In the last issue of heat processing (02/2024) there has been an editorial mistake concerning this article. The following is the same article with the mistake corrected.

CO_2-neutral process heat generation – a study for the Federal Environment Agency of Germany (Umweltbundesamt)

by **Dr. Christian Schwotzer, Katharina Rothhöft, Dr. Tobias Fleiter, Dr. Matthias Rehfeldt, Dr. Fabian Jäger-Gildemeister**

The advancing climate crisis requires a CO_2-neutral generation of process heat, especially in countries like Germany, which pursue ambitious defossilization goals and are home to energy-intensive industrial sites. This article presents an excerpt from the results of a comprehensive study conducted on behalf of the German Environment Agency by Fraunhofer ISI in collaboration with the Department for Industrial Furnaces and Heat Engineering at RWTH Aachen University. This study delves into the current use of fossil fuels for providing process heat in various energy-intensive industries in Germany and particularly demonstrates the technical potential for future CO_2-neutral process heat generation. To achieve this, the current state of the art of process heat generation in the metal and mineral industries as well as steam generation was analyzed, and approaches for CO_2-neutral transformation pathways for the industry were developed.

INTRODUCTION

Efforts to mitigate climate change are crucial, particularly in Germany, a location with a significant amount of energy-intensive industry, to achieve ambitious climate targets while preserving jobs and international competitiveness. Currently, process heat generation is heavily dependent on the use of fossil fuels, especially natural gas, with a low utilization of renewable energies (**Fig. 1 and Fig. 2**). Fossil energy sources dominate the metal industry, accounting for 87.3 %, while electricity represents 10.8 %, and hybrid heating systems make up 2.0 % for the applications considered in the study. The mineral industry shows an even stronger dependence, with fossil fuels accounting for 99.7 %. These figures illustrate the challenges and potential for technological innovations to provide CO_2-free process heat in these sectors.

Although some sectors are already using technologies for CO_2-neutral process heat supply or are planning to do so in the future, there is no comprehensive overview of the technical possibilities for generating process heat in energy-intensive industries in the context of future economic framework conditions.

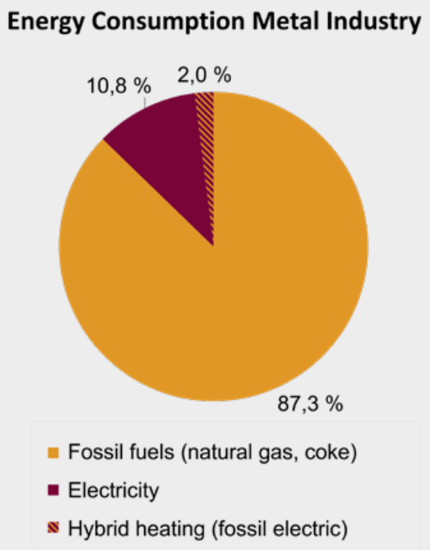


Fig. 1: Metal industry – distribution of total annual energy consumption by energy source.
(Notes: Mean values based on the sector analyses, total energy consumption 33,501 GWh/a)

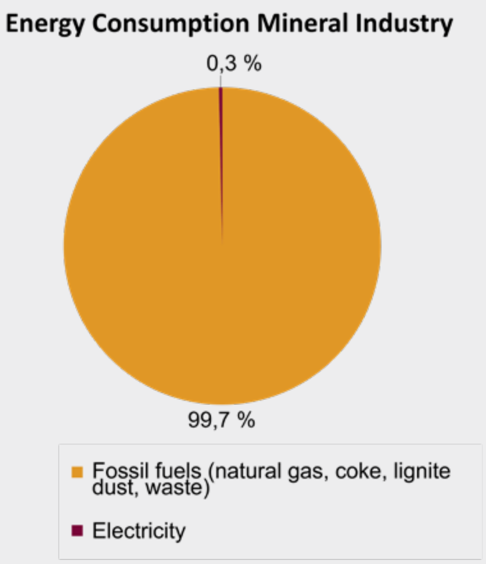


Fig. 2: Mineral industry – distribution of total annual energy consumption by energy source

(Notes: Mean values based on the sector analyses, total energy consumption 51.748 GWh/a)

In this study, technologies for the CO_2 neutral supply of process heat are considered from a technical, economic, and ecological perspective. The study was conducted for 13 industries and 34 exemplary applications in the metals and minerals industries, as well as for the cross-cutting technology steam generation (**Table 1**). For each application, alternative, CO_2-neutral technologies are examined for their technical feasibility, economic viability, and ecological impact. The focus is on the electrification of plant technology, the use of hydrogen, but also hybrid systems, and, in some cases, the use of biomass. From this comprehensive review of the current situation and the possible alternative technologies, findings and recommendations for implementation will be developed for industry, policymakers, and researchers to support the transformation to CO_2-neutral process heat generation.

