Power-2-Heat

Gas savings and emissions reduction in industry

IMPULSE

Agora Industry

:FutureCamp

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PUBLICATION DETAILS

IMPULSE

Power-2-Heat: Gas savings
and emissions reduction in industry

PUBLISHED BY

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Typesetting: RadiCon | Kerstin Conradi, Berlin
Translation: Dr. Ray Cunningham
Title picture: DIPA | iStock

277/05-I-2022/EN
Version: 1.0, November 2022

ACKNOWLEDGEMENTS

This project was developed in cooperation with representatives from companies and research organisations. With this publication, we would like to thank all those involved for their support, their technical expertise, and for constructive debate. The conclusions and findings of this study do not necessarily reflect the positions of the participants. The responsibility for the findings lies with Agora Industry and FutureCamp.

For their active support in the preparation of this publication, we would like to thank our colleagues, in particular Frank Peter, Simon Müller, Ada Rühring, Urs Karcher, Anja Werner, Oliver Sartor, Utz Tillmann, Olaf Malden, Nina Zetsche, Helen Burmeister, Mareike Herrndorff, Alexandra Langenheld, Thorsten Lenck, Uta Weiß, Matthias Deutsch, Jahel Mielke, Janne Görlach (all Agora Energiewende); Dietmar Schüwer, Alexander Jülich, Alexander Scholz (all Wuppertal Institute).

This publication can be downloaded as a PDF using this scan code.

Please cite as:
Agora Industry, FutureCamp (2022): Power-2-Heat: Gas savings and emissions reduction in industry

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Preface

Dear reader,

Russia's attack on Ukraine has intensified the need to rapidly reduce the consumption of fossil fuels, and of natural gas in particular. In addition to short-term measures to save gas in response to the energy crisis, there is also a need to focus on a structural reduction in industrial consumption of natural gas.

The EU Commission's REPowerEU plan calls on industry to reduce its natural gas consumption by around half by the year 2030. The Federal Climate Protection Act requires a reduction of around a third of industrial greenhouse gas emissions by 2030.

This study demonstrates the potential for the direct electrification (Power-2-Heat) of industrial process heat up to 500 degrees Celsius, as used for example in the paper, food and plastics industries, in pursuit of these targets.

By switching to electricity-based processes for industrial heat generation, both natural gas consumption and greenhouse gas emissions are significantly reduced. In addition, these processes support the integration of renewable energies as they offer flexible electricity consumption.

In order to facilitate the market ramp-up of these processes through a combination of subsidies and regulatory standards, a number of regulatory barriers must be removed. In our study, we show how this can be achieved.

I hope you enjoy reading this study.

Yours
Frank Peter
Director of Agora Industry

Key findings at a glance:

1	**A rapid industrial heat transition will contribute to climate protection and is necessary to fulfil Germany's contribution to reducing natural gas consumption as part of REPowerEU.** By 2030, industrial plants in Germany can save 90 TWh of natural gas through the electrification of process heat. This represents up to three quarters of the savings required from industry by the REPowerEU plan and a reduction of 12.5 million tonnes of CO_2 – 18 percent of the target for the industrial sector in the German climate protection law.
2	**The use of heat pumps and electric boilers in industry must proceed in tandem with the decarbonisation of the electricity sector.** Flexible electricity consumption helps to integrate a high share of renewable energy and to make better use of its volatile generation. Such flexibility will make it possible to meet the German government's target of 80 percent renewables by 2030 efficiently.
3	**Removing regulatory barriers and perverse incentives makes electrification more attractive and enables flexibility.** In order to stimulate flexible consumption, the introduction of time-differentiated grid charges must be made a political priority. Likewise, privileging natural gas-based technologies over applications using direct electricity must end.
4	**In the German Energy Security Act, the year 2035 should be set as the deadline for the phase-out of fossil fuels in process heating up to 500 degrees.** A special support programme can be used to close the cost gap for electricity-based technologies, and a statutory zero carbon standard for new investments can create planning and investment certainty.

Content

1 Executive summary

From an energy policy perspective, Russia's attack on Ukraine has highlighted Germany's heavy dependence on Russian energy imports. The huge reduction in natural gas supplies calls for immediate savings measures, but also for structural changes in our energy supply. Industry is under particular pressure here: with a consumption of 245 Terawatthours referring to the lower heating value (TWh_{LHV}) at the most recent count, industry uses almost 30 percent of the natural gas consumed in Germany. Of this total, 209 TWh_{LHV} is used purely for the production of process heat – in some cases in steam boilers, but mostly in CHP plants that convert part of this process heat into electricity. The remaining 36 TWh_{LHV} are used in the production of ammonia and methanol, and in refineries (Agora Energiewende 2022b).

The REPowerEU plan presented by the EU Commission on 18 May 2022 aims to quickly reduce dependence on fossil energy imports from Russia. It is especially directed towards natural gas savings in industry, which consumed 108 billion cubic metres of natural gas (1060 TWh_{LHV}) across Europe: in addition to the savings of 8 billion cubic metres (81 TWh_{LHV}) envisaged in Fit for 55, the plan aims to save a further 35 billion cubic metres (342 TWh_{LHV}) across Europe by 2030.

Process heat is used in many applications in industry, for example in drying processes in the paper and food industries or for process steam, which is needed for the production of plastics. In addition to natural gas, large quantities of other fossil fuels, such as coal or heating oil, are also used to provide process heat. In total, 510 TWh are required for the provision of process heat, which represents 22 percent of Germany's final energy consumption (BMWK 2022). These energy supply processes account for about two-thirds of industrial greenhouse gas emissions.

A rapid heat transition is therefore key to substantially reducing natural gas consumption and greenhouse gas emissions in the short to medium term. Various efficient processes are already available, especially in the temperature range below 500 degrees Celsius, which accounts for almost half of industrial demand for heat.

Renewable hydrogen is often the focus of political discussions on the decarbonisation of industry. What is often overlooked is that renewable electricity is scarce and must therefore be used as efficiently as possible. The production of renewable hydrogen is very electricity-intensive, which is why hydrogen will be scarce and expensive for the foreseeable future – and this is why it is important that the use of hydrogen in industry remains primarily for non-energy purposes. Similar principles apply to the use of biomass, which is only available in limited quantities and must also primarily be used for higher-value non-energy applications. The aim must be to keep competing uses to a minimum and to strengthen technology options that are suitable from a system perspective. For heat production, there are more energy and resource efficient options, especially in the lower temperature ranges up to 500 degrees Celsius, which should be used instead of alternative fuels.

All the various climate neutrality scenarios see the direct electrification of industrial process heat as a key strategy for the decarbonisation of industry (Prognos et al. 2022). At low temperatures, great potential is also seen in renewable heat sources such as (deep) geothermal energy and (concentrating) solar thermal energy (IN4climate.NRW 2021, Fraunhofer & Helmholtz 2022). In light of the German government's ambitious target for the expansion of renewable energies, the integration of volatile renewable electricity generation has a special role to play. Since the electrification of the demand side is key to this,

this study focuses on how synergies can be created between the decarbonisation of industrial heat and the power sector.

Our study shows that the direct use of electricity to generate process heat in industry has a three-fold positive effect on key climate and energy policy goals: 1) It contributes to the rapid reduction of greenhouse gas emissions and the achievement of climate neutrality by 2045. 2) It reduces the use of natural gas and other fossil fuels and thus helps to end the structural dependence on Russian gas imports. 3) By making electricity consumption more flexible, it supports the expansion and integration of renewable energy and thus the development of a fully renewable energy system.

1. **Achieving climate policy goals:** The electrification of process heating will bring industry a substantial step closer to achieving its climate goals. The Federal Climate Protection Act requires Germany to be climate-neutral in 22 years at the latest. After energy, the industrial sector is the sector with the second highest greenhouse gas emissions. In 2021, at 181 million tonnes of $CO_{2\text{-eq}}$, it remained just below its annual emissions level of 182 million tonnes of $CO_{2\text{-eq}}$ as stipulated in the Federal Climate Protection Act. Recently, emissions have risen sharply – in part due to the economic recovery following the pandemic lockdown. How greenhouse gas emissions will develop in the short term as a result of the current energy crisis is still uncertain. What is clear, however, is that structural measures must be taken to ensure that the annual target overshoots in the industrial sector forecast in the 2021 projection report do not occur after 2023 (Bundesregierung 2021). The replacement of CHP plants or steam boilers using natural gas by heat pumps and electric boilers for the generation of industrial process heat in the temperature range up to 500 degrees Celsius can save a total of approximately 12.5 million tonnes of $CO_{2\text{-eq}}$ by the year 2030. This corresponds to about 18 percent of the 68 million tonnes of GHG savings needed to meet the climate protection target for the industrial sector for the year 2030.

2. **Natural gas savings:** The use of heat pumps and electric boilers to generate industrial process heat can make a key contribution to achieving the REPowerEU targets by 2030 and will help to end structural dependence on imports of Russian gas. By using heat pumps and electric boilers to generate industrial process heat, a total of around 9.5 billion cubic metres (90 TWh_{LHV}) of natural gas can be saved in Germany by 2030. Together with the use of renewable hydrogen for non-energy purposes – and at high temperatures also as fuel – and other innovative applications, German industry can halve its natural gas consumption by 2030 and thus make an important contribution to European energy autonomy.

3. **Flexibilisation:** Heat pumps and electric boilers can be flexible in terms of their electricity intake. This kind of flexible electricity consumption is of key importance in enabling a high share of renewables in the power system, and is therefore important for the German government's goal of sourcing at least 80 percent of gross electricity requirements from renewable energy sources by 2030. At times when the feed-in of electricity from wind and solar power is particularly high, flexible consumers can increase demand. At times when electricity production from renewables is particularly low, flexible consumers can reduce demand. Such consumers can thus flexibly "match" volatile generation from renewable sources on the consumption side. This serves to buffer and secure both the production from renewables and also the price of electricity. Overall, flexible consumers effectively reduce costs in the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG) and reduce the need for additional electricity storage.

In order to ensure that the benefits of a rapid transformation of industrial process heating are realised, and to ensure that heat pumps and electric boilers quickly become the new standard technology for heat generation in industry, policymakers must put together a package of measures. The Energy Security Act should stipulate that all processes for the generation of industrial process heat up to 500 degrees Celsius should be fossil-free by the year 2035. This will ensure the reduction in the use of natural gas in the industrial sector needed to achieve the REPowerEU targets, and enable Germany to fulfil its responsibility to reduce its dependence on Russian gas imports in the European context.

To achieve this goal, existing perverse incentives deriving from free allocation in the EU ETS together with a range of subsidies to fossil fuel installations must be abolished. On the other hand, initial investments in particular must be subsidised and clear orientation must be provided by regulatory standards.

In addition, the reform of grid fees *is* a key element in encouraging electrification and flexibility in usage and must become a political priority for this legislative period. This is because the compatibility of economic efficiency and flexibility in electricity usage is currently hindered by the existing grid fee structure, which penalises flexible electricity usage. Electric boilers especially can take advantage of favourable electricity prices at times when the feed-in of renewables is particularly high. However, flexible and thus market-serving electricity usage is associated with low full-load hours, which under current regulations leads to high grid charges. This means that system-serving electrification has to date not been economically worthwhile compared to the base load operation of a CHP plant.

In contrast to electric boilers, heat pumps can reduce costs and emissions today already in base load operation through the efficient use of waste and environmental heat. The disadvantage of these devices, however, is the high investment cost. To nevertheless stimulate first projects and to make use of the positive effects of a rapid market ramp-up, a special support programme needs to be set up for a limited period of time. In order to enable a heat transition across industry it is necessary to ensure the ramp-up of supply and installation capacities, the rapid expansion of renewables and access to the necessary grid infrastructure.

Finally, the legal introduction of a *zero carbon* standard for new investments in process heat up to 500 degrees Celsius is indispensable for planning and investment certainty. Especially in the temperature ranges for which there are already commercially available CO_2-free technology options, there should be a legal standard for all new investments. This creates planning certainty for industrial users and plant manufacturers and avoids misplaced investments in fossil fuel systems.

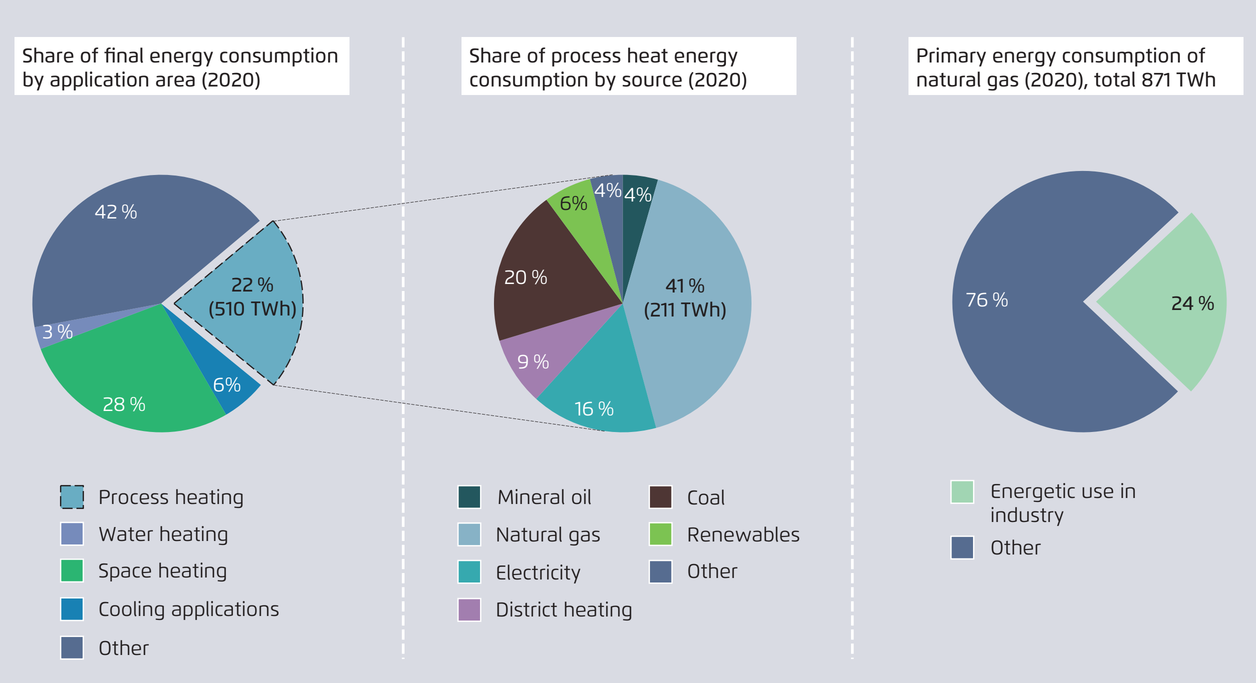
2 Industrial process heat: status quo and strategies for the transformation

In 2020, process heat accounted for 22 percent of Germany's total final energy consumption. 41 percent of process heat was produced using natural gas (BMWK 2022). Gas boilers are often used for this purpose in industry; however, as a rule, combined heat and power (CHP) plants are used, which convert part of the heat into electricity. Coal also plays an important part, at 20 percent. Mineral oils, at 4 percent, are less significant, but could be used again in greater quantities during the current energy crisis. Electricity is already a significant energy source, accounting for 16 percent, but its role in the production of process heat can be considerably expanded (cf. Fig. 1).

