Technology Data

Industrial process heat and CC

Energistyrelsen
Danish Energy Agency

ENERGINET

Technology descriptions and projections for long-term energy system planning

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
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* and *Energinet*, the Danish transmission system operator, publish 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 results 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 og Energinet 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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Introduction

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.

Chapters describing carbon capture was added to the catalogue in October 2020. Since this category of technologies delivers different services, a supplement guideline has been added.

Introduction to industrial process heating in Denmark

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

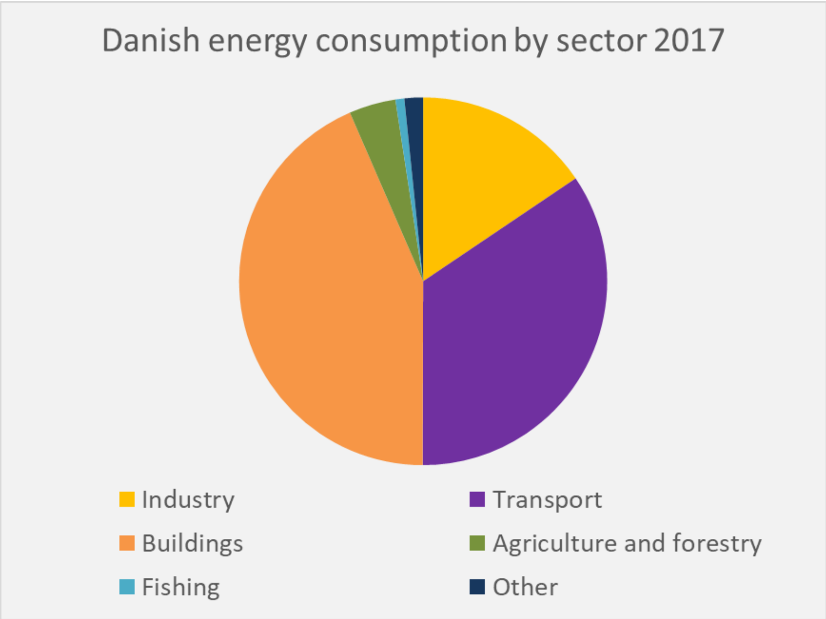

Figure 1: Final energy consumption in Denmark by sector (2017)[1]

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)

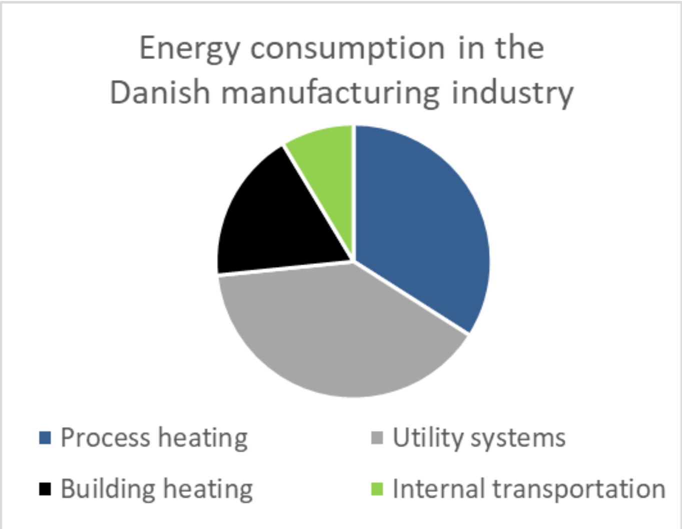

Figure 2: Energy consumption in manufacturing industry by overall end use (2018)[2]

[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.

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

[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 seperate Excelfile with datasheets

[5] It should be noted that while the clinker production itself requests temperature above 1000^{o}C, 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 100^{o}C.

- In the food and beverage industry, most processes take place at temperature below 100 ^{o}C simply because products are damaged when boiling

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

- Etc.

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 < ~150^{o}C)	Share of heating demand at high temperature (%) (t > ~150^{o}C)
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 < 150^{o}C
- Other processes > 150C

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.

[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

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 (160°C) is commonly used even though a majority of the process heating is to be delivered below 100°C.

In case traditional heat pumps are to be applied for process heating, investments to design and install by example a 80°C 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

Heat driven heat pumps

Absorption type heat pumps can be driven by applying gas or by applying high-temperature waste heat from production processes or CHP-plants. Absorption heat pumps next to cooling water/chilled water also delivers hot water at by example 60°C for various purposes in the facility.

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)

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

- Integrated with drying processes using superheated steam

Gasification

Application of gasification is to be considered relevant in many high temperature processes where fuel or high temperature heat is to be used directly in the process, by example:

- Gasification processes that produce gas directly for combustion inside the production processes

- Gasification processes that produce hot exhaust gas (800°C) that can be led directly to the process – eventually combined with combustion of other fuels e.g. natural gas.

"Hot disc"-technology

For large rotary furnaces in the cement and clinker industry typically applying coal/pet-coke, a "hot disc" technology has been developed enabling use of various biomass and waste sources for production of hot, combusted exhaust gas that can partly substitute current energy consumption

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, “hot disc”-technology enabling use of biomass resources in rotary kilns (cement etc.), but can’t be utilized for supply of process heating for other end-uses. Similarly, 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.

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

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

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.
By 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 <150^{o}C,
  8. Other processes >150^{o}C.

  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 ^{o}C 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 < ~ 150^{o}C	> ~ 150^{o}C

- ✓ ***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.

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

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.

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.

(i) Applications

1) **As described above in section Introduction to industrial process heating in Denmark heating of industrial processes is a complex area. For some demands the heating is supplied via traditional steam or hot water boilers while for other processes the heat is supplied via direct combustion of fuels inside the production process. Also, the temperature levels differ significant. Furthermore, the technologies are able to provide different end-uses. The technologies ability to provide different applications is described below in section Energy services is about energy services relevance,**
2) **Sector relevance and**

End- use relevance. The application is indicated in tables.

3) **Energy services**

It shall be stated which energy services the technology can deliver that is whether the technology can deliver direct or indirect process heat and at which temperature levels. It is for each technology indicated in a table with a format as the one in Table 6

Table 6: Energy services. The definitions of the temperature level and direct and indirect process heat are found in section Definitions. A technology can in general only deliver one *type of industrial process heating* but at more temperature levels.

Table 6: Energy services

Energy services	Indirect	Direct
High temperature	*Yes / No*	*Yes / No*
Medium temperature	*Yes / No*	*Yes / No*

4)
5) **Sector relevance**

It is stated if the technology is able to supply industrial process heating to fulfill the different sectors demand for a specific energy service. It is shown in a table with a format as the table shown. Definitions of main sectors are found in section Definitions.

Table 7: Sector relevance

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
Di / in	***Medium/ High***	**yes/no**	**yes/no**	**yes/no**	**yes/no**	**yes/no**
Di / in	***Medium/ High***	**yes/no**	**yes/no**	**yes/no**	**yes/no**	**yes/no**

6)

7) End- use relevance

It is stated which end-uses the technology can supply. It is shown in a table with a format as the table shown. Definitions of end-uses are found in section Definitions. The end-uses can be characterized by e.g. an energy services but not all technologies are able to deliver the end-use although they can deliver the energy service that characterize the end-uses. That is why it should be indicated if the technology is able to deliver the specific end-use.

Table 8: End-use relevance

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firing / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Technology n	Yes / No	Yes / No	Yes / No	Yes / No	Yes / No	Yes / No	Yes / No	Yes / No

8)

9) Application potential

To provide an overview of the application potential of the technology for the different sectors, the characterization of the three “application relevance” tables are combined into one sheet which provides an overview of the application potential in percentage of the total demand for the sector. The sheet is published in the quanitative part of the technology chapter and in the data sheet.

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.

Potential for Carbon Capture (CC)
For all technologies using fuels the potential for combining the technology with carbon capture technologies now or in the future is to be described including which CC technologies that are relevant.

There are processes (e.g. for cement production) where CO_2 is produced as a part of the production process but these processes are not categorized as industrial heating processes and therefore this catalogue does not touch on the ability to reduce CO_2 emission from these processes.

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:

(ii) Data for 2020

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 2020 (FID) and used for the 2020 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.

(iii) 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.

(iv) 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.

(v) 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]

(vi) Assumptions for the period 2020 to 2050

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).

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

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 New Policies Scenario provides the framework for the Danish Energy Agency’s projection of international fuel prices and CO_2-prices and is also used in the preparation of this catalogue. Thus, the projections of the demand for technologies are defined in accordance with the thinking in the New Policies Scenario, described as follows:

“New Policies Scenario: A scenario in the World Energy Outlook that takes account of broad policy commitments and plans that have been announced by countries, including national pledges to reduce greenhouse gas emissions and plans to phase out fossil energy subsidies, even if the measures to implement these commitments have yet to be identified or announced. This broadly serves as the IEA baseline scenario.” (ref. 7).

Alternative projections may be presented as well relying for example on the IEA’s 450 Scenario (strong climate policies) or the IEA’s Current Policies Scenario (weaker climate policies).

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)

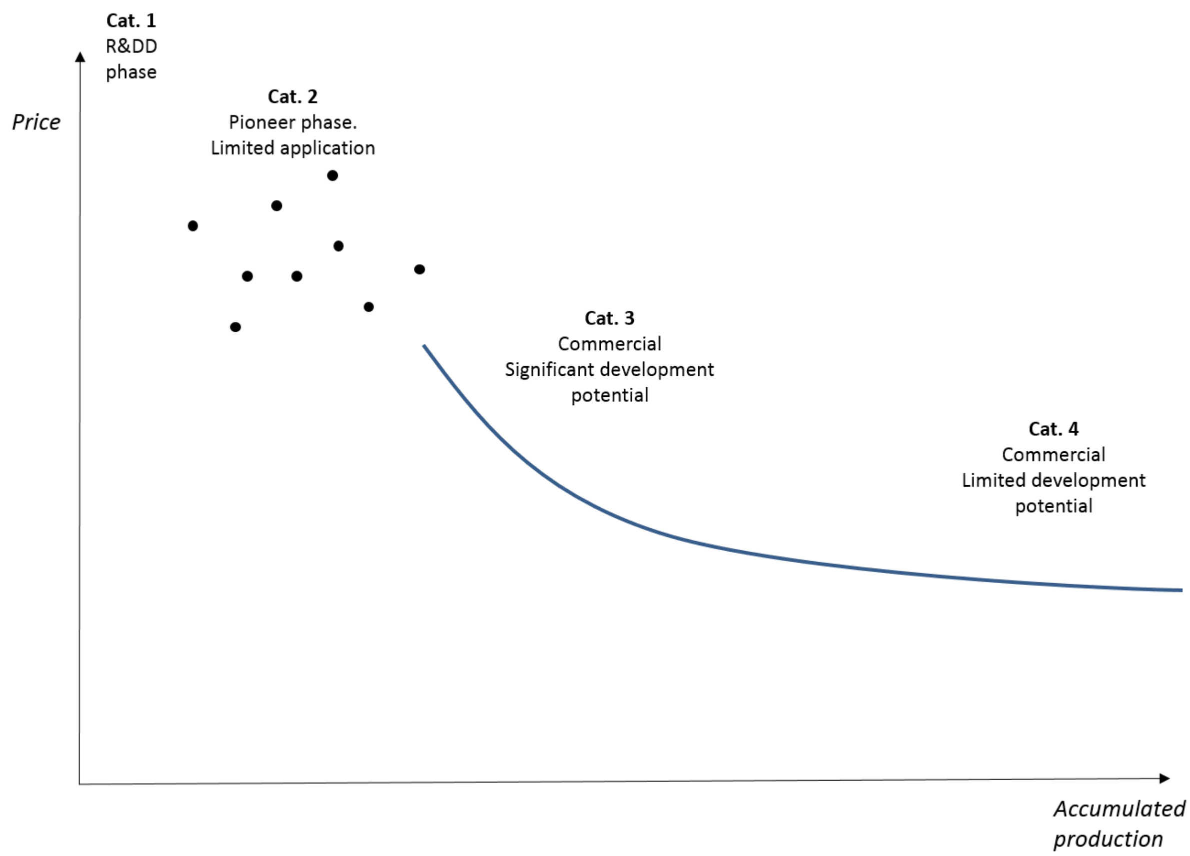

Figure 3: Technological development phases. Correlation between accumulated production volume (MW) and price.

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, 2030, 2040 and 2050). 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**	**2030**	**2040**	**2050**	**Uncertainty (2030)**		**Uncertainty (2050)**		**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)										

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.

Application potential

It is stated how large a share of the different sectors demand for a specific energy services the technology is able to supply. The share is expressed in two tables, the current application potential and the full application potential. The current application potential table represent the share that the technology can supply without additional investment cost. The full application potential is the maximum potential a technology can cover. To increase the potential from current to full, an additional investment is required.

For the heat pumps the additional investment could be additional piping cost to increase the share the technology is able to supply. These additional costs are included in section Assumptions for the period 2020 to 2050, in the technology chapters.
The current and full application potential are shown in tables with a format as the table shown. Definitions of main sectors are found in section Definitions.
The "application potential" of the technology for the different sectors is stated in percent of the total demand for the specific energy service for the sector. The application potential is included in a table besides the data sheet. An example of the structure of the table for the application

The end-use processes are classified according to typical energy services, however the 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.

Table 9: Application potential in percent of the total demand for the energy service for the sector, the table is in the separate Excel file for Data sheet and Application matrix

Application potential			"x,n" indicate which end-use, n ref. to note"	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	
Technology	Energy services	End-use		Direct %	Indirect %	Direct %	Indirect %	Direct %	Indirect %	Direct %	Indirect %	Direct %	Indirect %
Technology n	High temperature	6. Firing /Sintering											
		7. Melting /Casting											
		9. Other processes >150C											
	Medium temperature	2. Heating/Boiling											
		3. Drying											
		4. Dewatering											
		5. Distillation											
		8.Other processes <150ºC,											
	Room heat	12. spatial 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 ^{o}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.

Carbon Capture (CC)

For all technologies using fuels the potential for combining the technology with carbon capture technologies now or in the future is described as percentage reduction in CO_2 emission, in the notes it is stated which CC technology is assumed when predicting the reduction. The cost of the carbon capture technology will be described in the technology chapters about CC technologies in the *Technology Catalogue for energy carrier generation and conversion.*

Financial data

Financial data are all in Euro (€), fixed prices, at the 2019-level and exclude value added taxes (VAT) and other taxes.

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 2019 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.

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.

(vii) 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

(viii) 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€/$MW_{\text{heat capacity}}$.

(ix) 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.

(x) Business cycles

The cost of energy equipment shows fluctuations that can be related to business cycles. When projecting the costs of technologies, it is attempted to compensate, as far as possible, for the effect of any business cycles that may influence the current prices.

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

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, 2015.
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

Supplement guideline for Carbon Capture technologies

This supplement guideline for carbon capture technologies serve together with the guidelines for technology data for industrial process heat technologies 2020 as an introduction to the presentations of the different technologies in the catalogue, and as instructions for the authors of the technology chapters.

The main purpose of the technology catalogues is to provide generalized data for analysis of energy systems, including economic scenario models and high-level energy planning.

The general guideline is in the main catalogue for technology data for industrial process heat technologies 2020 (Energinet and the Danish Energy Agency). The chapter below is a supplement guideline for the extra sections, special for carbon capture plants/technologies.

Introduction

This catalogue covers data regarding plants/technologies designed for carbon capture related to power and heat plants and industrial production. The focus in this first edition is on post-combustion, pre-combustion and oxy-fuel combustion. Other CC technologies and processes are relevant for capturing CO_2 and/or reducing the CO_2 content in the atmosphere and could be included in this catalogue.

It is intended as specific chapters of the *Technology data for industrial process heat technologies*, and thus follows the same structure and data format. The supplement guideline only features the sections and assumptions that differs from the main catalogue. Meaning that for all the other sections the explanations are found in the main catalogue.

First services and boundaries are defined, then guidelines for the sections that differs from the sections in the main guidelines are given. These sections are both general assumptions and qualitative parts and quantitative parts of the catalogue. Templates for the data sheets are included in annexes.

Definition of the service

Carbon capture technologies (CC) are technologies that e.g. capture CO_2 from processes related to combustion or upgrading of fossil fuels and bio-fuels or from chemical processes in the industry (e.g. cement production) or that absorbs CO_2 directly from the air. Even as of today, CC is commercial and used around the world, although it has yet to become economically feasible in the power and heat sector and in the industry. The most common utilisation of the CC technologies today consists of a capture part, where CO_2, methane and hydrogen are separated from pure natural gas.[1] In Denmark today, the most common use of CC is for upgrading of biogas. Upgrading of biogas is described in chapter 82 of the *Technology Data for renewable fuels.*

This catalogue only includes descriptions of technologies that provides the carbon capture (CC) service. Transportation and storage technologies are not included.

The capture part of the CCS technologies can however be carried out using multiple types of systems. See examples of types and further descriptions in Table 10.