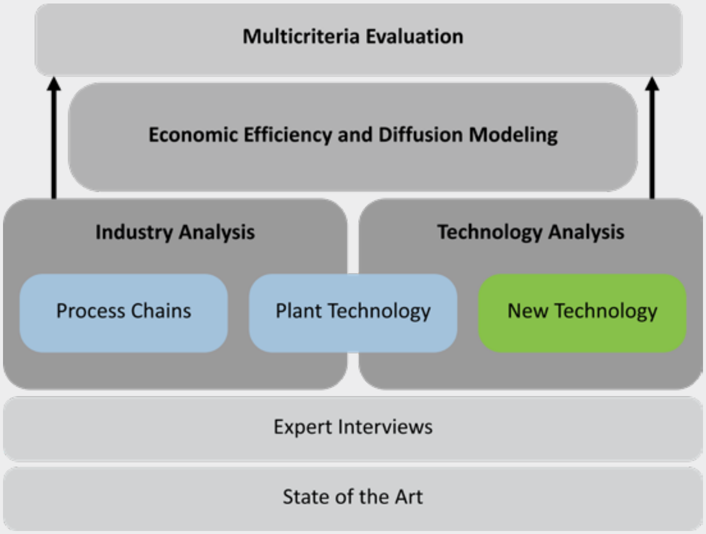


Fig. 3: Study approach

APPROACH OF THE STUDY

The study is based on an industry and technology assessment of the state of the art (**Fig. 3**). The results from the metal and mineral industries and the cross-sectional technology of steam generation were analyzed and summarized in consultation with experts. The central process chains were examined for each sector and the most important processes in terms of energy were identified. Each process chain contains several processes in which specific thermal process plants (industrial furnaces) are used, which are grouped into plant types. Based on the selected processes and plant types, applications are defined for further consideration. A reference technology and two to four CO_2-neutral alternative technologies (new technologies) are assigned to each application. Key figures such as specific energy requirements, process-related emissions, or investment costs are used for comparison.

The central findings of the study are summarized in 11 theses on the transformation of process heat generation (**Table 2**). In this article, Theses 1, 2, 6, and 9 are presented in detail, providing a broad overview of the essential findings. For a more in-depth examination of the theses, reference is made to the study (see the link at the end of this article).

THE INDUSTRIAL FURNACE FLEET IS HETEROGENEOUS

The metal industry and parts of the mineral industry are characterized by numerous small process plants with a throughput of less than 20 t/h and a plant capacity of less than 20 MW. At the same time, there are large facilities with significantly higher throughput and corresponding higher plant capacities. **Fig. 4** shows a selection of technical examples from the study. Examples of large plants include heat and annealing furnaces in the steel industry with capacities of up to 170 t/h or cathode shaft furnaces in the copper industry with throughputs of up to 80 t/h. It is observed that the specific energy requirement of a plant correlates with the process temperature. The higher the required temperature of a process, the higher the specific energy requirement.

Table 1: Overview of the sectors examined, associated reference technologies, and thermal processing plants

