TECHNOLOGIES FOR DEFOSSILISATION OF PROCESS HEAT: AN ANALYSIS AND OVERVIEW OF INDUSTRIAL PROCESSES AND TEMPERATURE REQUIREMENTS

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ABSTRACT

Process heat is the heat required in industrial processes during the manufacturing of a product. In Germany, process heat constitutes two-thirds of the industrial sector which corresponds to nearly 20% of Germany's total energy demand (NRW.Energy4Climate, 2022). This heat demand varies between the industrial sectors and is highly dependent on the quantities, processes, and particularly the production temperature requirements. Therefore, this paper presents an overview of industrial processes and available technologies with their respective temperature ranges to assist in the creation of concepts for the defossilisation of process heat. The process overview is split into industrial sectors and the corresponding temperatures are summarised in a table. After identifying available technologies for defossilisation through literature research, such as heat pumps, electric boilers, and solar thermal technologies, each technology is evaluated based on its advantages, limitations, and suitability for different temperature requirements in industrial processes. The technology overview is visualised through a diagram containing temperature levels and energy sources. The research conducted is based on German national data, but temperature requirements and available technologies can be applied to other countries as well. The data contained in this paper could be used to develop process heat concepts or as a market overview for the introduction of new technologies to defossilise process heat.

1 INTRODUCTION

The industrial manufacturing sector in the EU accounted for 21% of the final energy use in 2023. This corresponded to annual emissions of 706.5 million tonnes of CO_2 equivalents (Eurostat, 2024). Processes such as steel making in the metal industry, glass melting in the mineral industry, or drying in the paper industry have a high energy or, more specifically, process heat demand. In alignment with the EU Climate goals to achieve climate neutrality by 2050, many attempts are made to transform this industrial energy demand. Whilst defossilising electric (e.g. mechanical) processes simply requires the switch to renewable energy sources, process heat imposes many more technological difficulties to enable a transformation. The challenge of developing strategies for defossilising process heat lies in the diversity of industrial processes and their specific temperature demands. Gathering precise data across a wide array of products and processes within various industry sectors presents significant hurdles. While factors like resource availability, infrastructure, pricing dynamics, energy demand timeseries, and geographical conditions are also critical for process heat, their specificity excludes them from this study's scope. A thorough identification and analysis of these processes and requirements is imperative, and the process and technology temperature overview from this work provide a solid foundation for developing defossilisation concepts.

1.1 Industrial Processes

The manufacturing industry is classified under the Statistical Classification of Economic Activities in the European Community (NACE) through sector B 08 – 'Other Mining and quarrying' and C – 'Manufacturing'. The most energy intensive manufacturing sectors according to Eurostat are

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the petro-/chemical, non-metallic minerals, paper, food/beverages/tobacco and iron/steel industries (Eurostat, 2022). To show the relevance of temperatures on the energy demand, Figure 1 exemplifies the process heat demand in North Rhine-Westphalia (NRW), Germany, which can be seen as representative for other European temperature distributions, since it is one of the most industrial federal states of Germany (Wirtschaft.NRW, 2024). From literature, a temperature distribution was determined and then applied to the calculated process heat demand per industrial sector (Budt et al., 2024).

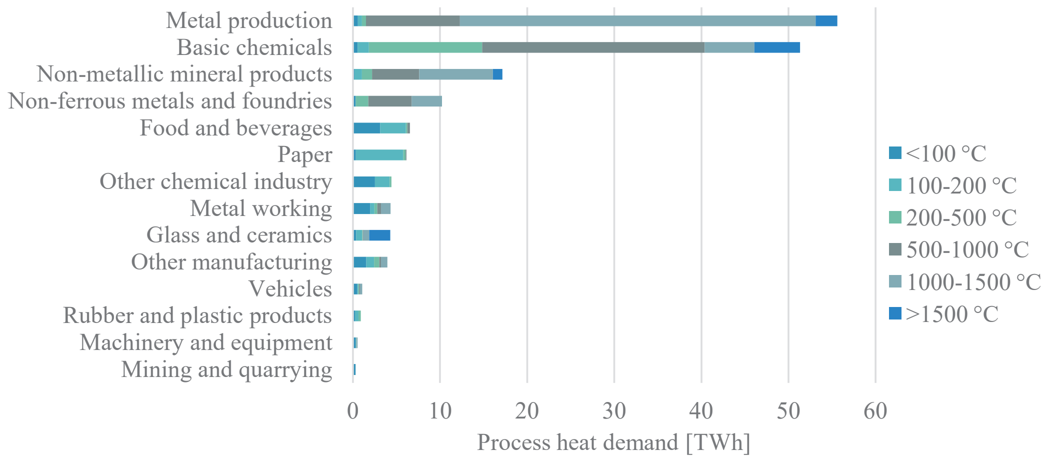

Figure 1: Temperature distribution of process heat demand in North Rhine-Westphalia (NRW), Germany, by industrial sector for 2020 (Budt et al., 2024)

In these sectors, each product has various manufacturing steps involved, which were identified and analysed, like boiling, drying, etc. The processes involving heat are tabularised along with their respective temperatures. Regardless of the product, industrial sectors often share processes with similar temperature levels that could potentially be served in a technologically similar way (von Thadden del Valle et al., 2023). This paper hence also discusses possible technologies for the supply of process heat.

