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Short Study: Energy-Efficient and CO2-Free Process Heat

| As of July 2024 |

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Courtesy Translation

Executive Summary

- **21 billion euros** could be saved annually in Germany in energy costs to provide process heat. This is a great opportunity for competitiveness and enables sustainable growth, despite the long-term energy and greenhouse gas saving requirements to achieve the climate targets. The trend of decoupling growth and consumption in recent years could thus be significantly accelerated.
- Through standard energy efficiency measures and switches in the provision of process heat, **33 percent of the final energy demand of industry** in 2022 (**226 TWh/a** of 680 TWh/a) could be saved in the area of process heat alone, with a high additional economic return and without production restrictions. Companies could thus save **49 percent** of their current **final energy consumption for process heat** (226 of 460 TWh/a) economically. This saving is roughly equivalent to the production volume of **four large coal-fired power plants plus** the capacity of **two LNG terminals**. Figure 1 illustrates the potential end-energy savings.
- The greatest potential exists for the measures "heat recovery", "electrification" and "waste heat recovery".
- **63 percent of these economic energy saving potentials (142 TWh/a** of 226 TWh/a) is **“market-oriented.”** This means the measures have a very attractive return on investment and are amortised within three years. Thereby up to **12.8 billion euros** can be saved annually in energy costs. Experience has shown that companies with established energy management have already implemented some of the potential or find it easier to implement the energy-saving potential.
- **The study identifies a further 84 TWh/a** of final energy savings and annual energy cost savings of around 8.2 billion euros that are not **"market-oriented”.** Although these potentials are economic, they can only be saved in the longer term with an attractive return. Many of the measures considered are amortised within approximately 5 years.
- In the future, renewable energy will be the standard primary energy source. Every kilowatt hour can only be consumed once. It is therefore essential to avoid conversion losses in terms of **primary energy efficiency**. Direct electrification should be preferred to indirect electrification (e.g. use of hydrogen). If the economic final energy saving measures assumed in this study were implemented, the primary energy demand would be around 69 TWh/a higher with increased consideration of hydrogen applications compared to a scenario with predominantly direct electrification.
- With direct electrification, a possible reduction in **primary energy demand** for process heat of around 57 percent from 572 TWh/a in 2022 to **248 TWh/a** in 2040 is estimated.
- A large part of the final energy demand for process heat can already be saved by **2030**. If 70 percent of the market-oriented potential is implemented, demand will be reduced to **360 TWh/a** (22 percent saving compared to final energy consumption for process heat in 2022). In 2040, the final energy demand in the scenario described is **318 TWh/a** (31 percent saving compared to the final energy consumption for process heat in 2022).

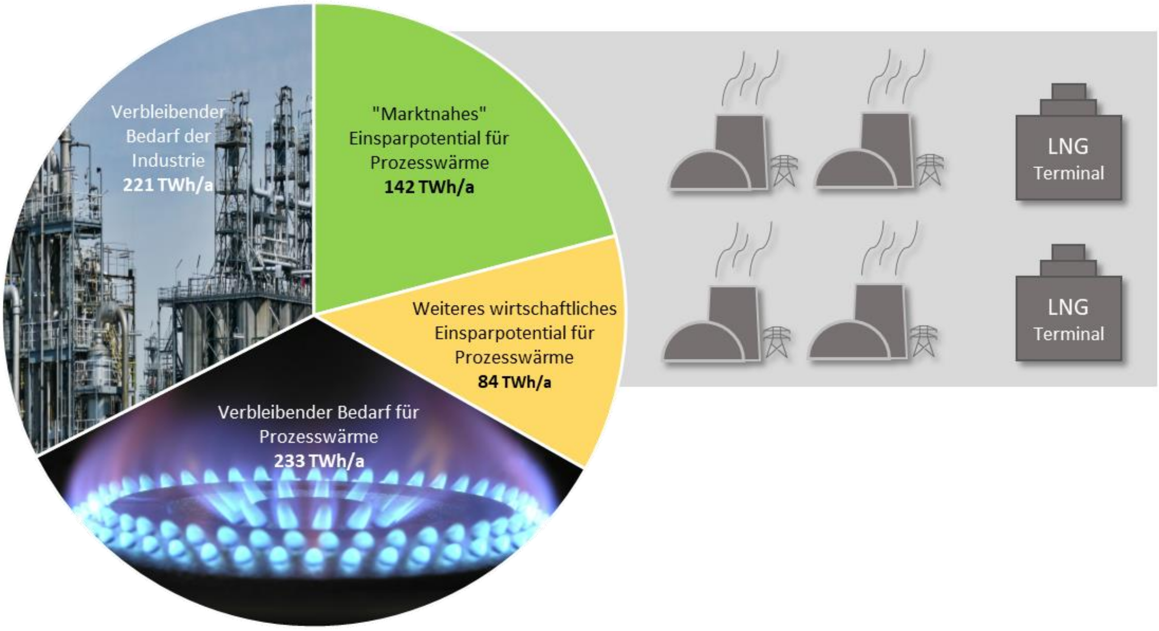

Figure 1: Share of economic final energy savings potential for process heat divided into near-market and other economic savings potential. The total savings are roughly equivalent to the production volume of four large coal-fired power plants plus the capacity of two LNG terminals.

Introduction

According to the Federal Climate Protection Act (ger. Klimaschutzgesetz, KSG), Germany's greenhouse gas emissions must be reduced to such an extent that net greenhouse gas neutrality is achieved by 2045 [1]. This goal shall be achieved by reducing primary energy demand by 50 % by 2050 compared to 2008 [2], [3]. The central elements of the energy transition in Germany are the expansion of renewable energies on the one hand and energy efficiency on the other [4]. According to the "Energy Efficiency Strategy 2050" by the Federal Ministry for Economic Affairs and Climate Action (BMWK), a significant demand reduction is expected among end users [5].