Industry	Reference technology	Thermoprocessing plants
Heating and annealing furnaces, steel rolling mills	Continuous heating furnace made of flat/long steel with natural gas heating	Walking beam furnace, pusher furnace
	Continuous flat steel heat treatment furnace with natural gas heating	Continuous annealing furnaces
	Discontinuous heat treatment furnace for flat steel with natural gas heating	Hood annealing furnaces
Foundry industry	Continuous cast iron melting furnace with coke heating (low capacity)	Cold blast cupola, hot blast cupola
	Continuous cast iron melting furnace with coke heating (medium capacity)	Hot blast cupola furnace
	Continuous cast iron melting furnace with coke heating (high capacity)	Hot blast cupola furnace
	Continuous aluminum melting furnace with natural gas heating	Shaft furnace
Non-ferrous metal industry: aluminum	Discontinuous melting/holding furnace made of semi-finished cast aluminum with natural gas heating	Chamber hearth furnace
	Continuous homogenization/heating oven made of aluminum strip/profile with natural gas heating	Pusher furnace, (roller) continuous furnace
	Discontinuous homogenization/heating oven made of aluminum strip/profile with natural gas heating	Deep furnace, chamber furnace, billet heating system
	Continuous heat treatment furnace Alu Band with natural gas heating	Floating belt oven, continuous oven
Non-ferrous metal industry: copper	Continuous melting furnace for copper wire rod with natural gas heating	Cathode shaft furnace
	Continuous heating furnace copper semi-finished product with natural gas heating (low capacity)	Lifting hearth furnace, walking beam furnace, roller hearth furnace
	Continuous heating furnace copper semi-finished product with natural gas heating (high capacity)	Lifting hearth furnace, walking beam furnace, roller hearth furnace
	Discontinuous heat treatment furnace for semi-finished copper products with natural gas heating (low capacity)	Bell annealing furnace
	Discontinuous heat treatment furnace for copper semi-finished products with natural gas heating (high capacity)	Bell annealing furnace
Forming technology	Continuous heating furnace for forged components with natural gas heating (drop forging)	Rotary hearth oven, continuous oven
	Discontinuous heating furnace for forged components with natural gas heating	Chamber forge furnace, wagon forge furnace
	Continuous heating furnace for steel sheet blanks with natural gas heating	Roller hearth oven
Hardening technology	Discontinuous carburizing/austenitizing furnace with natural gas pickling	Chamber furnace
	Continuous carburizing/austenitizing furnace with natural gas pickling (contract hardening shop)	Pusher kiln, belt kiln, roller hearth kiln
	Continuous carburizing/austenitizing furnace with natural gas pickling (company hardening shop)	Pusher kiln, belt kiln, roller hearth kiln
Glass industry including fiberglass	Continuous melting furnace container glass with natural gas pickling	U-flame Regenerative Furnace
	Continuous melting furnace for flat glass with natural gas pickling	Cross-fired Regenerative Furnace
Lime industry	Continuous lime kiln with low reactivity with coke heating	Normal shaft furnace
	Continuous lime kiln with medium/high reactivity with natural gas heating	PFR (Parallel Flow Regenerative) kiln
	Continuous lime kiln with high throughput with fuel mix heating	Rotary kiln
Cement industry	Continuous cement clinker kiln with fuel mix heating	Rotary kiln system
Ceramic and brick industry	Continuous brick kiln with natural gas heating	Tunnel oven
	Continuous refractory brick kiln with natural gas heating	Tunnel oven
	Discontinuous refractory brick kiln with natural gas heating	Bogie hearth furnaces
Food industry	Combined heat and power (CHP) plant for steam generation	
Paper industry	Natural gas boilers & biomass boilers for steam generation	
Chemical industry	CHP plant with peak load boilers for steam generation	

Additionally, the cross-sectional technology of steam generation was examined. The state of the art includes natural gas boilers or combined heat and power (CHP) systems. Industry-specific characteristics play a minor role in the selection of technology for achieving CO_2 neutrality. The technical requirements for end applications are less different compared to industrial furnaces. This includes performance, throughput, pressure, and temperature.

A transition to CO_2-neutral process heat generation encompasses various technical possibilities and obstacles, as

Table 2: Summary of study results as theses

Thesis 1	The industrial furnace fleet is heterogeneous
Thesis 2	The switch to GHG-neutral process heat generation is technically feasible by 2045
Thesis 3	Electrification and the use of hydrogen require research, development and demonstration
Thesis 4	Electrification requires a more comprehensive conversion of the system park than the use of hydrogen or synthetic methane
Thesis 5	Electrification is accompanied by slight efficiency gains in most application technologies
Thesis 6	Electrification is beneficial in many lower temperature applications - hydrogen at very high energy densities
Thesis 7	From a system perspective, the additional investment required for the new construction of the systems is rather low
Thesis 8	The switch to CO_2-neutral technologies is associated with significantly higher energy costs
Thesis 9	Due to long modernization cycles, the risk of stranded investments is high
Thesis 10	Hybrid system concepts can enable entry into CO_2-neutral process heat
Thesis 11	CO_2-neutral technologies reduce direct environmental impacts and environmental costs