CC technology	Plant description	Advantages	Limitations
Post-Combustion (Tsiropoulos I, 2017)	CO_2 is removed from the flue gas through absorption by selective solvents, the most promising as of today is mono ethanolamine (Used at the Boundary dam project)	Can be applied on existing technologies with a flue gas	Energy intensive and costly post separation methodology, requires direct connection to stationary plant
Pre-Combustion (Tsiropoulos I, 2017)	The fuel is pre-treated and converted into a mix of CO_2 and hydrogen, from which CO_2 is separated. The hydrogen is then burned to produce power.	As the technology is not necessarily linked to a power plant, the hydrogen produced can be utilised in multiple sectors e.g. transport	High investment costs, energy intensive in both electricity usage and fuel conversion loss.
Oxy-fuel combustion (Tsiropoulos I, 2017)	The fuel is burned with oxygen instead of air, producing a flue stream of CO_2 and water vapour without nitrogen. From this stream water is condensed and a stream of CO_2 is obtained. The oxygen required for the combustion is extracted in situ from air.	The flue gas would primarily consist of CO_2 and H_2O, which are easier and cheaper to separate.	Energy intensive and costly oxygen production, requires direct connection to stationary plant
Chemical Looping Combustion (Schnellmann, 2018)	A new combustion technology with inherent separation of CO_2, by transferring oxygen from the combustion air to the fuel using metal oxides. The flue gas from the combustion chamber only consists of CO_2 and H_2O.	Potentially low costs and high efficiencies in both electricity and carbon capture, as the separation process happen internal during combustion	Low on the development stage and has, for now, only been proven with gas as an input fuel. Requires direct connection to stationary plant
Direct Air to Capture (Keith, Holmes, Angelo, & Heidel, 2018)	CO_2 is captured directly from the air through absorption by selective solvents and large air conductors. Pure CO_2 is afterwards released for future processing The most used solvent today is $CaCO_3$.	Does not require a CO_2 heavy flue gas and can therefore be located close to storage or electro fuel production.	Very energy intensive

Table 10: Description of carbon capture technologies strength and weakness [1]

Except from the chemical looping combustion technology, all CCS technology does to a great extend rely on existing technologies put together in an innovative way. In Figure 4 the processes are illustrated.

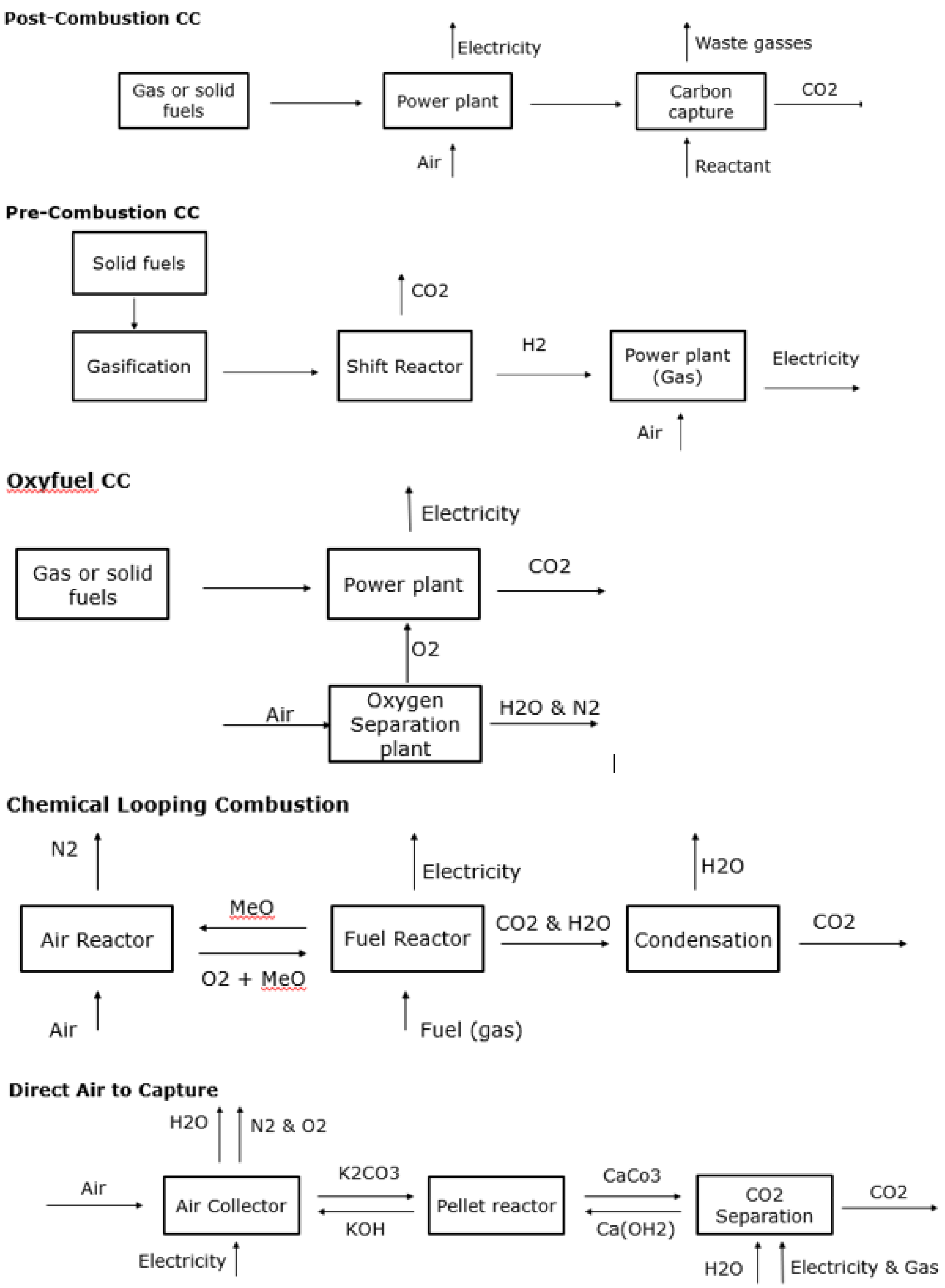

Figure 4: Diagrams of the differnet type of carbon capture systems [1]

The first three system types resemble the more traditional power plant solutions and has been proven at a larger scale, while Chemical looping combustion is only at demonstration scale and could be seen as a special case of oxy-fuel combustion. Direct Air to Capture (DAC), however distinguish itself significantly from the other four technologies, as its sole purpose is to capture CO_2 and not limit the emissions from power and heat production.[1]

This guideline will focus on how to describe the carbon capture part of the first three technologies in a way that is useful when the purpose is to deliver technology data for technical energy system modelling.

A challenge is where to put the boundaries for the CC systems, it is desirable that it is done in the same way for all the three carbon capture systems categories. Therefore, the CC technology is described as a module. The module features the CC technology and specifies input and output. Thus, the power plant technologies or other technologies related to the CC technology is not described in this context.

Using this approach, the modeler have to provide technology data for technologies not included in the descriptions e.g. power plants using hydrogen as fuel, power plants using pure oxygen instead of air, thermal gasification plants, plants producing oxygen or prices for inputs (e.g. for O_2 or syngas).

In Figure 5, Figure 6 and Figure 7 the suggested boundaries for the carbon capture processes are illustrated by the red dotted lines.

For post combustion carbon capture technologies (shown in Figure 5), a carbon capture[13] technology is described. The inputs are flue gas, energy and other auxiliary inputs. The reduced energy efficiency of the powerplant with post combustion CC is accounted for by an energy input to the CC. The output is CO_2, flue gas with lower CO_2 content and heat.

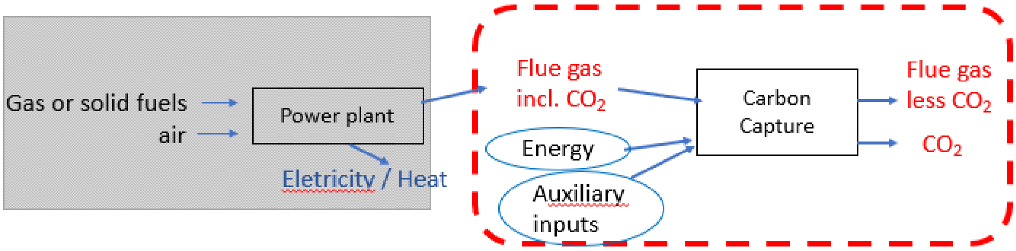

Figure 5: Post combustion

For pre-combustion carbon capture technology (shown in Figure 6) the shift reactor is described as the CC-technology. The inputs are syngas (from gasification of biomass), energy and other auxiliary inputs. The output is CO_2, H_2 and heat.

There will be no descriptions of the gasification plants nor of the powerplant burning H_2.

[13] There are different CC post combustion processes separating parts of the CO_2 from the fluegas e.g. absorption, adsorption, membrane and metal oxides [2].

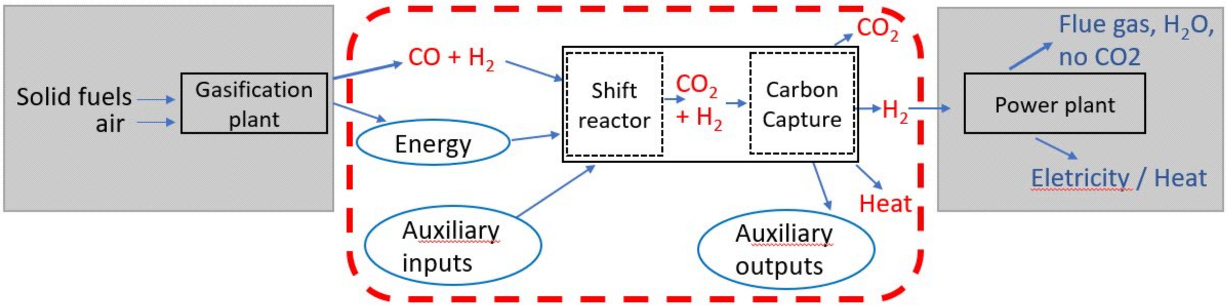

Figure 6: Pre-combustion

For oxy-fuel combustion carbon capture technology (shown in Figure 7) theCC process can be regarded as an addon module that includes all the required modifications . Inputs are flue gas from oxy-fuel combustion (consisting of CO_2 and H_2O), energy and other auxiliary inputs. The output is CO_2, H_2O and heat.

Oxy-fuel combustion processes can only produce modest purity CO_2 (~70-90%) hence a CO_2 post processing unit is required to upgrade the CO_2 to meet transportation or utilisation conditions as shown in Figure 7. Because of the relatively low quality of the raw CO_2, the CO_2 processing unit will be more comprehensive compared to other CC technologies.

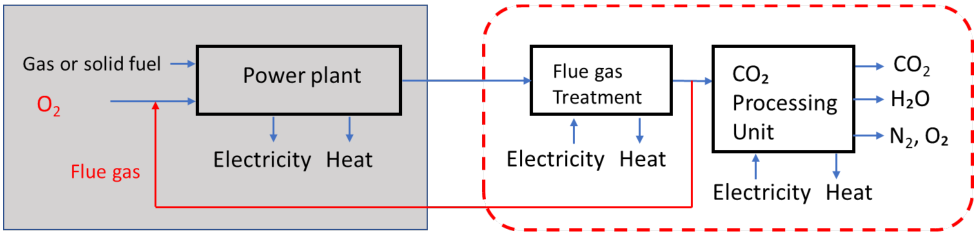

Figure 7: Oxy-fuel combustion

For direct air capture (DAC, shown in Figure 8) the CO_2 is captured directly from the air, hence the DAC module will have no interfaces to existing plants. The module comprises the entire capture plant and all auxiliary systems needed by the specific technology. Inputs to the module is air, energy and possibly (dependent on the specific technology) various auxiliaries.

As for the other CC technologies the DAC module will provide a concentrated low-pressure CO_2 stream which requires a CO_2 post treatment unit to upgrade the CO_2 to meet the quality requirements for transportation or utilisation processes.

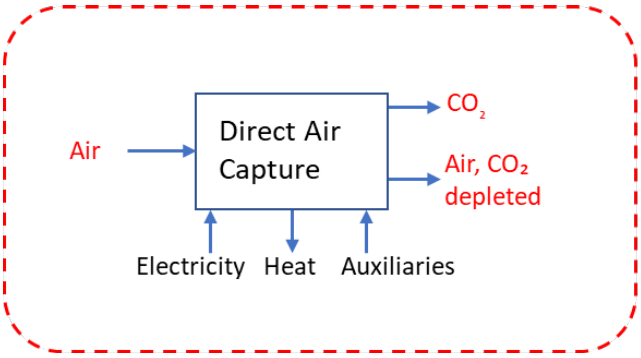

Figure 8. Illustration of Direct Air Capture (DAC).

All carbon capture processes need to deliver the captured CO_2 at a certain quality and at certain physical conditions (e.g. compressed CO_2), regardless whether the use is for geological storage or further utilisation. A CO_2 post processing unit (shown in Figure 9) will upgrade the CO_2 to required specification. Inputs to the post processing unit are raw CO_2 and electricity. Outputs are CO_2 (at required purity, pressure and temperature), water, heat and possibly O_2, N2 and Ar.

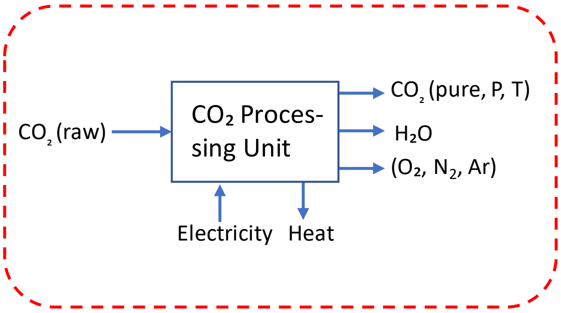

Figure 9. Illustration of CO_2 processing (conditioning) unit.

Guidelines for sections that differs from the main catalouge

General Assumptions

The data presented in this catalogue is based on some general assumptions, mainly with regards to the utilization time, load and start-ups of plants and technologies.

On the one hand, carbon capture technologies are assumed to be designed for continuous operation along the year, except for maintenance and outages. But their actual annual operation pattern will in general depend on the operation pattern of the technologies with which they are combined. Therefore, for the figures in this catalogue as default assumed load pattern is as assumed for the technologies generating electricity and district heating. The assumed number of annual operation hours is shown in Table 11. And the assumed number of start-ups for CC technologies are as shown in Table 12, unless otherwise stated.

Any exception to these general assumptions is documented in the relative technology chapter with a specific note. 3

	Full load hours (electricity)	**Full load hours** (heat)
CHP back pressure units	4,000	4,000
CHP extraction units	5,000	4,000
Municipal solid waste / biogas stand alone	8,000	8,000

Table 11: Assumed number of full load hours for technologies producing electricity and heating, 75 % of generation is expected to take place in full load and the remaining 25 % in part load.

	Assumed number of start-ups per year
Coal CHP	15
Natural gas CHP (except gas engines)	30
Gas Engines	100
Wood pellet CHP	15
Heat only boilers	50
Municipal solid-waste / biogas stand alone	5

Table 12: Number of start-ups for CC-technologies are assumed to be the same as for the power plant they are combined with.

Qualitative description

Input

The flue/process gas and other main materials (e.g. amines in scrubber systems) and gasses (e.g. O_2 in oxy-fuel combustion) and energy consumed (e.g. electricity and/or heat) by the technology or facility. Moisture and CO_2 content of the flue gas and required temperature of the input heat is specified.

Auxiliary inputs, such as chemicals or enzymes assisting the process are mentioned and their contribution described, if considered relevant.

Output

The output is the CO_2 capture percentage (i.e. CO_2 reduction in the exhaust gas), the CO2 purity, as well as co-product or by-products, for example process heat. Pressure of the output gasses and temperature of the output heat is specified as well. Other non-energy outputs may be stated such as condensate from flue gas, if relevant.

Quantitative description

For data sheets see the Excel file in the appendix

Typical total plant size

The total CO2 output per hour is used for describing the capacity, preferably a typical capacity. It is stated for a single plant or facility.

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.

It should be stressed that data in the table is based on the typical capacity. 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 in the main catalogue). The capacity range should be stated in the notes.

Input

All inputs that contribute to the mass and energy balance are included as main input and are expressed mass per t CO2 output and as molar/volume percentage in relation to the (flue or syn) gas input, or equivalently as.

The energy inputs (and outputs) are always expressed in lower heating value (LHV) and moisture content considered is specified if relevant.

Auxiliary inputs, such as **chemicals** or **enzymes** that are assisting the process but do not contribute to the energy balance are included as *auxiliary products* (under *input*) and are expressed in kg/t CO_2 output.

Output

Similar to the mass and energy inputs, energy outputs are expressed as mass or energy per t CO2 output.
Pressure of the output gasses and temperature of the output heat is specified as well.

Any energy co-product or by-product of the reaction has to be specified within the outputs, including process heat loss. Since fuel inputs are measured at lower heating value, in some cases the total efficiency may exceed or be lower than 100%.

The process heat (output) is, if possible, separated in recoverable (for example for district heating purposes) and unrecoverable heat and the temperatures are specified.

Investment costs
The investment costs are 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 plant, are also included.

The investment cost is reported on a normalized basis, i.e. cost per capacity (t CO2 output / hour). The specific investment cost is the total investment cost divided by the Typical total plant size described in the quantitative section.