The electrification of process heat in this way – switching from natural gas and other fossil fuels to renewable, electricity-based technologies – is urgently needed to reduce the consumption of gas and, at the same time, to enable Germany to achieve its climate protection targets under the Federal Climate Protection Act. The energetic use of natural gas in industry for the provision of heat and electricity accounted for 211 TWh_{LHV} or 24 percent of natural gas consumption in Germany in 2020. The EU Commission's REPowerEU plan envisages a reduction in natural gas consumption by 35 billion cubic metres (342 TWh_{LHV}) for industry across Europe, which roughly corresponds to a reduction of 41 percent.

The role of process heat in the German energy system and its share of German natural gas consumption

Figure 1



BMWK (2022), Agora Energiewende (2022a)

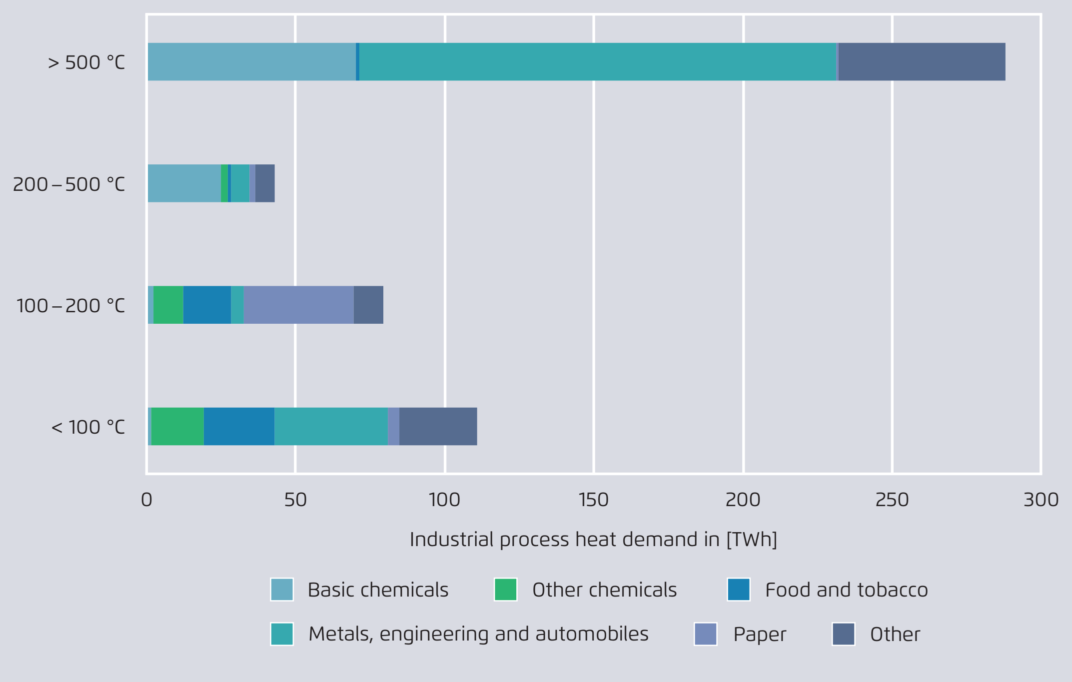
For Germany to contribute its full share to achieving the target, fundamental structural changes in the energy supply to industry are necessary. A rapid heat transition in industry is a prerequisite for this.

The temperature of the required process heat is of crucial importance for the selection of suitable transformation strategies and technologies.
As shown in Figure 2, industry requires process heat at different temperature levels. Especially in steel production and other metallurgical processes, but also for example in glass production, high temperatures of over 500 degrees Celsius are required. High-temperature heat is also required in the chemical industry, for example, to break down chemical molecules (cracking).

Heat up to 200 degrees Celsius is used above all in the food, paper and chemical industries. This includes processes for heating, boiling down or baking in industrial food production, and for drying paper. Overall, about 37 percent of the demand for heat is below 200 degrees Celsius. Heat at 200 to 500 degrees Celsius accounts for just under 10 percent of the demand in industry. Particularly for such low and medium temperatures, heat pumps and electric boilers offer efficient and market-ready technology options.

Suitable transformation strategies and technologies for decarbonising process heating can be broadly divided into two categories. Firstly, measures aimed at energy saving and efficiency through increased use of waste heat (efficiency first). This principle applies to all temperature ranges. Secondly, measures aimed at converting the primary energy source, for example to electricity-based technologies (as part of the energy or heat transition). The appropriate technologies and transformation paths may differ depending on the temperature range.

Final energy demand for the generation of industrial process heat by temperature level — Figure 2



Fraunhofer ISI (2016), values taken from UBA (2017)

2.1 Efficiency: improving waste heat utilisation

The top priority for the heat transition is the principle of 'efficiency first', i.e. reducing primary energy demand. The less energy is consumed, the less needs to be decarbonised through the use of renewable energies and electrification. A large proportion of the waste heat generated in industry has always been utilised. Wherever processes take place at high temperatures, waste heat is also produced. Such waste heat can be used to supply heat to processes that run at lower temperatures. This so-called heat or energy integration can be further improved by the use of heat pumps, thereby increasing energy efficiency. Heat pumps raise the temperature level of waste heat and thus make it more usable.[1] In this way, heat pumps enable the *upcycling* of heat, which contributes to the reduction of primary energy demand. In addition to waste heat generated directly at the individual industrial location, consideration can also be given to the use of industrial heat from other plants in the region, the integration of industrial facilities into heat grids and the use of heat sources in the environment.

The identification and exploitation of existing potential efficiency gains is at the core of any sustainable strategy for the transformation of industrial heating. Depending on the individual temperature level and application, various key technologies can be considered for decarbonising the primary energy demand that remains once efficiency measures have been implemented.

2.2 Renewable heat: key technologies for industry

A number of possible approaches and technologies are available for decarbonising process heating. A heat transition that is sustainable and economically viable and thus successful in the long term must take limited resources and future competing uses into account. The focus must be on precisely tailored solutions that are as energy- and resource-efficient as possible.

Use of alternative fuels

One obvious option for replacing fossil fuel combustion processes for heat generation is the use of alternative fuels. Burning plastic waste or biomass rather than conventional processes using natural gas requires only minor adjustments in terms of technical implementation and operation. However, bearing in mind possible competing uses, the purely energetical use of alternative fuels is not a sensible or sustainable strategy for the decarbonisation of process heat.

For example, the use of plastic waste as an alternative fuel conflicts with the goals of an energy- and resource-efficient circular economy. In future, limited quantities of plastic waste will be needed primarily for higher-value material uses (Agora Industry 2022). The incineration of typical plastic waste also releases large amounts of CO_2 and is therefore not compatible with climate neutrality.

The use of biomass as an alternative and renewable fuel is also much discussed. However, this must not be at the expense of other sustainability goals, such as global food supply or biodiversity. Ideally, its production and use can contribute to the urgently needed transformation of forests and agriculture towards more climate resilience and biodiversity. However, the combustion of sustainable biomass also causes direct biogenic CO_2 emissions which, measured against the heat provided, can be higher than the CO_2 emissions of the reference systems (for example, the use of natural gas in a steam boiler).

1 The functioning and the state of the art of heat pumps are described in chapter 3.2.

CO_2 emissions from sustainable biogenic fuels can be counted as climate neutral, but the use of these fuels for processes that can be decarbonised in other ways ignores their value as a source of renewable carbon for creating long-term CO_2 sinks. The use of biomass in construction or as a source of carbon for the production of lifespan chemical products can conserve the natural CO_2 sink capacity of forests, unlike its purely energetical use.

Use of renewable heat sources

The direct use of renewable heat sources offers an alternative: here, process heat is no longer generated from fuels such as natural gas or biomass, but by using local renewable heat sources – above all geothermal energy and solar thermal energy.

Deep geothermal energy harnesses the geothermal heat of deep rock strata at depths of 1 000 to 4 000 metres. Because of its particular geological conditions, Germany is regarded as having great potential for harnessing heat at temperatures of up to 180 degrees Celsius (Fraunhofer & Helmholtz 2022). However, the costs and risks of drilling for exploration and during operation of the facilities are high. Provided that these hurdles can be overcome through greater experience and better instruments for managing the financial risks, deep geothermal energy could make an important contribution to the industrial heat transition and to the Energiewende in general. In the short term, however, deep geothermal energy is likely to have only limited significance in reducing natural gas consumption and emissions.

Another option for the generation of low-temperature heat is Concentrated Solar Power (CSP). In combination with heat storage and other technologies, heat supply can be ensured even over a high number of full-load hours. One disadvantage of solar thermal energy is its large spatial footprint (IN4climate.NRW 2021). This makes solar thermal energy particularly suitable for producing small and medium amounts of heat, as well as for use in rural areas. Especially in places where the grid infrastructure for direct electrification is inadequate, but where sufficient free space is available, solar thermal energy can be a useful renewable heat source for industry.

Renewable heat sources such as solar or geothermal energy are important components of the industrial heating transition. However, due to technical, geological or spatial constraints, it can be assumed that they are more suitable for specific individual applications and cannot be deployed across the board for the industrial heat transition.

Use of electricity-based processes

Electricity-based processes such as heat pumps and electric boilers are a key and universal element of the industrial heat transition. There are also numerous other sector-specific options for the direct electrification of heat production. Examples are the use of electric arc, induction or infrared applications (Maddedu et al. 2020). Because of the breadth of their applicable range, this study focuses on the use of heat pumps and electric boilers, but the insights and principles that emerge can be transferred to other technologies for the direct use of electricity.

In addition to the direct use of electricity, which is the focus here, indirect electrification through the use of renewable hydrogen is also currently the subject of intensive discussion. Hydrogen has the advantage that it can replace natural gas in many fields of application with only minor changes to the technical processes in all temperature ranges.[2] Its use, however, is not energy efficient.

Efficiency losses in the production and use of renewable hydrogen mean that a great deal of electricity is required. Compared to direct electrification

2 The use of hydrogen could therefore also be dealt with in the section "Use of alternative fuels" (above). Because of the considerable effects for the electricity system and infrastructure of using electrically generated hydrogen, the use of hydrogen is addressed in this section.

with electric boilers, hydrogen-based heat requires about 60 percent more electricity. Compared to an efficient heat pump, the use of hydrogen to provide low-temperature process heat requires up to six times more renewable electricity (cf. Fig. 3).

In addition, the use of hydrogen requires the creation of an infrastructure for production, storage and transport. This entails considerable costs, which have to be covered at least in part by substantial public investment.

In the interests of a resource- and cost-efficient transformation, the decarbonisation of process heat – especially at low and medium, but also at high temperatures – should be focused on efficient direct-electric systems. This saves electricity compared to using hydrogen and thus facilitates the decarbonisation of the electricity sector. The lower the electricity demand, the faster fossil power plants can be replaced by renewable energy.

Figure 3 compares the temperature range that can be achieved by selected technologies with their electricity consumption. In addition to absolute electricity consumption, which should be kept as low as possible, the mode of operation is also crucial in an energy system based on volatile renewables. Flexible electricity use that adapts to production needs can facilitate the use of electricity and support the expansion of renewables.

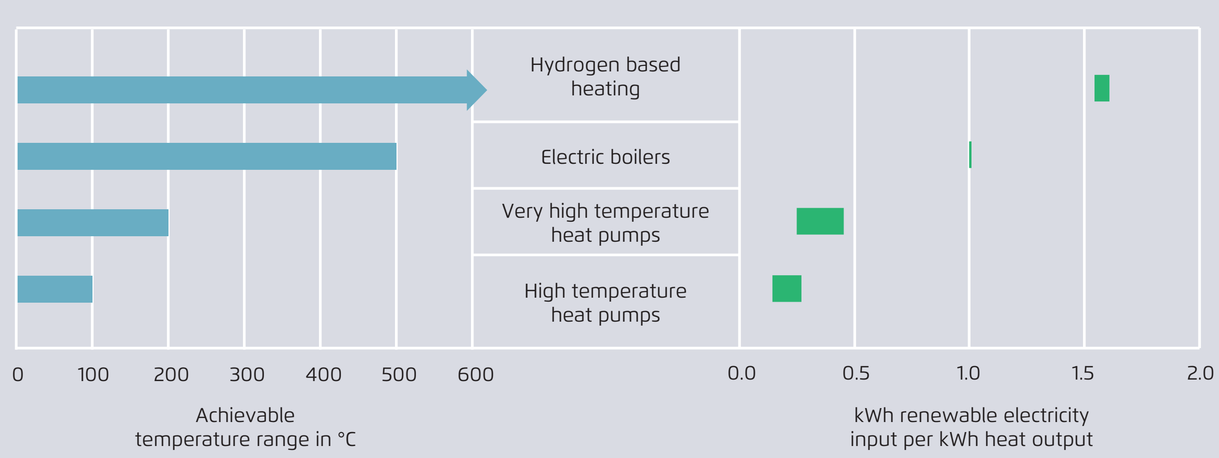
2.3 Flexibilities: direct electrification in a climate-neutral power system

The additional electricity demand from heat pumps and electric boilers does not have to make the decarbonisation of the electricity system more difficult, but can actually support the expansion and integration of renewable energies. By enabling a flexible way of operating which supports the system, the electrification of process heat can facilitate the use of renewable electricity and contribute to the efficient use of an increasing proportion of renewable energy in the electricity grid.

