatives to technologies within the selection, given their achievable temperature levels and applications (heat pumps, electric boilers, resistance heating). They do not therefore increase the electrification potential and are not investigated in this study. Lasers and electron beams are considered to be tools (e.g. for cutting and welding) rather than process heating sources and are thus excluded. Finally, the direct electrolysis of iron ore could address a highly relevant application without currently available direct electrification options but is not expected to be market ready by 2035.

3.1 Selected technologies

3.1.1 Electric boilers

Electric boilers have emerged as an alternative to fossil-fired boilers or combined heat and power generation (CHP) such as gas and steam turbines. Their application and use are equivalent to those of conventional boilers. Electric boilers are already established in industry. In industrial settings, electric boilers are gaining prominence due to their versatility, ease of installation and potential for high-temperature applications. Electric boilers (and heat pumps) can be used in steam-using applications in which combined heat and power generation such as gas and steam turbines is relevant today.

Electric boilers come in two types: electrode and resistance boilers. In an electrode boiler, the current is introduced directly into the water via an anode and flows through the water to a cathode. In resistance boilers, an electric current heats a metal or ceramic heating element (i.e. via resistance heating; see Section 3.1.3) and the heating element transfers the heat to the water via conduction (Fleiter et al. 2023b). Electric boilers are available in a range of capacities, accommodating various industrial demands. They typically provide capacities ranging from small-scale applications at around 10 kW to large-scale systems exceeding 10 MW (Expert Interview 2023). Furthermore, these boilers can attain maximum temperatures above 500 °C, facilitating processes that necessitate elevated heat levels which heat pumps cannot provide. Pressure levels can vary based on specific requirements, typically reaching up to 20 bar, though higher pressures can be achieved (Expert Interview 2023; PARAT Halvorsen AS 2023).

Fact sheet for electric boilers and potential technical development by 2035 for industrial application

→ Table 2

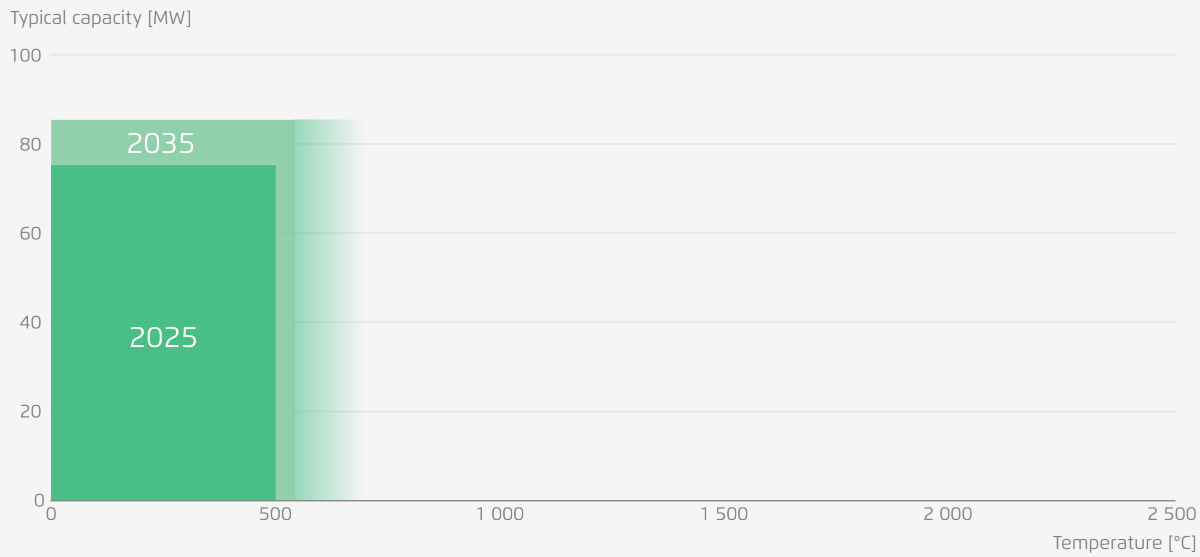
	2023	2025	2030	2035
Maximum temperature	500 °C[1]	500 °C	500 °C	500 °C
Heat production efficiency	99%[1]	99%	99%	99%
Capacity	up to 75 MW[2]	up to 75 MW	up to 75 MW	up to 75 MW
Advantages	Compared to heat pump: higher achievable temperatures, easier to integrate into existing systems and lower investment costs[3], existing operation experience in relevant applications			
Disadvantages	Compared to heat pump: lower efficiency			
Examples of relevant industries and processes	Steam generation in paper production, food industry and chemical industry[1]			
Technology readiness level	9 → Established technology (small capacities) → Application for higher temperatures and capacities no big hurdle → Economic barriers			

[1] Simplification according to Fleiter et al. 2023b, with steam demand typically limited to below 500 °C. Higher temperatures are possible but the huge majority of steam application require temperatures below 250 °C.
[2] PARAT Halvorsen AS 2023
[3] An estimate of economic aspects of heat pumps and electric boilers can be found in Agora Energiewende 2022 (https://www.agora-energiewende.de/en/publications/transformationskostenrechner-power-2-heat/).

The advantages that electric boilers offer over their conventional gas-fired counterparts are their higher efficiency levels, as they convert electrical energy into heat which is transferred directly into the medium without the energy losses associated with heat exchangers and flue gas. Additionally, electric boilers are inherently cleaner, emitting no greenhouse gases or pollutants during operation. Upfront costs for electric boiler installation and infrastructure combined can be higher than in traditional gas-fired systems. However, the most important barrier to wider use is the high electricity price compared to natural gas in most European countries. Several policy recommendations on this issue exist (e.g. Agora Industry and Future Camp 2022). The economic aspects relating to the substitution of CHPs or interaction with electricity systems have not been investigated in this study but do merit in-depth analysis, particularly with respect to flexibility, security of supply, support schemes and infrastructure.

Typical capacity versus temperature range of electric boilers in 2025 and potential technical development by 2035

→ Fig. 6



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3.1.2 Heat pumps

Heat pumps are unique among electrified heating technologies. Rather than converting electricity into heat, a heat pump moves heat from an area of low temperature (the "heat source") to an area of high temperature (the "heat sink"), similar to a refrigerator moving heat from the cold interior to the warm exterior of the unit. A heat pump has a closed loop of piping filled with a refrigerant. Before passing through the heat source (typically the air or ground), the fluid passes through an expansion valve that lowers its pressure and causes it to evaporate and thus to cool. The fluid absorbs heat from the heat source and is then compressed; as it condenses it heats up. The hot fluid then passes through a heat sink, such as water in the case of an industrial heat pump designed to produce steam. Heat passes from the refrigerant to the heat sink, and the refrigerant is pumped back to the expansion valve, beginning the cycle again.

Heat pumps can be used in a range of processes with relatively low temperatures and have very high efficiencies compared to conventional heating technologies. The system efficiency depends to a great extent on temperature lift and thus careful integration into the industrial process. Physical laws and technically available refrigeration agents impose limitations on the achievable temperatures (and thus applications). This study considers heat pumps for broad-ranging steam generation needs in food industries and paper production, as well as in other industries.

The typical maximum temperature output of commercialised heat pumps today is around 165 °C (Arpagaus et al. 2018), though these high-temperature heat pumps have relatively small capacities (660 kW). Larger heat pumps (20 MW capacity) are commercialised for temperatures up to 100 °C according to Madeddu et al. (2020). However, these estimates and the associated efficiencies depend primarily on the temperature lift[5]. Higher temperatures can thus be reached with higher-temperature

5 A heat pump operates according to the principles of thermodynamics, specifically the Carnot cycle. The Carnot cycle represents the theoretical maximum efficiency that a heat pump can achieve. It abstracts the achievable efficiency to two temperature levels: the heat source temperature and the heat sink temperature. For example, if the heat source is at 60 °C and the heat sink is at 180 °C, the maximum achievable coefficient of performance (COP) will be 3.8. In practical applications, however, high-temperature heat pumps typically reach around 50–60 percent of this theoretical limit - in this case a COP of approximately 1.9–2.3.

heat sources (e.g. waste heat from an industrial process). In combination with subsequent mechanical vapour compression (MVR) or direct-electric temperature boosting, even higher temperatures can be reached – albeit at the cost of efficiency. In any case, the technology (compression, refrigerant, boost) for systems with temperatures up to 250 °C does exist. Research and development work is aiming to achieve higher temperatures still (Stathopoulos 2023), and it is likely to be possible to supply up to 300 °C heat by 2035. To estimate the electrification potential, however, we assume a typical practical range of up to 200 °C (Table 3)[6] – combined systems (e.g. with a large electrode boiler component) may reach higher temperatures.

6 In the case of heat pump systems, the interaction of base system (heat pump), booster (electric or mechanic), heat source and sink and the resulting COP creates a wide range of potential systems that would be inadequately described by the respective maximum values.

Since heat pumps move rather than generate heat, they are more efficient than other heating technologies. Heat pump efficiency is expressed as a coefficient of performance (COP), which is the ratio of output heat to input electricity. Heat pumps are most efficient when delivering relatively small temperature increases, and their efficiency drops as the temperature increase grows larger. This makes them attractive for the recovery of waste heat. For example, a heat pump that extracts heat from 60 °C and outputs steam at 180 °C has a COP of between 1.9 and 2.2 (Arpagaus et al. 2018). Increasing the output temperature reduces the COP, while raising the temperature from the heat source – e.g. by using more attractive waste heat steams – increases the COP.

While industrial scale heat pumps are already technically mature and available, their diffusion faces various challenges. Their installation requires an external heat source such as waste heat or ambient air, and is thus more complex than fossil-fired boilers. Though the overall potential of these heat sources

Fact sheet for heat pumps and potential technical development by 2035 for industrial application

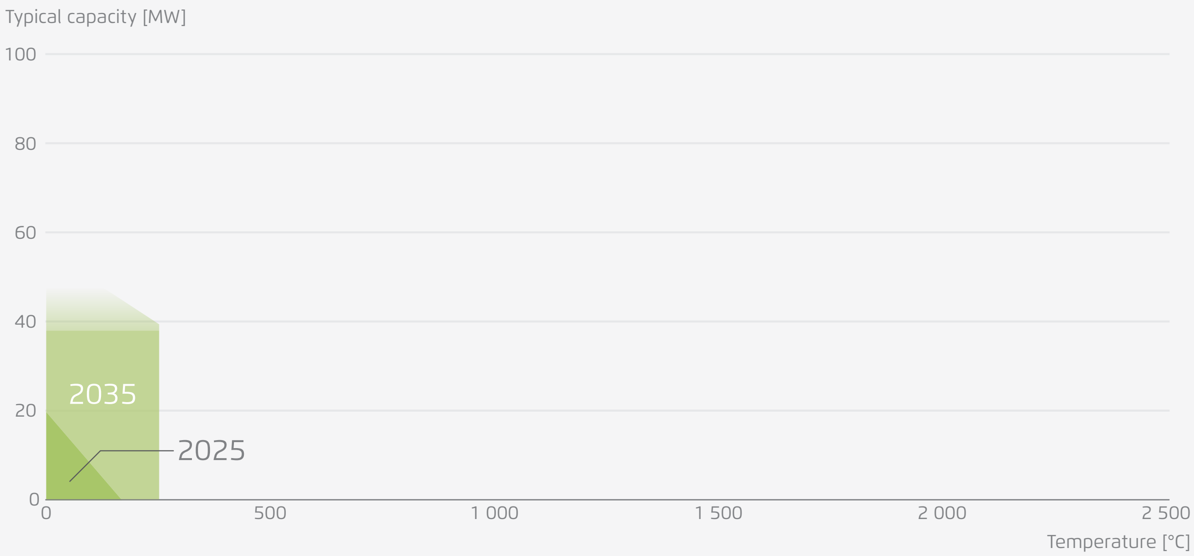
→ Table 3

	2023	2025	2030	2035
Typical maximum temperature[1]	165 °C	200 °C	200 °C	200-300 °C
Heat production efficiency[1]	150–600%	150–600%	150–600%	150–600%
Capacity[1, 2]	20 MW	Modular, expandable	Modular, expandable	Modular, expandable
Advantages	Very high efficiency[1,2], existing operation experience in relevant applications			
Disadvantages	Higher investment costs than electric steam boilers[1] More complex plant integration than electric steam boilers[1,2] Higher temperature lifts reduce efficiency			
Examples of relevant industries and processes	Steam generation in paper production, food industry and chemical industry[1,2]			
Technology readiness level	8 (at very high temperatures and high capacities) – 9 → Established technology (small/medium capacities) → Use in other applications (e.g. high capacities, high temperatures) requires further development → Economic barriers			

[1] Fleiter et al. 2023
[2] Expert Interview 2023

Typical capacity versus temperature range of heat pumps in 2025 and potential technical development by 2035

→ Fig. 7



Fraunhofer ISI (2024)

is expected to be more than sufficient (example study for Germany: Agora Energiewende and Fraunhofer IEG 2023), site-specific conditions and the availability of heat sources are relevant factors to be considered (compare Section 5.3). The higher investment costs than electric or gas-fired steam boilers (Rehfeldt et al. 2023) are another aspect.

The most important applications for heat pumps are to be found in industries with demand for low- to medium-temperature heat and steam. These include food processing (for cooking, sterilising etc.), pulp and paper (pulping, bleaching), chemicals/plastics (driving chemical reactions, plastic moulding), textiles (drying, heat setting) and shaping metal parts for vehicles (Agora Industry and Future Camp 2022; Rehfeldt et al. 2017; von Thadden del Valle et al. 2023). In many applications, the required temperature level may be lowered by implementing appropriate efficiency and process optimisation measures at best-available-technology (BAT) level – thereby increasing the suitability and efficiency of heat pumps. However, modifying existing processes in this way is complex and entails specific challenges which need to be addressed (compare Section 5).

3.1.3 Resistance heating

Electric resistance heating involves sending an electric current through a resistor[7] to produce heat of the desired temperature. Resistance heating offers precise temperature control, rapid heating and low maintenance. Resistance heating is already used today and can be adapted to various industrial applications and materials, from heating liquids and gases to melting metals and plastics. It is thus considered to be a broadly applicable solution for medium- to high-temperature process heat. This technique can be classified into two main categories: direct and indirect resistance heating.

Direct resistance heating involves applying an electric current directly to the material being heated. One example of an application is the electrical melting of container glass. Direct electric heating can only be applied to certain materials.

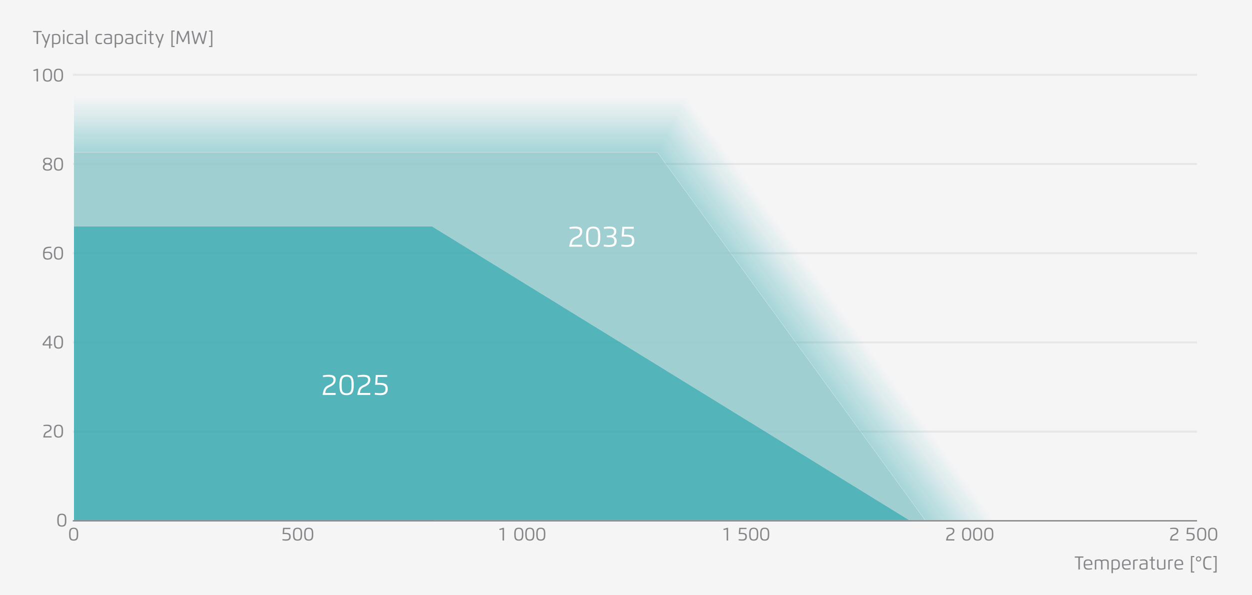
7 The resistor may be an external heating element (indirect) or the heated material itself (direct).

Fact sheet for resistance heating and potential technical development by 2035 for industrial application → Table 4

	2023	2025	2030	2035
Maximum temperature	1 850 °C[1]	1 850 °C	2 000 °C[2]	2 000 °C
Heat production efficiency	99%[1]	99%	99%	99%
Capacity	80 kW/m^2 [1]	80 kW/m^2	200 kW/m^2 [2]	1 MW/m^2 [2]
Advantages	High efficiency in wide temperature range[1, 2], existing operation experience in relevant applications			
Disadvantages	Power density (result of capacity and temperature) as limiting factor[3]			
Examples of relevant industries and processes	Indirect resistance heating: heat storage, calcination, aluminium processing Direct resistance heating: container glass[3]			
Technology readiness level	9 → There are applications that use it (small capacities) → Use in other applications (e.g. high temperatures, high capacities) requires further development → Economic barriers			

[1] Without inert gas atmosphere (Thermcraft, Inc.)
[2] With external heater (Expert Interview 2023)
[3] Fleiter et al. 2023b

Typical capacity versus temperature range of resistance heating furnaces in 2025 and potential technical development by 2035 → Fig. 8



Fraunhofer ISI (2024)

By contrast, indirect resistance heating employs resistor elements that are heated by sending an electric current through them. The heated elements in turn transfer heat to the environment via convection and radiation. Thus, indirect electric heating is independent of the material to be heated. The maximum achievable temperature in indirect resistance heating is limited by the material used for the heating element, which must not melt or chemically break down during operation. The most common material for heating elements is nichrome, a nickel-chromium alloy. It has a melting point of about 1 400 °C and can provide heat for industrial processes of up to 1 250 °C. When higher temperatures are needed, heating elements made of tungsten can provide heat of up to 2 500 °C, while graphite elements can even be used for up to 3 000 °C when surrounded by an inert gas such as argon or helium. The inert gas environment reduces oxidation and minimises wear and tear on the heating element, thereby extending the longevity of high-temperature resistance heating elements (Thermcraft, Inc.). However, maintaining an inert gas atmosphere in large-scale industrial processes is a challenge and the lifespan of the heating elements is low at high temperatures. Without an inert gas atmosphere, molybdenum di-silicide can be used at temperatures of up to 1 850 °C. The power density is another limiting factor. Resistance heating elements reach up to 80 kW/m^2 (Thermcraft, Inc.). In some applications, the limited surface area of today's furnaces poses a challenge in terms of incorporating an adequate number of resistance heating elements to achieve the necessary heat densities, while ensuring high production rates (Zaini et al. 2023; Expert Interview 2023).

Future developments could overcome those hurdles. Materials are being researched which are stable even at high temperatures and reach high power densities. External heaters are being developed which could be connected to existing furnaces and are also supposed to help overcome the problems associated with limited power densities (Expert Interview 2023). Furthermore, resistance heating elements could be combined with heat storage systems, an option which is further discussed in Section 3.1.8. Demonstration projects for high-temperature applications (direct and indirect resistance heating to reach 850 °C in cracker furnaces) are underway (Linde Engineering 2023).

3.1.4 Induction heating

Induction heating involves no heating element: the heat is generated directly inside the material being heated. When a conductive material is exposed to a fluctuating magnetic field, "eddy currents" (electrons moving in small circles) are induced inside the material. Although conductive materials such as metals allow electrons to flow, they nonetheless have some degree of resistivity, which converts some of the energy in the moving electrons into heat. This effect is called electromagnetic induction. In industrial applications, induction is used in furnaces up to 3 000 °C, mainly for melting or heating metals (Ambrell Induction Heating Solutions 2023; Hagedorn et al. 2021; Lucia et al. 2015).

Since the heat is generated inside the material to be heated, there are no heat transfer losses. Efficient modern induction heating system designs can convert electrical energy into heat with over 90 percent[8] efficiency (Lucia et al. 2015). Induction furnaces with a capacity of 42 MW are used today in the steel industry (Hagedorn et al. 2021). Induction heating is also used for a range of other metals (such as copper and aluminium, Fleiter et al. 2023b).