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.

The rent of land is not included but may be assessed based on the space requirements, if specified in the qualitative description.

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 plants are also not included. Decommissioning costs may be offset by the residual value of the assets.

Operation and maintenance (O&M) costs.
The fixed share of O&M is calculated as cost per plant size (€ per t (CO2 output/hour) per year), where the typical total plant size is the one defined at the beginning of this chapter and stated in the tables. It includes all costs, which are independent of how the plant is operated, e.g. administration, operational staff, payments for O&M service agreements, network use of system charges, property tax, and insurance. Any necessary reinvestments to keep the plant operating within the scheduled lifetime are also included, whereas reinvestments to extend the life beyond the lifetime 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 the data has been readily available.

The variable O&M costs (€/t CO2 output) 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.

All costs related to the process inputs (electricity, heat, fuel) are not included.

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.

References
Reference documents are mentioned in each of the technology sheets and technology chapters. References used in the guideline supplement are below:

[1] Screening of (B)CCS and (B)CCR, An overview of Carbon Capture technologies for energy modelling, Mikkel Bosack Simonsen & Kenneth Karlsson DTU, December 2018

[2] CO2 Extraction from Flue Gases for Carbon, Capture and Sequestration: Technical and Economical Aspects;

Leonie Ebner, Mining University of Leoben 2008

[3] CO2-mitigation options for the offshore oil and gas sector, SINTEF 2017.

301 Traditional heat pumps with certain limitations in maximum temperature and combined process heating and cooling

Contact information

- Contact information: Danish Energy Agency: Jacob H. Zeuthen, jhz@ens.dk; Steffen Dockweiler, sdo@ens.dk; Filip Gamborg, fgb@ens.dk
- Author: Niklas Bagge Mogensen, Viegand Maagøe

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.

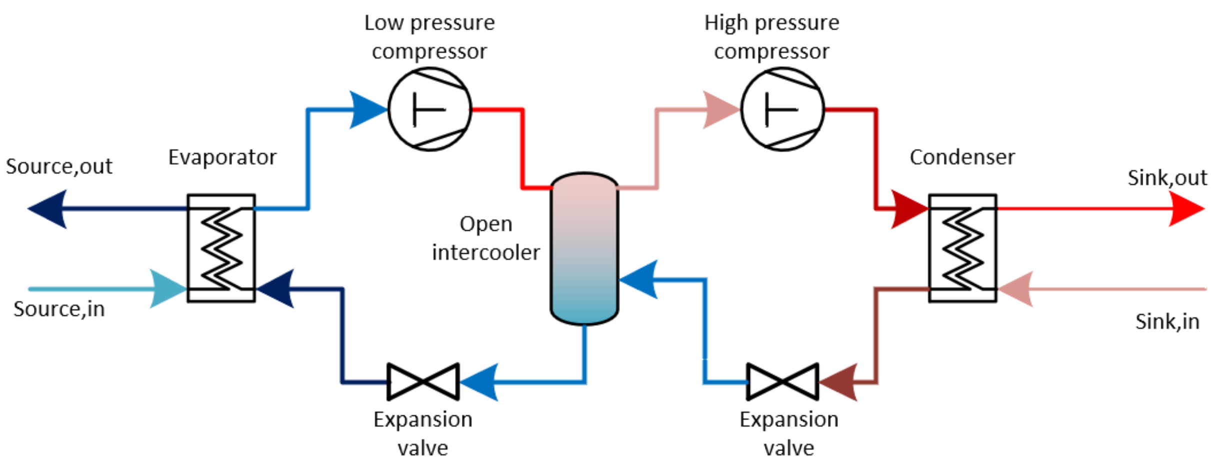

Figure 1: Sketch of two-stage compression heat pump

Figure 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, $\mathrm{T}_{\mathrm{lift,proces}} = \mathrm{T}_{sink,out} - T_{source,in}$. 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): $T_{lift,heatpump} = T_{process} - \Delta T_{source} = T_{sink,out} - T_{source,out}$.

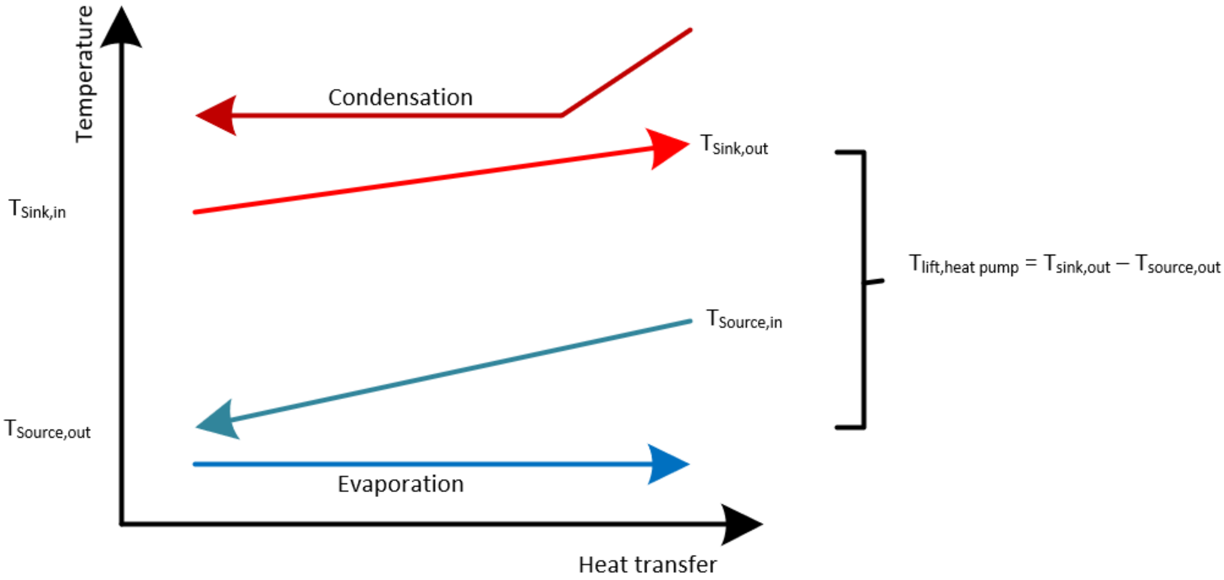

Figure 2: Q-T diagram depicting heat transfer in evaporator and condenser. Includes heat pump temperature lift

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.

(xi) Applications

The application potentials are described in the AP matrix as *Current application potential* and *Full application potential. Current application potential* is relevant for application where a heat pump can be installed locally at the point of heat demand. If a larger number of heating demands are to be covers by a centrally located heat pump, additional investment cost for pipe installation must be expected (in-direct investment cost). To increase the application potential from *Current application potential* to *Full application potential,* the indirect investment cost must be included, see Direct and in-direct investment costs.

1) Energy services

Table 1: Energy services

Energy services	Indirect	Direct
High temperature	*No*	*No*
Medium temperature	*Yes*	*No*

2)

3) Sector relevance

Table 2: Sector relevance

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
in	***Medium***	**yes**	**yes**	**yes**	**yes**	**yes**

4)

5) End- use relevance

Table 3: End-use relevance

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firering / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Traditionel heat pump	Yes	Yes	No	No	No	No	Yes	No

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]

Potential for Carbon capture

Not relevant

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]

(xii) 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.*

(xiii) 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.

References

[1] Danish Energy Agency, Technology Data for Energy Plants for Electricity and District heating generation, 2016, Technology Data catalogue. Version number 5

[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

Quantitative description

See separate Excel file for Data sheet and Application matrix

302 High temperature heat pump

Contact information

- Contact information: Danish Energy Agency: Jacob H. Zeuthen, jhz@ens.dk; Steffen Dockweiler, sdo@ens.dk; Filip Gamborg, fgb@ens.dk
- Author: Niklas Bagge Mogensen, Viegand Maagøe

Brief technology description

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 pumps, 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 1.

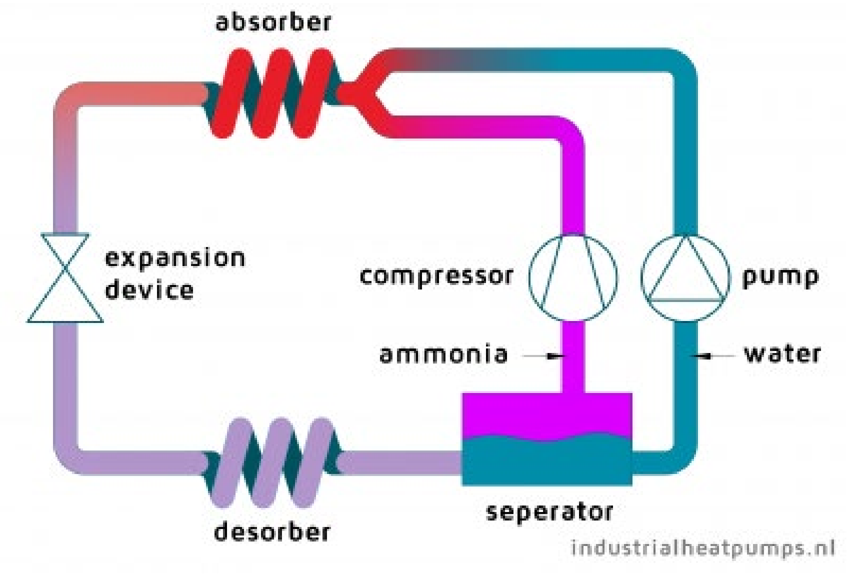

Figure 1: Simplified hybrid absorption-compression heat pump

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 [1][5], 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 [4]. 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 glide[14] 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.

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 [2].

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:[15]

"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."

The ability to replace steam generation with combustibles are driving the development and is crucial in order to reach the goals of industrial renewability, 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 [7]. 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.

[14] 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*.
[15] http://heatpumpingtechnologies.org/annex48/. Project start date: April 2016

Primo 2020, only two HACHP systems are installed in Denmark, with a total capacity of 2,5 MW.

Efficiencies

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

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

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

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*. A high glide will strongly affect the efficiency of the HACHP, which can achieve very high COPs[16] at high glides [3]. In short, this is because the process approaches the Lorenz cycle [4]. The Lorenz cycle can be simulated by putting an infinite amount of small normal vapour compression heat pumps in series.

The theoretical comparability of a standard vapour compression heat pump, compared to a HACHP can be seen in Figure 2**Error! Reference source not found.**. For instance, if a vapour compression heat pump can achieve a COP at 5 at a temperature lift of 60°C, the HACHP can achieve a maximum COP of up to 6,5 if a glide of 20°C can be reached on both the sink and source heat exchangers. In reality, the difference is a bit lower due to finite heat exchanger sizes and is of course dependable on the quality and scale of the components. Reaching the maximum COP might not always be economically feasible in real life conditions. If for instance a glide of only 5°C can be reached, the added complexity and cost associated with a hybrid heat pump might not be feasible.

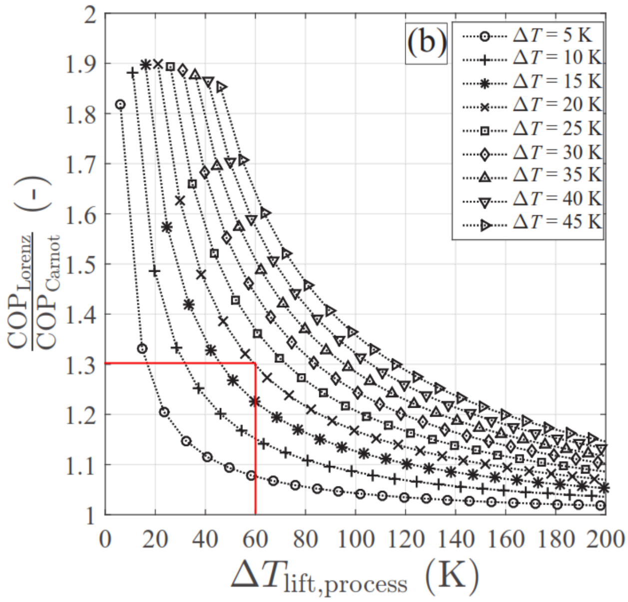

Figure 2: Theoretical advantage of using a HACHP compared to a normal vapour compression heat pump, as a function of temperature lift (x-axis), and glide [4]. $\Delta T_{Lift,proces} =$ **Sink outlet - Source inlet**

The efficiencies (COP) for HACHPs stated in the datasheets is chapter are calculated based on [4] and compared to existing plants in Denmark and Norway [2].

[16] COP defined here as $COP = \frac{Heating\ capacity}{Electricity\ consumption}$

Input

The primary input for this technology is electricity, which is consumed by the vapour compressor and the liquid pump.

The technology also needs a heat source. Exceeding a temperature lift of more than 90°C between heat source and heat sink (target temperature), will result in a steep decrease in the efficiency of the technology. E.g. if a target temperature is 120 °C, the heat source should be minimum 30 °C.

The heat source could be flue gas cooling and/or condensation. It could also be cooling of process water or waste water at elevated temperature levels or excess heat from existing chillers.

Output

This technology produces process heat up to 120 °C [2]. The heat source for the technology can also act as process cooling. Temperatures up to 98 °C can be achieved when using pure Ammonia. Temperatures above 98 °C can be achieved using a mixture of Ammonia and water.

In [4] it was found that the technology can be used to deliver heat at temperatures of 150 °C, however the HACHP is not yet commercial at delivering heat at such temperatures.

Even though HACHP can produce steam given the high temperature abilities, HACHP would not operate efficiently. Given low or no temperature glide for the heat sink, as the latent phase has constant temperature.

HACHP is much better suited for high pressure hot water. High pressure hot water is typical in the temperature range 80-175 °C, normally delivered by boilers. The HACHP then covers the heating up to 120-150 °C and additional boiler covers the rest of the temperature lift if needed. The same field of application is evident for hot oil.

(xiv) Applications

HACHP can be used where a normal vapour compression is currently used, and at higher temperatures; This includes drying processes, producing hot water for washing or pasteurization, and other similar processes requiring hot water in the sub 100°C range. See Table 1 for a list of end uses.

Table 1: Potential applications of high-temperature heat pumps

End-use	Relevance	Sector-comments
Heating/boiling (1)	Highly relevant for a wide variety of unit operations. Preheating product going into evaporation units.	Pasteurizing milk, fruit juice, water, Thermophile biogas upgrading plants, sugar juice for yeast production, Vegetable oil extraction Preheating before evaporation of sugar juice, milk, waste water Washing industry Preheating before distillation of alcohol and oil.
Drying (2)	Highly relevant for preheating of drying air	Milk powder, malt, coffee, wood, wood pellet, cereals, fertilizer, animal feed, seeds, sewage sludge, minerals, paper, pharmaceutical, washing powder, misc. food ingredient, potato starch.
Dewatering (Evaporators)	Limited relevance	
Distillation (3)	Partly relevant	Alcohol production, petrochemical
Firing/Sintering	Limited relevance	
Melting/Casting (4)	Limited relevance	
Other processes up to 150°C (5)	Highly relevant	
Other processes above 150°C (5)	Not relevant so far	

1) **Energy services**

Table 2: Energy services

Energy services	Indirect	Direct
High temperature	*No*	*No*
Medium temperature	*Yes*	*No*

2) **Sector relevance**

Table 3: Sector relevance

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
In	***Medium***	**yes**	**yes**	**yes**	**yes**	**yes**

As dewatering usually requires steam, HACHP is not considered relevant for that end-use.

3) End- use relevance

Table 4: End-use relevance

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firering / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Technology n	Yes	Yes	No	Yes	No	No	Yes	No

Typical capacities

The typical range of capacity for this technology is 0,5-5 MW_{heat} for one unit. A small temperature lift will typically result in higher capacity, due to the displacement rate and specific volume of the refrigerant.

Typical annual operation hours and load pattern

A realistic business case requires long operation hours, which is most likely to be obtained in continuous production processes. HACHP installed to deliver continuous process heat, will follow the operation hours of the facility and load pattern.

Depending on the type of heat source used, the HACHP follows ordinary heat pumps in terms of flexibility and maintenance ratios. If a steady heat source is used, the heat pump should be able to run with close to no interruptions throughout the year. Heat pumps can achieve higher COPs at part load operations due to the effectivity of the heat exchangers being increased with lower flow rates, which means that non-steady state operations are beneficial in terms of efficiency.

Regulation ability

Heat pumps, including HACHP, of this size > 0,5 MW_{heat} are often frequency controlled to operate in part-load.

Advantages/disadvantages

Advantages [4]

- Higher efficiency than regular electric heat pumps at large temperature glides > 10 K.
- Lower vapour pressure by decreasing volatile component concentration
- Temperature levels higher than heat pump

Disadvantages

- Higher investment cost than regular heat pump
- More difficult to control than regular heat pump
- Need large temperature glide to be efficient. HACHP will not efficiently supply heat for evaporation/boiling

Environment

As the HACHP uses electricity, no direct particles or gasses are emitted doing operation. Using ammonia and water as refrigerant. Ammonia is widely used refrigerant in heat pumps and refrigeration applications. Ammonia has no ozone depletion potential (ODP = 0) and no direct greenhouse effect (GWP = 0).