According to the coalition agreement of the Federal Government and the latest amendment to the Renewable Energy Sources Act (EEG), at least 80 percent of

Achievable temperature ranges and electricity requirements of electricity-based technology options for climate-neutral heat

Figure 3



Agora Industry (2022)

electricity consumption in Germany is to be provided by renewable energy sources by 2030.

If this ambitious expansion path is continued linearly after 2030, a climate-neutral power system is possible by 2035. The Agora Energiewende study *Klimaneutrales Stromsystem 2035* (climate-neutral power system 2035; Agora Energiewende, Prognos, Consentec 2022) sets out how this scenario can be achieved.

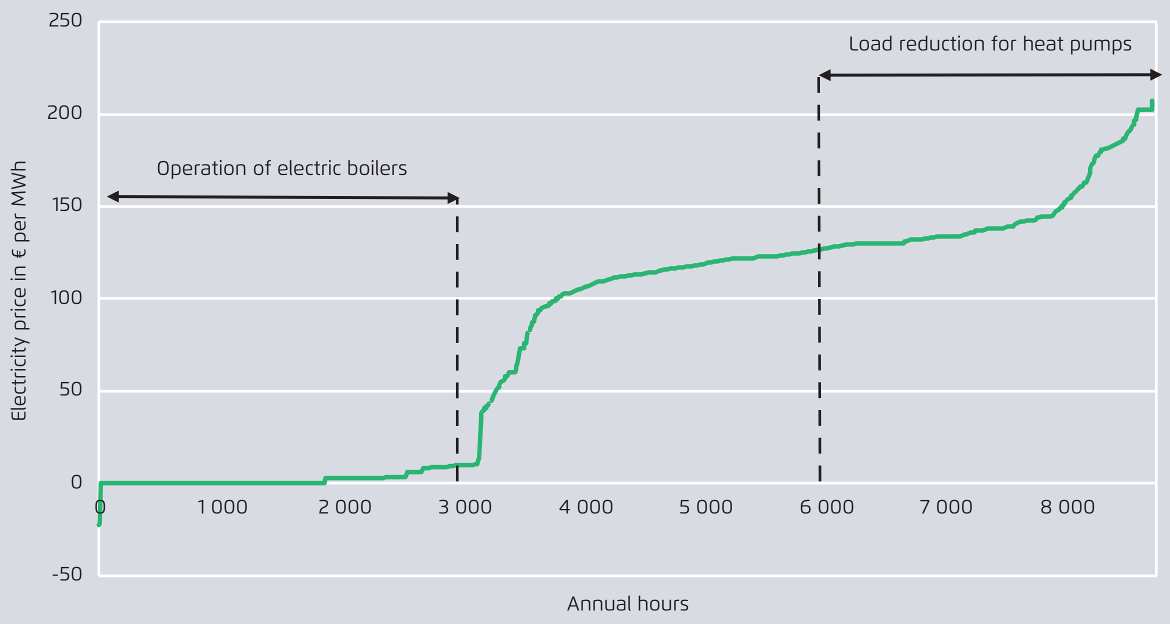
One challenge on the way to a climate-neutral power system is that electricity consumption in individual sectors such as industry and transport will increase in the course of the transformation. As shown in Figure 4, in a climate-neutral power system, electricity consumption can be expected to increase because of additional consumers to a total of 726 TWh by 2030 and 884 TWh in 2035. The electrification of industrial process heat, which today accounts for about one fifth of Germany's total final energy consumption, represents a substantial additional electricity demand and thus a major challenge for the electricity system. The goal must therefore be to balance the market ramp-up of electrification technologies with the expansion of renewables in order to avoid conflicts and increase synergies.

As long as they are operated flexibly, additional electricity consumers can efficiently modulate an electricity system increasingly based on renewables: in periods when the power feed-in from sun and wind is high, flexible consumers can generate additional loads. When renewable electricity is scarce, flexible consumers can reduce loads. In this way, flexible consumers support the expansion of

Gross electricity consumption in the scenario *Climate-neutral power system 2035* — Figure 4

Agora Energiewende, Prognos, Consentec (2022)

Electricity prices for the scenario *Climate-neutral power system 2035* Figure 5



Agora Energiewende, Prognos, Consentec (2022)

renewable energy, as they compensate for the variability of renewable electricity production through their flexible demand.

The improved alignment of electricity production with demand helps the decarbonisation of the power system. The widespread use of flexible electricity consumption to harness temporarily high supplies of renewable energy raises the market price for electricity, which during these periods is typically very low. This strengthens the economic case for the expansion of additional renewable energy sources. At the same time, it lowers the cost of the Renewable Energy Sources Act (EEG), as an increase in electricity prices leads to lower spending on feed-in premiums.

At times when little renewable electricity is being fed into the grid and electricity prices are high, flexible consumers can reduce their load. In the short and medium term, this can reduce the use of high-emission and expensive marginal power plants on the electricity market. Flexible consumers can also reduce the need for additional electricity storage in the long term, as they have the same effect on the balancing of supply and demand as the use of electricity storage. Through the use of efficient direct electrified systems, electricity losses from storage and retrieval can be avoided and infrastructure costs reduced. Flexible electricity applications such as heat pumps, electric boilers, electric vehicles and electrolysers can thus reduce the costs to the national economy of the expansion of renewables and of additional electricity storage facilities and help keep electricity costs low. Figure 5 shows electricity prices modelled for the Agora scenario *Climate-neutral power system 2035* as a load duration curve.

There are numerous options for making electricity procurement for industry more flexible, but in many cases, these options are very sector- and process-specific.[3] The electrification of process heat is a relatively easy and widely applicable way to increase flexibility in electricity consumption. In addition to the ongoing option of using heat storage in order to decouple electricity consumption from heat consumption, a hybrid operation in conjunction with existing fossil fuel plants is an excellent option for progressing towards climate neutrality. For example, back-up or security capacities can be electrified and operated alongside fossil fuel primary capacities. Even if back-up capacities are not needed, the addition of electric boilers or heat pumps can make economic and strategic sense. It enables both a diversification of the energy supply and at the same time the flexible procurement of electricity, which means lower electricity costs on average.

Electric boilers have relatively low investment costs. From an economic perspective, it can therefore also make sense to operate them at low full-load hours and therefore in times of low electricity prices.[4]

Compared to electric boilers, heat pumps are more capital intensive, but require less electricity. From an economic perspective, it therefore makes sense to operate them at high full-load hours, even at higher electricity prices. In terms of flexibility, heat pumps can reduce their load during periods of particularly low feed-in from renewables and when electricity prices are correspondingly high.[5]

3 One example is the particularly electricity-intensive production of aluminium, where flexibility can be enabled through process adjustments (SynErgie 2019).

4 The economic efficiency of electric boilers and current perverse incentives affecting their operation are examined in Chapter 3.4.

5 The economic efficiency of heat pumps is examined in chapter 3.5.

2.4 Synergies between electrified flexible heating and direct investment in renewable energy

In addition to their primary goal of reducing costs and direct emissions, companies increasingly want to mitigate their indirect emissions, for example from the generation of the energy they use. This can be achieved by investing in the development of renewable energy or by buying electricity generated using long-term green power purchase agreements (PPAs). In principle, this also gives companies access to the low electricity production costs of renewable energy. On an annual average, these are far below the prices of the electricity market, which determine the costs of electricity drawn from the grid.[6]

The risks for companies that invest directly in the expansion of renewable energies or PPAs can be minimised by combining these investments with electrification measures. To illustrate the principle, Figure 6 depicts the load duration curve for the power production of a hypothetical portfolio with 10 megawatts each of photovoltaics, onshore and offshore wind power. The graph shows that such a

6 Prices on the electricity market are set primarily by the costs of the marginal power plant used: while the production costs of renewable electricity are defined only by the interest on its investment costs, the market price is determined at all times by the balance of demand and supply. If the electricity supply from renewable energy sources is greater than the demand, the market price approaches zero, as its use does not incur any additional costs. If, however, demand is greater than supply, this demand must be met by thermal power plants, which are operated using natural gas, among other fuels. The costs for operating these expensive power plants then determine the market price for electricity and thus also the value of additional generation from renewable energies at this point in time. The active involvement of industry in the electricity market in the form of investments to expand renewable energy or through the operation of flexible loads does not fundamentally change this mechanism, but it does open up opportunities to manage risks and to create value for the company and the national economy through market-oriented behaviour.

portfolio can be combined with electric boilers with a capacity of about 7.5 MW, which allow quite large amounts of electricity to be used at up to 4 000 full-load hours per year. In addition, a further 7 MW of heat pumps can be used, which can be operated efficiently at between 4 000 and 8 000 full-load hours. A further 2.5 MW can be used in base-load operation in processes that do not allow flexible electricity input.

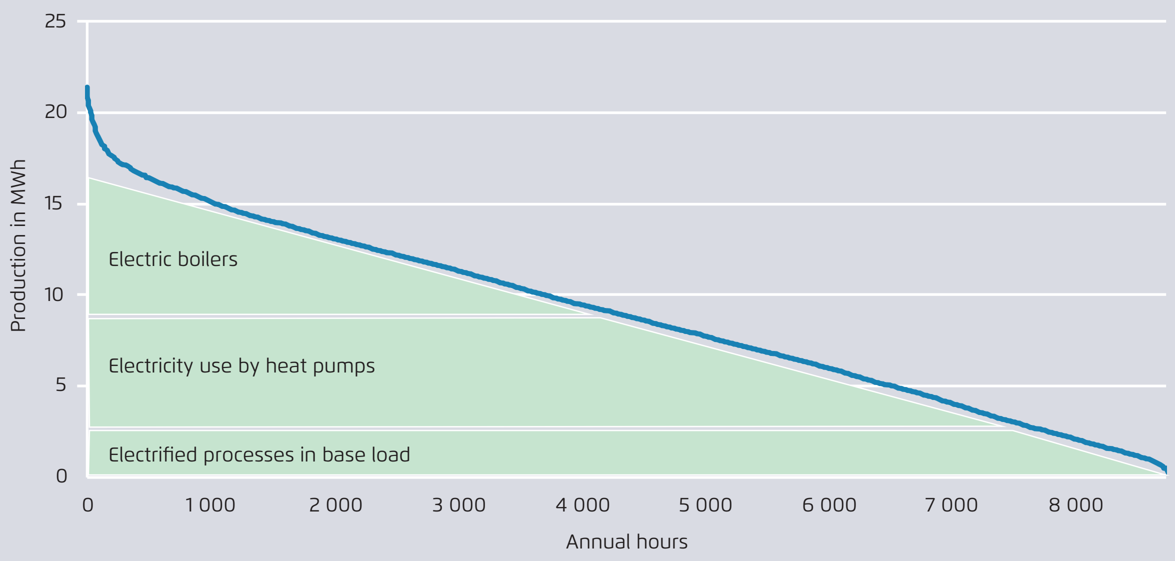
Thus, the investments in direct electrification and in the expansion of renewable energy mutually reinforce each other. For heat pumps and electric boilers, access to predictable and low electricity costs is ensured; for renewable energy generation, the electricity produced is guaranteed to be used at predictable and economically viable rates – even in periods when the feed-in of renewables into the electricity grid is high and electricity prices are low.

In addition, the company retains the flexibility to purchase additional electricity when market prices are low or to use its flexibility to sell its electricity on the market when prices are high.

By designing a portfolio of flexible loads and generation capacities and engaging energetically and effectively in the electricity market, a company can also create the space to operate electrified processes in the base load using low-cost renewable electricity.

Electricity production of a renewable portfolio consisting of 10 MW each of photovoltaics, onshore wind power and offshore wind power

Figure 6



Data basis for the yield by generation technology is national production in 2020 divided by nationally installed capacity based on the Agorameter

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3 Technology options for direct electrification

As a way to illustrate the principles, opportunities and challenges associated with the direct electrification of process heat, this study focuses on electric boilers and heat pumps as cross-cutting technologies with a wide range of applications.

Heat pumps and electric boilers differ in their underlying operating concepts: electric boilers are very simple heating systems that can be installed at relatively low cost and can be operated flexibly and in a way that reinforces the power system. They are efficient in the direct conversion of electricity into heat at temperatures of up to 500 degrees Celsius, but require a lot of electricity and thus also a large grid connection.

In contrast, heat pumps are innovative and in some respects, complex systems requiring higher investment costs, but allow waste heat from industrial processes or environmental heat to be used with relatively little electricity. This electrical utilisation of waste heat makes heat pumps highly efficient and particularly suitable for temperatures up to 200 degrees Celsius.

Electric boilers and heat pumps can be used in various industrial processes and integrated with other heat generation systems. They are thus cross-cutting technologies that are highly relevant for many industries. Even though, for the reasons mentioned above, we focus particularly on these technologies, many of the findings of this study can also be applied to other technologies. Examples are induction furnaces in metallurgy, infrared applications and E-crackers in the chemicals industry. Lighthouse direct electricity projects using electric boilers and heat pumps as well as the regulatory solutions discussed here thus also contribute to the development and implementation of other technologies and initiatives.

3.1 Technical description of electric boilers

Electric boilers use electrical energy to heat a heat transfer medium by means of electrodes. The live electrodes are brought directly into contact with the heat transfer medium. Figuratively speaking, they function like the immersion heaters that used to be used to boil water. Different heat transfer media can be heated, such as water, steam or heat transfer oils. In combination with downstream electrical superheaters, temperature ranges of up to around 500 degrees Celsius can be achieved (Agora Energiewende und Wuppertal Institut 2019). Compared to heat pumps, electric boilers have two advantages: higher temperatures can be reached, and no waste heat source is required for their use.

