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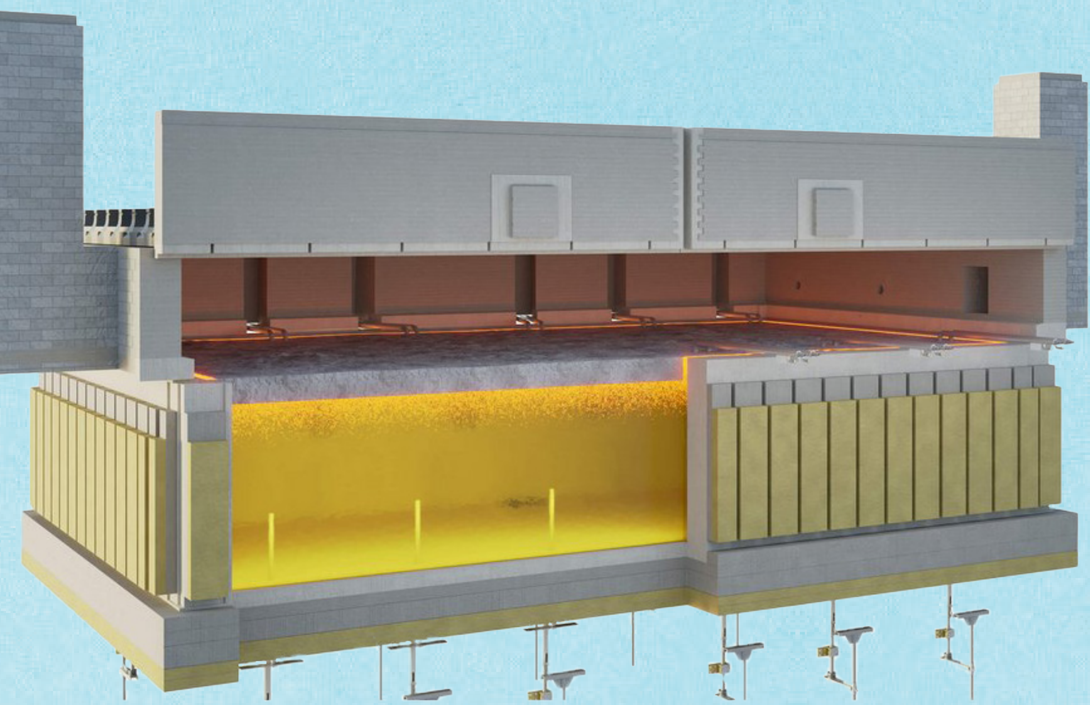

CO_2-neutral process heat using electrification and hydrogen

perspectives

policy brief

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CO_2-neutral process heat using electrification and hydrogen

Technologies, barriers and required action

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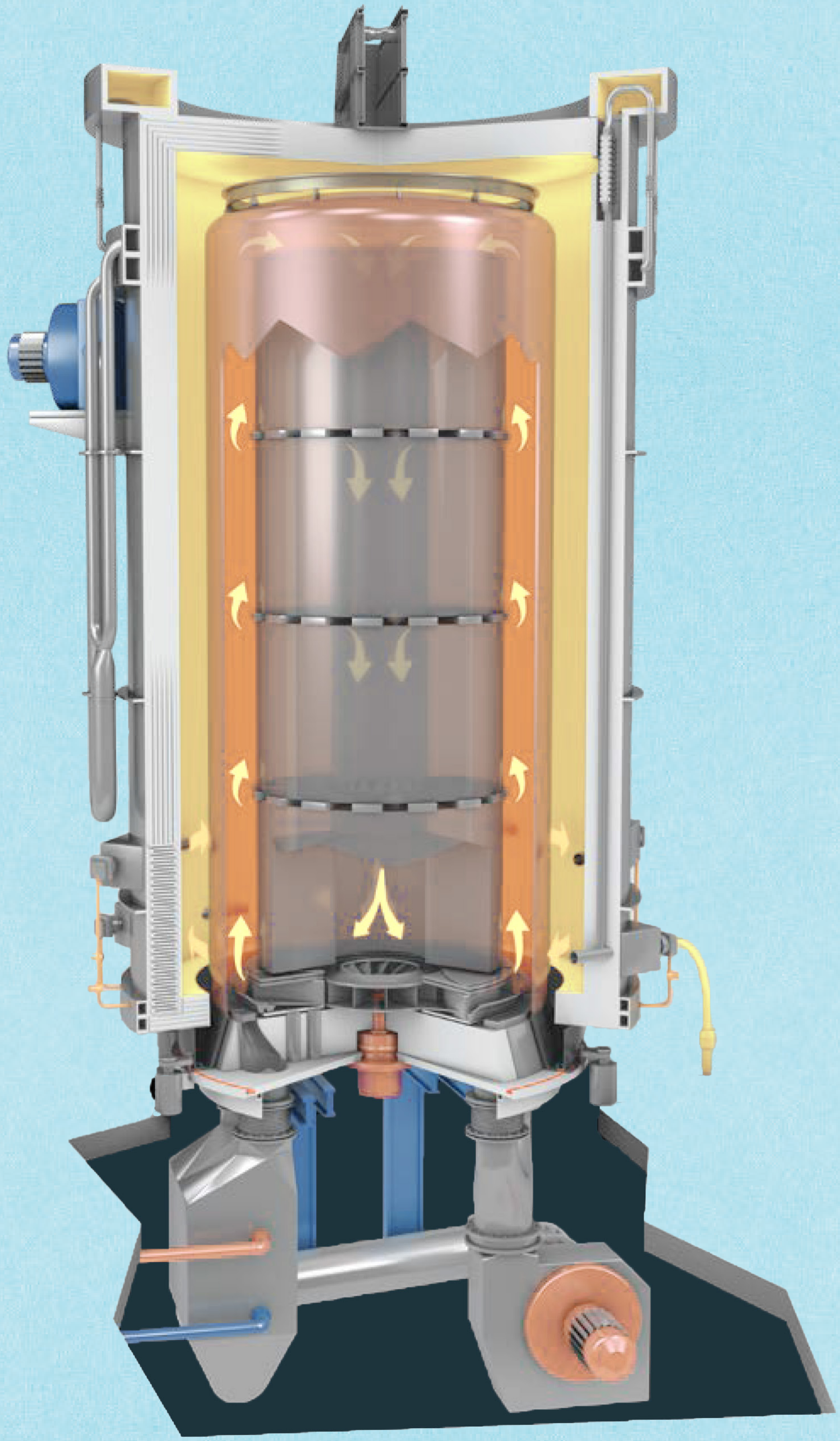

High-performance hydrogen bell-type annealing furnace
Picture credit: ©Tenova

Overview and summary

In 2022, process heat was responsible for about two-thirds of industrial greenhouse gas emissions [1]. Any transformation toward a climate-friendly industry also requires a successful heat transition by converting process heat to CO_2-neutral energy sources.

At present, this is only taking place in isolated cases and is being slowed down or prevented by a range of economic, regulatory and technical obstacles. **This policy brief provides a comprehensive overview of the technology potential of hydrogen and electricity for supplying process heat and indicates the main obstacles involved as well as the action required to design suitable policies.**

This policy brief is based on a recent study that examines technology potentials at the level of individual industries in Germany [2]. A series of workshops held as part of this study with companies from the respective industries identified the obstacles to implementation. From the viewpoint of industry, major barriers include insufficiently detailed knowledge about technical possibilities, the lack of operating experience and the low economic viability of emerging technologies. Uncertainty concerning future energy and CO_2 prices means companies are delaying implementation. At the same time, there is an urgent need for industrial and political stakeholders to act because of the long lifetimes of the installations involved. Against this background, the following core questions highlight key aspects that should be considered when switching to climate-neutral process heat and that are intended to provide orientation for policymakers. The policy brief draws on data for Germany and the figures related to economic aspects are very specific to this country's situation. On the other hand, the more technical aspects concerning technology maturity, R&D needs and energy efficiency potentials apply to other countries as well.

01

Which technologies are being used at present to supply process heat?

Currently, more than 400 TWh of energy are used to supply process heat; this is more than 70 percent of the annual energy demand in industry. Industrial energy supply is dominated by fossil energy sources; **natural gas** plays the most important role here with about 40 percent. **Electricity** has only a subordinate role with less than 5 percent, and no **hydrogen** is used. The **stock of industrial furnaces is very diverse** and installations are adapted to the respective production processes. These often require **temperatures of 1,000 °C and higher**, especially in the minerals and metal industries, as well as **very high energy densities**, which poses major challenges for electrification. The wide variety of different furnace types requires industry- and process-specific solutions for climate-neutral alternatives. There is a different situation in the food industry, the paper industry and parts of the chemical industry. Here, process heat is usually required in the form of **steam with a temperature below 200 °C or as hot water.** Process temperatures here are significantly lower and the production technologies are similar across industries – usually natural gas boilers or combined heat and power plants.

In the majority of cases, therefore, climate-neutral alternatives must compete with natural gas heating, the conventional standard technology used at present. The replacement of natural gas is made more difficult by the fact that most industries and companies have not yet had any hands-on experience with operating electric or hydrogen heating.

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How mature are CO_2-neutral technologies?

In general, converting the stock of installations is **technically feasible** by 2045. There are CO_2-neutral alternatives available or under development for all process heat applications, so that these could reach maturity in the next 5 to 10 years – assuming they undergo targeted development. The specific level of technology readiness varies and further development is urgently required for several applications.

When it comes to the **use of hydrogen**, many applications are still on a pilot and demonstration scale. However, no major technical obstacles have been identified for switching to hydrogen in conventional gas-heated furnaces. The **electrification of industrial furnaces**, on the other hand, is a more heterogeneous field. In the **metal industry**, electric furnaces in the form of induction furnaces and electric arc furnaces are available and are standard applications. In the **minerals industry**, electricity-based processes are not yet used, hardly available on a pilot and demonstration scale and face considerable technical challenges. There is a different situation when **supplying process steam**. Both hydrogen-based and electric **steam boilers** are already available for industrial applications. **Heat pumps** to produce process steam are commercially available in growing numbers, but still require further technical development for large-scale industrial applications, especially for higher temperature levels above 160 °C and higher steam pressures [3].

Rapid upscaling to industrial level is a **challenge** for the majority of applications. Practical experience with upscaling and the long-term operation of installations can dispel doubts and uncertainties regarding reliability and product quality and enable widespread market diffusion.
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03

What research and development is required?

There is a particular need for R&D to test new technology in set-ups that take account of the specific process characteristics in the respective industries. There are **three key directions for R&D**:

1. **Expanding the fields of application for electric heating technologies**. These include resistance heaters with heating elements, induction heating, plasma torches, direct electrical processes, electric arc heating and high-temperature heat pumps, each with different R&D issues.
2. **Testing and demonstrating hydrogen-based heating** for a wide portfolio of applications in different industries.
3. Reviewing the feasibility of and subsequently **testing emerging technologies such as flexible hybrid heating concepts**.

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Can CO_2 neutrality be achieved by retrofitting existing installations or is new construction necessary?

Generally speaking, **electrification** requires a more comprehensive retrofit of the stock of installations than the use of **hydrogen**. A transformation strategy should exploit synergies and be combined with the modernization of the stock of installations. The effort involved in converting processes to the respective CO_2-neutral alternative technology depends heavily on the specific application. Nevertheless, it is clear that, **in most cases, electrification requires new installations to be constructed**. Electrification therefore relies on windows of opportunity that result from the regular modernization of installations. In contrast, it will be **possible to retrofit** most of the installations that are currently heated using natural gas to **use hydrogen**. Exceptions are those plants that are currently heated with coal: Conversion to hydrogen here also requires extensive modifications or new constructions.
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What is the effect on energy efficiency?

Electrification has slight advantages over hydrogen heating and over the status quo in terms of an increase in energy efficiency at plant level. However, **there are considerable differences between the individual applications**. The expected efficiency gains due to electrification range from about 5 percent in the **ceramics and brick industry** to 40 percent in the **glass industry** – in each case measured against the status quo. Higher efficiency gains are possible when producing **hot water and steam** using **heat pumps**, which can amount to about 60 percent compared to natural gas-based steam generation. On average, however, the expected efficiency gains in industry due to the electrification of process heat production are lower than, e.g., in transport or buildings. No substantial efficiency gains can be made by switching from natural gas to (green) **hydrogen**. On the contrary, in this case, the focus is on the **upstream chain** of hydrogen production, which has additional efficiency losses of 30 percent compared to the direct use of electricity. The upstream chain must also be considered for **electrification**. If process heat does not make use of green power, the current electricity generation mix actually results in efficiency disadvantages compared to the use of natural gas.
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What environmental effects can be expected as a result of switching to climate-neutral processes?