Potential for Carbon capture

Not relevant to this technology

Research and development perspectives

General to all heat pumps with temperature levels above 90 °C, degrading of lubrication oil, degrading of refrigeration and temperature resistant components are the dominating challenges, this is also evident for HACHP. It is however an area with increasing focus [10]. Specific for HACHP the absorber and compressor are an area of focus in research and development for manufacturer.

The COPof the HACHP will be linked to the COP of vapour compressions heat pumps, as the primary energy consumption is from the compressor. Current reciprocating compressors can reach up towards 80% isentropic efficiency at a pressure ratio of 4. Continued development in compressor technology, especially modern screw compressors, can increase this and thus the COP of the HACHP. A conservative estimate of expected gain in COP is that up towards 10% can hence be expected towards 2050.

Currently the system can deliver heat at temperatures above 120 °C. On a theoretically level, temperature up to 150 °C should be economically and technically feasible, however the HACHP system is not commercially available yet at these elevated temperatures. It will require more research and development to reach this temperature level.

Examples of market standard technology

A good solution requires a heat source at higher temperature than ambient with a temperature glide > 10 K and delivers process heat also with a temperature glide. The system includes oil coolers, high efficiency electrical motor and frequency converters, which typically are water cooled. The heat from oil cooler, motor and frequency converter is often utilized as well.

Most common refrigerant mix is water and ammonia. Examples of installed plans using water/ammonia as refrigerant [2]:

Borregaard, Norway – 2 MW – Heat source 73/46 °C, Heat sink 70/95 °C, COP = 6,1

Frevar, Norway – 0,8 MW - Heat source 20/14 °C, Heat sink 75/95 °C , COP = 2,4

Løgumkloster, Denmark – 1,3 MW - Heat source 35/17 °C, Heat sink 35/100 °C , COP = 4,3

Skretting Stokmarknes Norway – 1,4 MW - Heat source 43/28 °C, Heat sink 35/85 °C , COP = 5,5

Arla Arinco, Denmark – 1,2 MW - Heat source 45/22 °C, Heat sink 55/85 °C , COP = 4,5

Prediction of performance and costs

The investment costs for HACHP follows the same trend for M€/MW of heating capacity as traditional vapour compressions heat pumps. They are however more expensive, regarding additional components in terms of the secondary fluid loop, a pump, a separator, and comparably larger heat exchangers. HACHPs currently suffer from limited industrial availability, as few suppliers currently exists. This limited number of commercial suppliers also increases the costs. INNOTERM, which is one of the few Danish suppliers, state that investment cost of HACHPs are 20% higher compared to ordinary vapour compression heat pumps, partly because each unit is fabricated by combining multiple suppliers of heat exchangers, pumps, compressors, and control system [9]. The cost difference between ordinary vapour compression heat pumps and HACHP is however expected to be lower in the future, as suppliers are expected to deliver pre-build systems, with fewer individual suppliers.

The maintenance cost is however lower compared to a vapour compressions heat pump running at the same conditions. This is because the pressures in a HACHP is generally lower, which reduces the wear on the system. The ability to use screw compressors further reduces the maintenance cost, which typically only requires a fifth of the maintenance of a reciprocating compressor [9].

Economy of scale and increased commercial availability will likely result in a reduction of nominal investment costs and maintenance for high temperature heat pumps.

Investment costs projections for high temperature heat pump up to 125 and 150 °C can be seen in Table 5. The cost of the heat pump with delivered heat at temperatures up to 150 °C are expected to be higher than for one that deliver at temperatures up to 125 °C, as it is not yet commercially available. The cost of the heat pumps up to 150 °C is corrected according to TRL Technology Readiness Level as described in [11]. It is corrected for process contingency cost (10 %) and project contingency cost (10 %).

Table 5: Current and future investment and operation costs

	2020	2030	2040	2050
Nominal Investment cost[17] [M€/MW$_{heat}$] – up to 125 °C	0,87	0,78	0,73	0,70
Nominal Investment cost[4] [M€/MW$_{heat}$] – up to 150 °C	1,05	0,93	0,88	0,84

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 [2]. 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.

In a Danish and European context there is increasingly focus on climate change and therefore also focus on energy efficiency and electrification. HACHP plays a role in terms of both energy efficiency and electrification, and it can be expected that HACHP experience a market-pull as is the case for vapour compression heat pumps.

[17] Including installation

All in all, the market share for high temperature heat pumps (Whether it be HACHP or other types) are expected to increase during a reasonable timeframe, as they are one of the most economically feasible ways to replace traditional boilers in process steam production with renewable technologies (Compared to i.e. electric boilers). The market share is expected to increase given that the price of using electricity will diminish and/or the price for using fossil combustibles will increase [6][7].

All of the above-mentioned prediction of future cost is also considered by assessing the technology in terms of 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.

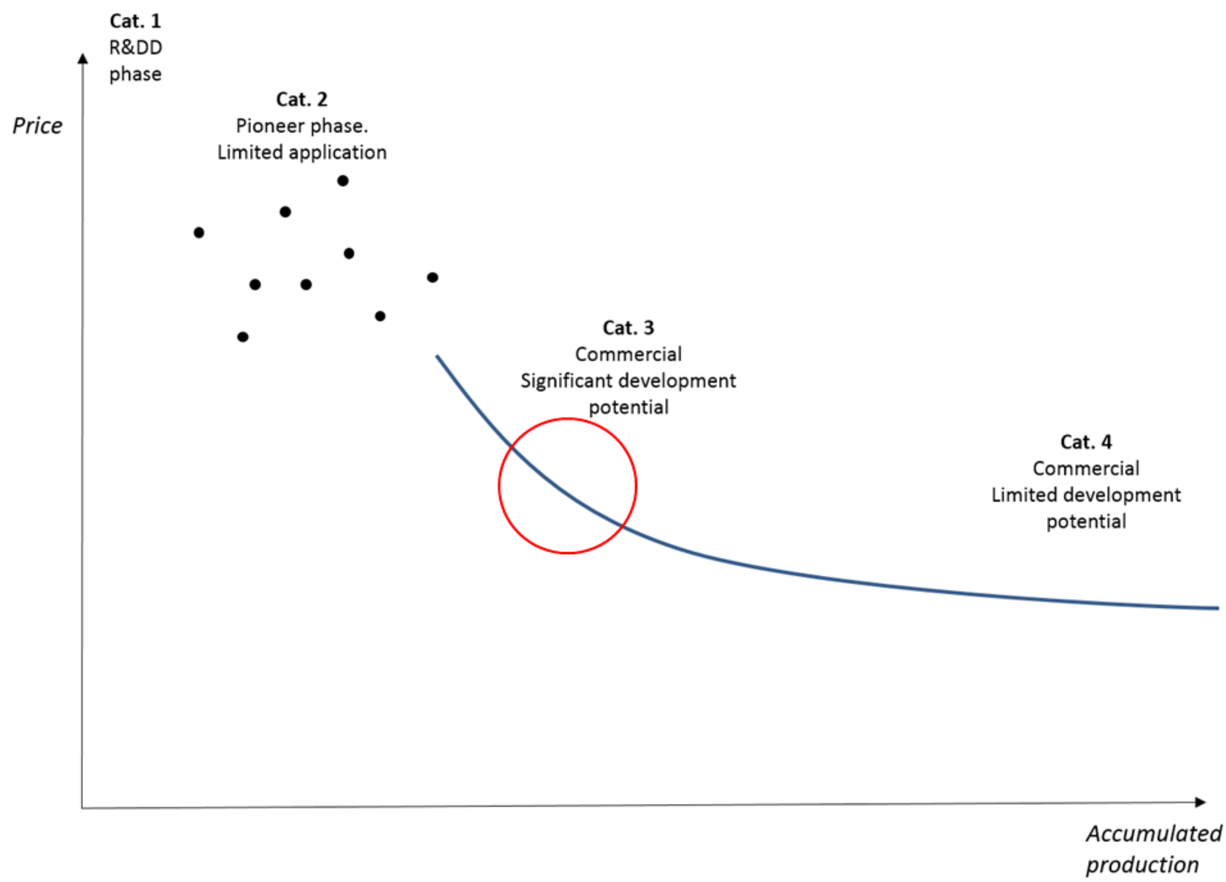

Figure 3: Technological development phases. Correlation between accumulated production volume (MW) and price.

Large scale HACHP is in Category 3. *Commercial technologies with moderate deployment*. Even though HACHP only has low-to-moderate deployment, the potential for improvement of performance is relatively low compared to the placement on the learning curve. This is explained by the HACHP is built upon other well-known and researched technologies, such as vapour compression heat pump, gas driven absorption heat pump and other absorption-based technologies. However, in terms of investment cost it is expected to decrease based on more pre-fabrication, market-pull and economy of scale, as described earlier in this section.

The potential for increasing mechanical efficiency and decreasing thermal loss are only considered to be a few percentage points over the next years. The essential part of increasing the efficiency of this technology, is better system integration resulting in more favourable temperature levels.

(xv) 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.*

(xvi) Related benefits and savings

Not relevant.

Uncertainty

The development of 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 HACHP will be more competitive, even with lower COP than state-of-the-art heat pumps. Reversely if the electricity cost also increases, a higher focus on performance of HACHP must be expected.

Increasingly climate awareness from manufacturers, society and policy makers is also expected to increase competitiveness of HACHP and vapour 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

Additional elaboration of the project can be found here:

http://industrialheatpumps.nl/en/how_it_works/hybrid_heat_pump/

Temperature glide is the temperature difference between inlet and outlet temperature for the heat source or heat sink.

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Quantitative description

See separate Excel file for Data sheet and Application matrix

303 Booster heat pump systems applying turbo compressors in combination with traditional heat pumps

Contact information

- Contact information: Danish Energy Agency: Jacob H. Zeuthen, jhz@ens.dk; Steffen Dockweiler, sdo@ens.dk; Filip Gamborg, fgb@ens.dk
- Author: Niklas Bagge Mogensen, Viegand Maagøe

Brief technology description

This technology is a combination of a traditional vapor compression heat pump, an evaporator vessel (sub 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 [1] and [2]. The system is yet to be implemented.

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

The system is depicted in Figure 1. The traditional heat pump[18] 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) [3]. 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 compressors, in series.

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

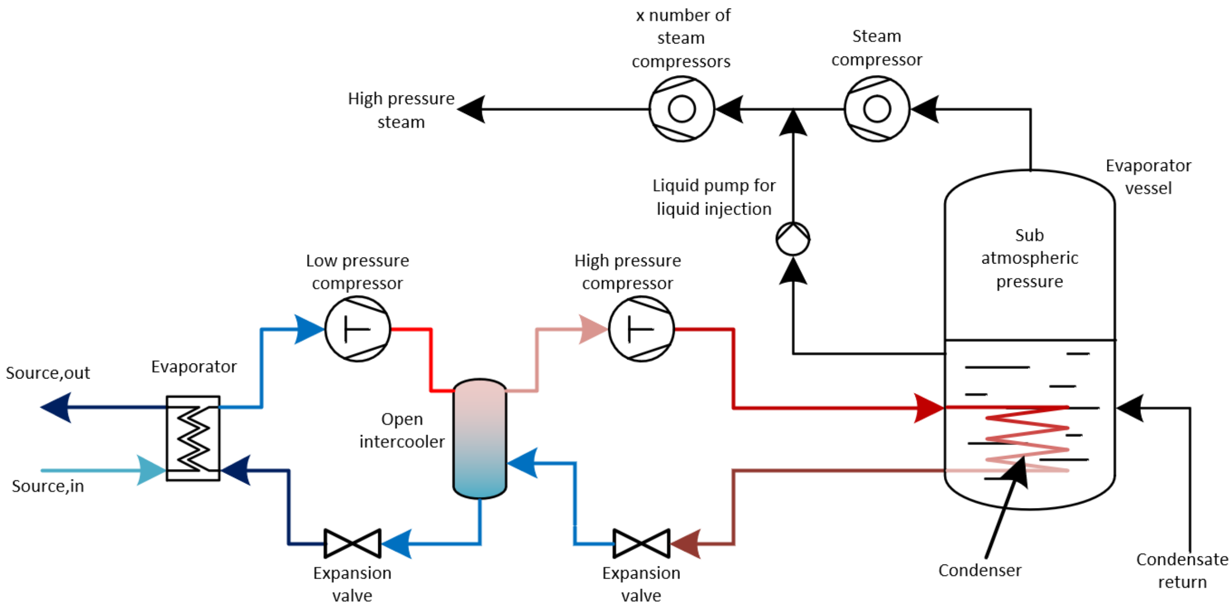

Figure 1: Sketch of two-stage compression heat pump in combination with booster turbo compressors. Components and process is described in detail above.

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.

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

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

The delivered heat is the enthalpy difference between the high-pressure steam and the condensate return, multiplied with the steam mass flow. The total power consumption includes power consumption for the traditional heat pump and the steam compressors. The power consumption for the steam compressors are specified from an offer from *Piller Blowers and Compressors GmbH* [3]. The isentropic efficiency of the steam compressors is in the range 75-80 %.

In this setup it would also be possible to have multiple heat pumps delivering heat to the evaporator vessel. This increases utilization of excess heat at different temperature levels. As evident to all heat pumps, a higher heat source temperature results in a higher COP.

Input

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

The heat source is assumed to be excess heat at 30 °C, cooled down to 20 °C. Lower temperature excess heat can also be utilized, but it will decrease COP and vice versa.

Output

The output of this heat pump is heat, in form of approximately 5 bar steam. Lower steam pressure will increase COP and decrease investment cost slightly. Steam of higher pressure will decrease COP and increase investment cost slightly.

(xvii) Applications

This system is expected to have a large application potential in the medium temperature levels, as it can substitute steam boilers to a large extend and drive the same processes as current steam systems. It is mainly limited by the amount of available excess heat.

1) Energy services

Table 1: Energy services

Energy services	Indirect	Direct
High temperature	*No*	*No*
Medium temperature	*Yes*	*No*

2) Sector relevance

Table 2: Sector relevance

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
in	***Medium***	**yes**	**yes**	**yes**	**yes**	**yes**

3) End- use relevance

Table 3: End-use relevance

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firering / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Booster heat pump systems	Yes	Yes	Yes	Yes	No	No	Yes	No

Typical capacities

This type of heat pump is expected to have a heating capacity ranging from 1-15 MW.

Typical annual operation hours and load pattern

Heat pump system such as this is expected to replace or supplement existing steam system, which are typically used in large production industries with continuous production and yearly operation hours > 8000 hours.

Regulation ability

The heat pumps are assumed to have a frequency controller, which enable the heat pump to regulated load, however a minimum load of approximately 50 % must be expected, due to the steam compressor limitations.

Advantages/disadvantages

A general advantage of heat pumps is that the heat pump is able to recycle excess heat, which enables a utilization of heat sources otherwise left unused by conventional heat production technologies. [4]

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. [4]

Compression heat pumps that are electrically driven have no emissions from burning fuel, meaning that these systems can be installed in locations with restrictions on exhaust emissions. [4]

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.

This system is not commercially on the market, this results in high investment cost.

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.

As Danish legislation prevents synthetic 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 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. [4]

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. [4]

Potential for Carbon capture

Not relevant.

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.

The individual components of this heat pump system are known, and the potential utilization is large as not many alternatives to fossil fuels fired steam boilers are at the market. It is therefore expected to be only a matter of time before systems such as this heat pump will be commercially available.

Examples of market standard technology

The heat pump system described in this chapter is yet to be installed in the industry. A similar technology is Kobelco SHG 165, which also uses a traditional heat pump to evaporate water and afterwards compress it in a steam compressor [6].

The market standard for traditional heat pumps are well described in [4] and [5].
In Terneuzen in the Netherlands a demonstration project includes an 8 MW_{heat} steam compressor system [6]. A similar compressor setup is expected to be utilized in this system.

Prediction of performance and costs

This exact heat pump system is not an available commercial technology at the moment, and the cost is an estimate based on cost of subsystems and corrected to the TRL (Technology Readiness Level [9]) and placement on learning curve.

The heat pump system is in category 2, with a TRL of around 4.