The Energy Efficiency Act (EnEfG) was passed in the fall of 2023. The Act defines energy efficiency targets that final energy consumption in Germany should fall by at least 26.5 percent by 2030 compared to 2008 (to 1,867 TWh/a) and by 45 percent by 2045 (to around 1,400 TWh/a).

Germany's primary energy consumption shall be reduced by at least 39.3 percent by 2030 compared to 2008 (to 2,252 TWh/a). No primary energy savings target is set for 2045. [6]

In 2022, the total final energy demand in Germany calculated by the Federal Environment Agency (Umweltbundesamt) amounted to 2,368 TWh/a [7]. The industrial sector accounts for a large share of 28 percent [7]. Accordingly, for a transformation towards greenhouse gas neutrality, the final energy demand in industry must be reduced and covered by renewable energies. Table 1 shows forecasts from various studies on reducing final energy demand in industry and primary energy demand by 2045.

Table 1: Forecast development of energy requirements from the base year 2008 to 2030/2045

	BDI “Climate Pathways 2.0”	**Dena study “Towards climate neutrality"**	**Climate neutral Germany**	**Germany on the path to climate neutrality 2045**	**Long-term scenarios T45 electricity**	**Long-term scenarios for the transformation of the energy system in Germany**
Primary Energy (total)	**2045**	**-50%**	**-55%**	**-55%**	**n/a**	**n/a**
Final Energy (Industry)	**2030**	**-8%**	**-13%**	**-14%**	**-13%**	**-12%**
	2045	**-17%**	**-21%**	**-19%**	**-23%**	**-19%**

Final energy consumption in industry is largely determined by the process heat applications. This accounts for 67.5 percent of final energy [14], [15]. In particular, the short study "Energy Efficiency Measures in Industry" estimates large energy-saving potentials in this area of application [16]. Similarly, the study "Power-2-Heat: Natural gas savings and climate protection in industry" sees great potential for savings, particularly through the electrification of process heat [17].

This study therefore analyses the energy efficiency potential for industrial process heat in greater depth. The basis for the in-depth analysis is the above-mentioned short study "Energy Efficiency Measures in Industry" [16]. Firstly, the chapter "Possibilities for increasing the final energy efficiency of process heat" describes and calculates economic and market-oriented economic final energy efficiency potentials for process heat. Then, in the chapter "Primary energy efficiency of process heat", the effects of process changes in heat generation/supply and the associated energy source changes on the primary energy demand are analysed. The topic of hydrogen is also included here. In the final chapter, "Elements of a process heat strategy of the Federal Government", technical paths to energy-efficient and decarbonised process heat in 2045 are derived from the analysis results.

Possibilities for increasing the final energy efficiency of process heat

Going forward, a large proportion of the industry's final energy demand of 680 TWh/a[1] will still be required in production processes [18]. The economic savings potential of the final energy demand depends on the state of the technology, energy prices as well as political and economic (e.g. desired return on investment, investment risk) conditions.

In this study, process heat is initially categorised according to temperature levels and the final energy demand for process heat of 460 TWh/a is divided between these levels. For the temperature range "less than 100°C", the final energy demand for space heating and industrial hot water is not taken into account. Examples of categorisation into temperature levels can be found in [9], [17] or [19], based on applications or alternative technologies for process heat generation. The basis for the classification in this study is an analysis commissioned by the Federal Environment Agency (Umweltbundesamt) [20]. In addition to a breakdown into different temperature ranges, the final energy consumption is also categorised by sector. These industry shares are comparable with analyses by AG Energiebilanzen e. V. (AGEB) [21] or the Federal Statistical Office [18]. This allows the savings potential to be estimated while also taking into account the applications/processes and using corresponding reference technologies.

In the following, the methodology used, which is based on the methodology in the above-mentioned short study "Energy efficiency measures in industry" [16], is briefly presented. For a more detailed explanation of the methodology used, we also refer to the study "Energy Efficiency Potentials and Barriers to Implementation in Industry" by Barzantny, Meyer et al [22]. We will then describe and illustrate the potential for the individual temperature ranges.

Methodology

A distinction is made between three types of potential:

- the potential for final energy savings, i.e. the possibilities for reducing electricity, fuel and heat consumption;
- the energy cost reduction potential, i.e. the potential for reducing the costs of electricity, fuel and heat; and
- the market potential, i.e. consideration of the investment required to realise the above-mentioned potentials.

Furthermore, potentials are determined for various framework conditions:

- "Economic potential": This includes measures that are economically viable over their lifetime, i.e. the net present value of the energy efficiency measure is positive. A return

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[1] In this study, data from the Federal Statistical Office [18] is used. All energy carriers utilised for energy purposes, except geothermal and environmental heat for heat pumps and solar thermal energy, are considered as final energy. The double counting of fuels used for electricity generation in on-site facilities and the electricity generated [39] is corrected using data from the Federal Statistical Office on self-generated electricity [38] and analyses by AGEB on combined heat and power generation in industry [40].

on equity of 8 percent[2] and a price trend in the heating price (constant € 80.83/MWh until 2028, then rising to € 173.5/MWh by 2060) are assumed. The heat price up to 2028 is composed of the breakdown of process heat into energy sources according to [14] as well as an electricity price of €155/MWh[3] and a natural gas price of €75/MWh.[4] The heat price for 2060 takes into account a new distribution of energy sources (80 percent electricity, 20 percent district heating) and an electricity price of €195/MWh.[5]

- "Market-oriented potential": It takes into account that economic measures are generally only implemented if the required static amortisation period (payback, here: three years) is met. The "market-oriented potential" is part of the "economic potential".
  [Note: However, even a static payback period of three years or less does not guarantee implementation, as other non-economic barriers such as preference structures etc. may stand in the way (see chapter on barriers in the previous short study [16]).