Switching to climate-neutral technologies tends to be associated with an **improvement in the emissions of (local) air pollutants**, especially when the switch is to electrification. Correspondingly, additional microeconomic costs are offset by substantial reductions in environmental costs for society as a whole. These macrosocial benefits should be integrated into the transformation strategy and how it is communicated.

For **greenhouse gas emissions**, there is the risk that electrification will lead to higher overall emissions in the energy sector in the short term, as around 460 g CO_2 on average are currently emitted per kWh of electricity purchased in Germany. However, this value will drop rapidly in the future with the continued deployment and expansion of renewable energy sources. Electrification should therefore be prioritized in the short term where it is accompanied by high efficiency gains in the applications, and where coal with its associated high emissions can be replaced. The rapidly falling CO_2 emissions in the electricity sector due to the planned phase-out of coal means that from about 2030 any use of electrification will reduce emissions. At the same time, there is an urgent need to act now and the long lifetimes of industrial installations offer only a few windows of opportunity for investment. In any case, reinvesting in fossil-based systems technologies with long lifetimes must be avoided. Even early investments will achieve net savings over the entire lifetime of the installations. Hybrid systems and the targeted use of electricity from renewable sources are additional short-term options.
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How economical are climate-neutral technologies?

In almost all larger process heat applications, it can be shown that energy and CO_2 costs determine the total costs of heat production – accounting in some cases for shares of more than 80 percent. The **energy costs** are therefore decisive for the economic viability of investments, while the systems' **procurement costs** are relatively unimportant. However, **electrification does not make economic sense for the majority of applications** when assuming current electricity and natural gas prices and a prospective CO_2 price of 122 euro/t CO_2. Many applications will only be economically viable if the price for electricity and the price for natural gas plus the CO_2 price reach parity. At present, the electricity price is roughly twice that of natural gas including the CO_2 price.

This clearly indicates a **need to act**. Widespread market diffusion of CO_2-neutral process heat depends on the availability of climate-neutral **electricity and hydrogen at competitive prices**. Investment subsidies alone will only be sufficient where electrification is associated with substantial efficiency gains. Furthermore, **flexible hybrid systems** should be seen as **transformation enablers** and promoted as such. By supplementing existing natural-gas fired systems, they can be a gradual and low-risk gateway to transformation and can flexibly turn on electric heating during times of low electricity prices.
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Where are the biggest risks of fossil lock-ins? Are there any interim solutions?

The **lifetime of industrial installations** is relatively long compared to other sectors, about 30 years on average. This makes it clear that reinvesting in fossil fuels should be avoided for almost all applications, as the respective systems will probably still be in operation in 2045. The **risk of fossil lock-ins** is particularly high for installations that currently have no economically viable **electrification** option in addition to a long lifetime. This applies to the majority of applications.

Hydrogen could be a solution in the future for gas-fired installations, since it is possible to convert existing systems at low cost. This could avoid possible high costs for shutting down systems early. Drawbacks here include uncertainties regarding the future local availability and price of climate-neutral hydrogen.
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09

What dependencies are associated with the necessary energy infrastructure?

Energy infrastructure is a key issue for both electrification and hydrogen use, and is associated with **implementation obstacles**. Uncertainties about **site connections** can result in an inability to act and **high additional costs for expanding infrastructure** can have a prohibitive effect.

Electrification results in much higher electricity demand at the individual sites, which requires **modernization of on-site infrastructure** (transformers and switching stations as well as networks). In addition, there are substantial increases in the demands placed on the **supply cables to the sites**. Many sites will have to switch from a medium-voltage connection to a high-voltage one. According to the **core hydrogen network** plan of December 2023, many glass smelters, paper mills and ceramic, cement and limestone plants with potential demand for hydrogen are not located within range of the core network.

Policymakers should enable the best possible **planning**. Processes such as the grid development plans, the core hydrogen network or the system development strategy in Germany could contribute to this. In addition to making the costs of retrofitting process heat installations eligible for funding, the **costs of modernizing infrastructure** should also be eligible when investing in climate-neutral process heat installations.

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Can the required amounts of energy be supplied by renewables in the future?

Converting process heat to climate-neutral energy supply will mean high **demand for electricity and hydrogen**. This additional demand is too large to be offset by potential efficiency gains. A **scenario with a high degree of electrification** would require an additional 140 TWh of electricity and 100 TWh of hydrogen for climate-neutral process heat. An **alternative scenario focusing on hydrogen** and moderate electrification would need an additional 50 TWh of electricity and 200 TWh of hydrogen. **Energy system analyses** show that a future energy system is able to supply these quantities based on renewable energies and what role the different energy sources play. **Wind energy and photovoltaics** are the main sources. Their rapid and ambitious expansion is the necessary condition for a supply of climate-neutral process heat.

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How can the mix of instruments enable the transition and what needs to be done?

The current **mix** already encompasses a number of different **instruments** designed to transform the market by making fossil process heat more expensive and by subsidizing climate-neutral installations. However, investment subsidies and CO_2 prices that remain below 150 euro/t CO_2 in the long term will not be sufficient in most sectors to make climate-neutral process heat competitive. **Energy costs** or rather the price difference between the electricity (or hydrogen) price and the gas price is decisive for the economic viability of electrification. The **regulatory framework** should be designed so that competitiveness is reached as early as possible. At present, tax relief for natural gas purchases is making alternative energy sources less economically viable. At the same time, **uncertainty** about future prices for climate-neutral electricity and hydrogen as well as CO_2 certificates is making investments less attractive. The carbon contracts for difference (CfDs) are a new instrument that is able to close this gap. It is therefore important to implement it quickly and evaluate it in a structured manner.

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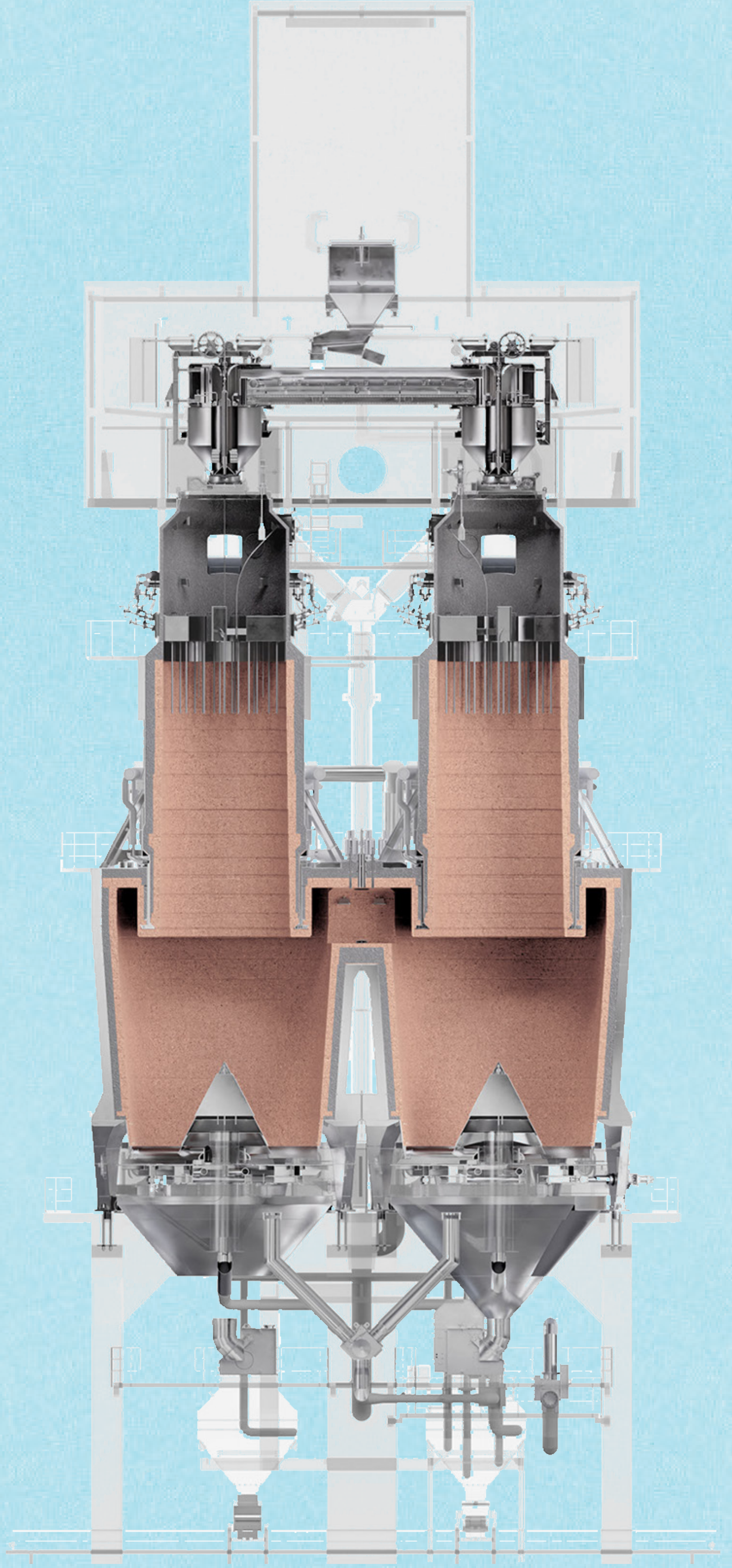
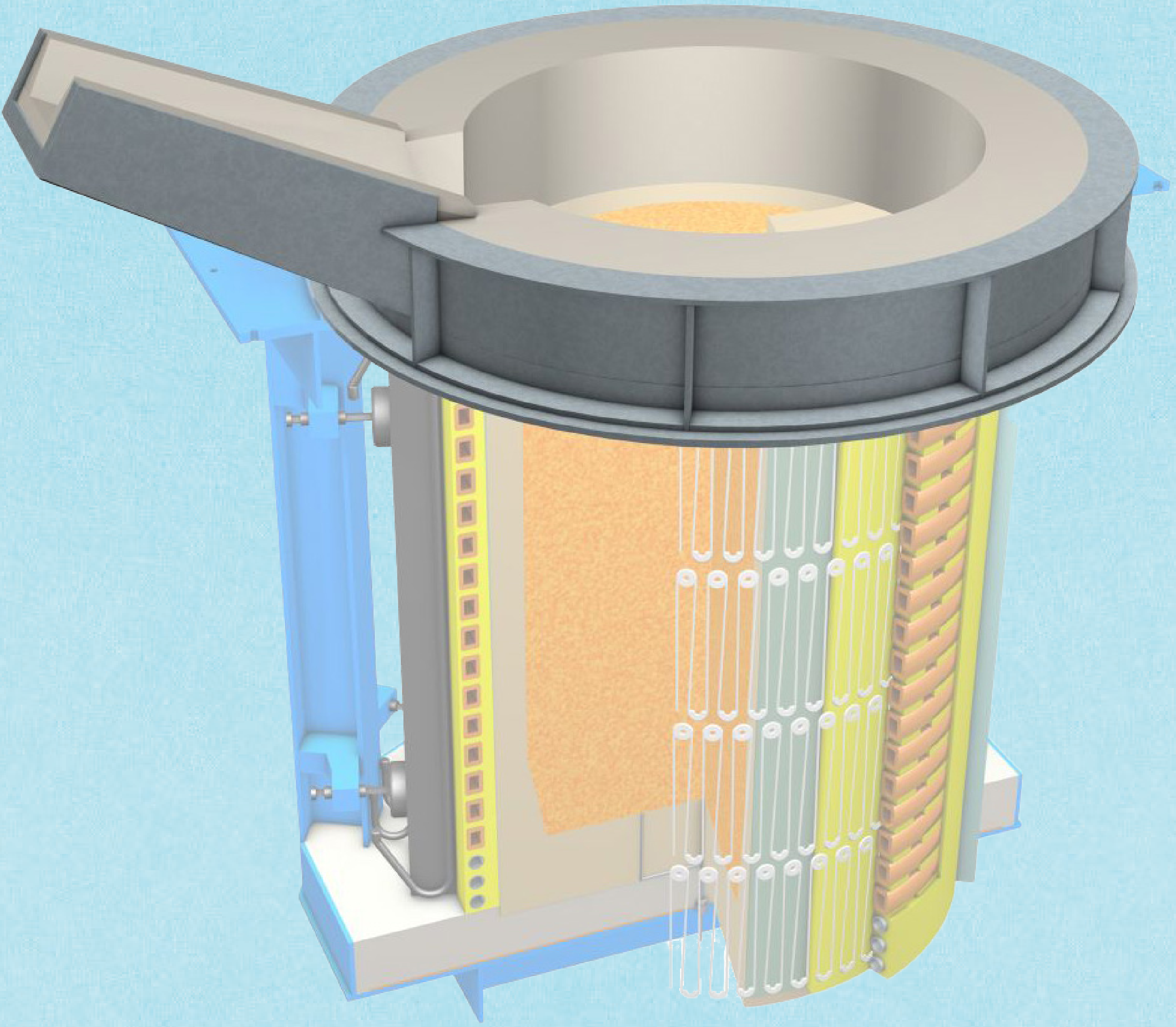


Parallel flow regenerative kiln
Picture credit: ©Maerz Ofenbau AG



Induction crucible-type coreless furnace
Picture credit: ©Induga

Detailed description

The following section takes a closer look at the key aspects that must be taken into account when switching to climate-neutral process heat and offers guidance for policymaking.