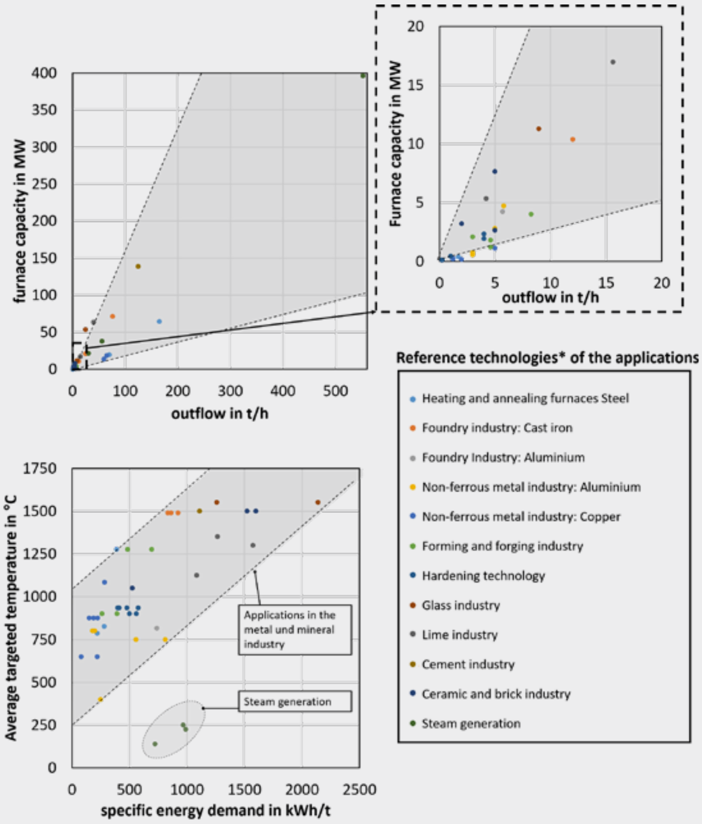


Fig. 4: Classification of the considered applications and reference technologies in the plant fleet in Germany based on characteristic parameters

(Notes: *Application-specific data based on the industry analyses; 37 applications in total (the respective reference technology and, where applicable, the electrical alternative is shown if already present in the portfolio to a greater extent)

well as investment costs and space requirements, depending on the industry and application. Accordingly, the necessary adaptation measures require a differentiated approach to the transition to CO_2-neutral process heat generation. An effective strategy to achieve CO_2 neutrality should take into account the unique characteristics of each industry's production processes, as well as the specific challenges and opportunities they present.

THE SWITCH TO GHG-NEUTRAL PROCESS HEAT GENERATION IS TECHNICALLY FEASIBLE

Despite the wide variety of plants and specific challenges, the transition to CO_2-neutral process heat generation is technically feasible by 2045.

The solutions will vary depending on the industry and application, and the effort required to transition from currently used reference technologies to CO_2-neutral alternatives varies significantly.

The heterogeneity of industrial furnaces has a significant impact on the feasibility of deploying CO_2-neutral technology in the future. While electrification is already state-of-the-art in applications such as the foundry industry, forming, or melting of aluminium with induction furnaces, it shows comparatively low technological maturity in sectors like the lime and cement industry, which are associated with fundamental technical challenges (**Fig. 5**). This significant heterogeneity in the existing plant stock and terms of Technology Readiness Level (TRL) [1] requires consideration in the development of transformation strategies.

Both hydrogen and electrification can have a significant impact, although further research and development are needed in many areas. Across applications, it is evident that electrification generally requires the construction of new facilities. Transitioning from natural gas-operated reference technology to hydrogen involves less technical effort in terms of plant technology and can be accomplished by retrofitting the burner technology.

Additionally, using hydrogen requires local infrastructure (pipes, valves) and its impacts on process and product quality need to be tested. Industrial-scale facilities are not yet available, resulting in a TRL of < 5, according to the study. However, with ongoing research and development in many projects, the TRL for many applications is expected to rise quickly in the coming years.