Possible final energy-saving measures are analysed for each temperature range of the process heat. The analysis starts with a consideration of the waste heat utilisation cascade and thus follows the principle of "efficiency first", which is mentioned in various studies [5], [17], [23] or [24] and also in Article 1 sentence 3 of Directive 2012/27/EU (Energy Efficiency Directive, EED). The waste heat utilisation cascade includes measures to avoid waste heat, heat recovery/integration and internal and external waste heat utilisation [25]. In addition, renewable heat sources such as solar or geothermal energy are taken into account as measures in the appropriate temperature ranges. Finally, alternative technologies or methods of process heat supply (e.g. electrification) are included. Representative technologies are selected for industries that are strongly represented in a temperature range and replaced by the most energy-efficient alternative technology. The compilation of measures and alternative technologies takes into account various studies [9], [10], [12], [16], [17], [19], [23], [24] and [26].

The methodology used to determine the potential is shown in Figure 2 below. Here, the calculation method is shown in the white and yellow fields and then example values for the temperature range "less than 100 °C" are given in the blue fields.

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[2] A moderate empirical value, which is also used in [16].

[3] The basis for electricity price determination is the average of the EEX front-year base values for 2025, 2026, 2027, and 2028 as of 4 March 2024 (€70/MWh), plus €50/MWh for grid fees, €15/MWh for charges and levies, and €20.5/MWh for taxes (excluding VAT).

[4] The basis for natural gas price determination is the average of the THE front-year base values for 2025, 2026, and 2027 as of 4 March 2024 (€31/MWh), plus €10/MWh for grid fees and €35/MWh for charges, levies, and taxes (including a CO2 levy of €10/MWh, also excluding VAT).

[5] The basis for electricity price determination in 2060 is the "vbw / Prognos Electricity Price Forecast 2023" [30] (€60/MWh), plus €100/MWh for grid fees, €15/MWh for charges and levies, and €20.5/MWh for taxes (excluding VAT).

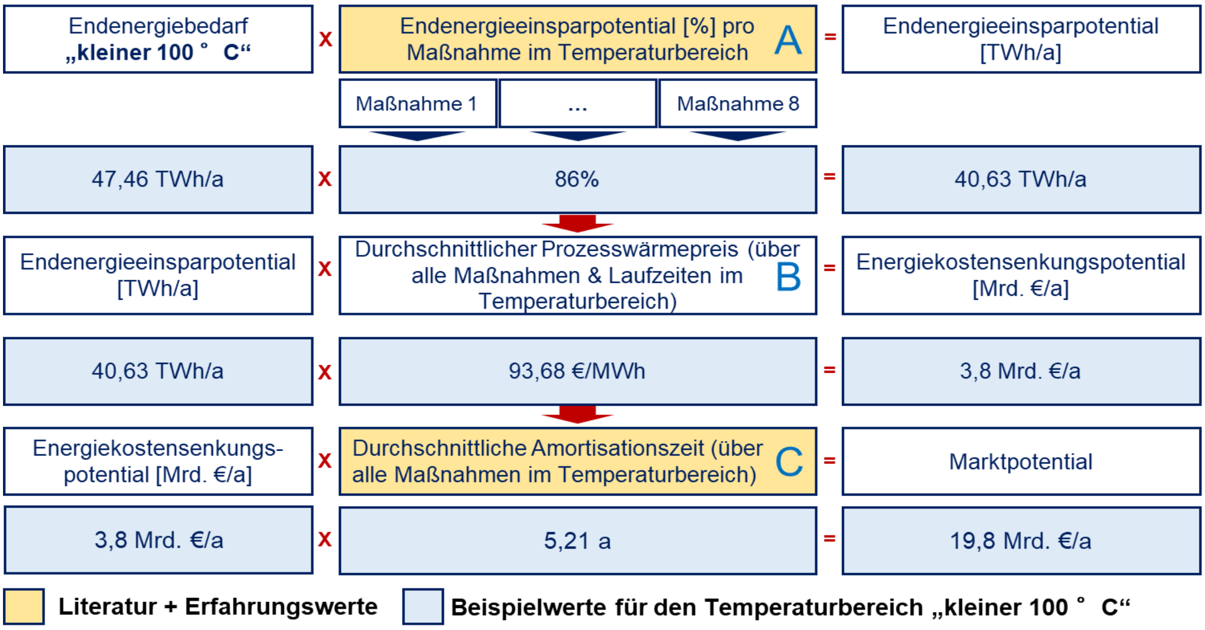

Figure 2: Methodology for the calculation of the potentials using the example of the temperature range “less than 100°C)

In this study, the final energy-saving potential of the individual measures is determined as a percentage based on literature and empirical values. For the estimation of the savings potential of alternative technologies (such as heat pumps or electrode boilers), [26] is used. When determining the final energy savings potential, a proportion of measures that have already been implemented is also estimated for each measure and deducted from the savings potential. In particular, the fact that some companies already have established energy management systems is taken into account.

As the measures influence each other, the savings of the individual measures are offset against each other so that a savings potential is shown as a percentage for each temperature range (see field labelled "A" in Figure 2). This percentage value and the final energy demand according to [20] are used to determine a savings potential in TWh/a for each temperature level. After standardising the individual percentage values of the measures within a temperature range, savings potentials in TWh/a can then be calculated for the measures in the individual temperature ranges. The economic energy cost reduction potentials are then determined using the assumed heat price development (see field labelled "B"). This study then introduces an improvement to the methodology from the previous short study [16] by considering a short and long average amortisation period for each measure instead of an average amortisation period. The two amortisation times are weighted according to frequency. The market potential (= necessary investment) is then determined using the energy cost reduction potential and the amortisation times (see field marked "C"). By calculating the corresponding sums over a temperature range, both the economic potential and the market-oriented potential of process heat for Germany can be determined.