01

Which technologies are being used at present to supply process heat?

Process heat is an important production factor and its use is usually the process step that creates value in almost all basic industries. Substantial amounts of mainly **fossil energy sources** are used to provide this at present. In 2019, this amounted to about 440 TWh of energy, which is roughly equivalent to the entire electricity consumption of Germany and has hardly changed since. The number one energy source with approx. 40 percent is **natural gas** that is used in almost every industry (see Figure 1) due to its low cost and relatively simple handling. **Coal** or coke is in second place with about 25 percent of the energy consumed for process heat and is used wherever the process requires it and where there is no connection to natural gas infrastructure, for example in foundries and the steel industry. **Renewable energies** only accounted for about 8 percent in 2019 and are used in the form of biogenic waste to produce heat, for example in paper making. **District heat** also has a role in low-temperature applications with 8 percent. At present, **electricity** plays a minor role with less than 5 percent. So far, electricity is only used where it offers significant advantages in terms of efficiency or process management, for example smelting metals and scrap in induction or electric arc furnaces in the metal industry, in inductive heating in metal working or in a few isolated small glassworks. Otherwise, electricity is not used at present in Germany to supply process heat due to its significantly higher cost compared to natural gas. **Hydrogen** is also not used at present for process heat. This makes it clear that the two main energy sources in the future, renewable power and hydrogen, currently have no relevance for supplying process heat.

The technologies and energy sources used today largely determine the possibilities and costs of conversion to a CO_2-neutral energy supply. The technologies and plants used differ considerably between the individual applications and are often very process-specific. Figure 2 reveals the wide range of temperatures of different applications in the individual sectors, which directly influences the electrification possibilities. In principle, process heat can be divided into low-temperature and medium-temperature heat in the form of hot water and steam (below 100 °C to below 500 °C) on the one hand, and industrial furnaces with high-temperature heat from 500 °C to significantly above 1,500 °C on the other. **High-temperature heat** applications use many different kinds of specialized furnace types, which are characterized by the fact that heat production takes place directly within the production process. Even if there is no complete inventory of all the installations producing process heat in Germany, current studies show how wide the range is [2]. A large number of process heat applications have a comparatively low throughput of less than 5 tonnes of product per hour and their capacity is below 5 MW (see Figure 3). These include copper and aluminum processing, for example, or hardening technology. This segment covers several thousand individual installations. Large installations have a throughput of more than 50 tonnes per hour and a capacity of more than 50 MW. The number of installations is much smaller. For instance, there are about 50 clinker furnaces in the cement industry and around 80 heating and annealing furnaces in steel rolling mills. In glass production there are about 200 glass melting tanks that cover the entire range of size class. In addition to size and temperature, the furnaces also differ in how they are operated. There are continuously and discontinuously operated installations.

In the field of **steam and hot water**, heat is generated separately from the production process. This means that the corresponding heat generators are less specialized and differ only in a few parameters such as temperature, steam pressure and thermal capacity. Steam and hot water are mainly used in paper production, the food industry and the chemical industry. Combined heat and power plants (CHP) are used at large sites with high demand for electricity and steam, e.g., in the paper industry. Smaller sites use simple gas boilers. Electricity plays hardly any role for cost reasons, although the relevant technologies are market-ready.

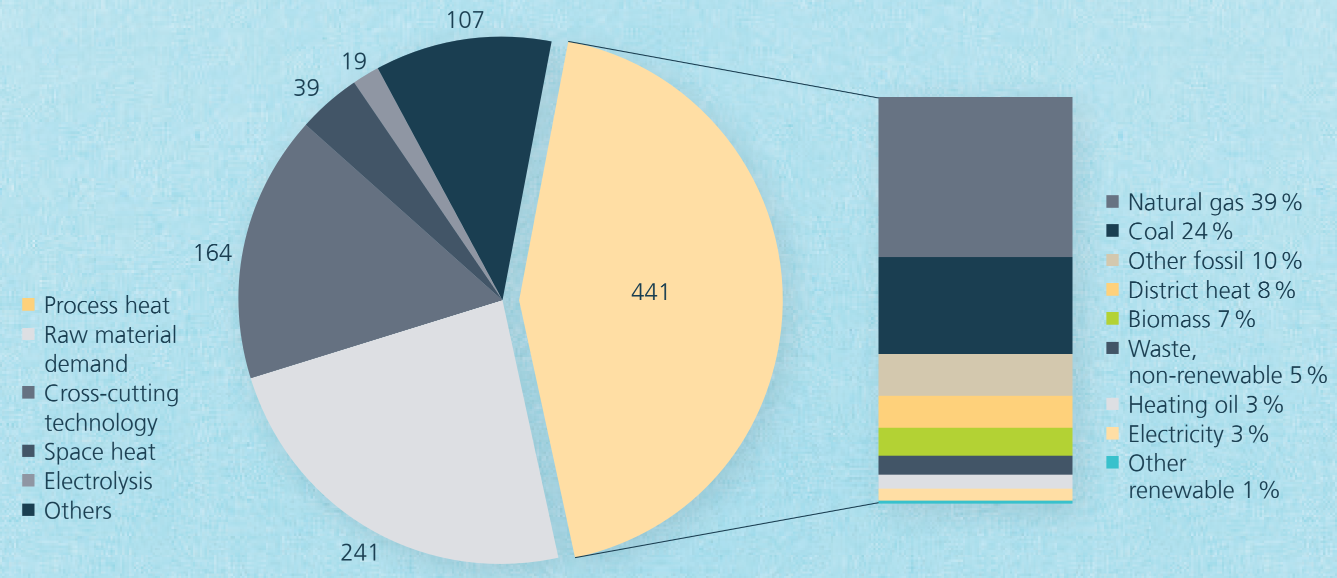


Figure 1: Energy demand of industry in 2019 in TWh (left) and energy sources for process heat (right)

Source: Fraunhofer ISI based on [4]

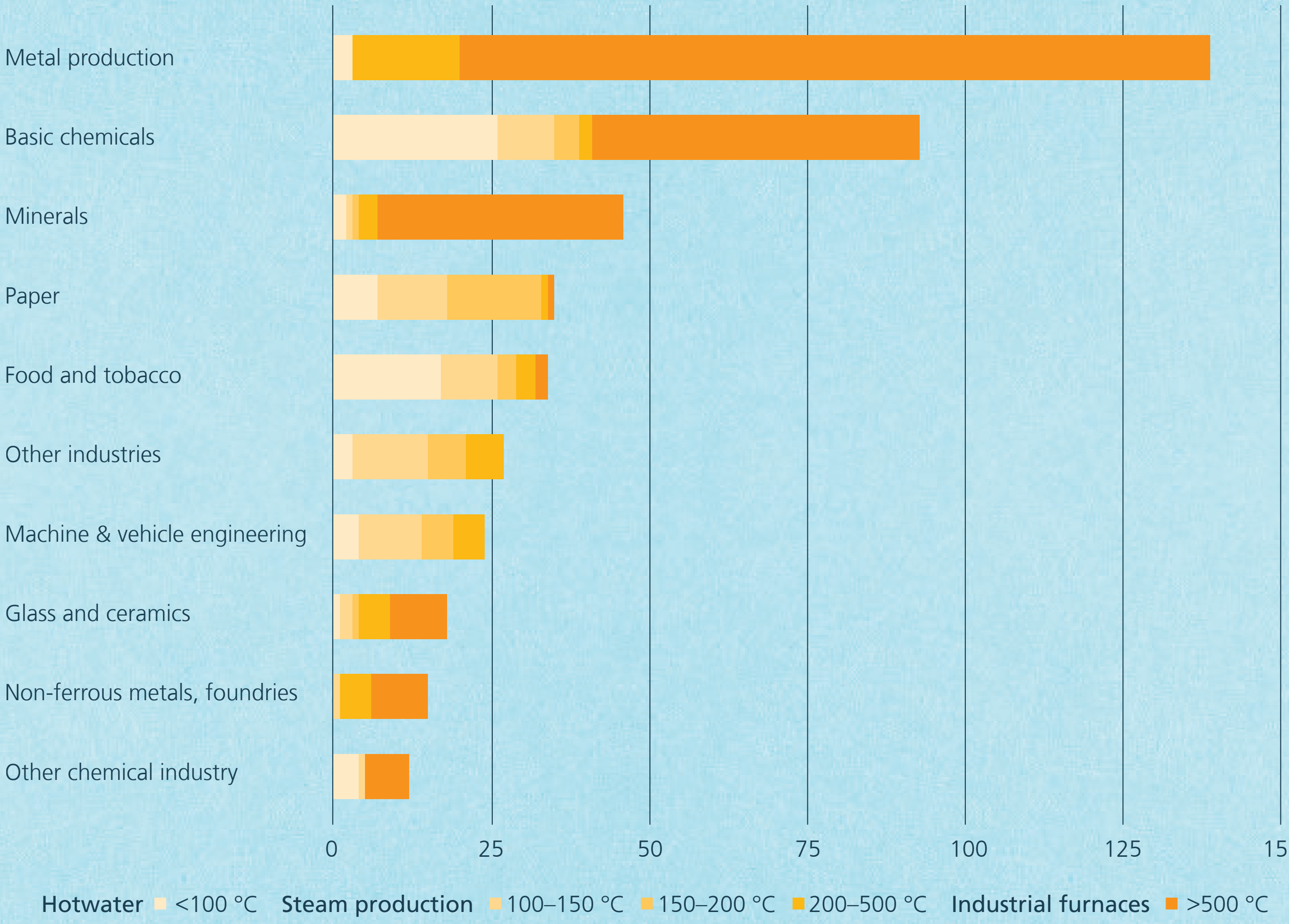


Figure 2: Final energy demand to produce process heat by temperature level and sector in 2019

Source: Fraunhofer ISI based on [4]

To be able to assess the potential and possibilities of hydrogen and electricity as the most important CO_2-neutral energy sources for process heat in the future, it is important to consider the **high degree of heterogeneity in the existing stock of installations**. This heterogeneity and the wide temperature range of process heat are essential in terms of physics and process engineering and will continue to exist even after switching energy source to renewable electricity or hydrogen. Developing an overall strategy for the industrial heat transition must take into account the sector-specific characteristics of production processes.

02

How mature are CO_2-neutral technologies?

Across all industries, hydrogen and electricity have the biggest technical potential to supply climate-neutral process heat. Other energy sources such as biomass and biogas, solar and deep geothermal energy as well as district heat can serve certain niche markets, but are not the focus of this policy brief due to their lower potential. Synthetically produced methane can completely substitute natural gas in applications. The main questions here concern the costs and potentials of supply.

A comparative assessment of **technology maturity** is possible using the so-called technology readiness level (TRL). These range from TRL1 “Basic observation and description of the functional principle” up to TRL 9 “Competitive use at industrial scale”. The technology leaves the laboratory from TRL 5 and pilot (TRL 5) and demonstration systems (TRL 6) are realized. Figure 4 provides an overview of the TRL for each application and industry.

The TRLs of **hydrogen use** are quite low with the technologies still at the level of pilots and demonstrations. However, no major technical obstacles have been identified for switching to hydrogen in conventional gas-heated **furnaces**. It can therefore be assumed that there could be a rapid rise in technology readiness level and that installations can be operated at industrial scale in the near future, when hydrogen is available in the required quantities. The corresponding research and development activities have been initiated over the past few years at national and especially at European level [5–7]. While burner technology is already advanced, there is a need for research at the process level in particular, e.g., on temperature distribution and product qualities. Since the processes in the metal and minerals industries have very different characteristics, a large number of different applications need testing. This results in a broad portfolio for research and development activities along industry-specific process chains. **Hydrogen-fueled steam generators**, on the other hand, are already commercially available for large-scale industrial use (TRL 9) and are already in use in industrial branches that have internal hydrogen flows, such as the chemical industry.

