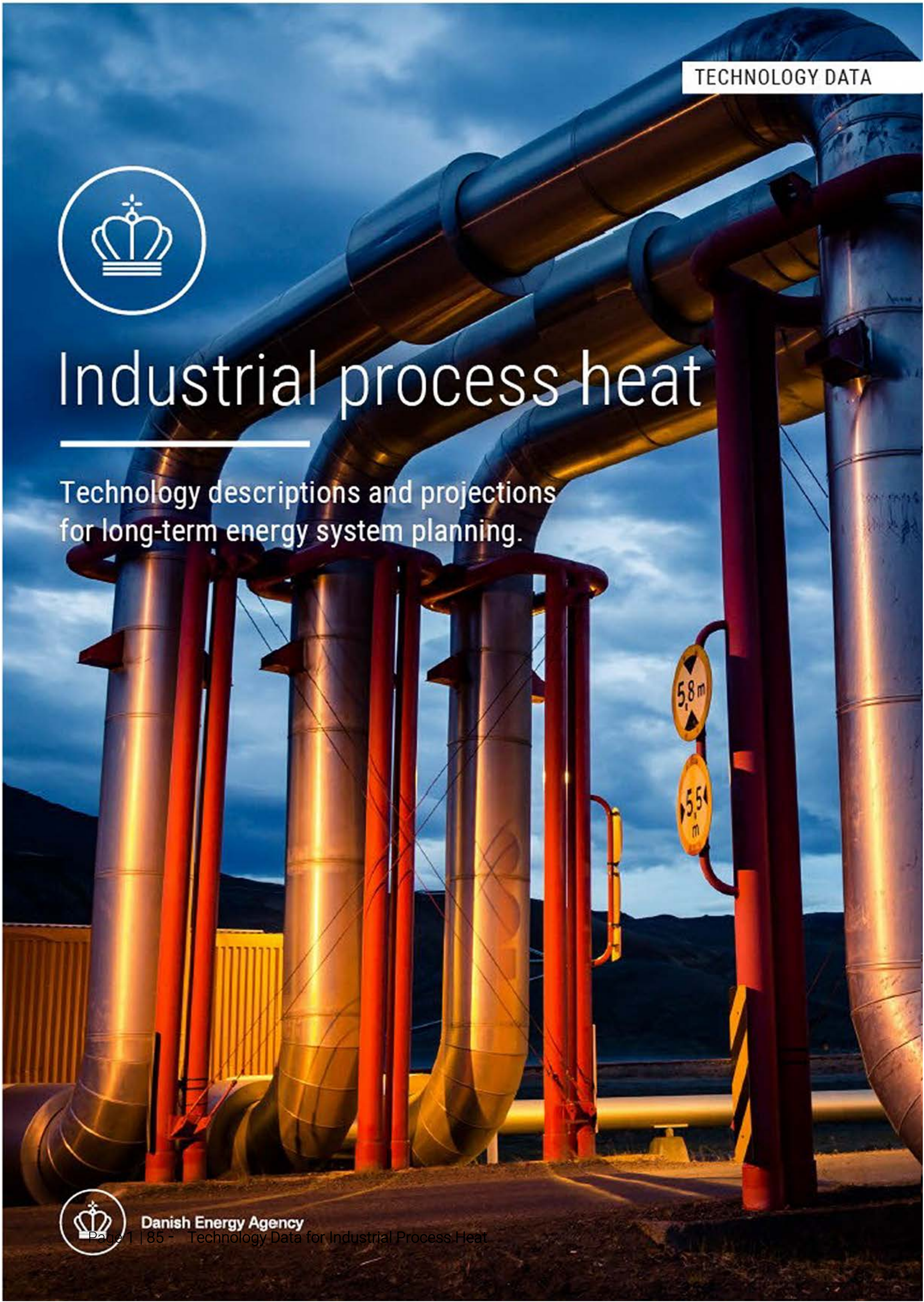

TECHNOLOGY DATA

Industrial process heat

Technology descriptions and projections
for long-term energy system planning.

Danish Energy Agency

Technology Data – Industrial process heat

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Amendment sheet

Publication date

Publication date for this catalogue is April 2020. The catalogue will be updated continuously as technologies evolve, if the data changes significantly, errors are found or the need for descriptions of new technologies arise.

The newest version of the catalogue will always be available from the Danish Energy Agency's web site.

Amendments after publication date

All updates made after the publication date will be listed in the amendment sheet below.

Version	Date	Ref.	Description
0006	January 2026	General update, special focus on HTHP	Updated and simplified heat pumps, high temperature heat pumps, electric boilers, boilers and direct firing. Removed chapters and datasheets on Heat driven heat pump, thermal gasification, hotdisc, dielectric assisted heating and infrared heating, these are available in an earlier version on the website. Removed descriptions on application potential. Renumbering of technologies.
0005	April 2024	Guideline/cover	Updated guideline in terms of scenario projection reference, price year, and further minor updates / new cover
0004	December 2022	310 Electric boilers, high pressure	Chapter updated with new text and datasheets
0003	November 2021	CC	Removal of carbon capture and transfer into the new Technology Catalogue for Carbon Capture, Transport and Storage
0002	October 2020	CC supplement guideline, CC introduction and 401-403	Carbon capture added to the catalogue
0001	April 2020		First published

Preface

The *Danish Energy Agency* publishes catalogues containing data on technologies for Energy Plants. All updates will be listed in the amendment sheet and in connection with the relevant chapters, and it will always be possible to find the most recently updated version on the Danish Energy Agency's website.

The primary objective of publishing technology catalogues is to establish a uniform, commonly accepted and up-to-date basis for energy planning activities, such as future outlooks, evaluations of security of supply and environmental impacts, climate change evaluations, as well as technical and economic analyses, e.g. on the framework conditions for the development and deployment of certain classes of technologies.

With this scope in mind, it is not the target of the technology data catalogues, to provide an exhaustive collection of specifications on all available incarnations of energy technologies. Only selected, representative, technologies are included, to enable generic comparisons of technologies with similar functions in the energy system e.g. thermal gasification versus combustion of biomass or electricity storage in batteries versus fly wheels.

Finally, the catalogue is meant for international as well as Danish audiences in an attempt to support and contribute to similar initiatives aimed at forming a public and concerted knowledge base for international analyses and negotiations.

Data sources and results

A guiding principle for developing the catalogue has been to rely primarily on well-documented and public information, secondarily on invited expert advice. Where unambiguous data could not be obtained, educated guesses or projections from experts are used. This is done to ensure consistency in estimates that would otherwise vary between users of the catalogue.

Cross-cutting comparisons between technologies will reveal inconsistencies which may have several causes:

- Technologies may be established under different conditions. As an example, the costs of off-shore wind farms might be established on the basis of data from ten projects. One of these might be an R&D project with floating turbines, some might be demonstration projects, and the cheapest may not include grid connections, etc. Such a situation will result in inconsistent cost estimates in cases where these differences might not be clear.
- Investors may have different views on economic attractiveness and different preferences. Some decisions may not be based on mere cost-benefit analyses, as some might tender for a good architect to design their building, while others will buy the cheapest building.
- Environmental regulations vary from between countries, and the environment-related parts of the investment costs, are often not reported separately.
- Expectations for the future economic trends, penetration of certain technologies, prices on energy and raw materials vary, which may cause differences in estimates.
- Reference documents are from different years. The ambition of the present publication has been to reduce the level of inconsistency to a minimum without compromising the fact that the real world is ambiguous. So, when different publications have presented different data, the publication which appears most in compliance with other publications has been selected as reference.

In order to handle the above-mentioned uncertainties, each catalogue contains an introductory chapter, stating the guidelines for how data have been collected, estimated and presented. These guidelines are not perfect, but they represent the best balance between various considerations of data quality, availability and usability.

Danish preface

Energistyrelsen udarbejder teknologibeskrivelser for en række el- og varmeproduktionsteknologier. Alle opdateringer vil registreres i rettelsesbladet først i kataloget, og det vil altid være muligt at finde den seneste opdaterede version på Energistyrelsens hjemmeside.

Hovedformålet med teknologikataloget er at sikre et ensartet, alment accepteret og aktuelt grundlag for planlægningsarbejde og vurderinger af forsyningssikkerhed, beredskab, miljø og markedsudvikling hos bl.a. de systemansvarlige selskaber, universiteterne, rådgivere og Energistyrelsen. Dette omfatter for eksempel fremskrivninger, scenarieanalyser og teknisk-økonomiske analyser.

Desuden er teknologikataloget et nyttigt redskab til at vurdere udviklingsmulighederne for energisektorens mange teknologier til brug for tilrettelæggelsen af støtteprogrammer for energiforskning og -udvikling. Tilsvarende afspejler kataloget resultaterne af den energirelaterede forskning og udvikling. Også behovet for planlægning og vurdering af klima-projekter har aktualiseret nødvendigheden af et opdateret databeredskab.

Endeligt kan teknologikataloget anvendes i såvel nordisk som internationalt perspektiv. Det kan derudover bruges som et led i en systematisk international vidensopbygning og -udveksling, ligesom kataloget kan benyttes som dansk udspil til teknologiske forudsætninger for internationale analyser og forhandlinger. Af disse grunde er kataloget udarbejdet på engelsk.

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Guideline

This document aims at describing how a technology catalogue for industrial process heating should be elaborated.

The document is based on the guidelines for energy technology data for generation of electricity and district heating, version August 2016 (Energinet.dk and the Danish Energy Agency).

As such, the preparation of a technology catalogue for industrial process heating to a wide extent will be similar to other technology catalogues prepared by the Danish Energy Agency – however certain principles and aspects of technology usage has to be described in more and slightly different details.

Therefore, the guideline for industrial process heating comprises mostly of the sections that are in the guideline for the catalogue for generation of electricity and district heating, but some of the descriptions differs slightly to make them applicable for describing industrial process heating technology. In addition, it encompasses supplement sections describing features specific for industrial process heating technologies.

The main purpose of the catalogue is to provide generalized data for analysis of energy systems related to industrial process heating including economic scenario models and inputs for high-level energy planning.

This catalogue covers data regarding energy technologies designed for providing industrial process heating, mainly for technologies that are relevant for the Danish industry.

The focus is on technologies that can deliver process heating to industrial processes using electricity or renewable energy. Technologies that produce the process heating more efficient than the traditional technologies are also in the scope of this catalogue. Main technologies utilized today and often fueled by fossil fuels e.g. boilers and direct firing are also described. Technologies used in other steps of the production with the aim to improve the efficiency of the production of the industrial product are exempt from the scope.

The technology catalogue for generation of industrial process heating is intended as a separate catalogue in the series of the catalogues *Technology Data for Energy Plants* which are developed and maintained in cooperation between the Danish Energy Agency and Energinet, thus in general it follows the same structure and data format as the catalogue for generation of electricity and district heating.

Section Introduction to industrial process heating in Denmark provides an introduction to industrial process heating, a definition of the energy services covered and some general assumptions.

In section New Technologies for industrial process heating new technologies suitable for producing industrial process heating that can make the shift toward CO_2 neutral industrial production possible is presented.

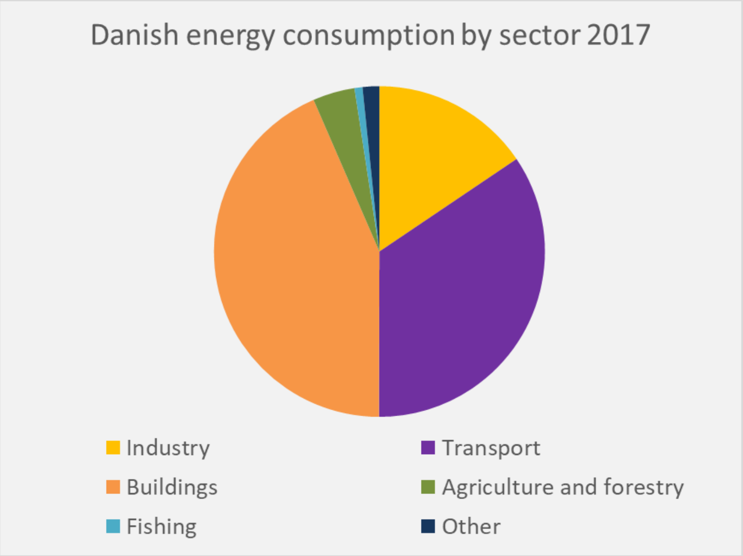
In section Special issues when modelling Industrial Process Heating *Special issues when modelling industrial process heating are described, Issues that should be considered when using the technology data for modelling are described*

The general assumptions are described in section General assumptions. The following sections Qualitative description and Quantitative description explain the formats of the technology chapters, how data was obtained, and which assumptions data is based on. Each technology is subsequently described in a separate technology chapter, making up the main part of this catalogue. The technology chapters contain both a description of the technologies and a quantitative part including a table with the most important technology data.

Introduction to industrial process heating in Denmark and catalogue guideline

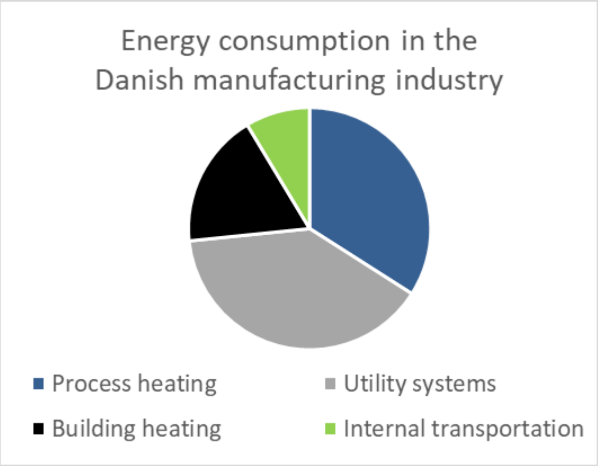
Of the total final energy usage in Denmark, manufacturing industry in 2018 consumes approximately 16% as illustrated in Figure 1 below.

Figure 1: Final energy consumption in Denmark by sector (2017)[1]



A sub-division of the energy consumption in the manufacturing industry shows that approximately 35% is used for process heating while 65% is used for other purposes (building heating, utility systems and transportation)

Figure 2: Energy consumption in manufacturing industry by overall end use (2018)[2]



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[1] Reference to Energistatistik 2017 issued by the Danish Energy Agency, see https://ens.dk/service/statistik-data-noegletal-og-kort/maanedlig-og-aarlig-energistatistik.

[2] Reference to "Kortlægning af energiforbrug i virksomheder", 2015, issued by the Danish Energy Agency, see https://ens.dk/sites/ens.dk/files/Analyser/kortlaegning_energiforbrug_virksomheder.pdf

Current technologies supplying industrial process heating

As compared to other energy consuming sectors, heating of industrial processes is a complex and diverse area comprising a variety of different technologies and heating principles.

Many industrial sectors will apply traditional utility structures based on boiler stations supplying steam or hot water for the whole production site. But other sectors demand high temperature heating and advanced technologies to produce products of a specific quality via a direct combustion of the fuels inside the production processes, for example:

- In the cement industry, clinker production traditionally requires supply of coal/pet coke for combustion directly in the kilns in order to process and calcinate raw materials at temperatures higher than 1000 °C

- In the brick industry, gaseous or liquid fuels are supplied directly to the furnaces via numerous burners in order to secure a high processing temperature and often also a certain surface quality of the bricks

- In glass melting, fuels are supplied directly to the furnaces as radiation heat from the flames are needed to penetrate the melted glass substance

In Danish industry, approximately 57% of process heating is supplied via traditional steam or hot water boilers while 43% is supplied via direct combustion of fuels inside the production process. A sub-division of this split is shown in Table 1 below.

Table 1: Share of direct process heating supply in various industrial sectors[3].

Industrial Sector, InterAct aggregation[4]	Share of direct firing for process heating (%)	Share of in-direct heating for process heating (%)
1. Food, beverages and tobacco	27%	73%
2. Commodity production	8%	92%
3. Cement and non-metallic mineral (+Extraction of gravel and stone)	71%	29%
4. Chemical industry	20%	80%
5. Metals, machinery and electronics	64%	36%

It is seen that especially the cement and brick industry sector apply a high share of process heating as direct firing inside the production processes while the percentage is significantly lower in the food and beverage industry.

Temperature levels of industrial process heating

Next to the above-described differences in how thermal energy is to be supplied to industrial processes, another important area to take into account when describing and modelling industrial process heating is at which temperatures process heating is to be delivered at.

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[3] Reference to memoes prepared by The Danish Energy Agency as background for the IntERACT-modelling

[4] The aggregation of the sectors is found in sepererate Excelfile with datasheets

While many of the above mentioned "direct fired" processes require high temperatures to take place (for example clinker production at 1000 ºC[5]), a majority of the industrial sectors in Denmark require heating at much lower temperatures, for example:

- In the food and beverage industry, most processes take place at temperature below 100 ºC simply because products are damaged when boiling

- In drying of wood and timber, heating is supplied at low temperatures (< 100ºC) to secure a slow and careful extraction of moist from the wood

In Table 2 below, the percentage of heating demand inside the industrial processes at various temperatures in selected sectors is illustrated.

Table 2: Requested temperatures of process heating in various sectors[6]

Industrial Sector, InterAct aggregation[7]	Share of heating demand at medium temperature (%) (t < ~150ºC)	Share of heating demand at high temperature (%) (t > ~150ºC)
1.Food, beverages and tobacco	95%	5%
2.Commodity production	94%	6%
3.Cement and non-metallic mineral (+Extraction of gravel and stone)	54%	46%
4.Chemical industry	89%	11%
5.Metals, machinery and electronics	36%	64%

The required temperature of individual processes is important to understand when looking into future options to adapt more climate friendly and carbon neutral heating technologies, by example for the use of heat pumps (where upper temperature limits influence on the type of heat pump technology).

End uses for industrial process heating

In Danish mappings of energy consumption in industrial processes, thermal energy usage is divided into the following end uses:

- Boiling and heating
- Drying
- Dewatering (evaporators)
- Distillation
- Firing and sintering
- Melting and casting
- Other processes < 150ºC
- Other processes > 150C

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[5] It should be noted that while the clinker production itself requests temperature above 1000ºC, a high share of the energy consumption in the process is at lower temperatures, especially in Danish cement industry applying "wet processing" where large amounts of water are to be evaporated at 100ºC.

[6] Reference to memoes prepared by The Danish Energy Agency as background for the InterACT-modelling

[7] The aggregation of the sectors is found in sepererate Excelfile with datasheets

Each of these end uses has specific temperature profiles and energy supply principles as described in the sections above – however some of them are supplied by common utility structures as described below.

Utility and supply structures for industrial process heating

An important issue to describe related to current supply of process heating in the industrial sector is that central supply system might require major reconstructions in order to enable use of new and more climate friendly heating technologies.

Overall, the layout of central steam or hot water systems for process heating most often is designed to meet the highest temperature in the production processes and by that many utility systems will most often supply steam and hot water at a much higher temperature than what is needed inside the production process.

In the food and beverage industry, by example, steam boilers at 8 bar (160ºC) is commonly used even though a majority of the process heating is to be delivered below 100ºC.

In case traditional heat pumps are to be applied for process heating, investments to design and install by example a 80ºC hot water circuit has to be added to the basic technology cost for the heat pump – which might impair feasibility of the heat pump significantly

New Technologies for industrial process heating

To convert industrial process heating into using CO_2-neutral and sustainable heat sources, a variety of technologies have to be taken into consideration, by example.

Compression heat pumps

Heat pumps are to be considered as a cornerstone in the future electrification of the industrial sector due to an efficient conversion of electricity into heating.

The specific type of heat pump - and the related business case - will depend on the specific application:

- Traditional heat pumps can utilize waste heat inside the production processes for heating of the processes themselves – however with certain limitations in maximum temperature[8]
- Traditional heat pumps can be used for combined process heating and process cooling thus improving the operating economy and the business case for installation
- High temperature temperature heat pumps can deliver heat at higher temperatures than traditional heat pumps but still with an impaired COP compared to lower temperature levels
- Booster heat pump systems applying turbo compressors in combination with traditional heat pumps can in general be applied for high temperature steam heating

Mechanical Vapour Recompression (MVR)

MVR-systems are most often applied for specific process purposes, by example:

- In evaporator systems, that traditionally are based on steam heated thermal evaporation (TVR)
- Integrated with drying processes using superheated steam

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[8] Traditional ammonia heat pumps will only be able to deliver heating up to 80-85ºC.

Electric heating technologies

A number of electric heating technologies are these years applied for very specific purposed but with potentials for wider applications, by example:

- Microwaves and high-frequency assisted heating can speed up many heating processes via heating the core of the product faster than possible with traditional heating methods thus reducing heating losses. In addition to the faster heating the uniform heating profile for this technology is an advantage in some production processes (and often the reason for using this technology).

- Infrared (IR) technology can be applied for a variety of drying processes enabling faster drying thus reducing heat losses

Electric boiler

Electric boilers are an alternative to fossil fuel based hot water and steam boilers.

Of the technologies listed above, certain will have a relatively high application potential in the future supply of industrial process heating while others are of very process-specific nature.

Besides the technologies listed above, other technologies may also be of interest, e.g. gas motor driven compression heat pump, membrane technology and hydrogen technologies.

Technologies currently utilized for producing industrial process heating are also relevant to include in the catalogue e.g. fossil and bio fueled boilers and direct firing.

All the technologies in this catalogue are considered retrofit, except MVR and microwave, which are considered grassroot. This is further elaborated in Additional remarks.

Special issues when modelling Industrial Process Heating

Due to the complexity of technologies applied for industrial process heating, a number of issues have to be taken into account when evaluating the application potential and the business case for a certain technology.

These special issues first of all are:

End-use and sector specific solutions

Many of the technologies listed above will have limited application potentials as they are only relevant in certain sectors or for certain end-uses of industrial process heating. By example, MVR-technology can only be applied for evaporator-, distillation- and drying processes.

A technology description should for each technology therefore assess maximum application potentials in individual sectors as illustrated in Table 3 below:

Table 3: Maximum application potential for technology N in various sectors

Industrial Sector, InterAct aggregation[9]	Maximum share of total sector demand for process heating by technology N (%)
1.Food, beverages and tobacco	
2.Commodity production	
3.Cement and non-metallic mineral (+Extraction of gravel and stone)	
4.Chemical industry	
5.Metals, machinery and electronics	

Temperature limitations

Next to limitations in sectors and end-use applications, some of the relevant technologies for industrial process heating will also have limitations regarding how high temperatures of process heating they can deliver.

This is first of all the case with heat pump technology, and similar to limitations due to product quality issues etc. above, also temperature limitations have to be assessed for each technology as illustrated in Table 4.

Table 4: Maximum temperature coverage on potential for technology N in various sectors

Industrial Sector, InterAct aggregation	Maximum share of total process heating covered due to temperature limitations by technology N (%)
1.Food, beverages and tobacco	
2.Commodity production	
3.Cement and non-metallic mineral (+Extraction of gravel and stone)	
4.Chemical industry	
5.Metals, machinery and electronics	

Direct and in-direct investment costs

As many industries today have central utility systems solely based on steam supply for all process heating, technologies not able to produce steam (by example heat pumps) will require that new or additional supply structures are to be established.

For most industries, small heat pumps can be installed for specific, individual and local purposes, but if large heat pumps are to be installed, extra investments for utility structures must be taken into account.

For technology description, estimated investment costs for small vs. large applications have to be added for the modelling as illustrated below:

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[9] The aggregation of the sectors is found in sepererate Excelfile with datasheets

Table 5: Basic and maximum application investments for technology N in various sectors

Industrial Sector, InterAct aggregation	Application potential for basic technology without re-building utility-structures (%)	Application potential for basic technology when re-building utility-structures (%)	Extra investment for maximum application (% of basis investment)
1. Food, beverages and tobacco			
2. Commodity production			
3. Cement and non-metallic mineral (+Extraction of gravel and stone)			
4. Chemical industry			
5. Metals, machinery and electronics			

Extra investments might also include investments for hot (and cold) water storage (tanks) to level out fluctuating loads.

Related benefits and savings

In industry, change of a certain heating technology is most often described as a business case, where necessary investments are weighed towards possible benefits/savings.

These benefits are usually cost savings related to changed energy supply, but often other benefits are to be taken into consideration when establishing the business case, by example increased production capacity, introduction of new products etc.

Operational hours

Various industrial sectors have varying annual operational hours, by example:

○ Energy intensive industries (cement, refineries)	> 8,000 hours per year
○ Food & beverage industry	
▪ Large companies	> 8,000 hours per year
▪ Small companies	3-5,000 hours per year

The benefit of business cases for new technologies are often proportional to the annual operational hours, and each application therefore has to be modelled according to realistic operational profile.