1.2 Process heat technologies

Heat can be supplied in a multitude of ways to the industrial processes. To generate process heat, combustion of different fuels, such as fossil/biogas or oil, can be used, as well as electric heat generation (e.g. boilers) or renewable sources such as solar or geothermal energy. This heat can be directly supplied, for example in furnaces (direct or indirect contact with the product), or indirectly using heat transfer mediums, such as steam or hot water.

A big debate surrounds the choice between defossilisation through electrification or the use of green hydrogen. One of the main arguments for electrification is that the conversion losses for synthesis are higher compared to those for Power-to-Heat (PtH) applications. While PtH has an efficiency of 97%, obtaining heat from hydrogen after electrolysis (Power-to-Gas-to-Heat, PtGtH) gives an efficiency of around 63% and similarly heat from synthetic methane (PtGtH) which has an efficiency of around 50% (Begemann et al., 2021). Availability and infrastructure, as well as high demand for hydrogen, should limit it to applications that require high flame temperatures or where complete electrification is technically not feasible, such as the steel industry (Begemann et al., 2021; Lopez et al., 2022). Scientific analyses on the decarbonisation of Germany until 2024 predict increased electrification of process heat in all scenarios, even in scenarios with preferred use of hydrogen (Fleiter et al., 2021).

All defossilized technologies were researched to obtain a maximum operating temperature and typical heat capacities. In this research, PtH technologies are only considered defossilised if the electricity comes from a renewable source. For high-temperature processes, specialized technologies are required like furnaces, whereas many technologies exist that provide lower temperatures (<500°C) which are often used as general-purpose technologies to provide e.g. process steam.

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1.3 Defossilisation of process heat

To provide assisting information to match the technologies to the processes, the temperature ranges and certain product and process requirements, such as material constraints and geographical limitations, were gathered. This paper is aimed at industries wanting to change their heat supply and researchers trying to identify possible applications for their developed technologies. Although the analysis and applicability of individual technologies to industrial processes already partially exists in the literature, this paper provides a complete temperature overview over technologies and processes from all industrial sectors comprising processes with low- to very-high-temperature requirements. The research carried out in this study is mainly based on German national data; however, most of the temperature requirements and available technologies explored can be applicable to other countries as well.

2 METHODS

The background for this paper is an extensive review of the literature. First, data on energy balances and other information on the different industrial sectors through reports of statistical offices, such as Eurostat (EU Statistical Office) and Destatis (German Statistical Office), were gathered. Then, the individual products within the industrial sectors were noted, as well as typical process steps involved in the manufacture of the product. This was filtered by processes that mainly require process heat and grouped by industrial sector and further by processes that share the same name but are used to manufacture different products, e.g. drying, in an Excel table.

The temperatures associated with these processes were thoroughly researched and examined. A limitation encountered was the availability of comprehensive and up-to-date temperature data for certain processes. Efforts were made to address this by cross-referencing multiple sources and ensuring the inclusion of the most recent and reliable data. Therefore, the table comprised various columns containing several temperature ranges for the same processes. The plausibility was checked, and temperatures were either averaged or excluded. The process temperatures were found in research papers that discussed the suitability of individual technologies for these processes, as well as in other academic papers, lecture slides, technical documents, and government reports.

Similarly, the technology overview started by gathering and mapping relevant information on process heat supply. This research analysed what technologies are used to supply process heat, how this heat is supplied and distributed to the process, what source is used and what kind of heat transfer occurs. A visualisation was created summarising all these research findings with the intention of the giving an overview of available technologies currently supplying process heat.

Additionally, a table with maximum temperature and heat capacity of the technologies was made. This information comes from manufacturer's technical sheets, government reports, and scientific papers and was further verified for plausibility. After obtaining both temperature information for processes and technologies, the suitability and limitations of the chosen technologies for the industrial sectors was inspected. This work presents a starting point for further investigation by providing a complete temperature overview of process heat technologies and processes covering all manufacturing sectors.

3 RESULTS

The results are divided into the process overview with the respective highest and lowest temperature per manufacturing process and the technology overview. The technologies are briefly explained along with advantages, limitations, and suitability for various processes due to specific material requirements.

3.1 Technologies for the defossilization of process heat

Figure 2 includes typical energy sources, technologies, and heat transfer mediums that are currently used to supply process heat. Both fossil and renewable technologies and sources are examined; however, this paper will only focus on the technologies that contribute to a defossilized process heat system. A brief explanation of each technology and achievable temperatures is provided in this chapter.