The **electrification of industrial furnaces** is heterogeneous with regard to the maturity and availability of technologies. In the **metal industry**, electric furnaces are available in the form of induction and electric arc furnaces and are standard use, e.g., for smelting, with the exception of primary steel production. In the **minerals industry** these technologies can only be used to a limited extent due to the different material properties of the raw materials used, so that completely different and mostly innovative electricity-based processes are necessary. As a result, the electrification of process heat in this industry still faces major technological challenges, for example due to the lower heat output of electrical resistance heating elements at high process temperatures compared to gas heating, or limitations with regard to the maximum operating temperature of the elements. The TRL of the technologies is therefore still low in the minerals industry, in particular (with the exception of smaller glass melting processes for special types of glass). Electric heating technologies need significant development here to enable their use at much higher outputs and application temperatures. This also includes the lifetime of electric heating technologies and other process engineering obstacles. To address these problems, activities are currently taking place in the glass industry, and new installations are being built in the field of hybrid glass melting tanks for container glass, which plan to use 80 percent electricity and 20 percent natural gas and then hydrogen later on [8].

There is a different situation for **electric steam generation**. The relevant boilers, so-called **electrode boilers**, are already commercially available at industrial scale (TRL 9). For example, two 20 MW electrode steam generators are used to produce steam (208 °C) in the 16 bar steam grid of Infraserv at the Höchst Industriepark in Frankfurt am Main. In the Chempark Leverkusen, a 7 MW electrode boiler with an additional superheater is used to provide steam with a temperature of 380 to 400 °C to the 32 bar steam grid [9]. As an electricity-based technology for steam generation, heat pumps are not yet very widespread, although they have considerable advantages in terms of efficiency. For electrification via so-called **high-temperature heat pumps**, the TRL is slightly lower depending on the required temperature of the steam and is in the range between 5 and 8 (some manufacturers also claim a TRL of 9) [3]. The term high-temperature heat pump or heat pump is used here as a synonym for electric compression heat pumps (closed systems) as these are the dominant technology in high-temperature applications. The types of such heat pumps available on the market offer good coverage of the temperature range up to about 160 °C, but with comparatively low steam capacities and mostly low heating capacities (< 1–5 MW) [3, 10]. There are a

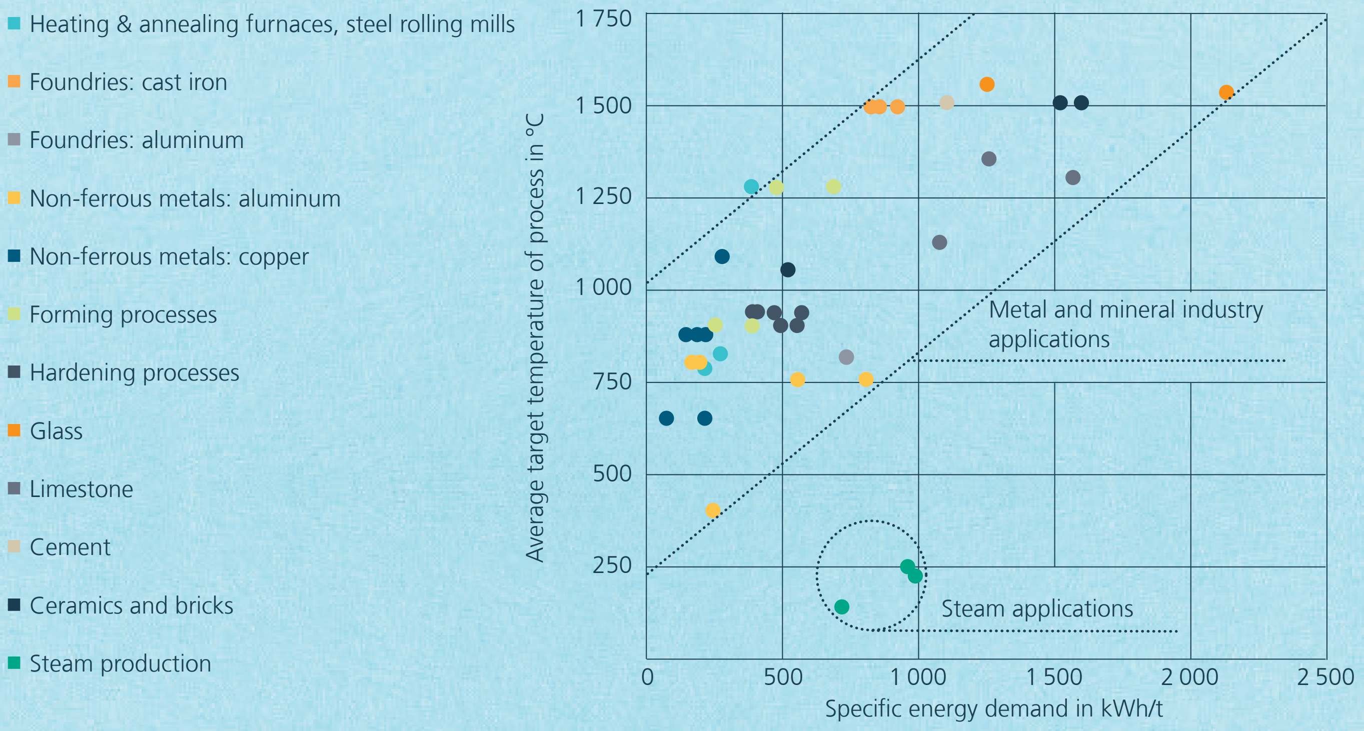


Figure 3: Classifying the applications and reference technologies in the stock of installations in Germany
Notes: based on characteristic parameters, application-specific data based on industry analyses; 37 applications in total (showing the respective reference technology and the electrical alternative if already present in the stock on a larger scale)
Source: own representation, RWTH Aachen based on [2]

Sector	Industry	Application (grouped)	Electrification	Hydrogen
Metals	Steel	Production of crude steel (primary)	<3	6
		Rolling mill: tempering flat steel	<4	<4
		Rolling mill: continuous heating flat/long steell	<3	<4
	Foundries	Melting aluminum	9	<5
		Melting cast iron (cupola furnace)*	<4/9	<4
	Hardening	Carburization and austenitization	9	<4
	Forming processes	Continuous heating forged parts	<5	<5
		Discontinuous heating forged parts	<3	<5
		Continuous heating steel plates	9	<5
	Aluminum	Melting/warming, homogenizing/heating	9	<4
	Copper	Melting, warming, tempering semi-finished products	9	<5
Minerals	Glass	Melting container glass**	<4/9	<4
		Melting flat glass	<3	<4
	Bricks, ceramics	Firing bricks	<4	<5
		Firing refractory bricks	<4	<5
	Cement	Burning cement clinker	<3	<4
	Lime	Burning in a shaft kiln	<2	<2
		Burning in a parallel flow regenerative kiln	<3	<4
		Burning in a rotary kiln	<3	<4
Steam	Chemicals	Chemical park steam supply***	9/5–6	9
	Paper	Paper drying***	9/7–8	9
	Food	Milk powder production***	9/7–8	9

Figure 4: Technology readiness level (TRL) of climate-neutral technologies
Figures are based on 100 % electricity or hydrogen supply, *TRL <4 for substituting large installations, TRL 9 for small ones such as crucible furnaces, **TRL <4 for large installations, TRL 9 for small ones, ***TRL 7-8 for high-temperature heat pumps and TRL 9 for electrode boilers
Quelle: own representation based on [2]

few individual solutions for temperatures up to 250 °C and for applications in the range above 10 MW [3]. More demonstration projects are expected in the next few years, and commercialization is estimated to be reached between 2024 and 2025 for temperatures of up to 120 °C, between 2025 and 2026 for temperatures up to 160 °C and by 2026 to 2027 for temperatures above 160 °C [11].

Other research and pilot projects are taking place at national and international level to scale up the technology. For example, a 200 kW pilot system with a COP of up to 3.6 has been integrated into a paper factory in the Netherlands, which provides steam at 120 °C [12, 13]. In another demonstration project, two 400 kW high-temperature heat pumps with a COP of up to 4.7 are being tested for supplying process heat up to 160 °C for industrial drying in the food industry [14]. According to manufacturers and research institutes, it is technically possible to scale up the technology to higher steam capacities, similar to the large heat pumps used for district heating or compressors in power plant turbines [15].

It should be noted that so-called open-loop systems (MVR and TVR) are usually limited to steam as the heat source and, in comparison to the closed systems considered here, cannot be used flexibly with other heat sources such as exhaust air or wastewater. Open-loop systems, some of them ready for commercial deployment (TRL 9), can reach temperatures of up to 350 °C. Combined approaches are also available on the market [3].

In general, it is **technically feasible** to convert the stock of installations by 2045 [2]. CO_2-neutral alternatives are either already available or are being developed for all fields of application. The respective level of technology readiness varies and further development is urgently required for several applications. Rapid **upscaling to the industrial level** is a challenge for the majority of applications. Practical experience with upscaling and the long-term operation of installations can dispel doubts and uncertainties regarding reliability and product quality and enable widespread market diffusion.

03

What research and development is required?

The heterogeneity of process heat applications calls for the use of different heating technologies and results in specific research and development requirements for the different technologies. These are summarized below.

The need for research and development in the field of **electrical resistance heating elements** concerns their limited power density, maximum application temperature and the lifetime of the heating element [16–18]. This includes new furnace concepts but also testing new heating element materials.

In the field of **induction heating**, research and development is needed on modifying the design of heating equipment for new applications. The key technical data and coil geometry of the installations must be adapted to the respective good (workpiece, melt). When heating rectangular workpieces, for example, it is difficult to achieve uniform heat distribution [19].

The use of plasma produced with electricity, i.e., ionized and electrically conductive gas in so-called **plasma torches**, allows a high power density and has the potential to reduce exhaust gas flows [20, 21]. However, these have not yet been tested for applications in the metal and minerals industries. The current drawbacks of this technology include frequent maintenance, complex cooling of the thermally charged components, which affects the overall efficiency of the system, and the short lifetime of the electrodes [21, 22]. There are theoretical approaches to using plasma torches to heat steel or sinter cement clinker as well. So far, however, these are limited to feasibility studies. According to [23], commercial use in the field of high-temperature heating should not be expected before 2035 [23–25].

In addition, research and development must be accelerated in the field of **direct electrical resistance heating**, which is rarely used. This process is used, e.g., when melting glass or for the molten salt electrolysis of aluminum, but also in the iron, steel and non-ferrous metal industries to heat billets, rods, tubes, sheets, strips and wires [16]. The process is characterized by high energy efficiency in many cases but is currently limited to applications with lower production volumes.

Electric arc heating can achieve high temperatures and high power densities [16]. Electric arc heating is very important in secondary steel production for melting scrap. Research and development should be launched into other applications that require high energy densities and temperatures that cannot be achieved using other electrical alternatives.

In the field of **high-temperature electric heat pumps** used to generate steam, there is a particular need to develop new synthetic refrigerants that have high critical temperatures, low greenhouse gas potential and no potential for ozone depletion as well as to research the use of natural refrigerants [10]. Further development of new compressors is necessary to increase both the output and the achievable temperatures in the short to medium term [26]. On the other hand, research is also being done on optimizing heat pump systems and improved system integration including heat exchangers, compressors and new control systems for greater flexibility.