Development perspective for new technologies

For some of the technologies listed in section New Technologies for industrial process heating above, the application potential must be expected to increase over the next decades due to increasing development of climate friendly solutions.

For example, di-electric heating so far has only been demonstrated for certain end-uses even though the theoretical application potential is much higher. This has to be modelled as part of the technology description

General assumptions

The boundary for both cost and performance data are the generation assets to deliver process heating to the inlet of the supply system for the industrial process, or in case of direct heating, to the process. In other words, the technologies are described as they are perceived by the supply system of the industrial processes receiving their energy deliveries in form of process heating. For direct combustion there is no supply system and the process heating is delivered direct into the process. Thus, stated capacities are net capacities, which are calculated as the gross generation capacity minus the auxiliary power consumption “capacity” at the plant. Similarly, efficiencies are also net efficiencies.

When comparing direct and indirect process heating the cost and efficiency of the local internal supply system must be considered, the same is the case when modelling substitution between the two.

Operation hours and the load profile for industrial process heating technologies are highly depending on the sector. Examples of expectations for these parameters are described above in section Operational hours. The operation hours will be discussed for the specific technology as stated in section Typical annual operation hours and load pattern. Furthermore, the assumption will be in the notes for the data sheet. These assumptions are used when calculating e.g. O&M cost for technologies in this catalogue.

Definitions

Definitions of terms used to simplify the description of industrial heating processes are listed below:

- ✓ *End-use*; there are 9 industrial end-uses.
  1. Heating/Boiling,
  2. Drying,
  3. Dewatering,
  4. Distillation,
  5. "Firing /Sintering",
  6. "Melting /Casting",
  7. Other processes <150ºC,
  8. Other processes >150ºC.

  All the industrial heating process can be categorized as one of them.

- ✓ *Type of industrial process heating: by that is meant if the process heating is supplied as* direct or indirect heating”

- ✓ *Temperature levels*: The supply of industrial process heating is divided into two temperature levels high and medium the boundary is set to 150 ºC but should not be understood as an exact boundary. The reason for not sticking to an exact temperature limit, when classifying the application potential for the technologies is that the end-use processes are classified according to typical energy services, however the same end-use can range in both high and medium temperature levels. If an end-use in a sector range in both high and medium temperature levels, the total application potential of the technology will be included in the energy service with the typical temperature level. For instance, if a steam boiler is used to supply heat to a drying process, which may require a temperature of 200 °C, the entire potential will in this case be included in the medium temperature energy service, as medium temperature is most common for drying process.

Temperature level:	**Medium**	**High**
Temperature (t)	t < ~ 150ºC	> ~ 150ºC

- ✓ *Energy services*: combination of which type of heating process (direct or indirect heating) and at which temperature levels:

	Medium temperature level	High temperature level
Direct		

Indirect

- ✓ *The five main sector* The NACE industrial sector is aggregated into five sector groups (main sectors) made up of sectors with similar characteristics with regard to end-uses and energy services. The aggregation is aligned with the industry in the TIMES-DK model used in Interact (the InterAct sectors[10]). The five main sectors are:

1. Food, beverages and tobacco
2. Commodity production
3. Cement and non-metallic mineral (+Extraction of gravel and stone)
4. Chemical industry
5. Metals, machinery and electronics

Qualitative description

The qualitative description describes the key characteristics of the technology as concise as possible. The following paragraphs are included where relevant for the technology.

Contact information

Containing the following information:

- Contact information: Contact details in case the reader has clarifying questions to the technology chapters. This could be the Danish Energy Agency, Energinet or the author of the technology chapters.
- Author: Entity/person responsible for preparing the technology chapter

Brief technology description

Brief description for non-engineers of how the technology works and for which purpose.

An illustration of the technology is included, showing the main components and working principles.

Mention how much capacity there is currently installed in Denmark especially for technologies, which are not widespread.

It shall also be mentioned why the specific technology is relevant for the industry. It is crucial that the description of the technology is not based on one special version of the technology of which there is only on plant in operation or only on supplier of the technology.

Some of the technologies are already described in the main catalogue for generation of electricity and district heating (e.g. boilers and heat pumps (low temperature)), the qualitative description will be brief and only focuses on what is specific when delivering the industrial process heating service. For additional information, a reference is made to the respective technologies in the main catalogue.

Surplus heat is reduced in case with energy integration, e.g. if surplus heat is used as heat source for heat pumps or other technologies.

Input

The main primarily fuels, consumed by the technology. If the technology needs waste heat at specific temperature, e.g. a heat pump, this also needs to be stated.

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[10] The aggregation of the interACT sectors is found in a separate Excel file for Data sheet and Application matrix

Output

The form of generated energy i.e. process heating, and any relevant by-products, especially for waste heat, the temperature and the pressure of the process heat (if steam). If a technology reduces surplus heat/waste heat it shall be included here.

Typical capacities

The stated capacities are for a single unit capable of producing industrial process heat. If the range of capacities vary significant the typical range is stated (also in the notes), and it is mentioned if the different sizes of capacity is characteristic for e.g. a specific sector.

Typical annual operation hours and load pattern

Which operation pattern and load profile that can be anticipated for the technology should be discussed. It is assumed according to section Operational hours that the annual operation time and load pattern will vary significant from sector to sector, the discussion should touch on this topic.

Regulation ability

Regulation abilities are not very relevant for industrial process heating as generating technologies most often are operated at 100% load. The technologies will most often have the necessary regulation abilities. This includes the part-load characteristics, start-up time and how quickly it is able to change its production when already online.

Advantages/ disadvantages

A description of specific advantages and disadvantages relative to equivalent technologies generating process heating and delivering the same energy service. Generic advantages are ignored; e.g. renewable energy technologies mitigating climate risks and enhance security of supply.

Environment

Particular environmental and resource depletion impacts are mentioned, for example harmful emissions to air, soil or water; consumption of rare or toxic materials; consumption of large amount of water (in general and relative to other technologies delivering same service); issues with handling of waste and decommissioning etc.

Research and development perspectives

This section lists the most important challenges to further development of the technology. Also, the potential for technological development in terms of costs and efficiency is mentioned and quantified if possible. Danish research and development perspectives are highlighted, where relevant.

Examples of market standard technology

Recent full-scale commercial projects, which can be considered market standard, are mentioned, preferably with links. A description of what is meant by “market standard” is given in the introduction to the quantitative description section. For technologies where no market standard has yet been established, reference is made to best available technology in R&D projects.

Prediction of performance and costs

Cost reductions and improvements of performance can be expected for most technologies in the future. This section accounts for the assumptions underlying the cost and performance in 2020 as well as the improvements assumed for the years 2030, 2040 and 2050.

The specific technology is identified and classified in one of four categories of technological maturity, indicating the commercial and technological progress, and the assumptions for the projections are described in detail (see section Learning curves and technological maturity).

In formulating the section, the following background information is considered:

Data for 2025

In case of technologies where market standards have been established, performance and cost data of recent installed versions of the technology in Denmark or the most similar countries in relation to the specific technology in Northern Europe are projected to 2025 (FID) and used for the 2025 estimates.

If consistent data are not available, or if no suitable market standard has yet emerged for new technologies, the 2020 costs may be estimated using an engineering-based approach applying a decomposition of manufacturing and installation costs into raw materials, labor costs, financial costs, etc. International references such as the IEA, NREL etc. are preferred for such estimates.

Direct and in-direct investment costs

As many industries today have utility systems solely based on steam supply for all process heating demands, technologies not able to produce steam (by example heat pumps) will require that additional supply structures for hot water should be established.

To increase application potential outside a few, narrow application potentials, additional investment costs will be necessary when establishing hot water supply to process heating. The cost will be stated in the data sheet and in the notes, it is stated when these costs should be included.

Related benefits and savings

In industry, change of a certain heating technology is most often described as a business case, where necessary investments are weighed towards possible benefits/savings.

These benefits are usually cost savings related to changed energy supply, but often other benefits are to be taken into consideration when establishing the business case, by example increased production capacity, introduction of new products etc.

It may be relevant, for example, if switching from a solid fuel which need of storage and logistics(eg coal) to a wiring fuel e.g. electricity, gas or district heating. And conversely, if changing from gas or electricity to solid biomass. In fact, especially for slightly smaller industries it is very relevant and a co-explanation for e.g. a slightly more expensive fuel such as gas can be competitive with coal. You could possibly. confine itself to handling and logistics costs

These non-energy benefits should be described when possible and relevant.

Cost of grid expansion

The costs of grid expansion caused by adding a new electricity generator or a new large consumer (e.g. an electric boiler or heat pump) to the grid are not included in the presented data.

The most important costs are related to strengthening or expansion of the local grid and/or substations (voltage transformation, pumping or compression/expansion). The costs vary significantly depending on the type and size of generator and local conditions. Performance and cost data for grid expansions can be found in the technology catalogue "Technology Data for Energy Transport"[11]

Assumptions for the period 2020 to 2050

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[11] "Technology Data for Energy Transport", Danish Energy Agency and Energinet, December 2017.

According to the IEA:

"*Innovation theory describes technological innovation through two approaches: the technology-push model, in which new technologies evolve and push themselves into the marketplace; and the market-pull model, in which a market opportunity leads to investment in R&D and, eventually, to an innovation*" (ref. 6).

The level of "market-pull" is to a high degree dependent on the global climate and energy policies. Hence, in a future with strong climate policies, demand for e.g. renewable energy technologies will be higher, whereby innovation is expected to take place faster than in a situation with less ambitious policies. This is expected to lead to both more efficient technologies, as well as cost reductions due to economy of scale effects. Therefore, for technologies where large cost reductions are expected, it is important to account for assumptions about global future demand.

The **IEA's Announced Pledges Scenario (APS)** is used as a central estimate for projections in the Technology Catalogue, whenever possible. The IEA describes the Announced Pledges Scenario in their 2022 version as follows:

"The Announced Pledges Scenario introduced in 2021 aims to show to what extent the announced ambitions and targets, including the most recent ones, are on the path to deliver emissions reductions required to achieve net zero emissions by 2050. It includes all recent major national announcements as of September 2022 for 2030 targets and longer term net zero and other pledges, regardless of whether these have been anchored in implementing legislation or in updated NDCs. In the APS, countries fully implement their national targets to 2030 and 2050, and the outlook for exporters of fossil fuels and low emissions fuels like hydrogen is shaped by what full implementation means for global demand. […] Non-policy assumptions, including population and economic growth, are the same as in the STEPS."

According to the IEA, the less ambitious **Stated Policies Scenario (STEPS)** *"provides a more conservative benchmark for the future, because it does not take it for granted that governments will reach all announced goals. Instead, it takes a more granular, sector-by-sector look at what has actually been put in place to reach these and other energy-related objectives, taking account not just of existing policies and measures but also of those that are under development. The STEPS explores where the energy system might go without a major additional steer from policy makers."*

The STEPS Scenario may be used as an upper bound and to assess the expected development of technologies based on a frozen-policy approach. Previous versions of the Technology Catalogue before updating the guideline in april 2024 have used the outdated New Policies Scenario, relatively equivalent to the current STEPS, as a central framework for projections (and supplemented by other outdated scenarios of the IEA). This scenario corresponds to the frozen-policy approach that the Danish Energy Agency uses to project international fuel prices and CO_2-prices and technologies may be assessed in that regard when suitable.

Technologies updated before this cutoff date and which do not contain any explicit methodological description within the chapter regarding alternative supplementary scenarios have been updated based in this previous methodology.

As a more ambitious projection, the **Net Zero Emissions by 2050 Scenario (NZE)** may be used as a lower bound for the technology development. According to the IEA, the NZE *"is a normative IEA scenario that shows a pathway for the global energy sector to achieve net zero CO2 emissions by 2050, with advanced economies reaching net zero emissions in advance of others. This scenario also meets key energy-related United Nations Sustainable Development Goals (SDGs), in particular by achieving universal energy access by 2030 and major improvements in air quality. It is consistent with limiting the global temperature rise to 1.5 °C with no or limited temperature overshoot (with a 50% probability), in line with reductions assessed in the IPCC in its Sixth Assessment Report."*

By using this approach, the quantitative data in the Technology Catalogue provides a sample space that is consistent with the IEA's Global Energy and Climate Model, encompassing relevant outcomes for policy assessments of technologies as well as technology developments in compliance with national targets, and international treaties.

Learning curves and technological maturity

Predicting the future costs of technologies may be done by applying a cost decomposition strategy, as mentioned above, decomposing the costs of the technology into categories such as labor, materials, etc. for which predictions already exist. Alternatively, the development could be predicted using learning curves. Learning curves express the idea that each time a unit of a particular technology is produced, learning accumulates, which leads to cheaper production of the next unit of that technology. The learning rates also take into account benefits from economy of scale and benefits related to using automated production processes at high production volumes. The cost projections are based on the future generation capacity in IEA's 2 DS and 4 DS scenarios (2017 values are assumed to be a good approximation for 2015) [3].

Learning rates typically vary between 5 and 25%. In 2015, Rubin et al published "A review of learning rates for electricity supply technologies" [4], which provides a comprehensive and up to date overview of learning rates for a range of relevant technologies, among which:

The potential for improving technologies is linked to the level of technological maturity. The technologies are categorized within one of the following four levels of technological maturity.

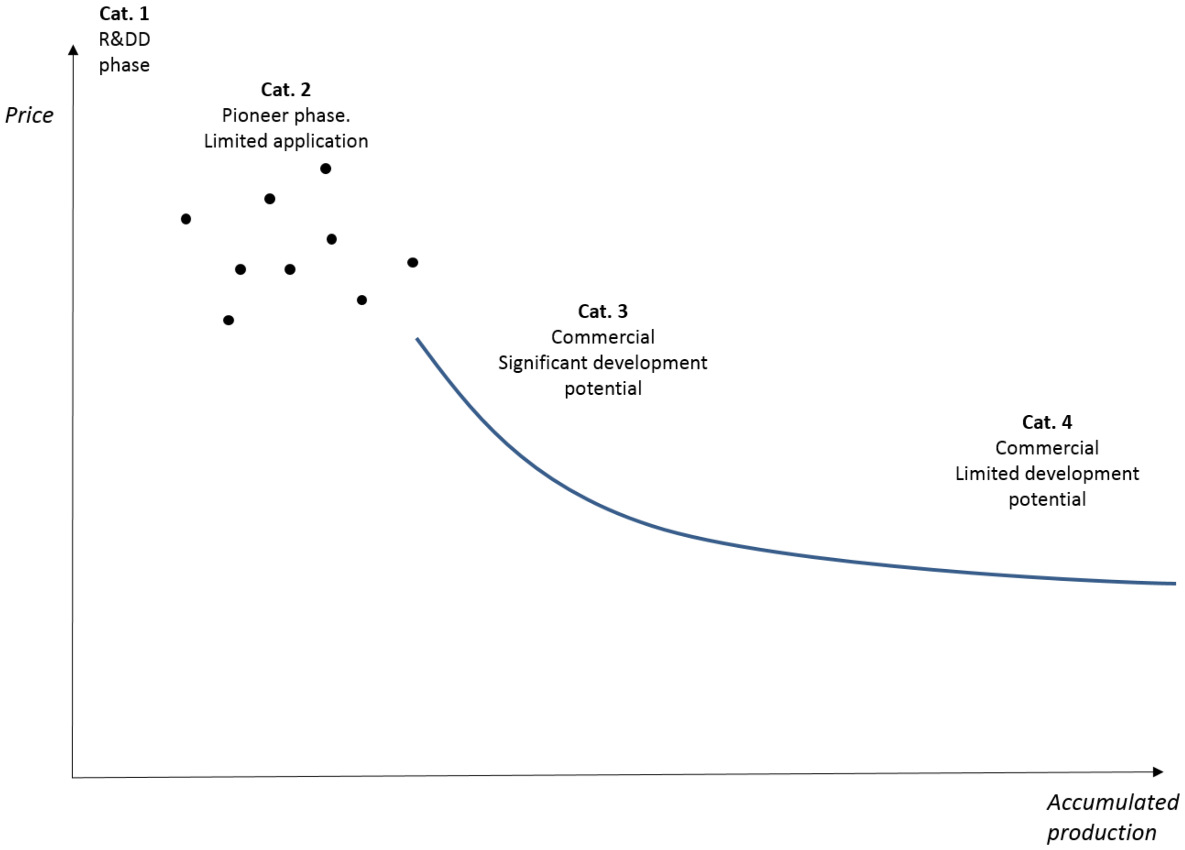
Category 1. Technologies that are still in the *research and development phase*. The uncertainty related to price and performance today and in the future is highly significant (e.g. wave energy converters, solid oxide fuel cells).

Category 2. Technologies in the *pioneer phase*. The technology has been proven to work through demonstration facilities or semi-commercial plants. Due to the limited application, the price and performance is still attached with high uncertainty, since development and customization is still needed. The technology still has a significant development potential (e.g. gasification of biomass).

Category 3. *Commercial technologies with moderate deployment*. The price and performance of the technology today is well known. These technologies are deemed to have a certain development potential and therefore there is a considerable level of uncertainty related to future price and performance (e.g. offshore wind turbines)

Category 4. *Commercial technologies, with large deployment*. The price and performance of the technology today is well known, and normally only incremental improvements would be expected. Therefore, the future price and performance may also be projected with a relatively high level of certainty. (e.g. coal power, gas turbine)

Figure 3: Technological development phases. Correlation between accumulated production volume (MW) and price



Uncertainty

The catalogue covers both mature technologies and technologies under development. This implies that the price and performance of some technologies may be estimated with a relatively high level of certainty whereas in the case of others, both cost and performance today as well as in the future are associated with high levels of uncertainty.

This section of the technology chapters explains the main challenges to precision of the data and identifies the areas on which the uncertainty ranges in the quantitative description are based. This includes technological or market related issues of the specific technology as well as the level of experience and knowledge in the sector and possible limitations on raw materials. The issues should also relate to the technological development maturity as discussed above.

The level of uncertainty is illustrated by providing a lower and higher bound beside the central estimate, which shall be interpreted as representing probabilities corresponding to a 90% confidence interval. It should be noted, that projecting costs of technologies far into the future is a task associated with very large uncertainties. Thus, depending on the technological maturity expressed and the period considered, the confidence interval may be very large. It is the case, for example, of less developed technologies (category 1 and 2) and longtime horizons (2050).

Additional remarks

This section includes other information, for example links to web sites that describe the technology further or give key figures on it.

References

References are numbered in the text in squared brackets and bibliographical details are listed in the end of the technology chapter prior to the data sheets, references for data in the data sheet is listed below the data sheet for each sheet also in the Excel version. The format of biographical details of references should be; name of author, title of report, year of publication.

Quantitative description

In this section it is explained how data in the data sheet is compiled.

In general, the catalogue describes retrofit technologies, but for some technologies it will be grassroot installation. If it is a grassroot installation it is stated here. Technologies considered grassroot will have a natural market pull and a replacement rate which is also stated here.

To enable comparative analyses between different technologies it is imperative that data are actually comparable. All cost data are stated in fixed 2015 prices excluding value added taxes (VAT) and other taxes. The information given in the tables relate to the development status of the technology at the point of final investment decision (FID) in the given year (2020, 2025, 2030, 2035, 2040 and 2050 where applicable). FID is assumed to be taken when financing of a project is secured, and all permits are at hand. The year of commissioning will depend on the construction time of the individual technologies.

A typical table of quantitative data is shown below, containing all parameters used to describe the specific technologies. The table consists of a generic part, which is identical for groups of similar technologies and a technology specific part, containing information, which is only relevant for the specific technology. The generic part is made to allow for easy comparison of technologies.

Technology	**Technology name**									
Energy/technical data	**2020[1]**	**2030[1]**	**2040[1]**	**2050[1]**	**Uncertainty (2030[1])**		**Uncertainty (2050[1])**		**Note**	**Ref**
					Lower	**Upper**	**Lower**	**Upper**		
Heat generation capacity for one unit (MW)										
Total efficiency, net (%), nominel load										
Total efficiency, net (%), annual average										
Auxiliary electricity consumption (% of heat gen)										
Forced outage (%)										
Planned outage (weeks per year)										
Technical lifetime (years)										
Construction time (years)										
Regulation Ability										
Minimum load (% of full load)										
Warm start-up time (hours)										
Cold start-up time (hours)										
Environment										
SO_2 (g per GJ fuel)										
PM2.5 (g per GJ fuel)										
NO_x (g per GJ fuel)										
CH4 (g per GJ fuel)										
N2O (g per GJ fuel)										
Financial data										
Nominal investment (M€ per MW)										

- of which equipment (%)										
- of which installation (%)										
Fixed O&M (€/MJ/s/year)										
Variable O&M (€/MWh)										
- of which is electricity costs (€/MWh)										
- of which is other O&M costs (€/MWh)										
Technology specific data										
Indirect investments cost (M€ per MW)										
Non energy gains (M€ per MW)										
Startup cost (€/MW/startup)										
Carbon capture removal of CO2 emissions (% of emission)										
Temperature heat source supply (°C)										
Temperature heat source return (°C)										
Cooling generation capacity for one unit (MW)										

[1] *Technology years may be updated from this shown example*

Each cell in the table contains only one number, which is the central estimate for the market standard technology, i.e. no range indications.
Uncertainties related to the figures are stated in the columns named *uncertainty*. To keep the table simple, the level of uncertainty is only specified for years 2030 and 2050.

The level of uncertainty is illustrated by providing a lower and higher bound. These are chosen to reflect the uncertainties of the best projections by the authors. The section on uncertainty in the qualitative description for each technology indicates the main issues influencing the uncertainty related to the specific technology. For technologies in the early stages of technological development or technologies especially prone to variations of cost and performance data, the bounds expressing the confidence interval could result in large intervals. The uncertainty only applies to the market standard technology; in other words, the uncertainty interval does not represent the product range (for example a product with lower efficiency at a lower price or vice versa).

The level of uncertainty is only stated for the most critical figures such as investment cost and efficiencies. Other figures are considered if relevant.

All data in the tables are referenced by a number in the utmost right column (Ref), referring to the source specified below the table.

Notes include additional information on how the data are obtained, as well as assumptions and potential calculations behind the figures presented is listed below the data sheet. Reference between notes and data is made by letters in the second utmost column in the data sheet Before using the data, please be aware that essential information may be found in the notes below the table.

It is crucial that the data for the technology is not based on one special version of the technology of which there is only on plant in operation or only on supplier of the technology.

The generic parts of the data sheets for industrial process heating technologies are presented below.

Generating capacity for one unit

The capacity, preferably a typical capacity (not maximum capacity), is stated for a single unit, capable of producing industrial process heating.

In the case of substantial difference in performance or costs for different sizes of the technology. The technology may be specified in two or more separated data sheets.

The capacity is given as net generation capacity in continuous operation, i.e. gross capacity (industrial process heat output from technology) minus own consumption (house load), equal to capacity delivered to the local industry supply system or in the process for direct heating technologies. Auxiliary electricity consumption for pumps etc. is not encountered in the capacity.

The unit MW is used for process heat production capacity. While this is not in accordance with thermodynamic formalism, it makes comparisons easier and provides a more intuitive link between capacities, production and full load hours.

The relevant range of sizes of each type of technology is represented by a range of capacities stated in the notes for the "capacity" field in each technology table, for example 0.5-5 MW for a Hybrid Absorption/ Compression High Temperature Heat Pump (HACHP).

It should be stressed that data in the table is based on the typical capacity, for example 2 MW for a HACHP. When deviations from the typical capacity are made, economy of scale effects need to be considered inside the range of typical sizes (see the section about investment cost). The capacity range should be stated in the notes.

Energy efficiencies

Efficiencies, for all industrial process heating technologies combusting fuels, are expressed in percent at lower calorific heat value (lower heating value) at ambient conditions in Denmark, considering an average air temperature of approximately 8 °C.

The efficiency of industrial process heating technology equals the total delivery of industrial process heating to the supply system for the industry divided by the energy consumption. Two efficiencies are stated; the efficiency at nominal load as stated by the supplier and the expected typical annual efficiency.

The auxiliary electricity consumption is not included in the efficiency but stated separately in percentage of capacity (i.e. MW auxiliary/MW heat).

The energy supplied by the heat source for heat pumps (both electric and absorption) is not counted as input energy. The temperatures of the heat sources are specified in the data sheet and chapters for the specific technologies.