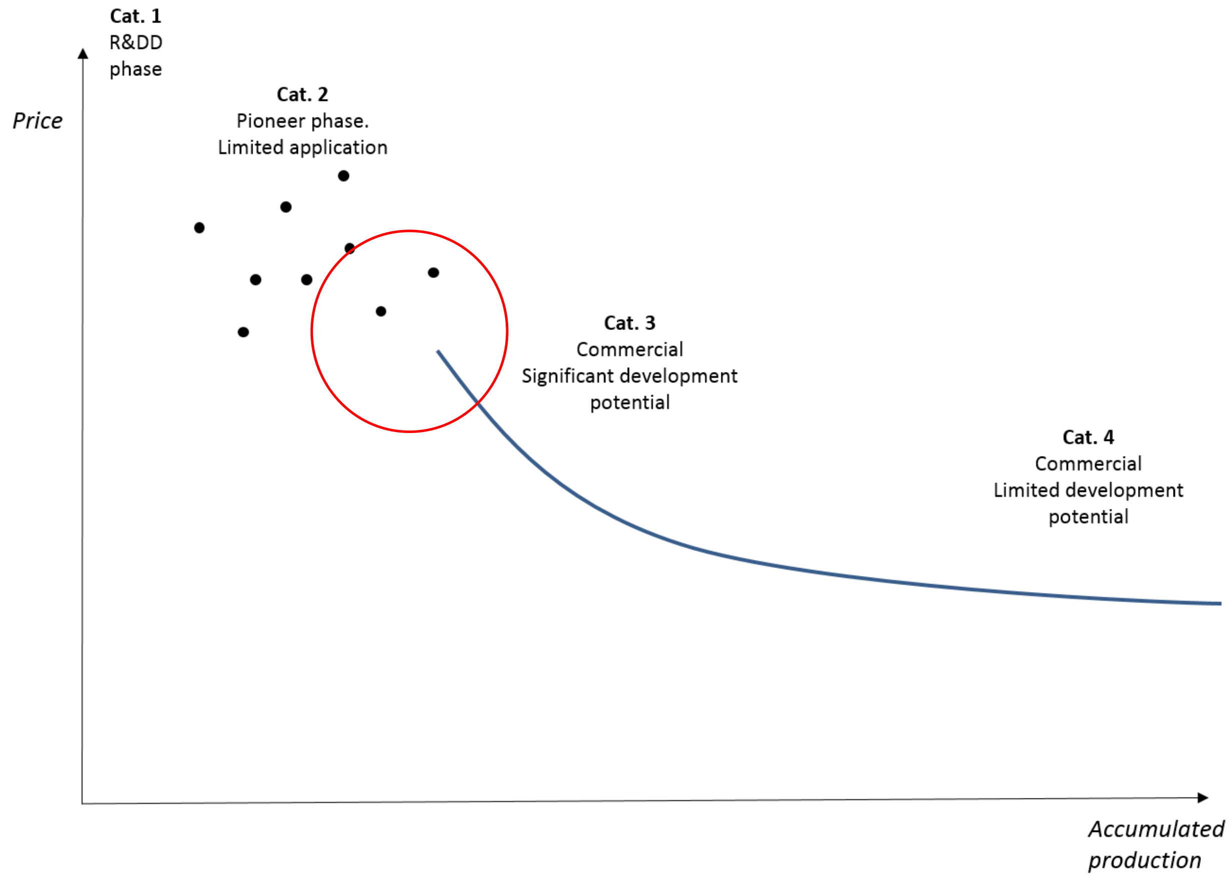

Figure 2: Technological development phases. Correlation between accumulated production volume (MW) and price.

The system cost consists of three subsystems, the traditional heat pump (3 MW), the evaporator vessel and the steam compressors. The total capacity of the system is ~4 MW.

The cost of the traditional heat pump is similar to the one in the chapter for traditional heat pump in this catalogue, (0.73 M€/MW).

The cost of the evaporator vessel is found based on cost correlation [7], with a specific cost of 0.03 M€/MW.

The cost of the steam compressors was obtained from the offer from [3], with a specific cost of 0.33 M€/MW.

The combined cost of the three subsystems are 1.09 M€/MW. To correct for the TRL the approach presented in [8] is used.

Figure 3 illustrates the development in cost, when going from TRL of 4-5 (current stage), to a mature technology.

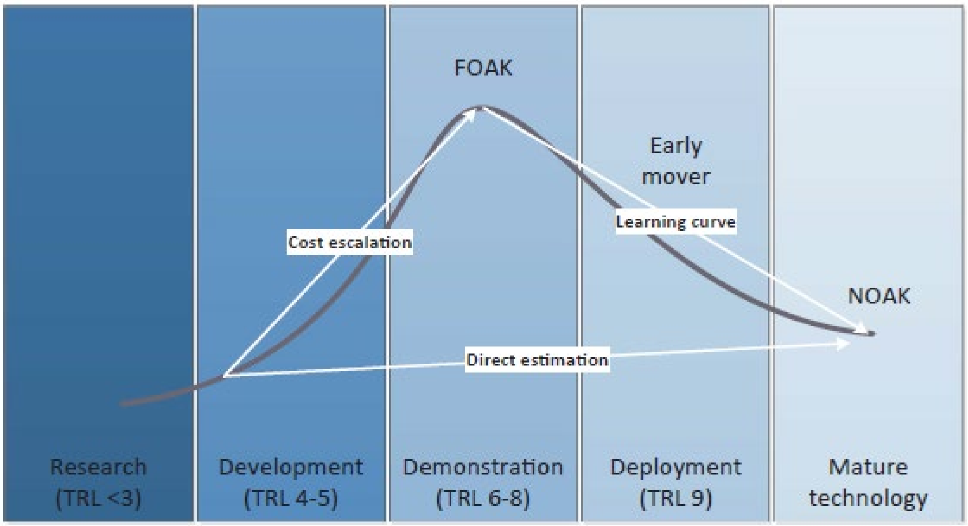

Figure 3: Typical capital cost trend of new technology. From [8]

The cost of FOAK (First Of A Kind) is calculated to be 1,63 M€/MW and represent the cost in 2020.

To estimate the cost in 2030, 2040 and 2050, NOAK (N'th Of A Kind), the following assumptions were made.

Learning rate	10 %
Number of systems in 2020	5
Number of systems in 2030	20
Number of systems in 2040	100
Number of systems in 2050	200

All the components are well known and used in other applications, therefore the increase in efficiency is expected to follow the same trend as traditional heat pumps and only increase a few percentage points. It is however expected that heat pumps with higher COP values will be installed but this will be due to better system integration.

(xviii) Direct and in-direct investment costs

The indirect investment cost represents piping rebuilt needed if increasing the *Current application potential* to *Full application potential.*

(xix) Related benefits and savings

Not relevant

Uncertainty

The uncertainty related to the investment cost is significant, as it relies on a theoretically approach. The cost of each subsystem is known with reasonable certainty, however the additional cost of combining the systems is less certain.

The heat pump system has a low TRL [8] and is in category 2 on the learning curve. This makes the future cost prediction highly dependent on the expected increase in installed units. The increase in installed units is influenced by the competitiveness of the heat pump, and therefore also linked to the costs of fuels, see [4].

Additional remarks

More detailed information on the working principle, see [1].

As mentioned earlier this heat pump system enable the possibility to utilized excess heat at different temperature levels. If excess heat at higher temperature are utilized the COP will increase.

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Quantitative description

See separate Excel file for Data sheet and Application matrix

304 Heat driven heat pump

Qualitative description

Contact information

- Contact information: Danish Energy Agency: Jacob H. Zeuthen, jhz@ens.dk; Steffen Dockweiler, sdo@ens.dk; Filip Gamborg, fgb@ens.dk
- Author: Niklas Bagge Mogensen, Viegand Maagøe

Brief technology description

Due to large similarities with the *absorption heat pump* in [1], this chapter focus on application.

For more details on qualitative description see, [1].

A principle of operation is depicted in Figure 1.

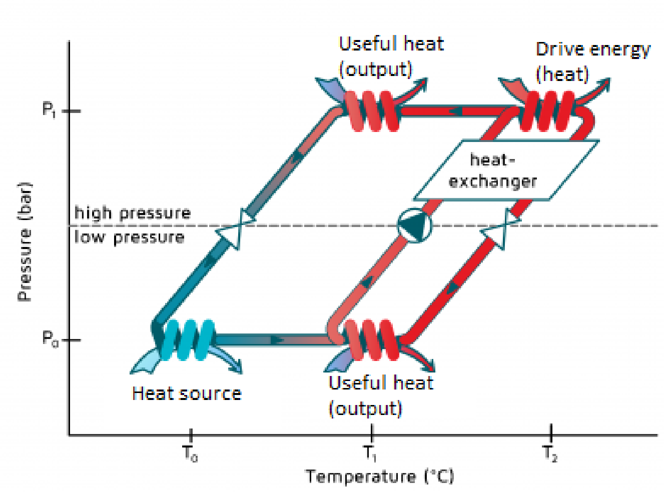

Figure 1: Principle of operation, heat driven heat pump, edited from [3]

Input

Inputs are heat source and drive energy (also heat).

The heat source can be ambient, low temperature waste heat, flue gas condensation or process cooling.

The drive energy is high temperature heat > 140 °C. Most common is hot flue gas, high temperature hot water or steam, but also high temperature waste heat could be used.

Output

The main output is heat. The heat driven heat pump delivers heat up to ~80-85 °C.

If process cooling act as heat source, process cooling will also be an output.

(xx) Applications

The heat driven heat pump can cover the same demands as the traditional heat pump to the same temperature limit, however this technology requires more specific inputs. Not many production sites have a need for 80-85 °C, low temperature heat source and high temperature heat source (drive energy) at the same time.

1) Energy services

Table 1: Energy services

Energy services	Indirect	Direct
High temperature	*No*	*No*
Medium temperature	*Yes*	*No*

2) Sector relevance

Table 2: Sector relevance

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
in	***Medium***	**yes**	**yes**	**yes**	**yes**	**yes**

3) End- use relevance

Table 3: End-use relevance

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firering / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Heat driven heat pump	Yes	Yes	No	Yes	No	No	Yes	No

Typical capacities

Absorption heat pumps are available in capacities of up to around 12 MW of cooling. The heat output including drive energy will thus be around 20 MW. Due to transportation limitation, a single unit is up to 6 MW of cooling [2], for larger capacities unit are coupled.

Typical annual operation hours and load pattern

Typical load pattern and annual operation follows that of the production site, as the heat pump rely on other technologies to provide drive energy. The heat pump will be installed in continuous production sites.

Regulation ability

See [1]

Advantages/disadvantages

See [1]

Environment

See [1]

Potential for Carbon capture

Depend on drive energy. Possible for flue gas, but not hot water or steam.

Research and development perspectives

See [1]

Examples of market standard technology

See [1]

Prediction of performance and costs

See [1]

(xxi) Related benefits and savings

If process cooling is used as heat source, process cooling can be considered a related savings, as it substitutes alternative process cooling supply.

Uncertainty
See [1]

Additional remarks

References
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Quantitative description
See separate Excel file for Data sheet and Application matrix

305 Mechanical Vapour Recompression (MVR)

Contact information

- Contact information: Danish Energy Agency: Jacob H. Zeuthen, jhz@ens.dk; Filip GamborgSteffen Dockweiler, sdo@ens.dk; Filip Gamborg, fgb@ens.dk
- 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 1.

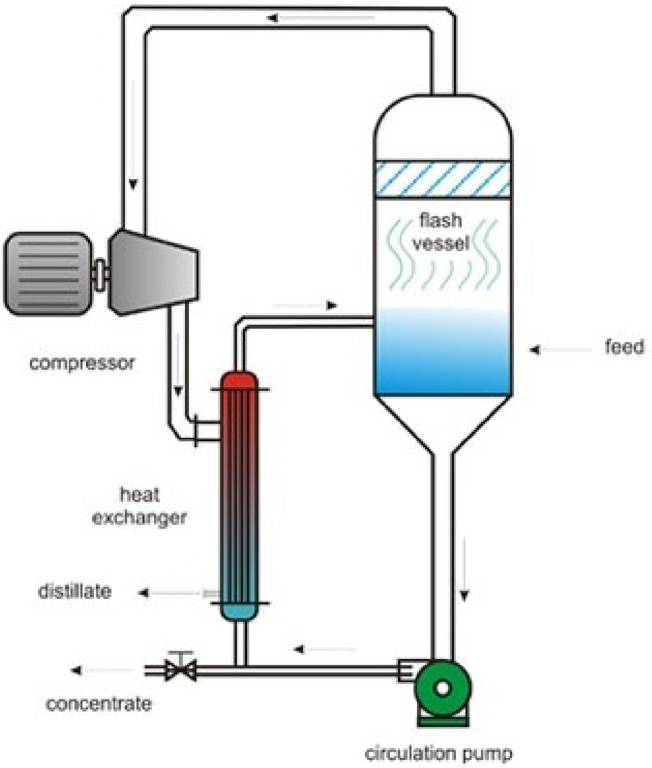

Figure 1: Simplified illustration of the MVR cycle. For a water treatment system, the feed is dirty water, the concentrate is highly concentrated pollutants, and the condensate/distillate is pure water.

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[19] [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 **7-13kWh/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[20]:

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

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].

(xxii) 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 1.

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 1: 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

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

[20] 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$_{steam}$

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].

1) **Energy services**

Table 2: Energy services

Energy services	Indirect	Direct
High temperature	*No*	*No*
Medium temperature	*Yes*	*No*

2) **Sector relevance**

Table 3: Sector relevance

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
in	***Medium***	**yes**	**yes**	**yes**	**yes**	**yes**

3)

4) **End- use relevance**

Table 4: End-use relevance

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firering / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
MVR	Yes	Yes	Yes	Yes	No	No	Yes	No

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

Potential for Carbon capture
Not relevant

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 Figure 3 as well as [10], the nominal investment cost based on system size in terms of treated water per day can be seen in Table 5.

Table 5: 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] and Figure 3

	2017	2020	2030	2050
Nominal Investment cost[21] <10 m^3/h [€/m^3/day]	7200	7030	6284	5645
Nominal Investment cost[3] 10-100 m^3/h [€/m^3/day]	4800	4686	4189	3763
Nominal Investment cost[3] >100 m^3/h [€/m^3/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 6. 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).

[21] Including installation

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 6: 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

(xxiii)

(xxiv) 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]

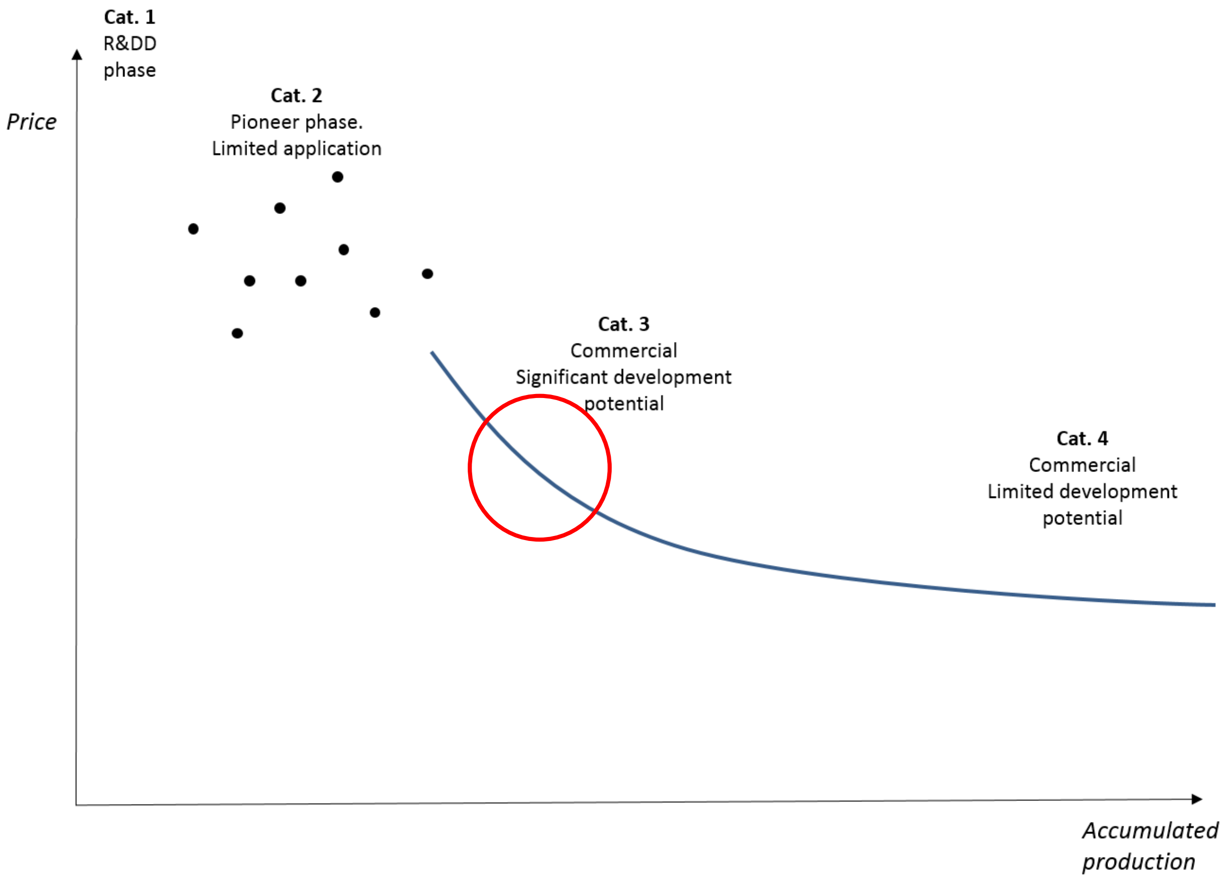

Figure 2: Technological development phases. Correlation between accumulated production volume (MW) and price.

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 %

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

Figure 3: Offer from manufacturer

References

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Quantitative description

See separate Excel file for Data sheet and Application matrix

306 Thermal gasification

Contact information

- Contact information: Danish Energy Agency: Jacob H. Zeuthen, jhz@ens.dk; Steffen Dockweiler, sdo@ens.dk
- Author: Niklas Bagge Mogensen, Viegand Maagøe

Brief technology description

This chapter describes thermal gasification used directly in industrial processes. The technology can also be used for hot water and steam production, but the technology in this chapter is valid for direct firing in processes.