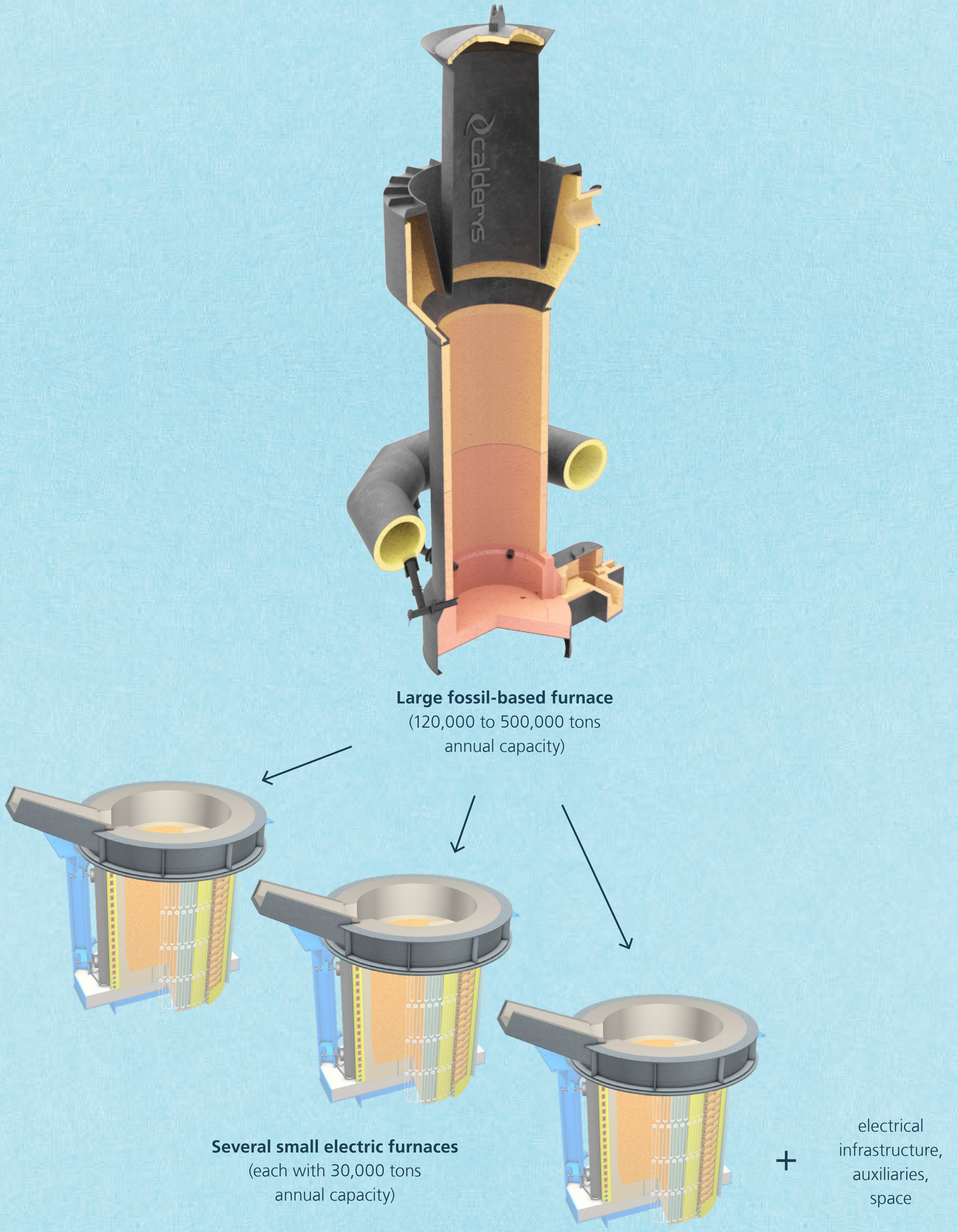


Figure 5: Schematic diagram of the electrification of fossil-fuel heated installations
Source: [43, 44], Picture credit: ©calderys, Induga

There is also research and development needed in the field of **hydrogen combustion** and for blends of hydrogen with natural gas. There are particular challenges concerning product quality and pollutant formation, especially of NO_x, due to high local combustion temperatures [27–29]. In addition, switching heating technology from natural gas to hydrogen also affects the flow and transmission of heat in the thermal process installation. For example, flames spread in a hydrogen-air mixture at roughly seven times the speed as when natural gas is burned. The much higher flame speed means that fundamental design modifications are needed in burner and installation equipment. Hydrogen's significantly higher upper flammable limit must also be taken into account [30–32].

In **hydrogen steam boilers**, pure hydrogen combustion is already technically feasible (e.g., in the chemical industry where hydrogen is already available as a by-product). Hybrid systems in combination with natural gas require additional control mechanisms: There are technical challenges concerning the corresponding premixing systems to supply standardized blends due to the high flame speeds and possible flashbacks.

With a focus on processes heated using fuel gas, **oxyfuel technology**, i.e., combustion with pure oxygen instead of air, is one way to improve the efficiency of these installations. The use of oxyfuel technology can, e.g., increase the energy efficiency of cupola furnaces by approximately 10 percent and reduce the amount of coke used by about 17 percent [33, 34]. Oxyfuel technology is currently used in individual cases for the production of specialized glass and fiberglass [35, 36]. Oxyfuel technology therefore has high potential to increase efficiency and decarbonization when burning hydrogen. However, the considerable reduction in the flow of exhaust gas due to the lack of atmospheric nitrogen and the fact that this consists entirely of steam means that the process parameters and heat recovery systems have to be adapted and tested.

Flexible installation technology has the potential to respond to fluctuating energy sources. This requires the examination and quantification of technical aspects. For example, the temperature and time requirements of the installations' start-up and shutdown processes and switching processes must be determined. In addition, the compatibility of different heating technologies should be analyzed, such as how long electric heating elements last in burner exhaust gas. **Hybrid systems** that combine multiple energy sources might be a solution for this, as in aluminum extrusion [37] or hybrid radiant tubes [38]. In future, these redundant systems could be used primarily to make use of fluctuating energy from renewable sources. However, these systems still require further testing in this regard. Furthermore, economic incentives for the system operators are lacking, so their participation on the balancing power and spot markets is correspondingly low [39].

Alongside new technologies, **energy efficiency** plays a major role in research and development. Thermal process engineering attempts to minimize the **production of waste heat** as a fundamental principle. In many applications, therefore, the heat from exhaust gases is used to preheat the burner air or, in some cases, to preheat the material, which significantly reduces the heat from the exhaust gases exiting the thermal processing installations [40, 41]. Heat losses through the furnace walls are also minimized using suitable furnace insulation. Waste heat leaving the system boundary of the thermal process installation is frequently used in other process steps within the process chain of a facility or to produce hot water or space heating in the facility. There is a need for research due to the fundamental differences in the combustion behavior of hydrogen compared to natural gas. This mainly concerns testing the processes and the combustion of 100 percent hydrogen and fixed or flexible blends with natural gas.

04

Can CO_2 neutrality be achieved by retrofitting existing installations or is new construction necessary?

The effort required to **convert the installations** differs greatly according to the individual technologies and applications. For most applications, more extensive conversion is necessary for the electrification of sites than for switching to hydrogen.

The majority of installations in the metals and minerals industry and in steam generation are currently heated with natural gas. Switching from natural gas to hydrogen involves considerable technical retrofit, in particular related to the components of the heating equipment (e.g., burner technology, flue gas system, heat recovery) but also the infrastructure (e.g., gas supply). Although switching from natural gas to hydrogen is in most cases simpler than switching to electricity.

Converting installations currently heated by natural gas to **electricity-based heating technologies** usually requires new construction. This affects the infrastructure required inside and outside the production site (grid connection, transformers), as well as different furnace geometries and sizes and even the replacement of a large installation with several smaller ones (see Figure 5). Many components can normally be reused when converting to electric steam generation using electrode boilers.

Converting an installation currently heated with natural gas to **hydrogen** requires less reconstruction than electrification, but even in these cases, modifications of the key components of the production facilities and the associated infrastructure are

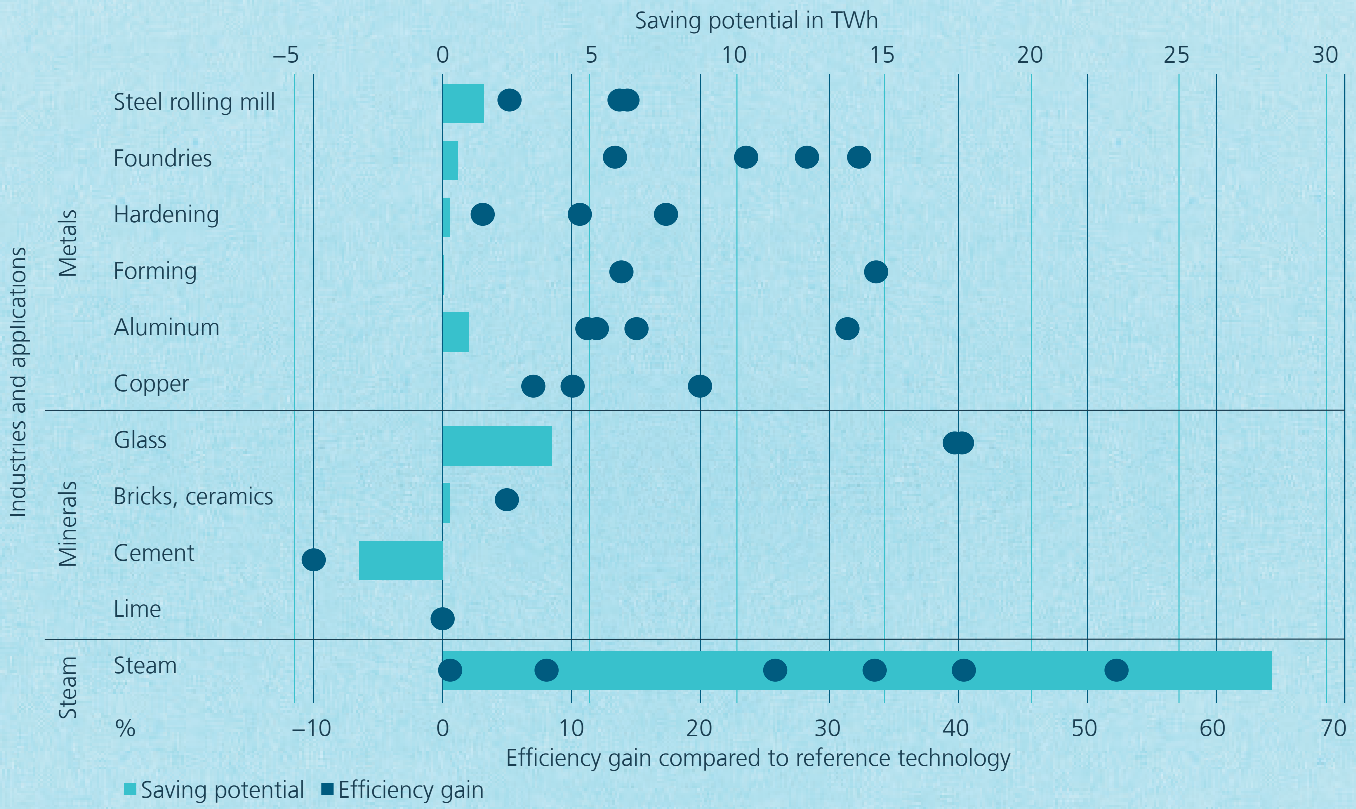


Figure 6: Energy efficiency advantages of electrification compared to the reference technology and saving potential if fully implemented

Source: own representation based on [2]

High-temperature heat pumps

The use of heat pumps as an electricity-based technology for steam generation is still not widespread in industry. If waste heat can be used at some locations, high-temperature heat pumps that use the **waste heat as a heat source** have clear **efficiency advantages** over electrode boilers. This technology has great potential in the food and paper industries, where process heat requirements are mostly below 200 °C, and for low-pressure steam generation in chemical parks [10].

At present, most of the systems already available on the market for supplying heat at temperatures of up to 160 °C or even 250 °C only cover the low range of thermal capacity (below 1 MW). Since only a few systems above 10 MW are ready for the market, the development of systems in the one to three-digit MW range constitutes an important step. Such **large heat pumps are still in their infancy in Germany**. In contrast to the district heating sector, the transparency of data in the industrial sector is still limited [45]. Examples of projects include a planned large-scale heat pump system in the chemical industry with 120 MW for steam generation or a large-scale heat pump with a thermal output of 3.2 MW and a flow temperature of 35 °C for decarbonizing a drying process in the food industry, which has been in operation since 2010 [46, 47].

necessary. In particular, an adaptation of the burner technology or a burner replacement can be expected, but not the completely new construction of gas-fired installations. Although the combustion parameters of hydrogen and natural gas differ, it can be assumed that processes conventionally heated with natural gas will have to be converted to hydrogen in the future by adapting the installation components (e.g., burner, flue gas system). Exhaust gas emissions (e.g., NO_x) can be regulated by adjusting the combustion technology, which is currently the subject of R&D projects. In the case of steam generation using hydrogen boilers, the main changes apart from the burner are the slightly increased costs for exhaust gas treatment (for NO_x, additional emission-reducing measures, so-called exhaust gas recirculation are required).

Applications in which solid fossil fuels such as coke, coal or residual materials are currently used require extensive technical modifications when switching either to power-to-heat (PtH) or power-to-gas (PtG) fuels, and correspondingly extensive research and development is also required. Important applications include cupola furnaces in the foundry industry, shaft furnaces in the lime industry and rotary kilns in the cement industry. Biogenic energy sources could be an alternative from a technical point of view here.

Generally speaking, electrification requires more comprehensive re-construction of the stock of installations than the use of hydrogen. A transformation strategy should exploit synergies with the modernization of the industrial capital stock.

05

What is the effect on energy efficiency?

On average, **electrification** shows marginal advantages in efficiency compared to current process heat technologies. However, there are considerable differences between the individual applications. Figure 7 shows efficiency gains of up to 40 percent in glass production where small melting furnaces are used in the container glass industry, whereas they are relatively low, at 5 percent, for ceramics and brick production. For the cement industry, it can even be assumed that full electrification will lead to increased consumption. In the metal industry, savings of over 30 percent can be achieved for special applications in which inductive heating is possible. The wide range of potential efficiency gains is due to the different technologies. For example, direct electrical heating can be used in small glass melting tanks, in which electrical energy is converted directly into heat in the melt, resulting in only minimal losses. A similar principle is used for induction heating. In this case, however, the induction coil usually also has to be water-cooled, which results in losses in the form of low-temperature waste heat. With all electrical heating concepts, transformation losses in the provision of electrical energy must be taken into account, such as losses due to wiring and capacitors, which reduce the overall efficiency of the system.