The expected typical annual efficiency takes into account a typical number of start-ups and shut-downs and is based on the assumed full load hours stated for each technology. Regarding the assumed number of start-ups for different technologies, an indication is given in the financial data description, under start-up costs.

Often, the efficiency decreases slightly during the operating life of an industrial process heating technology. This degradation is not reflected in the stated data. As a rule of thumb 2.5 – 3.5 % may be subtracted during the lifetime (e.g. from 40 % to 37 %). Specific data are given in ref. 3.

Some boilers are equipped with flue gas condensation equipment, a process whereby the flue gas is cooled below its water dew point and the heat released by the resulting condensation of water is recovered as low temperature heat. In these cases, the stated efficiencies include the added efficiency of the flue gas condensation equipment.

Auxiliary electricity consumption

For industrial process heating technologies, the consumption of electricity for auxiliary equipment such as pumps, ventilation systems, etc. is stated separately in percentage of heat generation capacity (i.e. MW auxiliary/MW heat).

For heat pumps, internal consumption is considered part of the efficiency (Coefficient Of Performance, COP), while other electricity demand for external pumping, e.g. pumping of the heat source fluid, is stated under auxiliary electricity consumption.

Cogeneration values

Cogeneration technologies will not be described as a part of this catalogue, although able to deliver industrial process heating.

Typical annual operation hours and load pattern

Various industrial sectors have varying annual operational hours, an example is given in section Operational hours and discussed for the specific technology as explained in section Typical annual operation hours and load pattern. In the notes it shall be stated which operation profile assumed for the data in the data sheet.

In the case of substantial difference in operation time depending e.g. on size of industries or sector. The technology may be specified in two or more separated data sheets.

Forced and planned outage

Forced outage is reduced production caused by unplanned outages. The weighted forced outage hours are the sum of hours of forced outage, weighted according to how much of full capacity was out. Forced outage is defined as the number of weighted forced outage hours divided by the sum of forced outage hours and operation hours. The weighted forced outage hours are the sum of hours of reduced production caused by unplanned outages, weighted according to how much capacity was out.

Forced outage is given in percent, while planned outage (for example due to renovations) is given in days per year.

Technical lifetime

The technical lifetime is the expected time for which an industrial process heating technology can be operated within, or acceptably close to, its original performance specifications, provided that normal operation and maintenance takes place. During this lifetime, some performance parameters may degrade gradually but still stay within acceptable limits. For instance, efficiencies often decrease slightly (few percent) over the years, and O&M costs increase due to wear and degradation of components and systems. At the end of the technical lifetime, the frequency of unforeseen operational problems and risk of breakdowns is expected to lead to unacceptably low availability and/or high O&M costs. At this time, the plant is decommissioned or undergoes a lifetime extension, which implies a major renovation of components and systems as required to make the plant suitable for a new period of continued operation.

The technical lifetime stated in this catalogue is a theoretical value inherent to each technology, based on experience. As stated earlier, typical annual operation hours and the load profile is specific for each industrial process heating technologies. The expected technical lifetime takes into account a typical number of start-ups and shut-downs (an indication of the number of annual operation hours, start-ups and shut-downs is given in the Financial data description, under Start-up costs).

In real life, specific plants of similar technology may operate for shorter or longer times. The strategy for operation and maintenance, e.g. the number of operation hours, start-ups, and the reinvestments made over the years, will largely influence the actual lifetime.

Construction time

Time from final investment decision (FID) until commissioning completed (start of commercial operation), expressed in years.

Regulation ability

Three parameters describe the regulation capability of the industrial process heating technologies:

A. Minimum load (percent of full load).
B. Warm start-up time, (hours)
C. Cold start-up time, (hours)

For several technologies, these parameters are not relevant, e.g. if the technology is regulated instantly in on/off-mode.

Parameter B. The warm start-up time used for by example heat pump technologies is defined as the time it takes to reach operating temperatures and pressure and start production from a state where the water temperature in the evaporator is above 100 °C, which means that the boiler is pressurized.

Parameter C. The cold start-up time used for boiler and heat pump technologies is defined as the time it takes to reach operating temperature and pressure and start production from a state were the boiler is at ambient temperature and pressure.

Environment

All technologies are assumed to be designed to comply with the regulation that is currently in place in Denmark and planned to be implemented within the 2025-time horizon.

The emissions below are stated in mass per GJ of fuel at the lower heating value.

CO_2 emission values are not stated, as these depend only on the fuel, not the technology.

SO_x emissions are calculated based on the following sulfur contents of fuels:

	Coal	Ori-mulsion	Fuel oil	Gas oil	Natural gas	Peat	Straw	Wood-fuel	Waste	Biogas
Sulphur, kg/GJ	0.27	0.99	0.25	0.07	0.00	0.24	0.20	0.00	0.27	0.00

For technologies, where desulphurization equipment is employed (typically large power plants), the degree of desulphurization is stated in percent.

NO_x equals NO_2 + NO, where NO is converted to NO_2 in weight-equivalents.

Greenhouse gas emissions include CH_4 and N_2O in grams per GJ fuel. CO_2 should not be included, is assumed calculated relative to the fuel in the models.

Particles includes only the fine particle matters PM 2.5($D_p < 2.5$ µm). The value is given in grams per GJ of fuel.

Financial data

Financial data are all in Euro (€), real prices, at the 2025-level and exclude value added taxes (VAT) and other taxes. IN previous versions of this catalogue, prices were given at the 2019-level.

Several data originate in Danish references. For those data a fixed exchange ratio of 7.45 DKK per € has been used.

When data about costs is found in sources is shown in other price years, the Danish net price index shall be used when stating the costs at 2025 price level.

European data, with a particular focus on Danish sources, have been emphasized in developing this catalogue.

Investment costs

The investment cost is also called the engineering, procurement and construction (EPC) price or the overnight cost. Infrastructure and connection costs, i.e. electricity, fuel and water connections inside the premises of a technology, are also included, but not the cost of an additional supply system, if required (see Section In-direct investment costs In-direct investments costs).

The investment cost is reported on a normalized basis, i.e. cost per MW. The specific investment cost is the total investment cost divided by the capacity stated in the table, i.e. the capacity as seen from the local supply grid.

Where possible, the investment cost is divided on equipment cost and installation cost. Equipment cost covers the components and machinery including environmental facilities, whereas installation cost covers engineering, civil works, buildings, grid connection, installation and commissioning of equipment. Cost may be disaggregated in a more detailed cost breakdown if it improves readability or understanding of the given technology.

It is assumed that the installation of the industrial process heating technology is done during a period of planned outage and therefore cost of lost production for the installation time is not included in the investments cost.

The owners' predevelopment costs (administration, consultancy, project management, site preparation, approvals by authorities) and interest during construction are not included. The costs to dismantle decommissioned technologies are also not included. Decommissioning costs may be offset by the residual value of the assets.

In-direct investment costs

As described in section Utility and supply structures for industrial process heating many industries today have utility systems solely based on steam supply for all process heating, thus technologies not able to produce steam (by example heat pumps) will require that additional supply structures should be established.

To increase application potential outside a few, narrow application potentials, additional investment costs will be necessary when establishing hot water supply to process heating. Furthermore, in relation to e.g. heat pump installation there could be considerable investment in the internal electricity connection.

Cost of an additional supply structure is stated in the data sheet and in the notes, it is stated when these costs should be included. The cost in €/MW (capacity of the technology) is set to the cost of an average size additional supply system related to the typical capacity set in the datasheet

Related benefits and savings

In industry, change of a certain heating technology is most often described as a business case, where necessary investments are weighed towards possible benefits/savings.

These benefits are usually cost savings related to changed energy supply, but often other benefits are to be taken into consideration when establishing the business case, by example increased production capacity, introduction of new products etc. Examples of related benefits and savings is given in Prediction of performance and costs.

The value of the no-energy benefits is stated when relevant and in M€/$MW_{\text{heat capacity}}$.

Cost of grid expansion

The costs of grid expansion from adding a new electricity generator or a new large consumer (e.g. an electric boiler or heat pump) to the grid are not included in the presented data.

The most important costs are related to strengthening or expansion of the local grid and/or substations (voltage transformation, pumping or compression/expansion). The costs vary significantly depending on the type and size of generator and local conditions. Performance and cost data for grid expansions can be found in the technology catalogue "Technology Data for Energy Transport"[12].

It is stated under technology specific data if it is expected that installation of the technology must be expected to cause need for investment in grid expansion.

Business cycles

Historic costs of energy equipment can show fluctuations that are related to business cycles. This was the case of the period 2007-2008 for example or more recently around 2021-2022, where prices costs of many energy generation technologies increased dramatically driven by rapid increases in global raw material costs and supply chain costs. The primary objective of the technology catalogues is to establish general representative techno-economic data for different technologies, which can form a basis for energy planning activities and technical and economic analyses. The catalogues do not attempt to reflect fluctuations in technology costs due to fluctuations in costs of labour and materials driven by e.g. global/regional crises or major events affecting short term supply or demand. The technology cost developments in the catalogues thus intend to reflect an average business cycle situation and macroeconomic environment in a general long-term equilibrium.

Contingency

Project owners often add a contingency to a project's capital cost estimate to deal with project overruns due to uncertainties and risks caused by uncertainties in the project definition. The Association for the Advancement of Cost Engineering International (AACE International) has defined contingency as "*An amount added to an estimate to allow for items, conditions, or events for which the state, occurrence, or effect is uncertain and that experience shows will likely result, in aggregate, in additional costs. Typically estimated using statistical analysis or judgment based on past asset or project experience*.". AACE International further describes contingency as "*…planning and estimating errors and omissions…..design developments and changes within the scope, and variations in market and environmental conditions**. The Technology Catalogues represent general techno-economic data for different technologies; and are not intended as basis for investment decisions. Therefore the data in the Technology Catalogues aim at not including contingency.

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[12] "Technology Data for Energy Transport", Danish Energy Agency and Energinet, December 2017.

*Source: AACE (2022) Cost engineering terminology https://library.aacei.org/terminology/welcome.shtml).

Economy of scale

The main idea of the catalogue is to provide technical and economic figures for particular sizes of technology. Where technology sizes vary in a large range, different sizes are defined and separate technology chapters (or just datasheets) are developed.

For assessment of data for technology sizes not included in the catalogue, some general rules should be applied with caution to the scaling of industrial technologies.

Example below is for the energy plants but is assumed that the same principle can be applied for the industrial process heating technologies

The cost of one unit for larger technologies is usually less than that for smaller technologies. This is called the 'economy of scale'. The basic equation (ref. 2) is:

$$\frac{C_1}{C_2} = \left(\frac{P_1}{P_2}\right)^a$$

Where: C_1 = Investment cost of technology 1 (e.g. in M€)

C_2 = Investment cost of technology 2

P_1 = Power generation capacity of technology 1 (e.g. in MW)

P_2 = Power generation capacity of technology 2

a = Proportionality factor

Usually, the proportionality factor is about 0.6 – 0.7 for power plants, but extended project schedules may cause the factor to increase. It is important, however, that the technologies are essentially identical in construction technique, design, and construction time frame and that the only significant difference is in size.

The relevant ranges where the economy of scale correction applies are stated in the notes for the capacity field of each technology table. The stated range shall at the same time represents typical capacity ranges.

Operation and maintenance (O&M) costs

O&M cost is divided into a fixed O&M and variable O&M.

The fixed share of O&M is calculated as cost per generating capacity per year (€/MW/year), where the generating capacity is the one defined at the beginning of this chapter and stated in the tables. It includes all costs, which are independent of how many hours the plant is operated, e.g. administration, operational staff, payments for O&M service agreements, network or system charges, property tax, and insurance. Any necessary reinvestments to keep the plant operating within the technical lifetime are also included, whereas reinvestments to extend the life are excluded. Reinvestments are discounted at 4 % annual discount rate in real terms. The cost of reinvestments to extend the lifetime of the plants may be mentioned in a note if data are available.

The variable O&M costs (€/MWh) include consumption of auxiliary materials (water, lubricants, fuel additives), treatment and disposal of residuals, spare parts and output related repair and maintenance (however not costs covered by guarantees and insurances).

Planned and unplanned maintenance costs may fall under fixed costs (e.g. scheduled yearly maintenance works) or variable costs (e.g. works depending on actual operating time) and are split accordingly.

Fuel costs are not included.

Auxiliary electricity consumption is included for industrial process heating technologies. The electricity price applied is specified in the notes for each technology, together with the share of O&M costs due to auxiliary consumption. This enables corrections from the users with own electricity price figures. The electricity price does not include taxes and PSO.

It should be noticed that O&M costs often develop over time. The stated O&M costs are therefore average costs during the entire lifetime.

Start-up costs

The O&M costs stated in this catalogue includes start-up costs and takes into account a typical number of start-ups and shut-downs. Therefore, the start-up costs should not be specifically included in more general analyses. They should only be used in detailed dynamic analyses of the hour-by-hour load of the technology.

Start-up costs are stated in costs per MW of generating capacity per start up (€/MW/startup), if relevant. They reflect the direct and indirect costs during a start-up and the subsequent shut down.

In general, the start-up cost for industrial process heating technologies is anticipated to be negligible. And the numbers of start-ups each year few.

Technology specific data

Additional data is specified in this section, depending on the technology.

Possible cooling generation capacity of a heat pump will be included here, as well as the heat source temperature set.

References

Numerous reference documents are mentioned in each of the technology chapters. The references mentioned below are for Chapter 1 only.

1. Danish Energy Agency,"Forudsætninger for samfundsøkonomiske analyser på energiområdet" (Generic data to be used for socio-economic analyses in the energy sector), May 2009.
2. "Economy of Scale in Power Plants", August 1977 issue of Power Engineering Magazine
3. "Projected Costs of Generating Electricity", International Energy Agency, 2010.
4. "Projected Costs of Generating Electricity", International Energy Agency, 2020.
5. "Konvergensprogram Danmark 2015". Social- og Indenrigsministeriet. March 2015.
6. "Energy Technology Perspectives", International Energy Agency, 2012.
7. International Energy Agency. Available at: http://www.iea.org/. Accessed: 11/03/2016.

Appendixes

Appendix is in a separate Excel file:

- Datasheets and application potential table
- InterAct sector aggregations

1. Traditional heat pumps

Datasheets updated January 2026 based on version 17 of reference [1]. The heat pumps are assumed to designed with certain limitations in maximum temperature and combined process heating and cooling

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Brief technology description

This chapter covers traditional compression heat pumps with certain limitation in maximum temperature of delivered heat, either with excess heat as heat source or with process cooling as heat source. The heat pump technology is the same whether the heat source is excess heat or process cooling.

The overall description of this heat pump technology is similar to the *compression heat pumps* described in "*Technology data catalogues for Electricity and District heating generation*" [1]. The purpose is to draw heat from a heat source (input heat) and convert the heat to a higher temperature (output heat). In this chapter, the compression heat pump technology will not be described in detail, but merely the differences between the heat pump described in the catalogue [1] and the one used in industrial processes.

The main difference is that this chapter focuses on the benefits of a two-stage reciprocating compression heat pump which is considered needed to achieve the relatively large temperature lift and large capacities at the same time. While this setup can – and is indeed utilized – in district heating systems, it is often mandatory to use a two-stage compression heat pump to achieve the required temperatures used in industrial processes.

Figure shows the principle diagram for a common two-stage compression heat pump. The system is more complex than a single stage compression heat pump, but it enables possibility for larger temperature lift between the heat source and the heat sink. The two-stage system typically has a higher efficiency COP (coefficient of performance) than a one-stage system.

Figure 4: Sketch of two-stage compression heat pump

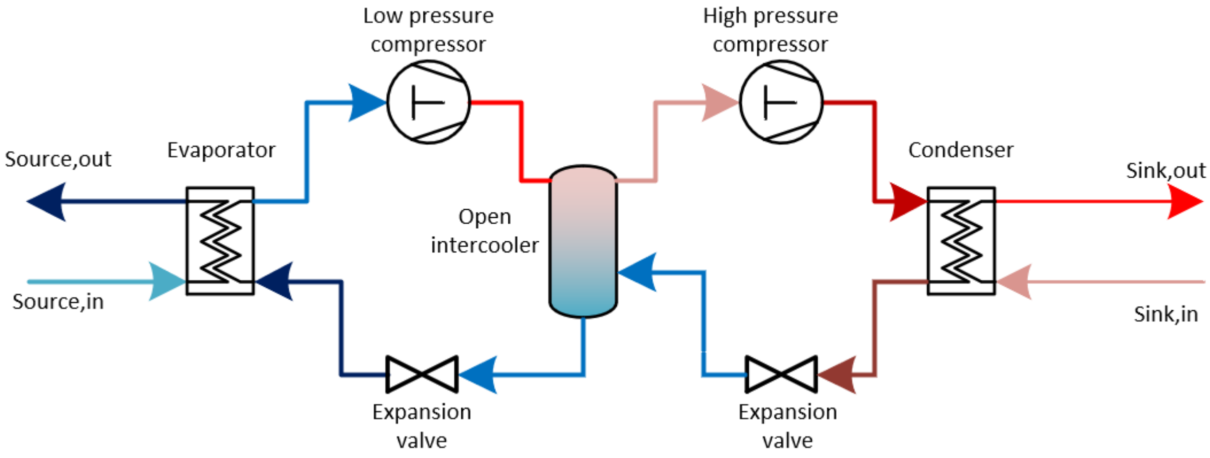
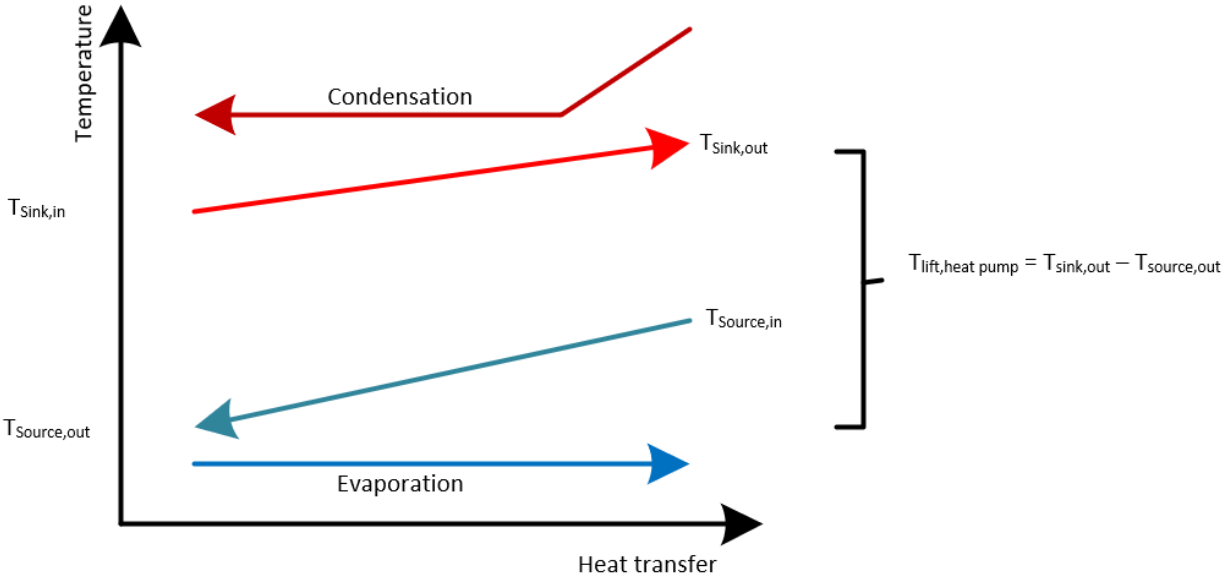


Figure 1 illustrates the heat transfer in the evaporator and condenser, where the source is cooled in the evaporator and the sink is heated in the condenser. The resulting temperature lift of the process is given by the temperature difference of the heat source inlet temperature and the heat sink outlet temperature, $\mathrm{T_{lift,proces}} = \mathrm{T}_{sink,out} - T_{source,in}$. The actual temperature lift performed by the heat pump, is the difference between the heat source outlet temperature and the heat sink outlet temperature (ignoring delta T over the heat exchangers between temperature of evaporation and source outlet, and temperature of condensation and sink outlet respectively): $T_{lift,heatpump} = T_{process} - \Delta T_{source} = T_{sink,out} - T_{source,out}$.

Figure 5: Q-T diagram depicting heat transfer in evaporator and condenser. Includes heat pump temperature lift



The heat pump is assumed to use excess heat or process cooling as heat source and thereby decreases the surplus heat at the installation site.

This chapter includes heat pumps with supply temperatures ($T_{sink,out}$) of 60 °C, 70 °C and 80 °C, with corresponding COP. For the heat pump with process cooling as heat source, only a temperature ($T_{sink,out}$) of 80 °C is considered in order to deliver hot water with a relatively wide application potential for the industrial site. The temperature difference between sink in and out, ($\Delta T_{sink} = T_{sink,out} - T_{sink,in}$) is expected to be 10-25 °C.

Efficiencies

The COP of a heat pump is given by delivered heat divided by power consumption.

$$COP = \frac{Heat\ delivered}{Power\ consumed}$$

In [1], the COP of the heat pump is calculated based on 40-60% of the theoretically Lorenz efficiency. Similar Lorenz efficiencies are be used in this chapter.

The Lorenz COP is defined as:

$$\mathrm{COP}_{Lorenz} = \frac{\bar{T}_{LM,sink}}{\bar{T}_{LM,sink} - \bar{T}_{LM,source}}$$

$\bar{T}_{LM,sink}$ is the logarithmic mean temperature difference of the sink, and $\bar{T}_{LM,source}$ for the source, both temperatures in Kelvin. The logarithmic mean temperature difference is defined as:

$$\bar{T}_{LM} = \frac{T_{out} - T_{in}}{\ln\left(\frac{T_{out}}{T_{in}}\right)}$$

In this chapter the COP is calculated based on the Lorenz efficiency:

$$COP = COP_{Lorenz} \cdot \eta_{Lorenz}$$

The estimated COP correspond well with COP values from manufacturers calculation software. A minimum temperature difference of 3 °C in heat exchangers were applied.

Input

The inputs for the heat pump are drive energy in the form of electricity, and a heat source i.e. industrial excess heat.

The drive energy is electricity.

The heat source is assumed to be either excess heat at 30 °C, cooled down to 20 °C, or process cooling where the heat source is cooled from 15 °C to 5 °C.

Output

The main output of a heat pump is heat. The heat will typically be delivered to the end user through a water-based distribution system but can also heat exchange directly with the product stream, depending on sector.

In the case with combined process heating and cooling, the output is also process cooling.

Typical capacities

Typical large heat pumps in Denmark have a capacity ranging from 0.5-5 MW. The capacity often depends on the temperature lift and refrigerant. Often units are connected in series or parallel, if more than around 2 MW heating is required.

Typical annual operation hours and load pattern

Large scale heat pumps are implemented in factories with continuous production and accumulation tank, which leads to many operation hours and often constant load pattern. Typical yearly operation hours are 7500-8000 hours.

Regulation ability

The heat pumps are assumed to have a frequency controller, which enable the heat pump to regulate load down to 10-25 %, depending on the compressor type and configuration.
More information is found in [1].

Advantages/disadvantages

A general advantage of a heat pump is that the heat pump can recycle excess heat which enables a utilization of heat sources otherwise left unused by conventional heat production technologies. [1]

In energy systems where electricity plays a vital role, compression heat pumps can incorporate electricity in heating systems in an effective manner. For processes that are electrically heated, heat pumps reduce power consumption and load on the electrical grid.

Compression heat pumps that are electrically driven have no direct emissions from burning fuel, meaning that these systems can be installed in locations with restrictions on exhaust emissions. [1]

The heat source must be available and suitable according to the required heat demand. Changes in flow or temperature of the heat source will affect the performance of the heat pump, which can increase the complexity of a heat pump system. [1]

Compared to most of the traditional heat production systems, heat pumps in general have higher investment costs, and lower energy consumption costs. [1]

Environment

The primary environmental impact of heat pumps stems from the drive energy consumption which is this case is electricity, and therefore depend on the electricity production technology and not the heat pump itself. [1]

As Danish legislation prevents synthetic HFC refrigerants in circuits with more than 10 kg of refrigerant, heat pumps with a capacity of more than 60-80 kW utilize natural refrigerants meaning that toxicities from leaks are well known and greenhouse gas emissions from refrigerants are negligible.

Because of the Danish regulation, only natural refrigerants are utilized in Denmark. These are hydrocarbons (propane, butane and iso-butane), carbon dioxide, ammonia, and water vapour. [1]

HFO refrigerants are also allowed in Denmark, as these have a GWP close to zero.