Thermal gasification can be a renewable alternative to natural gas used in industrial heating processes. The output from thermal gasification, produced from biomaterial, is producer gas (N_2, H_2, CO, CO_2, CH_4 and H_2O), which can be fired directly in the processes.. Biogas is also renewable alternative to natural gas and biogas has a relative stable gas production and a long reaction time when it comes to adjusting the gas production. If biogas is chosen for industrial processes it will be either necessary to have a storage facility that can accumulate the fluctuation in demand or an alternative consumer of surplus biogas (e.g. district heating network, hot water production, gas engine).

Thermal gasification has an adjustable load profile and can more easily be applied for the varying loads in industrial processes.

There exist several types of thermal gasification processes, however the up-draft (UD) gasifier where the biomass goes downward, and gas goes upward is one of the simplest and most used. In this system the coke residue and ashes go downward and is removes at the bottom of the system. This setup allows for more difficult fuels to be utilized and differences in types of gasification. A fluid bed is the gasifier type that is very fuel flexible. One example from Denmark is the LT-CFB (or Pyroneer gasifier), but internationally there are several fluid bed gasifiers available. Both Vølund [1] and Dall Energy [2] have gasifiers in operation in Denmark. The Dall Energy system can use rather wet and inhomogeneous biomass (incl. bio waste).

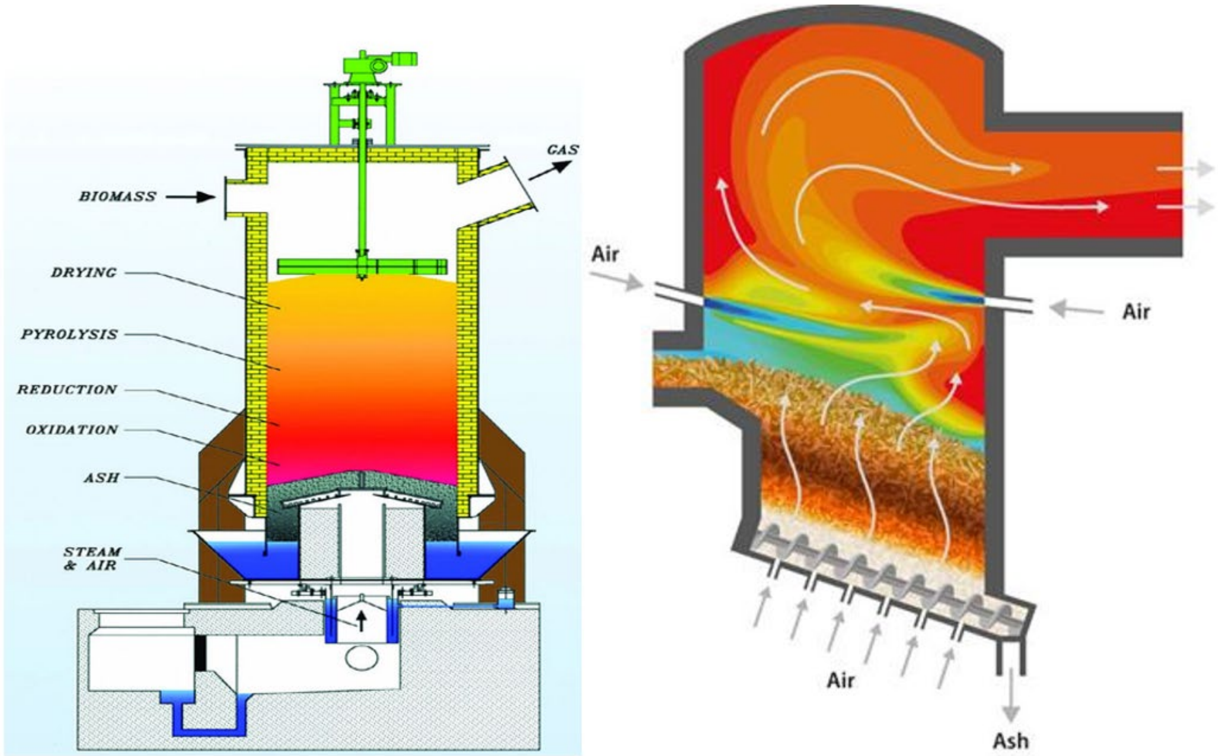

Figure 1: Simplified illustration of Vølund's (left) and Dall Energy's (right) Up Draft gasification equipment

On Figure 1 (right), the hot producer gas from the gasification unit is further combusted in an additional combustion chamber or direct firing in the process.

For more information about gasification technologies see the [3] and [4].

The technology incudes gasification equipment and direct firing in connection with the gasification.

Input

The input to the gasification process is biomass.

Output

The output is hot producer gas (N_2, H_2, CO, CO_2, CH_4 and H_2O) which is suitable for combustion directly in the process.

(xxv) Applications

The use of thermal gasification in Denmark has so far been limited to heat only or heat and power production. The potential applications can be seen in Table 1.

Table 1: Potential applications of thermal gasification

End-use	Relevance	Sector-comments
Heating/Boiling	Relevant for high temperature Heating	
Drying	Not relevant so far. But could be relevant for fluid bed dryers and for rotary dryers	Drying of sludge, drying of animal feed, wood pellet, grain drying
Dewatering/concentration (Evaporators)	Not relevant	
Distillation	Not relevant	
Firing/Sintering	Relevant where natural gas can be replaced by gasification gas	Brick production, Cement production, Asphalt
Melting/Casting	Relevant where natural gas can be replaced by gasification gas	Glass works, Rockwool
Other processes up to 150 °C	Not relevant so far	
Other processes above 150 °C	Not relevant so far	

Processes for production of e.g. glass, rockwool and bricks will require some modification of the process equipment and fuel switching is not straight forward. Demonstration projects/plants will be required in order to facilitate a change from fossil fuel to thermal gasification gas from biomass. Other processes like cement and drying of e.g. wood pellets will not necessarily need demonstration before full scale implementation. It has to be noted that FLS is already selling technologies that can utilise alternative fuels including bio-waste in the cement production [5] and [6].

The application of the gasification process is limited by the content of particles in the producer gas. The amount is, however, much lower than from conventional combustion processes. Furthermore, it is possible to remove particles and tar from the gas using bag house filters or candle filters. But the process and the final product will be exposed to the particulate matters and other impurity in the producer gas and the flue gas.

Biomass heating plants are sometimes troubled by problems in the feeding and storage facility, and because of that direct process heating can be a challenge. However, the gasifier has a certain resilience when it comes to upstream problems as it holds a large amount of biomass in the gasification chamber which can act as a buffer if feeding of fresh biomass for some reason is down.

1) **Energy service**

Thermal gasification for direct firing is only applicable in processes which can accept direct heating from flue gas or heated air stream. The energy services are shown in

Table 2.

Table 2: Energy services

Energy services	Indirect	Direct
High temperature	*No*	*Yes*
Medium temperature	*No*	*Yes*

2)

3) **Sector relevance**

It is assumed that the food industry would be reluctant to tolerate the tar content in the producer gas and flue gas from thermal gasification. Currently, the primary reason for not choosing thermal gasification in the food industry is the tar content, which is not acceptable. Removal of tar and particulate matter could lead to acceptance from the food industry.

For the high temperature demand in sector 3. Cement, the technology cannot produce the required high temperature heat. Cement production needs 1450 °C and direct thermal gasification can only reach 1200 °C.

Although, it must be assumed that it the producer gas is clean and dense enough then it would be possible to reach temperatures as high as when burning natural gas. Depending on the heat recovery integration there is some potential for thermal gasification. A case in CEMEX Rüdersdorf, Germany shows that 60% of the primary fuel (coal) could be substituted with direct thermal gasification [10].

Table 3: Sector relevance.

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
Di	***High***	**No**	**Yes**	**No**	**Yes**	**Yes**
Di	***Medium***	**No**	**Yes**	**Yes**	**Yes**	**Yes**

4)

5) **End- use relevance**

Any direct end-use is of relevance the end-uses: Dewatering and Distillation are excluded as these are purely indirect processes.

Table 4: End-use relevance

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firing / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Thermal gasification	Yes	Yes	No	No	Yes	Yes	Yes	Yes

Typical capacities

Typical capacities for updraft gasifier are in the range 2-10 MW [7]. But the upper bound is perhaps 30-50 MW.

Typical capacities for downdraft gasifier are in the range 1-5 MW [4].

Capacities above these levels are typically increased by parallel installation of units [4].

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 thermal gasification systems are flexible in terms of regulation and can go down to around 10% of maximum load for updraft gasifier [7] and 25-30 for downdraft gasifier [4].

Starting up and closing down can typically be done within 24-48 hours.

Advantages/ disadvantages

Advantages

- The thermal gasification is an alternative to natural gas fired direct firing processes
- Good regulation abilities
- The systems can hold a large amount of biomass in the gasification chamber which can act as a buffer if feeding of fresh biomass for some reason is interrupted.
- Can utilize fuel with high water content [4]

Disadvantages

- Implementation of thermal gasification in some processes will require modification of process equipment which may present a challenge.
- Even though the quantity of particles are small it can still limit application potential and it can be necessary to add particle removal.

Environment

The emissions from the process according to verified measurements by Dall Energy:

Emission	Danish Law	Danish Standard	Dall Energy
Dust (mg/Nm3)	40/100 (in chimney)	500-1000 out of furnace	20-70 out of furnace
NOx (mg/Nm3)	300	200-300	80-160
CO (mg/Nm3)			
100 % Load	625	0-600	>5
20% Load	625	Not possible	>5
10% Load	625	Not possible	>10

No emission data is stated in the data sheets below, as the specific utilisation of the producer gas is not covered, and the emission will depend on fuel and operation.

Potential for Carbon Capture (CC)

Biomass as fuel always result in CO_2 emissions, which enable the possibility of carbon capture. Additional information can be found in [8].

It is assumed that biomass is carbon neutral and therefore having net zero CO_2 emission. However, this does not mean CO_2 free combustion, and therefore there is a possibility for carbon capture.

In thermal gasification plants it is possible to add an additional stage where “water gas shift” is applied. In this stage the following chemical reaction takes place:

$CO+H_2O \leftrightarrow CO_2+H_2$

By doing so, CO is converted to CO_2 that can then be removed by an amine wash or other CO2 removal processes. With this additional stage included in the process the technology is also known as 'pre-combustion carbon capture'.

Research and development perspectives

From [4], which is considered relevant in this chapter:

"Up-draft gasification technology with CHP has been demonstrated over a long time in Denmark and abroad.

R&D is carried out, aiming at solving operational problems such as corrosion, process regulation etc. The main issues to be addressed include:
• Ability to handle a wider range of fuel properties, in particular waste wood and other biomass residues
• Establishing references of up-draft gasification plants for waste wood and other biomass residues to drive the incremental development."

Processes for production of e.g. glass, rockwool and brick will require some modification of the process equipment and fuel switching is not straight forward. Demonstration project/plants will be required in order to facilitate a change from fossil fuel to thermal gasification gas.

Examples of market standard technology

Vølund and Dall Energy have gasifiers in operation in Denmark:

- Sindal District Heating - Dall Energy UD – CHP – (6 MW_{th} in operation)
- Harboøre District Heating – Vølund UD – engine driven CHP - (3,5 MW_{th} in operation)
- Bogense District Heating - Dall Energy UD - heat only - (8 MW_{th} in operation)
- Sønderborg District Heating – Dall Energy UD – heat only - (9 MW_{th} in operation)

Other types of gasifiers have also been used in Denmark:

- Asnæs CHP - Pyroneer CFB – Add-on to coal driven steam cycle (6 MW_{th} now closed)
- Skive District Heating - Andritz Oy BFB – Engine driven CHP (20 MW_{th} in operation)

The above mentioned are not used for direct firing in industrial processes, but the technology can be considered the market standard.

More information can be found in
Review of biomass gasification technologies [1] – **in 2013**.

Prediction of performance and costs

The gasification technology is still regarded as a commercially young. Hence, it must be expected that the manufacturing of the gasification equipment/systems as well as sourcing of related components can be optimised if more units are sold. Secondly it may also possible to boost production from the units and by that reduce the specific investment costs (EUR/MW_{th}).

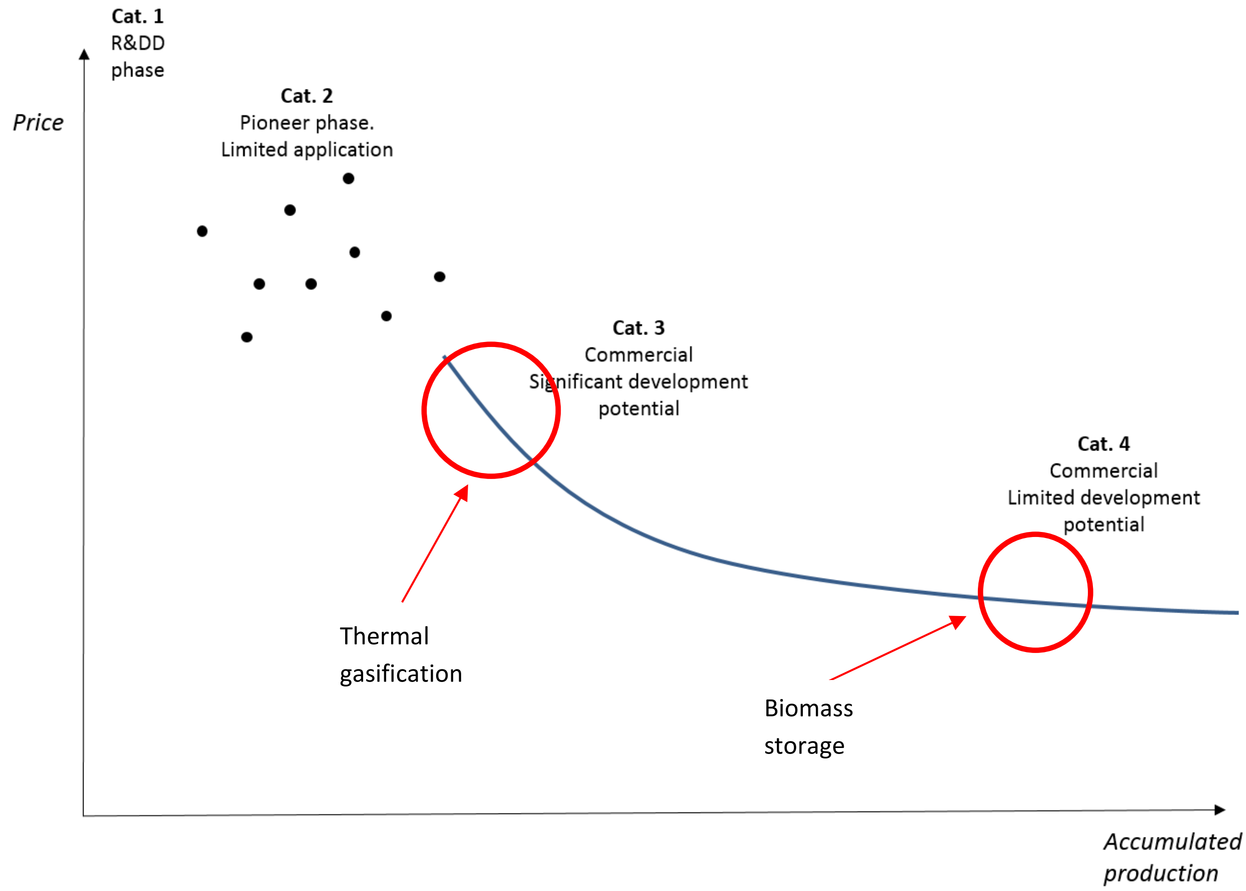

Figure 2: Technological development phases. Correlation between accumulated production volume (MW) and price.

The price per unit is expected to decrease with 25 % over the next 30 years.

The biomass storage is a mature technology and decrease in price is not expected unless a standard solution can be delivered including building design and crane installation and automation.

The efficiency of the system depends on the processes, and how well it utilizes the flue gas. According to [7] above 115 % can be achieved. This however requires the gasification is connected to the direct firing process and high utilization of the flue gas. To achieve this, it also sets certain requirements to the fuel.

The maximum efficiency is not expected to increase, as it is close to maximum possible. The efficiency depends on the process, and how it is connected with the thermal gasification unit. For instance, if the producer gas is used as direct firing in the process, the efficiency will be strongly influenced by flue gas temperature. The lower the flue gas temperature is, the higher the efficiency is.

(xxvi) Direct and in-direct investment costs

The indirect costs will be too strong a function of the specific process to put into a single value. This could include rebuild of process equipment or installation of connections between thermal gasification and process equipment.

(xxvii) Related benefits and savings

Changing from solid fuel to gas could improve product quality as pollutants are reduced. The value of this will depend on the product and the type of fuel change. A further cleaning of the gas is also possible, with could increase the benefits and application potential, but it will require an additional investment. Other than that, there is not any obvious process improvements.