8 The efficiency may be reduced by equipment along the on-site transformation chain.

Fact sheet for induction heating and potential technical development by 2035 for industrial application

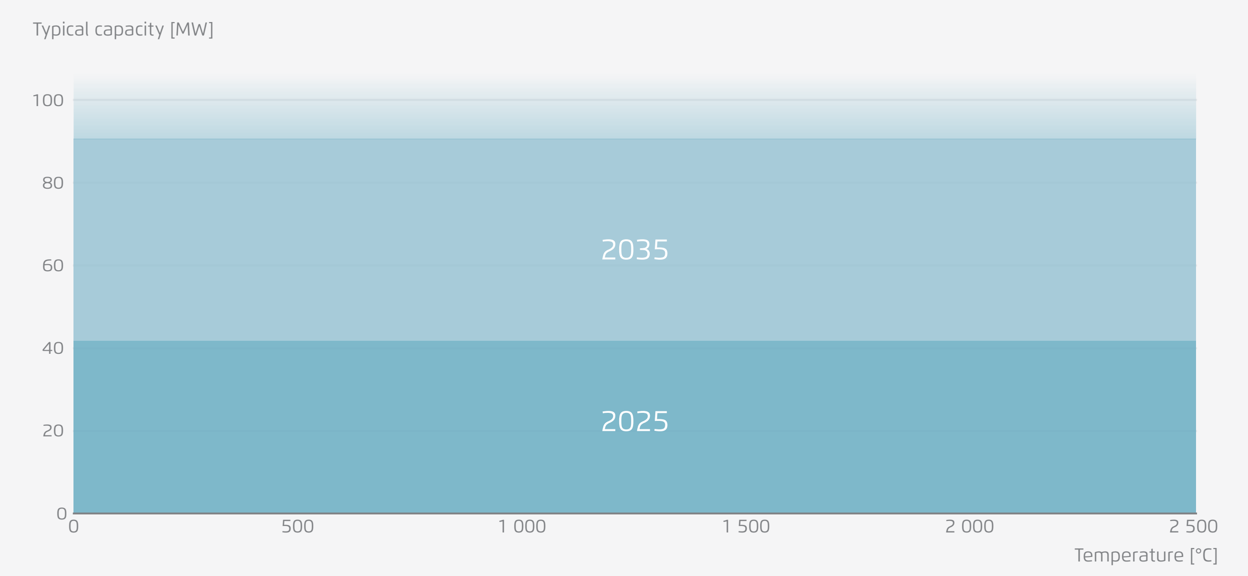
→ Table 5

	2023	2025	2030	2035
Maximum temperature	3 000 °C[1]	3 000 °C	3 000 °C	3 000 °C
Heat production efficiency	90%[2]	90%	90%	90%
Capacity	42 MW[2]	42 MW	>50 MW	>50 MW
Advantages	High temperatures, high capacities, existing operation experience in relevant applications[2]			
Disadvantages	Restricted to conductive materials[3] Limited by geometries[3] When competing with resistance heating: lower efficiency			
Examples of relevant industries and processes	Metal processing, e.g. melting, holding[3, 4]			
Technology readiness level	9 → Established technology in metal processing → Use in other applications requires further development → Economic barriers			

[1] Ambrell Induction Heating Solutions 2023
[2] Lucia et al. 2015
[3] Hagedorn et al. 2021
[4] Fleiter et al. 2023b

Typical capacity versus temperature range of induction heating furnaces in 2025 and potential technical development by 2035

→ Fig. 9



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3.1.5 Plasma torches

Plasma torches are a promising alternative to the fossil fuel burners used in industrial processes. They generate a rotating electric arc between two electrodes, heating up a defined carrier gas to temperatures of up to 5 000 °C. The carrier gas can be chosen according to the process requirements, with examples including air, nitrogen and CO_2. The high temperatures achieved are one of the main advantages of plasma torches, along with their high energy density, small installation size and fast start-up and shutdown capabilities. (Zaini et al. 2023) On the downside, plasma torches offer energy efficiencies of between 50 to 95 percent, which increases with the gaseous flow (Samal 2017)[9]. Due to their high cooling demand, the energy demand of a process can increase by 25 percent compared to fossil fuel-fired processes. Furthermore, the lifetime of plasma torches is limited, as the extreme conditions (high temperature and flow create abrasive wear) make regular replacements of the components necessary – plasma torches have to be categorised as operating materials/consumables (in contrast to CAPEX-oriented machine parts)[10]. While the actual component costs of replacement may not be relevant, the necessary maintenance work can restrict applicability. Today, plasma torches can reach up to 7 MW in industrial applications, and it is also possible to combine several individual plasma torches (Wilhelmsson et al. 2018).

Plasma torches are commonly used in precision heat applications such as plasma cutting and arc welding, as well as for metal melting (ALD Vacuum Technologies 2019; Samal 2017). Additionally, research is currently being conducted on the use of plasma torches

9 The wide range of efficiency reflects not only the heterogeneous applications of varying capacity and requirements, but also the genuine uncertainty about the potential development. Product descriptions in applications relevant to this study's scope claim efficiencies of below 80 percent (Surov et al. 2017).

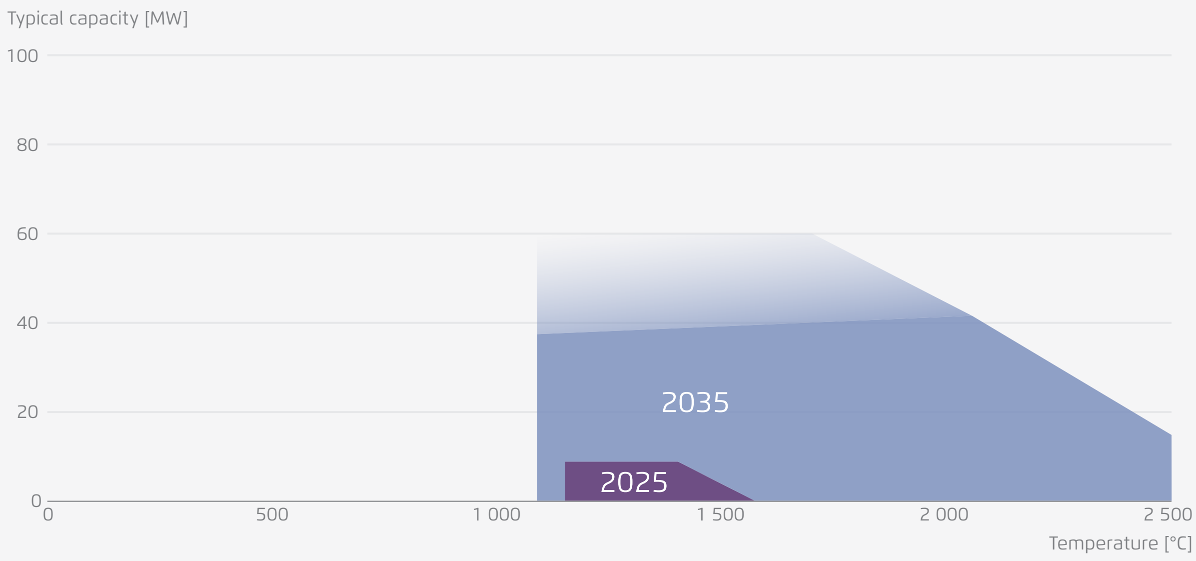
10 Not quantified in stakeholder interviews, but product descripp tions speak of "several hundred hours" in commercially available products and up to 2 000 hours in new developments (Surov et al. 2017) – which would currently necessitate about ten maintenance cycles per year.

Fact sheet for plasma torches and potential technical development by 2035 for industrial application → Table 6

	2023	2025	2030	2035
Maximum temperature	5 000 °C[1]	5 000 °C	5 000 °C	5 000 °C
Heat production efficiency	50–90%[2]	50–90%	50–90%	50–90%
Capacity	8 MW[3]	8 MW	20 MW	50 MW
Advantages	High temperatures, application similar to some degree to natural gas burners[4]			
Disadvantages	Low lifetime/high wear[4] Cooling requirements limit efficiency[4]			
Examples of relevant industries and processes	Indirect heating at high temperatures (i.e. sinter of cement clinker)[4]			
Technology readiness level	7–9 → There are applications that use it (small capacities) → Use in other applications (e.g. clinker burning) requires further development → Economic barriers			

[1] Zaini et al. 2023
[2] Samal 2017
[3] ScanArc Plasma Technologies AB 2023
[4] Wilhelmsson et al. 2018

Typical capacity versus temperature range of plasma torches in 2025 and potential technical development by 2035 → Fig. 10



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in the cement industry (Wilhelmsson et al. 2018) and on the development of alternating current (AC) plasma torches which might offer increased efficiency and longer lifetimes (Surov et al. 2017). Future developments might increase the lifetime and power input of plasma torches while reducing their cooling demand, making them an attractive alternative to fossil fuel burners.

3.1.6 Electric arc furnace

Electric arc furnaces (EAF) use a plasma arc to convert electricity into heat. In contrast to plasma torches, heat transfer occurs through direct exposure to the plasma arc rather than a carrier gas. Temperatures as high as 1 800 °C can be achieved. Though EAFs are primarily used to produce steel from steel scrap, they can also melt various other types of metals.

Most EAFs use three-phase alternating current and three electrodes. An arc passes from an electrode to the metal in the furnace, the electricity travels through the metal and a second arc carries the electricity up to the receiving electrode. The sending and receiving electrodes vary with the three-phase current. Direct current EAFs also exist; they have a single electrode, and the receiving cathode is at the bottom of the vessel. Highly conductive graphite electrodes are used that are consumed during the process, thereby generating a small amount of emissions.

The efficiency of heat production can vary depending on the application. The efficiency of energy transfer in high current systems greatly affects the heat production efficiency, which typically ranges from 90 percent to 95 percent. With a market share of about 40 percent in European steel production, EAFs are considered to be a mature technology and, compared to the primary steel production route, already achieve substantial energy savings (International Energy Agency 2020; Thekdi et al. 2015; Guo and Irons).

Fact sheet for electric arc furnaces and potential technical development by 2035 for industrial application

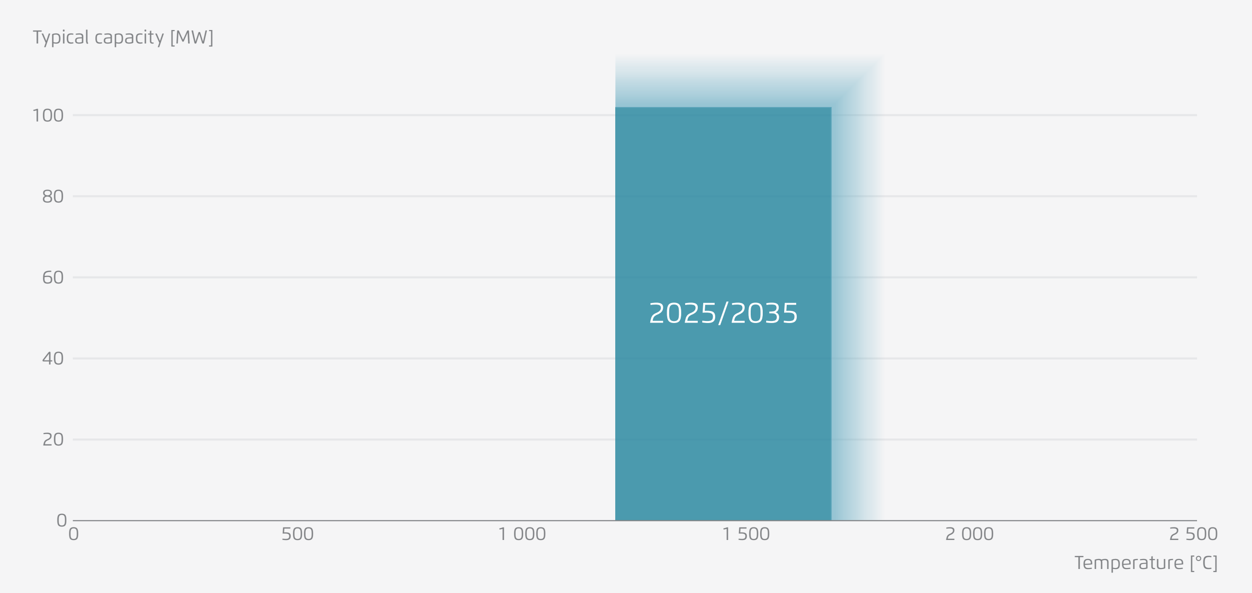
→ Table 7

	2023	2025	2030	2035
Maximum temperature	1 800 °C[1]	1 800 °C	1 800 °C	1 800 °C
Heat production efficiency	90–95 %[2]	90–95 %[2]	90–95 %[2]	90–95 %[2]
Capacity	200 MW[3]	200 MW	200 MW	200 MW
Advantages	High capacity High temperatures			
Disadvantages	Process-related emissions due to consumption of graphite electrodes			
Examples of relevant industries and processes	Secondary steel production Metal melting			
Technology readiness level	9 → Established technology			

[1] International Energy Agency 2020
[2] Kirschen et al. 2009
[3] Toulouevski and Zinurov 2010

Typical capacity versus temperature range of electric arc furnaces in 2025 and potential technical development by 2035

→ Fig. 11



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3.1.7 Shock-wave heating

A heating technology new to industrial applications is shock-wave heating.

Shock-wave heating uses high pressure waves to rapidly heat a material with rotating cascades of blades. The sudden compression of the material generates intense heat in the fluid due to the rapid increase in pressure. If air were used as the fluid and pumped into a furnace, the application would be similar to that of gas burners. However, the heat transfer would be dominated by convection. Initial experiments have reached temperatures of 700 °C at a power input of 1 MW. Shock-wave heating could potentially achieve temperatures of 1 500 °C and power inputs of 50 MW by 2030. Applications include electric steam cracking, lime calcination and cement clinker burning (Expert Interview 2023; Seppala et al.).

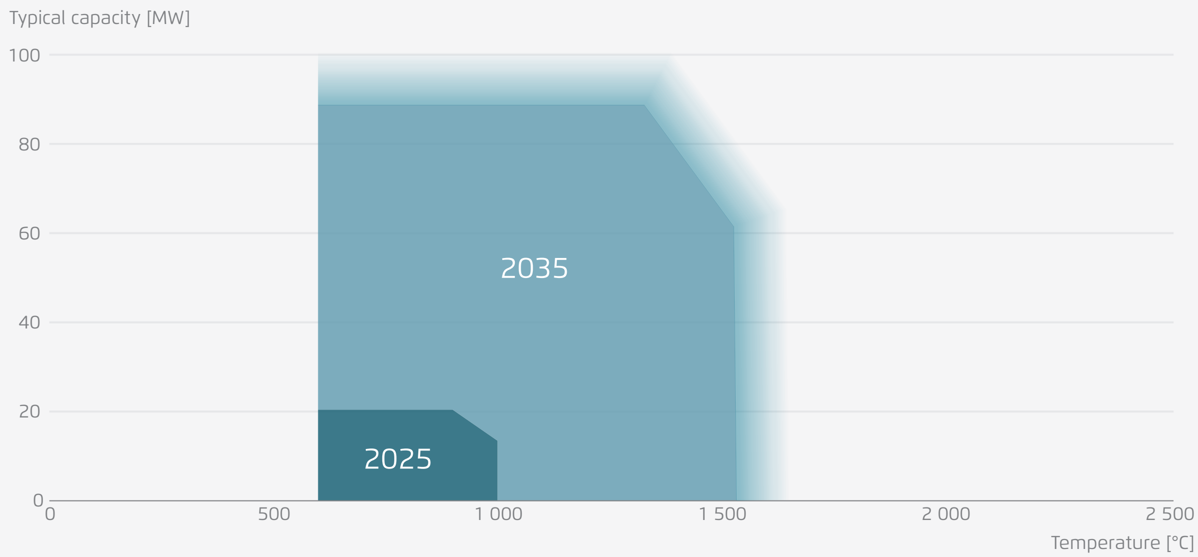
It is important to note that the technology is still in development and its future progress is uncertain. For the purposes of this study, it is assumed that the technology will have been scaled up to industrially relevant capacities by 2035 at the latest. The plans of technology manufacturers are more ambitious and aim for broad availability before 2030 (Expert Interview 2023).

Fact sheet for shock-wave heating and potential technical development by 2035 for industrial application → Table 8

	2023	2025	2030	2035
Maximum temperature	700 – 1 000 °C	1 000 °C	1 500 °C	1 500 °C
Heat production efficiency	90%	90%	90%	90%
Capacity	1 MW	5 – 20 MW	~ 50 MW	50 – 100 MW
Advantages	High temperatures, efficiencies and capacities			
Disadvantages	High uncertainty regarding development and scaling			
Examples of relevant industries and processes	Indirect heating at high temperatures (i.e. sinter of cement clinker, electric cracker)			
Technology readiness level	6 → First phase of pilot tests completed → Commercial launch planned for 2025			

Fraunhofer ISI (2024), based on Expert Interview (2023)

Potential capacity versus temperature range of shock-wave heating, potential technical development by 2025 and 2035 → Fig. 12



Fraunhofer ISI (2024)

3.1.8 Combined thermal storage technologies

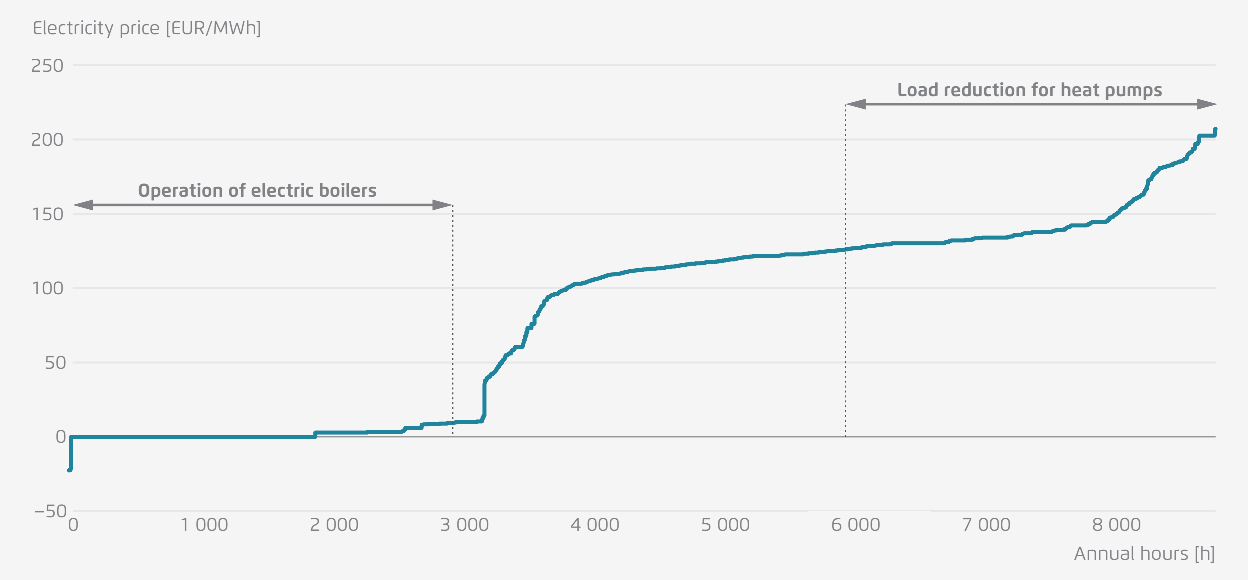
Combined thermal storage systems offer a dynamic approach to managing thermal energy. Typically, these systems use resistance heating to generate heat that is stored in a medium such as molten salt or bricks. The stored thermal energy can be released to deliver process heat on demand, for example to ensure the constant production of process steam.

The benefit of such systems is their adaptability as drop-in solutions (compare Section 5.3), allowing for easier integration into existing industrial processes. Furthermore, they allow procedures to be adapted to fluctuating electricity prices and local renewable energy sources to be integrated into industrial processes (Figure 13): for example, a price signal-based mode of operation would include constant operation of the industrial process but would shift the use of grid-based electricity to low-price hours (while unloading in high-price hours). When coupled with on-site generation, operation modes would seek to balance generation and demand locally, e.g. with generation peaks of PV over the day[11]. Thermal storage solutions provide the means to balance out both daily and long-term fluctuations in heat demand and as such may support grid balancing. It is anticipated that upcoming heat storage systems will experience a heat loss of approximately 1 percent per day, with the exact amount depending on the storage temperature. Modular solutions can offer scalability.

Thermal storage systems are suitable for a variety of industrial applications. Combined heat storage systems currently being developed may be able to produce and store heat at temperatures of up to 2 000 °C. However, it is important to note that space requirements on site and initial investment costs may pose challenges (Khare et al. 2013; Kyoto Group 2023; Rondo Energy, Inc. 2023; Heatrix 2023; Expert Interview 2023). Cost estimates, although based on limited industry-scale experience, indicate a relevant cost advantage (in EUR/kWh of storage capacity)

11 This stylised depiction ignores the economics of storage solutions regarding the trade-off of capacity, flexibility potential and storage CAPEX compared to process-related OPEX. In practice, the intended load shifting is thus subject to further restrictions and considerations.