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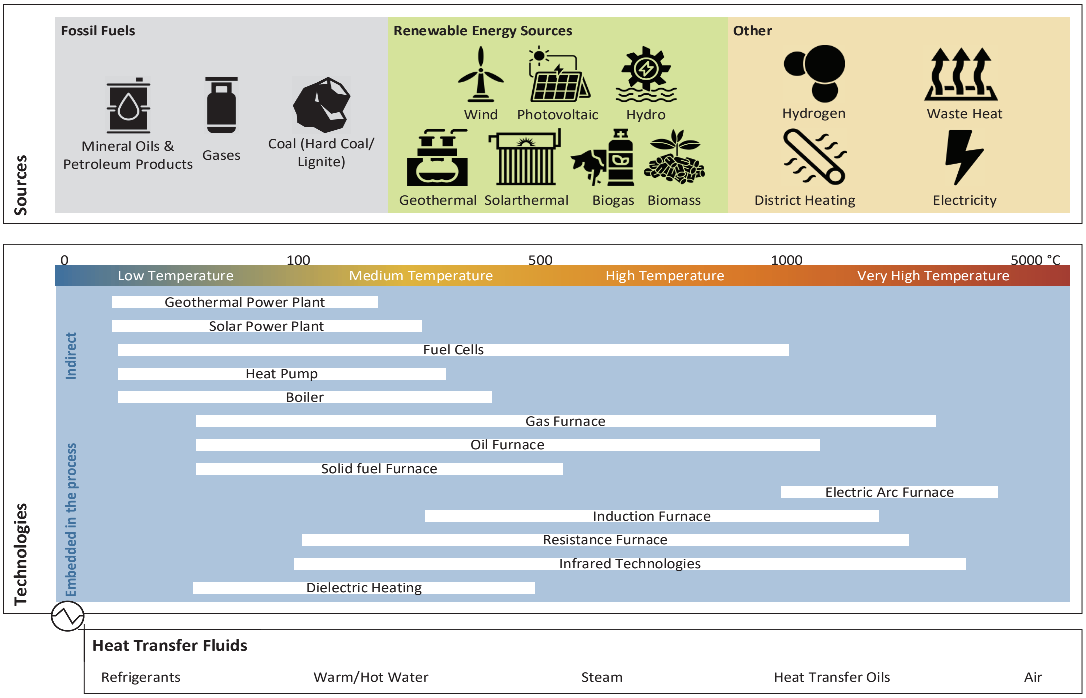

Figure 2: Overview for the different options of process heat supply with its sources and technologies. Own research, including (Begemann et al., 2021; Brauner, 2016; Brett et al., 2008; Cudazzo et al., 2005; Klute et al., 2024; Leicher et al., 2023; Naegler et al., 2016; Schabbach and Leibbrandt, 2021)

Geothermal energy encompasses the heat stored in the Earth's crust and its practical application in engineering (Umweltbundesamt, 2023). Geothermal energy is divided into shallow geothermal energy and deep geothermal energy, with the latter considered from a depth of 400 metres (Begemann et al., 2021). Geothermal energy for process heat is set to reach around 200 °C (Bracke and Huenges, 2021), depending highly on its location.

Solar thermal collectors produce process heat by converting incident solar radiation to thermal energy. They are split into three types of solar thermal systems: flat plate collectors, vacuum tube collectors, and parabolic trough collectors. Maximum achievable temperatures vary due to location and solar incidence, but are assumed to be at 250 °C (Schabbach and Leibbrandt, 2021).

In a cogeneration setup, *fuel cells* can provide (waste) heat from the electrochemical reaction. There are various types of fuel cells, such as Polymer Electrolyte Membrane (PEM) Fuel Cells or Solid Oxide Fuel Cells (SOFCs); however, in this paper they are summarised as a singular potential technology enabling process heat temperatures of up to 1000 °C (Brett et al., 2008).

Heat pumps (HP) are classified as PtH technology. The main advantage of heat pumps is the ability to have coefficients of performance (COP) greater than 1. HP can be classified into four categories based on the temperatures they can achieve. Low-temperature heat pumps can reach temperatures up to 60 °C, medium-temperature heat pumps up to 80 °C and high-temperature heat pumps reach up to 120 °C. Heat pumps that can achieve temperatures higher than 120 °C are classified as ultra-high temperature heat pumps (Wolf, 2017). There are four types of heat pumps further differentiated in this paper: compression heat pumps (vapour compression – max. 200 °C, gas compression – max. 250 °C), adsorption heat pumps (not suitable for industrial processes), absorption heat pumps (AHP) (Type I – max. 90 °C, Type 2 – max. 230 °C), and mechanical vapour recompression (MVR) heat pumps (max. 280 °C) (Arpargaus, 2023; Klute et al., 2024).

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Boilers are typically used to provide process steam, which is then conducted to the different processes. Boilers can use combustion of fuels to provide heat or can be electrically heated, either as resistance boilers or electrode boilers. Electrode boilers reach temperatures up to 500 °C (Münnich et al., 2022) and resistance boilers around 350 °C (Begemann et al., 2021).

Here, *gas/oil/solid fuel furnaces* are only fuelled by fossil-free alternatives, such as biomass, biogas, bio-oil, and biodiesel. In the case of all furnaces, the product can be either in direct contact with the firing process or indirectly. Furnaces can hence transmit the process heat to the product through radiation, conduction, and convection. Hydrogen burners reach temperatures of around 3000 °C (Begemann et al., 2021), and bio- or synthetic methane burners can provide around 2460 °C (Leicher et al., 2023). Combustion of biomass typically supplies temperatures up to 500 °C (Naegler et al., 2016).

Electric arc/induction/resistance furnaces are PtH technologies and use electric arcs, electromagnetic induction, and electric resistance to generate heat. They are known to achieve good temperature control with high efficiency (Begemann et al., 2021) and are typically used in high-temperature processes reaching temperatures of 4000 °C (Salzgitter Mannesmann Stahlhandel, 2024), 2000 °C (Dhakal et al., 2012), and 2400 °C (Rosenhain and Coad-Pryor, 1919) respectively.

Infrared technologies use electromagnetic (infrared) radiation for process heat and reach temperatures of about 3500 °C (Cudazzo et al., 2005). They belong to the group of PtH technologies.

Dieletric heating is a PtH technology that utilises the principle of dielectric loss to generate heat in materials. Dielectric heating technologies can reach temperatures of about 500 °C (Brauner, 2016).