Despite the thorough analysis methodology and the due care and thoroughness of the various evaluations, there are still some points that require critical appraisal concerning the validity and reliability of the results. The final energy saving potentials determined always refer to German industry as a whole. At the level of individual companies, the relative potentials vary depending on the sector, type of production, implementation status of efficiency measures, existing infrastructure, etc. The amortisation periods are also very different. In the case of individual companies, it is also quite possible that the capital invested will flow back faster or slower than assumed here in terms of amortisation times. Additionally, the determination of energy prices has an influence (differences depending on company size and energy requirements). Especially in combination with the lack of consideration of the timing of the implementation of the measures (depending on the modernisation cycle of individual systems).

Calculated saving potentials

The analysis in the course of this study has shown that the cumulative economic final energy savings potential across all temperature ranges (i.e. implementation of measures with a positive net present value) is 226 TWh/a (33 percent of the final energy demand of the German industry in 2022) and can be realised with a total investment sum of € 91.7 billion. The investment sums (market potential) of individual bundles of measures can be seen in Figure 5. The calculated economic final energy savings potential exceeds the forecast of the development in Table 1 and saves energy costs of €21 billion per year. The final energy savings are potentially close to the market amounting to 142 TWh/a (21 percent of the final energy demand of the German industry in 2022). This could save energy costs of 12.8 billion euros per year.

For the assessment, the final energy demand for process heat of 460 TWh/a was divided into six temperature levels (see Figure 3). In the figure, the final energy demand for each temperature range is also divided into the share of economic savings potential (blue) and the remaining share that cannot be saved through economic efficiency measures (orange). It can be seen that the proportion of the economic final energy saving potential decreases as the temperature increases (illustrated by the percentage values on the right-hand side).

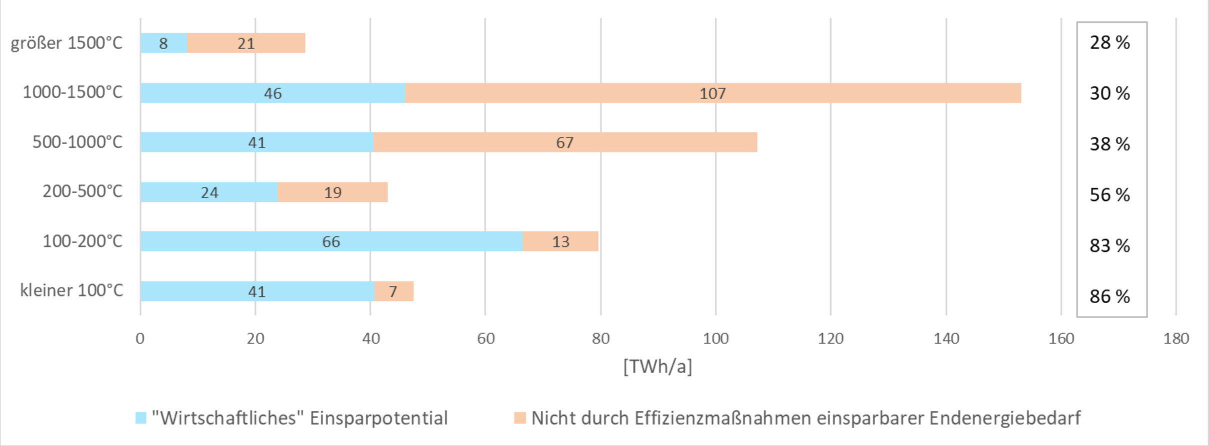

Figure 3: Breakdown of the final energy demand for process heat by temperature range, showing economic (blue) and non-economic (orange) savings potential. The percentage values in the right-hand box are the share of the economic savings potential in the final energy demand per temperature range.

Figure 4 shows the difference between "economic" and "market-oriented" final energy savings potential for each temperature range. In addition, the economic final energy saving potentials are divided into savings through efficiency measures and savings through process changes in the heat supply.