The efficiency levels of an electric boiler are close to 100 percent. This means that for every kWh of electricity used, up to one kWh of heat can be provided. The capacity of electric boilers for industrial steam generation is typically in the range 10 to 40 MW (AGFW, Hamburg Institute, Prognos, 2020). Larger capacities can be achieved by connecting several individual boilers in parallel.

Compared to heat pumps, electric boilers have low investment costs. However, in addition to the investment in the system itself, additional costs may be incurred for system integration and for the expansion of the grid connection.

Aside from the cost factor, another possible obstacle to the rapid implementation of electric boiler projects is the availability of the electricity grid infrastructure required. Electric boilers increase the electricity demand of the industrial sites involved, in some cases considerably. This is why the expansion of the grid and the processes involved in setting up the corresponding grid connections must be accelerated so as not to delay the implementation of these projects.

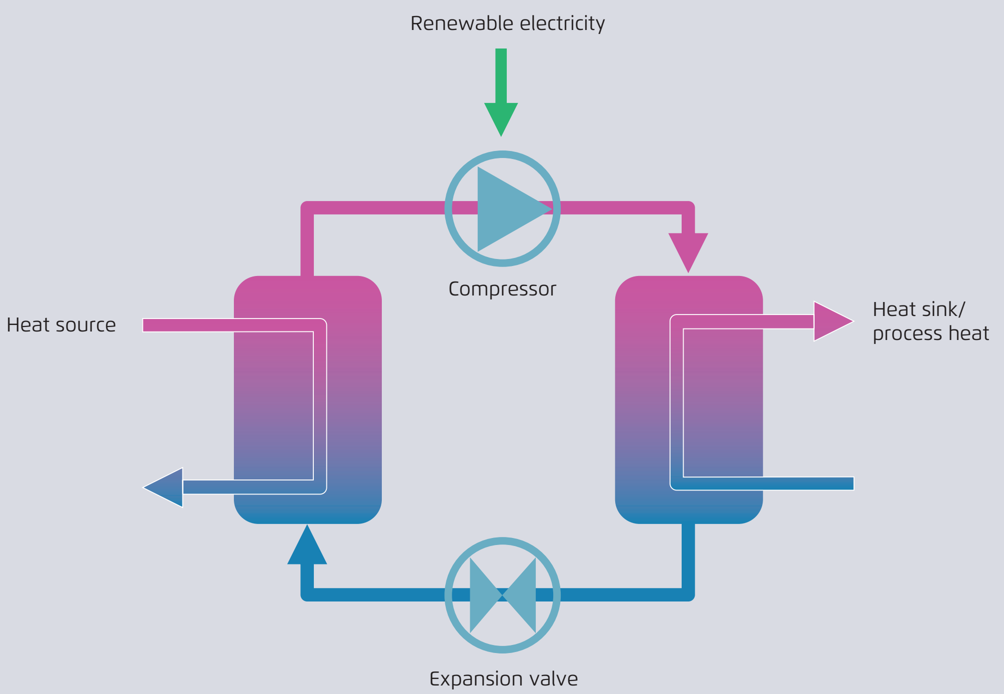
Because of their lower investment costs compared to heat pumps, electric boilers are particularly suitable for flexible operation. For the calculations made in this study, an electric boiler with a capacity of 25 MW is assumed. We further assume that the electric boiler is used flexibly in combination with an existing CHP plant or an existing gas boiler. The investment costs for the boiler in this study are estimated at 175 euros per kW of electrical capacity. In addition, an integration factor of 1.5 is applied to reflect the grid connection and integration costs.

3.2 Technical description of heat pumps

The use of heat pumps is a very efficient form of heat supply. An operating fluid circulates inside a closed circuit, absorbing heat at low pressure and low temperature from a suitable heat source. The heat source can be industrial waste heat or environmental heat. The heated operating fluid is compressed by means of an electrically driven compressor, which also raises the temperature. The heat can then be transferred and utilised at high temperatures. After the heat has been extracted, the operating fluid is depressurised.

This causes its temperature to drop again and it can in turn absorb heat from the heat source. Figure 7 is a schematic illustration of how a heat pump works. In addition to its function of providing process heat, a heat pump can cool the flow of waste heat through the utilisation of this heat and thus provide cooling. In

Functional diagram of a heat pump — Figure 7



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many industrial locations, the provision of cooling is needed and can therefore be monetised in addition to the heating function.

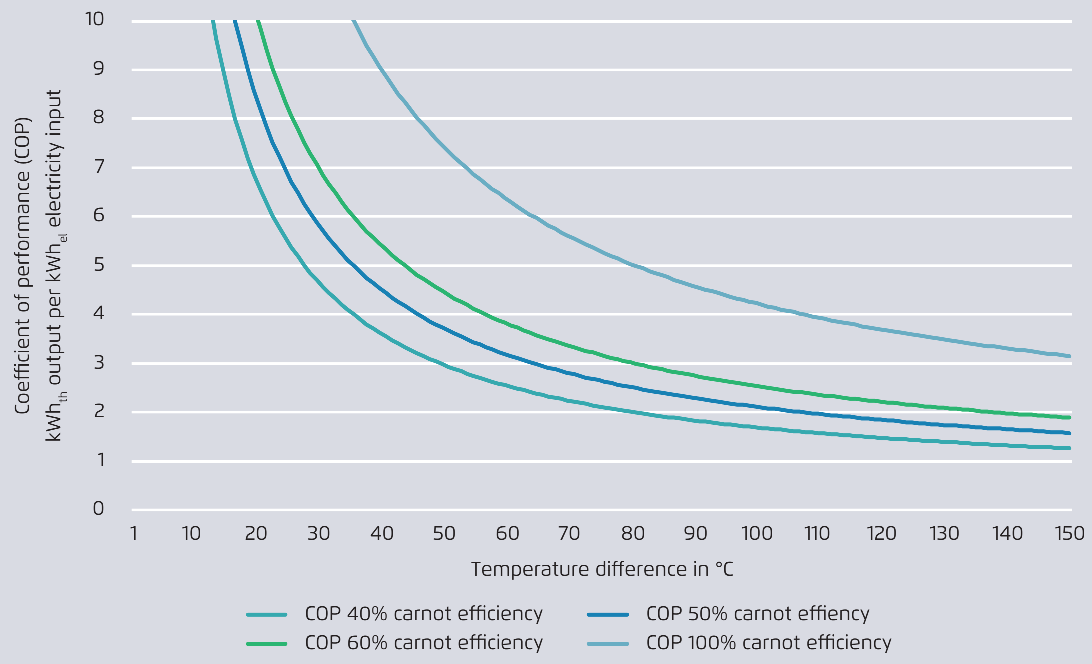
With currently available systems, a temperature boost in the range of 50 to 100 degrees can be achieved, depending on the waste heat source. In the standard process, this means that process heat of up to about 150 degrees Celsius can be generated. Through the use of downstream compressors, higher temperature levels up to about 200 degrees Celsius can be achieved. In principle, heat pumps can also be used at higher temperatures as long as the temperatures of the heat source and heat sink are in an appropriate ratio.

The high efficiency of heat pump technology is due to the fact that waste or environmental heat is tapped at a low-temperature level and through the application of electrical energy is released at a higher temperature level in the form of process or usable heat. The temperature difference between the heat source and the heat sink determines the efficiency of the system. The coefficient of performance (COP) defines the ratio between the electrical energy used and the useful heat gained. The coefficient of performance indicates how many kilowatt hours of heat output can be provided from one kilowatt hour of electricity.

Figure 8 shows the theoretical maximum for the coefficient of performance *(COP Carnot)* as well as the actually achievable coefficients depending on their Carnot efficiency and the temperature difference. The Carnot efficiency describes the variance between actually achievable values and the theoretical maximum. Existing heat pump systems currently achieve Carnot efficiencies in the range of about 40 to 60 percent (Arpagaus und Cordin, 2019).

The COP of a heat pump as a function of temperature difference and the Carnot efficiencies

Figure 8



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Heat pumps can have very different specifications and performance figures depending on the availability of waste heat and the required temperature increase. This study looks at two configurations which can be considered representative of the range of technologies available.

Firstly, we look at a high-temperature heat pump with a capacity of 7 MW.[7] With a source temperature of 30 degrees Celsius and a sink temperature of 85 degrees Celsius, the heat pump spans a temperature difference of 55 degrees Celsius with a coefficient of performance of 3.7. The investment costs are estimated at 700 euros per kilowatt (AGFW 2020).

Secondly, we look at a very high-temperature heat pump with a downstream vapour recompressor and an output of 6.7 MW. This very high-temperature heat pump spans a temperature difference of 130 degrees Celsius (temperature source: 50 degrees Celsius, temperature sink or process temperature: 180 degrees Celsius) and has a coefficient of performance of 2.2. The investment costs are estimated at 870 euros per kilowatt hour (Joormann und Laister 2019).

The investment costs for heat pumps are significantly higher than for electric boilers. In addition to the investment in the system itself, considerable additional costs can arise for accessing heat sources at the industrial site and for integrating the system. These are taken into account in our calculations, using an integration factor of 1.5 in relation to the system costs. However, the costs for integration into the production network can vary greatly depending on the specific application.

Industrial heat pumps are currently still rare in practice. Supporting lighthouse projects can help to bring heat pumps into wider use: establishing heat pumps as a standard technology in industry, scaling up production capacities, and of course further advances in technological development can lead to a reduction in investment costs and improvements in performance.

3.3 Ecological principles for the operation of electric boilers and heat pumps

As described in chapter 2.3, the use of electrification technologies must be compatible with the decarbonisation of the electricity system. While the use of electric boilers and heat pumps in industry reduces direct greenhouse gas emissions, an increase in electricity consumption will lead initially to higher emissions from the electricity sector. Emissions are thus shifted from industry to the electricity sector. Greenhouse gas emissions from the electricity sector will be reduced over the medium term through the expansion of renewables.

For the generation of industrial process heat up to 500 degrees Celsius, CHP systems using natural gas are currently regarded as the industry standard. Depending on the efficiency of the unit, heat production with natural gas via a gas-fired steam boiler emits around 220 grams of CO_2 per kilowatt hour of heat (Agora Energiewende and Wuppertal Institut, 2019). For CHP plants, we assume an equivalent distribution of emissions between electricity and heat and thus arrive at the same emission intensity.

For effective climate protection, the sum of the emissions from the electrified plant and the electricity used must be lower than that of the gas-fired reference plant.

Figure 9a shows the sum of direct and indirect emissions from the operation of an electric boiler and of two representative heat pumps depending on the

7 Heat production.

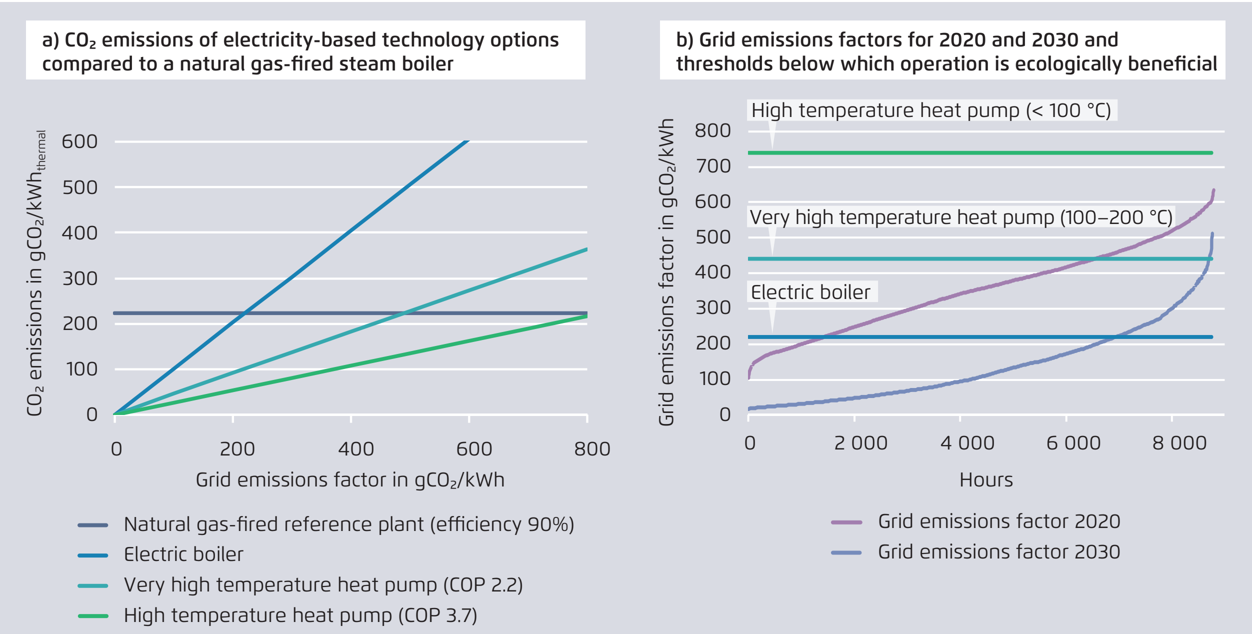
grid emissions factor.[8] The emissions from an electric boiler increase in linear fashion with the grid emissions factor. At around 220 grams of CO_2 per kilowatt hour of electricity, there is equivalence between the emissions from the electric boiler and those from a gas-fired steam boiler or a CHP plant. Only up to this intersection point – at an electricity emissions factor below 220 grams per kilowatt hour – does the electric boiler save emissions compared to the gas-fired reference plant.

Compared to the electric boiler, heat pumps require less electricity to produce the same amount of heat. Proportionate to the coefficient of performance, the indirect emissions from electricity use increase at a correspondingly slower rate. Thus, even with a higher emission intensity from the electricity mix, a heat pump can still produce heat in such a way that an overall CO_2 reduction is achieved.

Figure 9b situates the thresholds below which CO_2 reductions can be achieved against the grid emissions factor for 2020 and the projected figures for 2030, which were modelled on an 80 percent share of renewables in the electricity sector (Agora Energiewende, Prognos, Consentec 2022). In the case of the historical figures from 2020, the threshold of 220 grams of CO_2 per kilowatt hour was not exceeded for around 1 400 hours. For a net CO_2 reduction to take place, it would only make sense to operate the electric boiler during the 1 400 hours in which a large

8 The so-called grid emissions factor denotes the emission intensity of the electricity grid at a given point in time. As shown in Figure 9b, it is highly dependent on the electricity being fed into the grid at that point, including from renewable energy sources.