Ammonia is a widely applied natural refrigerant that can be dangerous to mammals and especially aquatic life forms. Because of this, ammonia systems must comply with certain safety measures regarding construction, location and operation. [1]

Research and development perspectives

There is a large potential for utilization of high temperature heat pump in the industries. This is a great focus for both researchers and manufactures. At the moment one of the limiting factors for high temperature heat pump, are the compressors, where the high temperature presents a challenge. "*Temperature-resistant compressors and stable lubricating oils are decisive components for the further development and commercialization of HTHPs*" [3].

For development and research with focus on refrigerant see [1]

Examples of market standard technology

See [1]

Prediction of performance and costs

In general, the prediction of cost follows the trend described in [1] and has the same placement on the learning curve, however the costs are higher. This is due to two-stage compression heat pumps, frequency controller and utilization of excess heat.

Regarding energy efficiency, the mechanical work of compression heat pumps relates to the temperature difference between heat source and sink. A theoretical COP can be calculated from the temperatures in the system, whereas an actual COP further relates to mechanical losses and thermal losses within the system. The difference between the theoretical and the actual COP value is the efficiency of a specific system. [1]

As the practical efficiency depends on both mechanical and thermal losses, it is expected that the efficiency will only increase a few percentage points during the next years. It is however expected that heat pumps with higher COP values will be installed but this will be due to better system integration. [1]

Direct and in-direct investment costs

Current application potential represents implementing a heat pump to cover a single demand (placed near the process heating demand). The full application potential represents a central placed heat pump with additional piping installation needed to cover more process heating demands.

The indirect investment cost represents additional piping installation needed when covering more potential than *Current application potential*.

Related benefits and savings

For the heat pump delivering both process heating and cooling, process cooling can be considered a related savings, as it substitutes alternative process cooling supply.

Uncertainty

See [1]

Additional remarks

For additional information see [1].

This chapter includes datasheet for supply temperature of 60 °C, 70 °C and 80 °C, all with excess heat as heat source.

For combined heating and cooling the supply temperature is 80 °C, and cooling for process is cooled from 15 to 5 °C.

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[2] EHPA, Large Scale heat pumps in Europe, 2019

[3] Zühlsdorf, B., Bantle, M., & Elmegaard, B. (Eds.), *Book of presentations of the 2nd Symposium on High-Temperature Heat Pumps. SINTEF*, 2019

2. High-temperature heat pumps

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Introduction to technology

There is currently a significant development underway in the field of heat pumps, leading to an increasing number of high-temperature heat pumps becoming available on the commercial market, alongside numerous ongoing development projects. This also means that a variety of suppliers are introducing different technologies to the market, based on varying system configurations, refrigerants, and compressor technologies. These technologies are typically tailored to specific applications, and there can be considerable variation in both CAPEX (capital expenses) and COP (coefficient of performance) across the different solutions. [1]

The technologies in the following chapters are defined as heat pumps providing temperatures above 100 °C supplying hot water. High-temperature heat pumps (HTHPs) are advanced thermal systems that provide heat at temperatures exceeding 150 °C, making them suitable for a wide range of applications in industry. These heat pumps operate on the same principles as conventional heat pumps but employ modified components and potentially new working fluids that enable them to achieve high efficiency and performance at elevated temperatures. [2]

The market for HTHPs is in strong development and is getting bigger and better all the time, and the interest for HTHPs has been significantly increasing over the past few years. The overall system configuration and performance depends strongly on the choice of refrigerant, the temperature levels, and the compressor technology.

The main advantage of HTHPs is the fact that they can deliver heat with higher efficiency than, for example, electrical boilers. The most efficient HTHPs tend to be based on the Carnot process with phase change as method to absorbing and releasing of energy at two different pressure levels controlled by a compressor and an expansion valve. The expansion takes place in the liquid phase, and the compression takes place in the gas phase. Depending on the choice of refrigerant, capacity, temperature level and temperature lift, various compressor technologies apply. These technologies can, among others, be screw compressors, piston compressors, centrifugal compressors, and blowers.

The physical properties of the refrigerants are decisive for the temperature levels that can be covered and especially for how high supply temperatures can be achieved. The technology used depends on the refrigerant via e.g., specific volume, pressure ratio, heat transfer coefficient, mixability with different oil types, hazard classes and so on. Generally, the focus in the area is on natural refrigerants such as CO2, water, and hydrocarbons. [1]

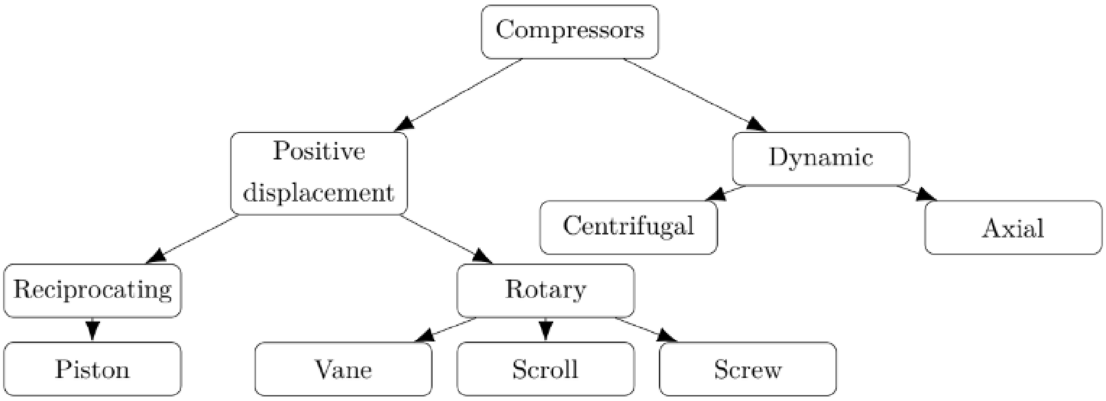
The efficiency for HTHPs strongly depends on the required temperature lift, as a higher temperature lift results in more work for the compressor. In addition to this, the supply temperature is a restriction for

HTHPs due to temperature limitations for the components in the HTHPs. The maximum temperature is increasing all the time as new developments are ongoing.

Compressor technologies

A range of different compressor technologies are currently available on the market and under development, each offering distinct advantages and disadvantages.

Figure 6: Various groups of compressors used for heat pumps and refrigeration systems



Below is a brief summary of the available compressor technologies that are used for industrial sized heat pumps.

- Piston compressors. Typically used for smaller capacities (0-1 MW)
- Screw compressors. Typically used for medium capacities (0.5-8 MW)
- Turbo (dynamic) compressors. Typically used for high capacities (1-40 MW)

Piston compressor: In this type, the gaseous refrigerant at lower pressure is sucked in through a valve when the piston moves downwards. When the piston moves upwards, the gas is compressed to a higher pressure. The disadvantages of this type of compressor are the pulsating volume flows and the possible occurrence of a liquid hammer. [7]

Screw compressor: In this type of compressor, compression is accomplished by two counter-rotating screw-shaped rotors. The advantages of screw compressors are, for example, the compact design and the high speeds that can be realized. A disadvantage is the oil injection that is necessary for sealing. Moreover, it requires oil management systems and oil degradation at high temperatures might be an issue limiting the application.

Turbo compressor: In contrast to the other compressors described above, the turbo compressor is a fluid-flow machine and does not operate on the displacement principle. In this type of compressor, the energy is transferred to the medium by means of rotating impellers. The pressure increase is achieved by means of a diffuser. The advantage of this type is the small space requirement, the large flow rates, the good speed control, and the low abrasion. However, the feasible pressure ratios per stage are low. Typically, water vapor recompression systems are operated using large compressors or high-speed oil-free turbo compressors with high flow rate and low-pressure ratio to compensate for the low density of the water vapor.

Refrigerants

The physical properties of the refrigerants are decisive for which temperature ranges can be covered and especially for how high supply temperatures can be achieved. The technology used then depends on the refrigerant via e.g., specific volume, pressure ratio, heat transfer coefficient, mixability with different oil types, hazard classes, etc.

HFOs (Hydrofluoroolefin) are generally not used for many new developments of HTHPs due to the focus on GWP. The major advantages of heat pumps with HFOs are that they to a large extent can be fitted in the existing, well-proven heat pump technology by some limited modifications concerning the lubricants and the polymer materials to reach higher temperatures without many modifications.

The major disadvantages are the long-term uncertainty due to the environmental impact of the refrigerants as one of the break-down products of the HFO refrigerants are in the group of PFAS substances. Consequently, there is a realistic risk that they will be phased out. Therefore, natural refrigerants are mainly used for HTHPs. [3] [4]

CO_2 systems have been successfully introduced to commercial refrigeration, but many systems are currently being developed as HTHPs using CO_2. These systems are suitable for processes requiring a high temperature glide for the heat sink, e.g. spray dryers.

The major advantages of CO_2 systems are the possibility of using them for high temperature glides and a well-proven hardware coming from many years of experience with CO_2 as refrigerant for cooling systems. The major disadvantages are the requirements of a large glide to achieve a reasonable COP, meaning that CO_2 systems will only be available for a limited number of applications. Currently, demonstration systems running at temperatures up to 150 °C are being tested. [5] [6]

Ammonia is a well-used refrigerant for heat pumps at temperatures below 90 °C. The temperature limit of approximately 90 °C (due to high discharge pressures) means that it cannot be used for HTHPs using single-stage systems. It is, however, usable for two-stage systems as the lower stage.

The major advantages of ammonia are well-established technology and several installations for reference in the industry. Ammonia can serve as the lower stage heat pump in a two-stage system. The major disadvantages are the temperature limit of 90 °C that prohibits steam production and the toxicity and flammability that requires safety measures.

Hydrocarbons cover a range of refrigerants with varying critical temperatures. Typically, propane (R-290), butane (R-600) and pentane (R-601) are used for HTHPs. Hydrocarbons can be used for a wide range of applications and are suitable for moderate temperature glides for the heat sink. Typically, hydrocarbons fit very well into two-stage systems with pentane as the upper stage resulting in supply temperatures above 150 °C.

The major advantages of hydrocarbons are well-demonstrated technologies with high Technology Readiness Levels (TRL) and high supply temperatures for a wide range of applications. The major disadvantages of hydrocarbons are the safety concerns and difficulties due to ATEX security.

Water/steam is a well-known and well-established medium for heat transfer in the process industry; the energy source is usually a gas- or oil-fired boiler. The advantage is that a lot of components for steam systems are available, but there is only a little tradition for steam compression and heat pumps, so the compressor is the ‘missing’ component for a high temperature heat pump based on water as refrigerant. Different suitable compressors for this purpose are coming on the market.

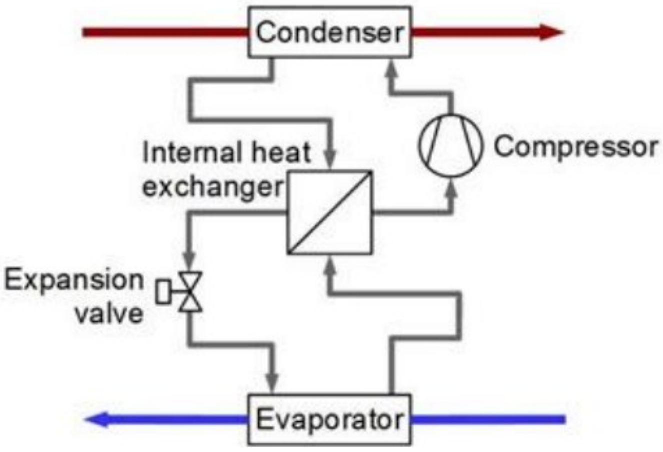
The boiling point for water at 1 bar is 100 ºC, which means that the processes involving the heat source temperatures below this will result in vacuum conditions in the heat exchangers and for the compressor operation which can result in high pressure ratios. Typically, the water HTHPs are mainly suitable for applications with no or low temperature glide (typically steam production).

The major advantage of steam or water vapor as media is that it is a well-established medium for energy infrastructure and it is environmentally friendly, non-toxic, non-flammable long term solution. The major disadvantage is the large volume flow that is required at lower heat source temperatures, and in some cases the handling of vacuum conditions for part of the system.

Low temperature lifts

When dealing with low temperature lifts for the heat pump, a temperature difference between the heat source and the heat sink of up to approximately 50 °C is typically assumed. This temperature lift allows the compressor to handle the lift in a single stage, enabling the system to be designed as a single-stage system.

Figure 7: A typical single-stage system. Can be with or without internal heat exchanging depending on refrigerant and supply temperatures. [1]



This provides several advantages for systems with low temperature lifts. Firstly, there is no need for additional heat exchange between the low and high stages, and secondly, the capital expenditure for equipment procurement can be significantly reduced. An example of a simplified single-stage system is shown in the figure below. It also illustrates that the system consists of relatively few components, which can help reduce the system's CAPEX. Sometimes, an internal heat exchanger is used in the system cycle to increase COP, but this will also affect CAPEX and will need to be calculated for the specific case.

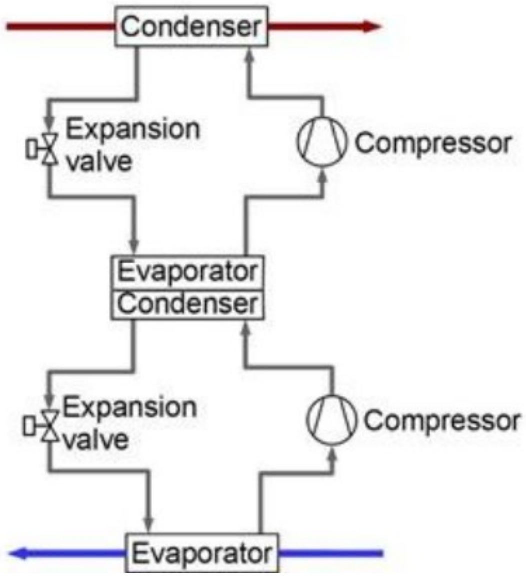
When an end user is evaluating the potential for implementing a heat pump in industrial processes, the first step should be to assess whether it is possible to reduce the temperature difference between the heat source and the heat sink, allowing for the possibility of a single-stage system. Below is a list of potential measures that could enable a single-stage configuration:

- Investigate whether the heat sink temperature can be reduced. This could involve lowering the temperature requirements in industrial processes or applying the heat pump in areas where lower temperatures are acceptable.
- Explore whether high-temperature waste heat sources are available. For example, steam or hot water may be discharged to a stack and could potentially be recovered.
- Consider whether investments in production processes could reduce operating temperatures. In some cases, investments in new production equipment may be offset by the reduced cost of a simpler heat pump system.

High temperature lifts

When a heat pump is required to operate with a high temperature lift (above 70 °C), it is typically necessary to design the system in multiple stages. This often involves constructing several heat pump units in series, forming what is known as a cascade system, where the heat sink of one heat pump serves as the heat source for the next. Such configurations increase initial capital expenditure (CAPEX) and make the overall business case more complex.

Figure 2: The cascade cycle consists of two refrigeration cycles (low- and high-temperature refrigeration cycle), which are connected by a heat exchanger (so-called evaporator-condenser). In this heat exchanger, the refrigerant of the low-temperature cycle condenses, and the refrigerant of the high-temperature cycle evaporates simultaneously. [1]



A wide range of heat pump suppliers now offer cascade systems, and the level of expertise has grown to a point where the overall business case can still be competitive with alternatives such as gas and oil. However, a cascade system generally requires more maintenance than a single-stage system, and the interaction between the stages must be carefully optimized to ensure a high COP.

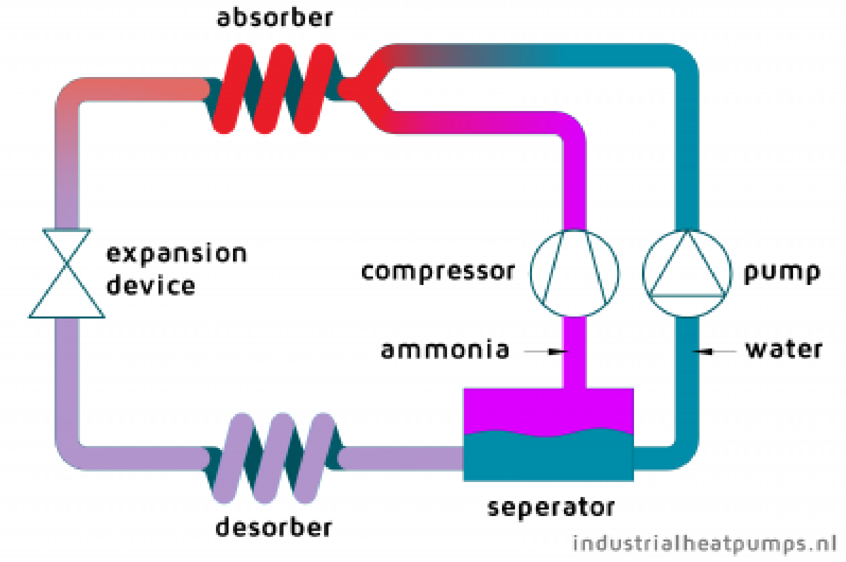
Hybrid absorption/compression heat pumps (HACHP)

Hybrid absorption/compression heat pumps (HACHP) are a new type of heat pumps being introduced to the market. The technology is not new, but advancements in compressor technology and the flux towards sustainable ways to produce process heat have resulted in this technology becoming relevant.

HACHP is one of several types of high temperature heat pumps. HACHP has been selected for this chapter based on the following reasons. HACHP can use natural refrigerant (some of the other types uses HFC which are not allowed in Denmark), It is currently on the marked with large heating capacities, > 0,5 MW. Other types of high temperature heat pumps use natural refrigerant, but generally they currently have smaller capacities than the scope of this chapter.

The main difference between a normal vapour compression heat pump, is that HACHPs use a zeotropic refrigerant, typically a mixture of ammonia and water. As the two fluids have different evaporation pressures, they individually evaporate and condensate at different temperatures. The zeotropic refrigerant, where the fluids are mixed, evaporates and condenses through a temperature range instead. This transforms the evaporation/condensation processes into an ab/de-sorption processes instead (hence the name), which results in an improved COP. A separate fluid loop (typical water) with a pump is also present, together with a liquid separator. A simplified setup can be seen on Figure 3.

Figure 3: Simplified hybrid absorption-compression heat pump



The advantage of the HACHP compared to ordinary vapour-compression heat pumps is that the saturation temperature is increased with the zeotropic refrigerant. Industrial available compressors are currently limited to an upper pressure limit of 60 bars [8] [10], at which pure ammonia – which is the most widely used refrigerant – have a saturation temperature of 98°C. Combined with a minimum ΔT in the heat exchangers, this limits vapour-compression heat pumps to an upper temperature limit of ~95°C. Adding 25% water however, increases this limit to 152°C [9]. HACHPs is thus capable of delivering heat at much higher temperatures.

HACHP can simultaneously supply cooling if temperature levels are compatible and can be used in series with conventional boilers as preliminary heating if very high temperatures are required. It is recommended to have a temperature difference between hot and cold side of less than 90 °C, at higher temperature differences the COP decrease sharply.

The heat pump requires a heat source which can be either dependent or independent of other industrial processes. Using a process-dependent heat source (such as flue gas or other excess heat sources) can lead to higher efficiencies due to these being at a higher temperature level. Using non- process-dependent heat sources (such as sea/tap-water, air, geothermal) can however lead to increased flexibility due to these sources typical being independent on other processes.

As the COP of a HACHP is strongly linked to the glide13 in temperature, processes with large temperature variations are required. For instance, pipe trace heating or other processes requiring less than 10°C in difference between the in- and outlet temperatures, will be more efficient with an ordinary vapour compression heat pump. Subsequently, having a process where a large temperature difference is required, i.e. heating water more than 10°C, will result in a HACHP being more efficient [3]. A HACHP is hence performance wise the optimal choice when high glides can be achieved, and/or high sink temperatures are wanted.

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[13] The use of a zeotropic refrigerant effectively means that instead of transferring energy at a fixed temperature, the refrigerant changes temperature throughout the heat transferring process. The amount of change is defined as the *glide*.

Hybrid Energy A/S have currently implemented HACHPs in numerous places (e.g. in drying processes at Arla Arinco, food processing, district heating). Hybrid Energy A/S currently state they can reach more temperatures higher than 120°C [11].

The general interest for high temperature heat pumps is high, both in industry and academia.

Heat Pumping Technologies [12] is an international collaboration project with numerous countries looking at promoting heat pump technologies and integration capabilities. They currently have an ongoing project specifically looking at high temperature heat pumps:[14]

"Industrial heat pumps (IHP) are active heat-recovery devices that increase the temperature of waste heat in an industrial process to a higher temperature to be used in the same process or another adjacent process or heat demand. While the residential market may be satisfied with standardised products and installations, most industrial heat pump applications need to be adapted to unique conditions.

In addition, a high level of expertise is crucial. This Annex is a follow-up-annex from the previous completed Annex 35 "Application of Industrial Heat Pumps". Industrial heat pumps within this Annex are defined as heat pumps in the medium and high-power range and temperatures up to 150 °C, which can be used for heat recovery and heat upgrading in industrial processes, but also for heating, cooling and air-conditioning in commercial and industrial buildings." [12]

The ability to replace steam generation with combustibles are driving the development and is crucial in order to reach the goals of an industry based on renewable energy, although it requires favourable ratios of the price of electricity compared to combustibles, which can limit the current business case for implementing high temperature heat pumps in Denmark [13]. It is however expected to see commercially available heat pumps producing up to 150°C steam or hot oil in the next 3-8 years (i.e. by 2028-2033).

Ultimo 2025, 8 HACHP systems are installed in Denmark, with a total capacity of 9 MW.

Efficiencies of high-temperature heat pumps

The efficiencies of heat pumps in general are strongly dependent on the temperature lift, here defined as:

$$\Delta T_{\text{Lift,process}} = \text{Sink outlet - Source inlet}$$

With the sink being the reservoir where the high temperature heat is wanted, and source being the used heat source.

This is because of the definition of the theoretically possible COP, called $\text{COP}_{\text{Lorenz}}$. This is given by:

$$\text{COP}_{\text{Lorenz}} = \frac{\overline{T}_{\text{sink}}}{\overline{T}_{\text{sink}} - \overline{T}_{\text{source}}}$$

From this, it can be seen that the theoretically achievable COP decreases as the temperature lift increases. This means that for heat pumps, it is crucial to minimize the temperature lift in order to improve efficiency. The sink temperature and source temperature levels has little influence by themselves. The theoretical efficiency cannot be fully achieved in practice, and a typical real-world efficiency is expected to be around 55% of the theoretical COP due to various system losses.

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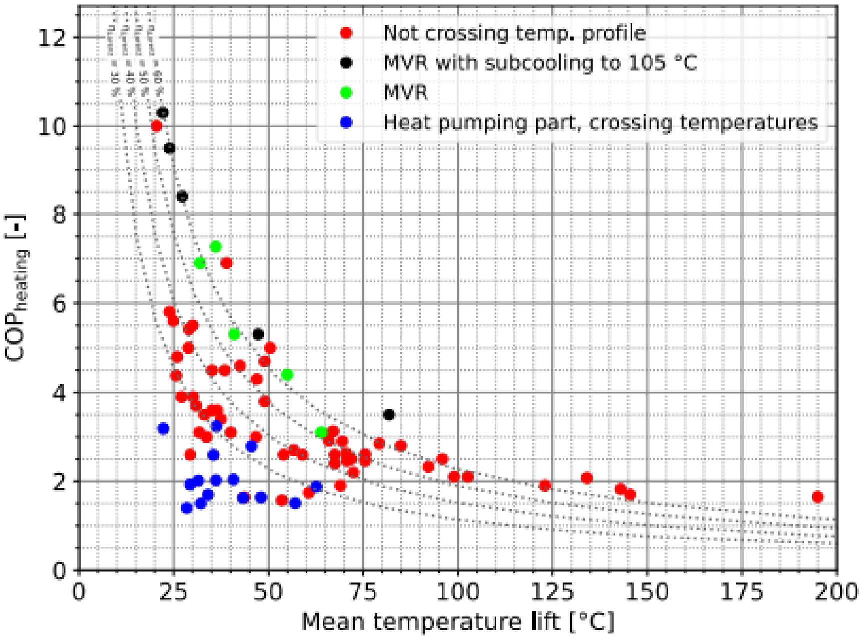
[14] https://heatpumpingtechnologies.org/project68/ . Project start date: June 2025

The relationship between temperature lift and COP is also illustrated in the figure below, which shows the results of a study conducted in Annex 58 across a wide range of demonstrations and technologies. The data clearly demonstrates that higher temperature lifts result in lower COPs.