Uncertainty

Due to the variety of application potential for the technology some uncertainty must be expected. General averages have to be made to account for variations. This holds true for both the prices but also the efficiency of the technology.

In general, for the thermal gasification technologies: "Even though several plants have been in successful operation for several years the uncertainty regarding price and performance for future developments remains considerable. The data assumes considerable learning curve effects. However, there is a widespread number of different principles and variants of the technology, of which many are pioneer projects, and it is not clear which improvements can be realized, and how far." [4]

Additional remarks

Review of biomass gasification technologies [1] – in 2013.

Table 5: Review of stakeholders and area of operation

Stakeholder/Technology group/Company	Area of operation	Website
Ammongas A/S *n.a.2020*	Pilot and demonstration plants	www.ammongas.dk
Babcock&Wilcox Vølund	Demonstration and market introduction	www.volund.dk
BioSynergi Proces ApS *n.a.2020*	Demonstration plant, developing and marketing	www.biosynergi.dk
Dall Energy A/S	R&D, consultancy on demonstration plants	www.dallenergy.com
Danish Fluid Bed Technology ApS	Consultancy and R&D	www.ltcfb.com
DONG Energy *n.a.2020*	R&D, pilot and demonstration plants	www.pyroneer.com
Haldor Topsøe	R&D, pilot and demonstration plant and market introduction	www.topsoe.com
Organic Fuel Technology	Pilot plant (R&D and demonstration plants are part of the vision)	www.organicfueltechnology.com
TK Energy ApS	Development projects, demonstration plants	www.tke.dk
Weiss A/S *n.a.2020*	Demonstration plants	www.weiss-as.dk
Skive Fjernvarme I/S	CHP plant operation	www.skivefjernvarme.dk
AAEN Consulting Engineers A/S	Consultancy on demonstration plantt	www.aaenas.dk
Danish Gas Technology Centre	Research and development	www.dgc.dk
Danish Technological Institute	Education, R&D, pilot and demonstration plant	www.teknologisk.dk
FORCE Technology	RD&D, feasibility studies, market studies	www.forcetechnology.com

Company closures

Table 6: Companies active in the field of gasification in 2013 listed and their activity is described. Some of the company are not active in the field of thermal gasification in 2020, this is shown by n.a. 2020 added after the company name

EP Engineering ApS (company was ceased in September, 2013)	Pilot and demonstration plant	No longer in business
Stirling DK (company went bankrupt in 2013)	Pilot and demonstration plants, market introduction	No longer in business

Table 7: Gasification technologies in Denmark

Table 2. Gasification technologies in Denmark, adapted from [6]

Gasifier name	Stakeholder/ Technology owner/ Developer	Type of gasifier	Thermal fuel power MW_{th}	Purpose	Development stage
Alternating Gasifier	Ammongas A/S, Babcock & Wilcox Vølund A/S	Twin bed filter	200+	Fuel production (gas)	Pilot
Vølund Updraft Gasifier	Babcock & Wilcox Vølund A/S	Up-draft	15-200	CHP – IC engine	Commercial
The CHP system of BioSynergy	BioSynergi Proces ApS	Open core down draft	0-15	CHP – IC engine	Demonstration
Staged Down Draft Gasification	Risø DTU, Weiss A/S, Dall Energy, COWI A/S	Multiple steps sown-draft	0-15	CHP – IC engine	Demonstration
Pyroneer A/S	DONG Energy A/S, Risø DTU, Danish Fluid Bed Technology ApS	Low temperature circulating fluid bed	1-200	CHP – co-firing fuel	Demonstration
Tar reforming etc.	Haldor Topsøe		15-200+	Fuel (gas & liquid)	Commercial
Catalytic low temperature pyrtolysis process	Organic Fuel Technology A/S	Catalytic low temperature pyrolysis	1-15	Fuel (liquid)	New/Pilot
Biomass Gasification Gas Engine	Aaen Consulting Engineers, Skive District Heating, Carbona	Circulating fluid bed	15-200	CHP – IC engine	Demonstration
Unknown status of the technologies due to the companies closure					
Close Coupled Gasification (CCG)	*EP Engineering ApS*	*Vibrating grate fluid bed*	*0-1*	*CHP – steam engine*	*Pilot*
Stirling engine with up-draft gasifier	*Stirling DK ApS*	*Up-draft*	*0-1*	*CHP – Stirling engine*	*Commercial*
BlackCarbon	*Stirling DK ApS*	*Pyrolysis*	*0-1*	*CHP – Stirling engine*	*Demonstration*

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[1] http://www.volund.dk/Biomass_energy/Technologies/Gasification_of_biomass, accessed 2020

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[6] FLSmidth, https://www.flsmidth.com/en-gb/company/about-us/product-brands/pfister, accessed 2020

[7] Dall Energy, Personal communication, 2019

[8] IOGP, The potential for CCS and CCU in Europe, REPORT TO THE THIRTY SECOND MEETING OF THE EUROPEAN GAS REGULATORY FORUM 5-6, JUNE 2019

[9] https://vbn.aau.dk/ws/portalfiles/portal/123284438/A_review_of_biomass_gasification_technologies_in_Denmark_and_Sweden.pdf, accessed 2020

[10] IEA https://www.ieabioenergy.com/wp-content/uploads/2019/01/IEA-Bioenergy-Task-33-Gasification-of-waste-for-energy-carriers-20181205-1.pdf, accessed 2020

Quantitative Description

See separate Excel file for Data sheet and Application matrix

307 Hotdisc

Contact information

- Contact information: Danish Energy Agency: Jacob H. Zeuthen, jhz@ens.dk; Steffen Dockweiler, sdo@ens.dk
- Author: Niklas Bagge Mogensen, Viegand Maagøe

Brief technology description

The Hotdisc is a combustion device used to substitute calciner[22] fuel in the cement production process. The main advantages of the Hotdisc, is its ability to use waste as fuel and especially the size of the waste. It can burn a wide variety of solid waste e.g. whole truck tires [1], which eliminates the expense of shredding and in general treatment of waste before burning it. General information on cement production can be found in [2].

The Hotdisc has four inlets:

- Tertiary air (from clinker cooler)
- Alternative fuel (waste)
- Preheated raw meal
- Emergency cold raw meal (not in used during normal operation)

The alternative fuel is added to the Hotdisc and lands on the rotating disc, the hot tertiary air is added along with the preheated raw meal[23], together the three elements produces combustion gases, partly calcined meal and combustion residue [1]. The alternative fuel is transported on the rotary disc approximately 270° before reaching the scraper. The partly calcinated meal are discharged in the riser duct. The heavy residues fall down to the kiln inlet. The rotational speed of the rotating disc is controlled to minimize unburned fuel and limit unwanted emissions. The retention time can be up to 45 minutes.

[22] Calciner is a part of the cement production system. For general information on cement production see, [2]
[23] Raw meal is crushed limestone with additives such as clay, sand or iron ore result in the desired chemical composition

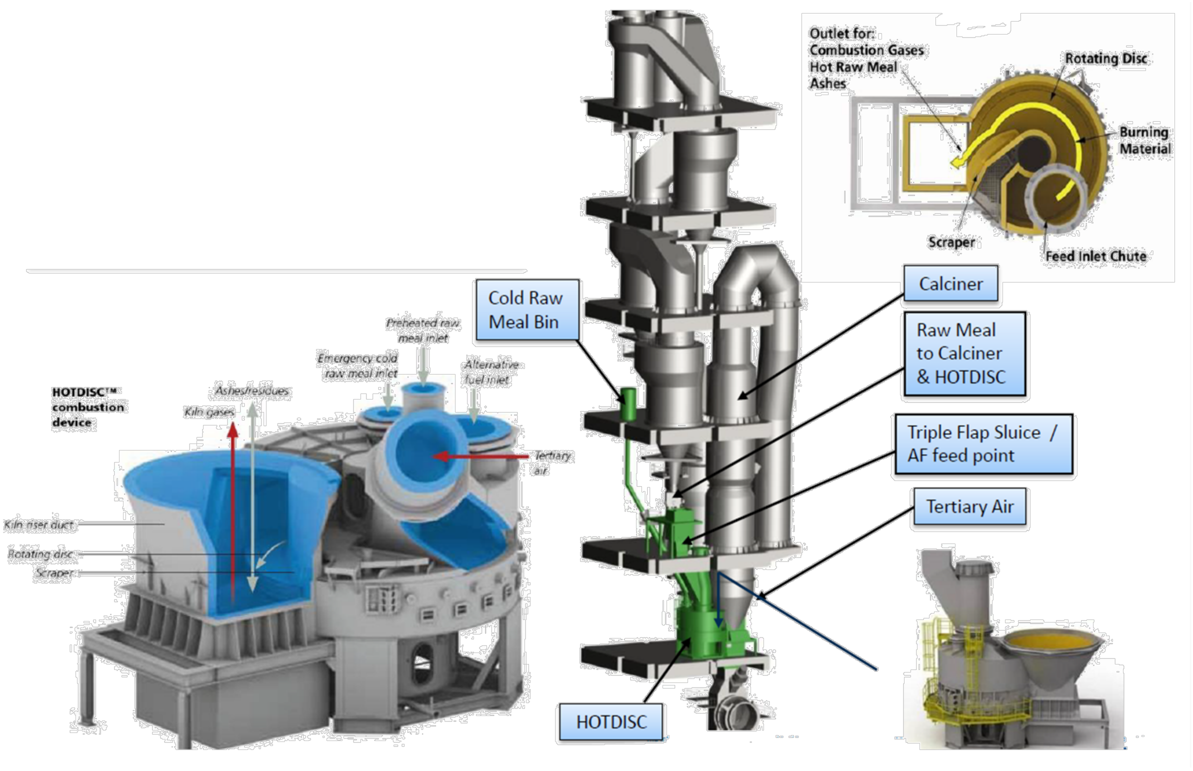

Figure 1: Illustration of Hotdisc with inputs and output and placement of Hotdisc in calciner system, from [1]

The Hotdisc can be retrofitted into existing system and incorporated into new systems. The calciner needs to be positioned directly above the kiln inlet, e.g. In-Line calciner kiln system [1]. Information on kiln systems can be found in [3].

Input

Waste in general, for instance whole tires, large chucks of wood and municipal waste. Biomass could also be used as fuel.

Other inputs are tertiary air and preheating raw meal, but these are considered a natural part of the cement production and are available.

Output

The output is heat, which substitutes calciner fuel. The ashes and residues fall down to the rotary kiln and becomes a part of the final product.

(xxviii) Applications

The Hotdisc can be used in In-line kiln systems in the cement production process. It is possible to rebuild a separate-line kiln system to use the Hotdisc system, but it will require an additional investment for kiln rebuilt.

1) Energy services

Table 1: Energy services

Energy services	Indirect	Direct
High temperature	*No*	*Yes*
Medium temperature	*No*	*No*

2) **Sector relevance**

Table 2: Sector relevance

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
Di	***High***	**no**	**no**	**Yes**	**no**	**no**

3)

4) **End- use relevance**

Table 3: End-use relevance

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firering / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Hotdisc	No	No	No	No	Yes	No	No	No

Typical capacities

The capacity ranging from 10-100 MW [4], assuming a 50 % substitution of the calciner fuel.

Typical annual operation hours and load pattern

Cement production are typical continuous production and yearly operation hours > 8000 hours, which will be the same for the Hotdisc, as it is an integrated part of the system.

Regulation ability
The Hotdisc can regulate down to 10 % of nominal capacity.

Advantages/disadvantages
The main advantage is the ability to use a wide variety of waste, and often with no treatment before burning.

Due to changing chemical reactions in the kiln line when substitution a fuel with another fuel, various measures has to be taken to adjust the operating conditions and process parameters to obtain the needed clinker quality. Hence substituting fossil fuels in the cement production can be challenging, but the Hotdisc function enables the possibility of substituting some of the fossil fuel.

It is a disadvantage that the Hotdisc only can be retrofitted into an In-Line kiln system. If the Hotdisc is to be implemented in a separate-line kiln system, it will require a rebuild of the kiln.

Hotdisc cannot easily be implemented in production of white cement, as the control of oxides in the mix is important, which is difficult to do with a Hotdisc. Hotdisc is only used for grey cement production, which lowers the potential.

At the moment the Hotdisc is limited to the cement production, which limit the potential usage of the technology.

Environment
The environmental impact is assumed equal the *WtE CHP and HOP plants*, see [5] and [6]. I practice it can vary and it will depend on the fuel and cleaning system at the specific site.

Potential for Carbon capture
If carbon capture is to be used, it would have to be for the entire kiln system, and not just the Hotdisc. The combustions gasses from the Hotdisc ends up in a shared chimney for the kiln system. The flue gas in the chimney included CO_2 from combustion as well as the CO_2 produced as part of the cement production, which enable potential for carbon capture.

Research and development perspectives
The Hotdisc is relatively simple and development is not expected to be significant for the disc itself, however to control of the waste may present certain possible improvements.

A Hotdisc that can be implemented in a Separate-Line kiln system could be a topic for further development.

Currently the Hotdisc technology, as described in this chapter, can only be used in the cement industry. It is however considered possible to redesign the system so it can be integrated in other rotary kiln processes and used in other sectors than cement industry. It will require manufactures to invest in development of the technology.

Research regarding utilizing Hotdisc for white cement production could also be an area of focus, but it will depend on the market demand and manufacturers.

Examples of market standard technology
In 2016 a total of 12 Hotdisc system were in operation, with the majority in Europe [7], however not in Denmark.

Prediction of performance and costs
The technology has been implemented for more than 15 years, and the system itself is fairly simple. The cost of the Hotdisc is only expected to decrease slightly in the future.

(xxix) Direct and in-direct investment costs

The indirect investment cost represents a potential rebuilt of the kiln system needed when covering more potential than *Current application potential,* assuming the current application potential covers a separate line kiln system.

(xxx) Related benefits and savings

Not relevant

Uncertainty

Hotdisc fully commercial (Category 4) with small uncertainties for costs. The individual kiln system in a retrofit may vary from installation to installation depending on how accessible the kiln system is.

Additional remarks

References

[1] FLSmidth A/S, Hotdisc combustion device, 2011
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[6] Danish Enegy Agency, Technology Data - Energy Plants for Electricity and District heating generation, 2016

[7] Ingeniøren, https://ing.dk/artikel/flsmidth-teknologi-goer-kinas-cement-groennere-187824, 2016

Quantitative description

See separate Excel file for Data sheet and Application matrix

308 Dielectric assisted heating

Contact information

- Contact information: Danish Energy Agency: Jacob H. Zeuthen, jhz@ens.dk; Steffen Dockweiler, sdo@ens.dk
- Author: Niklas Bagge Mogensen, Viegand Maagøe

Brief technology description

Dielectric heating is most commonly known as microwave heating. Microwave heating is best known from heating of food and water in larger kitchens or at home. When microwave heating is utilized in industrial processes it is most often microwave assisted heating and not only microwave heating as in domestic households.

Unfortunately, there is a lack of awareness of the possibilities for utilization of dielectric assisted heating for industrial processes, therefore the utilization of the technology in the industrial sector is low today.

The dielectric method is utilizing the dielectric features in the material heated. Dielectric features are the ability to convert high frequency electromagnetic waves into heat. The heat comes from energy losses when the waves goes through a non-conductive material and are stopped. The energy is transformed from electro-magnetic wave energy to thermal heat.

Table 1. Examples of conductive and non-conductive material [1]

Conductive	Non-conductive
copper	paper
aluminium	Teflon
platinum	glass
gold	rubber
silver,	oil
ionised water	asphalt
plants	fiberglass
iron	porcelain
steel	ceramic
brass	quartz
bronze	(dry) cotton
mercury	(dry) paper
graphite	(dry) wood
concrete	plastic
	air
	diamond
	water

The dielectric process is limited to heating of non-conductive materials where other electrical heating methods can be used for conductive material e.g. inductive heating which is know from heating of metal both in kitchens and during metal melting (high frequency induction).

There are two types of dielectric heating – microwaves and radio-frequency. Microwave frequencies are in the 900-3000 MHz and Radio frequency installations operate in the 10-30 MHz range. Industry has used both technologies since the 1940s [2].

A dielectric heating system consist of a microwave generator, waveguides and an application area.

Microwaves are generated in the generator with a magnetron, the microwaves are led via the waveguides to application chamber. The application chamber can be either a conveyer system or a batch system.