Electricity prices for the scenario *Climate-neutral power system 2035* → Fig. 13



Agora Energiewende, Prognos, Consentec (2022)

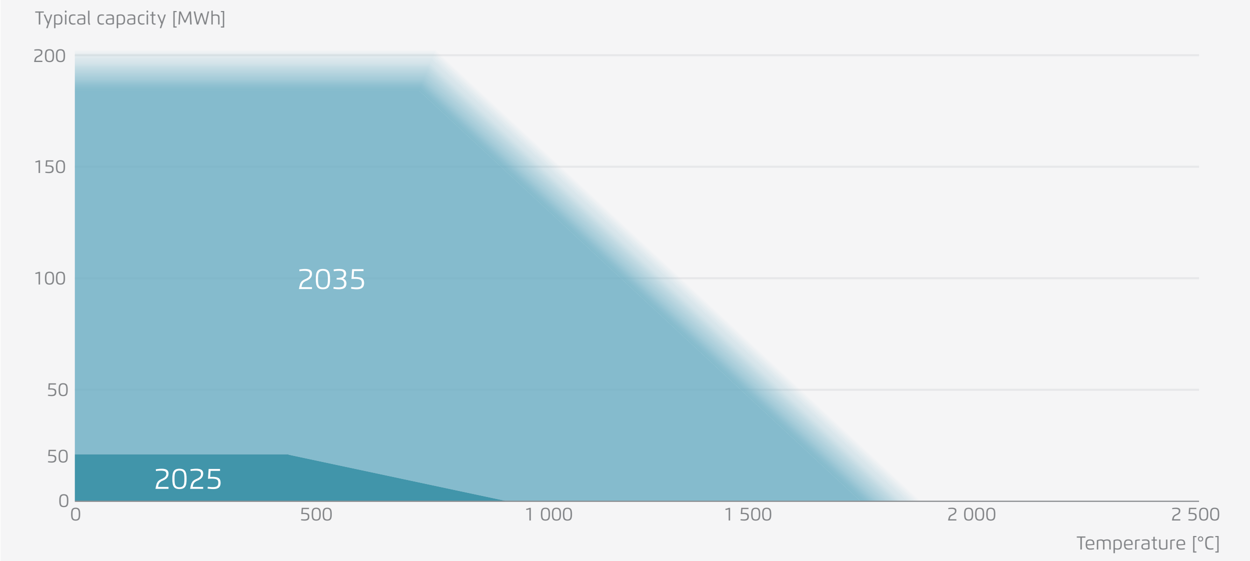
of thermal storage compared to electrical batteries, ranging from a factor of five to ten. Thermal storage technologies promise to reduce power purchase costs for companies and provide demand-side flexibility to the power system. In order to counter the volatility of renewable energies, the focus is often on storing electricity using batteries and hydrogen. However, if heat rather than electricity is required for end

Fact sheet for combined thermal storage technologies and potential technical development by 2035 for industrial application → Table 9

	2023	2025	2030	2035
Maximum temperature	1 000 °C [1]	1 000 °C	1 500 °C [2]	1 500 °C – 2 000 °C [4]
Heat production efficiency	90% [1,2]	90%	90%	90%
Capacity	18 MWh [3]	120 MWh [3]	300 MWh [1]	300 MWh
Advantages	High flexibility			
Disadvantages	Additional investment and space requirements			
Examples of relevant industries and processes	Indirect heating at low to high temperatures			
Technology readiness level	7–9 → Applied on a small scale in industries → Further research necessary for higher temperatures and capacities			

[1] Rondo Energy, Inc. 2023
[2] Heatrix 2023
[3] Kyoto Group 2023
[4] Expert Interview 2023

Typical storage capacity versus temperature range of combined thermal storage technologies in 2023 and potential technical development by 2035 → Fig. 14



Expert Interview 2023; Heatrix 2023; Kyoto Group 2023; Rondo Energy, Inc. 2023.

use, thermal storage systems offer advantages: such systems do not generally require rare materials, can achieve high round-trip efficiencies and therefore offer relatively low costs. (Expert Interview 2023; Rissman and Gimon 2023; Agora Energiewende, Prognos, Consentec 2022).

3.2 Technologies out of scope

The following technologies are not investigated in this study. For each technology, the reasons for their prioritisation and selection are stated individually.

In short, technologies with expected market entry at full industrial scale by 2035 or earlier are considered. Other electric heating technologies such as dielectric heating, infrared heating, direct electrolysis of iron production, electron beams and ultra-violet light are either not expected to be relevant before 2035 (direct electrolysis), apply only to niche applications (lasers, ultraviolet) or merely represent alternatives to considered technologies (dielectric and infrared) without increasing the electrification potential. Their potential for additional electrification and efficiency improvements may be investigated in subsequent analyses.

Fact sheet: Dielectric heating → Table 10

Maximum temperature	2 200 °C (heat treating and sintering ceramics)[1], 140 °C (epoxy curing)[2], 100 °C (cooking, drying)[2]
Heat production efficiency	70%
Heat transfer efficiency	100% (heat generated inside processed material)
Examples of relevant industries and processes	Food processing (cooking, drying, sterilising), timber (curing adhesives), foam (drying), textiles (colour drying, curing finishes)

1 Allan et al. 2008; Microwaves In High-Temperature Processes 2003
2 Ferrite Microwave Technologies; Horikoshi 2021

In addition to these direct electrification technologies, other technologies or concepts to supply CO_2-neutral or low-CO_2 have not been investigated either (e.g. biogenic energy carrier, carbon capture and usage/storage (CCU/S), solar thermal and geothermal systems). However, these technologies are highly relevant to the decarbonisation of the industry sector and their properties and potentials should be investigated in dedicated studies.

Dielectric heating involves using radio waves or microwaves to excite polar molecules such as water or some types of plastic (whose atomic configuration gives a negative charge to one end of each molecule and a positive charge to the other end) (McHugh 2016).

The temperatures achieved by dielectric heating vary depending on the substance being heated and the application. Dielectric heating is most commonly used for cooking or drying, where water evaporates at 100 °C and escapes the system, preventing any further temperature rise. In enclosed systems where water cannot escape, and for curing epoxy adhesives, temperatures can reach 140–150 °C (Ferrite Microwave Technologies; Horikoshi 2021). The efficiency is about 70 percent and thus lower than that of resistance heating (New Zealand Energy Efficiency and Conservation Authority 2019).

Dielectric heating is mainly used in similar applications to high-temperature heat pumps (or resistance/plasma technologies in selected high-temperature applications). While specific process requirements (e.g. sterilisation requirements, workpiece geometry or atmosphere) may still result in relevant differences, this study considers heat pumps to be the technology with the broader application range. Especially steam as a heat medium is not limited by the material to be heated. An analysis of both technologies would not significantly increase the direct electrification potential, which is why dielectric heating is not investigated in detail.

An infrared (IR) heater contains an emitter that is heated (often by electrical resistance) and gives off infrared radiation in a specific direction. An infrared heater's maximum temperature is limited by its emitter, which must not melt or chemically break down.

The efficiency of IR heat transmission depends on the proportion of IR that is absorbed by the intervening air, as well as on the IR reflectivity of the material being heated. Only the proportion of radiation that is absorbed raises the temperature of the material. Infrared does not penetrate deeply into materials, heating only the surface; heat gradually penetrates more deeply via conduction. Industrial applications for infrared heating include drying and curing paint and powder coatings, heating and forming plastics,

Fact sheet: Infrared heating → Table 11

Maximum temperature	1 370 °C
Heat production efficiency	96% (ceramic emitter), 85% (quartz lamp emitter), 56% (metal tube emitter)
Heat transfer efficiency	Depends on IR reflectivity of the heated material: 85–96% (when heating plastics), 70–90% (when heating wood), very low when heating most metals
Examples of relevant industries and processes	Paint and powder coatings (drying, curing), plastics (heating, forming), glass (laminating, bending), textiles (coating, laminating, drying), wood (laminating)

Reference: MOR Electric Heating Association

Fact sheet: Laser heating

→ Table 12

Maximum temperature	Millions of °C (demonstrated)[1]
Heat production efficiency	30% (typical)[2], 50% (demonstrated)[2]
Heat transfer efficiency	Depends on the reflectivity of the heated material: 80–90% (when heating wood)[3], 5–60% (when heating metals)[4], wide range of values when heating plastics
Examples of relevant industries and processes	Metals (cutting, welding, engraving), wood (cutting, marking), 3D printing (sintering)

[1] Lawrence Livermore National Laboratory
[2] Hecht 2016
[3] Haller et al. 2002
[4] Keyence Corporation

laminating and bending glass, laminating wood, and textile manufacturing processes such as drying, coating and screen printing (Linteris et al. 2012; Rocky Mountain Instrument Co.; Dupleix et al. 2013; Burkholder).

Infrared heating might play an important role in electrifying certain processes and should be considered as an option in appropriate applications. However, its applications are similar to those for resistance heating (albeit limited by material). It does not therefore increase the electrification potential and is not considered any further here.

A laser is a device that emits focused, coherent light by using electricity to excite the electrons in a lasing medium. Lasers reach very high temperatures. Their key advantage is their ability to apply high-temperature heat to small and precise areas. Their efficiency is relatively low, however, so lasers are primarily used as tools for cutting sheets of material, welding and engraving or marking, such as burning a design into a wood product (Hecht 2016). The use of lasers for the provision of process heat is considered to be very limited, so laser heating is not considered any further here.

In an electron beam, electrons from a current applied to a tungsten filament are guided into a high-velocity beam using electrical or magnetic fields. These electrons strike a workpiece, transferring enough energy to vaporise metal. Electron beams are capable of vaporising even tungsten, the metal with the highest boiling point (5 930 °C), which is one step in the process of physical vapour deposition of metallic coatings (Angstrom Engineering).

Electron beams are primarily used for welding and machining parts, particularly parts made of refractory metals (those with extremely high melting

Fact sheet: Electron beams

→ Table 13

Maximum temperature	5 930 °C (vaporisation of tungsten) and higher[1]
Heat production efficiency	Likely very low
Heat transfer efficiency	Likely near 100% (electrons travel through a vacuum and cannot be optically reflected)
Examples of relevant industries and processes	Welding and machining parts, refining certain strong and heat-resistant or reactive metals

[1] Angstrom Engineering; Sullivan 1977

points, such as tungsten, molybdenum, niobium, tantalum etc.) and sometimes titanium. They are also used for refining and melting strong and heat-resistant or highly reactive metals (ALD Vacuum Technologies).

Electron beams must be used under high vacuum conditions (to prevent the electrons from colliding with air molecules); furthermore, the process emits X-rays, meaning that it has to be undertaken robotically in a vacuum chamber (DeLalio 2016). Industrial processes involving electron beams are very high cost and therefore unlikely to be suitable for most heating applications.

Electrolysis of iron ore (molten oxide electrolysis)

The electrolysis of iron involves applying electricity directly to a bath of molten/dissolved material in order to process it. In the case of aluminium, the principle is applied commercially in the Hall-Héroult process. If applied to iron production, the technology would cut the energy losses of hydrogen production, transport and reduction of currently planned direct reduction processes (Agora Industry and Wuppertal Institute 2023). In addition, it would be more flexible in terms of raw material usage, as it allows lower-quality iron ore sources to be exploited. The principle is already applied to high-value metals (on a small scale) and may be applied to the processing of iron ore, eliminating the need for hydrocarbons as a reducing agent (as in the blast furnace or direct reduction process). Due to its low technology readiness – this study does not expect market relevance before 2035 – and the current ambition of major steel-producing countries to drive forward hydrogen-based direct reduction, it is not investigated any further[12].

Ultraviolet light

Ultraviolet (UV) light has the potential to replace heat in some applications. UV is already used today for sterilisation and for curing UV-sensitive polymers. In some cases, UV may be able to replace heat when it comes to sterilising surfaces, equipment and products in the food industry. Furthermore, UV-cured coatings and adhesives may be able to substitute thermally-cured equivalents. UV light does not penetrate opaque objects, so it is best suited to surface applications (sterilising surfaces, curing coatings) and to curing adhesives when at least one of the objects to be bonded is transparent to UV light.

While ultraviolet light heating may have a role to play in electrifying some processes, its potential applications are to some extent similar to those of other technologies such as resistance heating, so it does not increase the electrification potential and is not considered any further here.

3.3 Resulting technology potential

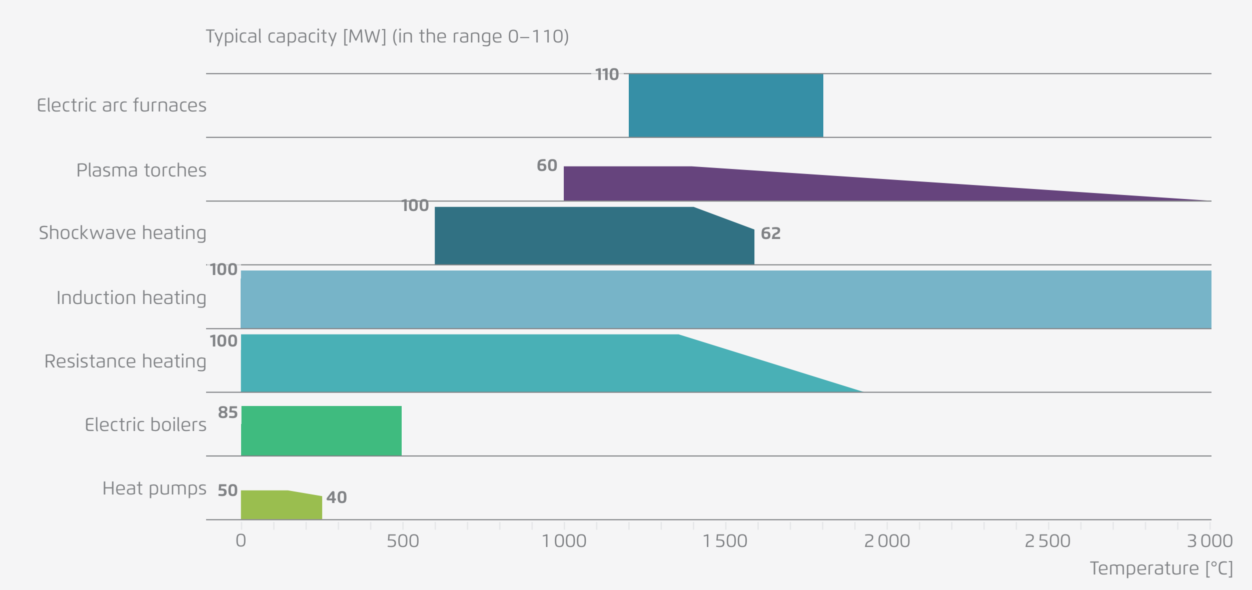
The investigated technologies have the potential to cover a wide range of temperatures and capacities. Heat pumps and electric boilers cover low- and medium-temperatures, while resistance, shockwave, induction and plasma heating extend the temperature range to potentially 2 000 °C – with varying applicability for different materials and sectors. As presented in Figure 15, the capacity of a process heat installation (up to the range of 100 MW[13]) and the temperature of process heat (steam up to 500 °C, with most applications and energy demand not higher than 250 °C; high-temperature heat in industrial furnaces up to 1 700 °C) are the two dimensions that define the spectrum of solutions that direct electrification technologies need to encompass (indicated in Figure 15 by the edges of the blue areas).

12 Technology suppliers did announce highly ambitious plans on a commercial scale during the 2020s, however (Boston Metal 2023). Close monitoring of the developments is advisable.

13 For example, a typical integrated cement plant with 1 Mt cement production per year has a thermal capacity of its main equipment (rotary kiln) of about 120 MW (usually split into two or three installations). A typical reheating furnace for steel processing has a capacity of around 70 MW (at about 1.4 Mt physical production).

Potential development of electric heating technologies by 2035 – expected capacity versus temperature

→ Fig. 15



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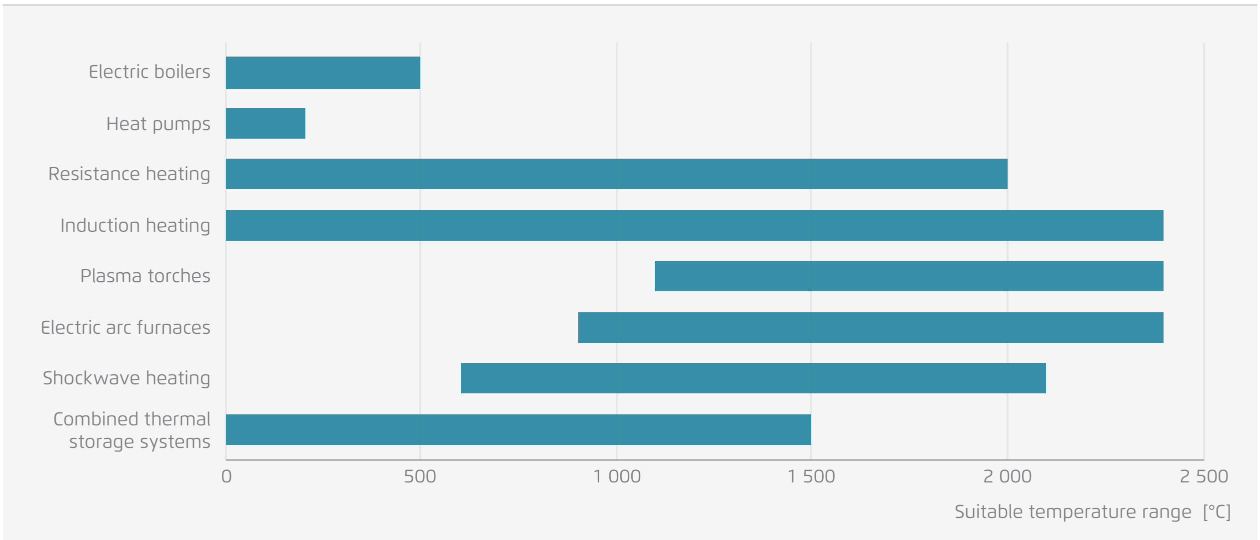
For further clarification, the potential development of the achievable temperature range of electric heating technologies by 2035 is shown in Figure 16, while the potential development of the achievable heating efficiencies of electric heating technologies by 2035 is shown in Figure 17.

Resistance heating is a versatile technology with the potential to be developed to a high level in the future, enabling its broad applicability. However, integrating resistance heating into existing production plants (brownfield) is challenging and requires the adaptation of installations. Plasma technology might be an

Potential development of suitable temperature range of electric heating technologies until 2035

→ Fig. 16



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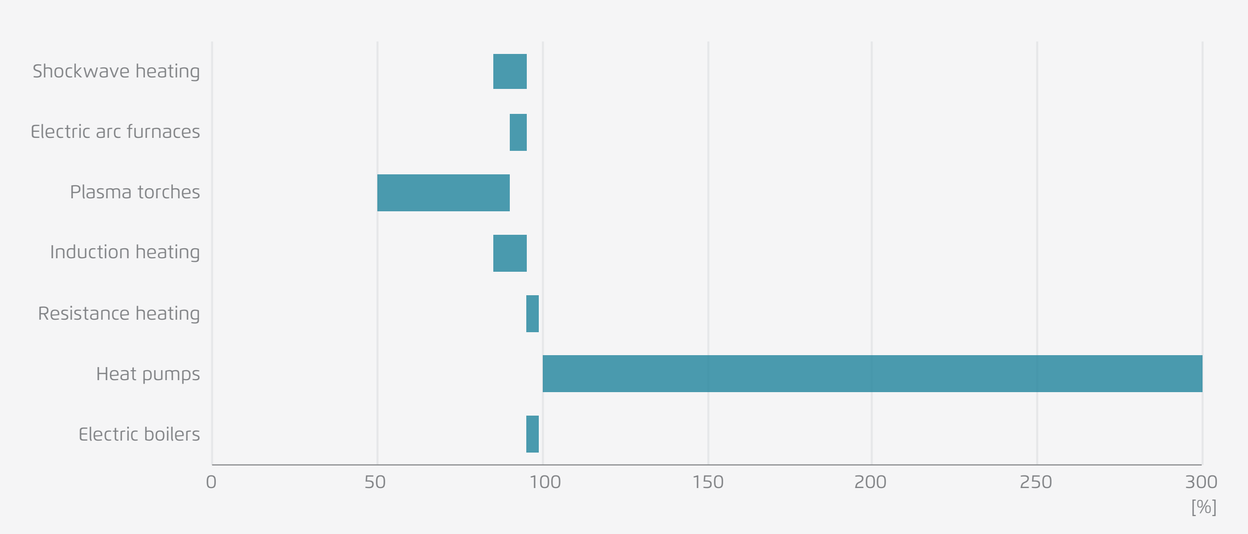
Potential development of achievable heating efficiencies of electric heating technologies until 2035. Efficiency of heat pumps depends on temperature lift. → Fig. 17



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attractive alternative for high-temperature applications, as it could be integrated more easily into existing furnaces. Furthermore, novel technologies like shock-wave heating and thermal storage systems might make direct electrification more attractive or even increase the applicability of electric heating.

Along the dimensions temperature and capacity, the investigated direct electrification technologies cover the demand of a wide range of bottom-up investigated applications (Figure 18). The generation of steam by electric boilers and heat pumps offers very great potential for early electrification. At the same time, heat pumps in particular entail considerable efficiency advantages over gas fired boilers. For metal processing, induction heating is a key technology.

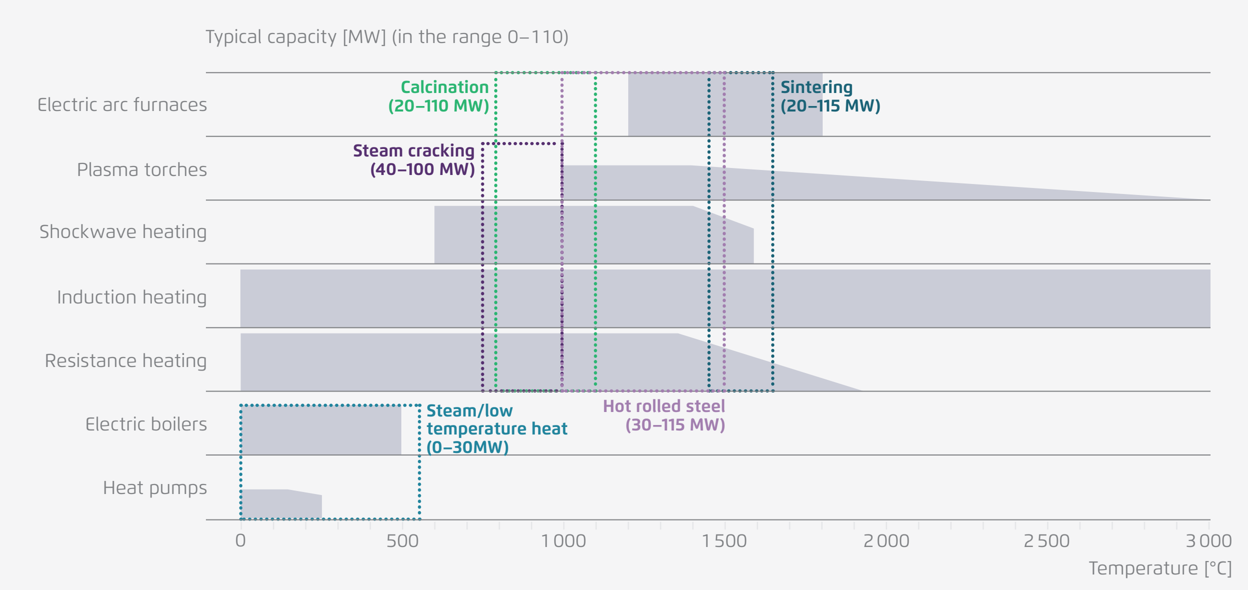
High-capacity, high-temperature applications such as cement sintering or some elements of hot steel rolling pose challenges to current technologies. Future advances in resistance heating, plasma torches and other novel heating technologies such as shock-wave heating have the potential to close this gap. Current restrictions such as low lifetime (plasma torches) and efficiency compared to gas-fired furnaces (depending on application) make these technologies less attractive in the short term.