Figure 4: Actual COPs from Annex 58 showing the correlation between a lower COP and a higher mean temperature lift.[1][15]



Input

The input to a high-temperature heat pump consists of electricity, heat source in, and heat sink in.

Electricity is primarily used to power the compressor, and depending on the heat pump's COP, this input can account for anywhere from 20% (COP = 5) to over 50% (COP < 2) of the desired energy to the heat sink. The advantages of electricity include high supply security and low environmental impact, which can lead to additional long-term savings due to CO_2 taxation.

The **heat source in** is the actual energy source for the heat pump. This is where energy is transferred to the heat pump, either through sensible or latent heat extraction. Energy recovery may be straightforward, for example by utilizing waste heat from production processes, or less obvious, where external air or district heating might be used as the energy source. It is essential to assess the amount of energy available at the heat source in, since this energy—combined with the compressor energy—must match the energy demand on the heat sink side.

The **heat sink in** refers to the medium that needs to be heated or evaporated so it can be used in the required processes. If the temperature difference between heat sink in and heat sink out is large, there will be a significant temperature glide. In contrast, applications such as steam generation (evaporation) typically involve a small temperature glide – this is covered in the chapter on steam generating heat pumps.

Output

The output is primarily defined as heat sink out, but it may also include heat source out.

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[15] A crossing temperature profile is defined as the case where a part of the sink side has a lower temperature than a part of the source side temperature glide. Crossing temperature profiles would typically allow for directly recover part of the heat purely with a heat exchanger.

The **heat sink out** is the useful energy extracted from the heat pump, typically delivered as pressurized hot water or steam in a high-temperature heat pump. The typical temperature range for high-temperature heat pumps is around 100 °C to 200 °C, with higher temperatures generally associated with fewer commercially available options. As of 2025, commercially available heat pumps can reach temperatures of up to approximately 150 °C.

The **heat source out** is usually not utilized in high-temperature heat pumps, as it simply represents the cooled or condensed heat source in. However, there may be benefits in cases where the cooling of the heat source results in savings elsewhere, such as reduced load on a cooling tower.

Applications

HTHPs can be used in many different areas such as drying, boiling, bleaching, pasteurization, sterilization, distillation, moulding and colouring. This is typically relevant for industries like pulp & paper, food & beverage, chemicals, metal, plastic, automotive, wood, textiles etc.

Table 6: Potential applications of high-temperature heat pumps

End-use	Relevance	Sector-comments
Heating/boiling	Very high relevance – heat pumps can replace or supplement conventional boilers for a broad range of processes. They are particularly valuable when preheating feed streams or supplying evaporation units.	Used in pasteurization of milk, juice, and water; upgrading of biogas and yeast production; extraction of vegetable oils; preheating before evaporation of sugar juice or milk; treatment of wastewater; washing and cleaning processes; and preheating before distillation of alcohol and oil.
Drying	Highly relevant – especially for preheating drying air or directly supplying hot air for drying processes.	Applied in drying of milk powder, coffee, cereals, animal feed, seeds, wood pellets, paper, pharmaceuticals, and chemicals. Also suitable for wastewater sludge treatment and food industry processes (e.g. starch and powdered ingredients).
Dewatering (Evaporators)	Limited relevance – mostly applicable when temperature levels can be matched to evaporation demands.	Possible in cases where evaporation units require moderate temperatures.
Distillation	Moderate relevance – heat pumps can partly replace conventional heating sources in alcohol and petrochemical distillation.	Alcohol production (e.g. breweries, bioethanol) and petrochemical processes.
Firing/Sintering	Limited relevance due to very high temperature demands that often exceed the range of heat pumps.	Some potential in low- to medium-temperature preheating stages.
Melting/Casting	Limited relevance – mainly constrained by material-specific high temperature requirements.	Could be relevant in certain metal and plastic industries where lower melting ranges apply.
Other processes up to 150°C	Highly relevant – heat pumps can often cover a significant share of these needs with high efficiency.	Includes many food, chemical, and industrial processes requiring controlled heating below 150 °C.
Other processes above 150°C	Emerging relevance – as technology develops, more applications at higher temperatures become feasible.	Potential in advanced industrial heating, high-temperature drying, and next-generation chemical processing.

In general, the most significant leaps developments are seen in heat pumps with high capacities. This is because it is possible to use specially designed equipment, which is typically more costly but can achieve higher temperatures and better efficiency. Large-scale heat pumps (5 MW and above) are available with supply temperatures above 150 °C with suppliers even offering supply temperatures of 200 °C. Commercially available systems closer to 1 MW are for now limited to supply temperatures of 150 °C. It is expected that a commercial roll-out up to 200 °C will happen within the next 3 years.

Furthermore, most development is taking place in heat pumps delivering liquid-to-liquid or liquid-to-steam, as demand is highest in these areas and it enables the heat pump manufacturers to produce the most compact system. Standardized heat pumps will typically deliver indirect heating. Direct heating with heat pumps will require process specific solutions.

High-temperature heat pumps producing hot air are very similar to hot water heat pumps in their construction and developmental status and show promise in multiple drying applications. Supplying hot air often requires a customized air-side heat exchanger (e.g., large surfaces or surfaces) and careful air handling integration, which increases footprint and CAPEX relative to water-based systems. Considering the cleaning of the air heat exchanger is of utmost importance, to ensure continued performance. In practice, all heat pumps supplying water may be retrofitted to supply hot air instead, but the modification cost will vary dramatically depending on the air volumes and contaminants in the flow.

Typical capacities

High-temperature heat pumps can typically be connected either in parallel or in series, meaning there is no theoretical upper limit to their capacity. Currently, projects are being demonstrated with heat pumps up to 80 MW in size for district heating. Due to their relatively complex design, heat pumps generally require more physical space compared to traditional boiler systems. Additionally, the choice of refrigerant has a significant impact on the overall size of the heat pump.

Typical annual operation hours and load pattern

It is generally most beneficial for the overall business case to operate the heat pump as much as possible. This is because heat pumps typically have a high CAPEX compared to other technologies, while their fuel cost is usually lower. As a result, maximizing operating hours is key to achieving the lowest possible LCoH (Levelized Cost of Heat) compared to alternative technologies.

Therefore, it is recommended to size the heat pump to cover the base load of the production, allowing for continuous operation. A heat pump can be turned on and off as needed, and it can also be operated with variable frequency control that allows the heat pump to run at reduced capacity (typically down to 25-50%).

Regulation ability

High-temperature heat pumps are often frequency controlled to operate in part-load. Part-load operation may impact COP.

Advantages/disadvantages

Advantages [9]

- Electricity as power input ensures low CO2 impact and high supply security.
- Better efficiency than electrical boilers.
- Typically, lower fuel cost compared to traditional boilers (depending on temperature lift)

Disadvantages

- Higher CAPEX than traditional boilers
- More complex system layouts making service difficult
- Physically larger systems than traditional boilers

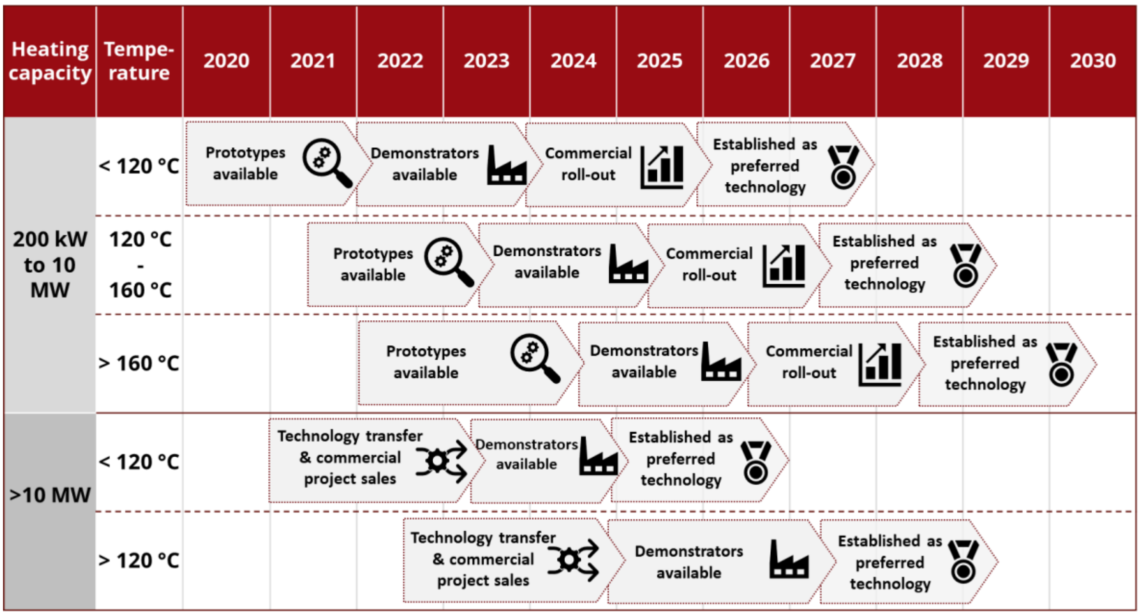
Environment

Since a high-temperature heat pump (HTHP) operates using electricity, it does not emit CO_2 directly during operation. The associated emissions depend on how the electricity is generated. The development of heat pumps is increasingly focused on the use of natural refrigerants, and regulations against the use of HFOs (hydrofluoroolefins) as refrigerants are becoming increasingly stringent.

Research and development perspectives

Multiple development and demonstration projects are underway. Based on current momentum, strong market demand, and political focus on electrification and decarbonization, the following outlook is projected for the next 5–7 years (i.e. 2030-2032).

Figure 8: Expected developments of the available delivery temperature of high-temperature heat pumps.



Availability of HTHPs

Commercial availability of HTHPs with supply temperatures up to above 200 °C is expected to grow significantly. This is driven by both established manufacturers increasing focus and numerous startups entering the field. Availability will expand across capacity, temperature range, technology, and refrigerant types.

Refrigerants

HFOs: Usable up to ~145 °C but face regulatory uncertainty due to decomposition into PFAS-related compounds.

Hydrocarbons: Likely to be widely adopted due to suitable thermodynamic properties across temperature levels. Systems may use cascade configurations with two hydrocarbon stages. Flammability must be addressed.

Steam (Water Vapor): Offers higher COP (10–15% better than HFOs/hydrocarbons) and no flammability/toxicity concerns. Feasibility depends on compressor development due to large volume flows at low inlet temperatures. [14]

CO_2: Especially suitable for hot water production (under pressure) and processes with high temperature glide.

Capacity Ranges

HTHPs supplying temperatures up to approximately 200 °C are currently linked to large capacities (7–70 MW) and research projects. Lower capacities are expected to be addressed within 5 years for these temperatures, primarily using hydrocarbon and steam systems. Smaller systems typically need standard components to reduce costs and are therefore a bit lower in temperature currently.

Temperature Integration

Ongoing analysis focuses on industrial process integration of both centralized and decentralized HTHPs. These are compared with alternatives like biomass or hydrogen. Business cases will be developed based on energy prices and CAPEX/OPEX.

HTHPs are expected to be economically viable up to 200–250 °C, especially for large-scale systems. Development for smaller-scale integration is ongoing. [15]

Steam vs. Hot Water Systems

Due to energy losses of 30–50%, steam infrastructure is increasingly being replaced by pressurized hot water systems (90–180 °C). This trend favors heat pump deployment and may simplify integration, potentially enabling wider use of CO_2 systems alongside HFOs, hydrocarbons, and steam.

Examples of market standard technology

There are numerous examples of demonstration projects across a wide range of industries. An overview is provided in Annex 58 [1], and a selection of demonstration projects is presented below:

- Distillery, Ireland – 1 MW – Heat source 60/60 °C – Heat sink, water at 115/115 °C – COP: 5.0
- Sewage, Norway – 0.5 MW – Heat source 100 °C – Heat sink, water at 146 °C – COP: 4.5
- Refinery, Japan – 1.9 MW – Heat source 65/60 °C – Heat sink, water at 20/120 °C – COP: 3.5
- Milk spray dryer, Denmark – 1.9 MW – Heat source 4/0 °C – Heat sink, air at 10/120 °C – COP: 2.1

Prediction of performance and costs

Many factors influence future performance and cost. In this context, energy prices are excluded from consideration, with the focus placed solely on capital expenditure (CAPEX) and performance (impacting OPEX). The investment cost includes the heat pump, necessary piping to existing hot water or steam loop, and minimal construction work. Any additional cost associated due to insufficient electrical connection at site is excluded. The indirect investment costs cover the additional costs associated with converting a steam circuit to a hot water circuit with a couple of main consumers. This cost is highly uncertain and will be affected by the complexity of the site and piping infrastructure.

Historically, heat pumps have had relatively high investment costs, making it difficult to achieve a strong business case over their lifetime. This has limited market uptake, as customers often wait for better economic feasibility. However, trends now indicate increasing potential for improved business cases, which in turn drives higher production volumes, reduces CAPEX, and further strengthens project economics.

As a result, a broader range of low-CAPEX technologies is emerging and continues over the coming years, contributing to an overall downward trend in prices. As previously mentioned, investment cost is highly dependent on the required temperature lift. As a rule of thumb, a cascade system is almost twice as expensive as a single-stage system in terms of equipment cost.

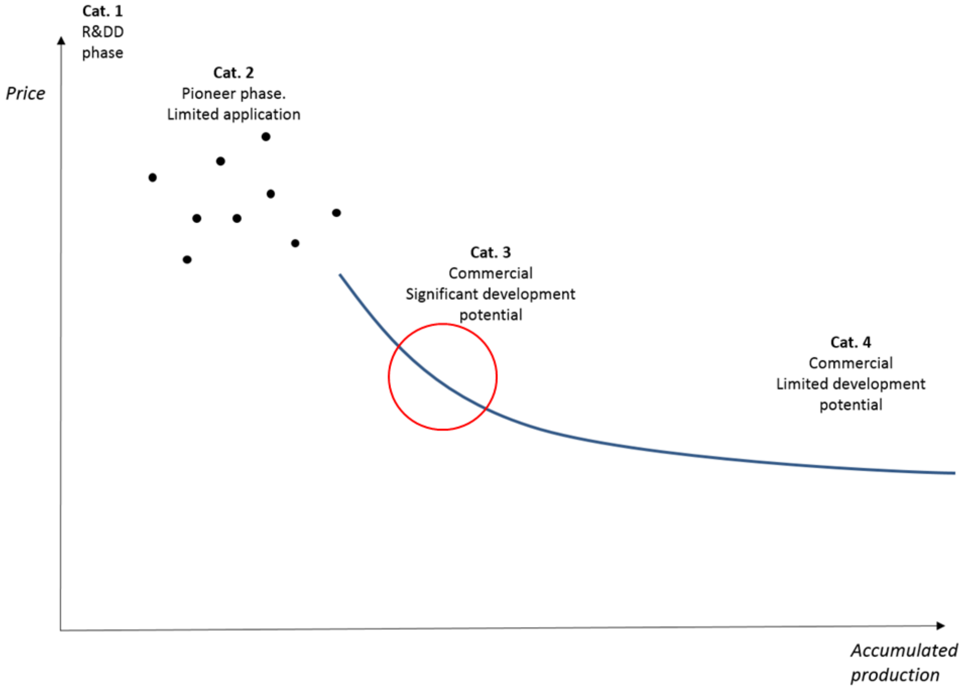
The ongoing development is expected to support better series production of heat pumps. However, rising raw material costs may partially offset these gains and impact overall integration costs.

Table 7: Current and future expected CAPEX

Technical parameters	2025	2030	2040	2050
Nominal Investment cost [M€/MWheat] – up to 125 °C	1.20	1.15	1.05	1.00
Nominal Investment cost [M€/MWheat] – up to 150 °C	1.55	1.50	1.40	1.35

With reference to the IEA, “Innovation theory” describes technological innovation through two approaches: the technology-push model, in which new technologies evolve and push themselves into the marketplace; and the market-pull model, in which a market opportunity leads to investment in R&D and, eventually, to an innovation [12]. The level of “market-pull” is to a high degree dependent on the global climate and energy policies. Hence, in a future with strong climate policies innovation can be expected to take place faster than in a situation with less ambitious policies.

Figure 5: Technological development phases. Correlation between accumulated production volume (MW) and price. [12]



The efficiency of heat pumps has already been described at a general level earlier in the section, but demonstrations indicate that heat pumps are becoming increasingly efficient, thereby reducing OPEX. This is mainly due to improvements in compressor efficiency, as well as the possibility of operating heat pumps with lower safety margins in relation to temperatures, as operations are gradually optimized through experience and development projects.

Uncertainty

The deployment and subsequently the future investment cost and performance is relatively uncertain as these to a great extend is driven by electricity and fuel cost.

If the fuel cost increases, the HTHPs will be more competitive. Reversely if the electricity cost also increases, a higher focus on performance of HTHPs must be expected.

Increasingly climate awareness from manufacturers, society and policy makers is also expected to increase competitiveness of HTHPs. Aiming for a lower degree of fossil fuel in the industrial section, lower taxes and subsidies relate to non-fossil fuels are expected.

Additional remarks

A detailed description of the current development level can be found here:

https://heatpumpingtechnologies.org/annex58/task1/ and further material will be produced in https://heatpumpingtechnologies.org/project68/.

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3. Steam-generating heat pumps

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Introduction to technology

When specifically considering steam-generating heat pumps, they are typically used either as a replacement for or a supplement to the central boiler system in industrial production. There can be many advantages to using a heat pump as a supplement or substitute for a traditional boiler system, but there are also a number of important considerations that must be addressed to achieve the optimal solution.

Below are some general rules of thumb for successful integration of steam-generating heat pumps, followed by a more detailed description of relevant technologies. [1]

- Investigate whether the steam demand in the production processes is highly variable or relatively constant. If the steam consumption fluctuates significantly, it may be necessary to use the heat pump as a supplementary energy source, primarily covering the base load. The business case deteriorates if the heat pump is not operated as much as possible, and it should ideally run at full load as often as possible to avoid oversizing, which reduces efficiency and increases CAPEX. This issue can sometimes be mitigated by installing a steam accumulator, although in most cases this significantly increases CAPEX.

- If multiple steam pressure levels are used in the production process, the heat pump should supply steam at the lowest pressure level. In a traditional boiler, you pay for the energy consumed, whereas with a heat pump, you pay for both the energy and the temperature lift, which impacts the COP.

- Investigate the possibility of supplying steam from the heat pump via direct steam injection into the processes. This can increase the heat pump's COP by eliminating the need for a heat exchanger between the heat pump and the production processes. However, in some cases, there are requirements for the steam to meet certain standards—for example, food-grade quality—which can complicate direct injection.

- There may be waste energy available in the form of low-pressure vapor (e.g., vacuum steam), which can be upgraded directly to a higher pressure using a compressor. This is known as Mechanical Vapor Recompression (MVR) and will be addressed in a later section.

Direct/indirect steam

For steam-generating heat pumps, a distinction is made between direct and indirect steam production. This has briefly been described above, and the difference between the two methods is as follows:

- **For direct steam injection**, the steam is delivered directly into the process, eliminating the need for a heat exchanger between the heat pump and the steam. This increases the efficiency of the heat pump and reduces CAPEX. However, this method is relatively complex in practice and imposes several limitations in terms of steam quality. If a heat pump with direct injection is to be used in the food industry, strict requirements are placed on the cleanliness of the steam, which increases the cost of the heat pump components and thus raises CAPEX.
- **For indirect steam production**, the heat pump operates as a traditional high-temperature heat pump (HTHP), as described in the previous section. The only difference is that there is no

temperature glide on the sink side, which limits the range of usable refrigerants. As a result, hydrocarbons or water are typically used as refrigerants in steam-generating heat pumps. [2]

Steam-generating high-temperature heat pump systems applying steam compressors

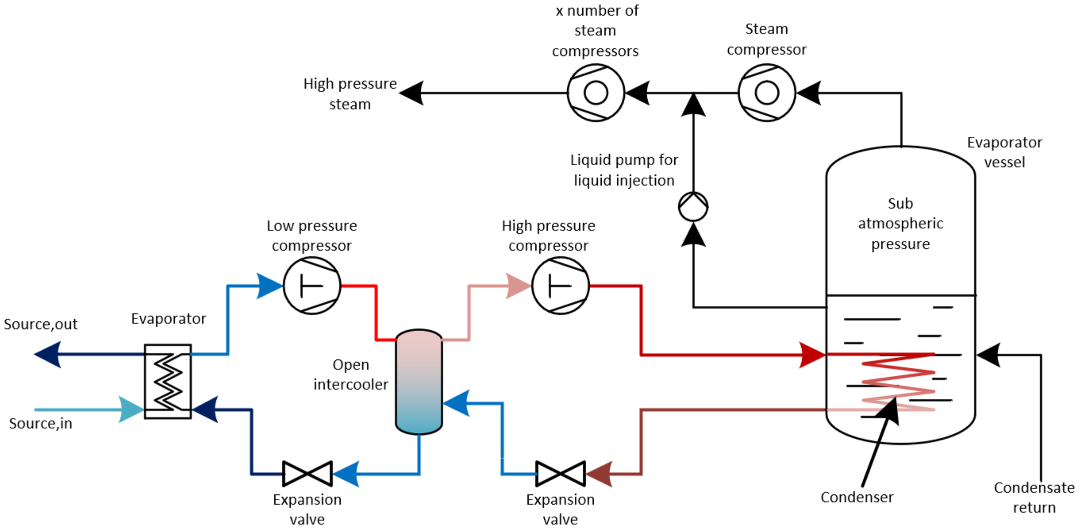
This technology is a combination of a traditional vapor compression heat pump, an evaporator vessel (around atmospheric pressure) and a number of turbo steam compressors. The system is presented in literature and referred to as Cascade heat pump with a multi-stage R-718 cycle for steam generation [3] and [4].

The technology is included in this catalogue, as an increasing demand for heat pump systems with the ability to produce steam on a large scale is experienced. It is expected to see the technology on the market within a 5-year period.

The system is depicted in **Error! Reference source not found.**. The traditional heat pump[16] supplies heat at a temperature around 85-90 °C to the *sub atmospheric pressure vessel*. The heat is supplied to the water in the vessel, which evaporates, as the pressure is sub atmospheric. The evaporated water vapor is compressed in turbo *steam compressors*. The pressure increase per steam compressor causes a temperature increase of 8-10 K (increase in saturation temperature) [5]. After each steam compressor liquid injection is applied as intercooler before next compression step. This catalogue considers a saturation temperature of 150 °C after the last steam compressor. This setup requires 7-8 steam turbo compressors or 1 screw compressor in series, but the complexity is greatly reduced when the pressure ratio is lower.

The heat input to the traditional two stage heat pump is excess heat with a temperature set of by example 30/20 °C (source-in and source-out on the figure), by utilizing the excess heat as heat input, it decreases the amount of surplus heat which possibly could have been used in a district heating network.

Figure 9: Sketch of two-stage compression heat pump in combination with booster turbo compressors. Components and process is described in detail above. [6]



Examples of market standard technology

There are numerous examples of demonstration projects across a wide range of industries. An overview is provided in IEA Annex 58. A selection of realized projects producing steam is presented below:

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[16] Description on Traditional heat pump can be found in the chapter *Traditional heat pumps with certain limitations in maximum temperature*

Animal feed, Norway – 1.8 MW – Heat source 30/25 °C – Heat sink 120 °C – COP: 2.2

Pharma, Sweden – 1.5 MW – Heat source 36/34 °C – Heat sink 178/183 °C – COP: 1.7

Chemical plant, United Kingdom – 12 MW – Heat source 152/105 °C – Heat sink 211 °C – COP = 5.3

Prediction of performance and costs

See the section about high-temperature heat pumps. 15% are added due to steam-generation requiring more expensive materials and systems. Especially the steam-generating heat exchanger is the main course of the higher price.

Table 4: Current and future expected CAPEX

Technical parameters	2025	2030	2040	2050
Nominal Investment cost [M€/MWheat] – up to 125 °C	1.40	1.30	1.15	1.10
Nominal Investment cost [M€/MWheat] – up to 150 °C	1.75	1.65	1.50	1.45

Example of calculations using the data sheet

When estimating the costs and efficiency of a heat pump, a number of factors must be taken into account. These are reviewed in the data sheet and below is a calculation example for a heat pump intended to supply steam. The source temperature is 60 °C and the supply temperature is 140 °C steam. The thermal capacity needed is 2 megawatts.