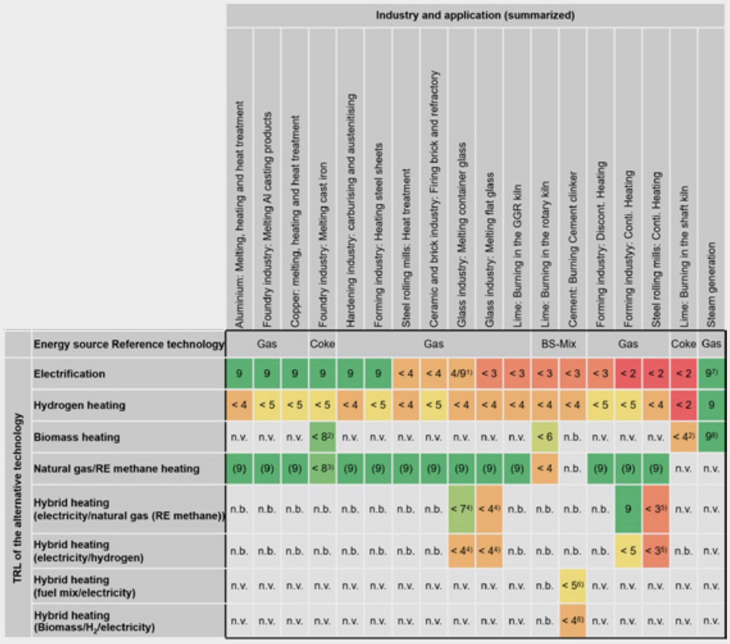
Scaling all alternative technologies to an industrial level and testing them in operational deployments are crucial. Some technologies face significant technical barriers, such as the electrical heating of rotary kilns in lime or cement production or the continuous heating in steel rolling mills. These processes and their plant technology are characterized by very high process temperatures and production capacities, requiring heating technologies with a high energy density, which are not possible with current state-of-the-art electrical heating technologies. The use of hydrogen also presents a particular technological challenge, especially in areas where solid fuels like coke are currently used, such as in shaft kilns for lime burning or in cupola furnaces of iron foundries.

As a result, alternative, bio-based fuels are being considered for these applications. The sustainable potentials of bioenergy carriers are controversial – at any rate, they are foreseeably too limited to serve as a broad replacement for fossil energy sources in the industry. In this study, their use was assumed exclusively for internal production quantities in the paper industry. However, for these fuels to be a viable option, they need to be produced in sufficient quantity and quality. On the other hand, CO_2-neutral techniques for steam generation using hydrogen and for electrification are already available for industrial use today.

ELECTRIFICATION IS BENEFICIAL IN MANY LOWER TEMPERATURE APPLICATIONS, HYDROGEN AT VERY HIGH ENERGY DENSITIES

Simplified application fields for the considered alternative technologies can be defined based on characteristic metrics such as plant throughput and process temperature (average target temperature) (**Fig. 6**). Additionally, other parameters need to be considered, such as the technology readiness level, the effort required for technical retrofitting, or energy efficiency.

There are electric heating technologies available for use in metal and mineral industries with a throughput of less than 20 t/h and a process temperature of up to 1000 °C. However, the technological boundaries are constantly evolving, and its application fields are continuously expanding. Some technical solutions are now available at higher process temperatures, such as inductive melting



		Industry and application (summarized)																	
		Aluminium: Melting, heating and heat treatment	Foundry industry: Melting Al casting products	Copper: melting, heating and heat treatment	Foundry industry: Melting cast iron	Hardening industry: carburising and austenitising	Forming industry: Heating steel sheets	Steel rolling mills: Heat treatment	Ceramic and brick industry: Firing brick and refractory	Glass industry: Melting container glass	Glass industry: Melting flat glass	Lime: Burning in the GGR kiln	Lime: Burning in the rotary kiln	Cement: Burning Cement clinker	Forming industry: Discont. Heating	Forming industyy: Conti. Heating	Steel rolling mills: Conti. Heating	Lime: Burning in the shaft kiln	Steam generation
	Energy source Reference technology	Gas			Coke	Gas							BS-Mix		Gas			Coke	Gas
TRL of the alternative technology	Electrification	9	9	9	9	9	9	< 4	< 4	4/9[1]	< 3	< 3	< 3	< 3	< 3	< 2	< 2	< 2	9[7]
	Hydrogen heating	< 4	< 5	< 5	< 5	< 4	< 5	< 4	< 5	< 4	< 4	< 4	< 4	< 4	< 5	< 5	< 4	< 2	9
	Biomass heating	n.v.	n.v.	n.v.	< 8[2]	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	< 6	n.b.	n.v.	n.v.	n.v.	< 4[2]	9[8]
	Natural gas/RE methane heating	(9)	(9)	(9)	< 8[3]	(9)	(9)	(9)	(9)	(9)	(9)	(9)	< 4	n.b.	(9)	(9)	(9)	n.v.	n.v.
	Hybrid heating (electricity/natural gas (RE methane))	n.b.	n.b.	n.b.	n.b.	n.b.	n.b.	n.b.	n.b.	< 7[4]	< 4[4]	n.b.	n.b.	n.b.	n.b.	9	< 3[5]	n.v.	n.v.
	Hybrid heating (electricity/hydrogen)	n.b.	n.b.	n.b.	n.b.	n.b.	n.b.	n.b.	n.b.	< 4[4]	< 4[4]	n.b.	n.b.	n.b.	n.b.	< 5	< 3[5]	n.b.	n.v.
	Hybrid heating (fuel mix/electricity)	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.b.	< 5[6]	n.v.	n.v.	n.v.	n.v.	n.v.
	Hybrid heating (Biomass/H_2/electricity)	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.b.	< 4[6]	n.v.	n.v.	n.v.	n.v.	n.v.