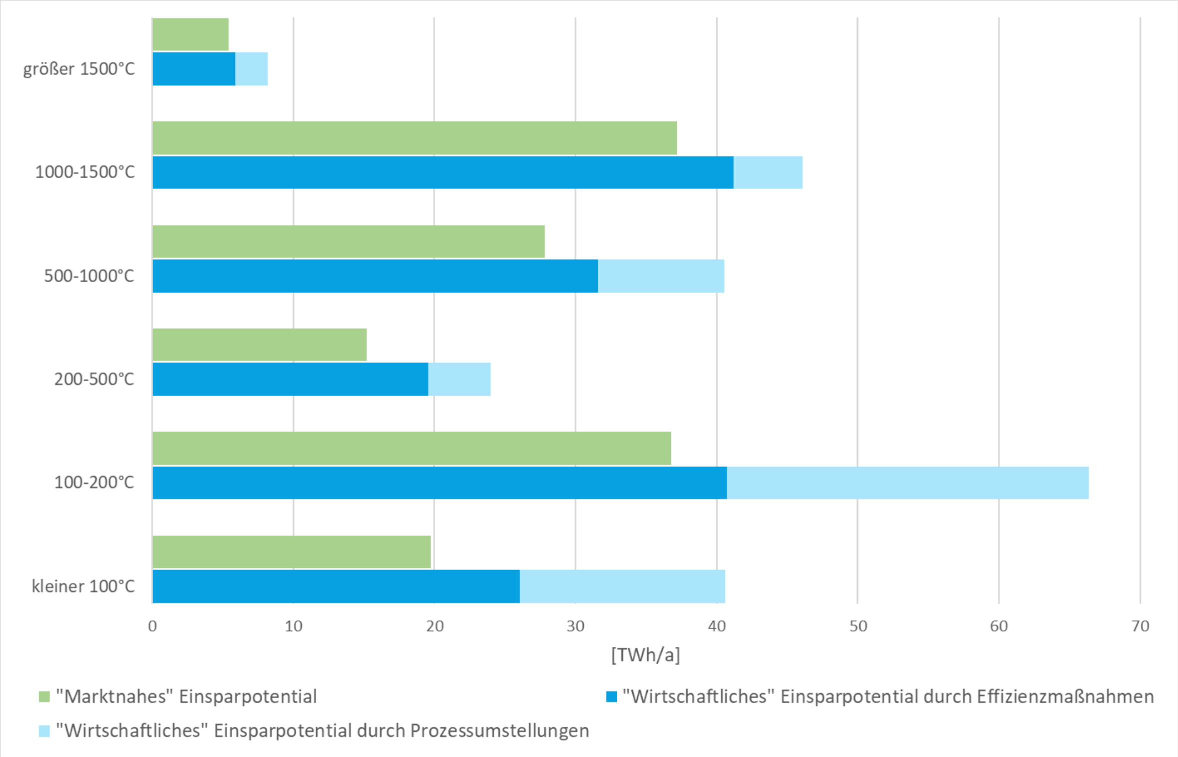

Figure 4: Comparison of "economic" and "market-oriented" final energy saving potentials of the temperature ranges

The greatest differences between "economic" and "market-oriented" final energy savings potential are shown for the two ranges up to 200 °C. As illustrated by the bar chart of the economic savings potential, conversions in the heat supply (process changes), such as heat pumps or high-temperature heat pumps, make a major contribution here.

Waste heat utilisation also accounts for a large proportion of the savings. The resulting modification measures entail comparatively high investments. Nevertheless, the measures often have a positive net present value, as they have an effect over long utilisation periods. The potential in higher temperature ranges is dominated by energy efficiency measures. Here, the market-oriented final energy saving potential is similar to the economic final energy saving potential.

Companies with established energy management systems have often already realised some economic final energy saving potentials. Therefore, when determining the final energy savings potential (see chapter on Methodology), a proportion of measures that have already been implemented is estimated for each measure and deducted from the savings potential.

Table 2 below shows the measures with the greatest final energy-saving potential per temperature range for industrial process heat.

Figure 5 below visualises the economic final energy saving potential of the individual bundles of measures (area of the circles proportional to the numerical value in TWh/a), the market potential (x-axis) and the average amortisation period of all measures in the bundles of measures (y-axis). This shows the great savings potential of efficiency measures such as "heat recovery/integration", "waste heat utilisation" or "process switchover through electrification". The market potential for these measures is comparatively large.

Table 2: Measures with the greatest potential for final energy savings in process heat per temperature range

Temperature levels	**Measures with the greatest economic saving potential**		
	greatest potential	**Second-greatest potential**	**Third-greatest potential**
Less than 100 °C	Waste heat utilisation	Process switchover: heat pump/high-temperature heat pump	Heat recovery/integration
100-200 °C			
200-500 °C	Heat recovery/integration (air preheater, economiser etc.), exhaust steam utilisation (ger: Fegedampfnutzung)	Improved user behaviour and/or controlling	System optimisation (e.g. condensate recovery)
500-1000 °C	Heat recovery/integration (e.g. recuperative burner)	Improved user behaviour and/or controlling	Electrification in: - " Primary chemicals " - "Metal production" - "Non-ferrous metals and foundries"
1000-1500 °C			Electrification in: - "Metal production" - "Non-ferrous metals and foundries"
More than 1500 °C			Electrification in: - "Glass and ceramics" - "Metal production"

Figure 5 shows that many energy efficiency measures are amortised within around five years. The arrows show the shortest and longest average amortisation period for the measure in a bundle of measures. The position of the centre of the circles thus illustrates the weighting of the amortisation periods.