All researched technologies were aggregated in a table including their peak power and temperatures. It has to be noted that these two are not necessarily linked as they might stem from different sources. The graph in Figure 3 can therefore only be seen as the maximum existing technology options to understand their suitability for different processes. Configurations and combinations of these technologies, such as connecting several in series or parallel, might be possible for some options, such as geothermal energy with heat pumps (Klute, 2023), but these setups were not further investigated in this article.

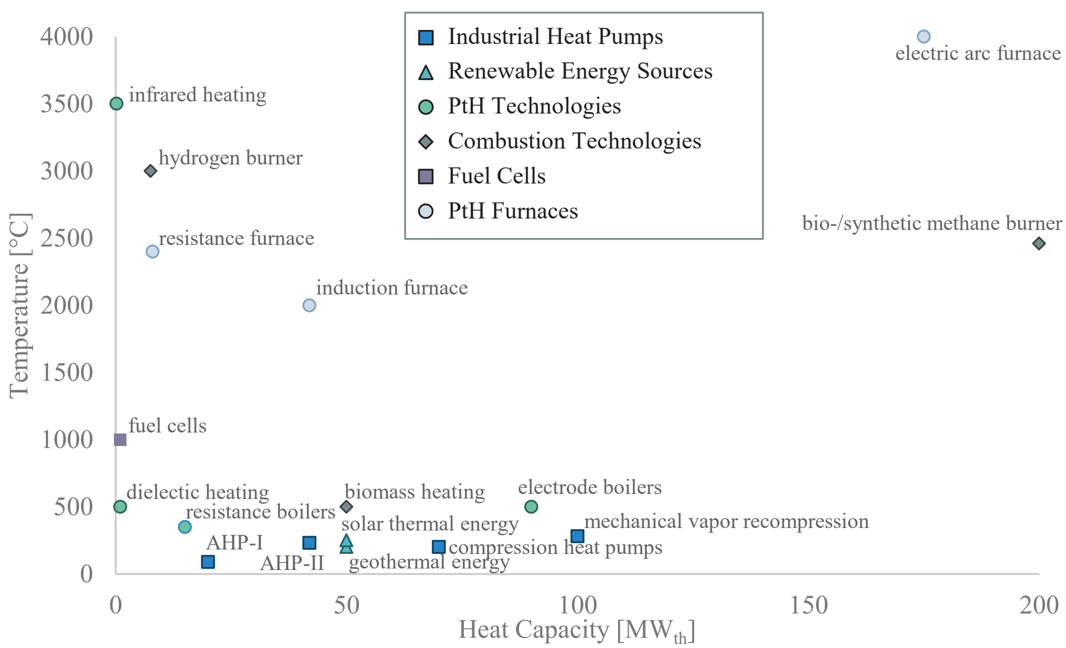

Figure 3: Technology comparison with heat capacity and temperatures. Own research, including (Danish Energy Agency and Energienet, 2020; Klute et al., 2024)

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The technologies were further grouped into *Industrial Heat Pumps* (compression heat pumps, AHP-Type I, AHP-Type II, mechanical vapour recompression heat pumps), *Renewable Energy Sources* (solar thermal and geothermal), *PtH Technologies* (infrared heating, dielectric heating, resistance boilers, electrode boilers), *Combustion Technologies* (biomass heating, hydrogen burners, bio/synthetic methane burners), *Fuel Cells* and *P2H Furnaces* (resistance, induction, and electric arc furnace).

3.2 Overview of industrial processes with respective temperature ranges

Table 1 provides an overview of the industrial sectors with their respective NACE code and definition, and different gathered processes from the individual sectors. In part, sectors were grouped as one to reduce duplications of similar processes or when the energy demand of the individual sector is too low. A few sectors are not listed here, as their energy demand is either comparatively low or the product portfolio too diverse to summarise typical processes, such as *C 32 Other Manufacturing* or *C 33 Repair and installation of machinery and equipment*.

Table 1: Overview of industrial processes per NACE sector with respective temperature ranges. Own research, including (Arpargaus, 2023; Blesl et al., 2009; Rieberer et al., 2015; Sabine Frisch et al., 2013; Schmitt, 2014; Stefan Wolf et al., 2012)

NACE Code	NACE Name	Process	Temperature [°C]	
			Min	Max
B 08	Other mining and quarrying	Drying	450	450
C 10 C 11	Manufacture of food products Manufacture of beverages	Drying	40	750
		Evaporating	40	200
		Pasteurization	60	150
		Sterilizing	100	140
		Boiling/Cooking	70	120
		Distillation	40	100
		Brewing	45	90
		Concentrating	60	80
		Tempering	40	80
		Smoking	20	110
		Blanching	65	95
		Evaporating	40	130
		Purifying/Cleaning	60	110
		Washing	35	80
		Cristallizing	65	80
		Carbonatation (lime kiln operation)	1100	1100
		UHT (Ultra-High Temperature) Processing	135	150
		Baking	120	300
C 12	Manufacture of tobacco products	Fermenting	10	100
		Steam Treatment	60	60
		Casing	70	120
C 13 C 14	Manufacture of textiles Manufacture of wearing apparel	Coloring	40	160
		Drying	60	130
		Washing	30	110
		Bleaching	40	100
		Fixing	150	180
		Pressing	80	100
		Cleaning	30	70
C 15	Manufacture of leather and related products	Tanning	30	70
		Colouring/Dying	20	60
		Drying	50	120
		Bleaching	20	50
		Ironing	90	90
C 16 C 31	Manufacture of wood and of products of wood and cork,	Bonding	120	180
		Pressing	120	200