Temperature lift: From 60 °C to 140 °C (80 K)

Size: 2 MW

Sink: Steam

Estimating COP:

1) Access the data sheet for HTHPs with supply temperatures up to 150 °C.
2) Find the efficiency (COP) based on a temperature lift of 80 K. This is estimated to 2.4 (240%).
3) Due to steam generation, calculate the new efficiency based on the decrease rate (15%-points in 2025).
4) The COP is estimated to 2.25 (225%).

Estimating CAPEX:

1) Access the data sheet for HTHPs with supply temperatures up to 150 °C.
2) Find the nominal investment (includes equipment and installation). This is estimated to 1.55 MEUR/MW capacity.
3) Add the extra cost of steam generation equipment at 0.2 MEUR/MW capacity.
4) Add the extra cost of equipment for a temperature lift above 75 K at 0.2 MEUR/MW capacity.
5) This will result in a total nominal investment of 1.95 MEUR/MW capacity resulting in a total investment of 3.90 MEUR for the given heat pump with a size 2 MW.

References

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4. Mechanical Vapour Recompression (MVR)

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- Author: Niklas Bagge Mogensen, Viegand Maagøe

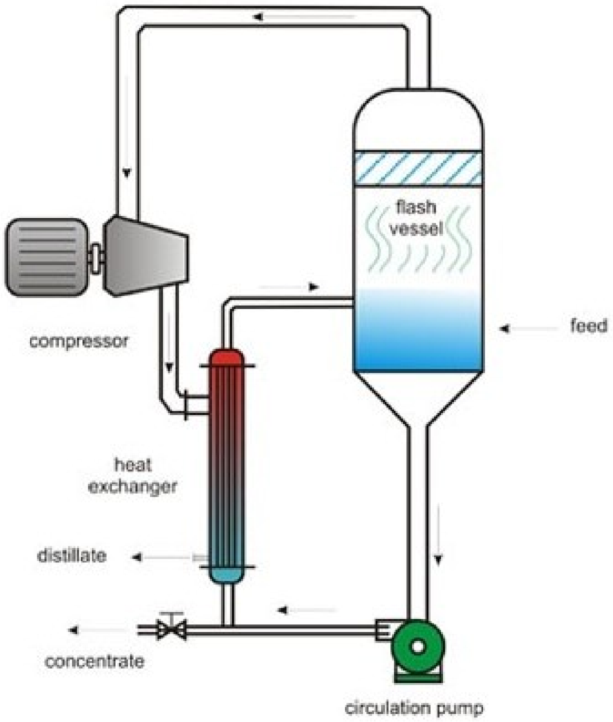
Brief technology description

A Mechanical Vapour Recompression (MVR) system is a way to efficiently utilise excess or wasted vapor/steam and convert it into a useful resource. It utilizes the same principles as Thermal Vapour Recompression (TVR), only difference between MVR and TVR is the drive input, for TVR the drive input is high pressure steam and the MVR it is electricity. It is not a new technology, but its integration and propagating throughout industrial processes can make a significant contribution to the progress towards using sustainable energy sources.

The key herein lies in the fact that MVR systems can, for instance, convert current evaporation processes from using steam from boilers with combustibles as fuel sources, into being run solely by electricity.

An MVR system is fairly simple. It captures excess vapor, typically steam, from (for instance) an evaporation process, and compresses it through a compressor. This increases the pressure as well as the temperature of the vapor. The vapor is then used to heat the original substance/product, from which vapor is produced through evaporation. This is then captured by the MVR system. The cycle thus repeats. The outlet is condensate which often consists of very pure water, and a concentrate. An illustration of the concept is seen on Figure 10.

Figure 10: Simplified illustration of the MVR cycle. For a water treatment system, the feed is dirty water, the concentrate is highly concentrated pollutants, and the condensate/distillate is pure water.



Efficiencies

MVR systems are the most thermodynamic efficient way of evaporation [2]. This is primarily because the latent heat of the vapor is always re-used in the process, instead of being condensed elsewhere. Comparing with other evaporation technologies such as multi-effect evaporation, the system is furthermore more compact, which reduces the overall heat loss. Other systems also commonly use process steam as heat source (such as falling film evaporation), which results in a high exergetic loss when used to dry products below 100°C, resulting in an overall low efficiency. As MVR systems only have a small temperature difference between the medium and the recompressed steam, this is not a problem in these systems.

Comparing with traditional steam boilers, recompression typically requires 10-20 times less energy for the same amount of steam produced[17] [3]. MVR systems can evaporate water at 5-30 kWh/m^3 [1][5], depending on the temperature difference between the vapor and the product, the overall temperature of the brine, and the compressor efficiency. A value between 7-13 kWh/m^3 is typical for large sized plants [6], and 25 kWh/m^3 for smaller plants. A low temperature difference results in low power consumption of the compressor, but requires a larger heat transfer area, and thus higher investment costs [5].

Multi-effect TVR evaporators usually require ~0.33 kg of steam pr. kg of evaporated water [11] [12]. This can be converted into ~0.25 kWh/kg of evaporated water[18]:

$$769\ \frac{kWh}{ton_{steam}} \times 0.33\ \frac{ton_{steam}}{ton_{evapwater}} \div 1000\ \frac{kg_{evapwater}}{ton_{evapwater}} = 0{,}25\ \frac{kWh}{kg_{evapwater}}$$

Using a value of 20 kWh/m^3 water for MVR systems, this can be converted into 0,02 kWh/kg of evaporated water. The MVR system hence uses ~12-13 times less energy compared to the Multi-effect TVR evaporator. However, the energy used in MVR systems is electric, and not thermal, so the running costs ultimately depends on the costs of fuel/electricity and efficiency of the steam boiler (not taken into account here).

Input

The main input is electricity, to power the compressor.

A small amount of heat, usually steam, is required during startup.

Output

The output is medium pressure steam, which is mainly used in evaporation processes, but the steam can also be used for process heating and drying.

The temperature is entirely dependent on the process and evaporation media, but as steam is the most common vapor, temperatures at or just above 100°C is common, but lower temperatures can also be achieved, depending on the pressure and media. The maximum temperature depends on compressors maximum operation temperatures, which are typically able to handle discharge temperatures at about 150°C [7].

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[17] Assuming that the post process low pressure steam is vented or condensed in cooling towers.

[18] Assuming the cost of steam is based on the latent heat and additional 125C of heating, and a constant density of water. ~769 kWh/ton$_{steam}$

Applications

MVR systems are most commonly used in evaporation processes, e.g. water treatment systems and dairy industry, but it can also be used for drying, desalination, distillation, and boiling processes. A detailed description can be seen in Table 8.

MVR will have a natural market pull, as MVR is expected to replace TVR systems when they are worn out. It is not expected to replace well-functioning existing TVR systems.

Table 8: Potential applications for MVR systems

End-use	Relevance	Sector-comments
Boiling (1)	Highly relevant for a wide variety of unit operations.	Beer brewing, Food production, Animal feed
Drying (2)	Some processes have the possibility to dry in superheated steam	Sludge, various food products or bi-products, e.g. animal feed
Evaporators	Highly relevant for supplying heat at most evaporators.	Sugar, milk, salt, misc. food industries, ingredients, misc. waste water streams, biogas plants reject concentration
Distillation (3)	Some processes have possibilities	Alcohol distillation
Firing/Sintering	Not relevant	
Melting/Casting (4)	Not relevant	
Other processes up to 150C (5)	Limited possibilities	
Other processes above 150C (5)	Not relevant so far	

An MVR system requires no external supply steam during normal operation and is thus not dependable of a central boiler house. The MVR system does require steam during start-up phase, this can either be supplied by integrated steam boilers or other steam supply. The MVR system is thus an isolated system, and the heat produced by the system cannot be utilised in other processes. Comparing with other evaporation technologies such as multi-effect evaporation or multi-stage flash, the system is less complex and simpler to control [2].

Typical capacities

Typical capacities for larger production sites are in ranging from 5-50 MW thermal.

The capacity ranges from 100-100.000 kg/h of evaporated media for a single unit [1].
As the temperature differences between the recompressed vapor and the product is small (typically between 2°C-10°C [6]), the process is suitable for sensitive products when used for drying purposes.

Smaller MVR system exists, for instance Envotherm [15] has systems with capacities down to 40-50 kg/h [15], these are however considered smaller than the scope of the chapter. The specific cost of smaller systems is higher.

Typical annual operation hours and load pattern

An MVR system features very reliable operations, as the only moving components is the compressor and a small pump. The system is however reliant on a heat input at start up to facilitate the evaporation process from the product, otherwise no vapor is present for recompression. This can either be from a steam supply, or from an electric heater.

MVR systems are typically installed in large companies with annual operation hours >7000 hours.

Regulation ability

An MVR system follows the flexibility of the compressor, which is the key component. Using a frequency converter, the flowrate for the system can be varied from 100% down to ~50% of the maximum load. No yearly fluctuations should be present. Maintenance follows that of similar systems with compressors as key components, and 0.5 weeks/year of outage should be expected [9].

Advantages/disadvantages

Advantages [13]:

- High efficiency
- Electric driven
- Uptake less space compared to TVR
- Low long-term costs

Disadvantages [13]:
- High investment cost
- Efficiency depends on production volume

Environment

As the MVR system uses electricity as its energy source, no direct particles or gasses are emitted doing operation

Research and development perspectives

Price reductions trends are based on [9] and are expected to follow the same trend as other heat pumps as they share the same key components (Compressors and heat exchangers)

Examples of market standard technology

AKV Langholt, Denmark, 13 MW (evaporation)

CP Kelco, Denmark 26 MW (evaporation)

CP Kelco, Germany, 17 MW and 14 MW (evaporation)

Arla Foods Arinco, Denmark, capacity unknown (evaporation)

Irish Distillers, Ireland, capacity unknown (distillation)

Prediction of performance and costs

Based on a case from 2017 which implemented an MVR system in an industrial laundry water cleaning progress see Error! Reference source not found. as well as [10], the nominal investment cost based on system size in terms of treated water per day can be seen in Table 9.

Table 9: Nominal investment costs based on size of unit in evaporated water/hour. Price reductions trends are based on [9] and are expected to follow the same trend as other heat pumps as they share the same key components (Compressors and heat exchangers). Today-prices based on [10]

	2017	2020	2030	2050
Nominal Investment cost[19] <10 m³/h [€/m³/day]	7200	7030	6284	5645
Nominal Investment cost[3] 10-100 m³/h [€/m³/day]	4800	4686	4189	3763
Nominal Investment cost[3] >100 m³/h [€/m³/day]	700	683	611	549

It is expected that the efficiency of the compressors continues to improve, with it the efficiency of the MVR systems increases. A 5-15% increase in compressor efficiency can be expected towards 2050, which will results in lower electricity consumption of MVR systems [9]. New double effects systems can further improve the efficiency by up to 7% and are especially applicable doing desalination processes [8].

The efficiencies are summed in Table 10. The efficiencies are stated in two ways:

1. Electricity to steam substitution compared to similar technologies using steam: For instance, an efficiency of 1300 means that for 1 kWh of electricity used in a MVR system, substitutes 13 kWh of steam (heat) used in a multi effect evaporators (TVR).
2. Baseline efficiency: Comparing the energy consumption of MVR system, to the heat of evaporation (0.63 kWh/kg). This is comparing to "boiling the water in a pot", with no heat regeneration. This should hence not be used to compare the efficiency, as this method is generally not used anymore.

Table 10: Efficiencies for MVR systems compared to 3-effect TVR and Baseline (equal to pure boiling of water)

	2020	2030	2040	2050
Comparable Efficiency *electricity to energy of evaporation* [%]	1260	1320	1380	1430
Baseline Efficiency *electricity to energy of evaporation* [%]	4240	4430	4620	4810

Related benefits and savings

In some cases, the implementation of MVR can result in increases production capacity. Especially if available space is a limitation. [14]

Learning curves and technological maturity

MVR is considered to belong in Category 3. *Commercial technologies with moderate deployment*. It relies on the same components and technologies as large-scale heat pump, which is also considered to belong in category 3 [9].

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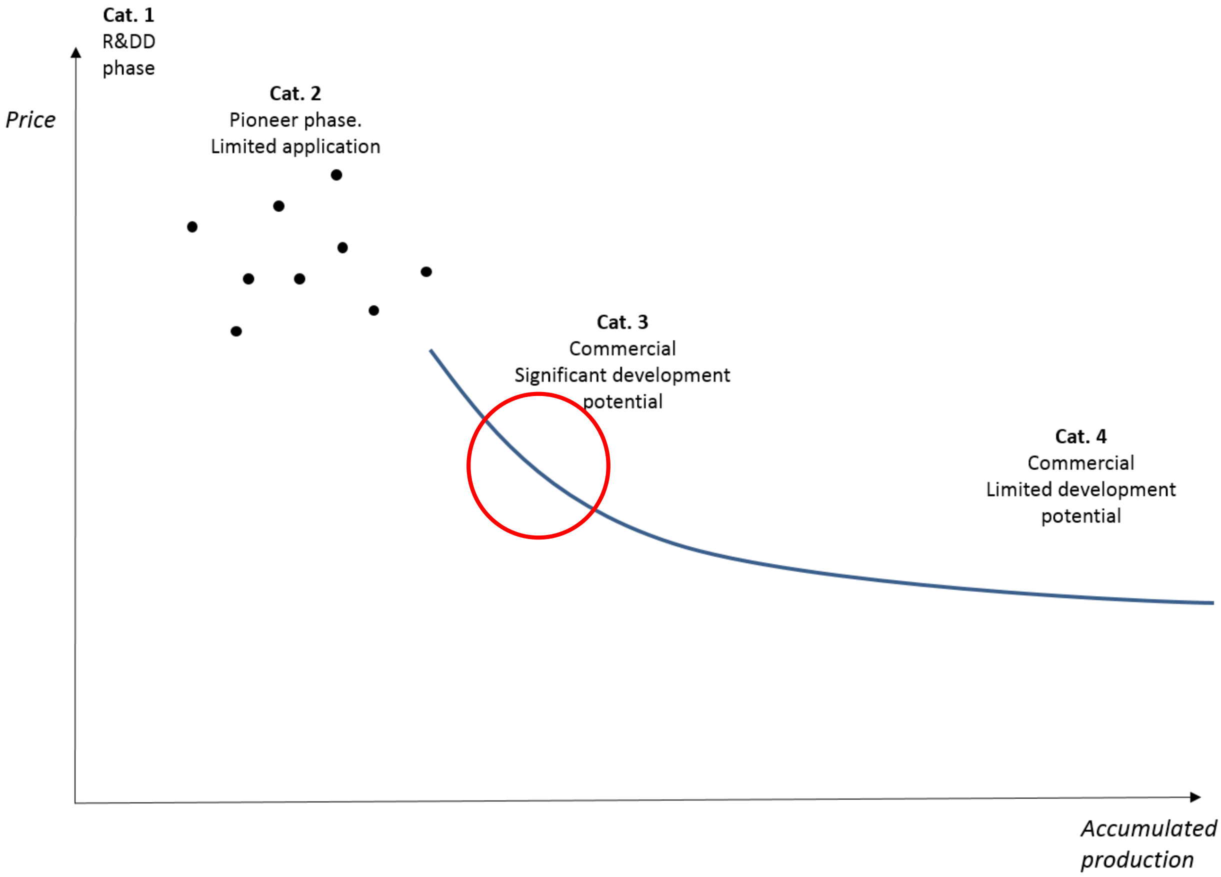
[19] Including installation

Figure 11: Technological development phases. Correlation between accumulated production volume (MW) and price.



Uncertainty

The development of future investment cost and efficiency is relatively uncertain as these to a great extend is driven by electricity and fuel cost.

A decrease in electricity cost or increase in fossil fuel cost will make both electric driven heat pumps and MVR more attractive. As illustrated with the learning curve, increased production resulted in reduced investment cost.

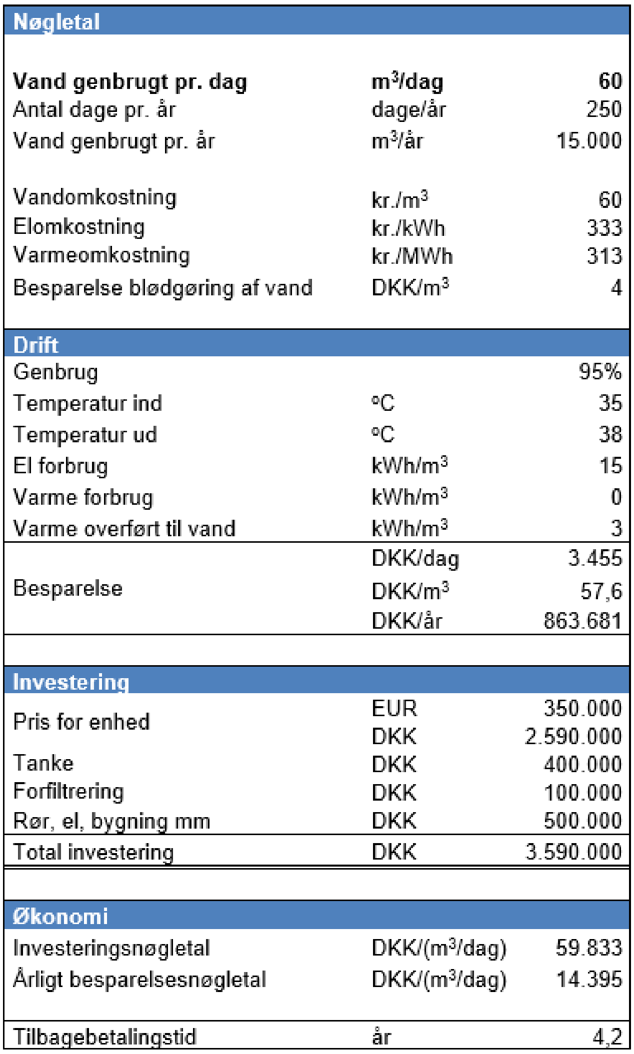
Increasingly climate awareness from manufacturers, society and policy makers is also expected to increase competitiveness of MVR and vapor compression heat pumps. Aiming for a lower degree of fossil fuel in the industrial section, lower taxes and subsidies relate to non-fossil fuels are expected.

Additional remarks

It is expected that MVR will have a natural market pull. Implementation of MVR is expected to happen when a factory increase production or needs to replace old TVR. It is therefore expected to reach the application potential gradually over a time period.

	2020	2030	2040	2050
% of application potential	10 %	40 %	70 %	100 %

Figure 12: Offer from manufacturer



Nøgletal		
Vand genbrugt pr. dag	**m³/dag**	**60**
Antal dage pr. år	dage/år	250
Vand genbrugt pr. år	m³/år	15.000
Vandomkostning	kr./m³	60
Elomkostning	kr./kWh	333
Varmeomkostning	kr./MWh	313
Besparelse blødgøring af vand	DKK/m³	4
Drift		
Genbrug		95%
Temperatur ind	°C	35
Temperatur ud	°C	38
El forbrug	kWh/m³	15
Varme forbrug	kWh/m³	0
Varme overført til vand	kWh/m³	3
Besparelse	DKK/dag	3.455
	DKK/m³	57,6
	DKK/år	863.681
Investering		
Pris for enhed	EUR	350.000
	DKK	2.590.000
Tanke	DKK	400.000
Forfiltrering	DKK	100.000
Rør, el, bygning mm	DKK	500.000
Total investering	DKK	3.590.000
Økonomi		
Investeringsnøgletal	DKK/(m³/dag)	59.833
Årligt besparelsesnøgletal	DKK/(m³/dag)	14.395
Tilbagebetalingstid	år	4,2

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5. Electric boilers (industrial process heating)

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Amendments after publication date

Date	Ref.	Description
December 22	Qualitative description and datasheets	Chapter updated with new text and datasheets

Brief technology description

This chapter describes electric boilers in the range up to 60 MW using electricity to produce hot water or steam for industrial heating purposes. This chapter is an extension of the *electric boiler* chapter described in the technology catalogue *Technology Data - Energy Plants for Electricity and District heating generation* [1, p.306], with focus on steam and hot water production with supply temperatures of > 150 °C.

The boiler type described in this chapter is heating elements using electrode or resistance systems. Electrode systems are typically used for larger applications but can operate in a seamless span from 1-60 MW. Resistance boilers are typically used for smaller capacities (up to 2-4 MW), these boilers are supplied by low voltage (400V or 690 V) and the installation will often require a new transformer[20]. Electrode boiler capacities that typically are larger than 2-4 MW, are directly connected to the medium to high voltage grid at 6.3-22 kV depending on the voltage available in the local distribution grid.

This chapter describes boilers used for pressurized hot water and for high-pressure[21] steam production, related to Danish industry, and the difference between these two types. Furthermore, the focus of this chapter is the pressures and temperatures most relevant for Danish industry. In Danish industries, steam boilers typically operate at pressure and temperature of 8 bar and 175 °C, and the steam is saturated or slightly superheated. For pressurized hot water boilers, the typical operating pressure is 7 bar and up to 145 °C. These facts are independent of which kind of energy the boiler utilizes.

Therefore, for both steam and hot water boilers, boilers complying with the following characteristics are considered relevant to include:

- Low - and medium voltage boilers (resistance or electrode boiler)
- Operating pressure
    - 1-12 bar
    - 12-16 bar

When exceeding an operating pressure of around 12 bar, the boiler investment cost and maintenance cost increases considerably. Again, when operating pressure becomes higher than 16 bar, both the investment cost and maintenance cost increases significantly once again [2], [3], and [4]. But operating pressures above 16 bar are rarely used in the industry. The few examples found during the preparation of this chapter show that the high operating pressure was chosen because the existing installations

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[20] Both resistance and electrode boilers will likely require new power supply cable from medium voltage grid to factory, the cost for these are not included in CAPEX in the data sheet for this chapter.

[21] High-pressure steam in relation to Danish industry. Here 16 bar is high pressure, thus not referring to plants with steam turbines for electricity production.

included a steam turbine for electricity production and not because of any process requirements. Thus, it was concluded that only very few processes in the Danish industry require steam pressure and temperature above 16 bar and 200 °C. Furthermore, the heating demand in these processes is small. Therefore, boilers with an operating pressure above 16 bar are not included in this chapter nor in the data sheets. The conclusion is based on interviews with experts and suppliers, [3], [6] [7] and on the results in the revised mapping of the consumptions in the Danish industry [8]. If superheated steam is needed, a designated heater is added after the boiler, which is not common and only used in few specific processes in the industry[22].

For process heating with indirect heating[23] demand above 150 °C supplied with water/liquid, thermal oil is used for specific processes. The heating demand covered by thermal oil is limited. Currently thermal oil boilers are most often gas or oil fired, but electric thermal oil boilers do exist in the market. The advantage of thermal oil compared to pressurized hot water or steam is, that thermal oil can be heated to around 300 °C without being pressurized. Electrical thermal oil boilers are only available for low voltage (resistance boiler). Electrical thermal oil boilers are seldom used in the Danish industry [4] and is therefore not included in this chapter. Thermal oil boilers are for instance used for heating bitumen during production of asphalt.

The section above is based on interview with suppliers [2], [3], [4], [5] and experts with knowledge on Danish industry and process demands [6] and [7].

From [1, p. 307], the working principle of heating water with electricity is described:

"The water in electrode boilers is heated by means of an electrode system consisting of (typically) three-phase electrodes, a neutral electrode, and a water level & flow control system. When power is fed to the electrodes, the current from the phase electrodes flows directly through the water in the upper chamber, which is heated in the process. The heat production can be varied by varying the level and the flow through the upper chamber and the power that is led through the electrodes, thus enabling output to be controlled between 0 and 100 %. The heat production and power outtake also depend on the temperature of the water and the conductivity of the water.