Fig. 5: Technology readiness level (TRL) of the alternative technologies (summarized)

(Notes: Applications with the same TRL within an industry have been summarized for a clearer presentation. The focus of the analyses was on the technical potential of complete electrification as a Power-to-Heat (PtH) alternative and the use of hydrogen as a Power-to-Gas (PtG) alternative. For alternative technologies labeled "n.v.," no significant R&D applications were identified within the study. For a TRL < 1, a foreseeable implementation of the considered alternative technologies within the study is not realistic. These techniques will not be considered further in the subsequent economic analyses (labeled "n.b."). For a TRL < 3, availability of the technology is assumed from the year 2040. For a TRL < 9 and ≥ 3, availability of the technology is assumed from the year 2030.

1. For plants with a throughput < 10 t/d, complete electrification is possible. For plants with a higher throughput, this is not the case.
2. When using biomass, the quality of the fuel is crucial for process control and product quality. The requirements for biomass fuel are specific to the application and plant. Here, individual testing of the overall system (plant/fuel/product) is necessary.
3. In the past, a plant in Germany was operated with low capacity. For larger plants, the TRL is assessed to be lower.
4. Hybrid heating here refers to technology examples with an electrification share of > 50%, in contrast to plants with an auxiliary electric heating with a share of significantly < 50%, which are often state of the art.
5. Hybrid heating technologies with an electrification share of > 50% (as also for the application of continuous heating of forging components) are conceivable as future alternative technologies, however, the capacities of these plants are significantly smaller (1/10).
6. Hybrid heating comprises different technology examples with an electrification share between 10% and 60%.
7. TRL 9 refers to electrode boilers as a commercially available electricity-based technology. High-temperature heat pumps range from TRL 5-8 depending on the required steam temperature.
8. TRL 9 refers to electrode boilers as a commercially available electricity-based technology. High-temperature heat pumps range from TRL 5-8 depending on the required steam temperature.)

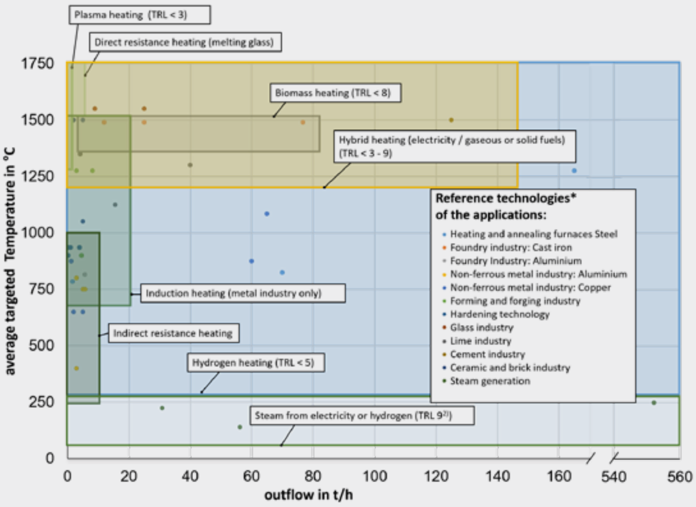


Fig. 6: Classification and application potential of the alternative technologies under consideration