CO_2 emissions of electricity-based technology options in the context of emissions from the electricity system — Figure 9



The grid emissions factors for 2020 are historical values taken from the Agorameter (Agora Energiewende 2022a); the grid emissions factors for 2030 correspond to an electricity system that is 80 percent based on renewable energy (Agora Energiewende, Prognos, Consentec 2022).

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amount of renewable electricity was available. A systematic expansion of renewables increases the CO_2 savings from electric boilers to a corresponding extent. Such a systematic expansion of renewables would mean that by 2030 already more than 6 000 full-load hours would be ecologically beneficial and lead to CO_2 reductions.

Thanks to their high efficiency and low electricity consumption, heat pumps already reduce CO_2 emissions when operating with today's electricity mix at high full-load hours.

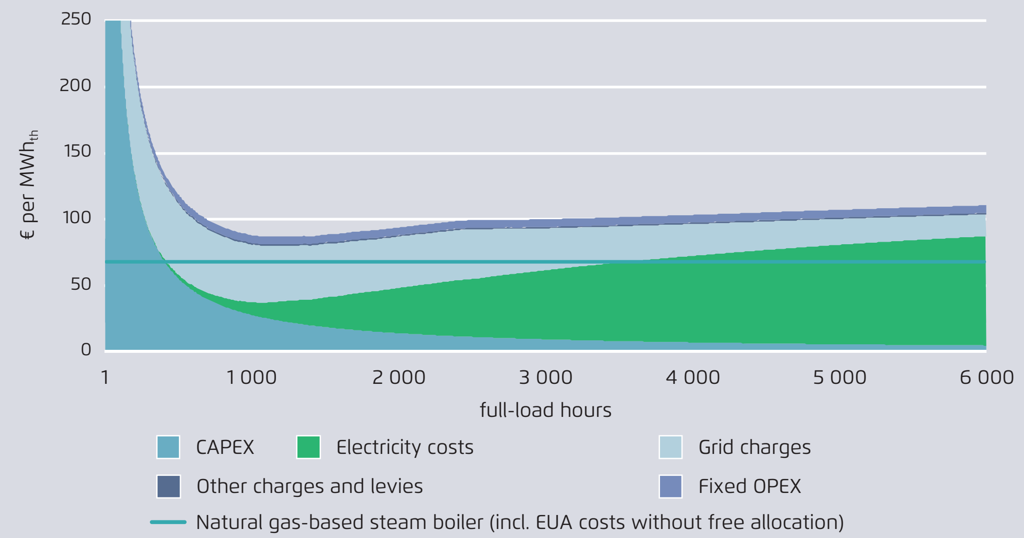
3.4 Cost-effectiveness of electric boilers: reforming the grid fee structure

Electric boilers are not very capital-intensive, but require large amounts of electricity. This means that the economic viability of electric boilers is primarily dependent on low electricity costs, which, in addition to taxes and levies, are made up of the electricity market price and grid charges.

Figure 10 shows the average operating costs of an electric boiler as a function of the number of full-load hours. The electricity prices are sorted in ascending order following the principle of a load duration curve and correspond to a model drawn up for the year 2030 (Agora Energiewende, Prognos, Consentec 2022). Low electricity prices correlate with largescale electricity production from renewables. Therefore, both in cost terms and in terms of the system, operation at low full-load hours makes sense.

Average costs for the operation of an electric boiler as a function of the number of full-load hours

Figure 10



Electricity prices in accordance with *Climate-neutral power system 2035* averaged over full load hours (Agora Energiewende, Prognos, Consentec 2022); grid usage charges as applied by grid operator Westnetz in 2021 (Agora Energiewende 2021); assumed natural gas price: €39/MWh_{LHV} ; assumed CO_2 pricing: 100 €/EUA

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However, the current regulations governing the allocation of grid costs hinder a flexible and system-serving operation. The existing structure of grid charges was developed for a fossil fuel energy system. In the case of industrial electricity procurement, the grid charges are made up of a work component for the electricity consumed and a power component for the service of the grid access (This concept is unique to the German power sector). The work component is based on the total electricity consumption over a calendar year, while the power component is based on the peak demand occurring in the year (§ 17 (2) StromNEV). This is intended to reward electricity consumption that remains as far as possible at a constant level. At low full-load hours, high costs for the power component for the service of grid access prevail, which is intended to reward the most uniform electricity supply possible. On the other hand, low full-load hours are penalised with high grid charges.

If one were to consider only the investment and electricity costs in Figure 10, the lowest costs would be incurred at around 1 000 full-load hours. Compared to the fossil fuel reference system, with natural gas prices at 39 euros per MWh_{LHV}, an electric boiler could save costs at up to 3 500 operating hours. If grid charges as per the current regulations are taken into account, then electric boilers, and especially their operation in a system-serving manner, forfeit their economic advantage. At the actual lowest cost level of 1 000 hours, grid charges account for about half of total operating costs, and cost savings compared to the fossil fuel reference system are impossible in any operating mode, due to the current grid fee structure.

The existing system of grid charges is therefore completely unsuitable for the promotion of system-serving electricity use. In addition, there are other perverse incentives, which are summarised in the Infobox.[9]

Infobox: Grid charges

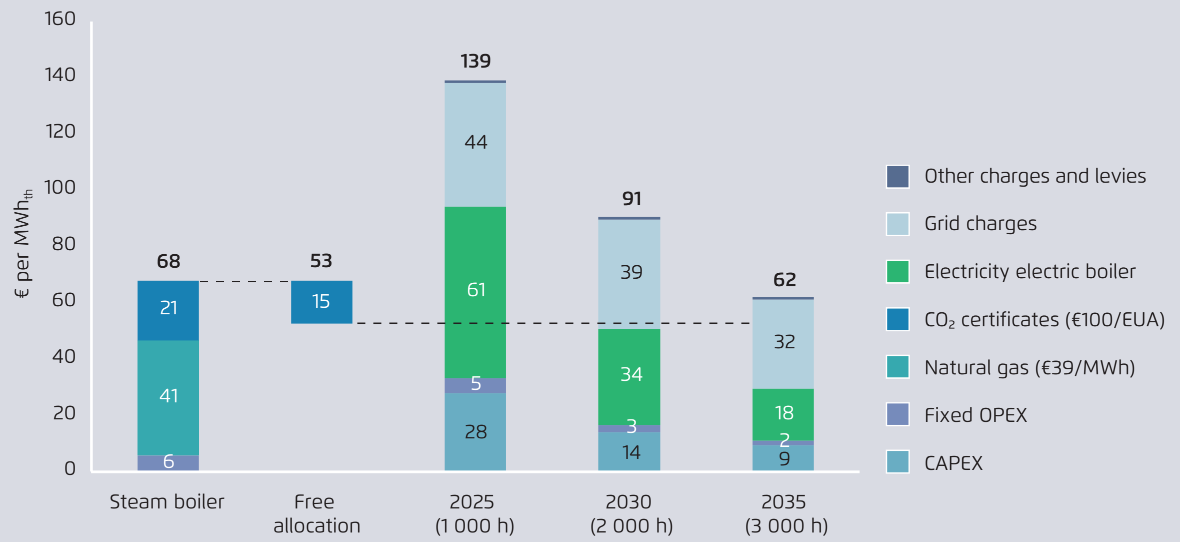
For large industrial electricity consumers, there is a further perverse incentive in addition to the general system structure of grid charges: § 19 (2) StromNEV provides for large reductions for a constant electricity consumption of more than 10 GWh. Above 7 000 full-load hours, grid charges are reduced by 80 percent, above 7 500 hours by 85 percent and above 8 000 hours by a full 90 percent. For companies whose electricity consumption is already large and who benefit from this regulation, the flexible and system-serving electricity consumption of an electric boiler can mean that the required full-load hours as defined in § 19 (2) StromNEV are not reached. Due to the current massive subsidisation of inflexible consumption, making electricity consumption more flexible can lead to very high additional costs, especially for large industrial consumers. The current regulatory regime discourages the kind of flexible electrification of industry that is actually in the national economic interest, and thus actively hinders the reduction of gas consumption, of greenhouse gas emissions, and of the costs of our energy system.

With the expansion of renewables, the full-load hours in which it makes ecological and economic sense to operate an electric boiler instead of a gas-fired steam boiler will increase over time. Based on the assumptions of the Agora scenario *Climate-neutral power system 2035*, these will be 1 000 full-load hours in 2025, rising to about 3 000 hours by 2035. Figure 11 shows the costs for the electric boiler in five-year steps and compares them to those of a gas-fired reference steam boiler. For the reference system,

9 A detailed analysis of the existing regulatory framework and the criteria for a future grid fee structure consistent with the energy transition was published by Agora Energiewende in an impulse paper in August 2021 (Agora Energiewende 2021).

Average costs for operating an electric boiler compared to a gas-fired steam boiler for the years 2025, 2030 and 2035 with increasing full-load hours

Figure 11



Electricity prices reflecting full-load hours according to Agora Energiewende, Prognos, Consentec (2022); grid charges as applied by grid operator Westnetz in 2021 (Agora Energiewende 2021)

Agora Industry, FutureCamp (2022)

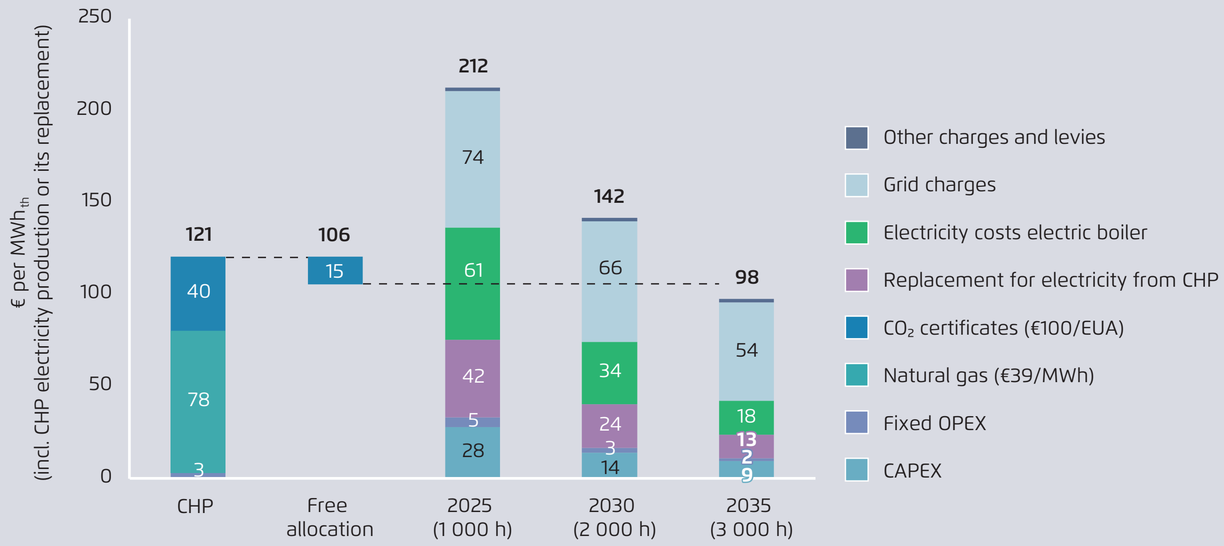
it is assumed that natural gas prices will fall somewhat in future and will be at around 39 euros per MWh_{LHV} in 2025. For the CO_2 price, 100 euros per EU emission allowance (EUA) is assumed. Electricity prices are still assumed to be high in 2025 and to fall with the expansion of renewables up to 2035. In addition, it is assumed that the fossil fuel reference plant has already been fully depreciated and that capital costs are therefore only incurred for the electric boiler. This also corresponds to hybrid operation of an electric boiler with gas-fired plants. The capital costs (CAPEX) are annualised to the full-load hours. This results in a decreasing proportion of investment costs in relation to heat production as the number of full-load hours increases.

The influence exerted by the EU ETS is greatly weakened in sectors that are at risk from *carbon leakage* by the allocation of free allowances. In the reference plant under consideration, costs for emission rights amount to 21 euros per MWh. Free allocation reduces the effective CO_2 costs by 15 euros, bringing them down to 6 euros per MWh. Free allocations for the generation of heat and steam are made for both CHP plants and steam boilers via the heat benchmark. The fuel used to generate the heat is irrelevant in this context. However, the EU Allocation Regulation (EU-ZuVO) explicitly excludes an allocation for heat generated using electricity. Thus, a switch to electricity-based heat generation always results in the loss of free allocation.

Electric boilers can be operated in hybrid mode with steam boilers or fossil fuel CHP plants in order to take over some of their workload temporarily and flexibly. Taking over heat generation from CHP may also lead to a reduction in electricity production. When this happens, the reduced electricity production in a

Average costs for the operation of an electric boiler in comparison to a gas-fired CHP system for the years 2025, 2030 and 2035 with increasing full-load hours

Figure 12



Electricity prices as in *Climate Neutral Power System 2035* reflecting full-load hours (Agora Energiewende, Prognos, Consentec 2022); grid charges as applied by grid operator Westnetz in 2021 (Agora Energiewende 2021)

Agora Industry, FutureCamp (2022)

hybrid concept of this kind must be compensated for by the purchase of additional electricity. The relevant cost comparison is shown in Figure 12.[10]

Overall, the comparison of costs over time shows in both cases that the operation of electric boilers still involves substantial additional costs, especially in the year 2025. Under current regulations, a cost advantage will only arise when the electricity system is increasingly renewables-based and climate-neutral. The additional costs are therefore incurred primarily in the market ramp-up phase of the transformation.

In order for the use of electric boilers to become economically viable today already and to exploit their advantages for the electricity system, grid charges must be reformed, the advantages accruing to fossil fuel plants through unequal treatment in the EU ETS must be eliminated, and capital costs must be subsidised. Another option for improving the economic competitiveness of electric boilers is to combine them with the purchase of renewable electricity through direct investments or through green PPAs (see chapter 2.4).