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	except furniture; manufacture of articles of straw and plaiting materials Manufacture of furniture	Drying	40	150
		Steam treatment	70	120
		Cooking	80	90
		Coloring	50	80
		Staining	40	80
		Thermodiffusion Beams	80	100
		Water Preheating	60	90
		Preparation Pulp	120	170
		Pickling	50	65
C 17	Manufacture of paper and paper products	Drying	60	250
		Boiling	60	180
		Bleaching	40	150
		Discoloration	50	100
		Cleaning	30	70
		Heating	40	80
		Softening	120	135
C 19	Manufacture of coke and refined petroleum products	Coking	900	1400
		Distilling	350	400
		Conversion	600	600
		Thermal Cracking	360	900
		Catalytic Cracking	700	700
		Hydrocracking	480	480
		Delayed Coking	500	500
		Calcinating	1200	1200
		Desulfurization	300	350
		Reforming	500	500
		Pyrolysis	2500	2500
C 20	Manufacture of chemicals and chemical products	Thermal Cracking	750	900
		Catalytic Cracking	400	600
		Dehydrating	500	500
		Hydrating	120	180
		Steam Reforming	700	900
		(Ammonia-) Synthesis	350	550
C 21	Manufacture of basic pharmaceutical products and pharmaceutical preparations	Fermenting	20	40
		Sterilizing	120	300
C 22	Manufacture of rubber and plastic products	Injection Molding	90	300
		Pellet Drying	40	150
		Preheating	50	70
		Preparing	120	140
		Distilling	140	150
		Separating	200	220
		Extending	140	160
		Blending	120	140
		Processing	140	310
		Manufacturing	50	220
C 23	Manufacture of other non-metallic mineral products	Melting	1450	1650
		Drying	120	300
		Firing/Sintering	500	2500
		Shaping	900	1200
		Calcinating	1000	1000
		Modifying	1500	2000
C 24 C 25	Manufacture of basic metals Manufacture of fabricated metal products, except machinery and equipment	Drying	60	250
		Staining	20	100
		Degreasing	20	100
		Plating	20	110
		Phosphating	30	95

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		Chromating	20	80
		Rinsing	40	70
		Paint Stripping	50	70
		Purifying/Cleaning	30	70
		Pelletizing	1000	1000
		Gasifying	1200	1300
		Direct Reduction	1050	1050
		Melting	660	3500
		Hot Rolling	500	1250
		Cold Rolling	25	700
		Recrystallization Annealing	680	1230
		Hot Forming (Forging)	950	1280
		Semi-hot Forming	750	950
		Work Hardening	20	700
		Electrolysis	950	950
		Burning	180	180
		Pouring	415	1670
C 28	Manufacture of machinery and equipment n.e.c.	Surface Treatment	20	120
		Purifying/Cleaning	40	90
C 29 C 30	Manufacture of motor vehicles, trailers and semi-trailers Manufacture of other transport equipment	Compression Molding	70	130
Various sectors		Space Heating	20	80
		Hot Water (boiler feed or auxiliary water)	20	110
		Preheating	0	100
		Washing/Cleaning	20	90
		Process Heat Networks	110	120

Some processes are highly product specific such as Ultra-high-temperature (UHT) processing in the *C 11 Manufacture of beverages* which is mostly known in the milk production (Gühl et al., 2020). Other processes have a large temperature spread as they include the manufacture of products within the sector with varying temperature requirements. One example is Drying in the *C 10 Manufacture of Food Products* which ranges from 40 to 750 °C as it contains the drying of sugar beet pulp after sugar crystallisation for animal feed production which reaches the maximum temperatures indicated by this process (Gühl et al., 2020). Milk powder drying can reach temperatures of 300 °C (Gühl et al., 2020) whereas other drying processes within this industry tend to stay below this temperature (Arpargaus, 2023). The higher temperatures in the range provided for the drying process in *C 23* refers to the manufacture of clinker and cement (Holcim WestZement GmbH, 2015). Work hardening in *C 24 Manufacture of basic metals* occurs at temperatures up to 700 °C for steel manufacturing (Technikdoku, 2018). Some temperature ranges might not include the required temperatures for all products in that industrial sector, as processes and products within that sector were first determined top-down.

4 DISCUSSION

From the temperature overview it can clearly be seen that the sectors grouped by economic activities contain large differences in the process temperatures required for the corresponding products. However, a few processes exist across various industries that require similar temperatures (von Thadden del Valle et al., 2023). These are processes such as dyeing, drying, fermenting, boiling/cooking and welding. Some technologies are hence suitable as cross-sectoral technologies. Also, considering waste heat streams from processes of nearby companies could be a viable path to the defossilisation. The use of external waste heat is still not widespread, as integrating these heat streams poses several challenges, such as different load profiles or regulatory requirements. Nevertheless, several projects strongly recommend integrating waste heat from other companies into one's own processes (Hadam et al., 2022).

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Since too many factors exist, that contribute to choosing a suitable technology for the respective process, matching technologies to processes purely based on temperature levels would not suffice and is therefore not done in this work. Other factors such as resource availability, infrastructure, pricing dynamics, energy demand timeseries, and geographical conditions have to be considered in order to conduct informed process heat transformation concepts. However, an example is given demonstrating the defossilisation of a drying process through the use of the previously mentioned technologies.