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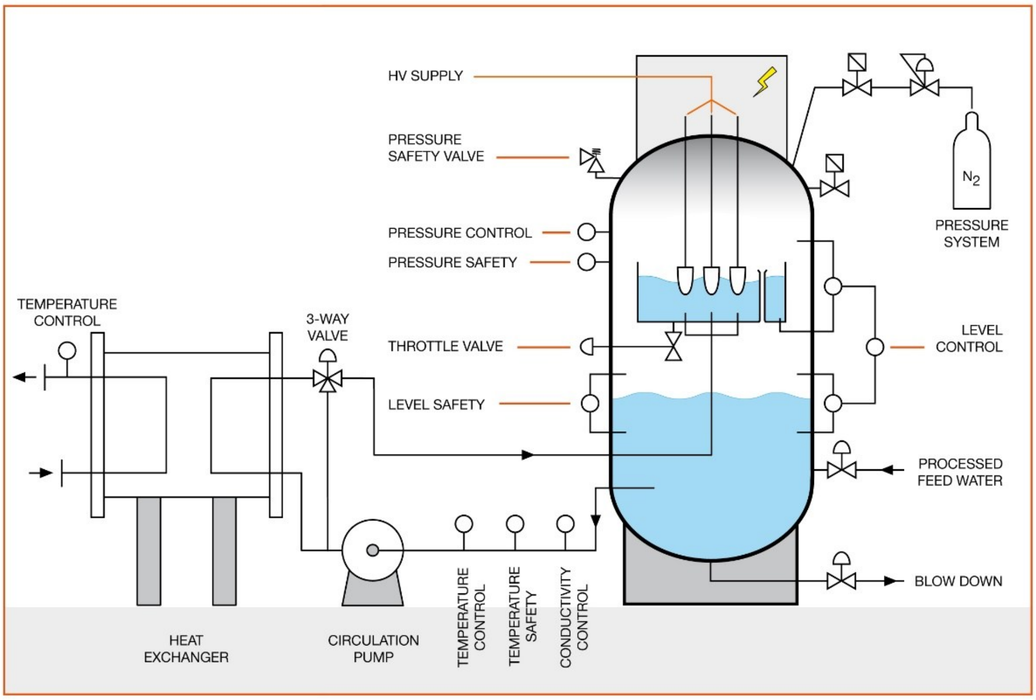
[22] Superheated steam is not included in this chapter.

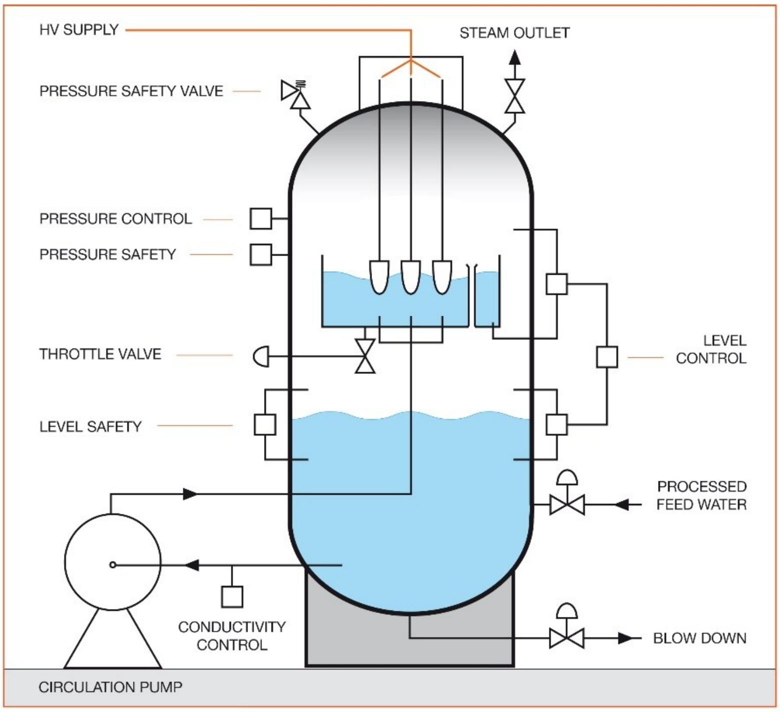
[23] "Indirect heating" means heating supplied to a process via a media e.g. steam or hot water - as compared to "direct heating", where fuels are combusted directly into the process (by example in cement kilns)

Figure 13: Schematic illustration of an electrode boiler for hot water production, [2]. HV is an abbreviation of "high voltage".



Error! Reference source not found. illustrates the production of high-pressure hot water. The water in the boiler heat exchange with the hot water system, with the use of a heat exchanger and circulators pumps.

Figure 14: Schematic illustration of an electrode boiler for steam production, [2]. HV is an abbreviation of "high voltage".



This system does not have a heat exchanger and the steam produced is supplied directly to the steam system. The feed water needs water treatment before it is let into the boiler.

Input

Input is electricity.

Output

Saturated steam up to 16 bar or high-pressure hot water up to 16 bar.

Applications

The set-up of the application potentials has been aligned with the revised mapping of the consumptions in the Danish industry, thus not anymore in accordance with the description in the guideline in the introduction chapter of this catalogue. The application tables have been combined into one table, except for the sector relevance which is no longer shown. It is assumed that whether the type of heating supply can be utilized for the specific end-use is not dependent of the sector. If a specific sector ("Branch code") deviate significantly it will be specified in a note.

Table 2 shows the current application potential divided on end-uses and on type of heat supply for electric steam boilers. The application potential is independent in size of heat generation capacity and in size of pressure, for sizes of the pressures included in this chapter.

Table 11: Energy services, electric steam boiler for all heating capacities and up to 16 bar

Current application potential	Type and temperature of process heating supply			
	Steam			
End-use	**<100°C**	**100-150°C**	**150-200°C**	**>200°C**
Other processes	100%	100%	100%	0%
Firing /Sintering	100%	100%	100%	0%
Distillation	100%	100%	100%	0%
Dewatering	100%	100%	100%	0%
Heating/Boiling	100%	100%	100%	0%
Space heating	100%	100%	100%	0%
Melting /Casting	100%	100%	100%	0%
Drying	100%	100%	100%	0%

Table 12: Energy services, electric hot water boiler for all heating capacities and up to 16 bar

Current application potential	Type and temperature of process heating supply			
	Water/liquid			
End-use	**<100°C**	**100-150°C**	**150-200°C**	**>200°C**
Other processes	100%	100%	0%	0%
Firing/Sintering	100%	100%	0%	0%
Distillation	100%	100%	0%	0%
Dewatering	100%	100%	0%	0%
Heating/Boiling	100%	100%	0%	0%
Space heating	100%	100%	0%	0%
Melting/Casting	100%	100%	0%	0%
Drying	100%	100%	0%	0%

Table 12 shows the end-use relevance for hot water boilers. Hot water boiler is seldom applicable for dewatering (evaporation), as the process often utilize properties of steam, e.g. pressure control in injector. In the revised mapping of the energy consumptions in the Danish industry, it is also shown that the heating demand for dewatering with water/liquid is close to zero. The same is evident for firing/sintering and distillation.

The full application potential (in contrast to the previous method the possibility to convert from steam to hot water or vice versa) is no longer included in the tables, however the cost of the conversion is still included as in-direct cost in the datasheet.

Typical capacities

Resistance-boilers are available in the span 6-5.000 kW/unit. Electrode boilers are available in the seamless span 0-60 MW/unit, with typical appliances being 5- 50 MW/unit [1, p. 308].

Typical annual operation hours and load pattern

The annual operation hours and load pattern depends on the role of the electric boiler at the production site.

If the boiler substitutes an existing fossil fuel boiler at a large production site, it will typically have many operation hours > 8000 and follow the load pattern of the production.

If the boiler supplements an existing boiler and only operate when the electricity price is favorable, it will follow the electricity market and have low operation hours < 500.

An electric boiler can also provide auxiliary services for the electrical grid. It is important to consider the operational strategy of the electric boiler as the electric boiler can be called upon to both up- and downregulate depending on the service. It is thus necessary to have an alternative heat supply to ensure that heating can always be supplied.

Regulation ability

See [1, p. 308]

Advantages/disadvantages

See [1]

Environment

During operation, the electric boiler uses electricity and the environmental impact from operation depends on the origin of the electricity. Apart from the emissions, due to the consumed electricity, electric boilers have no local environmental impact [1, p. 308].

Research and development perspectives

The technology is well developed, tested and commercially available. No significant research and development are expected.

Examples of market standard technology

See [1, p. 309-310]

Prediction of performance and costs

The electric boilers are very similar to the one described in [1, p. 310], and the prediction of cost and performance follows the same trend. The cost of high-pressure hot water boilers and steam boilers is based on information from suppliers [2] and [3].

The indirect investment cost represents additional piping installation needed if increasing the application potential.

Both resistance and electrode boilers will likely require new power supply cable from medium voltage grid to factory, the cost for these are not included in this chapter.

Uncertainty

See [1, p. 311]

Additional remarks

The operating costs of an electric boiler are highly dependent on the costs of electricity, i.e. the market price of electricity and currently applicable taxes and fees.

A complete substitution of fossil fuels fired hot water or steam boilers, depends on fuel cost. The electric boiler can also be installed as a supplement and only operate a favorable electricity price and/or provide auxiliary services.

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6. Traditional steam and hot water boilers

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Brief technology description

This chapter focuses on different types of boilers in industry, with the main purpose of producing steam or hot water. At larger production sites, it may also include power production, also referred to as CHP plants. The share of CHP plants currently in operation in Danish industry is however low and decreasing, therefore CHP plants will not be included in this catalogue.

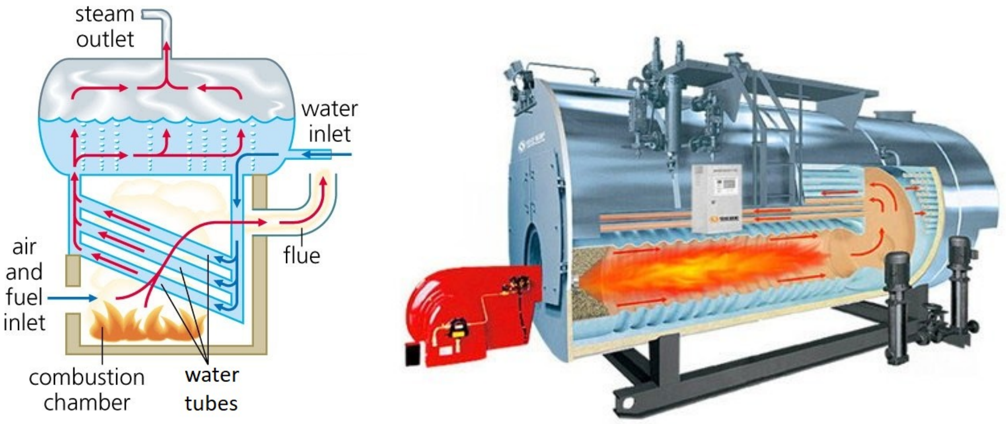
The different types of boilers can be categorized according to type of fuel used. This chapter includes the main types of fuel in Danish industry:

- Coal
- Gas (Natural gas and Biogas)
- Wood (Chips)
- Oil (Gasoil)

Common to all types of boilers is that they include a furnace or burner which generate combustion gases that then heat pressurized water and produce steam or hot water. This steam or hot water can be distributed across an industrial site for multi-purpose heating demands.

Figure 1 shows a drawing of two boiler designs. On the left, a water tube boiler is depicted, and on the right, a fire tube boiler (also called shell boiler) is depicted. Hot water and steam can be produced on both types. Wood and coal, if not pulverized, are most suited for water tube boilers. Oil and gas can be used in both types.

Figure 1: Schematic of a furnace and burner producing steam or hot water. (Left) is a water tube boiler and (Right) is fire tube boiler (shell boiler).



Further description of the technologies can be found in [2] and [3].

The boilers used for hot water and steam are almost identical in working principle [4]. Some of the auxiliary systems used for steam boilers, e.g. water treatment using reverse osmosis (RO) and water softening systems are not necessary for the hot water boiler. For fire tube boilers, this, in addition to a lower requirement on operating pressure, makes the investment cost of hot water boilers lower than steam boilers [8,9]. This price reduction is quantified in the Quantitative description (Excel sheet) for gas and oil boilers. However, data was not available to make the same quantification for coal and biomass boilers, though some reduction in price is still expected based on the characteristics described above.

Condensing the flue gas from gas- and biomass fired boilers can significantly increase the efficiency of the boiler by utilizing the latent heat of the water vapor in the flue gas [1,7]. As coal does not produce water, this cannot be done in this process. Some oils contain high levels of sulfur and the flue gasses from combustion of these oils will therefore be very corrosive to the heat exchanger. Flue gas condensation is therefore not used for these types of oils and is not considered for oils in general in this catalogue.

It is expected that hot water boilers have a slightly higher efficiency than steam boilers. This is caused by a typically lower water inlet temperature in the hot water boiler compared to the steam boiler. As the water temperature is lower, it is possible to cool the flue gas more in a hot water boiler than a steam boiler. A lower flue gas temperature equals higher efficiency.

Input

The inputs to the different boiler types are the same as listed earlier: coal, natural gas, biogas, wood and oil.

Output

The output for all boiler types is steam or hot water.

For production of hot water, the temperature range is typically 80-175 °C and pressure 2-13 bar.

For steam the pressure ranges from 2-100 bar, but most typical in the range 5-25 bar. Resulting in temperatures in the range of 125-300 °C.

Applications

The boilers can be used to produce steam or hot water. Instead of being used in a specific process, they are often placed as a central utility supplying many processes through a steam or hot water distribution network. In general, as seen on the temperature levels above, the hot water boilers can deliver heat to medium temperature processes and steam boilers can deliver heat to both high and medium temperature processes.

In terms of the end-uses, the steam boiler is used in all areas except the very high temperature processes like "Firing/sintering" and "Melting/casting". Hot water boilers have the same limitations, and in addition cannot be used for "Dewatering" and is not typically used for "Other processes > 150 °C".

Boilers vary in complexity depending on the necessary operating pressure. Industrial steam boilers are available at up to 100 bar operating pressure (311 °C saturation temperature) while hot water boilers are available at up to 175 °C. An additional increase in steam temperature will require substantial increases in the pressure in the boiler. Simultaneously, the latent heat decreases rapidly when approaching the critical pressure of water which lowers its benefits as a heat carrier.

The recommended regulation (ramping rate) of boilers can vary a lot from product to product. The regulation in warm operation is between 7%-60% per minute. This is for increasing the load. Reducing the load can be done instantaneously, however it is recommended that a short ramp down period is still used [10].

Since the steam boilers have a large volume of saturated water/steam, they can momentarily function as steam accumulators, covering demand peaks. The limit to this functionality is defined by the lowest acceptable steam pressure for the demand process. Additionally, one needs to consider the shrinking and swelling to control the water level in the boiler and consider the steam space load to make sure that the steam quality is not reduced [10][11].

If hot water boilers are to be installed on a site with an existing steam system an additional investment cost for new hot water pipe installations must be expected (in-direct investment cost). This is often more expensive than the boiler itself.

Typical capacities

The available capacity is in the range 1-50 MW. The typical or average unit size for steam boilers is between 1-10 MW (1.5 – 15 ton/h). Multiple units are sometimes used for redundancy or if demand loads are highly varying.

Typical annual operation hours and load pattern

The load pattern is mostly determined by the production pattern in the specific industrial site, as most systems do not include a buffer tank (the boiler itself acts as a buffer for a limited amount of time as described above). For continuous production, the boiler will only be out of operation during forced outage or maintenance.

Regulation ability

The minimum capacities are listed in the following for the different types of fuel.

	Coal	Natural gas and biogas	Wood chips	Oil
Minimum capacity	15 %	15 %	20 %[24]	15 %

- [24] [3], Wood Chips, HOP,6 MW feed

Advantages/disadvantages

The advantages/disadvantages for coal, natural gas and biogas and wood boilers are described in the Technology Catalogue for Energy Plants for Electricity and District heating generation [3].

The advantages/disadvantages for oil boilers are described in the Technology Catalogue for Heating installations [2].

Environment

The environmental aspects for coal, natural gas and biogas and wood boilers are described in the Technology Catalogue for Energy Plants for Electricity and District heating generation [3].

The environmental aspects for oil boilers are described in the Technology Catalogue for Heating installations [2].

Potential for Carbon capture

All of the fuels included result in CO_2 emissions, which enable the possibility of carbon capture. Additional information can be found in [6].

It is assumed that wood and biogas are carbon neutral and therefore have net zero CO_2 emissions, this does not mean CO_2 free combustion and therefore have a possibility for carbon capture.

Research and development perspectives

In the following, the main research and development perspectives will be briefly described. For additional information it is referred to [3].

Wood

A different version of the technology is to utilize updraft gasification and gas combustion of biomass. This makes the plant much simpler and possibly less expensive. It also makes the plant more flexible in terms of possible multifuel, and it reduces emissions [3],[5].

Coal and oil

Both coal and oil have very limited possibilities for improvement, as both technologies are well known and optimized.

Gas

The main research focus for gas fired boilers is the burner. The research is to make the burner compatible with other types of fuel, to increase flexibility.

When utilizing raw biogas, additional sulfur cleaning may be required to minimize corrosion.

Examples of market standard technology

Examples of market standards for coal, natural gas and biogas and wood boilers are described in the Technology Catalogue for Energy Plants for Electricity and District heating generation [3].

Examples of market standards for oil boilers are described in the Technology Catalogue for Heating installations [2].

Prediction of performance and costs

No major developments are expected towards 2050, as boiler technologies are well tested and have been used for several decades. Boilers are reaching the thermodynamic limits, and no noteworthy efficiencies are hence to be expected.

Additional prediction of performance and costs is based on similar technologies, described in other technology catalogues [2] and [3].

Direct and in-direct investment costs

The indirect investment cost represents additional piping installation needed if installing a hot water boiler where a steam boiler was previously installed.

Uncertainty

Uncertainties are based on similar technologies, described in other technology catalogues [2] and [3].

Additional remarks

Thorough description of each technology can be found in [2] and [3], only with slightly different purposes (output) but overall description and working principle are similar.

Coal is seldom used as fuel, and some coal boilers are either converted to natural gas in order to save on O&M or changed to wood to save taxes and to reduce emissions.

When using the Quantitative description in the separate Excel sheet, the overall efficiency can be found by adding improvements found in “Technology-specific data” to the “Total efficiency, net [%]”. As an example, for gas and oil boilers, if a flue gas condenser is added and a hot water boiler is chosen instead of a steam boiler, the total efficiency is:

$$\text{Total efficiency} = 94\% + 6\% + 1\% = 101\%$$

The percentages can be added since they are given in %-points in the data sheet. The efficiency can go above 100% for condensing boilers, since the standard efficiency calculation is based on the lower heating value (which does not include water vapor).

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7. Direct Firing

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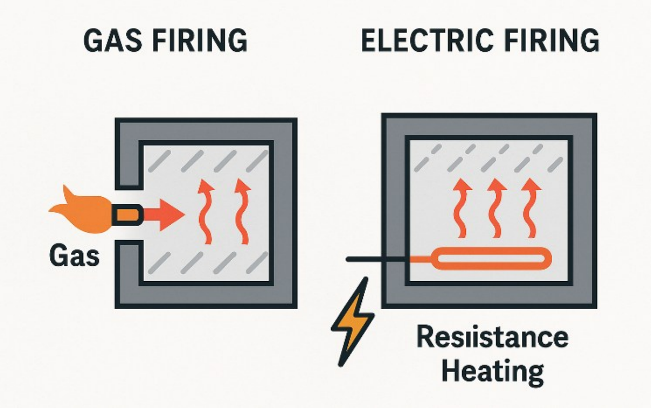
Brief technology description

Direct firing is a widely used thermal processing method in various industrial sectors, where heat is delivered directly to the material or process through combustion or electric means. In widely used gas-fired systems, fuel is combusted in proximity to or in direct contact with the target material. The heat released from combustion gases is directly transferred to the product through convection and radiation. Direct electric firing refers to the use of electrical energy to generate heat, where unlike combustion, these systems generate heat without emissions at the point of use.

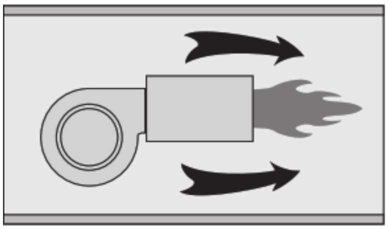
Figure 2: Direct gas firing vs. electric firing



Due to the variety in the application for both fossil fuel based and electric firing and thus the variety in the adoption of the equipment, this technology review is limited to the actual burner or heating element. Furthermore, the technology review is limited to processes where the heating element (be it electric or a burner) is in direct contact with the heated medium. While the heated medium can be air, water or other fluids, this review is limited to the consideration of air, which will always be the case for oxidizing burners but not always the case for electricity.

Today the simplest and widest used burners are for gaseous or liquid fuels. These can be used for almost all purposes and direct firing technology is spanning wide in terms of areas of usage.

Figure 2: A burner in a duct [14]



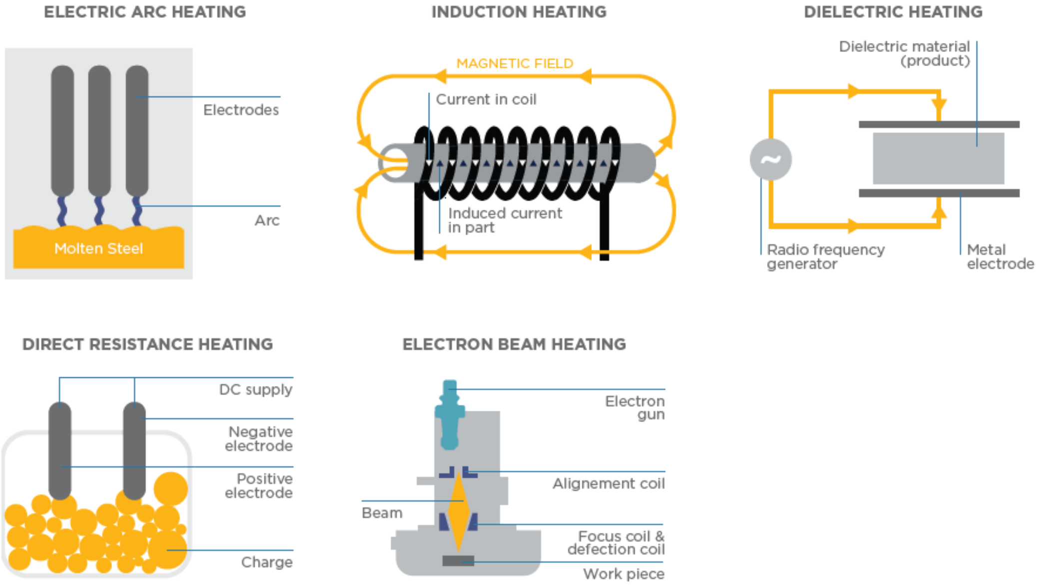
A variety of fuels can be used depending on the process, and burners can be flexible to burn multiple different fuels. An example is shown in Figure 3.

Figure 3: Burners for fossil-based fuels

Left: Boiler burner from Ebico (JETFLEX). “It is suitable for various fuels, including monoblock type burner, split type burner, and non-standard customized burne” [15].

Right: Multifuel burner from FCT International (Turbu-Jet AF) “Primary fuel: coal, petcoke or natural gas. Multi-fuel capability: can be used in combination with all fuels particularly alternate fuels: Liquids: solvents, oils, etc. Solids: RDF, sewage sludge, rice husks, etc” [16]

Figure 4: Representative heating processes using electricity [1]



Electrification of direct firing processes is gaining momentum at present due to the push for industrial heat decarbonization, energy efficiency, and precise thermal control.

Electric-based process heat is typically categorized into direct heating and indirect heating and consists of different methods as represented in Figure 4. The focus of this study is limited to direct electric firing or direct resistance heating.

Resistance heating is one of the most common approaches to electrifying industrial heating processes. While resistance heating itself can be classified into two categories as direct and indirect resistance heating, this study only focuses on direct resistance heating. It involves sending an electric current through a resistor to produce heat of the desired temperature and offers precise temperature control, rapid heating and low maintenance [3].

Figure 5: Example equipment based on resistance heating [2]

Electric oven

Electric furnace

Electric air heater

This technology is capable of directly replacing most natural gas fired industrial heating equipment without major modifications in some industries and applications [2]. As shown in Figure 5, in ovens, resistance elements provide radiant and convective heat for drying, curing etc. processes; in furnaces, they deliver uniform, controllable high temperatures for metal, glass, and ceramic processing; and in air heaters, they heat air streams for drying or HVAC systems in the same way gas burners do. Given the mode of heat delivery as radiation and convection, which is similar to that of combustion systems, and because electric heaters are compact, efficient, and require no exhaust gas handling, industries such as food, chemicals, textiles, and metals can switch to electric heating with minimal process changes while gaining cleaner operation, higher efficiency, and finer temperature control. The following table summarizes some of the technical characteristics of direct electric firing technologies.