(Notes: *Application-specific data based on industry analyses; a total of 40 applications (displaying the respective reference technology and, if already available on a large scale, the electrical alternative); not all reference technologies can be replaced by alternative technologies (especially electrical ones) with identical production volumes; the Technology Readiness Level (TRL) of the overall system is low for many applications

1) **For the use of hydrogen in the metal and mineral industries, the technology readiness level of the overall plant is rated as low (TRL < 5) due to the lack of hydrogen availability, the deployability in pilot or demonstration plants, and the effects on the process have not yet been sufficiently tested in many cases. However, individual components (e.g., burners) often already have a significantly higher TRL**
2) **In contrast to the use of hydrogen in the metal and mineral industries, the downstream process steps or product properties remain unaffected in steam generation. Hydrogen-fired steam generators are commercially available for large-scale use (TRL 9) and are already in use in industries with internal hydrogen flows, such as the chemical industry.)**

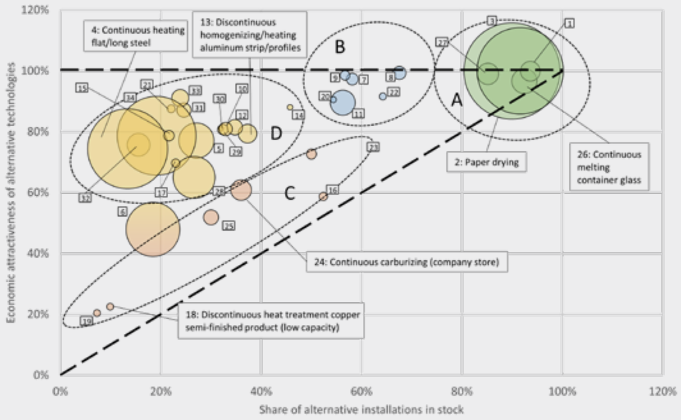


Fig. 7: Diffusion and attractiveness of CO_2-neutral plants in 2040 by application (exemplary)

of metallic materials. However, processes that require high process temperatures and high throughput, such as burning and melting in the mineral industry, are still in their early stages of development and have a low TRL. For these applications, heating technologies with a high energy density, such as hydrogen or bio-based energy carriers, are necessary to replace solid carbon carriers.

It has been observed that electrification is well established for many industrial applications that require lower process temperatures (< 1000°C) and smaller plant capacities (< 20 t/h). This presents an opportunity for rapid adoption of technology.

Even though electric heating technologies are already advanced for some applications in the metal industry, they are not commonly utilized in Germany. The reasons behind this issue are complicated and involve various factors, such as specific aspects of production, the space required, the infrastructure, and the cost differences between electricity and fossil fuels.

The electrification of continuous processes can lead to higher plant and space requirements since multiple smaller, intermittent electrical facilities are usually needed to match the production capacity of a single fossil-fueled plant. Additionally, the required infrastructure, such as electrical connection capacity at the site, poses a challenge. Moreover, the historically low economic viability compared to gas heating has particularly hindered investment in electric heating.

Heating with hydrogen can be advantageous for applications that require high energy densities due to high productivity and process temperatures. Traditionally, these applications have been operated with natural gas, and currently, no fully electrified alternative can be quickly deployed. Hydrogen can be used as an option for all gas-heated applications. It can be beneficial where electrification is hindered by insurmountable technical obstacles or where no energy efficiency gains are possible through electrification.

DUE TO LONG MODERNIZATION CYCLES, THE RISK OF STRANDED INVESTMENTS IS HIGH

The service life and modernization cycles of many plants typically range from 20 to 50 years. Consequently, new investments significantly impact the long-term transformation of the existing infrastructure. Since long service lives and modernization cycles can substantially slow the transformation process, early climate and energy policy signals are crucial to prevent investments in new, durable fossil-fuel plants.

For CO_2-neutral technology to be adopted in the market, it must first be available and economically viable. The rate at which it diffuses into the market is also influenced by factors such as its lifespan, modernization cycle, and the age of the existing plant stock. The conditions for market diffusion can vary across different industries and applications and can be categorized into different groups. For the year 2040, four groups (A, B, C, and D) are defined, which differ in terms of the economic attractiveness of the CO_2-neutral alternative technology and the proportion of CO_2-neutral plants in the existing stock (**Fig. 7**).