Adapting processes helps address such technological limitations. Clinker production for example uses rotary kilns with very high (~1 700 °C) peak temperatures. However, calcination takes place at lower temperatures and could be directly electrified with existing technologies. In paper production, using a longer paper machine (i.e. allowing more time for drying) can lower the required steam temperature and make it easier to use heat pump technologies. Economic hurdles apply to all of these changes, especially when existing installations are involved. Sector-specific potentials and requirements are discussed in Section 4.

While the efficiency of most electric heating technologies is not heavily influenced by temperature, the efficiency of a heat pump decreases with temperature lift. The use of waste heat reduces the temperature lift. In general, the efficiency of electrical heating technologies is higher than that of fuel-based technologies, with the potential exception of plasma torches (subject to development and properties of application). More energy-efficient solutions are often harder to integrate into existing processes than less energy-efficient ones (for example heat pump – electric boiler). Table 10 shows the temperature range and heating efficiency of the investigated technologies and the furnace efficiency of the corresponding furnace. The furnace efficiency includes not only the heating efficiency, but also losses due to exhaust gas and furnace walls. Due to the absence of exhaust gas, electric heating technologies usually increase furnace efficiency.

Potential development of electric heating technologies by 2035 and industrial applications – expected capacity versus temperature

→ Fig. 18



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Temperature range and heating efficiency of investigated technologies

→ Table 14

Technology	Max. temperature [°C]	Heating efficiency [%]	Furnace efficiency [%]
Natural gas boiler	700	89 – 97 [1]	
Heat pump	200	Up to 650, typical values around 200 – 300 [2]	
Electric boiler	500	99 [1]	
Natural gas furnace	2 000	90 – 95 [9]	30 – 80 [1]
Resistance heating furnace	1 850	99 [3]	
Induction furnace	3 000	90 [4]	75 [5]
Plasma torch	5 000	50 – 90 [6]	
EAF	1 800	90 – 95 [7]	40 – 75 [7]
Shock-wave heating	1 500	90 [8]	

[1] Fleiter et al. 2023b. [2] Arpagaus et al. 2018. [3] Thermcraft, Inc. [4] Lucia et al. 2015. [5] Hagedorn et al. 2021. [6] Samal 2017. [7] Kirschen et al. 2009. [8] Expert Interview 2023. [9] Depending on furnace type, compare Fleiter et al. 2023b.

4 Applications and electrification potentials

4.1 Industrial sectors

The industrial sectors in scope (compare Section 1) include highly heterogeneous activities. Their properties range widely both in terms of the temperature demand of the individual applications and the typically installed capacity. For the purposes of this study, industrial activity is differentiated according to the classification applied in Eurostat energy balances. Production processes that are highly relevant to process heat generation and greenhouse gas emissions are represented by specific applications in order to link them to potential direct electrification technologies (Section 3.1). Exemplary applications are presented for each of the major energy-intensive activities (Table 11), the remainder being filled by analogy (compare Section 2.5).

Applications are chosen to reflect sector-specific opportunities and challenges. 33 applications in total were evaluated. A full quantification was carried out for 14 of them, including an estimate of their fuel demand[14] and electrification potential. These 14 applications cover a large part of the heat demand above 500 °C. The fuel demand of applications below 500 °C is estimated using the forecast model. The generation of steam is a major driver of fuel demand in this temperature range and is dominated by the activities paper, chemicals and food.

The energy demand of electric heating technologies was taken from the literature where available. In cases where literature-based data was absent or did not accurately represent the current state of the art, however, assumptions based on the investigations of electric heating technologies (see Section 3) were used. Specifically, our findings indicated that resistance, induction and shock-wave heating had the potential to deliver efficiency gains ranging from 0 to 10 percent compared to existing natural

14 Specific energy consumption (SEC) is typically stated in GJ/t. 1 GJ/t corresponds to 277.8 kWh/t.

Fuel and electricity demand and carbon dioxide emissions of the analysed sectors in the EU-27 in 2019 → Table 15

Industrial sector	Fuel demand [TWh][1]	Electricity demand [TWh][1]	CO_2 emissions [Mt][2]
Iron & steel	404	108	147
Chemical & petrochemical	421	166	112
Non-ferrous metals	47	60	14
Non-metallic minerals	325	64	190
Food, beverages and tobacco	210	111	36
Paper, pulp & printing	273	104	24
Others[3]	389	320	127

[1] Eurostat Energy Balance 2019
[2] UNFCC 2023
[3] Others: Transport equipment, Machinery, Mining & quarrying, Wood & wood prod-ucts, Construction, Textile & leather, Not elsewhere specified (industry)

gas-fired installations. These improvements are believed to be due to the enhanced heat transfer and reduction in heat losses due to the lack of exhaust gases. Plasma heating is assumed to entail a 15 percent increase in energy demand, primarily due to the necessity for cooling measures[15], as outlined in Wilhelmsson et al. (2018).

Steam applications operating at temperatures of up to 200 °C are assumed to involve a reduction in energy demand ranging from 0 to 50 percent, depending on the selected technology[16]. It is assumed that steam applications operating in a temperature range of 200 to 500 °C will have the potential to reduce energy demand by 0 to 33 percent[17]. This reduction is achieved by using electric boilers in combination with heat pumps.

Both estimated energy-saving ranges are comparable with the best available technologies (BAT) and are considered conservative (technologies may achieve higher values, but uncertain site-specific conditions may apply). A substitution could bring about additional practical energy savings if the new system is the best available technology and the system it is replacing is not (modernisation effect). The scope for extrapolating the electrification potential of these applications to the sector as a whole is discussed in Section 4.2.

15 As mentioned in 3.1.5, however, the broad range of efficiency values stated for plasma torches did not permit any conclusive evaluation. The applied values should be regarded as an uncertain estimate – the efficiency potential for plasma torches could well be higher.

16 An energy saving of approximately 0% is achieved if a gas boiler is replaced with an electric boiler. The difference between a BAT gas boiler and a BAT electrode boiler in terms of efficiency is small (2%), though it can potentially be higher, depending on how the gas boiler is operated and maintained. A 50% energy saving can be achieved by replacing a gas boiler with a heat pump with a COP of 2, see Section 2.1.2 and Fleiter et al. 2023b. Higher energy savings might be feasible in some processes, especially space heating.

17 An energy saving of 0% is achieved if a gas boiler is replaced with an electric boiler. A 33% energy saving can be achieved by replacing a gas boiler with a heat pump with a COP of 1.5, see Section 2.1.2 and Fleiter et al. 2023b.

4.1.1 Iron & steel

The iron and steel sector involves the production of iron and crude steel, and their further processing into flat and long steel products. Key applications within the sector include oxygen steel production in integrated blast furnace/basic oxygen furnace (BF/BOF) plants, secondary steel production using the electric arc furnace (EAF), and hot steel rolling (including reheating and heat treatment furnaces)[18].

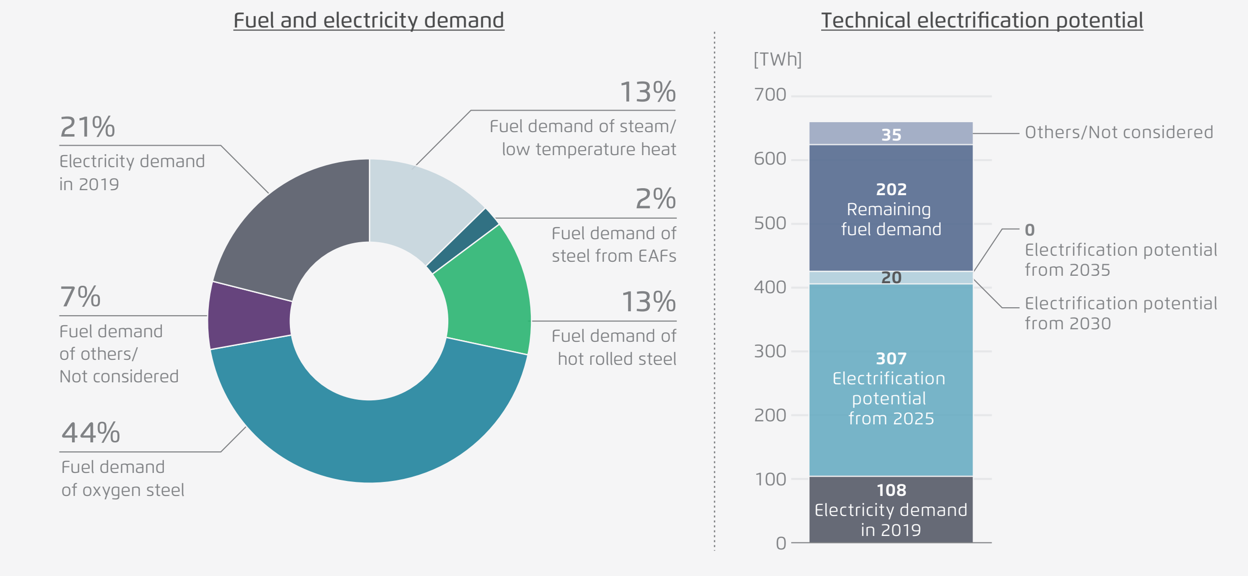
The production of oxygen steel on the BF/BOF route, steel in EAFs, heating for hot rolling, and heat treatment account for approximately 72 percent of the sector's energy demand. Figure 19 (left) illustrates the energy demand of the evaluated applications as a proportion of the overall fuel demand in the sector. If the modelled applications below 500 °C are also taken into account, 7 percent of the sector's energy demand remains. This remaining fuel demand is attributed to applications such as the melting of cast iron, the heating of forged components, the heating of steel sheet blanks (press hardening) and the hardening of steel. The sector's aggregated electrification potential is shown in Figure 19 (right). The energy demand for processes which were already electrified in 2019 is part of the electricity demand in 2019.

Production of crude oxygen steel on the BF/BOF route

The main way in which primary oxygen steel is produced involves converting iron ore into metallic iron in a blast furnace and then converting the iron into steel in a basic oxygen furnace. Typically these furnaces are closely linked to form a single blast furnace / basic oxygen furnace (BF/BOF) system.

18 Coke ovens, which convert coal to coke for use in blast furnaces, are considered an energy transformation activity in Eurostat. While the produced coke is viewed as energy use by the iron and steel industry, Eurostat does not regard the fuel consumed by the coke ovens themselves as part of the iron and steel industry's energy use. For practical purposes, both their energy use and emissions must be allocated to steel production.

Final fuel demand by product and electricity demand in the EU-27 in 2019 and technical electrification potential of the iron and steel sector → Fig. 19



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In 2019, 87 Mt of crude steel were produced in the EU-27 using the BF/BOF production route (World Steel Association 2020). This route has an estimated combustible fuel demand of 16 GJ/t of steel[19] and an electricity demand of 0.9 GJ/t (Arens et al. 2012).

The blast furnace uses coke not only to provide heat but also to chemically reduce (remove oxygen atoms from) iron ore, lower the melting point of the ore and provide mechanical stability to the furnace while allowing the reducing gases (CO and CO_2) to permeate the material. Heat alone is not sufficient to drive this chemical reaction, so simply replacing fuels with electrified heat in a blast furnace is not feasible[20].

The most promising alternative to the BF/BOF route involves producing direct reduced iron (DRI). On the DRI route, a reducing gas (natural gas-based mix of CO, CO_2 and hydrogen or pure hydrogen) is heated to over 900 °C and then fed to a shaft furnace, well below the melting point of iron. There, iron ore is chemically reduced to metallic iron in the solid state. The iron is then fed to an EAF (or an electric smelting furnace (ESF) is used with different process steps), where it is melted, impurities are removed and the carbon content is adjusted to produce steel. Alternatively, direct reduced iron can be heated and compressed to a denser form, called hot briquetted iron, and shipped to another facility where an EAF is used to convert it to steel.

The direct reduction step can be accomplished with the MIDREX process. The reduction requires 50 kg/t of hydrogen and 1.9 GJ/t of natural or renewable gas. The gas heater needs another 22 kg/t of hydrogen but can be electrified, resulting in an electricity demand of 2.4–2.7 GJ/t (Kopfle and Ripke, PhD 2017). The EAF has a fuel demand of 0.6 GJ/t and an electricity demand of 1.4 GJ/t (Cirilli 2017).

19 This energy total includes coal and coke use. It deducts the energy content of any blast furnace gas (a combustible byproduct of ironmaking in a blast furnace) that is sold or used on site. Off-gas balancing creates uncertainty and is a major challenge to bottom-up calculations, as off-gases are often used in on-site power plants that also supply public grids. Estimating the energy use of steel production is thus ambiguous. The selected value of 16 GJ/t reflects this uncertainty by deducting roughly half the literature values of off-gas production. Different sources suggest a combustible fuel demand of between 15 and 21 GJ/t for the BF/BOF route, due to variations in the composition of syngas (the gas mixture formed from coke). The value of 16 GJ/t has been used in this study to best align per-tonne estimates of energy use with sector-wide total energy use reported in energy balance tables.

20 Partial electrification of hot air supplied via the tuyeres is conceivable but offers no promising decarbonisation path.

Alternatives to the DRI route are based on the electrolysis of iron ore, which involves applying an electrical current to separate oxygen atoms from metallic iron. There are two types of iron electrolysis: in molten oxide electrolysis (MOE), iron ore is melted in an electrochemical cell, then iron and oxygen are separated using an applied current. MOE is still at an early development stage and faces challenges such as how to improve the stability of the anode material (Shatokha 2016; Boston Metal 2023). Aqueous electrolysis involves finely grinding iron ore, mixing the ore into an alkaline or acidic solution and applying a current to cause the iron particles to deposit on an electrode. Both electrolysis technologies are unlikely to be ready for significant commercial deployment by 2035 (Agora Industry and Wuppertal Institute 2023), so they are outside the timeframe considered in this study (compare Section 3.2).

Production of crude steel in electric arc furnaces

In 2019, 63 Mt of crude steel were produced in the EU-27 in electric furnaces, mostly EAFs (World Steel Association 2020). EAFs are used to melt steel scrap with electric plasma arcs (described in Section 3.1.6). The molten metal is cast in billets, blooms or slabs and processed further to produce flat and (primarily) long steel products.

The main energy source of EAFs is electricity (1.4 GJ/t). Furthermore, modern EAFs typically employ natural gas burners around the edges to ensure even heating (0.3 GJ/t) and reduce electricity consumption. Carbon-containing materials (such as coal 0.3 GJ/t) are added for reaction control purposes and to aid in removing impurities; the carbon-based electrodes are consumed during the process. Electrifying the gas burner results in a total fuel demand of 0.3 GJ/t and an electricity demand of 1.7 GJ/t (Cirilli 2017; Kirschen et al. 2009; Demus et al. 2016).

Steel rolling

Steel rolling is used to shape raw steel into flat and long steel products – hot rolled steel that is typically sold to other industrial firms which turn the steel into finished goods. 124 Mt of hot rolled steel were produced in the EU-27 in 2019 (World Steel Association 2020). Steel rolling can involve a number of processes, including (re-)heating, hot rolling, pickling, cold rolling, surface treatments and thermo-mechanical rolling (Fleiter et al. 2023b). Among these processes, the continuous heating of flat/long steel and the heat treatment of flat steel are analysed for their electrification potential.

Today, the fossil fuel demand for steel rolling of flat products in Germany is roughly 2.0 GJ/t, while the electricity demand is 0.4 GJ/t. About 70 percent of the total fuel demand is associated with heating for hot rolling, and the remaining 30 percent is for heat treatment (Fleiter et al. 2023b). These figures are assumed to be similar in all EU-27 countries.

During hot rolling, the metal is heated to 1 250 °C using gas burners. This is above steel's recrystallisation temperature. Using rollers, the hot steel is flattened to a strip of the desired thickness, then cooled. Reheating the workpieces (slabs, billets, blooms) requires very high energy densities. A typical furnace used for heating the steel, such as a walking beam furnace, reaches a thermal power of up to 100 MW. The high energy densities required cannot be achieved by the resistance heating elements available in existing reheating furnaces because the furnace's surface area, in conjunction with the energy density of resistance heating elements, is currently too small (Fleiter et al. 2023b; Expert Interview 2023).

Carrying out the hot rolling immediately after steel casting can reduce the heating energy required for hot rolling by 30 percent (Tercelli 2020), however. The gas burners could then be replaced by induction heating elements (Primetals Technology 2021). Already available, this concept is considered to have technical electrification potential, though it requires a new production line rather than a retrofit of

Electrification potential of the iron & steel sector

Since secondary steel is already largely electrified (compare Figure 19, electricity use in secondary steel is part of "electricity demand in 2019"), it offers little additional electrification potential. While it may be possible to shift some production from primary to secondary steel, this strategy is limited by scrap availability and quality, issues not studied in this report[1]. Therefore, the main electrification potential in the iron and steel sector depends on the scope for electrifying primary steelmaking.

Due to the low technological maturity of iron ore electrolysis routes, it is difficult to avoid the need for a molecule-based reducing agent in iron smelting. Switching to the hydrogen-DRI route primarily constitutes indirect electrification (via green H_2), though it does involve some direct electrification. Together with the electric gas heater for the DRI, the EAF accounts for roughly a third of the energy demand, with the hydrogen representing the other two thirds.

For hot rolling, new production lines could be based on induction with careful process design, and future developments in high-temperature, high-capacity electric heating technologies (such as increasing the power output of plasma torches) might allow electrical heating to be retrofitted to existing production lines. Applications not explicitly included in the bottom-up calculation might be electrified by inductive and resistance heating. The electrification potential of hot steel rolling is extrapolated to applications that are not quantified individually.

1 The potential for unused steel scrap is limited. The availability of steel scrap relative to the demand for new steel depends to a large extent on anthropogenic storage, i.e. the steel currently used in cars, buildings and other products. The stagnation of global steel use (and thus the increased generation of scrap relative to new demand) could strongly impact scrap-based production ratios. The collection and sorting of scrap are also relevant aspects.

existing production lines and furnaces. The electricity demand for induction-based hot rolling is assumed to be between 1 and 1.4 GJ/t of steel.

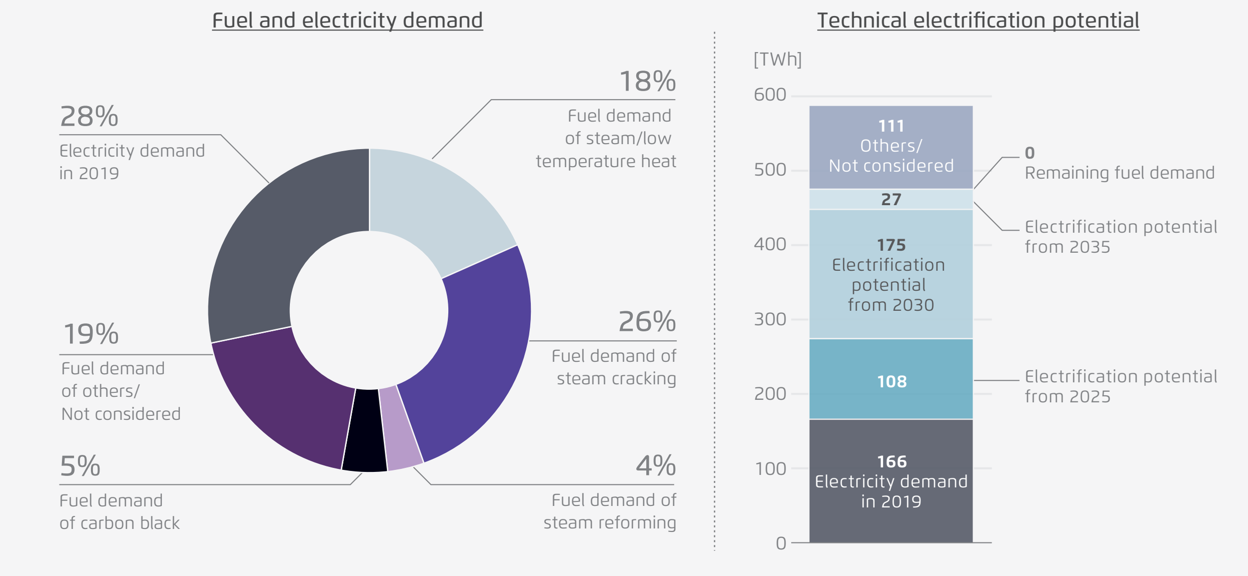
Heat treatment of strip steel, also known as annealing, is carried out either in continuous annealing furnaces or in batches in bell-type annealing furnaces at approximately 600 °C to 750 °C. This modifies the internal crystalline structure of the steel, thereby improving its formability. Continuous annealing furnaces have an installed power of up to 30 MW. Heat treatment could be electrified with resistance or induction heating; with sufficient demand, commercial furnace solutions could become available by 2030. The energy demand for electric heat treatment is estimated to be between 0.6 and 0.86 GJ/t of steel (Fleiter et al. 2023b).

4.1.2 Chemical & petrochemical

The chemical industry supplies over 30 000 chemicals for use in different sectors, such as plastics for packaging or fertilisers, paints, adhesives, detergents and many others. However, most of these chemicals, which account for the majority of CO_2 emissions from the industry, are derived from only ten basic chemicals (Münnich et al. 2023) . In the Eurostat energy balance, this sector encompasses a range of activities, from the production of large quantities of basic chemicals to the manufacture of highly specialised pharmaceuticals.