10 In the course of the project, a transformation cost calculator was developed which can be used to test different cost and technology assumptions. The Excel tool is available to download online: **https://www.agora-energiewende.de/en/publications/transformations-kostenrechner-power-2-heat/**

3.5 Cost-effectiveness of heat pumps: reducing capital costs and fossil fuel subsidies

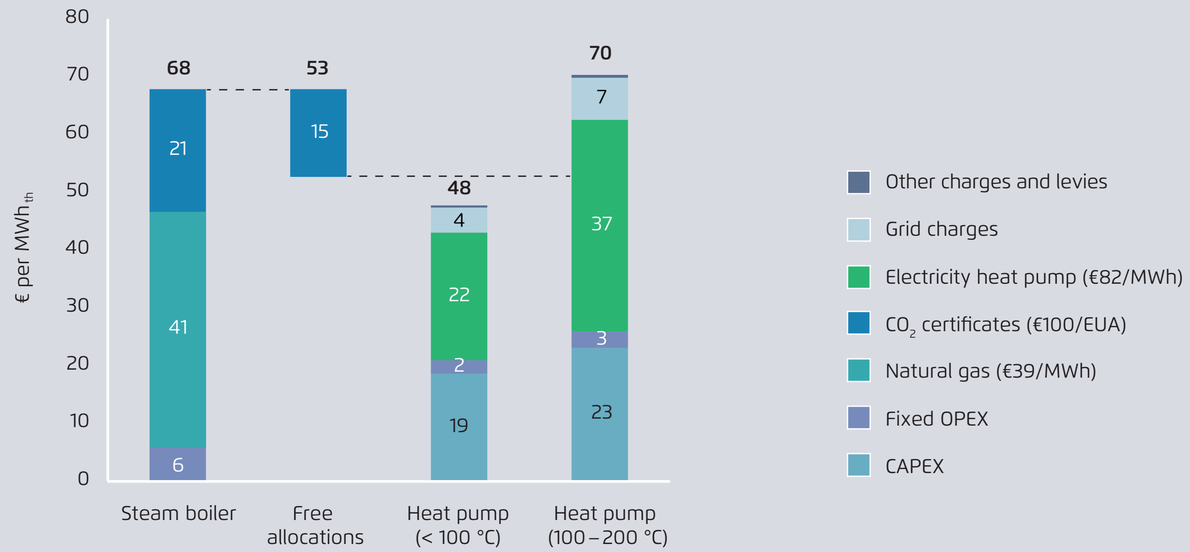
As shown in Figure 9, heat pumps can already achieve CO_2 reductions with today's electricity mix at high full-load hours due to their high efficiency and low electricity consumption. In addition, heat pumps are particularly economical at high full-load hours due to their comparatively high investment costs.

Flexibility can thus be enabled in particular through load reduction when renewables feed-in is particularly low and electricity prices are high. For industrial processes that require a heat supply with base load capability, heat pumps can at first be combined with existing fossil fuel plants or thermal energy storage systems.

Figure 13 shows a cost comparison between the two representative heat pumps (cf. chapter 3.2) and a gas-fired steam boiler. As previously described in chapter 3.4 for electric boilers, existing regulations for the free allocation of CO_2 certificates in the EU ETS distort the influence of emissions trading in favour of established fossil technologies in the case of heat pumps as well. Provided that waste heat sources are available, high-temperature heat pumps are already on the verge of being economically viable under the current regulatory framework. Very high-temperature heat pumps incur additional costs under these conditions.

The high capital and integration costs represent a major cost item and thus a major hurdle to a speedy implementation in practice. To achieve a rapid market ramp-up and to prevent new fossil fuel investments, it makes sense to provide initial assistance with capital costs. In addition to technical challenges,

Average costs for heat pumps compared to a gas-fired steam boiler in 2030 — Figure 13



Electricity prices as in *Climate Neutral Power System 2035* averaged over the 6 000 cheapest full-load hours; grid charges as applied by distribution grid operator Westnetz in 2021 (Agora Energiewende 2021)

Agora Industry, FutureCamp (2022)

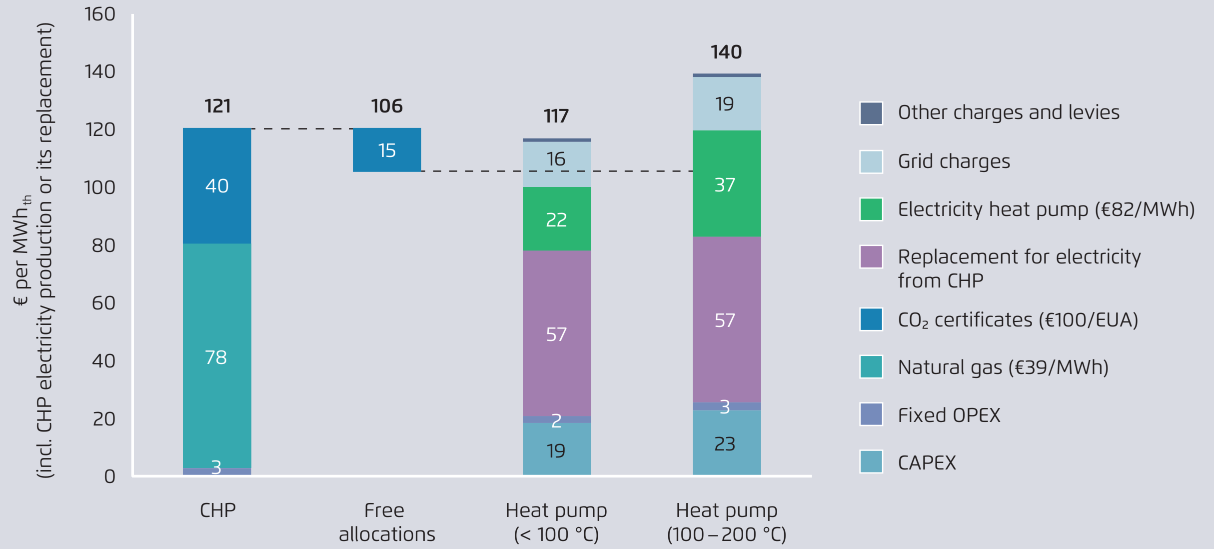
another barrier to the development of heat pumps for the very high-temperature range is that heat pump manufacturers often have less knowledge of industrial needs in these temperature ranges and the market potential is unclear (Marina et al. 2021).

The development of industry-specific standard requirements, for example for a representative paper production site, can help in bringing about an efficient market ramp-up. Clear standards and a coordinated market ramp-up can help to increase the serial production of heat pumps and to reduce the investment costs required.

Figure 14 depicts a situation in which heat pumps replace some or all of the output of an existing CHP plant. In our assumption, replacing the heat generation from the CHP plant – as already discussed above in the comparison with an electric boiler – leads to a reduction in electricity production, which has to be compensated for by the purchase of additional electricity. Existing privileges for CHP plants and the use of self-generated electricity impose a cost penalty on the purchase of grid electricity from renewables via the grid. Under the Energy Tax Act, there are tax privileges for natural gas (§ 53a EnStG). Moreover, no additional costs for grid fees or surcharges are incurred for the use of self-generated electricity. According to § 18 StromNEV, operators of CHP plants can apply for compensation for avoided grid fees (vNNE) from the distribution grid operator for electricity fed into the grid. This option will expire at the end of this year for newly commissioned CHP plants, but many existing plants benefit from this exemption. These privileges lead to further costs for the additionally required purchase of electricity from the grid and thus put the operation of heat pumps at an additional disadvantage compared to CHP plants.[11]

11 In the course of the project, a transformation cost

Average costs for heat pumps compared to a gas-fired CHP in 2030 — Figure 14



Electricity prices as in *Climate-neutral power System 2035* averaged over the 6 000 cheapest full-load hours (Agora Energiewende, Prognos, Consentec 2022); grid charges as applied by grid operator Westnetz in 2021 (Agora Energiewende 2021)

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The cost gap to fossil fuel CHP plants can be closed through the reform of the EU ETS, the gradual dismantling of privileges for self-generation by fossil fuel plants and investment costs support to ensure a rapid market ramp-up.

3.6 Market potential of heat pumps

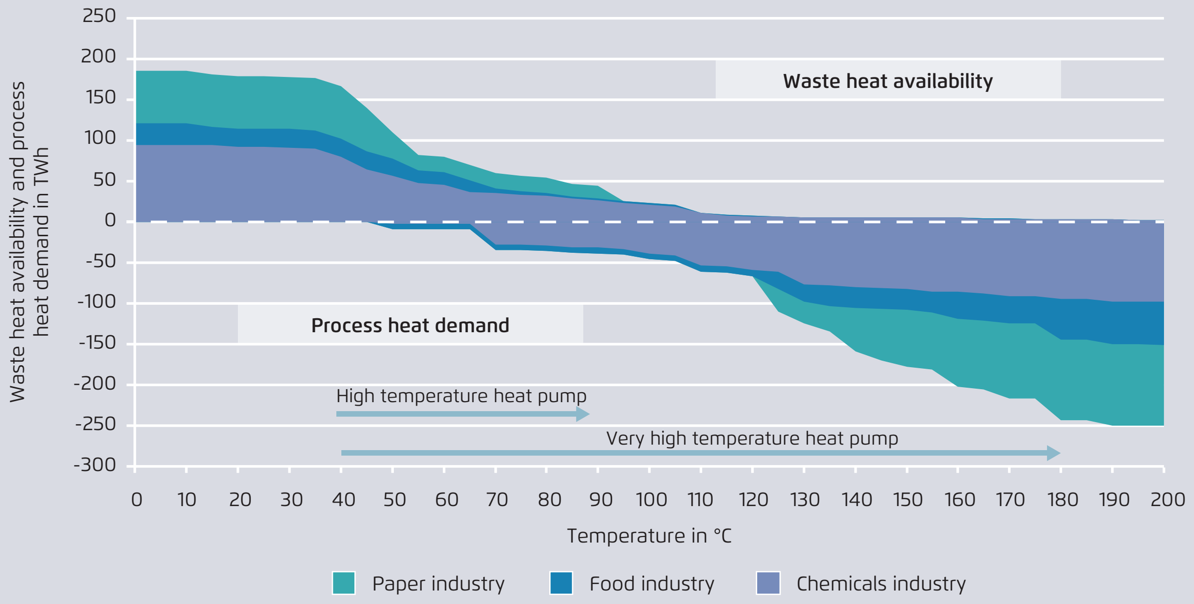
The increased use of heat pumps is dependent on the availability of suitable heat sources. On the one hand, the amount of heat available must be sufficient for the amount of process heat required. On the other hand, the temperature difference between the heat source and the heat sink must be small so that high efficiencies and correspondingly low operating costs can be achieved. In addition to the temperature increase required, the physical form of the waste heat, i. e. the waste heat flow, is also important: the exhaust air from a data centre requires a different approach compared to liquid waste heat flows, which usually have a higher energy density.

These considerations limit the market potential for industrial heat pumps. Because industry in Germany is highly diversified and heterogeneous, the usability of waste heat must be assessed on both a process- and site-specific basis.

Studies show that the waste heat potential is particularly large in the range below 100 degrees Celsius, but that significant potential can also be mobilised in the medium temperature range (Rehfeldt et al. 2018, Blesl et al. 2022, Marina et al. 2021). Detailed data at the process level suggest substantial opportunities for

calculator was developed which can be used to test different cost and technology assumptions. The Excel tool is available to download online: **https://www.agora-energiewende.de/en/publications/transformations-kostenrechner-power-2-heat/**

Waste heat availability and process heat demand in selected sectors in the EU28 — Figure 15



The arrows symbolise the temperature increase that can be achieved with the heat pumps described in chapter 3.2.
Agora Industry, FutureCamp (2022) based on Marina et al. (2021)

the use of heat pumps, particularly in the food, paper and printing industries, but also in the chemicals industry. The study by Marina et al. (2021) looked at the potential for integrating heat pumps in 57 typical processes in the paper, food, chemical and petrochemical industries. At the EU level, the study identified a market potential of 180 TWh for the use of heat pumps at temperatures up to 200 degrees Celsius in the four sectors.

Figure 15 shows the aggregated data from Marina et al. (2021) on available waste heat and process heat demand in the European paper, food and chemicals industry for temperatures up to 200 degrees Celsius. The positive number range represents the availability of waste heat, and the negative the demand for process heat. The arrows below the diagram show the temperature increase that can be achieved using the exemplary heat pumps described in this study. Most of the available waste heat in all sectors is in the range of 40 to 100 degrees Celsius – usually in the form of (moist) air and condensate. Only a small proportion of the available waste heat is in the range above 100 degrees Celsius. It should be noted, however, that this figure combines data for all European locations and that it cannot be assumed that waste heat potential and process heat demand are necessarily in spatial proximity.

In addition, there are waste heat sources that can be used in all sectors. In compressed air generation, usable waste heat arises at temperatures of 45 to 60 degrees Celsius. Waste heat from process cooling can be utilised at temperatures of up to 60 degrees Celsius, and waste heat from wastewater treatment at temperatures of up to 50 degrees Celsius. Waste heat from steam generators can be utilised at temperatures between 80 and 180 degrees Celsius (Blesl et al. 2022). The range of industrial heat sources is being complemented by renewable heat sources such as concentrated solar or geothermal energy, which can provide temperatures of up to 200 degrees Celsius depending on geographic location and land availability (Fraunhofer & Helmholtz, 2022).

4 Market ramp-up scenario: the potential for reducing natural gas consumption and greenhouse gas emissions

In order to achieve the climate protection goals for industry, no new investments should be made in fossil fuel technologies for heat generation (cf. Boston Consulting Group 2021). A rapid market ramp-up of heat pumps and electric boilers can contribute greatly to this and to energy autonomy. In the temperature range up to 500 degrees Celsius, around 120 TWh of natural gas are used in German industry; coal, heating oil and other fossil fuels account for just under 50 TWh in this temperature range (Fleiter et al. 2016). The electrification strategies described in this study can also be applied to the substitution of coal, heating oil and other fossil fuels. For the sake of simplicity – and because of its political relevance – only natural gas is used as a basis for the calculations in this study.