In Group A ("Advanced"), applications are included where economically attractive CO_2-neutral technologies are available early and can be replaced relatively quickly due to short plant lifespans. These applications can achieve complete defossilization (in the calculated scenario, over 80 % diffusion) by 2040 and are found in glass manufacturing and steam generation.

In Group B ("Boosted"), applications exist for which attractive CO_2-neutral technologies are available by 2040, but which show lower diffusion due to longer plant lifespans. This group includes foundries and forming technology companies.

Applications whose CO_2-neutral technologies are economically less attractive but can greatly benefit from potential diffusion are assigned to Group C ("Cornered"), which includes copper processing and hardening applications.

Where there is a lack of economically viable CO_2-neutral technologies and rapid diffusion, applications are assigned to Group D ("Delayed"). This group includes cement, lime, aluminium, and steel production, where particular risks for fossil fuel lock-ins exist, thus necessitating action.

The speed of development towards a CO_2-neutral industry depends on the time it takes to replace an old plant with a new one. For many applications, there is a risk that although the CO_2-neutral plant is economically attractive, it may not be constructed due to the presence of an existing fossil fuel plant and its modernization cycle.

Furthermore, there is an economic risk associated with replacing fossil-fueled plants prematurely before they reach the end of their lifespan. Since the service life of plants can span several decades, even strong economic signals may have a delayed effect. Long service lives and modernization cycles significantly slow down the transformation process. Therefore, early climate and energy policy signals are crucial to prevent investments in new fossil fuel plants.

Additionally, in many applications, it is anticipated that fossil fuel plants will not reach the end of their technical lifespan.

Cost differences between conventional and CO_2-neutral plants arise mainly from energy costs. Consequently, to enhance the economic competitiveness of CO_2-neutral alternative technologies, two conditions are critical: 1. The availability of climate-neutral electricity and hydrogen at competitive prices, and 2. an increase in the price of CO_2.

CONCLUSION

To achieve the goal of defossilizing the German industry, it is necessary to provide CO_2-neutral process heat. The analysis of the current state of technology in the metal and mineral industries, as well as steam generation, as part of the results presented in this study, shows a great heterogeneity in the plant fleet, and highlights the high proportion of fossil fuels used along the process chains. The examination of CO_2-neutral alternative technologies indicates that a transition by 2045 is technically feasible, with electrification and hydrogen playing central roles.

The heterogeneity of the plant fleet in the industry requires differentiated approaches, where an industry-specific transformation strategy should consider the characteristics of the production processes. The risk of stranded investments due to long modernization cycles underscores the urgency of early climate and energy policy signals to prevent investments in new fossil plants and to promote the market diffusion of CO_2-neutral technologies.

SOURCES AND STUDY

All the results presented in this article are taken from the study “CO_2-neutral process heat generation” (in German: „CO_2-neutrale Prozesswärmeerzeugung - Umbau des industriellen Anlagenparks im Rahmen der Energiewende: Ermittlung des aktuellen SdT und des weiteren Handlungsbedarfs zum Einsatz strombasierter Prozesswärmeanlagen“). The authors of the article would like to thank everyone who contributed to the creation of the study. A list of these individuals can be found in the document. The study and further documents are available on the website of the Federal Environment Agency im Germany (Umweltbundesamt). Link to the study (only German version): https://www.umweltbundesamt.de/publikationen/co2-neutrale-prozesswaermeerzeugung

FOOTNOTES

[1] Definition according to: https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

AUTHORS

Dr. **Christian Schwotzer**
Department for Industrial Furnaces and Heat Engineering
RWTH Aachen University, Germany
schwotzer@iob.rwth-aachen.de

Katharina Rothhöft, M.Sc.
Department for Industrial Furnaces and Heat Engineering
RWTH Aachen University, Germany
rothhoeft@iob.rwth-aachen.de

Dr. **Tobias Fleiter**
Fraunhofer Institute for Systems and Innovation Research
Karlsruhe, Germany
tobias.fleiter@isi.fraunhofer.de

Dr. **Matthias Rehfeldt**
Fraunhofer Institute for Systems and Innovation Research
Karlsruhe, Germany
matthias.rehfeldt@isi.fraunhofer.de

Dr. **Fabian Jäger-Gildemeister**
Federal Environment Agency of Germany
(Umweltbundesamt)
Dessau-Roßlau, Germany
fabian.jaeger-gildemeister@uba.de