Key applications within the sector include steam cracking, ammonia production, steam generation for the production of a variety of products and the production of carbon black. The electrification potential of process heat is estimated for the production of ethylene, for its by-products carbon black, and

Final fuel demand by product and electricity demand in the EU-27 in 2019 and technical electrification potential of the chemical and petrochemical sector → Fig. 20



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for ammonia. These applications account for about 74 percent of the total fuel demand of the chemical industry and 53 percent of its total energy demand (Figure 20). The electrification potential of these applications is extrapolated to the chemical and petrochemical sector.

Steam cracking

Steam cracking is used to produce ethylene and other high-value chemicals (HVCs) and aromatics needed in the production of plastics. Naphtha or gaseous hydrocarbons are mixed with superheated steam and cracked at temperatures above 800 °C (Fleiter et al. 2013). The distribution of the product slates may vary according to the process conditions (i.e. shifts between different types of olefins is technically possible).

The process heat demand for ethylene (being representative of HVCs) excluding feedstock is 35.9 GJ/t (Rehfeldt et al. 2017). 16.6 Mt of ethylene were produced in the EU-27 in 2019 (Eurostat 2023).

Electrified steam crackers that employ resistance and shock-wave heating are currently being built at demonstration scale. With electrification, the efficiency of these steam crackers is expected to be as high as 95 percent, versus 40 percent efficiency for today's fuel-based steam crackers (Linde Engineering 2023; Jasi 2023). Electrified steam cracking technology is expected to be available at commercial scale by 2030.

Steam generation

Steam is used in a variety of processes in the chemical industry. Chemical facilities use superheated steam at temperatures of up to 500 °C, a level that can readily be reached with direct electrification. Though steam is used in many chemical industry processes, the production of plastics (adipic acid, polycarbonates) and soda was analysed by way of an example in this study because of its high total fuel demand at temperatures below 500 °C.

→ Adipic acid is important as an intermediary product in the production of nylon. The production of adipic acid has a fuel demand of 26.9 GJ/t (Forschungszentrum Jülich GmbH 2023), of which

50 percent is assumed to be under 200 °C and another 25 percent to be between 200 and 500 °C (Rehfeldt et al. 2017)[21]. The electricity demand is 1.4 GJ/t (Forschungszentrum Jülich GmbH 2023). 0.56 Mt of adipic acid were produced in the EU-27 in 2019 (Eurostat 2023).

- Polycarbonate is a thermoplastic material that is used for example in digital data carriers such as CDs or as an alternative to glass. The production of polycarbonates requires 12.9 GJ/t of fuel and 2.66 GJ/t of electricity (Forschungszentrum Jülich GmbH 2023). 100 percent of the heat demand is at temperatures of under 200 °C (Rehfeldt et al. 2017). 1.34 Mt of polycarbonates were produced in the EU-27 in 2019 (Eurostat 2023).
- Soda is used in the production of soap and detergents. Furthermore, it is used in the paper industry to prepare virgin fibres and recycled paper. Soda has a fuel demand of 11.3 GJ/t (Forschungszentrum Jülich GmbH 2023). 70 percent of the energy demand for the production of soda is below 200 °C (Rehfeldt et al. 2017). 8.06 Mt of soda were produced in the EU-27 in 2019 (Eurostat 2023).

High-temperature heat pumps suitable for the electrification of heat up to 200 °C are expected to be available by 2025. This study assumes that these heat pumps will reduce energy demand by 50 percent, though higher energy savings are possible (see Section 3.1.2). For the electrification of heat of between 200 and 500 °C, the use of high-temperature heat pumps (as a first heating stage) in combination with electric boilers could reduce energy demand by up to 33 percent.

Carbon black

Carbon black is produced by pyrolysis of gaseous or liquid raw materials from petroleum, natural gas or coal. In a furnace's combustion chamber, temperatures of 1 200 to 1 900 °C are generated by burning the material. Oil is injected into the furnace, along with a strictly limited amount of air, to ensure the injected oil is only partially combusted (under-stoichiometric combustion). This incomplete combustion results in soot, as well as hydrogen and other by-product gases. The mixture is cooled down and the soot is retrieved as the main product (Fleiter et al. 2013; Forschungszentrum Jülich GmbH 2023). It is used as pigment and in tyres.

The fuel demand of this process is 64.8 GJ/t and its electricity demand is 1.8 GJ/t (Fleiter et al. 2013; Forschungszentrum Jülich GmbH 2023). 1.5 Mt of carbon black were produced in total in the EU-27 in 2019 (Eurostat 2023).

The electrification of process heating for carbon black is expected to be feasible by 2035 thanks to resistance heating, shock-wave heating or plasma heating technologies. Alternatively, carbon black could be produced at commercial scale from biogenic sources or from carbon captured from the atmosphere (KIT Karlsruher Institut für Technologie 2022).

Steam reforming

Today, ammonia is produced from natural gas by steam methane reforming. This process involves converting methane (CH_4) into H_2 and CO_2. The temperature of the steam reforming process is up to 550 C. Subsequently, in the Haber-Bosch process, the H_2 reacts with nitrogen (N_2) to form ammonia (NH_3). This process is exothermic and does not therefore require process heating. During the process, electricity is used to compress the gas. Part of the CO_2 is then used in further process steps (urea production).

11.69 Mt of ammonia were produced in the EU-27 in 2019 (Eurostat 2023). The fuel demand of synthesis gas production (steam reforming) is 6.6 GJ/t and its electricity demand is 7.5 GJ/t (Geres et al. 2019).

Since the Haber-Bosch process relies on H_2 as an input, it is a natural choice for indirect electrification using green H_2. This and heat integration of synthesis gas generation and further processing eliminates the need for process heat generation. Technically

21 The integration of processes shifts the actual importance of temperature profiles to the plant level rather than the process level, however.

Electrification potential of the chemical & petrochemical sector

Transitioning towards a climate-neutral industry has far-reaching impacts on the chemical and petrochemical sector. As fossil energy carriers often serve as feedstock, switching to renewable feedstock will have an impact on the demand for process heat.

The chemical industry has significant potential when it comes to the electrification of process heating, particularly in electrified steam cracking and steam production (compare Figure 20, which shows at least 18 percent of final energy demand is for steam generation and 26 percent is for steam cracking). Carbon black also has potential, albeit on a smaller scale. Considerable efficiency gains are possible, especially at temperatures at which heat pumps can be employed.

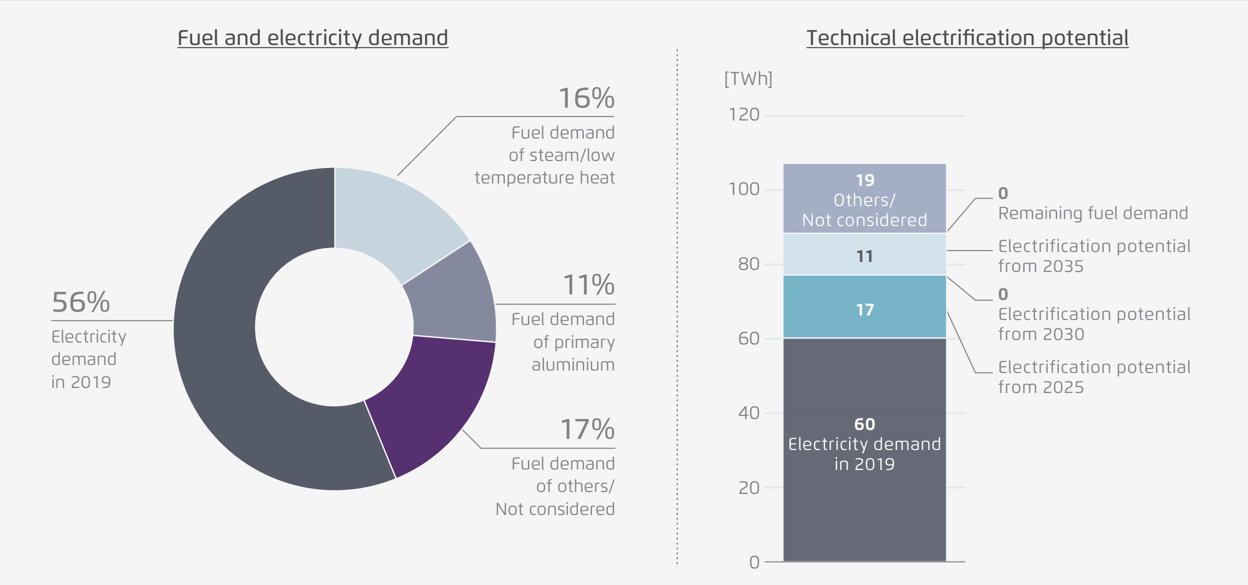
speaking, electrification might be feasible with resistance or shock-wave heating, thus reducing the energy demand by up to 10 percent.

4.1.3 Non-ferrous metals

The non-ferrous metals sector involves producing and processing metals other than iron and steel, principally aluminium, chromium, copper, manganese, zinc, titanium, lead and nickel. These metals and their alloys are essential in advanced industries such as energy generation, computing, electronics, telecommunications and transport (Cusano et al. 2017).

Key applications within the sector include primary aluminium production and the processing of aluminium and copper (Fleiter et al. 2023b). Electricity accounts for a large proportion of the sector's energy requirements, most of which is used in the production of primary aluminium by electrolysis (Figure 21). The energy demand for processes which were already

Final fuel demand by product and electricity demand in the EU-27 in 2019 and technical electrification potential of the non-ferrous metals sector → Fig. 21



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electrified in 2019 is considered to be part of the electricity demand in 2019.

Primary aluminium production

3.4 Mt of primary aluminium were produced in the EU-27 in 2019 (International Aluminium Institute 2023). Primary aluminium production (i.e. from aluminium ore or "bauxite") has a fuel demand of 19.2 GJ/t and an electric energy demand of 56.1 GJ/t. Alumina (aluminium oxide) is first separated from other mineral components of bauxite by means of the Bayer process. This multi-step process involves crushing the bauxite, adding sodium hydroxide and heat in a pressure vessel, and calcination in a rotary kiln (International Aluminium Institute 2010). The alumina is then chemically reduced to aluminium by electrolysis with high electricity demand (53.5 GJ/t). Finally, the aluminium is cast to form aluminium ingots (Peppas et al. 2023; Cusano et al. 2017).

Electricity is already used to convert the alumina to aluminium metal. Electrifying the conversion of bauxite to alumina (via electrified process heating) is being developed by the aluminium producer Alcoa (ARENA 2022). The production of alumina from non-bauxite minerals such as anorthosite (Angelatou et al. 2022) is currently being researched. This report assumes that electrification of the primary aluminium production will be feasible by 2035, reducing the energy demand by up to 10 percent.

Non-ferrous metals processing

Non-ferrous metals processing includes aluminium melting, aluminium homogenising, aluminium heat treatment, copper melting, heating of semi-finished copper products for hot forming, heat treatment of copper semi-finished products, and other applications. These applications can be accomplished in electric furnaces using electric arcs, induction or resistance heating. Electrification is expected to be technically feasible and would deliver efficiency gains of 10 to 30 percent. (Fleiter et al. 2023b)

4.1.4 Glass, cement and other non-metallic minerals

The non-metallic minerals sector is the European industry's largest emitter of carbon dioxide (UNFCC 2023). This sector includes a range of output products, including cement, glass and brick.

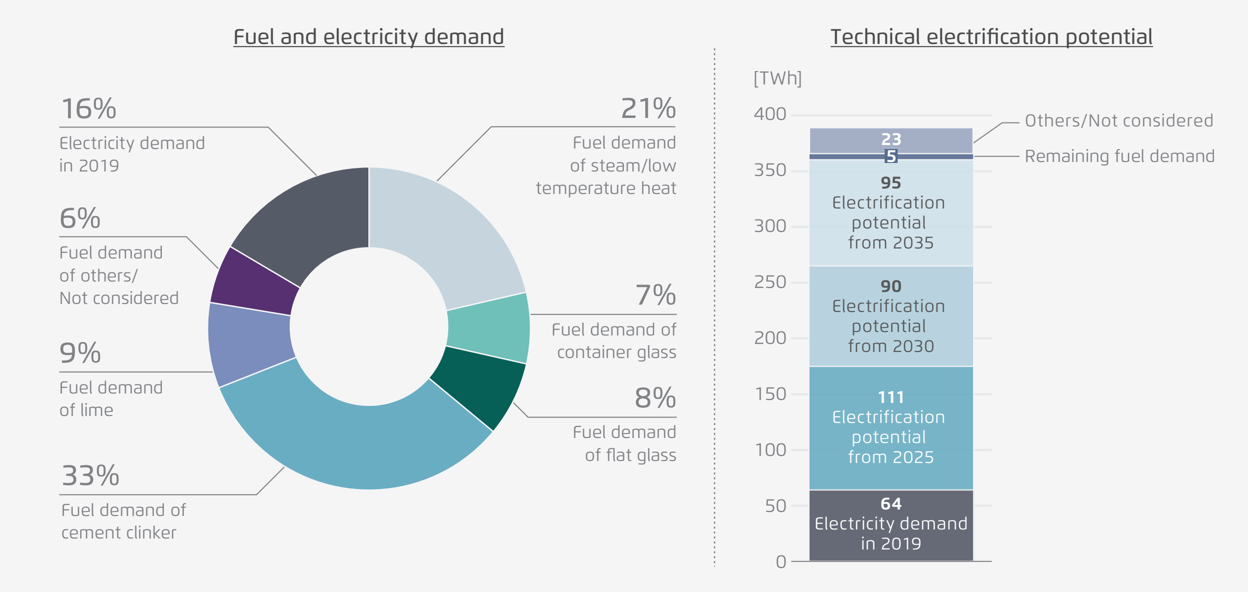
Key applications within the sector include the melting of glass, the production of lime and the calcination and sintering of cement clinker. These applications cover about 67 percent of the sector's fuel demand. The electrification potential for these key applications is extrapolated to those applications which are not covered (e.g. various ceramics). Together with the process heat demand of below 500 °C, 94 percent of the sector's energy demand is covered (Figure 22). An overlap of steam demand and internal waste heat for drying applications is likely. This may increase the proportion of the energy demand of "others/not considered" in Figure 22. In qualitative terms, however, the investigated applications cover the range of

→ Electrification potential of the non-ferrous metals sector

Electricity already accounts for a large proportion of the energy used by the non-ferrous metals sector (about 56 percent, Figure 21), including the production of primary aluminium from alumina and the processing of non-ferrous metals in electric furnaces. A large proportion (36 percent) of the remaining fossil fuel use supplies temperatures below 500 °C and could be easily electrified. Even at high temperatures, induction and resistance heating offer efficient alternatives to fuel-based heating.

Final fuel demand by product and electricity demand in the EU-27 in 2019 and technical electrification potential of the non-metallic minerals sector

→ Fig. 22



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relevant applications and their process conditions in this sector well. It therefore seems possible to extrapolate them to those applications not considered and to the sector as a whole.

Container glass and flat glass

Two important applications in the glass industry are the melting of container glass (used for bottles and jars) and the melting of flat glass (used for windows and mirrors). In addition, there are various types of special glass and glass fibres. Highly heterogeneous product portfolios with diverse process conditions and product finishes exist, especially in the case of special glass. These have not been investigated in detail, as melting and forming account for the bulk of the energy demand.

About 20 Mt of container glass were produced in the EU-27 in 2019. Melting of container glass has a fuel demand of 4.9 GJ/t and an electricity demand of 0.5 GJ/t (Fleiter et al. 2023b). This process could be fully electrified with glass smelters heated by electric resistance, an already commercialised technology. Electrification would increase the energy efficiency of the process by 47 percent (Leisin and Radgen 2022).

About 10 Mt[22] of flat glass were produced in the EU-27 in 2019. Melting of flat glass has a fuel demand of 10.7 GJ/t and an electricity demand of 0.7GJ/t (Fleiter et al. 2023b). Electrifying the flat glass production faces challenges in terms of ensuring high product quality (Fleiter et al. 2023b). Initial approaches to overcoming these challenges include testing combined gas burners with electric resistance heating. Glass melting tanks with an electrification rate of 60-70 percent are expected to be available on the market by 2035. Electrification is expected to reduce the energy demand by 40 percent, resulting in a fuel demand of 1.9 GJ/t and an electricity demand of 4.5 GJ/t (Expert Interview 2023).

22 EU-28 production of flat glass totalled 11 Mt (Glass Alliance Europe 2023) in 2019. Assuming that the UK's share of the production of flat glass was similar to its share of container glass production, namely 11% (FEVE The European Container Glass Federation 2015), this would mean that 9.8 Mt were produced in the EU-27 in 2019.

Lime

Lime has many applications, such as in the steel industry (to remove impurities from steel), in construction (to stabilise soils and add strength to asphalt) and to remove pollutants from exhaust (e.g. in coal-fired power plants) and drinking water. In total, 27 Mt of lime were produced in the EU-27 in 2019. Lime can be categorised as soft-burnt (fired at slightly lower temperatures, resulting in a product that is more reactive and porous) or hard-burnt (fired at higher temperatures, resulting in lower porosity and reactivity). EU lime production facilities can be divided into those that produce hard-burnt lime, those that produce soft-burnt lime and those with particularly large capacities (irrespective of the type of lime they produce) (Fleiter et al. 2023b). The chemical process of producing lime from limestone is similar to calcination in cement clinker production – and thus shows similar properties.

Soft-burnt lime is mostly produced in parallel flow regenerative kilns (PFRK) at temperatures of 1 000–1 250 °C. The typical power input is 7–25 MW. The fuel demand is 3.8 GJ/t and the electricity demand is 0.1 GJ/t (Fleiter et al. 2023b). PFRK account for a 47 percent share of production (Schorcht et al. 2013). Electrification might be feasible using plasma or resistance heating before 2030 and could reduce the energy demand by up to 10 percent (Project LEILAC1 2021; LimeArc Process AB 2023) [23].

Hard-burnt lime is produced in annular shaft kilns (ASK), mixed-feed shaft kilns (MFSK) and other kilns at temperatures of 1 200–1 400 °C. The fuel demand is 4.5 GJ/t and the electricity demand is 0.1 GJ/t (Fleiter et al. 2023b). MFSKs, ASKs and other kilns account for a 35 percent share of production (Schorcht et al. 2013). Due to the high temperatures that are required, electrification is considered to be challenging. By 2035, electrification might be feasible using plasma heating (albeit with an increased energy demand of up to 15 percent) or by resistance heating (with a reduction in energy demand of up to 10 percent).

Particularly large quantities of lime are produced in long rotary kilns (long rotary kiln - LRK) with or without preheater (preheated rotary kiln - PRK) at 1 000–1 400 °C. The fuel demand is 5.6 GJ/t and the electricity demand is 0.1 GJ/t (Fleiter et al. 2023b). Rotary kilns account for a 19 percent share of production (Schorcht et al. 2013). The most promising technologies and energy efficiency implications for the electrification of rotary kilns are similar to the options for electrifying kilns used in the production of hard-burnt lime, as outlined above.

Cement clinker

Clinker is the main ingredient in cement, which is the binder used in concrete (and certain other applications, such as making stucco). 117 Mt of clinker were produced in the EU-27 in 2019 (Eurostat 2023). The manufacture of cement clinker has a fuel demand of 4.0 GJ/t and an electricity demand of 0.5 GJ/t. The process of cement clinker production can be separated into two stages (Fleiter et al. 2023b).

The first stage is calcination, which – in modern plants – largely takes place in a pre-calciner. Calcium carbonate (from limestone) is heated to above the calcination temperature of 830 °C and breaks down into calcium oxide and carbon dioxide. The resulting process-related CO_2 emissions make up about two thirds of the total emissions (Fleiter et al. 2023b). This process accounts for up to 60 percent of the total energy demand (Verein Deutscher Zementwerke e.V. 2002). The second stage is sintering, which takes place in a rotary kiln at temperatures of 1 200 to 1 450 °C (Fleiter et al. 2023b).

Electrifying the calcination process is currently being developed and could be feasible by 2030. In addition to avoiding CO_2 from fossil fuel combustion, electrification would make it easier to capture the process-related carbon dioxide emissions because

23 Direct electrification via indirectly heated shaft kilns (in which heat generation and product are physically separated) also offers the opportunity to apply carbon capture technologies and thus address process-related greenhouse gas emissions. However, this indirect heating is also possible with combustion-based heating.

Electrification potential of the non-metallic minerals sector

The non-metallic minerals sector is not easy to electrify due to the high capacities and temperatures of furnaces. Full electrification of these high-capacity furnaces remains challenging and will require the further development of either or several of the mentioned technologies (Section 3.1). The production of cement clinker accounts for 33 percent of the sector's fuel demand (Figure 22). Further developing and deploying electric pre-calciners may therefore have a significant impact on the sector's fuel demand. Such partial electrification (later followed by full electrification) is a near-term option, and technological solutions to electrify most of the sector's fuel demand could be developed by 2035. The increased efficiency to be gained by electrifying the sector will depend on the development of these technologies. While resistance or shock-wave heating could reduce the sector's energy demand, plasma heating might increase it (for details about the technical potential/ developments regarding plasma torches, see Section 3.1.5).

The unavoidable emissions emitted during processes in this sector put pressure on the transition towards carbon capture. This is giving rise to a discussion about the compatibility of direct electrification and extensive carbon capture. One key point in this discussion is whether the availability of carbon capture options eliminates incentives to decarbonise the energy supply. Carbon capture will need to be regulated in order to limit its use to genuinely unavoidable GHG emissions and thus incentivise electrification of energy use. By eliminating the need for combustion air, electrification can facilitate carbon capture (Project LEILAC1 2021).

they would not be mixed with combustion exhaust, avoiding the need for energy-intensive CO_2 separation (Project LEILAC1 2021). Electrification could be accomplished using resistance heating and could potentially reduce energy demand by up to 10 percent.