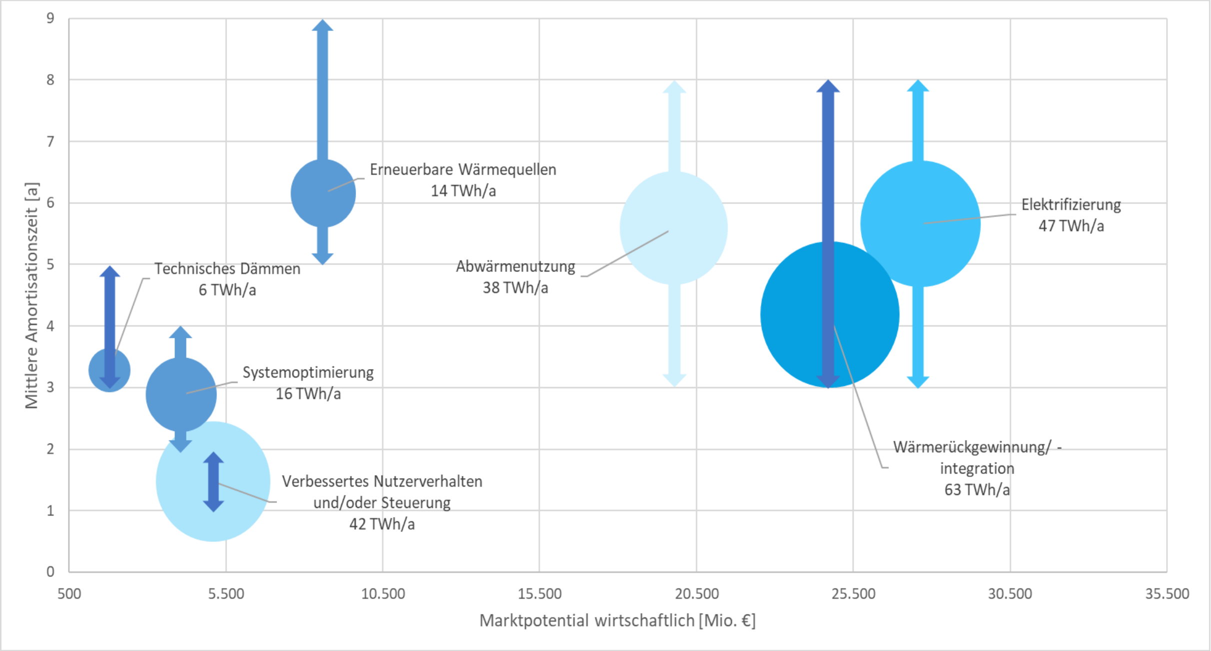

Figure 5: Final energy saving potential, market potential and average amortisation time by measure

Primary Energy Efficiency of Process Heat

The alternative technologies that are optimal from an energy efficiency perspective are selected to calculate the economic final energy saving potentials presented. Here, direct electrification yields large final energy savings [17], [26]. In addition to the choice of technology, alternative fuels such as green hydrogen or synthetic methane are also being discussed, particularly for the higher temperature ranges. However, only very low final energy savings potentials are expected for this indirect electrification [26]. Since 80 percent of the final energy savings are achieved through efficiency measures (e.g. measures to avoid waste heat, heat recovery/integration and waste heat utilisation), the final energy savings potential changes slightly at first glance if indirect electrification is used instead of direct electrification. However, this is only the case if the alternative fuels are calculated as final energy sources without considering the upstream chain [26]. However, due to conversion and transport losses, around 1.4 times the amount of electricity is required to produce green hydrogen. Synthetic methane requires 1.8 times the amount of electricity [23].

[17] also mentions a higher demand for renewable electricity for hydrogen. Therefore, the analysis at the final energy level is not very meaningful for comparing the choice of technology, depending on the definition of the final energy source. For this reason, a comparison of primary energy levels is also carried out as part of this study. Green hydrogen is considered as the fuel.

The proportion of energy sources in the process heat mix changes as a result of the process adjustments in heat generation/supply. For direct electrification of process heat, the share of electricity increases from approx. 8 percent [14] to up to 50 percent in 2040.

For indirect electrification, the energy source "green gases" increases from 0 percent to approx. 42 percent. This is comparable with other scenarios for the direct or indirect electrification of process heat [13]. It should be noted that not all processes will be decarbonised after the implementation of the economic energy-saving measures considered. Accordingly, energy sources such as natural gas or oil, and possibly also coal, will continue to be available until 2040. Therefore, once the measures have been implemented, further process adjustments will be necessary in the provision of heat.

The primary energy demand in the current state (2022) is calculated using the distribution of energy carriers according to [14] and primary energy factors from DIN V 18599-1. Here, the primary energy factor for electricity is 2.8. The starting point for calculating the primary energy demand after the implementation of all considered measures in 2040 is the reduced final energy demand after the exploitation of economic final energy-saving potentials. The primary energy demand is determined using the new proportions of energy carriers and the primary energy factors. For electricity, a factor of 1.0 is used, assuming it will be fully generated from renewable sources by then. The primary energy factor for hydrogen is determined by multiplying the electricity factor by 1.4. This results in economic primary energy savings of 324 TWh/a through direct electrification. In comparison, the savings are reduced to only 255 TWh/a if hydrogen is chosen. Additionally, a scenario without the discussed economic final energy-saving potentials is considered. In this case, only the share of natural gas in the energy mix is replaced by hydrogen. Despite the significantly lower primary energy factor for electricity in 2040, the primary energy savings amount to just 0.8 TWh/a. An overview of this can be found in Figure 6:

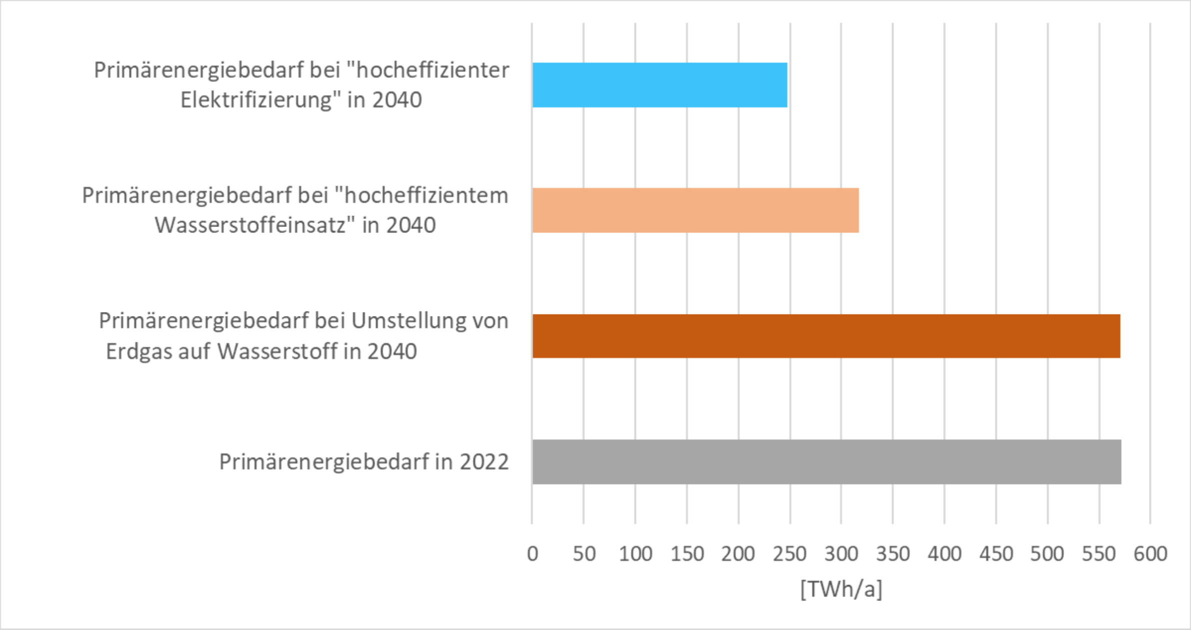

Figure 6: Economic primary energy demand for process heat in 2022 and depending on increased electrification or the use of hydrogen

In the following Figure 7, the economic final energy-saving potentials of the various alternative technologies (represented by the area of the circles, the numerical value in TWh/a, and the y-axis) as well as the primary energy efficiency factor (x-axis) are illustrated.

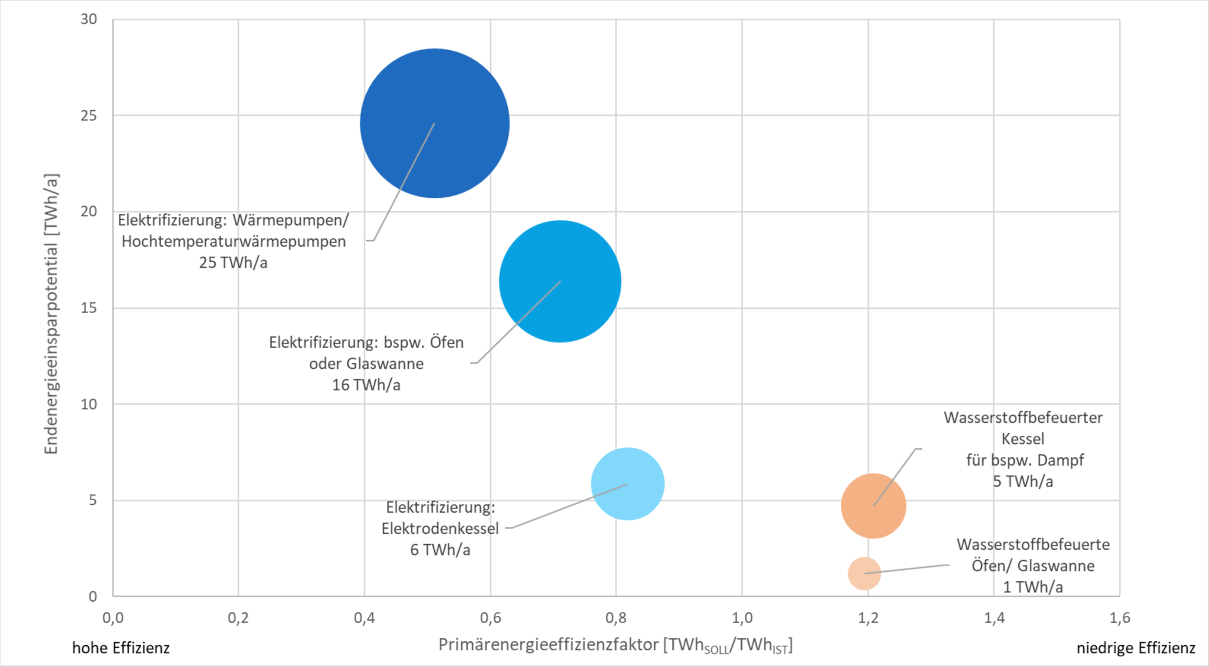

Figure 7: Economic final energy saving potential and primary energy efficiency facts of different technologies

The primary energy efficiency factor is defined here as "primary energy demand after the change of energy carrier and economic savings" divided by "primary energy demand in the current state (here, 2022)." This shows that the primary energy efficiency factor for hydrogen technologies is greater than one. Consequently, these measures require more primary energy than at present. The lower final energy savings, along with conversion and transport losses, and thus the high primary energy factor for hydrogen, are the main reasons for this. Direct electrification reduces the primary energy demand. Moreover, these technologies, especially heat pumps/high-temperature heat pumps, have significant final energy-saving potentials.

When deciding on a process adjustment in heat generation/provision, primary energy efficiency should also be considered. Where direct electrification is possible, indirect electrification should be avoided. From an energy efficiency perspective, direct electrification is particularly recommended in lower temperature ranges. For higher temperature ranges, hybrid solutions (more than 50 percent electric, with additional gas heating) could be of interest [23], [26]. As a last resort, despite the described high conversion losses, alternative fuels such as green hydrogen might still be a suitable technology choice in certain cases. Here, individual decisions should be made considering final and primary energy efficiency, infrastructure, state of the technology, production volume of the plant, etc.