The most used technique for drying food products is convective hot air drying. Warm air with low relative humidity flows into the drying chamber, dries the product, and then exits the chamber with high relative humidity (Moscetti et al., 2018). To heat and dry the air before entering the drying chamber, combustion processes using fossil fuels are mostly employed. The moist air leaving the drying chamber is usually not reused. Heat pumps can utilize the energy stored in the exhaust air by drying it through condensation, then using a suitable heat source (e.g. waste heat from a different process) and compression to raise it to the required temperature level for re-entering the drying chamber. A final process design could be a closed-loop drying system, where the heat pump reintroduces the energy of the latent heat from the exhaust air in the drying chamber as dehumidified and re-heated air (Lauermann, 2022). As always, the efficient use of the heat pump is tied to the existing process conditions.

Most technologies are only suitable for providing heat under 500 °C, which reduces the available technologies for high-temperature processes. Resistance heating temperatures vary depending on the material and are commonly used in glass melting and the manufacture of aluminium. Induction heating is often used for induction hardening and melting of metals, as well as induction heating in rolling mills and forges. Electric arc furnaces are often used for the manufacture of secondary steel and steel casting. Both hydrogen and bio/synthetic methane burners are considered technologies which should only be used if no alternative is available. They are partly used, for example, in the steel production and ceramics and glass manufacturing (Begemann et al., 2021).

Although fuel cells are mentioned as a technology for providing process heat, their main purpose is to generate electricity through an electrochemical reaction. This reaction also produces (waste) heat which can be harnessed to provide process heat. The suitability of the installation of a fuel cell for process heat on-site must therefore be examined thoroughly and might not be the most ideal option.

Heat pumps are considered to be one of the leading technologies for the defossilisation of process heat in the low- to mid-temperature ranges. Compression heat pumps rely on a heat source with a sufficiently high temperature to reduce the required temperature lift and hence provide a better COP. The reachable temperature also depends on the selection of refrigerant. Refrigerants that are recommended for high-temperature heat pumps are R1336mzz-Z, R1233zd(E) and R1234ze(Z) (Arpargaus, 2023). AHP-Type I requires a constant heat stream of around 100 °C. Mechanical vapour recompression also needs steam as input and is therefore not suitable for industries without this waste stream (Stefan Wolf et al., 2012).

Both dielectric and infrared heating is suitable for drying processes. Dielectric heating is often used for the drying of paper, textile, and glass fibres. Infrared heating is highly dependent on the absorption properties of the material which is why highly reflective materials are less suited. Therefore, this technology is limited to the manufacture of specific products and is commonly used for the drying and polymerising of colours and coatings as well as in the food industry (Bechem et al., 2015).

Boiler technologies typically produce process steam or are integrated in the process by heating the (liquid) product. Electrode boilers are commonly used because of their high efficiency, whilst resistance boilers tend to have lower heat capacities (Brauner, 2019). Biomass boilers depend on the availability of this biomass. Different countries prioritize biomass utilization based on their national concepts.
Both geothermal and solar thermal energy are well suited to provide process heat for processes in the low- to mid-temperature range. Examples of the use of geothermal energy for process heat exist in Romania for milk pasteurisation (Lund, 1997) and in Germany in an ongoing project for paper drying (Kabel Premium Pulp & Paper GmbH, 2020). An example of solar thermal energy is the integration

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into a brewery in Spain (Hirsch et al., 2023). Both geo- and solar thermal energy have geographical limitations, and solar thermal energy also depends on the radiation of the Sun and the available space.

A technology which is also essential for defossilisation is heat storage. This was excluded from the technology overview, as it typically does not generate the heat itself but stores excess or waste heat to minimise costs and improve the efficiency of the process. It is commonly used in combination with renewable energy sources, to supply heat in peak production periods with lower solar radiation levels.

It should be emphasised that the selection of the optimal technology for the defossilisation of process heat always depends on the specific requirements of each individual application as well as on the existing and future energy infrastructure. A thorough examination and evaluation of the aspects in place needs to be conducted. This research should merely provide an incentive and an overview to understand the possible ways our industry can be transformed to achieve climate neutrality.

5 CONCLUSION

In conclusion, this research paper conducted an extensive literature review to gather information on the supply of process heat and its defossilisation. Substantial work has been invested to provide a comprehensive overview of processes from all the manufacturing sectors with their respective temperature ranges, previously missing from literature. Additionally, several technologies were identified and related to their possible applications to achieve climate neutrality in the industrial sector. The paper also visualised these available technologies, considering factors such as maximum heat capacity and temperature. However, it is important to check on-site conditions and perform a thorough cost analysis to determine the suitability of the technologies for specific industries and processes. Additionally, logistics and infrastructure should be considered when choosing a technology for defossilisation. Ultimately, this study highlights the high demand for process heat in industrial processes. When measures to improve the efficiency of the process heat system are conducted, a switch to fossil-free alternative technologies is still necessary. This paper emphasises the existence of numerous technologies that can contribute to the achievement of a climate-neutral industry. It also provides key indicators that can aid in comprehending and further advancing towards this objective.

REFERENCES

Arpargaus, C. (2023) *Hochtemperatur-Wärmepumpen für industrielle Anwendungen* [Online]. Available at https://www.vea.de/files/user_upload/vea-hauptseite/newsroom/veranstaltungen/2023/4_-_hochtemperatur-waermepumpen_fuer_industrielle_anwendungen_arpagaus.pdf.

Bechem, H., Falke, T. and Schnettler, A. (2015) *Potenziale für Strom im Wärmemarkt bis 2050 : Wärmeversorgung in flexiblen Energieversorgungssystemen mit hohen Anteilen an erneuerbaren Energien ; Studie der Energietechnischen Gesellschaft im VDE (ETG) (2015),* VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V., Lehrstuhl und Institut für Hochspannungstechnik 0000 [Online]. Available at https://publications.rwth-aachen.de/record/538328.