When using **heat pumps** to generate hot water and steam particularly high efficiency gains are possible, although this depends on the required temperature levels and cannot be implemented in all applications. Electrically heated steam boilers (electrode boilers) are slightly more efficient than gas-fired boilers.

Overall, electrification of process heating will be accompanied by efficiency gains, although these will be lower on average than in the transport or building sector. Furthermore, the waste heat-conducting substances change when switching from a fuel-fired to an alternative electric technology. For example, when switching from fuel to electric induction furnaces, more waste heat is generated at lower temperatures in liquid cooling substances than at very high temperatures in exhaust gas.

Converting from heating with natural gas to **hydrogen** offers only slight energy efficiency gains if any at all. This is mainly due to the similar system technology, such as burners or heat recovery. No significant changes in the waste heat flows can be expected, particularly when natural gas or hydrogen is combusted with air, so that without further process modifications or specific heat recovery systems, no significant increases in efficiency will occur.

Overall, when assessing the energy efficiency of future technologies, there are still areas with high levels of uncertainty, as most installations are not yet in industrial use. In the case of electrification in particular, mass and energy balances change fundamentally.

While this observation relates purely to the application side, i.e., the generation of process heat, the two energy sources also differ in terms of **efficiency on the supply side**. This depends heavily on the future energy system. In the case of green hydrogen, there are energy losses of around 30 percent in the production of the hydrogen. These are not included in Figure 6 due to the limits of the system selected and they more than compensate for any slight efficiency gains on the application side. However, the direct use of electricity in a future CO_2-neutral system may also result in corresponding conversion losses if hydrogen power plants are used at times of low PV and wind feed-in. Hydrogen also offers systemic advantages, such as lower costs for seasonal storage and large-scale transportation over long distances. In terms of the system, the comparison of hydrogen use with direct electrification requires a complex assessment framework that takes into account the additional energy losses during electrolysis, cost aspects and possible process and procedural advantages.

06

What environmental effects can be expected as a result of switching to climate-neutral processes?

The majority of the **environmental effects** caused by process heating systems result from the high amounts of energy required to operate the installations during their use and less from the environmental impact of the production and construction of the installation technology itself. The switch to electrified or hydrogen-based process heat installations is not likely to be accompanied by a significant impact on metallic, mineral or biotic resources when compared to conventional installation technology [2]. On the contrary, the environmental impacts associated with energy use are of particular importance. All the environmental effects along the entire energy supply chain must be taken into account, from extraction, conversion and transportation through to local use of the energy sources in the processing plants.

Electrification of the processes initially leads to the elimination of emissions caused by the thermal use of on-site energy sources. These include **CO_2 emissions as well as other air pollutants such as nitrogen oxides, sulfur oxides and particulate matter**. The environmental impacts shift to the electricity sector, which is why emissions from electricity generation and its upstream chains must be taken into account for a complete assessment.

The following basic analysis, without taking upstream chains into account, illustrates the problem: In 2022, the average **CO_2** emissions of the electricity mix were around 0.46 kg per kWh of purchased electricity [48]. CO_2 emissions from the direct use of natural gas for process heat are around 0.18 to 0.2 kg CO_2 per kWh of natural gas and around 0.33 to 0.39 for hard coal [49]. Due to the expected rapid increase of renewable energies in the electricity mix and the phasing out of coal-fired power generation, it can be assumed that the CO_2 intensity of the electricity mix will already be below 0.2 kg CO_2 per kWh of electricity in 2030 [50]. This simple comparison shows that electrification may lead to additional emissions in the short term. The decisive factors are energy efficiency gains on the application side and the emission factor of the reference technology. Switching from coal/coke to electricity already results in net CO_2 savings today, as will switching from natural gas from around 2030. Switching to a green electricity supply leads to high emission savings in every case.

In the **short term**, electrification should be prioritized especially where emission-intensive coal/coke is replaced or where electrified processes enable high efficiency gains compared to the use of natural gas (see Figure 6). The latter would be the case, for example, with the use of high-temperature heat pumps (see Question 05) or hybrid glass melting [8]. The use of **flexible partial electrification** would also be a sensible short-term strategy, for example to supplement gas-fired installations. This enables the flexible use of electricity at times when prices are relatively low due to high feed-in from wind and PV installations. At these times, the emission factor is also significantly lower than the annual average. However, this would require either redundant installations or hybrid process heat technologies, which are currently still in the development stage for many high-temperature applications.

Simultaneously, time is of the essence when it comes to converting installations and the long service lives of industrial installations offer very few opportunities for investment (see Question 08). Accordingly, each investment must be weighed up on a case-by-case basis. If re-investment in fossil-fired installations is planned in the short term, electrification still makes sense despite higher emissions in the short term, as emissions will be reduced over the service life as a whole. **Re-investment in heating technology based on fossil fuels should be avoided**.

When using **hydrogen**, in the medium term any increase in nitrogen oxide emissions on site due to higher combustion temperatures is regarded as manageable on the process side [2]. However, how hydrogen is produced, such as steam reforming or electrolysis using conventional or renewable electricity, also plays a decisive role. Accordingly, the environmental impacts associated with the respective hydrogen generation and supply variant must be taken into account.

07

How economical are climate-neutral technologies?

The economic efficiency of climate-neutral process heat compared to the fossil-fueled reference technology – usually a natural gas-fired installation – is decisive for its diffusion on the market. The following statements are based on a methodology that uses the **levelized costs of heat production** as an indicator of economic profitability. The cost of heat generation therefore represents the total of all costs incurred per product unit for the generation of process heat. This includes costs for energy and CO_2, maintenance and operation as well as for investments calculated over the entire service life. Almost all of the applications examined show that **energy and CO_2 costs determine 80 percent or more of the total heat generation costs** [2]. The reasons for this are, on the one hand, the long service life and the mode of operation, which corresponds to continuous or multi-shift operations in many installations and thus leads to very high full-load hours. On the other hand, the comparatively low specific investments come into play, as large installations benefit from economies of scale. As a result, energy costs are decisive when it comes to profitability.

Generally speaking, business models that benefit from switching to CO_2-neutral process heat are therefore largely based on a combination of high CO_2 prices and low prices for climate-neutral energy sources, primarily green electricity and hydrogen. In order to make this more specific, a **reference case** is calculated that reflects today's energy prices, with the addition of an increased CO_2 price that represents the expectation for 2030 and is significantly higher than the average of recent years. The reference case assumes electricity prices (in EUR) of 13 to 19 ct/kWh, hydrogen prices of 18 to 27 ct/kWh, natural gas prices of 6 to 8.5 ct/kWh and a CO_2 price of 122 euro/t CO_2. The resulting additional costs of CO_2-neutral process heat are high for most applications compared to the reference technology heated by natural gas (Figure 7). Based on these assumptions, the operation of electrified or hydrogen-fired plants is associated with permanent economic operational losses and is therefore not viable. The exceptions are those applications where electrification is associated with high efficiency gains. Based on the assumptions made, the economic efficiency of hydrogen is worse than that of electrification.

Even if some of the investments that companies can currently access were subsidized, this would not fundamentally change the picture, as for most applications the importance of investment costs is significantly lower than that of energy costs.

Figure 7 also shows the economic viability for a hypothetical **case of transformation** in which adjusted assumptions make climate-neutral technologies competitive compared to the fossil reference technology in most applications. The result is based on significantly lower prices for electricity (6 to 9 ct/kWh) and hydrogen (10 ct/kWh), as well as slightly higher prices for natural gas (6.5 to 9 ct/kWh) and CO_2 (150 euro/t CO_2). The electricity price is similar to today's stock market prices in Germany. The price of natural gas was adjusted upwards compared to the reference price to reflect the existing energy tax relief in Germany.

Although the methodology used takes into account the price ranges (Eurostat price bands) resulting from different quantities of electricity and natural gas used, it cannot adequately reflect the heterogeneity of the applications.

For most companies, a complete switch to electricity or hydrogen is currently very risky or not economically viable. Nevertheless, options are available, such as **partial electrification or flexible hybrid systems**. By using hybrid systems, for example through the addition of electric steam generation to existing gas-fired CHP plants, it is possible to benefit from the use of electricity when its stock market price is lower. Furthermore, hybrid electricity-gas systems offer additional advantages. The step-by-step transition mitigates risk, a later conversion of the gas supply to hydrogen can be carried out more easily and the use of several energy sources helps to cushion market risks. However, the current regulatory framework in Germany hinders or prevents the use of such flexible hybrid systems, as the grid fees are prohibitively high for systems that only operate at a low number of annual full load hours. Current incentive structures are designed to favor inflexible operation with a high number of full load hours [51].

Other possibilities for practical implementation exist wherever electrification is associated with very high efficiency gains. This is the case with the use of **heat pumps in steam generation**, but also with **electric glass tanks**. Based on the assumed energy and CO_2 prices, these technologies are already competitive compared to the gas-fired reference technology.

There is a clear **need for political action**. Widespread market diffusion of CO_2-neutral process heat depends on the availability of climate-neutral electricity and hydrogen at competitive prices. Only a few applications will benefit from investment funding alone.

08

Where are the biggest risks of fossil lock-ins? Are there any interim solutions?

Lock-ins in fossil fuel installations are investments that consolidate a fossil fuel system. For the purposes of the following analysis, this refers to installations that will not reach the end of their service life until after 2045, the year when Germany aims to achieve climate neutrality. These investments increase the costs of converting to climate-neutral installations, as they would have to be replaced prematurely. The risk of fossil lock-ins is therefore directly dependent on the service life of the plant and the economic viability of climate-friendly alternatives.

The average **service life** of industrial installations is around 30 years [2], which is significantly longer than the remaining 20 years until 2045 when climate neutrality is supposed to be achieved in Germany. In the very heterogeneous portfolio of installations, the individual service life can vary greatly, some can be as short as 15 to 20 years and some can be significantly longer at around 50 years [2]. This makes it clear that reinvestment in fossil fuels should be avoided for almost all applications.

Therefore, the **regulatory framework** must make it possible to invest in climate-neutral installations in good time. A particularly high risk of fossil lock-ins exists in applications with a long service life and poor economic efficiency. This risk is further