The sintering step, which requires higher temperatures, is more difficult to electrify. The use of plasma has been shown to work but could increase energy demand by 15 percent (Wilhelmsson et al. 2018).

Alternatively, shock-wave or resistance heating technologies might be available by 2035 and could reduce energy demand by up to 10 percent.

4.1.5 Food, beverages and tobacco

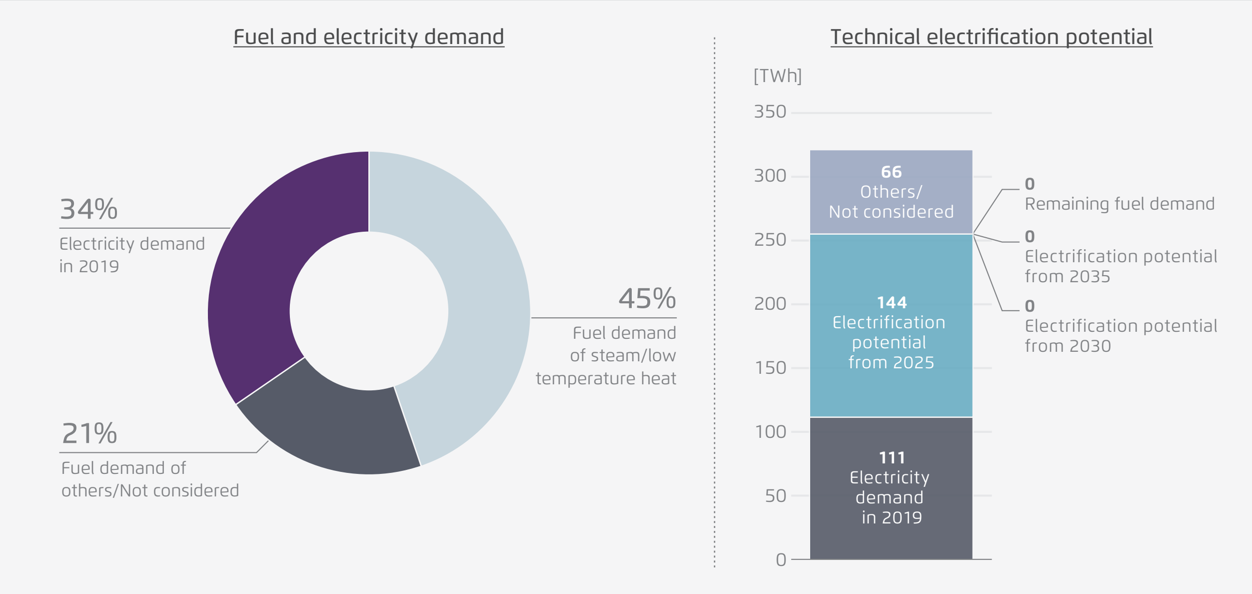
According to the Eurostat energy balance, the food, beverages and tobacco sector involves a range of activities such as bread baking and cheese production. Key applications within the sector include steam generation and baking (Expert Interview 2023). Most

Electrification potential of the food, beverages and tobacco sector

The technological challenges for electrification are considered to be low, as several electric technology options for steam generation exist (compare Section 3.1). Through resistance heating, electric boilers and heat pumps, it is considered technologically feasible to fully electrify virtually all applications of the food, beverages and tobacco sector (Expert Interview 2023, compare Figure 23). Substantial energy savings could be achieved by extensively using heat pumps at low temperatures, while other electrification technologies would offer smaller energy savings. This sector (together with some chemical applications and paper production) is the best candidate for early and fast direct electrification.

Final fuel demand by product and electricity demand in the EU-27 in 2019 and technical electrification potential of the food, beverages and tobacco sector. Applications considered are part of the fuel demand for steam/ low temperature heat.

→ Fig. 23



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of the industry's fuel demand is below 200 °C, with notable exceptions being the production of sugar and some high-temperature drying processes (e.g. milk powder). Fossil-fired steam boilers play an important role in the industry (Expert Interview 2023). Electricity for pumps, fans and other mechanical end-uses accounts for a large proportion of the energy demand (Figure 23).

4.1.6 Paper, pulp & printing

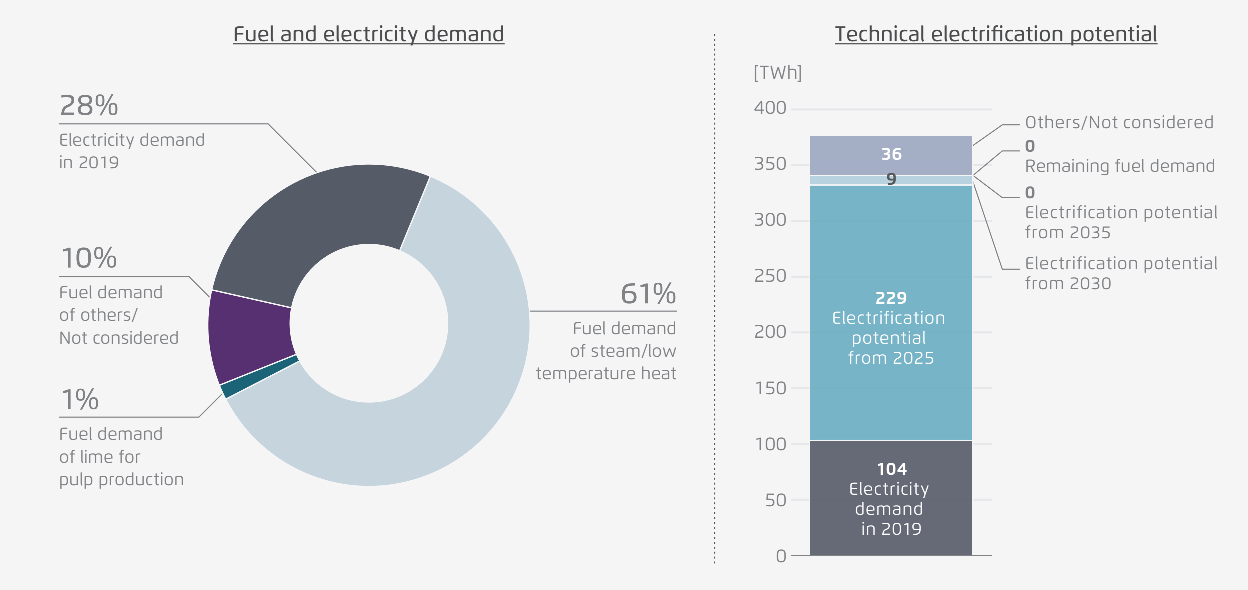
The paper, pulp and printing sector's primary output is packaging paper and board (Confederation of European Paper Industries 2020). Key applications within the sector include paper production and pulping. Over 82 percent of this sector's fuel demand is used to generate temperatures below 200 °C, and nearly all of this heat is in the form of steam. Non-steam-based drying technologies, which are outside the scope of this study (see Section 3.2), may be suitable for these purposes, though electrifying the steam generation process (using electrode boilers and/or heat pumps) is considered more relevant. This is due in particular to the long lifetimes and high capital expenditures of paper machines, which limit the options, incentives and windows of opportunity for modifying the core production process. The internal use of biogenic residues is often regarded as a tool for transformation purposes.

Chemical pulp production (low temperature/steam demand)

Accounting for about 70 percent of European production, the most common kind of pulp production is Kraft pulp (Confederation of European Paper Industries 2020). Secondary fibres have a much-reduced energy demand and are highly relevant in some countries (e.g. Germany).

To make Kraft pulp, wood chips are mixed with a strong alkaline solution. This mixture (known as white liquor) is heated for several hours at high pressure and temperature (155–175 °C) in a digester. After cooking, the hot pulp is transferred to a blow tank in which the wood chips break down into fibres or pulp. The filtering and washing step involves separating the pulp and the cooking liquor (known as black

Final fuel demand by product and electricity demand in the EU-27 in 2019 and technical electrification potential of the paper, pulp and printing sector → Fig. 24



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liquor). Finally, black liquor is processed in the chemical recovery system to reclaim the cooking chemicals and energy (Rahnama Mobarakeh et al. 2021).

Chemical recovery is a crucial aspect of the chemical pulping process. It involves evaporating water from the black liquor in a boiler, which recovers white liquor through reaction with caustic lime and generates high-pressure steam. The white liquor is then returned to the digester, while the steam is used in a combined heat and power system (CHP) to produce process steam (medium-low pressure steam) and electricity (Rahnama Mobarakeh et al. 2021).

The pulping process has a fuel demand of 20.4 GJ/t of pulp and an electricity demand of 0.3 GJ/t (Rahnama Mobarakeh et al. 2021). 19.2 GJ (94 percent) of the fuel demand is to deliver heat at low temperatures and could be electrified by heat pumps and electric boilers, reducing the energy demand by up to 50 percent. The remaining 1.2 GJ (6 percent) of the fuel demand is for the lime kiln and recausticiser for the chemical recovery of black liquor (Rahnama Mobarakeh et al. 2021). Using resistance or shock-wave heating, electrification could be technically feasible by 2030, which could reduce the energy demand by up to 10 percent.

Paper production (low temperature/steam demand)

The paper production process involves several energy-intensive steps. First, multiple types of pulp (either in fibre suspension or dry form) are prepared and blended to achieve the desired paper properties (compare previous sections). This process may include refining, cleaning and screening. Mineral fillers or chemical additives can also be added to the pulp to achieve specific quality enhancements. The pulp is then fed into the paper machine, consisting of a headbox, wire section, press section and dryer section. The most energy-intensive step is the dryer section, which consumes a significant amount of steam. Heat recovery systems are typically used to capture and reuse heat in exhaust gases, mitigating some of the energy consumption. Additional finishing applications such as coating and calendaring may

Electrification potential of the paper, pulp & printing sector

Solutions for electrifying applications in the paper, pulp and printing sector are technically available. Current economic considerations, dictated for the most part by the spread between natural gas and electricity prices, pose a major challenge to the actual realisation of the technical potentials. The vast majority of the industry's fuel demand is used to produce temperatures below 200 °C, which can already be achieved by heat pumps and electric boilers (Figure 24). Electric solutions to cover the high-temperature heat demands (i.e. heating of the lime kilns in pulp production) might be available by 2030.

follow before the final paper is rolled and stored for market delivery (Rahnama Mobarakeh et al. 2021; Schaffrath et al. 2023).

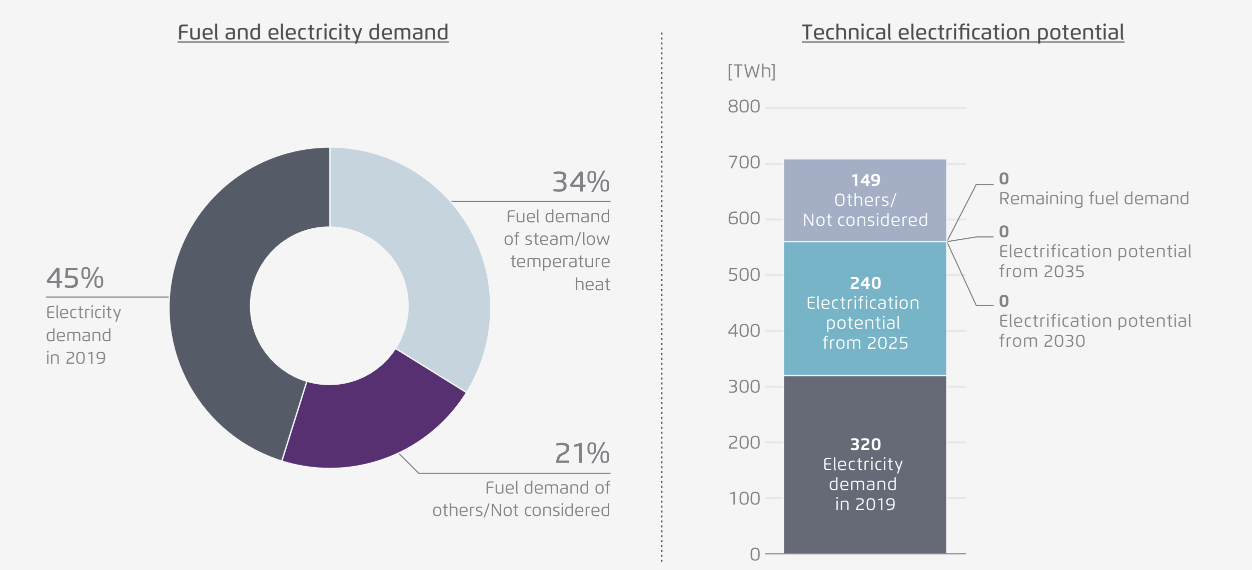
The fuel demand for the production of paper depends on the kind of paper or cardboard and ranges from 4.2 to 5.5 GJ/t (Fleiter et al. 2023b). As process heat is mainly provided in the form of steam, electrification via electric steam boilers or heat pumps is technically feasible (Expert Interview 2023; Schaffrath et al. 2023), potentially reducing the energy demand about 50 percent (Fleiter et al. 2023b).

4.1.7 Others

Sectors in the Eurostat balance which are not explicitly considered in this study are transport equipment, machinery, mining & quarrying, wood & wood products, construction, textile & leather and industries not elsewhere specified. These are subsectors that are usually labelled "non-energy-intensive", with highly heterogeneous products and processes.

These sectors had a total fuel demand of 389 TWh and an electricity demand of 320 TWh in 2019 (Eurostat Energy Balance 2019). Their energy demand consists primarily of electricity for mechanical end-uses and

Final fuel demand by product and electricity demand in the EU-27 in 2019 and technical electrification potential of other sectors not covered in this study → Fig. 25



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low-temperature heat (Figure 25). However, certain applications may require high-temperature heat (e.g. heat treatment of workpieces, lacquering). In total, these sectors were responsible for 127 Mt of CO_2 emissions in 2019 (UNFCC 2023).

For the energy demand that is not covered, we assume that the electrification potential is similar to that of the food, beverages and tobacco sector and of the paper, pulp and printing sector, and is extrapolated accordingly. This extrapolation uses the generally low temperature of heat demand as a proxy and thus assumes that none of the many different processes is without electrification potential. Though special care has been taken to screen relevant applications in this sector, further investigation of the heterogeneous sector is required.

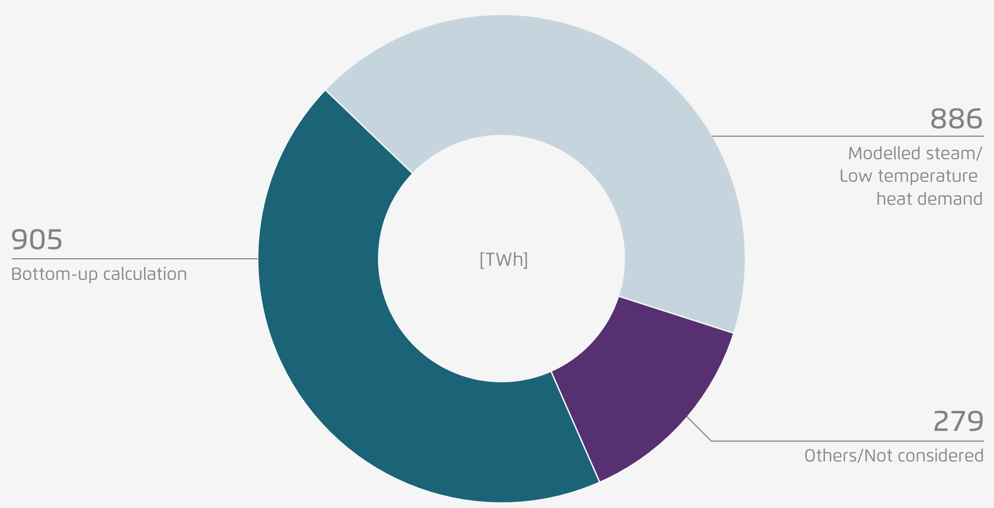
4.2 Transferability of considered applications to entire industry sector

In order to analyse the technical potential for electrifying process heat, a quantitative analysis of 14 major applications from six sectors was carried out, as presented above. The production volume, specific energy consumption (SEC) of the fuel-fired technology and the SEC of an electric alternative to these applications were estimated from the literature and from expert interviews.

As well as conducting this process-specific bottom-up assessment, the demand for low-temperature process heating (<500 °C) using steam or hot water was also estimated. This is similarly based on a process-specific approach using the simulation tool FORECAST. Where estimates of applications were not available, sector estimates of the proportion of steam and hot water in overall process heating were used (see Section 4.1.7).

This bottom-up assessment highlights a gap if results are compared to the overall fuel demand in industry. One major reason is the use of fuel for process heating in smaller applications. The electrification potential of the applications that are covered on a bottom-up basis is used as a proxy for the potential of the other applications (compare Section 2.5).

Top-down coverage of fuel demand of quantified applications of total industrial fuel use in the EU-27 in 2019 → Fig. 26



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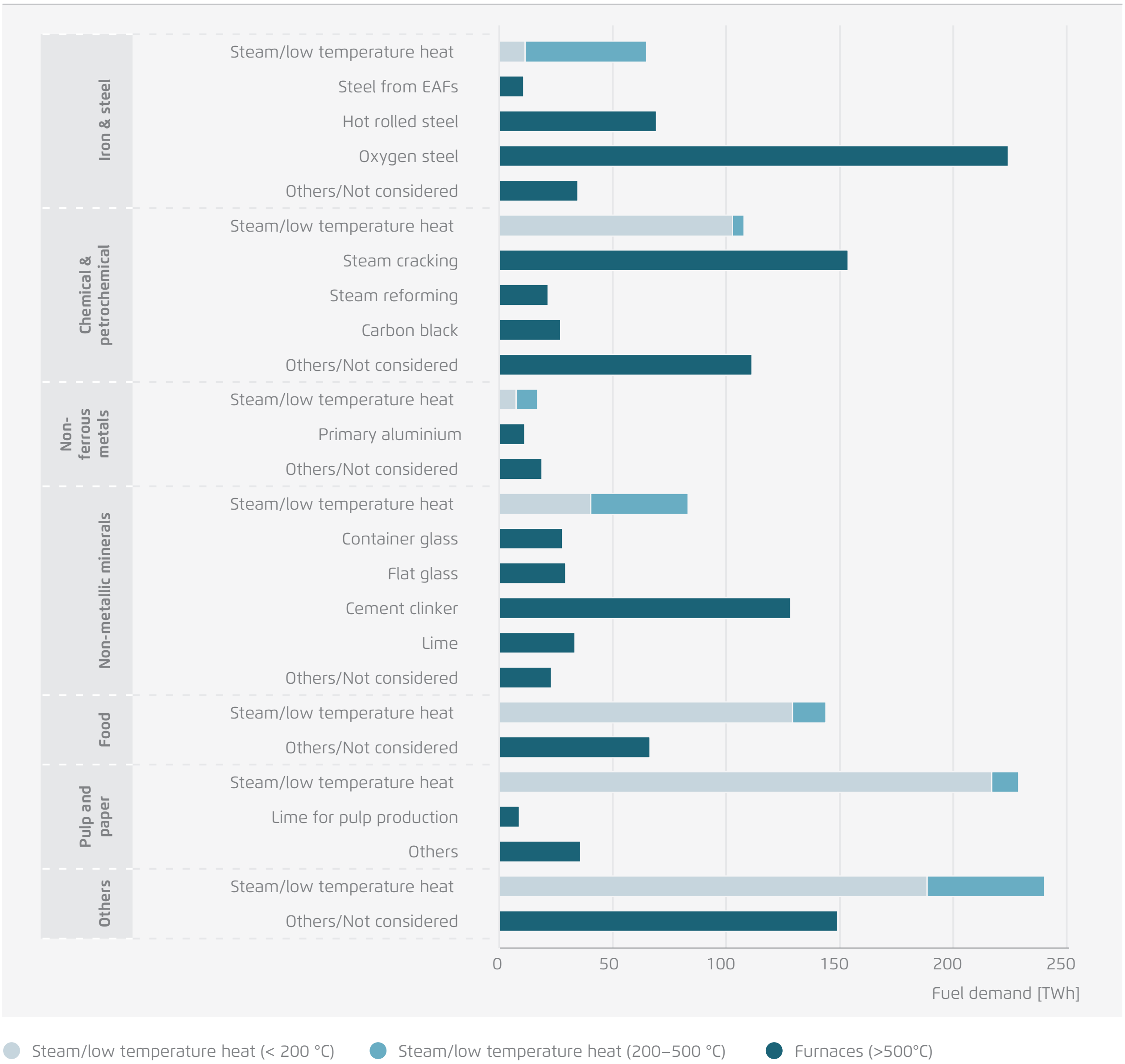
Fuel demand of the investigated applications in the EU-27 in 2019 → Fig. 27