Begemann, T., Budt, M., Glasner, C., Herrig, S., Reinert, C. and Schüwer, D. (2021) 'Industriewärme klimaneutral - Strategie und Voraussetzungen für die Transformation'.

Blesl, M., Kempe, S., Ohl, M., Fahl, U., König, A., Jenssen, T. and Eltrop, L. (2009) 'Wärmeatlas Baden-Württemberg - Erstellung eines Leitfadens und Umsetzung für Modellregionen'.

Bracke, R. and Huenges, E. (2021) *Roadmap Tiefengeothermie für Deutschland*.

Brauner, G. (2016) *Energiesysteme: regenerativ und dezentral*, Wiesbaden, Springer Fachmedien Wiesbaden.

Brauner, G. (2019) *Systemeffizienz bei regenerativer Stromerzeugung*, Wiesbaden, Springer Fachmedien Wiesbaden.

Brett, D. J. L., Atkinson, A., Brandon, N. P. and Skinner, S. J. (2008) 'Intermediate temperature solid oxide fuel cells', *Chemical Society Reviews*, vol. 37, no. 8, pp. 1568–1578 [Online]. DOI: 10.1039/B612060C.

https://doi.org/10.52202/077185-0027

Budt, M., Janßen, K., Rath, M., Eicker, T., Bussmann, G., Dresen, B., Born, H. and Göttsche, J. (2024) *Wärmestudie NRW: Vorstellung Zwischenergebnisse* [Online]. Available at https://www.energieatlas.nrw.de/site/Media/Default/Dokumente/Foliensatz_Veranstaltung_Waermestudie-NRW_20240126.pdf.

Cudazzo, M., Ondratschek, D. and Strohbeck, U. (2005) *Hocheffiziente Verfahren zur Pulverbeschichtung von Holzwerkstoffen* [Online]. Available at https://pudi.lubw.de/detailseite/-/publication/51463-hocheffiziente_verfahren_zur_pulverbeschichtung_von_holzwerkstoffen.pdf.

Danish Energy Agency and Energienet (2020) 'Technology Data for Industrial Process Heat'.

Dhakal, P., Ciovati, G., Rigby, W., Wallace, J. and Myneni, G. R. (2012) 'Design and performance of a new induction furnace for heat treatment of superconducting radiofrequency niobium cavities', *The Review of scientific instruments*, vol. 83, no. 6, p. 65105 [Online]. DOI: 10.1063/1.4725589.

Eurostat (2022) *Complete energy balances: Statistics | Eurostat* [Online]. Available at https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c__custom_10379771/default/table?lang=en (Accessed 13 March 2024).

Eurostat (2024) *Air emissions accounts for greenhouse gases by NACE Rev. 2 activity - quarterly data* [Online]. Available at https://ec.europa.eu/eurostat/databrowser/view/env_ac_aigg_q__custom_11594023/default/table?lang=en (Accessed 29 May 2024).

Fleiter, T., Rehfeldt, M., Manz, P., Neuwirth, M. and Herbst, A. (2021) *Langfristszenarien für die Transformation des Energiesystems in Deutschland 3. Treibhausgasneutrale Hauptszenarien. Modul Industrie*.

Gühl, S., Schwarz, M. and Schimmel, M. (2020) *Energiewende in der Industrie-Potenziale und Wechselwirkungen mit dem Energiesektor: Branchensteckbrief der Nahrungsmittelindustrie* [Online]. Available at https://www.bmwk.de/Redaktion/DE/Downloads/E/energiewende-in-der-industrie-ap2a-branchensteckbrief-nahrung.pdf?__blob=publicationFile&v=4.

Hadam, M., Arnold, K., Taubitz, A. and Budt, M. (2022) *Klimahafen Gelsenkirchen: Bottom-Up-Studie zur Dekarbonisierung der Prozesswärme,* Fraunhofer UMSICHT and Wuppertal Institut [Online]. Available at https://www.klimahafen-gelsenkirchen.de/fileadmin/user_upload/KlimahafenGelsenkirchen/2022-12-06-DBU-Studie_Klimahafen_GE_Langfassung.pdf.

Hirsch, T., Krüger, D., Stengler, J., Buck, R. and Lackoviv, L. (2023) *Solarthermisch erzeugte Prozesswärme für industrielle Anwendungen*.

Holcim WestZement GmbH (2015) *Zementherstellung: im Werk Beckum-Kollenbach* [Online]. Available at https://www.holcim.de/sites/germany/files/documents/HOLCIM_LAFARGE_Zementherstellung_Beckum_web_14.pdf.

Kabel Premium Pulp & Paper GmbH (2020) *Das Projekt Kabel ZERO - Eine Tiefen-Geothermie-Anlage zur klimaneutralen Papiertrocknung* [Online]. Available at https://www.kabelpaper.de/kabel-zero/ (Accessed 25 January 2024).

Klute, S. (2023) *Identifizierung und Bewertung von Verfahrensrouten für die industrielle Prozessdampferzeugung aus Tiefengeothermie: Am Beispiel der Papierindustrie*, Dissertation, Bochum, Ruhr-Universität Bochum.

Klute, S., Budt, M., van Beek, M. and Doetsch, C. (2024) 'Steam generating heat pumps – Overview, classification, economics, and basic modeling principles', *Energy Conversion and Management*, vol. 299, p. 117882 [Online]. DOI: 10.1016/j.enconman.2023.117882.