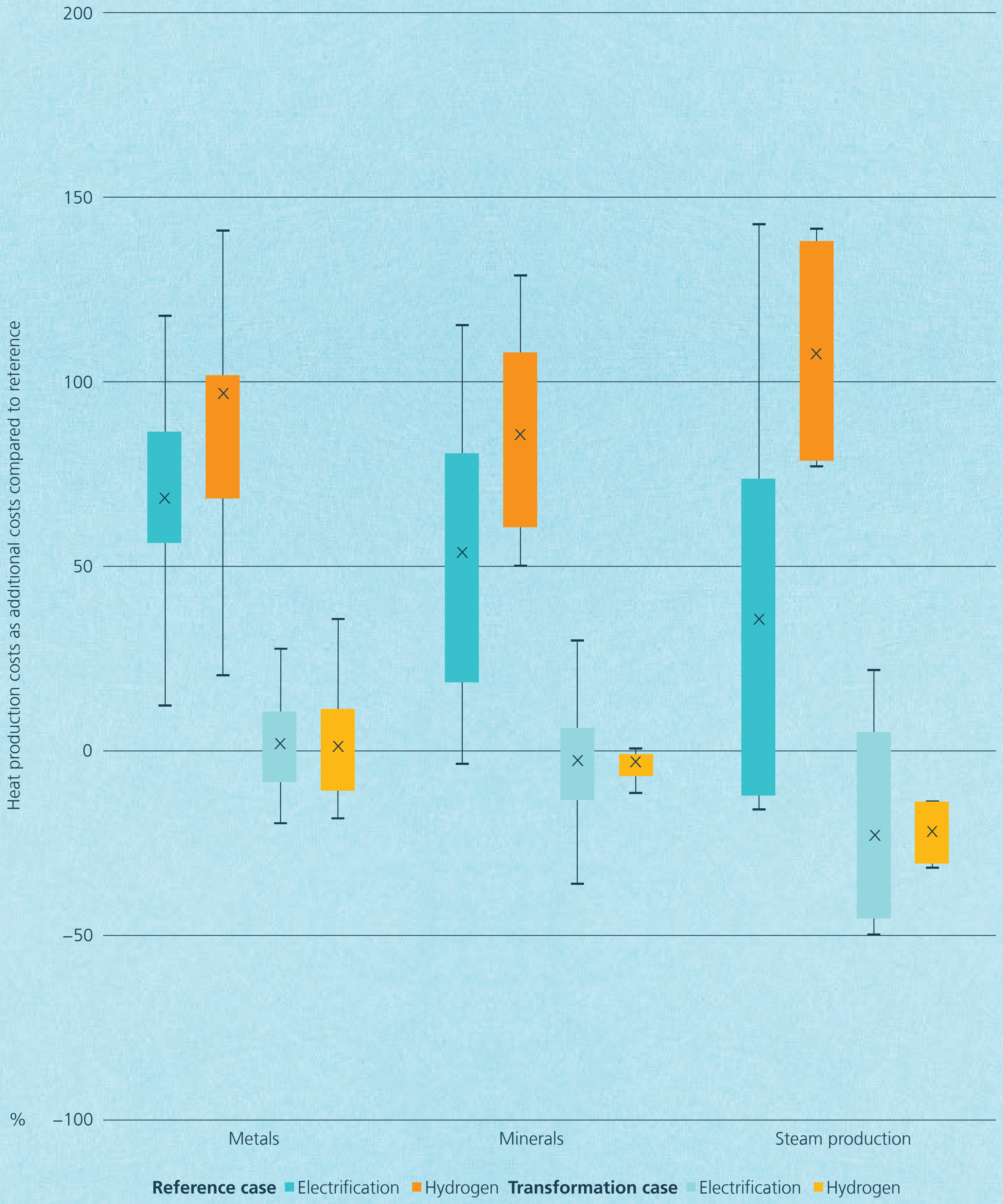


Figure 7: Range of heat production costs for electrification or hydrogen use as changes compared to the reference technology
Reference case assumptions: Electricity 13–19 ct/kWh; hydrogen 18–27 ct/kWh; natural gas 6–8.5 ct/kWh; CO_2 122 €/t CO_2
Transformation case assumptions: Electricity 6–9 ct/kWh, hydrogen: 10 ct/kWh; natural gas 6.5–9 ct/kWh; CO_2 150 €/t CO_2
Source: own representation based on [2]

increased if technologies are not yet fully developed and further research and development is required before they can be used at industrial scale.

The **combination of cost-effectiveness and service life** is shown in Figure 8 for a sample of important applications. This means that only a few applications have the necessary prerequisites to become climate-neutral through electrification by 2045 under the current framework. The corresponding technologies shown in the second quadrant are already economical compared to the fossil reference technology and, with a service life of around 20 years, the entire stock can still be replaced by 2045 without early decommissioning. These include heat pumps and electric glass melters, as they can achieve significant savings through greater efficiency.

The majority of applications, however, is still associated with significantly higher **costs** than the fossil reference technology. If their average service life is less than 20 years (quadrant III), then fossil lock-ins can be prevented by rapidly reforming the economic framework to make climate-neutral alternatives competitive. This is not the case for most applications. The average service life is well over 20 years and the climate-neutral technology is not economically competitive (quadrant IV). Even if the economic conditions improve in favor of climate-neutral technologies, a complete conversion of the existing installations by 2045 would only be possible if existing installations were replaced before the end of their regular service life. This means that investments in fossil-fueled installations in recent decades have already led to lock-ins and additional costs in the long term.

Market diffusion can be accelerated and premature replacement of existing installations avoided in cases where a conversion to climate-neutral technologies can also be achieved through less fundamental retrofitting. This would be technically possible for most applications when switching from natural gas to **hydrogen**. The drawbacks here, however, include the economic uncertainties regarding future local availability and the price of climate-neutral hydrogen.

In applications where electrification is still associated with major technical challenges anyway and coal/coke is currently still being used, the switch to gas-fired processes can be regarded as a **transitional solution**, provided these can be operated with green hydrogen in the future. This enables investments in potentially climate-neutral installations and leads to high CO_2 savings in the short term. The most prominent example of this is switching from crude steel production in blast furnaces to the direct reduction of iron ore.

For most applications though, additional economic incentives are needed to replace fossil fuel installations by climate-neutral alternatives. However, these will not be sufficient as long as there is no incentive to replace existing systems with a long service life more quickly.

09

What dependencies are associated with the necessary energy infrastructure?

Both electrification and the switch to hydrogen present multiple challenges for the energy infrastructure at the respective site and beyond. These can account for a considerable proportion of the necessary investments or delay the transition.

The **electrification** of process heat will lead to a significant increase in the demand for electricity and the required **connected load** at individual sites, which the current electricity infrastructure is not designed for. Comprehensive modernization of the **electrical infrastructure**, such as transformer and switchgear systems and lines, is therefore absolutely essential. The costs associated with the energy infrastructure have to be calculated individually for each site and have not yet been specifically investigated.

Insufficient **power lines** to a site can also make electrification more complicated. A reliable assessment of how relevant this is for the majority of sites is not possible due to a lack of data. However, a study on the transformation of the glass industry provides a more detailed illustration of the problem [10]. According to this study, the sites of the glass industry are mostly connected to the electricity grid via medium-voltage lines. Capacities range from 3 to 15 MW, which require a voltage of 10 to 20 kV. In most cases, connection to the high-voltage grid will be required for an (almost) fully electrified glass melting tank [10]. Although Germany has a dense high-voltage grid, this can be a serious obstacle to the electrification of individual sites. If the connection point provided by the grid operator is located further away, industrial companies have to reinforce lines at their own expense. Extensions to infrastructure on this scale require long periods of time for planning, approval and construction.

In the case of **hydrogen**, the connection of individual sites is still subject to much greater uncertainty. Nevertheless, the planning status of the **hydrogen core network** as of December 2023 allows initial estimates to be made. Figure 9 shows an estimate of the potential hydrogen demand of individual industrial sites in combination with the planning status of the core network. This simple comparison already makes it clear that the large chemical and steel sites were taken into account in the planning. However, the plans did not include companies in the mineral industry, such as glass smelters, ceramic, cement and limestone plants, which are out of range of the core network.

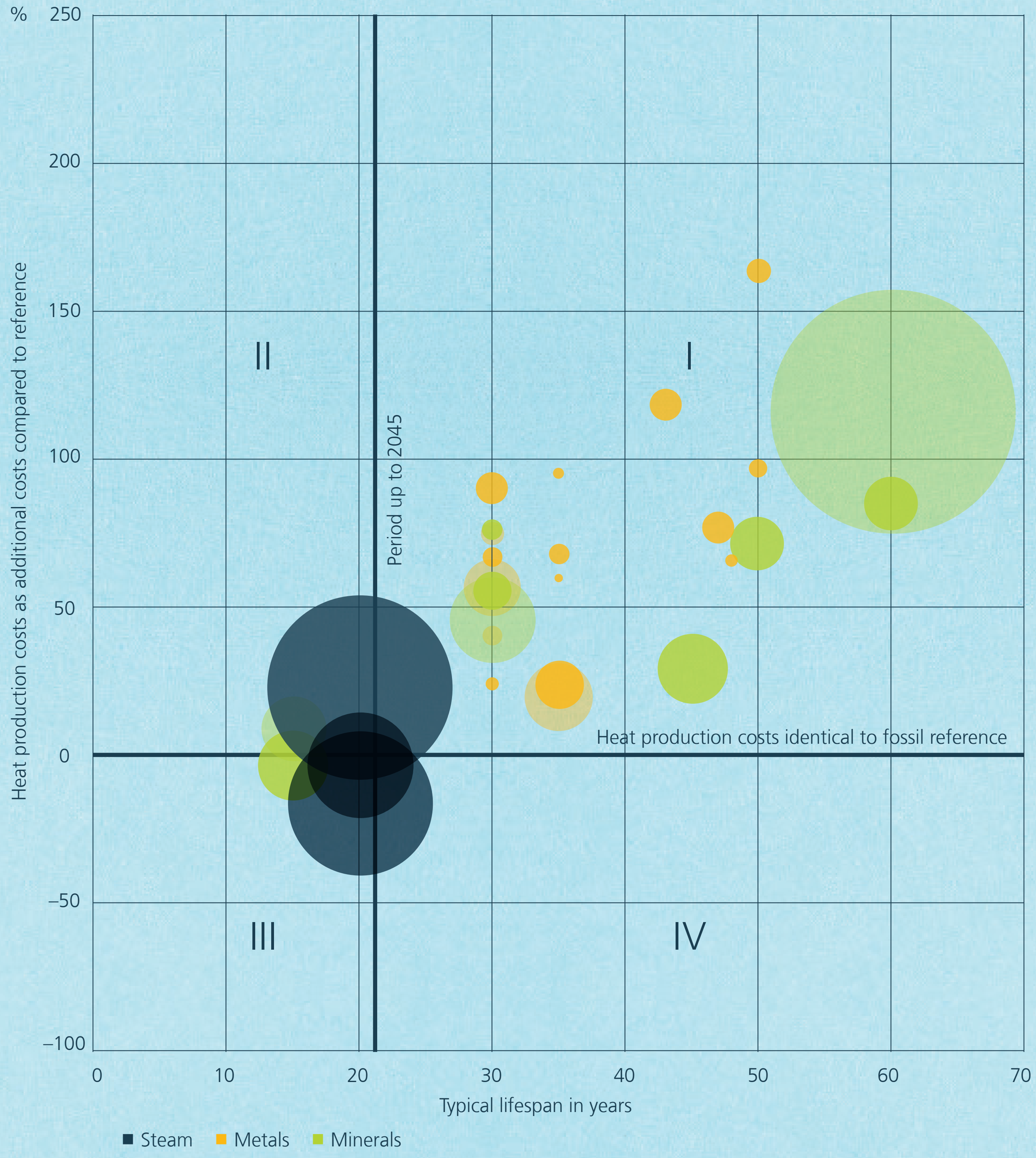


Figure 8: Economic viability of CO_2-neutral installations as additional costs compared to the reference technology over the service life of the fossil reference technology
The size of the circles indicates the respective amount of energy.
Assumptions: Electricity 13–19 ct/kWh; hydrogen 18–27 ct/kWh; natural gas 6–8.5 ct/kWh; CO_2 122 €/t CO_2
Quadrant I: Lack of economic efficiency and long service life of installations lead to high lock-in risks
Quadrant II: Lack of economic efficiency and short system service life
Quadrant III: High economic efficiency and short system service life result in low lock-in risks
Quadrant IV: High efficiency and long system service life
Source: own representation based on [2]

Although it is likely that additional hydrogen pipelines will be developed – especially in the longer term – industrial companies cannot plan with them at present. As a result, there is considerably less room for maneuver due to the continued high level of uncertainty.

Challenges are also expected with regard to the technical design of the **hydrogen infrastructure at the site**. Based on the same amount of energy, the volume flows of methane and hydrogen differ at a ratio of 1:3.3, which can be a limiting factor in pipelines that are already operating at high capacity. Some older natural gas pipelines are also at risk of leaking hydrogen. In some cases, it is sufficient to replace seals and valves, but it may also be necessary to completely rebuild an existing system. Prior to conversion, these factors must be checked on a case-by-case basis.

Most industrial companies are therefore facing major challenges when it comes to infrastructure. In addition to the more technical questions about the infrastructure at the site, there is **uncertainty about the future connection to electricity and hydrogen grids**. Policymakers should enable the best possible planning. Processes such as the grid development plans, the core hydrogen network or the system development strategy in Germany could contribute to this. Although a full picture of the infrastructure requirements for all sites is not yet available, it is already clear that a switch to climate-neutral process heat can only succeed if the electricity infrastructure is significantly strengthened and a hydrogen infrastructure is established.

10

Can the required amounts of energy be supplied by renewables in the future?

According to AG-Energiebilanzen, the industry in Germany purchased well over 200 TWh of electricity and over 400 TWh of fossil fuels such as natural gas and coal in 2021. This means that huge quantities of predominantly fossil fuels have to be replaced in order to switch to climate-friendly processes. **System analyses** provide information on the quantities of electricity and hydrogen that a climate-neutral industrial sector will require in the future. Uncertainties with regard to the development of electrification or hydrogen use are examined using scenarios. In the long-term scenarios, [4] future demand is calculated depending on the degree of electrification. A high degree of electrification would require an additional 140 TWh of electricity and 100 TWh of hydrogen for climate-neutral process heat. With a focus on hydrogen and moderate electrification, an additional 50 TWh of electricity and 200 TWh of hydrogen would be needed. The shortfall to the 400 TWh above could be bridged via efficiency gains, the circular economy, district heating, ambient heat, biomass and other smaller energy sources.