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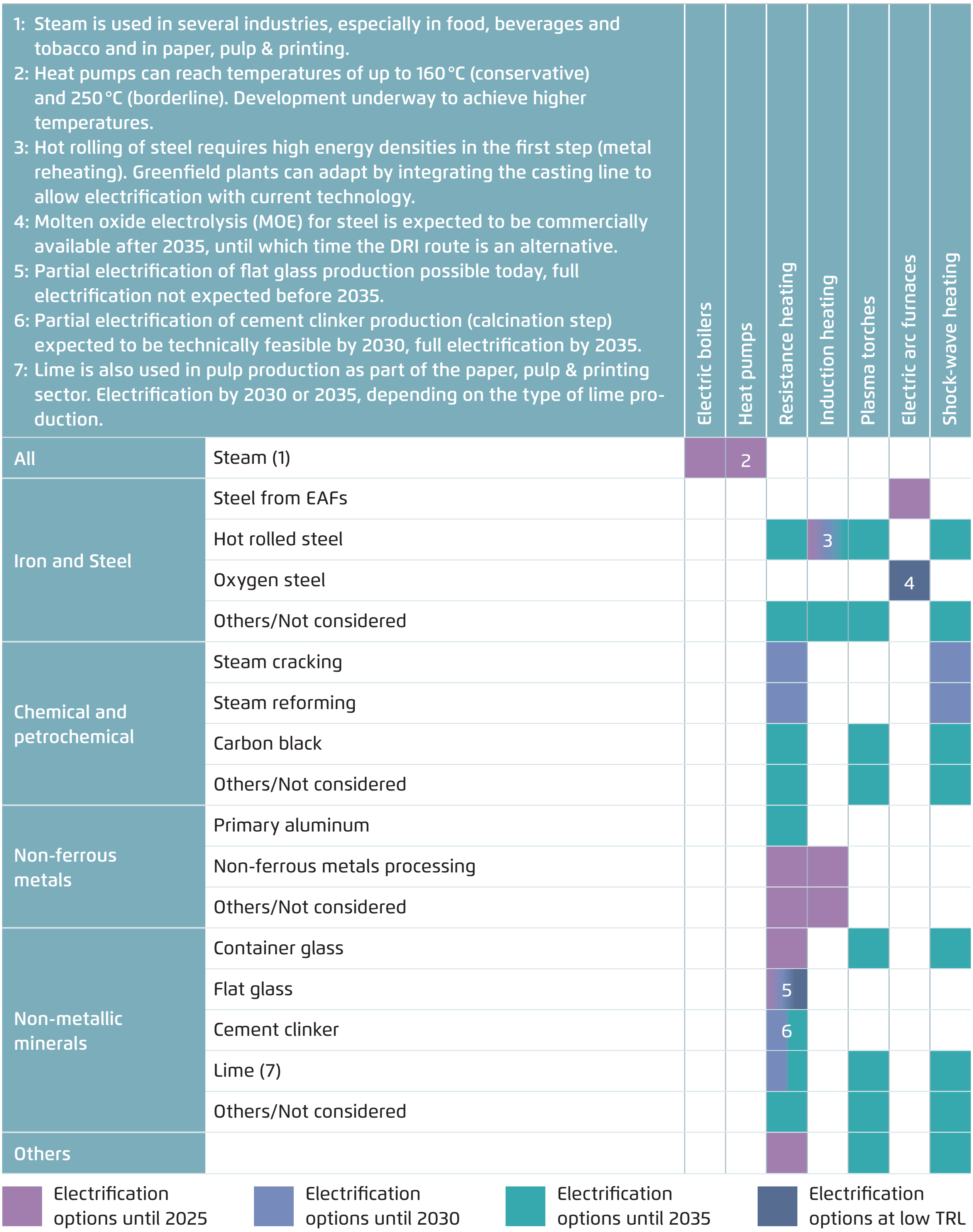
4.3 Overall electrification potential of the European industrial sector

In this Section the identified capabilities of the technologies in the respective subsectors are combined and presented as aggregated electrification potential. Technologies such as resistance heating, plasma torches and shock-wave heating show applicability in many subsectors. Further research is needed to realise this potential, especially in applications with high capacities. Steam heating by heat pumps and electric boilers is technologically mature and applicable in many industries. Electric heating technologies are already used in the non-ferrous metals sector and may become more attractive in the future. Figure 28

Overview of electrification technologies and matching with industrial applications and potential market readiness based on the results of Sections 3.1 and 4.1 → Fig. 28



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provides an overview of the electrical heating technologies examined in Section 3.1 and their applicability to the applications analysed in Section 4.1.[24]

In addition, hybrid technologies that use a combination of fossil fuels (potentially indirect electrification) and direct electrification (e.g. direct reduction of iron ore using natural gas or hydrogen combined with electric steelmaking) could enable partial electrification earlier than indicated in Figure 28. These options typically seek to overcome existing constraints to direct electrification. The degree to which direct electrification is applied can vary widely and there is a risk of lock-in, which means there is a risk that a significant investment, if made, may limit the ability to explore or adopt other direct electrification technological advances or solutions in the future.

In addition, there are other decarbonisation technologies that do not fit into the selected technology classification. Though not explicitly a direct electrification process, the new alumina process (Angelatou et al. 2022) could potentially provide the required process heat electrically.

The direct electrification potentials of the applications in question (4.1) and extrapolation of these potentials according to the transferability of the technologies to their respective sectors (4.2) allow the overall technical potential of direct electrification to supply process heat to European industry to be calculated. In total, 1 860 TWh (90 percent) of the final energy demand not yet electrified (2 070 TWh, EU-27 in 2019) can be replaced by direct electrification using technologies that are expected to be available before 2035, as illustrated in Figure 29. A large proportion of the electrification potential can be realised with the technologies available today (see *Electrification potential in 2025*). Very considerable early electrification potentials have been demonstrated in sectors that mainly use steam and hot water for process heating, such as the food, pulp and paper sectors, and others such as textiles and leather, and wood and wood products. Overall, about 1 290 TWh (62 percent) of the fuel demand could technically be replaced by direct electrification using technologies already on the market today. The electricity demand in 2019, including processes that are currently electrified, was 930 TWh. The chemical or non-metallic minerals sectors are further examples with considerable potential for electrification, though further technology development and upscaling is required. Industry representatives expect technologies to be ready here by 2030, or by 2035 at the latest. The iron and steel sector is the major outlier, where full electrification is technically not feasible even in the longer term with the technologies considered in this report (compare Sections 3 and 4). The main reason is the need for a reducing agent, i.e. as a feedstock. Today this is mainly coal, and may in the future be hydrogen. Consequently, about 200 TWh of fuel demand which cannot be directly electrified remains in this sector[25].

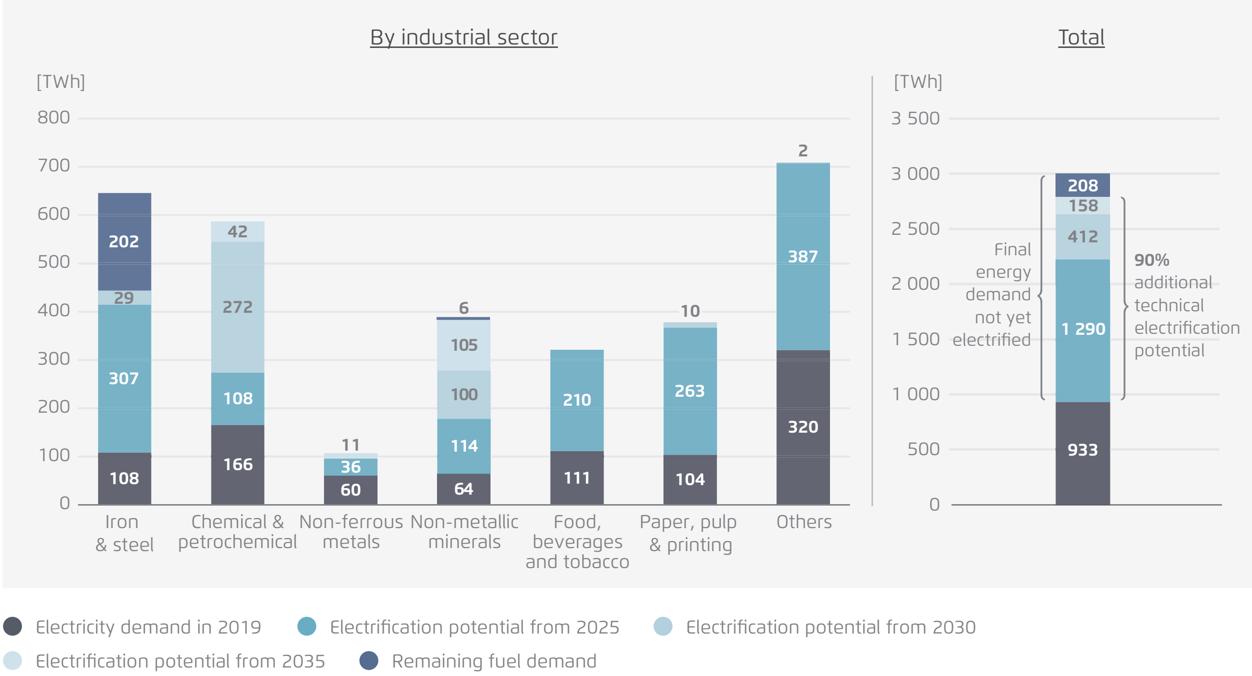
The potential is measured as that proportion of the fuel demand to supply process heat that can be substituted by electrification. These figures should be differentiated from the resulting electricity demand. The electricity demand typically varies, as electric technologies achieve different efficiencies than today's fossil-based technologies. Figure 30 considers the respective differences in efficiencies and illustrates the potential electricity demand according to the choice of electrification technology. The resulting additional electricity demand ranges between 1 290 and 1 930 TWh (EU-27, 2019). Together with the existing electricity demand in 2019 (930 TWh, EU-27), the total electricity demand increases to between 2 220 TWh and 2 860 TWh. The wide range is due to the many possible technical options and their varying efficiencies, giving rise to a high degree

24 Note that in this study (compare Section 1.4) the proportion of final energy demand that is already electrified – consisting primarily of the supply of mechanical energy, secondary steel production in EAF and only limited process heat generation – is presented as "electricity demand in 2019" because it is based on statistical data. It is thus excluded from the additional electrification potential but pre-sented as part of the total final energy demand.

25 This result excludes the potential shifts between secondary and primary production, which has a relevant potential impact on energy efficiency, circular economy and electrification but is also subject to highly specific requirements that have not been investigated in this study (e.g. product quality, scrap availability).

Technical potentials for direct electrification in the EU-27 in 2019

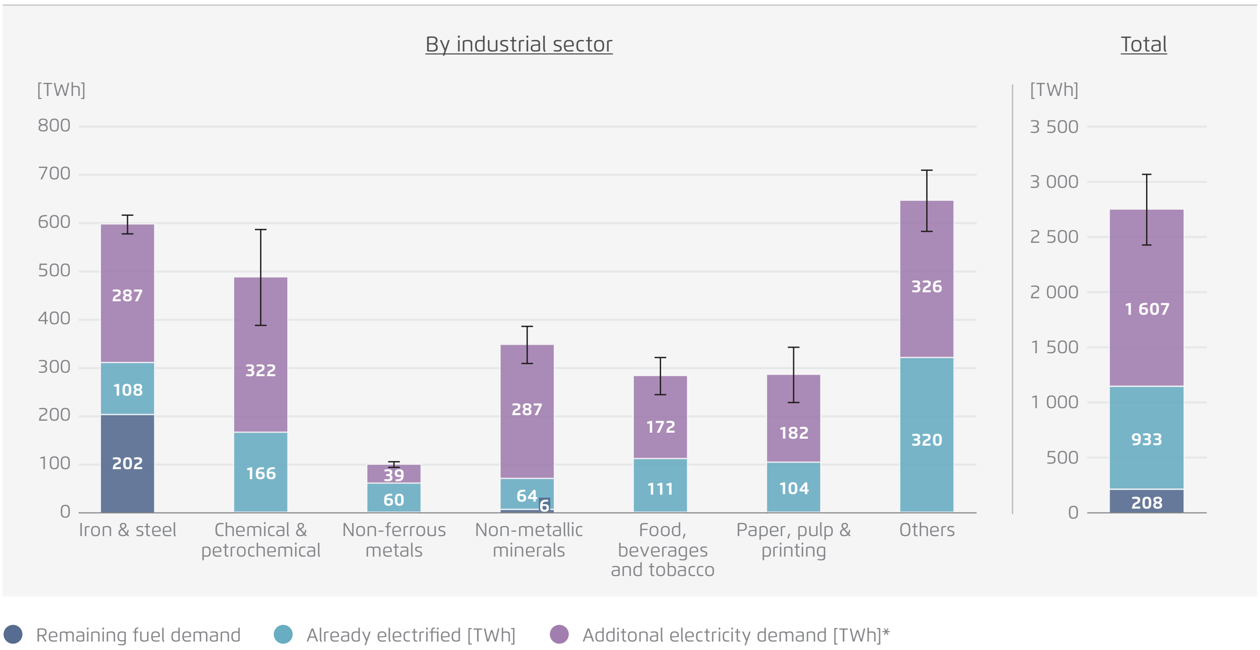
→ Fig. 29



Fraunhofer ISI (2024)

Full electrification potential in the long term (beyond 2035); resulting final energy demand by industrial sector and total with lower and upper limits for additional electricity demand depending on the choice of electrification technology in the EU-27 in 2019

→ Fig. 30



Fraunhofer ISI (2024). Note: Margins depend on the choice of electrification technology in 2019 in the EU-27 countries.

of uncertainty. Heat pumps for example could drastically reduce the energy demand, but because integrating them into existing processes is more complex, electric boilers may be installed instead. About 210 TWh of the fuel demand remains and cannot be directly electrified.

The absolute values given in Figure 30 cannot be used as a projection or forecast of future electricity demand, as they refer to the energy balance of 2019 – changes to the industrial structure and activity (e.g. brought about by material efficiency or sufficiency strategies), as well as system-wide energy efficiency gains beyond the effects of electrification, are not considered here.

4.4 Resulting total electricity demand depending on the proportion of direct and indirect electrification

This section discusses the implications for electricity demand according to the level of direct electrification. To this end it is assumed that a proportion of today's fuel demand will be electrified indirectly, e.g. by switching to hydrogen produced via water electrolysis. To reflect the uncertainty over the degree to which direct electrification will compete with hydrogen use, three cases are defined in which the ratio of direct to indirect electrification varies (see Figure 31). Resulting electricity demands therefore also include the electricity require to produce the necessary hydrogen, based on the assumption that hydrogen will be produced via electrolysis with an efficiency rate of 70 percent[26].

Case one "Direct electrification / upper bound" considers the maximum direct electrification potential calculated in the report, including technologies expected to be mature by 2035 (see Section 4.3). In this case, the total electricity demand would rise from about 930 TWh today to between 2 520 TWh and 3 160 TWh – depending on the technology chosen and its respective efficiency.

Case two "Direct electrification/ lower bound" excludes certain hard-to-electrify applications for which significantly higher technical, economic or organisational barriers have been identified (compare Section 5) and assumes that their process heat needs will be met by switching to hydrogen instead. These are applications which are not expected to be fully electrified before 2035, including production of flat glass and lime, sintering of cement clinker (see Section 4.1.4), production of carbon black (see Section 4.1.2), primary aluminium (see Section 4.1.3) and hot rolled steel (see Section 4.1.1). Though hydrogen might indeed allow these applications to be decarbonised, it should be noted that using hydrogen might also require processes to be adapted and a reliable infrastructure and supply chains to be in place. In case two, the resulting increase in total electricity demand would range between 2 640 TWh and 3 230 TWh, which is only marginally higher than in case one with full direct electrification.

Case three "Indirect electrification" assumes that today's fuel use for process heating is completely replaced by hydrogen and ignores any additional direct electrification potential beyond today's level. In this case, the total electricity demand would substantially increase to 3 890 TWh[27].

Comparing the three cases reveals the wide range of resulting total electricity demand. Following the most efficient direct electrification route in all applications (case 1: direct electrification/upper bound) could reduce the electricity demand by about 1 370 TWh compared to the use of hydrogen only (case 3: no additional direct electrification). Case 2 (direct electrification/lower bound) allows for a more nuanced understanding of the implications. Interestingly, the difference between case 1 and case 2 is relatively minor (2 520 TWh vs. 2 640 TWh). One main reason for this is that efficiency gains from direct electrification may be relatively small in the hard-to-electrify applications compared to hydrogen use – especially if direct electrification technologies

26 The conversion to synthetic fuel is not considered here.

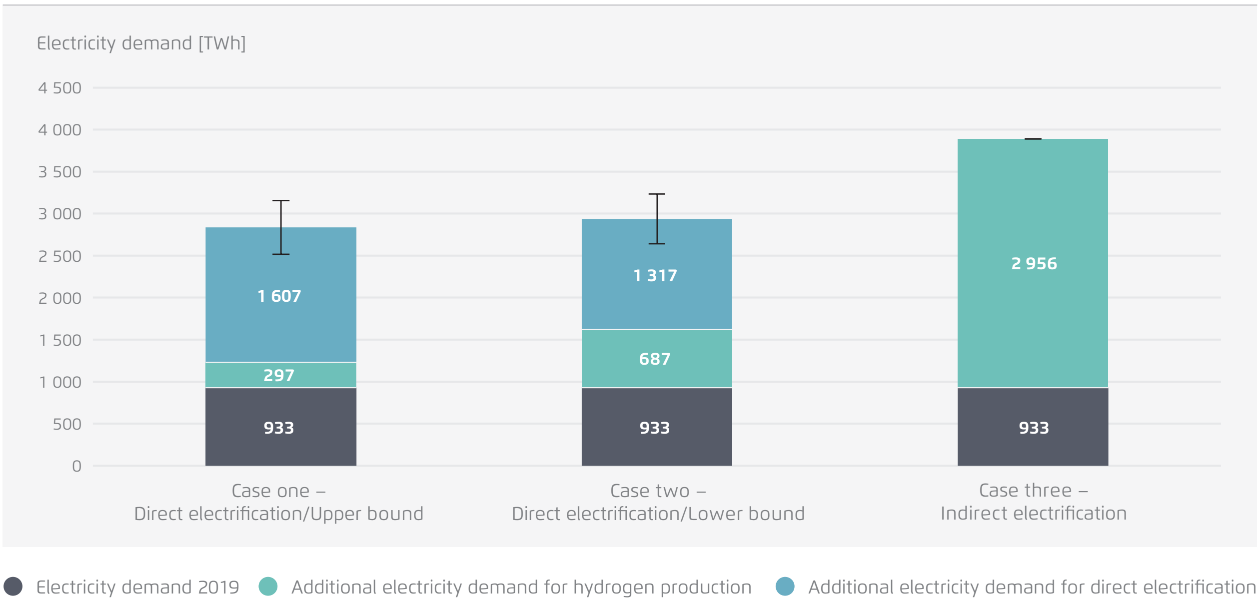
27 All values include the 933 TWh of base electricity demand of the industrial sector (EU-27) in 2019.

of lower efficiency are needed to supply the applications. Comparing case 3 with case 2 paints a different picture: the efficiency gains from direct electrification are huge in this scenario and the switch to hydrogen results in much higher overall electricity demand. This is chiefly due to the fact that direct electrification of low-temperature applications can facilitate substantial efficiency gains if for example heat pumps are used, whereas the use of hydrogen entails an assumed efficiency penalty of 70 percent in its generation alone (if based on electrolysis) – despite any efficiency improvements that may be achieved by direct electrification on the end-use (application) side (as discussed in Section 3.1).

To summarise, comparing the three defined cases shows that opting for direct electrification rather than hydrogen use in process heating can substantially reduce the overall future electricity demand but is not equally advantageous in all applications. In high-temperature applications that are hard-to-electrify, direct electrification may yield limited efficiency gains compared to hydrogen use, whereas the efficiency gains to be achieved by direct electrification in low-temperature applications are huge if heat pumps are applied on a large scale.

Resulting total electricity demand for direct electrification and for hydrogen production with lower and upper limits for additional electricity demand depending on the choice of electrification technology

→ Fig. 31



Fraunhofer ISI (2024)

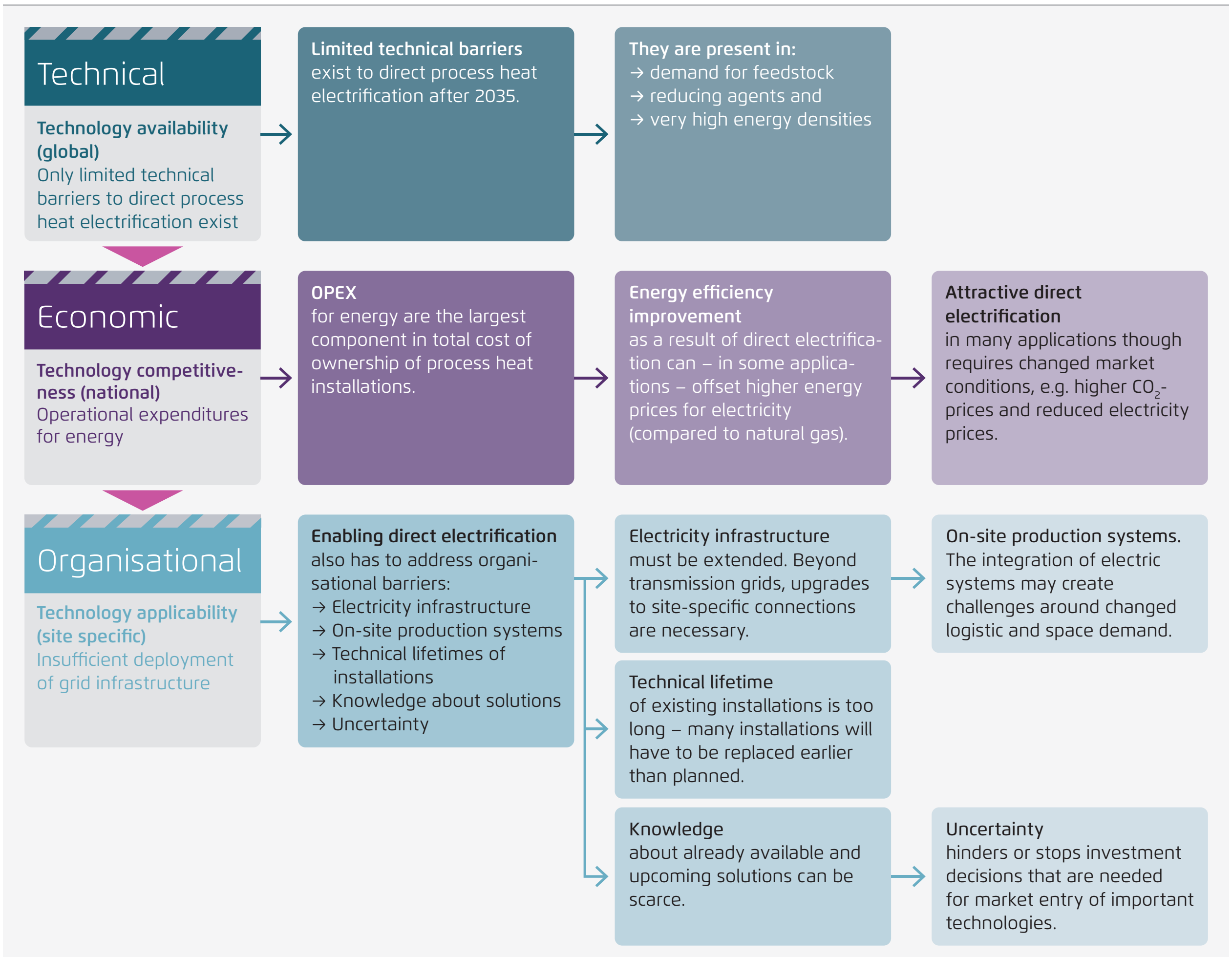
5 Current barriers and future prospects

Despite the current technical availability of direct electrification technologies for several important applications (Section 3), their current diffusion is low and fossil fuels still dominate process heat generation (Figure 4). If left unaddressed, existing barriers can also be expected to affect the exploitation of future potentials [28]. This study therefore identifies several challenges in interviews with technology users and manufacturers and then groups them according to technical (Section 5.1), economic (Section 5.2) and organisational (Section 5.3) aspects. By describing the various barriers and challenges, we can already begin to identify ways to overcome them and foster diffusion of direct electrification technologies – this

28 Compare International Renewable Energy Agency 2023: "The electrification of process heat, as a strategy to mitigate carbon emissions and transition toward a more sustainable energy landscape, faces multifaceted challenges. While the concept of providing process heat through electrical heating holds promise, its successful implementation varies considerably across diverse industrial applications, each presenting unique technical and logistical hurdles."