Lauermann, M. (2022) *ANNEX 59 - Heat Pumps for Drying* [Online]. Available at https://heatpumpingtechnologies.org/annex59/ (Accessed 7 May 2024).

Leicher, J., Giese, A. and Görner, K. (2023) 'Wasserstoff als Dekarbonisierungsoption für Hochtemperaturprozesswärme -Auswirkungen auf die Bildung und Bewertung von Stickoxidemissionen' [Online]. Available at https://www.researchgate.net/publication/374812858_Wasserstoff_als_Dekarbonisierungsoption_fur_Hochtemperaturprozesswarme_-Auswirkungen_auf_die_Bildung_und_Bewertung_von_Stickoxidemissionen.

https://doi.org/10.52202/077185-0027

Lopez, G., Farfan, J. and Breyer, C. (2022) 'Trends in the global steel industry: Evolutionary projections and defossilisation pathways through power-to-steel', *Journal of Cleaner Production*, vol. 375, p. 134182 [Online]. DOI: 10.1016/j.jclepro.2022.134182.

Lund, J. W. (1997) *Milk pasteurization with geothermal energy*.

Moscetti, R., Raponi, F., Ferri, S. and Massantini, R. (2018) *Trocknung - Allgemeine Aspekte* [Online], Viterbo, Italien. Available at https://orgprints.org/id/eprint/35089/1/e-learning_4.1_Lebensmitteltrocknung.pdf (Accessed 7 May 2024).

Münnich, P., Metz, J., Hauser, P., Kohn, A. and Mühlpointner, T. (2022) *Power-2-Heat: Erdgaseinsparung und Klimaschutz in der Industrie* [Online]. Available at https://www.agora-industrie.de/fileadmin/Projekte/2021/2021-05_IND_DE-P4Heat/A-EW_269_Power-2-Heat_WEB.pdf.

Naegler, T., Simon, S., Gils, H. C. and Klein, M. (2016) 'Potenziale für erneuerbare Energien in der industriellen Wärmeerzeugung', *BWK*, 6/2016.

NRW.Energy4Climate (2022) *Klimaneutrale Prozesswärme: Eine nachhaltige Prozesswärmeerzeugung ist unerlässlich, um Industrieprozesse klimaneutral umzugestalten* [Online], NRW.Energy4Climate. Available at https://www.energy4climate.nrw/industrie-produktion/energiebedarf-der-industrie/klimaneutrale-prozesswaerme (Accessed 15 March 2024).

Rieberer, R., Zotter, G., Hannl, D., Moser, H., Kotenko, O., Zottel, A., Fleckl, T. and Malenkovic, I. (2015) *IEA Heat Pump Programme Annex 35: Anwendungsmöglichkeiten für industrielle Wärmepumpen,* TU Graz – Institut für Wärmetechnik and AIT – Energy Department [Online]. Available at https://www.nachhaltigwirtschaften.at/resources/iea_pdf/endbericht_201517_iea_hpp_annex35_anwendungsmoeglichkeiten_fuer_industrielle_waermepumpen.pdf.

Rosenhain, W. and Coad-Pryor, E. A. (1919) 'A high-temperature electric resistance furnace', *Transactions of the Faraday Society*, vol. 14, p. 264.

Sabine Frisch, Martin Pehnt, Philipp Otter and Michael Nast (2013) *Prozesswärme im Marktanreizprogramm (MAP)* [Online]. Available at https://www.researchgate.net/publication/259902979_Prozesswarme_im_Marktanreizprogramm_MAP#pf4.

Salzgitter Mannesmann Stahlhandel (2024) *Stahl-Lexikon: Elektrolichtbogenofen* [Online]. Available at https://www.salzgitter-mannesmann-stahlhandel.de/de/encyclopedia/E/elektrolichtbogenofen (Accessed 15 March 2024).

Schabbach, T. and Leibbrandt, P. (2021) *Solarthermie*, Berlin, Heidelberg, Springer Berlin Heidelberg.

Schmitt, B. (2014) *Integration thermischer Solaranlagen zur Bereitstellung von Prozesswärme in Industriebetrieben*, Dissertation, Kassel, Germany, Universität Kassel [Online]. Available at https://www.reiner-lemoine-stiftung.de/en/pdf/dissertationen/dissertation-bastian_schmitt.pdf.

Stefan Wolf, Jochen Lambauer, Markus Blesl, Ulrich Fahl and Alfred Voß (2012) 'Industrial heat pumps in Germany: Potentials, technological development and market barriers'.

Technikdoku (2018) *Umformen Allgemein* [Online]. Available at https://technikdoku.com/umformen-allgemein/ (Accessed 15 March 2024).

Umweltbundesamt (2023) *Geothermie* [Online] (Accessed 27 November 2023).

von Thadden del Valle, C., van Beek, M. and Budt, M. (2023) *Klassifikation der Industriebranchen aus energietechnischer Sicht* [Online]. Available at https://publica.fraunhofer.de/entities/publication/54c1fe41-037b-41ab-811c-669f82c80c3c/details.

Wirtschaft.NRW (2024) *Industrie: Wir sind Industrie* [Online]. Available at https://www.wirtschaft.nrw/industrie.

Wolf, S. (2017) *Integration von Wärmepumpen in industrielle Produktionssysteme : Potenziale und Instrumente zur Potenzialerschließung*.

https://doi.org/10.52202/077185-0027