In the following section, a market ramp-up of heat pumps and electric boilers is modelled based on the potentials and implementation options identified by previous studies as well as on the political targets for climate protection and the reduction of natural gas consumption. This market ramp-up is ambitious, but feasible under certain governing conditions.

Heat pumps and electric boilers are currently still the exception in industry. For this to change, a coordinated market ramp-up must be launched. Industrial demand for direct electric systems must be stimulated. At the same time, production and installation capacities must be scaled up to meet the emerging demand. It is important that the focus is on the principle of 'efficiency first', because the switch to electrified heat must be implemented as part of a plant-specific overall concept in such a way that only absolutely necessary quantities of heat are produced. While such efficient energy systems are very plant-specific, sector-specific concepts can and must be developed.

Industry associations in particular have the opportunity to support information exchange between companies on efficiency-enhancing measures. The research and development of new systems can also benefit from an intensive exchange with industry and associations: the development of industry guidelines for standardised applications and heat requirements can accelerate the availability of technical solutions.

It is also important for the market ramp-up that the industrial heat transition is carried out in synergies with the decarbonisation of the electricity sector: the reduction in direct emissions through electrification must also lead to a net reduction in emissions when taken together with the additional emissions generated in electricity generation.[12] In order for the synergies described in chapter 2.3 to be realised, a regulatory framework must be developed that is compatible with an electricity system based entirely on renewables and that ensures long-term planning certainty in electricity procurement. For the market ramp-up of electric boilers especially, it is crucial that a reform of the grid charges is carried out soon.

Furthermore, grid capacities are a limiting factor for the increased use of direct electric systems. In particular, where CHP plants are replaced by direct electric plants, in addition to the electricity consumption of the heat pump or the electric boiler, in many cases an additional electricity purchase is necessary to compensate for the reduced electricity production

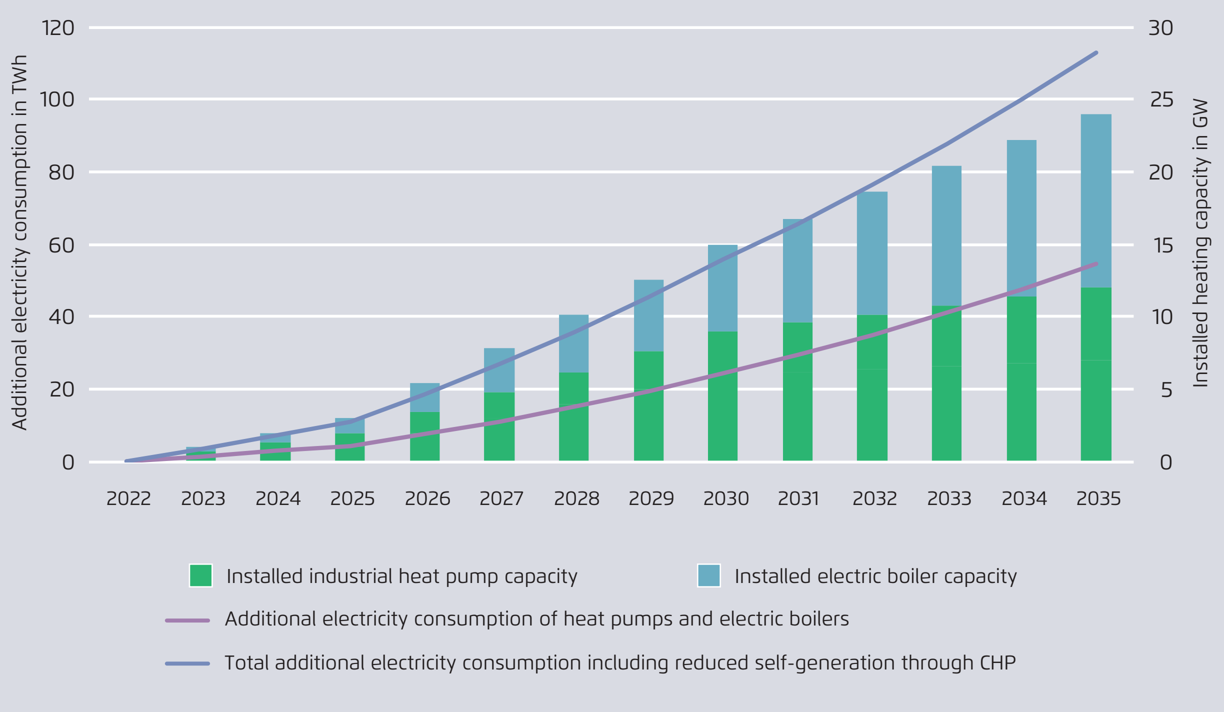
12 The production of heat and electricity using natural gas in a combined heat and power plant is established practice in industry and is the reference system for calculating emission reductions here.

from the CHP. In such cases, particularly large grid capacities are needed. Where grid capacities are not yet sufficient to completely replace fossil fuel plants, part of the supply from the existing plant can be replaced using a heat pump or an electric boiler. Such partial electrification diversifies the energy supply and enables flexibilities to be introduced that serve the increasingly renewable system.

If the regulatory and practical prerequisites are created, direct electric systems make sense not only from the point of view of energy sovereignty and climate protection, but also from the perspective of economic and corporate strategy. All upcoming new investments must be put into climate-neutral technologies, not only to avoid *stranded assets* in fossil fuel technologies (cf. Boston Consulting Group 2021), but also because of the current high prices and uncertain price development of fossil fuels. At lower temperatures, heat pumps are emerging as the technology of choice. Due to their higher electricity demand, electric boilers are mainly used in a time flexible manner – for example in combination with thermal energy storage systems.

Our modelling shows that by 2030 heat pumps with a total heat output of 9 GW and electric boilers with an output of 6 GW can be brought into use. The full-load hours of heat pumps are primarily determined by application-specific requirements, whereas the operation of electric boilers is primarily determined by the availability of cheap electricity from renewables. Based on the assumptions made in the Agora scenario *Climate-neutral power system 2035*, running electric boilers will be both ecologically and economically justifiable at 1 000 full-load hours in 2025, 2 000 full-load hours in 2030 and 3 000 full-load hours in 2035.

Installed capacities and additional electricity consumption in an ambitious market ramp-up — Figure 16



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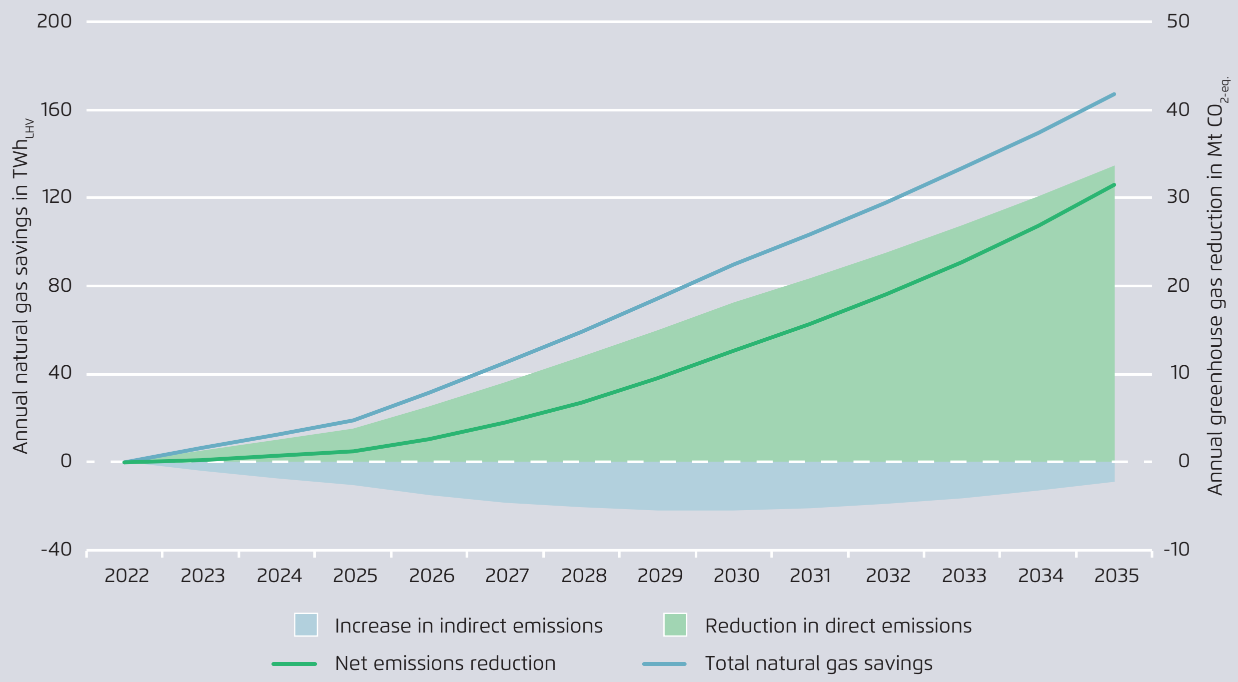
Assuming the specific investment and integration costs set out in chapter 3, the scenario presented requires investments of around twelve billion euros until 2030. Particularly at the beginning of the market ramp-up, a special support programme is needed to compensate for the initially still high investment costs and for current perverse incentives both in the grid fee structure and within the framework of the EU ETS, as well as to stimulate investments in lighthouse projects.[13]

Figure 16 shows the evolution of the installed heat capacity and the additional annual electricity consumption resulting from its operation. Around 24 TWh of electricity will be required to operate the installed plants in 2030. It is assumed that the newly installed plants will replace all or some of the output from existing CHP plants, which produce electricity as well as heat. In addition to the electricity consumption of the heat pumps and electric boilers, electricity must therefore be purchased to compensate for the electricity production lost through the scaling back or replacement of CHP plants. Altogether, about 56 TWh of electricity will be required.

The reduction in direct emissions from industry is offset by indirect emissions from the electricity sector for the additional electricity consumption. Figure 17 illustrates this shift together with the net greenhouse gas savings. Emissions initially transferred from industry to the electricity sector via the additional electricity demand are eliminated by the decarbonisation of the electricity system. Through a system-serving mode of operation, the additional emissions from the electricity sector are more than compensated for by direct emissions savings from

13 Investments in the first plants are subject to higher risks due to a lack of operational experience as well as in connection with the expansion of renewable energy and the associated electricity prices.

Natural gas savings and net emissions reduction | Figure 17



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industry. Altogether, annual emissions can thus be reduced by 12.5 million tonnes of $CO_{2\text{-eq}}$ by 2030. Assuming that all newly installed heat pumps and electric boilers shown here replace natural gas-fired CHP plants, up to 90 TWh_{LHV} of natural gas can be saved by 2030.

Figure 18 presents natural gas savings in the context of the REPowerEU plan and emissions reductions in the context of the Federal Climate Protection Law.

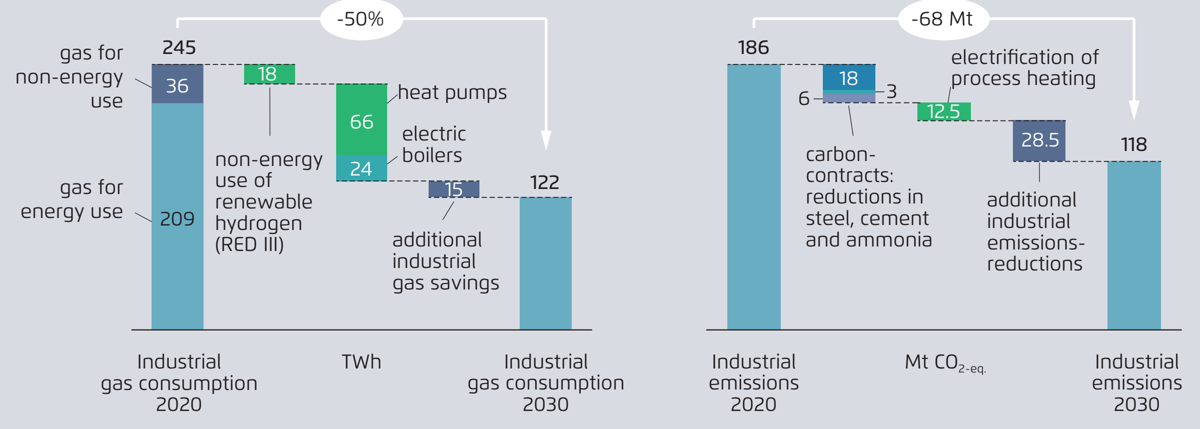
The 90 TWh_{LHV} of natural gas savings represent a 37 percent reduction in industrial natural gas consumption by 2030. Together with further savings measures, a 50 percent reduction in industrial natural gas consumption in Germany is possible, which would require further savings of approximately 33 TWh_{LHV} of natural gas. RED III requires that 50 percent of the hydrogen used for non-energy purposes must be supplied as renewable hydrogen by the year 2030. This represents a natural gas saving of 18 TWh_{LHV}. In addition, natural gas can and should also be saved in the temperature range above 500 degrees Celsius through energy efficiency and innovative direct electric and hydrogen-based processes. These complementary measures can be expected to save a further 15 TWh_{LHV} of natural gas.

Under the Federal Climate Protection Law, greenhouse gas emissions in the industrial sector must be reduced by 68 million tonnes by 2030.[14] Altogether, all new investments in industry over this decade need to be channelled into technologies that reduce emissions and are compatible with the goal of climate neutrality. A rapid heat transition at below 500 degrees Celsius can save 12.5 million tonnes of $CO_{2\text{-eq}}$ and thus contribute about 18 percent to the achievement of the target. The upcoming transformation of the steel, cement and ammonia industries, which is underpinned by carbon contracts for the industrial transformation, can save a total of 27 million tonnes of $CO_{2\text{-eq}}$ by 2030 (Agora Industrie et al. 2022). In order to cut the remaining 28.5 million tonnes, a series of measures must be taken. Key among them *are* the strengthening of the circular economy, the non-energy use of biogenic raw materials, the heat transition at temperatures above 500 degrees as well,

14 Compared to the figures for 2020.

Potential for reducing natural gas consumption and GHG emissions through an industrial heating transition in combination with other measures

Figure 18



Agora Industry (2022)

and efficiency improvements. In particular, the phase-out of coal use in industry is another necessary step for the achievement of the sectoral targets for industry.