Dimensions and modes of action of barriers

→ Fig. 32



Fraunhofer ISI (2024), Agora Energiewende (2024) is expanded upon in Section 6. The barriers apply to different levels (Figure 32): while general technical availability can be seen as a global property, actual economic competitiveness is dictated to a significant extent by national regulations (e.g. energy taxation, subsidies, flexibility options). Finally, concrete applicability in a particular process and company depends on site-specific conditions (e.g. access to infrastructure, space for new installations).

The analysis shows that technical barriers – though still currently relevant to applications with special technical requirements (energy density, temperature) – are relatively low and can reasonably be expected to be overcome in virtually all applications by 2035.

Economic, regulatory and organisational hurdles present greater challenges to the widespread adoption of direct electrification technologies than technical difficulties do. Policymakers can address the majority of these barriers, however.

5.1 Technical barriers

The identified electrification potentials (Figure 29) show that only **limited technical barriers to direct process heat electrification exist** and are expected to remain after 2035. Electrification could reduce the fuel demand by 90 percent with the technologies that will be available by 2035 (see Section 4.3). Many different applications, especially in low-temperature ranges, can already be electrified today. The limitations (in high-temperature ranges) apply only to specific – but highly relevant – applications or are caused mainly by other barrier dimensions (see Sections 5.2 and 5.3). The technologies that are developed by 2035 may overcome technical barriers and enable the direct electrification of the majority of applications.

There are three notable exceptions to this general finding. **First**, the use of fossil energy carriers as **feedstock** in chemical processes cannot be directly electrified, as the molecules are part of the product (as is the case with ammonia and olefins for plastic production). These applications are not investigated further in this study. **Second**, where fossil fuels are used as a **reducing agent** – the most relevant application being iron production in the primary steel route – the technologies for direct electrification are not yet available nor expected to be market-ready by 2035 (Section 2.3). Instead, indirect electrification (via hydrogen-based direct reduction of iron ore) is the most likely path given the technologies currently available, existing and announced projects and subsidy programmes in major European steel producing countries (e.g. Harthan, Förster, et al., 2023). **Third**, energy-intensive process steps in some applications exceed the capabilities of existing technologies in terms of **heat density** – reheating furnaces in steel processing being one example[29]. This limitation may be relevant to certain processes in the steel, chemical and minerals industries.

Several novel technologies investigated in this study are expected to alleviate the third issue (heat density) as new materials are developed for resistance heating (Section 3.1.3) – extending both temperature range and heat density[30] – or for shock-wave heating (Section 3.1.7), which to some degree substitutes the function of fossil fuel burners (heat transfer mechanisms need to be considered[31]) and thus enables at least partial direct electrification[32]. With the technology readiness and development assumed above (Section 3), technologies for all investigated applications may well be available by 2035. The technical barriers to direct electrification identified in this study thus appear to be low.

Technologies do not become available or achieve market diffusion of their own accord, however: they need to be developed, upscaled and deployed, and they need to be demonstrated to gain experience. In the case of high-temperature process heat, current

29 Source: Stakeholder interview with metal industry.

30 Source: Technology manufacturer's contribution to project workshop

31 Heat transfer in process heat applications predominantly involves heat convection or radiation. The balance of these mechanisms depends on the process temperature, with higher temperatures (above 600–800 °C) seeing marked shift towards radiation as the more efficient mechanism (e.g. in natural gas burners). Some novel technologies use heat convection rather than heat radiation and this shift in heat transfer is a challenge that must be considered in furnace and process design.

32 Source: Interview technology with manufacturer

technical challenges may lead to investments in indirect electrification, including infrastructure and long-lasting equipment, which would hamper the introduction of newly developed or improved direct electrification technologies and increase the overall energy demand. Thus, early market-ready solutions and incentives for their implementation are important means of overcoming existing barriers and helping to realise the ambitious development goals of technology manufacturers.

5.2 Economic barriers

Economic barriers involve important intertemporal aspects and thus also highlight uncertainties (compare Section 5.3), e.g. concerning available alternative energy carriers. As things currently stand, direct electrification competes with natural gas use. The barriers described by technology manufacturers and end-users relate mainly to this current status. However, prospective considerations also take the potential future competition between direct electrification and hydrogen into account. In both cases, the energy carrier price is highly relevant. However, future electricity prices are uncertain and subject to regulatory action – hydrogen prices even more so. The analysis thus focuses on the current status (though elements of the identified barriers may be applied also to competition between direct electrification and hydrogen).

Economic barriers were considered highly relevant by the decisionmakers interviewed for this study (both on the user and technology supplier sides). They determine the competitiveness of the technologies, so addressing them is an important means of realising the potential of direct electrification. Two major aspects can be identified: **first** and foremost, the lion's share (usually more than 85 percent) of the total costs of ownership (TCO)[33] of a process heat installation are defined by the **operational expenditures for energy** (and CO_2 pricing, if applicable) (Fleiter et al. 2023b). The competitiveness of direct electrification technologies can therefore be roughly estimated on the sole basis of their relation to the respective fossil fuel price (often natural gas) plus the CO_2 price versus the electricity price. The result is underwhelming in many cases (compare Agora Energiewende and Fraunhofer IEG 2023). In current and expected market environments[34], direct electrification technologies often need to achieve substantial efficiency gains or other benefits (e.g. high COP in heat pumps or product quality/process control improvements) to compete with natural gas-based process heat technologies. Fleiter et al. (2023b) estimate that applications without these advantages, assuming natural gas prices at the 2019 level, could require electricity prices of around EUR 0.06/kWh in addition to CO_2 prices of EUR 300/t for widescale electrification to become economically attractive. Such price levels would give direct electrification a relevant economic advantage over natural gas in terms of heat generation costs. This barrier cannot be addressed (or only to a limited extent) by improving the technology due to the technical limitations of efficiency gains. Thermal energy storage is a special case and a potential enabling technology because it reduces the average electricity costs – not by improving efficiency but by enabling firms to buy electricity during the lowest-priced hours or from inexpensive, off-grid solar and wind installations (compare Section 3.1.8). **Second**, a fuel switch to direct electrification frequently involves new installations and their integration into existing processes, with **capital expenditures** exceeding those entailed by merely replacing or refurbishing existing fossil installations, including necessary changes to on-site and surrounding infrastructure such as increasing the electricity capacity that serves the industrial facilities in question (see Section 5.3). While this has limited impact on the TCO, higher upfront capital requirements may increase project risk and uncertainty.

33 The concept of "total costs of ownership" relates to all the costs incurred during the lifetime of an investment and allocates them to a relevant indicator (e.g. heat generation costs) in order to compare competing options. Often-used categories are capital expenditures (capex, including financing), operational expenditures (opex, including energy costs) and others (such as maintenance and personnel).

34 Notwithstanding energy carrier price spikes related to the energy crisis, which may have caused and still cause different outcomes in some cases.

The economic barriers can only be addressed by technologies or users to a limited extent, with technology development possibly reducing their relevance somewhat. However, the energy price difference between electricity and fossil energy carriers is an external factor that is subject to regulations. One obvious conclusion might be to lower the differential costs of electricity and natural gas. Electricity prices can be reduced in several ways (e.g. tax reforms, structural changes to electric grid fees, targeted subsidies for energy-intensive applications). On the other hand, the economic attractiveness of natural gas prices can be reduced by CO_2-pricing mechanisms such as the EU-ETS, if these are applied with sufficient ambition. One of the main challenges involved in using economic incentives is the need to create price signals that urge early action (compare organisational barrier) while avoiding economic shocks and social disruptions.

5.3 Organisational barriers

The third dimension – and by far the most diverse – comprises the organisational (or logistical) challenges entailed by the on-site transition from fossil- to electricity-based process heating. At the same time, these are the least researched barriers[35] because they are highly site-specific – thus any representation must rely on anecdotal evidence. In this study, the information gained from interviews with technology suppliers and end-users has been validated in a workshop (Section 2.5) to create some degree of intersubjectivity and obtain robust insights.

The study identifies five groups of barriers that can be attributed to organisational/logistical challenges.

First, the **insufficient deployment of grid infrastructure** poses a challenge to direct electrification. The existing on-site and surrounding infrastructure is primarily designed for compatibility with fossil-fuel systems, resulting in high natural gas connection capacities but comparatively low electric capacities[36]. Therefore, direct electrification requires a significant expansion of electric infrastructure, as well as the scaling back of the fossil fuel connection. In many cases, this involves upgrading existing electrical connections to the high-voltage grid and installing additional infrastructure at the plant, such as transformers. The costs associated with these upgrades can often exceed the capital costs of the electrified industrial equipment itself[37]. Furthermore, the investing company is reliant on external actors, such as approving authorities and grid operators, which introduces uncertainty and longer lead times. This situation highlights the importance of addressing insufficient grid infrastructure deployment and ensuring a reliable supply of electricity for successful direct electrification. **Second**, replacing fossil with direct-electric installations can **physically change the on-site production structure**. Examples include the integration of heat pumps into processes that previously used one central heat generation installation[38], increased space requirements for electric solutions (e.g. the replacement of one fossil shaft furnace with multiple induction furnaces or the addition of thermal storage) and dependency on other actors nearby (e.g. shared heat and material streams or infrastructure). Electrifying existing installations (brownfield investments) can prove a major challenge[39] – and the technological change involves risks of longer production stops than the usually yearly refurbishment of existing installations. Greenfield projects offer greater flexibility and easier integration but must be seen as the exception. Nonetheless, integrating decarbonised heat solutions involves effort, regardless of the decarbonisation route that is chosen. **Third**, existing process heat installations have **technical lifetimes** of several decades, so the

35 Despite this limitation, it may be assumed that relevant aspects of the extensive literature on energy efficiency and its barriers apply and sufficiently describe important considerations.

36 Source: recurring argument in multiple interviews with process heat users (steam, mineral, metal).

37 Source: recurring argument in multiple interviews with process heat users (steam, mineral, metal).

38 Thorough heat integration aims to limit the required peak temperature stream and is especially relevant when it comes to utilising the potential of high-efficiency improvements with heat pumps.

39 Source: recurring argument in multiple interviews with process heat users (steam, mineral, metal) – individual interviewees report few or no potential issues with integration, e.g. due to existing backup installations and sufficient space on site.

window of opportunity for their routine replacement is in many cases closing or has already closed. Lifetimes of 40 years are usual (below 20 years being the exception), which leaves average installations built after 2010 as (partially) stranded investments that require early replacement. Early replacement incurs additional costs and effort. **Fourth**, though knowledge of the technically available and economically attractive direct electrification options is growing, it is not widely available. Often there is a lack of experts to keep track of the technical possibilities. Transfer costs[40] can therefore be high and exceed the actual investment, as operational experience of and competence in the use of electrical systems may need to be built up within the workforce[41]. **Fifth**, interaction with public infrastructure and political decisions generates **uncertainty**, creating incentives to wait/postpone investments or hope for the availability of cheap and abundant hydrogen[42]. For example, some European governments have indicated plans to support clean hydrogen, so industrial firms may choose to wait in the hope that cheap and abundant hydrogen will become available rather than investing in electrification technologies. This includes uncertainty about the reliability of electricity supply and grid stability. Some actors have said that they are considering investing in individual back-up capacity. The expected or feared effects of considerable concentrated electricity demand on the grid play a role in decision-making processes, as does the perceived lack of availability of skilled experts to operate electric solutions[43]. The organisational barriers are thus inextricably linked to the regulatory and economic barriers (compare Section 5.2) – ranging from flexible electricity demand and grid charges (e.g. for storage solutions) to the granularity of price signals.

Several of the investigated technologies can address some of these barriers. In particular, the commercialisation of *drop-in solutions* may reduce the challenges associated with the second barrier (the need to physically change the on-site production structure), as these technologies aim to minimise the impact of electrified process heat generation on surrounding processes. A simple example is an electric steam boiler that replaces its natural gas-fired counterpart. Other more complex systems are thermal storage solutions which reduce uncertainties regarding the security of supply (the fifth barrier) by enabling a limited degree of independence[44]. In both cases, self-contained/modular systems may ease the transformation strain on existing systems.

Being both an advantage and a disadvantage of drop-in concepts, the reduced depth of integration may exclude efficiency improvements but has the potential to greatly accelerate technology diffusion with semi-standardised systems. An alternative design strategy would include a deep retrofit of the entire production system. The “efficiency first” principle strives to improve heat integration and process design; only then are new heating systems introduced – ideally lowering energy losses and required capacities. This concept may arguably entail the better technical solutions, but at the expense of speed. It seems plausible that a combination/target-group appropriate mix of these approaches will emerge – drop-in solutions for many brownfield installations outside their regular re-investment cycle, and deep optimisation for direct electrification in greenfield installations and those undergoing major revisions. Both strategies may serve to address the fourth and fifth barrier (reducing uncertainty and increasing knowledge).

40 The costs of gathering and organising decision-relevant information, measurable in working hours of the responsible energy manager or additional employee.

41 Source: personal impression of the authors gained during some stakeholder interviews in which relevant direct electrification technologies were not considered despite highly engaged and ambitious plans.

42 From an end-user perspective, hydrogen (or synthetic fuels) seems especially attractive, as the modifications to the existing stock are on a much lower scale than those needed for direct electrification – shifting the lion’s share of the transformation effort to system level (electricity generation, electrolysis, electricity grid and hydrogen grid).

43 Source: interviews with technology users

44 In localised or grid-wide high-demand situations, for example, major consumers might be asked to reduce their power intake to support the grid operator in stabilising the grid. Thermal storage systems may allow the consumer to adapt to this demand while still ensuring continuous production. However, this may require a higher-capacity grid connection.

6 Outlook: Overcoming the challenges to accelerate electrification

This analysis shows that the potentials for direct electrification in process heating are huge and that many technologies are already mature or will likely be available in the coming years. Economic and organisational barriers mean that electrification still plays only a niche role in process heating, however. Overcoming organisational barriers, and above all establishing a market framework that makes direct electrification cost-competitive with the use of natural gas, are the main goals when it comes to tapping the enormous potential direct electrification offers for climate-neutral and energy-efficient process heating. Relevant starting points to overcoming barriers are discussed in this outlook and should be analysed in depth in follow-up investigations.

Tilting the economic scales – electricity as the new primary energy carrier needs to be competitive with natural gas

Direct electrification currently competes mainly with the fossil status quo: natural gas. Depending on the sector, country, demand volume and other aspects, electricity as the energy carrier for process heat generation is more expensive than natural gas – even considering CO_2 pricing at current levels. Considering all cost components (supply, taxes and grid fees and other charges), many applications that involve no scope for realising substantial efficiency gains via direct electrification (high temperature, high capacity) require an electricity price that is at least close to or on a par with the CO_2-adjusted natural gas price (Fleiter et al. 2023b) to allow for sufficiently fast diffusion of the entire stock of process heat plants. This could be achieved by providing financial support for investments in electric heating technologies and by reducing the cost of electricity or increasing the price of CO_2 emissions.

Increasing security of supply and mitigating uncertainty

Efforts to expand generation and transport capacities can help address perceived uncertainty regarding the security of supply with green and stable electricity. Additionally, decentralised on-site storage solutions for process heat, integrated into direct electrification, can provide a complementary approach and alleviate the concerns of investors during the early transformative years. These solutions not only benefit the site itself but also entail potential advantages for the system as a whole, such as flexibility. Regulatory adjustments may be needed to fully exploit this potential (Agora Industry and Future Camp 2022).

To decrease uncertainty, it is crucial to have published plans for hydrogen backbone or core grids that can provide clarity about future access to hydrogen. Communication about these plans should not only highlight the opportunities for specific sites such as iron and steel plants or chemical parks but should also clarify exclusivity. Transparent communication about economic incentives for hydrogen use, including subsidies and plausible price levels, can also contribute to reducing uncertainty.

Access to green electricity needs to be improved in terms of both generation capacity and grid connection of industrial sites. Shortening the planning phase for such projects and implementing measures to strengthen confidence in electricity availability and reliability are essential steps towards increasing planning security.

Developing and upscaling technologies

Although this study makes assumptions about technology improvements and – most importantly – about commercial and market-level readiness, this will not happen automatically. Though technical challenges can be overcome, active support with scaling up direct electrification technologies is vital, especially in the demonstration and commercialisation phases of concepts that push the technical boundaries of electrification (in terms of energy density or temperature range) or that extend its use to include new processes and materials (metals, non-metallic minerals, some high-temperature chemical processes). Overcoming technical challenges is not sufficient; it must be demonstrated that electrified processes work reliably at industrial scale in continuous long-term operation and do not harm product quality. This might be achieved by an industrial alliance supporting technical learning, financial incentives for first-of-its-kind industrial-scale installations, accompanied by a target-oriented regulatory framework for the competing energy carriers.

Facilitating technology learning by early market introduction

Technologies for direct electrification are already available in many sectors. High uncertainty with regard to future electricity prices and the lack of experience of long-term operation increase the perceived risks involved in a large-scale adoption at individual sites. In this case, partial electrification can be a useful first step and should be supported to facilitate early adoption and technology learning. Examples include electric heat pumps or boilers that are added to an existing gas CHP unit and run in hybrid mode according to electricity market signals. Such strategies reduce investment risks, accelerate the transition and can potentially provide flexible demand for the energy system. However, several barriers – which differ from country to country – still prevent adoption: in Germany, network charges incentivise long annual running hours and make plants with low running hours and high loads less competitive (See Agora Industry and Future Camp 2022).

Striking a balance between quality and quantity

Conflicting targets exist along the axes of fast versus thorough integration of direct electrification into existing industrial systems. Fast integration can be achieved using standardised drop-in solutions that immediately replace fossil systems with minimal intervention. They may fail to tap the full efficiency potential, however. Thorough integration of direct electrification considers the entire production system and yields higher efficiencies, but requires in-depth analyses by highly skilled experts and tailor-made solutions. This comprehensive approach tends to slow down diffusion as compared to standardised drop-in solutions. Both paths can improve the implementation rate of direct electrification and accelerate the transformation. A regulatory framework should allow for both approaches according to company needs and capacities.

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8 Appendix

Guideline for interviews with stakeholders

1. End user

Category	Questions
Process and technology understanding	Please briefly describe the production process used in your company – at which point do process heat requirements occur and at what temperature level?
	Which electrification technology is suitable in principle for your process?
	What circumstances (technically) limit the technologies?
	Have you already made attempts to implement electrification technologies? If yes, which?
Site conditions	What conditions at your site would have to be changed in order to electrify directly?
	Which of these can you influence yourself?
	If you are already piloting or considering piloting electrification technologies, which location-related challenges do you see?
Investment decision	How long do you have a process heating system before you usually think about replacement/modernisation?
	[Probably not transferable, anecdotal] When is your next window for a plant replacement?
	Which criteria are decisive when deciding for or against a particular electrification technology?

2. Technology manufacturers

Category	Questions
Technology understand-ing & market development	Please briefly describe your technology – in what form is electrification used to generate process heat?
	What are the main technical hurdles to the broad market launch of your technology?
	What are the use cases for your technology? In what form is an application already being piloted/what is the development status of the technology?
	[if already market available] Which other hurdles are there (economic, political)?
	[if already market available] What are the hurdles to opening up further application areas (e.g. temperature-level heat pumps)?
	Which industries do you consider to be developable as customers by 2030/2040? What proportion of applications in the industries?
	Which power classes (MW) can you currently cover?
Scaling options	What upscaling do you think is possible/planned by 2030/2040?
	Upscaling of power classes (i.e. maximum power of delivered technology in MW).
	Do you see challenges in ramping up production capacity (i.e. number of furnaces that can be converted)? → Technology itself → Value chain (inputs, installation, maintenance, infrastructure)

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Agora Industry

Publication details

About Agora Industry
Agora Industry develops scientifically sound and politically feasible concepts for successful pathways to a climate-neutral industry – in Germany, Europe and internationally. The organisation which is part of the Agora Think Tanks works independently of economic and partisan interests. Its only commitment is to climate action.

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