The corresponding system calculations for the **supply side of the energy system** show how these energy volumes can be provided by renewables in the future [53]. These include additional requirements from the transformation of the building and transport sectors and calculate complete base years with hourly resolution to take into account the weather dependency of renewables. The results underline the importance of a significant expansion of electricity generation from wind and PV in Germany and in the European system. In concrete terms, electricity generation in Germany will more than double from just under 600 TWh in 2025 to 1240 TWh in 2045. With over 90 percent of electricity generation, wind and solar energy dominate the generation mix. Almost half of the additional electricity generation will be used to produce hydrogen. In addition to the domestic expansion of renewables, the expansion of electricity and hydrogen infrastructures to create a European network is the second pillar of a climate-neutral energy supply. Green hydrogen will be imported from other European countries and produced at sites with very good wind and solar energy potential. The interlinked European hydrogen system offers flexibility in the event of short-term weather fluctuations, but most importantly it provides seasonal balancing to integrate large quantities of solar energy into the system making use of large-scale underground storage.

It is important to understand these scenarios in terms of potential targets from which conclusions can be drawn. They are not predictions of what the future system will look like. Assumptions can be challenged and the course of developments may vary. A large number of different scenarios have already been calculated, which show that although potential obstacles, such as a slower expansion of wind energy or the electricity grids, make the overall system more expensive, they do not prevent its fundamental feasibility.

In addition, a large number of other studies are available that confirm these results and show how the future energy system can supply a climate-neutral industry in Germany [54–56]. The significance of individual system components and strategies may vary, but they all show that a European climate-neutral sector-coupled energy system is feasible. However, they also show that process heat can only be successfully converted to electricity and hydrogen if the expansion of wind and PV energy is further strengthened.

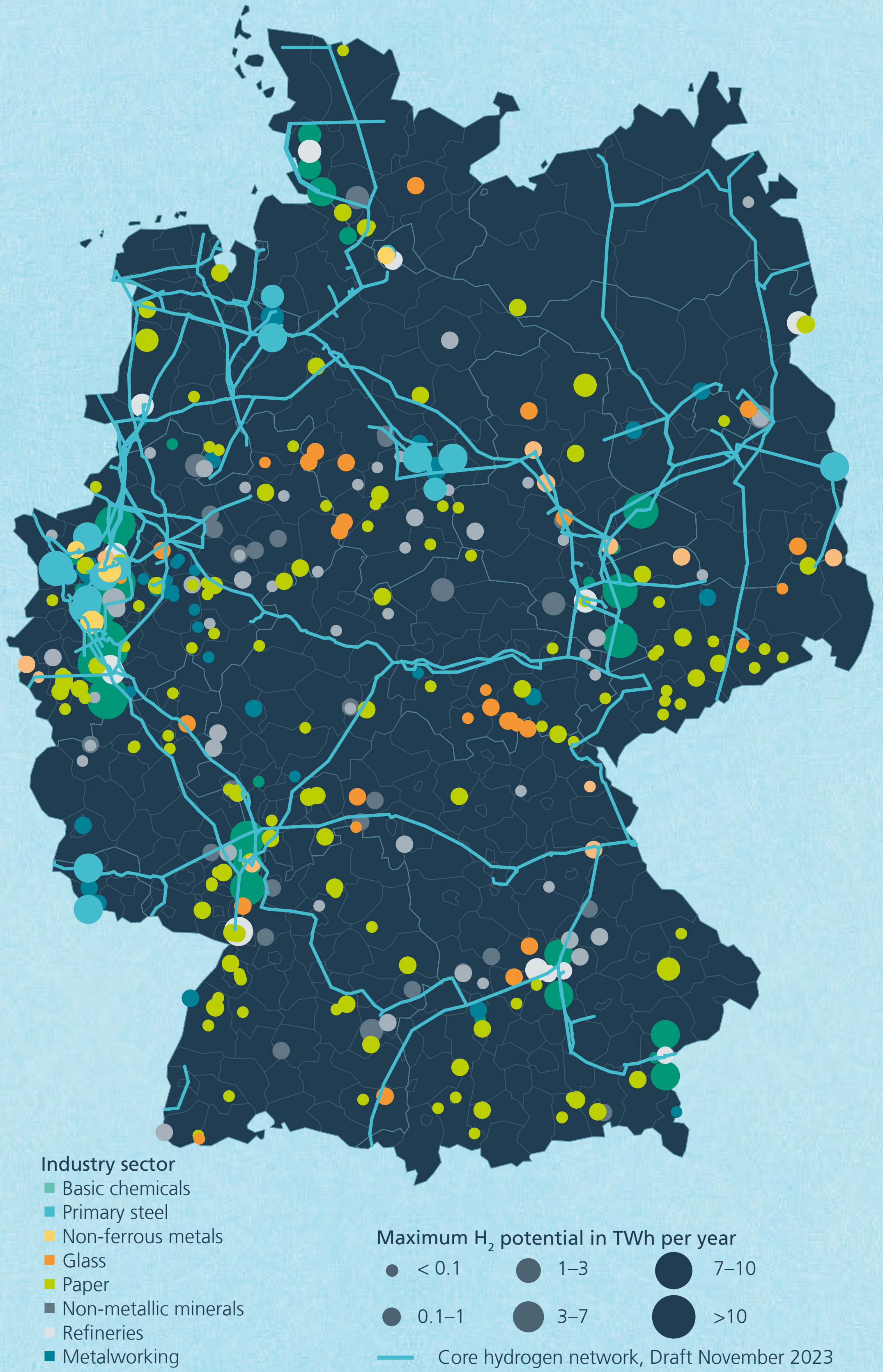


Figure 9: A comparison of the possible future hydrogen demand of individual industrial sites with the proposed design of the hydrogen core network

Source: own representation based on [52] and data from TU Berlin, Energy and Resource Management

11

How can the mix of instruments enable the transition and what needs to be done?

The current policy mix in Germany already encompasses a number of different instruments designed to transform the market by making fossil process heat more expensive and by subsidizing climate-neutral installations [50].

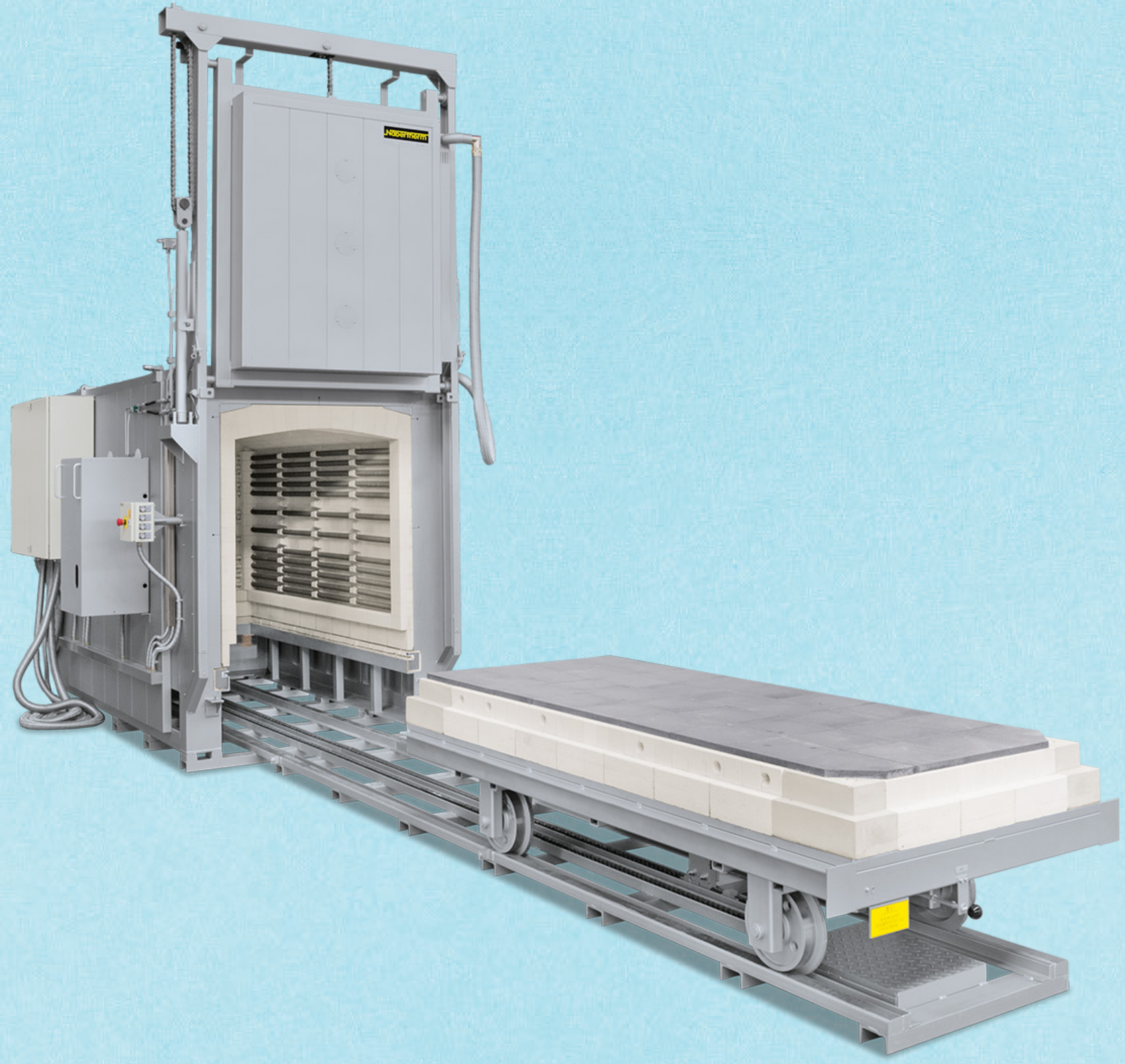
The basis of the policy mix is the CO_2 price of the **EU Emissions Trading Scheme** (ETS I), which currently applies to over 800 energy-intensive installations in primary industry and makes it more expensive to generate process heat using fossil fuels [57]. In the future, the recent reform of the ETS I and the decision to phase out free allocations will strengthen the price signal. Possible gaps in the coverage of ETS I, for example in less emission-intensive processes in the food industry, were closed in Germany via national emissions trading for fuels and recently also at EU level via the ETS II.

In recognition of the fact that investments in climate-neutral process heat are not yet economically viable with the CO_2 price alone, several **funding programs** have been set up. They offer funding for various different target groups according to the level of investment or degree of innovation. These include the “Federal Funding for Industry and Climate Protection” program and the “Federal Grant Programme for Energy and Resource Efficiency in Industry” (EEW), as well as the EU Innovation Fund. Recent developments strengthen the funding of investments in climate-neutral process heat: For example, a new funding module for electrification in small and medium-sized businesses has been set up as part of the EEW. This enables funding not only for the installation technology in the narrower sense, but also for the necessary electrical infrastructure. Nevertheless, action is still required: The programs for large companies and those offering investment subsidies in particular, restrict funding based on the degree of innovation; so that often only the “first of a kind” system is eligible for funding, while there is a similarly high profitability gap for subsequent investments.

A number of incentives require companies to develop concrete **plans for transformation**. Most companies participating in EU ETS I must present appropriate climate neutrality plans in order to receive a full allocation of certificates. At the same time, transformation plans are eligible for funding under the federal EEW funding program.

Furthermore the observation in this policy brief clearly shows that investment subsidies and CO_2 prices that remain below 150 euro/t CO_2 in the long term will not be sufficient in most sectors to make climate-neutral process heat competitive in Germany [58]. The **price difference between electricity and natural gas prices** is crucial for the economic viability of electrification. Large consumers currently benefit from a reduction in electricity tax, grid fees and levies, yet the electricity price paid by industrial companies is on average still significantly higher than the price of natural gas. The widespread electrification of process heat requires an **electricity price** at about the same level as today's natural gas price including the CO_2 penalty. This does not necessarily have to apply to applications that are already electrified, such as mechanical energy or lighting. On the contrary, limited public funds can be used more efficiently if they are used in a targeted manner for process heat. Many companies are also currently benefiting from tax relief on the price of natural gas, which significantly reduces the profitability of alternatives. Flexible hybrid systems could be a solution in the transition by enabling electric operation at times of low exchange prices (see Question 07). However, a correspondingly flexible operation is prevented by the current **grid fee regulations**. The structure of grid fees should be changed in order to incentivize flexible operation in line with market signals.

At the same time, investment is prevented both by the highly uncertain future prices of climate-neutral electricity and hydrogen, and the CO_2 price. With the **carbon contracts for difference**, a new instrument has been set up that can provide a solution in the short term by closing this gap in running costs at the same time as reducing uncertainties. This instrument funds differential costs compared to the fossil reference technology and awards them to the projects with the lowest abatement costs as part of an auction. It could play a key role in enabling the transformation, but it must first prove itself in practice. Therefore, it is important to implement it quickly and evaluate it in a structured manner.



Bogie hearth furnace with electro-hydraulic lift door and a motorized bogie
Picture credit: ©Nabertherm

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