Beyond 2030, direct electrification can continue to make an important contribution to climate protection and to energy sovereignty for Germany. The market ramp-up of heat pumps and electric boilers depicted in Figure 16 can – in accounting terms – displace all fossil fuels from industrial heating below 500 degrees Celsius by 2035. This would require bringing 12 GW of electric boilers and 12 GW of heat pumps into operation by 2035. The 170 TWh of fossil fuels mentioned at the start (natural gas, coal, heating oil and others) can be completely substituted in this way.

The GHG savings of 31.5 million tonnes $CO_{2\text{-eq}}$ shown in Figure 17 would be achieved if 170 TWh of natural gas were substituted. In fact, however, only 120 TWh of natural gas are used in the temperature range under consideration, resulting in an emissions reduction of about 24 million tonnes of $CO_{2\text{-eq}}$. A further 15 million tonnes of emissions reductions result from the replacement of coal, oil and other fossil fuels, which produce higher emissions than natural gas relative to their energy content. Altogether, and taking residual emissions in the power sector into account, a complete phase-out of fossil fuels at up to 500 degrees Celsius results in a GHG reduction of about 39 million tonnes $CO_{2\text{-eq}}$ compared to the status quo.

5 Recommendations for action

5.1 Existing regulations and perverse incentives

The electrification of process heat represents a change from established industrial processes based on fossil fuels to innovative electrification technologies. Market entry is made more difficult by various regulatory framework conditions that favour established technologies.

Under the EU ETS, heat generators receive free allocation based on the heat benchmark. The benchmark is neutral about the fuel used and is based on the specific emission values of a natural gas boiler. In the current allocation period (2021 to 2025), about 75 percent of the actual emissions of a natural gas boiler are covered by free allocation ((EU) 2019/331 and (EU) 2021/447). From 2026, the emissions values will be lowered; according to the currently valid directive, the heat benchmark will then still cover 67 percent of the actual emissions value. However, in the current trialogue procedure for the amendment of the EU ETS directive, some proposals involve a tightening of the adaptation rates, so that from 2026 only 50 percent of the actual emissions from a natural gas boiler would be covered by the heat benchmark (COM (2021)551). There is no free allocation for electricity generation from CHP plants.

Free allocation applies in particular to heat supply in sectors that are at risk of *carbon leakage*. This applies, for example, to a large proportion of the heat used in the chemicals, paper, iron, and steel industries. For heat supply outside the sectors at risk from *carbon leakage*, a smaller proportion of the allocation is free of charge, currently 30 percent.

Under the current regulations, there is no entitlement to allocation for electrical heat generation. This means that the cost benefits associated with emission savings are reduced by the loss of free allocation.

To prevent this effect, the principle of free allocation would have to be phased out, which is already on the political agenda (in some sectors at least) due to the introduction of the Carbon Border Adjustment Mechanism (CBAM). Initially, the scope of the heat benchmark would have to be amended so that electrification is not accompanied by a loss of allocation entitlement. A third possibility is to create a temporary monetary compensation, which is currently possible at least in some sectors through electricity price compensation. However, the problem at the moment is that the number of sectors eligible for aid is very limited and, in addition, aid is only granted to facilities that have a direct link to production. Centralised supply of heat, which is currently common at chemical plants, for example, remains excluded from this.

CHP plants in particular benefit from a number of tax exemptions under current law which hinder a switch to electrified heating options. The abolition of the EEG levy and of the CHP and offshore levies for electricity for heat pumps under the Energy Financing Act improves the starting position for the use of grid electricity by heat pumps, but for a level playing field between the use of CHP and the use of renewable electricity, further privileges for the operation of CHP plants would have to be reduced. These include tax relief for natural gas or other fuels used in CHP plants within the general framework of energy taxation (§ 53a EnStG). Highly efficient CHP plants are completely exempt from energy taxation anyway. In addition, there are various concessions for electricity generated in CHP plants that indirectly benefit their operation. Notable among these are exemptions for CHP electricity from electricity tax (§ 9 StromStV), explicit subsidies for CHP electricity that is fed into the grid and that is consumed by the producer (§ 7 KWKG), a comprehensive exemption from grid charges and grid levies for such self-generated electricity, and the currently still applicable compensation for the grid utilisation charges avoided (§ 18 StromNEV).

Increasing flexibility is a key element of the energy transition and is vital in order to achieve the ambitious goals for the expansion of renewables. As shown in the analyses above, in the medium term the operation of electric boilers in particular will only make sense in operation with low full load hours, both in economic and ecological terms. However, the current structure of grid charges favours high and constant electricity consumption in industry – flexible consumption is unattractive in comparison. The existing grid fee structure, which is partially based on peak demand, encourages constant operation (§ 17 (2) StromNEV). A particularly serious obstacle to flexibility is posed by individual grid charges pursuant to § 19 (2) StromNEV, sentence 2 ff., which for more than 7 000 hours of use per year require a reduction in grid charges of 80 percent, for more than 7 500 hours a reduction of 85 percent and for 8 000 hours a reduction of 90 percent. Operating below these thresholds as a result of using individual flexible systems such as electric boilers or heat pumps can lead to significant additional costs: flexible operation means that industrial consumers no longer have privileges with regard to grid charges, and additional costs are incurred.

The regulatory barriers described are perverse incentives in economic terms. In addition, there are other non-cost-related barriers to switching to direct electrified production processes. These include a lack of widespread awareness of the innovative technologies available, path dependencies and preferences for established technologies, and a lack of standardisation of applications. These barriers also need to be addressed by any package of measures aiming at the market ramp-up of heat pumps and electric boilers.

5.2 Action plan to support the market ramp-up

Chapter 4 showed how a rapid market ramp-up of heat pumps and electric boilers can contribute to achieving the legally binding climate targets and reducing natural gas consumption in industry in accordance with the REPowerEU targets. Appropriate framework conditions and policy instruments must be put in place to remove the barriers mentioned above, to create planning certainty for all stakeholders and to design a market ramp-up that reinforces the system and is economically optimal.

Phase-out of fossil fuels for heat below 500 degrees Celsius by 2035

In addition to the targets laid down in the Federal Climate Protection Law, the REPowerEU targets set the ambition parameters for the market ramp-up. These have to be translated into national law. A suitable opportunity would be an extension of the Energy Security Act (EnSiG), which contains provisions for crisis management as well as for preempting crises in energy supply. The scope of this law should be broadened to include a longer-term strengthening of energy sovereignty. For the industrial sector, the Energy Security Act should be supplemented by a paragraph that requires the phase-out of the use of fossil fuels at temperatures below 500 degrees Celsius by 1 January 2035. Achieving this goal requires the swift implementation of a package of measures that address the aspects below.

Market ramp-up programme

1. Mitigating investment risks and closing the cost gap
2. Prioritisation and planning security through clear standards
3. Incentives for system-serving flexibility
4. Removing perverse incentives for fossil fuel technologies
5. Implementation campaigns and the acceleration of the technology ramp-up

1. Mitigating investment risks and closing the cost gap

→ **Special support programme**

A temporary special support programme for lighthouse projects should be launched to subsidise the investment costs for heat pumps and electric boilers. Support for the first larger systems will help to overcome financial hurdles and to accelerate the establishment of heat pumps and electric boilers as standard technologies across industry. Financial support hedges against risks and compensates for a lack of experience with pilot plants. The costs for grid connection, installation and integration into the production site should automatically be eligible for subsidies. Both the use of waste heat (through heat pumps) and electrification measures using the current electricity mix should be eligible for funding. Eligibility for support should be linked to the mandatory implementation of energy saving measures in the course of energy audits.

→ **Green electricity-PPAs**

In order to support companies investing in renewable electricity procurement, the state should initially assume the default risks of green electricity PPAs for those companies. This is because higher electricity prices can be expected in the short and medium term – particularly as a result of higher natural gas prices. So that this does not become an obstacle to switching to the use of direct electricity, companies should be supported in their investments in renewable electricity procurement.

2. Prioritisation and planning certainty through clear standards

→ ***Zero carbon* standard**

Embedding a *zero carbon* standard in law should ensure that no new investments are made in fossil-fuel plants for the generation of heat for industrial processes at temperatures below 500 degrees Celsius. The legal provisions required could be incorporated in the Federal Climate Protection Law or in a new Industrial Heating Act to be created in the Federal Immission Control Act (Bundesimmissionsschutzgesetz, BImSchG).
All technologies classified as *zero carbon* are highly efficient, and either use renewable energy directly or will be completely CO_2-free by the year 2035.
In particular the standard covers enhanced waste heat recovery, steam regeneration, heat pumps, electric boilers, solar thermal, concentrated solar thermal, geothermal systems and integrated electrification and waste heat technologies.
The use of biomass is usually not included.
In order to establish uniform standards at EU level, the German government should at the same time advocate the incorporation of such a standard in EU law, for example in the context of the EU Gas Package (COM(2021) 803, COM(2021) 804).

→ **Waste Heat Utilisation Ordinance**

A waste heat utilisation ordinance should be introduced to boost the efficient use of waste heat and prevent the electrification of medium and lower temperature ranges at the expense of efficiency at the plant level.

→ **Enabling efficiency requirements for EU ETS installations**

In the course of these efficiency measures, § 5 (2) BImSchG, which prohibits additional efficiency requirements for EU ETS installations, should be deleted.

→ **Legal time limits on the use of fossil fuels**
Furthermore, in line with the objectives of the Federal Climate Protection Law, a statutory time limit of 1 January 2045 on the use of fossil fuels in industrial plants should be incorporated in the Federal Immission Control Act (BImSchG) in order to create planning certainty for investments in the area of medium- and high-temperature process heating as well.

3. Incentives for system-serving flexibility

→ **Reform of the grid fee structure**
Electricity grid charges must be reformed into time-differentiated grid charges so that they incentivise the provision of system-serving consumption flexibility in industry and reduce the privileges for extremely constant electricity consumption (see detailed proposals in Agora Energiewende, 2021). The reform of grid charges is becoming ever more important as the share of renewables in the electricity grid increases and must be made a political priority in this legislative period. This should be done in the context of the Climate-Neutral Power System platform envisaged in the coalition agreement, with the aim of the federal government presenting concrete reform proposals by mid-2023.

→ **Electricity price signals**
In light of the requirements of a climate-neutral electricity system, the introduction of temporally and spatially differentiated electricity price signals should also be examined in the context of the Climate-Neutral Power System platform.

4. Removing perverse incentives for fossil fuel technologies

→ **Reform of the EU ETS**
At the European level, a rapid and ambitious agreement is key in the ongoing trialogue process on the reform of the EU Emissions Trading Directive. Reforming the heat benchmarks and reforming or reducing the free allocation for sectors exposed to international competition are both important in this context. A step-by-step reduction of the free allocation for fossil fuel technologies will reduce the competitive disadvantage faced by electricity-based and CO_2-free technologies. A temporary monetary compensation – in line with EU state aid law – should be created to compensate direct electric applications for their current disadvantage compared to fossil fuel plants.

→ **Removal of privileges for CHP plants**
In order to reduce the structural advantages enjoyed by fossil-fuelled CHP plants, the energy tax concession for fuels used in CHP plants must be gradually dismantled within the framework of the Energy Tax Act (§ 53a EnStG). Other advantages enjoyed by CHP electricity, such as those granted under the Electricity Tax Ordinance (StromStV) or the Combined Heat and Power Act (KWKG), which lead to perverse incentives that favour fossil-fuelled plants, must also be phased out (§ 9 StromStV, § 7 KWKG).

5. Implementation campaigns and the acceleration of the technology ramp-up

→ **Implementation campaigns**
The federal government, the chambers of commerce and industry and sector associations should provide special support for small and medium-sized enterprises (SMEs) during the technology switchover through targeted implementation campaigns. This includes the establishment of simple advisory portals that support companies in the selection of

suitable zero-carbon technologies for their particular needs ("quick check"). Industrial associations should also support their members through the technology switchover by identifying standardised technological options for typical applications (see *Supportive industrial policy* below).

→ **Grid connection and approval procedure**
To ensure that the absence of an adequate grid connection does not represent an obstacle to the installation of heat pumps or electric boilers, the grid connection procedure must be accelerated. The federal government should set up a digital platform for the uniform nationwide processing of grid connection applications. Grid planning should also be adapted to the requirements of a climate-neutral energy system with respect to the distribution grid. This includes ensuring that grid operators adhere to clear specifications and deadlines for grid connection applications for the installation of heat pumps and electric boilers. In order to accelerate approvals for plants, consideration should be given to introducing a modification notification instead of an immission control permit for *zero carbon* technologies. At industrial sites or facilities where fossil-fuelled energy generation systems are replaced by climate-neutral energy and steam supplies through RES-E, heat pumps or e-boilers, there will overwhelmingly be no significant change in the environmental and safety regime for the site; emission levels at the site are likely to decrease in almost all cases. Unless emissions increase, project developers should be able to simply notify the authorities of changes in the energy supply without having to apply for an immission control permit. Insofar as the change comes under building law, the introduction of a building law notification option – for example in the state building codes – could create a level playing field so that project developers will choose to use the acceleration option. For cases where a change notification is not sufficient, the development of a standard approval procedure for zero-carbon technologies should be explored.

→ **Supportive industrial policy**
In order to increase production capacity for industrial heat pumps and electric boilers and to promote the training of skilled workers, a joint strategy must be developed by politics, industry, manufacturers, chambers of commerce and the skilled trades. Industry guidelines for standardised applications, e.g. for specific heat pump types and configurations, can contribute to a more serialised production of large heat pumps than is currently possible. Sector-specific stakeholder dialogues should be established to develop these standards. This would enable accelerated production of heat pumps.

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277/05-I-2022/EN

About Agora Industry

Agora Industry is a division of Agora Energiewende that develops strategies and instruments for climate-neutral industrial transformation – in Germany, the EU and globally. Agora Industry works independently of economic and partisan interests. Its only commitment is to climate action.

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