Table 13: Technical characteristics direct electric firing

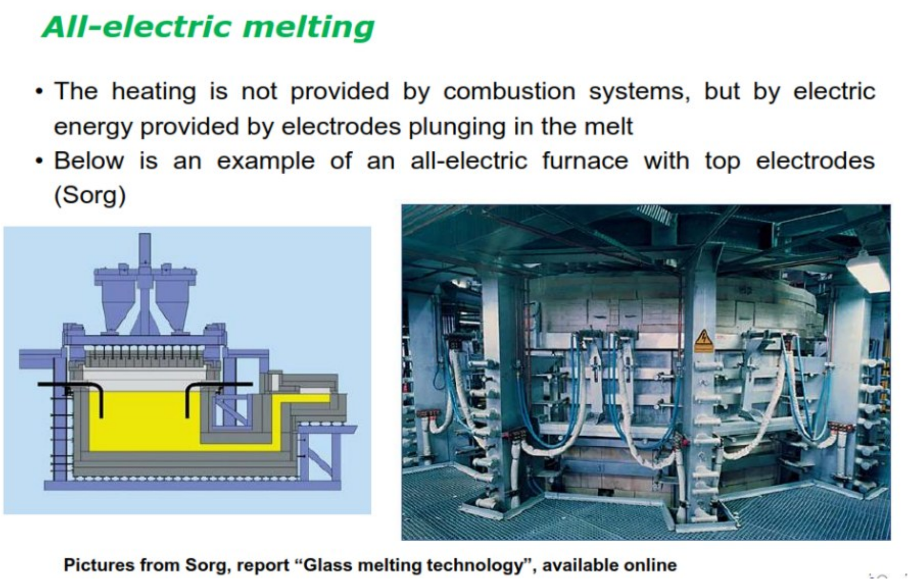
Topic	Description
Temperature range	Currently up to 1,800 ºC [1, 2] Meets the temperature demands of most industrial heating processes, except for the highest-temperature applications such as cement kilns, steelmaking etc.
Heat flux	High Dependent on the configuration of the resistive element and the use of convective drivers such as fans [2]
Heated materials	A wide range of materials are applicable. • Heating elements are in direct contact with the heated medium such as air, water or other fluids • Avoids potential contamination of heated materials with fuel or combustion particulates
Emissions	Emissions are typically scope 2 emissions and dependent on the grid emission factor at different geographical locations.

Technical maturity	High • Established in industry (small capacities) • Use in applications such as very high temperatures and high-capacity systems require further development [2, 4]

In contrast to like-for-like burner swaps or electric element retrofits, some electrification pathways involve substantial process redesign.

For some high-temperature processes (e.g., glass melting), electrification may require replacing major process components and installing electrodes directly in the melt—effectively a new furnace, see Figure 6. Note that this report's investment figures cover only the burner/heating element; replacement or redesign of the surrounding process equipment is out of scope and can dominate total CAPEX in such cases.

Figure 6: Electric glass furnace - slide from [12]



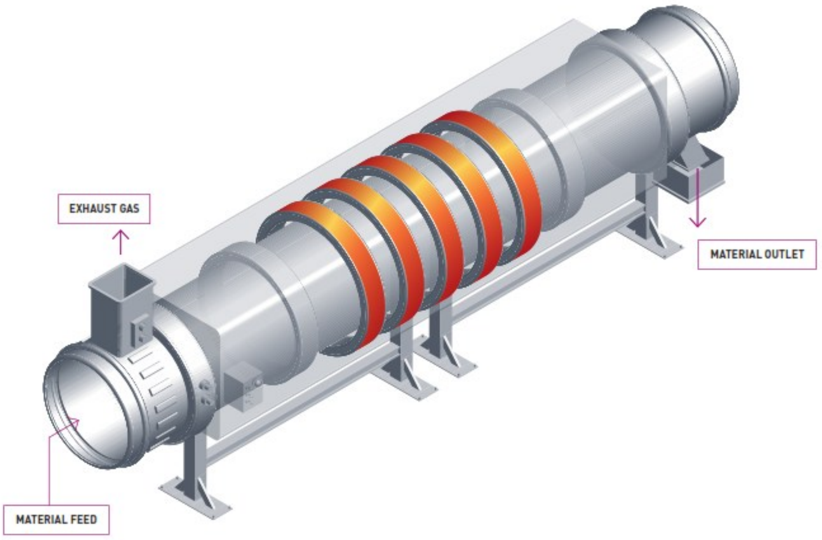
All-electric melting

- The heating is not provided by combustion systems, but by electric energy provided by electrodes plunging in the melt
- Below is an example of an all-electric furnace with top electrodes (Sorg)

Pictures from Sorg, report "Glass melting technology", available online

Another example is rotary kilns which, depending on process, can be converted to electricity. For direct-fired kilns, this often entails shifting to electrically heated indirect configurations or installing electric hot-gas generators, which amounts to substantial process redesign and, in many cases, a new or heavily modified kiln rather than a simple burner change (see Figure 7). As with glass melting, this report's investment figures cover only the burner/heating element; replacement or redesign of the kiln and ancillary process equipment is out of scope and can dominate total CAPEX.

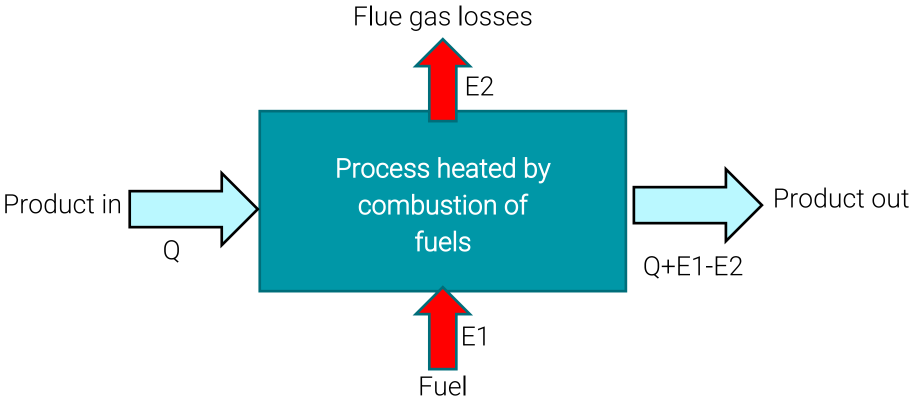
Figure 7: Electrically heated Kiln [13]



Depending on the process the efficiency will vary, however since it is direct firing, all the available electrical energy is converted to heat and is transferred to the air stream. For some processes using electricity could be advantageous as a fresh supply of oxygen to burn the fuel in conventional combustion systems is not necessary and the flue gas losses can then be eliminated. This is not true for e.g. drying processes as the moisture has to be removed through the air stream.

Since the degree of heat recovery is a function of the process and not related to direct firing itself, this is not accounted for in the analysis. The efficiency of all the technologies at the point of use is set to 100%, but system efficiency including loses in the process equipment is between 0.5-0.95.

Figure 8: Energy balance of a direct firing process



Input

The most prevalent fuels for direct firing in different industries is (list is not ranked):

- Natural Gas
- Biogas
- LPG
- Fuel and gas oil
- Coal
- Petcoke

- Biomass
- Electricity
- Waste

Solid fuels are used in heavy process industry such as cement or mineral wool manufacturing. Natural gas is utilized in many different applications where a cleaner flue gas is necessary. Electricity is used directly in spray towers in the dairy industry as well as in the metal industry. In the metal industry, the electricity is typically supplied with an induction furnace which is different from the technology reviewed here.

Output

Typically, the output is hot process air/flue gas, depending on the process this temperature will vary considerably. E.g. drying timber will be carried out at a low temperature (<100 °C) whilst cement industry will take place at >1000 °C and a glass furnace at upwards of 1500 °C.

Applications

Direct firing with air as the heated medium is widely applied in industry, with the specific fuel type determining its suitability for different processes. Fossil fuel direct firing, particularly with natural gas, is currently dominant in both medium-temperature applications (400–800 °C) such as drying of minerals, biomass, textiles, and chemicals, as well as in high-temperature processes >800 °C, and up to 1,600 °C) including cement and lime kilns, glass furnaces, ceramics firing, and metal reheating. In these cases, the direct introduction of hot combustion gases into the process provides very high energy transfer efficiency, although exposure to NO_x, SO_x, particulates, and moisture means it is only viable where product purity is not critical. Multifuel burners using coal or biomass are also used in large-scale, high-temperature direct firing applications, but their pollutant emissions and system complexity restrict their use in sensitive sectors such as food and pharmaceuticals.

Electric direct firing with air as the heating medium is already applied in medium-temperature processes between 400–800 °C where clean, precisely controlled heated air is essential, for example in food processing, pharmaceuticals, specialty chemicals, and drying or curing of coatings and composites. Here, the “flue gas” is simply heated air, free of combustion products, making electricity the cleanest option. However, the extension of electric direct firing into very high-temperature processes >1,000 °C remains limited by material constraints on heating elements and system scalability. Research into advanced alloys, ceramics, and refractory designs is therefore critical to enable electric direct firing to reach the extreme air temperatures required for sectors such as cement, glass, and metals. If these developments are successful, electric direct firing could provide a pathway to decarbonize some of the most energy-intensive industries while maintaining process quality and efficiency.

Energy services

Direct firing, whether powered by gas or electricity, provides energy services by transferring heat directly to the process stream. In direct gas firing, combustion gases and the hot air stream flow into the process, delivering high-efficiency heat transfer but limiting applications to robust products such as aggregates, minerals, or biomass that can tolerate flue gas exposure. In direct electric firing, resistance elements heat the process air stream directly, supplying clean, uniform heated air without combustion by-products. This makes it attractive for medium-temperature applications like drying, curing, and baking, and high-temperature processes such as direct hot air injection into kilns or high-temperature dryers where product exposure to electric heating elements is acceptable.

Indirect firing introduces a separation barrier between the heat source and the process. In indirect gas firing, heat is transferred through tubes or heat exchangers with some efficiency loss compared to direct firing. In indirect electric firing, resistance elements heat chamber walls, radiant tubes, or heat exchangers, ensuring fully clean, controlled hot air or atmospheres. This enables medium- and high-temperature services such as food and chemical drying, metal heat treatment, ceramics, and glass processing where purity, atmosphere control, or product integrity are essential.

Sector and end-use relevance

Depending on the type of fuel, all the sectors for direct firing are relevant at both high and medium temperatures.

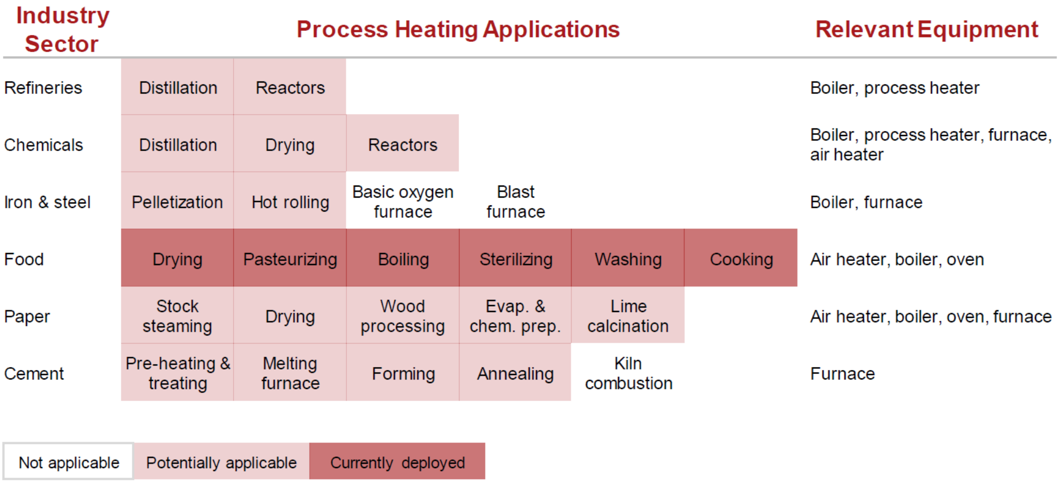
Natural Gas can be used for virtually any process at any temperature, from medium-temperature drying and curing to high-temperature kilns, furnaces, and calciners. The only notable exception is certain plastic molding equipment, which is generally fully electric to allow precise temperature control and prevent contamination or uneven heating.

Multifuel Burner: Solid fuels such as coal or biomass, are generally suitable for high-temperature robust processes but are limited in sensitive applications. Solid fuels inherently produce pollutants such as NO_x, SO_x, particulate matter, and sometimes mercury, making them unsuitable for processes where the heating media contacts the product directly, such as in food and beverage production. Additionally, the complexity of solid fuel feed and handling systems, along with operational constraints, makes these burners impractical for smaller-scale operations; most commercial solid fuel burners are rated above 7–10 MW.

Electricity provides the cleanest form of direct heating. The “flue gas” or heating media in electric direct firing is simply heated air, free of combustion by-products, which enables its use across medium- and high-temperature processes without risk of contamination. This makes electric direct firing particularly attractive for sensitive applications, including pharmaceuticals, food processing, and fine chemicals, while also offering precise temperature control and rapid response.

Figure 9 illustrates several process heating applications in various industrial sectors, where fossil fuel-based technologies are currently employed. The technological transition is currently taking place from fossil-based firing to electric firing. While technology replacement in low-medium temperature industries like the food industry can be straightforward with direct electric firing, high-temperature heavy industries may need major component upgrades and electricity infrastructure upgrades to accommodate the increased electricity demand.

Figure 9: Direct electric firing end-use applications [1]



Industry Sector	Process Heating Applications						Relevant Equipment
Refineries	Distillation	Reactors					Boiler, process heater
Chemicals	Distillation	Drying	Reactors				Boiler, process heater, furnace, air heater
Iron & steel	Pelletization	Hot rolling	Basic oxygen furnace	Blast furnace			Boiler, furnace
Food	Drying	Pasteurizing	Boiling	Sterilizing	Washing	Cooking	Air heater, boiler, oven
Paper	Stock steaming	Drying	Wood processing	Evap. & chem. prep.	Lime calcination		Air heater, boiler, oven, furnace
Cement	Pre-heating & treating	Melting furnace	Forming	Annealing	Kiln combustion		Furnace

Not applicable	Potentially applicable	Currently deployed

Typical capacities

Typical capacities vary depending on the chosen fuel:

- **Natural Gas:** Can be bought from very small to very large capacities. From just a couple of kW to 61 MW for the Eclipse Vortometric 36V [5]. Multiple burners can be combined with no upper limit. For this study the size range of 1-10 MW.
- **Electricity:** The heaters are consisting of heating elements which can be combined to arbitrary sizes. The size from 1-10 MW has been chosen again to enable a direct comparison.
- **Solid Fuels:** Due to complexity of feeding and milling systems these are generally larger in capacities. Looking into the two manufacturers, FCT International and FLSmidth their capacities span from 7-250 MW. For this study, a 10 MW unit has been investigated.

Typical annual operation hours and load pattern

Operation hours is entirely dependent on the process. For the large industrial systems, operation hours will be high (>8000) whereas smaller systems will have varied operations hours.

Regulation ability

The burners are all very flexible in terms of regulation, both the natural gas burner and the multifuel burners can go down to around 10% of maximum load [5] [6].

For the electric heaters the surface temperature is the critical parameter. This means that at a large flow of air at a low temperature there is no concern going down in load. However, low air flow at a high temperature can cause some problems. Even with this reservation a minimum load corresponding to 15% of maximum can be achieved [3]. At high air flows it will be possible to go lower.

Advantages/ disadvantages

The advantages of direct firing in general are:

- No conversion or distribution losses.
- Very high temperatures are possible for most fuels.
- Low capital expenditures in comparison with indirect heating.
- Easy and very flexible regulation capabilities.

The disadvantages of direct firing in general are:

- Flue gas in direct contact with the product, limits the potential to processes that are not “sensitive” in that manner.

Environment

Emissions will vary depending on the fuel

- **Natural Gas:** The emissions from a gas boiler in [6] should be identical.
- **Electricity:** Will depend on the means of electricity production or the grid emission factor.
- **Solid Fuels:** Will depend on the fuel mix.

Potential for Carbon Capture (CC)

All the fuels included result in scope 1 CO_2 emissions, which enable the possibility of carbon capture (except for electricity). Additional information can be found in [11].

It is assumed that wood and biogas are carbon neutral and therefore have net zero CO_2 emissions, but this does not mean a CO_2 free combustion. Therefore, there is a possibility for carbon capture and in that case a possibility of negative emissions.

Research and development perspectives

Direct firing is a well-established technology widely used in industrial processes for heating air or gases across medium- and high-temperature applications. However, for electric direct firing, there is still a substantial need for research and development to extend its applicability to very high-temperature processes close to 2,000 °C [4]. Current limitations are primarily related to material constraints in heating elements, insulation, and structural components, which must withstand extreme temperatures without degradation, loss of efficiency, or safety risks. Advances in high-temperature alloys, ceramics, and refractory materials could significantly expand the operating range of electric direct firing systems, making them suitable for applications traditionally dominated by fossil fuel combustion [4]. However, much of the innovation required also depends on modifications of the process equipment itself rather than the direct firing equipment. Larger electric direct firing is also being developed instead of using multiple smaller capacity units in parallel.

In the cement industry, the CemZero project is a notable example, aiming to develop a fully electric cement manufacturing process by 2030. [17]. This initiative seeks to replace fossil fuel combustion in cement kilns while maintaining high-temperature process stability, product quality, and energy efficiency, potentially enabling a near-zero-emission pathway for one of the most energy-intensive industries.

Beyond cement, several other sectors could benefit from high-temperature electric direct firing through R&D:

- **Metals and alloys processing:** Electric direct firing could support furnaces for metal reheating, heat treatment, or sintering of advanced alloys and composites, offering clean, controllable high-temperature air streams.

- **Ceramics and glass manufacturing:** Research could enable fully electric kilns capable of reaching 1,200–1,600 °C, allowing precise temperature profiles for firing ceramics or melting glass without combustion contamination.

- **Chemical and catalyst production:** Controlled, high-temperature electric air streams could improve lab- and pilot-scale chemical reactions, sintering of catalysts, or thermal processing of sensitive powders.

- **Energy-intensive materials:** Industries such as refractory materials, cement substitutes, or advanced composites could explore high-temperature electric direct firing for sustainable manufacturing.

Overall, R&D in high-temperature electric direct firing holds the potential to decarbonize energy-intensive sectors, provide cleaner and more controllable process heat, and expand the adoption of electric heating in applications that have traditionally relied on fossil fuels.

Examples of market standard technology

1) Natural Gas: Danish Crown A/S, singeing furnace.
   Danish Crown A/S, one of the largest meat processing companies in Europe, utilizes natural gas-fired singeing furnaces in its slaughtering and meat preparation facilities. Natural gas offers clean, controllable combustion and consistent high temperatures, making it the market standard for hygienic surface treatment in the food industry.

2) Solid Fuels: Aalborg Portland A/S, multiple rotary kilns with mixed fuel firing.
   Aalborg Portland A/S, Denmark's leading cement producer, operates large rotary kilns that use mixed-fuel firing systems, combining solid fossil fuels (e.g., coal, petcoke) with alternative fuels such

as biomass, waste-derived fuels, and other secondary materials.
This is the industry-standard approach for cement clinker production, which requires sustained temperatures above 1,400°C for the calcination and clinker formation processes, providing reliable high-temperature performance and flexibility in fuel use for energy and cost optimization.

3) Electricity: Arla Foods amba HOCO and AKAFA, spray drying.
Arla Foods amba operates large-scale dairy processing facilities, including the HOCO and AKAFA plants, which use electricity-driven systems extensively in spray drying operations for milk and whey powder production. Electrically driven systems provide precise temperature management and enable integration with renewable power sources, supporting efficient and sustainable food production.

Prediction of performance and costs

The direct firing technology costs will depend on the fuel and the application.

Direct and in-direct investment costs

The direct investment costs of the different direct firing technologies have been established based on unit prices given by three manufacturers [7] [8] [9]. For clarity, all investment figures in this chapter cover only the burner or electric heating element; process-equipment replacements (e.g., new electrode furnaces for glass melting) are excluded and can dominate total CAPEX.

Auxiliary costs have been estimated by Viegand Maagøe as a general average. Auxiliary costs could cover the fuel supply system, such as gas piping for a gas burner or electric installations and grid connection for an electric heater. The prices are only corrected for inflation compared to the previous version of the technology catalogue as the sources of the prices believed they were still representable.

Table 14: Nominal investment costs.

Fuel	Natural Gas	Solid Fuels	Electricity
Capacity Range	1-10 MW	10 MW	1-10 MW
Specific Cost	0.015 M€/MW	0.220 M€/MW	0.060 M€/MW
Equipment	67%	67%	67%
Installation	33%	33%	33%

The indirect costs related to implementing direct firing or a direct firing fuel change will vary a lot depending on which process is considered. Changing a glass furnace from one fuel to another would require a large reconstruction or more commonly, a new oven. Conversely changing a burner and fuel system in a spray dryer has vastly smaller indirect costs. It does not make sense to quantify the indirect costs across the entire Danish industry, and this is therefore left out of the analysis.

Related benefits and savings

Changing from a solid fuel system to a gas fired system or from a gas fired system to an electrically heated system could improve product quality as pollutants are minimized. This will depend on the product and the type of fuel change.

A fuel change in a multifuel burner from solid to gas could increase capacity as the heating value (energy density) differs.

Cost of grid expansion

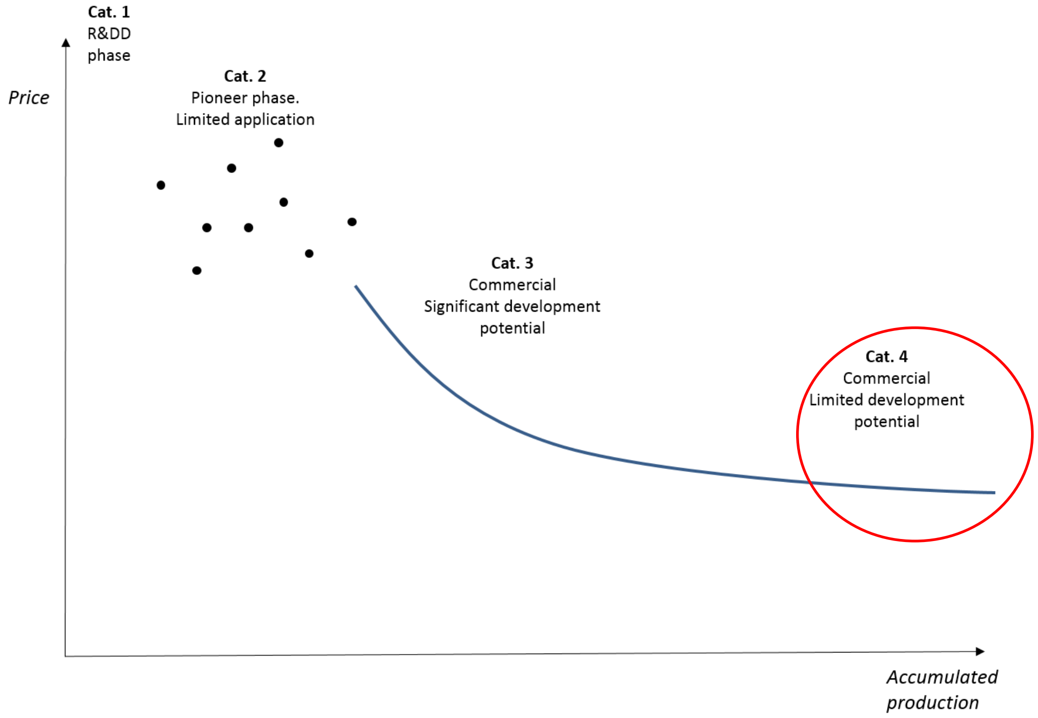
The costs of grid expansion caused by adding a new large consumer to the grid are not included in the presented data.

Learning curves and technological maturity

Direct firing is situated in Category 4. *Commercial technologies, with large deployment*. The price and performance of the technology today is well known, and normally only incremental improvements would be expected. Therefore, the future price and performance may also be projected with a relatively high level of certainty. Except for high-temperature and high-capacities where developments are still underway.

No change in the costs is expected as the technology is considered mature.

Figure 11: Technological development phases. Correlation between accumulated production volume (MW) and price



Uncertainty

As stated, the technology is considered mature and the uncertainty related to cost projections is considered smaller than those of pioneering technologies.

Due to the variety of application potential for the technology the data comes with a degree of uncertainty. General averages have to be made to account for variations. This holds true for both the prices but also the efficiency of the technology.

For high-temperature and high-capacities the technology is more uncertain and undeveloped while R&D activities are currently taking place

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