Elements of a Process Heat Strategy for the Federal Government

Through proposed energy efficiency measures and process adjustments in heat generation/provision, the German industry can achieve significant final and primary energy savings in the provision of process heat, enabling the attainment of our climate goals. From the present analysis, the following approach and energy efficiency developments can be derived:

First, efficiency measures (e.g. measures to avoid waste heat, heat recovery/integration, and utilisation of waste heat) should be implemented. This will significantly reduce the share of energy that needs to be provided through adjustments in heat provision, thereby also reducing the associated high investment costs. If major investments for, e.g., new or refurbished plants are planned due to modernisation measures or process adjustments, individual efficiency measures may be postponed. Subsequently, renewable heat sources should be utilised wherever possible. Based on the market-oriented final energy-saving potentials, a minimum level for the development of process heat final energy efficiency can be defined: 80 percent (100 TWh/a) of the market-oriented saving potentials from efficiency measures and the utilisation of renewable heat sources (or about 70 percent of the total market-oriented saving potentials of 142 TWh/a) should be realised by 2030 at the latest. This would make it possible to achieve a final energy demand of approximately 360 TWh/a (= 78 percent of the final energy consumption for process heat in 2022) for process heat provision by 2030.

This should be followed by a gradual process adjustment with a focus on electrification. For instance, heat pumps and electrode boilers are already commercially available for large-scale applications, so initial process adjustments could potentially be carried out before 2030. However, other alternative technologies still require further development, scaling up, and operational experience. They should be available by 2030 according to [26]. Overall, at least the remaining near-market potentials (42 TWh/a) should be fully utilised by 2040. Consequently, the final energy demand for process heat provision by 2040 could be around 318 TWh/a (= 69 percent of the final energy consumption for process heat in 2022).

As illustrated in Figure 4, there are additional potentials beyond the developments outlined. These measures for process heat provision can be implemented economically if they are calculated over the entire lifespan. This could save up to 33 percent of the final energy demand in the industry overall. The main reasons for the rejection of economically viable energy-saving potentials are structural, economic, and socio-psychological barriers to implementation. For a detailed discussion of these barriers, please refer to the previous short study [16].

In principle, however, the estimated economic saving potentials should be fully exploited, meaning that all currently non-near-market measures should also be implemented. Even when these have been tapped, fossil fuels will continue to be used in 2040. Accordingly, regardless of potential savings, further process adjustments with available technologies will be necessary for complete decarbonisation, both subsequently and in parallel. Complete decarbonisation must be achieved by 2045. The preference is for direct electrification. Where appropriate, indirect electrification through alternative fuels (green hydrogen or synthetic methane) can be considered as a last resort. Therefore, by 2045, it is feasible to reduce the final energy demand for process heat by 226 TWh/a (= total economic final energy-saving potential) to 235 TWh/a.

The potential development of primary energy demand is discussed overall until 2040, as described in the chapter "Primary Energy Efficiency of Process Heat", due to the change in energy carriers. In terms of primary energy efficiency, the greatest possible savings should be targeted. As a result, the primary energy demand for process heat could be reduced to 248 TWh/a by 2040 through direct electrification.

Literature

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About the Authors

The SWK E², which became an institute at Niederrhein University of Applied Sciences in 2017, offers interdisciplinary research and teaching expertise in the field of energy, with a focus on the analysis and optimisation of energy systems and processes. The energy systems considered are primarily from the areas of industrial energy plants, conventional heating, cooling, and power plant technology, as well as renewable energies. Given our interdisciplinary approach, we always take into account both economic and ecological aspects.

The institute was founded in 2012, initially as an interdisciplinary competence centre, in cooperation with our longstanding and reliable partner, SWK AG (Krefeld Municipal Utilities). The professors associated with the institute have different specialisations and come from various departments of the university. They are supported by around 25 academic and student staff members.

The research focus of the institute lies in the analysis and optimisation of energy systems and processes. The institute's services include conducting energy audits, implementing energy management systems, and developing transformation concepts. Over the past five years alone, more than 60 energy audits have been conducted, identifying over 500 energy-saving measures.

Jörg Meyer has been a professor of energy technology and energy management at Niederrhein University of Applied Sciences since 1 September 2016 and heads the SWK E² Institute there. He has extensive knowledge of various energy technologies and energy efficiency measures, as well as of the energy market, energy industry, and energy policy. Mr Meyer has many years of experience conducting energy analyses and preparing studies. He has been active in the energy sector for nearly thirty years, focusing on improving energy procurement, energy supply, energy distribution, energy conversion, and energy use in industrial plants and buildings. The experience from several hundred energy analyses across almost all sectors was utilised in this study.

Prof. Dr.-Ing. Frank Alsmeyer has been teaching and researching at Niederrhein University of Applied Sciences since 1 March 2010 in energy and process system technology and has been part of the SWK E² Institute since its inception. His focus is on medium-sized energy systems, such as those in municipalities or large industrial enterprises, and their transformation towards climate neutrality. Key aspects include energy efficiency and sector coupling, and methodologically, the analysis of large data sets and computer-assisted simulation with physical and data-driven models. Before his appointment, Mr Alsmeyer had been involved since 1997 in the simulation and optimisation of process engineering, primarily in the chemical and petrochemical industries, and through collaboration with the relevant specialist departments, he gained extensive insights into the corporate practices of the process industries, which he was able to incorporate into this study.

Marius Madsen completed his master's degree in "Energy Engineering and Management" at Niederrhein University of Applied Sciences. Since 2017, he has been working and researching at SWK E². His work focuses on the analysis of large data sets. Moreover, he has deepened his extensive knowledge of energy efficiency, energy management, and energy technology through numerous projects. These areas of expertise have been well integrated into this study.

Louisa Zaubitzer has specialised in process engineering, particularly in the chemical industry. Since the end of 2023, she has been researching optimisation methods for energy systems at

SWK E². Before that, she spent seven years in the chemical industry. During this time, she completed a dual bachelor's degree in "Process Engineering", where she gained valuable practical experience through her training as a chemical technician. Following that, she worked for three years as a project engineer focusing on process engineering calculations for various plants and processes. At the same time, she expanded her expertise through a master's degree in "Computer-Aided Process Engineering". The specialist knowledge and practical experience she gained were incorporated into this study.