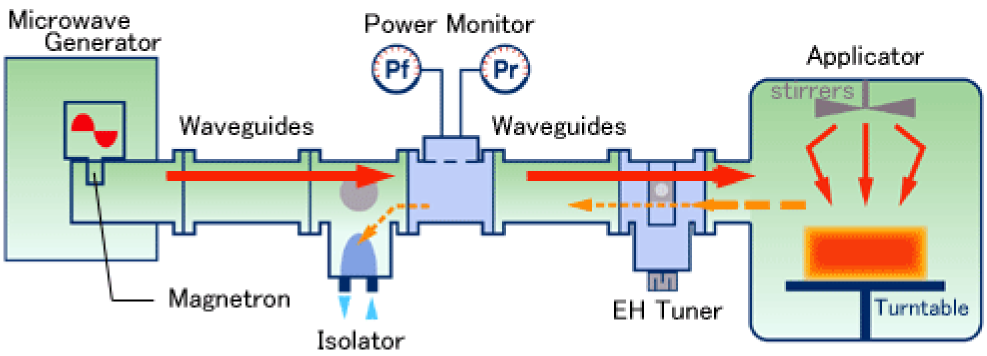

Figure 1: Schematic drawing of microwave system [7]

The Danish company Kallesøe Machinery makes equipment to cure and set EWP (Engineered Wood Product) glue, by means of radio-frequency heating. According to [2], a single 200 MW Kallesøe machine can process more than Hyne Timber's annual glulam[24] output in just one month. It is also stated in [2] that, radio-frequency curing is also extremely energy efficient as it heats only the glue, without heating the wood at all. Compared to curing in a gas-fired kiln, it uses less than 10% of the energy.

Figure 2: Kallesøe timber press [2]

Citation from Microwaves&RF [3]:

"The firm supplies systems for microwave drying and sterilization at 915 and 2450 MHz. The systems can process both solid and liquid foods while preserving the essential nutrients within the food, as well as preserve its appearance and flavour. Such microwave heating/drying systems are considered "environmentally friendly" for their lack of exhaust gases and efficient use of electrical energy."

[24] Wood glued together

Figure 3. Industrial microwave heating system (Max Industrial Microwave)

Citation from Bi. Elle Microwave Engineering Company [4]:

“Microwave technology ensures a drastic cut in treatment times in the following applications:

COOKING – HEATING DE-FREEZING – DRYING – DEHYDRATION – BULK AND PACKED PRODUCT PASTEURISATION”

Another usage of dielectric heating is the EcoPalm treatment method. The EcoPalm is used in sterilization of palm trees from the deadly RPW beetle [8].

Figure 4: Pictures of EcoPalm [8]

Efficiency

The primary loss originates from cooling of the microwave generator. The heat removed by the cooling process can rarely be utilized in the process and represent a loss which decreases efficiency.

The efficiency is in the range 85-99 % and depend on the system integration.

Input

The input is electricity.

Output

The output is heating of process. The heat from cooling of the microwave generator could potentially be used for other purposes.

(xxxi) Applications

Industries are able to use microwave assisted heating for several processes. The potential energy saving is estimated as high as 30% or even 50% of current energy consumption as shown in

Table 2 and in the Brick example below [5].

Table 2 Use of electrical heating in Danish Industry by Birch & Krogboe A/S (Elforsk), 2003[5].

Industrial sector	Electricity consumption	Current heating method				Potential shift in technology	Expected saving potential
	[GWh/y]	Resistant	IR	Induction	Dielectric		[GWh/y]
Bakeries	54	X				IR or dielectric	0-19
Wood	24	X				Dielectric	3-10
Paper	4		X				0
Pharmaceutical	10	X				Dielectric	1-2
Production of cleaning agents etc.	4	X				Dielectric	0-1
Plastic	19	X				Dielectric or IR	3-5
Iron and metal	63	X	X	X		Induction	5-20
Furniture	18	X				Dielectric	1-4
Total industry	**197**						**13-52**

R&D has also been focused on the use of microwave heating of less traditional processes as brickworks [6]. The results are positive and will be able to limit the energy consumption and especially the emissions from the traditional fossil fueled heated brick process. However, needs the final push through full scale testing.

The main advantages from using microwave heating of brickworks [6] are::

- Up to 50% reduction in energy consumption
- 30-50% reduction of burning time
- Improved product quality (more uniform heating and therefore lower maximum temperature)

The current use of dielectric heating in Denmark is limited. This is most likely caused by lack of knowledge, need for changes and relatively high electricity cost compared to traditional use of fossil fuels. The potential for use of dielectric heating is described below:

Table 3: Potential applications of dielectric heating

End-use	Relevance	Sector-comments
Heating / Boiling (1)	Relevant	Food processing and kitchens
Drying (2)	Relevant	Food, Pharmaceutical, Chemical Paper, Wood, Cement construction
Dewatering/concentration (Evaporators)	Limited relevance	
Distillation (3)	Limited relevance	Small volumes - microwave accelerated steam distillation (MASD)
Firing/Sintering	Relevant – need demonstration	Brick sector
Melting/Casting (4)	Partly relevant	
Other processes up to 150°C (5)	Currently not relevant	Plastic
Other processes above 150°C (5)	Currently not relevant	

1) Energy services

Dielectric assisted heating applies heat directly to the product and is considered direct heating. The technology can however substitute currently indirect systems and is therefore also considered relevant for indirect potential. For instance, a sterilization process is often performed with the use of steam, but some sterilization processes could utilize dielectric heating instead.

Table 4: Energy services

Energy services	Indirect	Direct
High temperature	*No*	*No*
Medium temperature	*Yes*	*Yes*

2) Sector relevance

Dielectric heating cannot be used with conductive materials, witch excludes the metal dominated sector, 5. Metals, machinery and electronic.

Table 5: Sector relevance

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
Di	***High***	**yes**	**yes**	**yes**	**yes**	**no**

3)

4) End- use relevance

Dielectric heating can be used for heating/boiling and drying. It could in theory also be used for distillation and to some extend firering/sintering (Brick sector). It is however not considered relevant at the current state of the technology deployment.

Table 6: End-use relevance

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firering / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Dielectric assisted heating	Yes	Yes	No	No	No	No	No	No

Typical capacities

The typical capacities are in the range of 1-1000 kW.

Typical annual operation hours and load pattern

The annual operation hours and load pattern is highly dependent on the dielectric heating application.

Regulation ability

The microwave system has almost no start up time. For batch production the regulation is on/off operation. For continuous process, the system regulates the load, according to the flow of the process stream.

Advantages/disadvantages

The main advantages of using microwaves are according to Bi.Elle [4]:

- Treatment times are up to 20 times faster than traditional systems = maximum velocity + minimum heat loss.
- Oven to "cool walls": the microwaves heat only the product = maximum economy.
- It does not require preheating and wait time at start-up = maximum efficiency.
- It has no thermal inertia during starting and stopping = maximum performance.
- It can be turned on or off by signals from other machines = maximum automation.
- The microwave does not need operator for operation = maximum autonomy.
- The microwave does not need maintenance = maximum reliability.

Another advantage is the possibility to obtain more flat temperature profile through the product and thereby lower the maximum temperature in the product. A flatter temperature profile decreases thermal stress in the material.

Disadvantages are:

- Limited lifetime operation hours of the microwave generator, approximately 10.000 hours.
- Cannot be used to process conductive materials
- Requires homogenous process stream in some applications, e.g. baking industries, if the distribution of water concentration is uneven, the product will not bake/cook evenly.
- Electricity cost is higher than the cost for the alternative fuel (often gas).
- Not relevant for all material because microwave ingress depends on material properties of the actual product

Environment

Not relevant, the utilized electricity.

Potential for Carbon capture

Not relevant, the utilized electricity.

Research and development perspectives

The dielectric heating technology is well known, but the end-use chamber (application chamber) is often specifically designed for the purpose in question, which requires development to some extent.

Examples of market standard technology

The application variety of dielectric heating covers a large span, which makes it difficult to name a market standard technology. The dielectric heating technology can either be dielectric heating only or it can be dielectric assisted heating. An example of the latter is a continuous tunnel system in the food industry which utilizes both dielectric heating and hot air. [8]

Some of the manufacturers are [3]:

- Max Industrial Microwave
- Cellencor
- Advanced Microwave technologies
- Bi.Elle

Prediction of performance and costs

The microwave generation itself is well known and considered a category 4. on the learning curve. Therefore, only a small decrease in investment cost are expected. The efficiency is not expected to increase noteworthy in the future.

(xxxii) Direct and in-direct investment costs

A dielectric heating system is typically installed with a single purpose in the process and cannot contribute elsewhere in the process. Direct and in-direct investment costs are not relevant, as a system is installed with one purpose, and an additional investment will not increase the potential of the system.

(xxxiii) Related benefits and savings

It has previously been mentioned that dielectric process heating can increase production speed, and thereby decrease heat loss compared to alternative systems. In specific applications, the heating method can have a positive effect on the chemical composition in a mixture. In certain applications in the food industries, dielectric heating can preserve flavor better than alternative technologies.

Uncertainty

The cost of the microwave generator is fairly well described, but the waveguide and the application chamber design can vary a lot, which make the cost very application dependent. An uncertainty of 50 % in investment cost can be expected.

Most of the systems are dielectric assisted heating and thus dependent on the secondary system, which also represents an uncertainty.

Additional remarks

It is expected that dielectric assisted heating will have a natural market pull. Implementation of dielectric heating is expected to happen when a factory increases production. 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 %

Dielectric heating bear resemblances to inductive heating, as the heating process does not rely on conductive heating in the material.

References

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Quantitative description

See separate Excel file for Data sheet and Application matrix

309 Infrared heating

Qualitative description

Contact information

- Contact information: Danish Energy Agency: Jacob H. Zeuthen, jhz@ens.dk; Steffen Dockweiler, sdo@ens.dk
- Author: Niklas Bagge Mogensen, Viegand Maagøe

Brief technology description

Infrared (IR) systems emit infrared radiation that can be used to heat an object. Infrared systems can both be gas fired or electrical driven. This chapter focus on electrical driven heaters.

Electrical infrared systems have been used in industrial heat processes since the 1930s. [1]

Infrared heat is waves of electromagnetic radiation and has a frequency of 30-400 THz (1000-0,78 µm) [1]. The wavelengths and placement of infrared radiation in the electromagnetic spectrum can be seen in Figure 1.

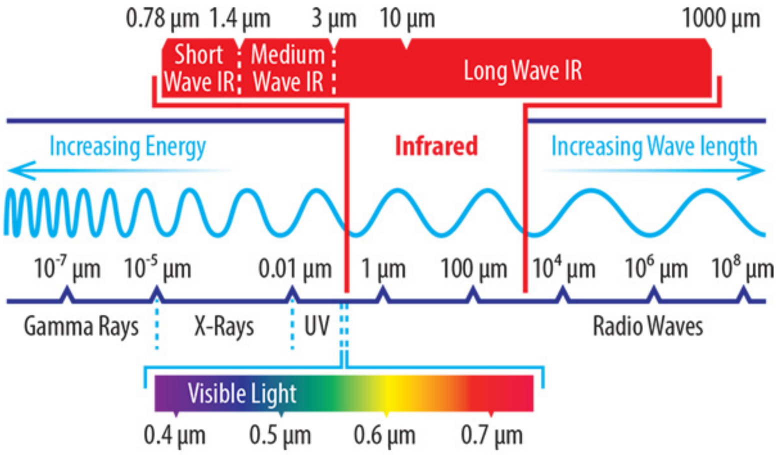

Figure 1: Infrared in the electromagnetic spectrum [2]

For industrial purposes these infrared waves are utilized in three subdivisions, as shown in Figure 2:

- Shortwave (near infrared)
- Medium wave (mid infrared)
- Long wave (far infrared)

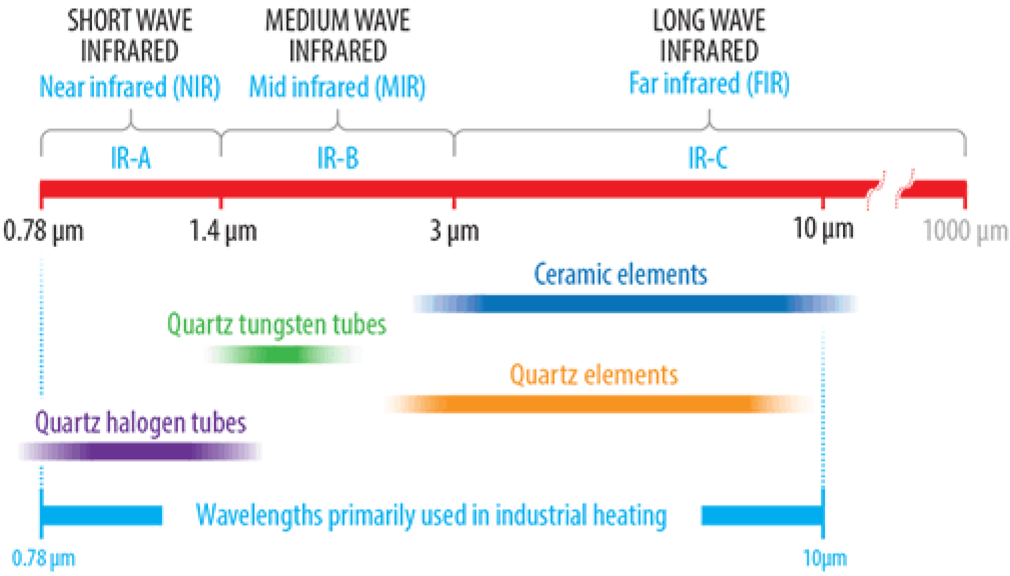

Figure 2

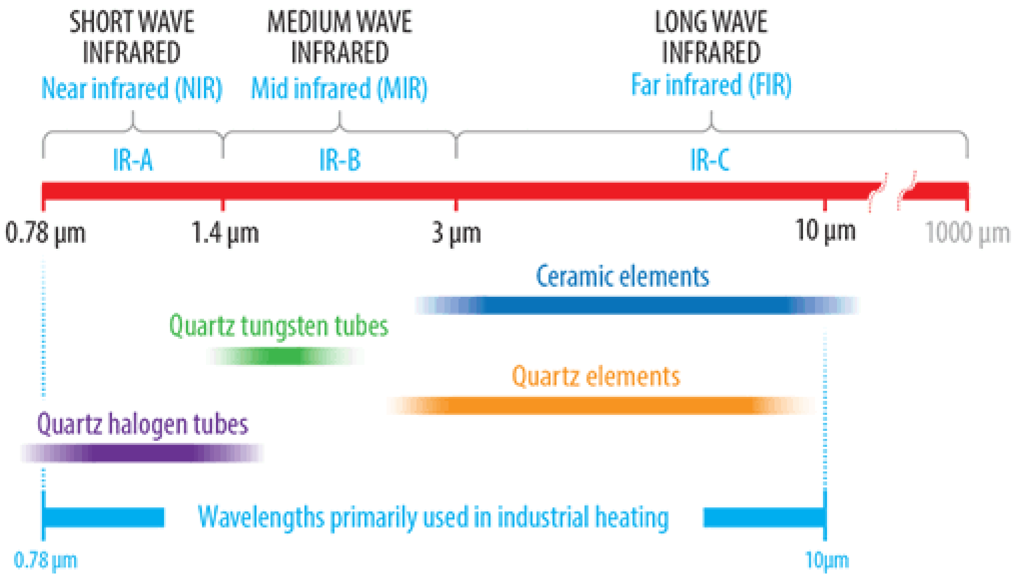

Figure 2: Infrared subdivisions and types of infrared element for different wave length

For more theoretical explanation of infrared wave and heating principle, see [2].

Infrared heating is highly efficient for heating of surfaces, and often many times faster than a gas oven. Radiant energy heats material directly, in contrast to a gas convective oven which heat the surroundings of the material to a higher temperature than the target temperature. [1]

"Infrared systems are designed according to the temperature requirement and the ability of the target material to absorb infrared radiation. In general, shorter infrared wavelengths correspond to higher power densities and can reach very high temperatures of over 2,000°C. The temperature and intensity of infrared systems can be adjusted for different products and can even heat different sections of an object to different temperatures. For example, infrared can be

calibrated to heat the surface of a coated object while passing unabsorbed through the coating itself."[1].

Efficiencies

The conversion of electricity to heat is 100 % for an infrared heater. Not all the electricity is converted to radiant heating [3], some is converted to convective heating, which depending on the system setup can present a loss, which lowers the efficiency slightly. According to [2] the conversion from electricity to radiant heating is 80-95 %. If the convective heating also is utilized, then the efficiency could reach 100 %. The application where the infrared heaters are considered in this chapter are close to the product to heated, which enable high efficiency. Total electricity to heat efficiency of > 95 % is expected.

Input

The input is electricity.

Output

The output is process heating.

(xxxiv) Applications

Infrared heating has many application possibilities, according to [1] it can be used in the following processes:

- Curing
- Drying
- Gluing
- Laminating
- Melting
- Preheating
- Shrinking
- Soldering
- Sterilization
- Tempering.

It is important to notice than many of the applications listed above are minor end-use energy intensive consumers. Meaning that even though infrared heating has many application possibilities, the application potential based on energy amount, is not high.

Figure 3 gives examples of utilization of the different subdivisions of infrared heating.

	Wavelength (µm)	Emitting temperature	Power density (kw/m2)	Response time	Efficiency*	Applications
Near infrared	0.76—1.2	1800-2,500°C	160-300	<1 sec	85-95%	Drying coatings, paper, textiles. Deeper penetration for baking, roasting etc
Medium infrared	1.2-3	800-1,800°C	40-160	<30 sec	80-85%	Efficient surface heating of glass, plastic, water.
Far infrared	3-10	400-600°C	10-40	5 minutes	50-60%	Food processing. Space heating in buildings such as factories.

**Conversion of electrical energy into radiant heat.*

Figure 3: Examples of utilization of infrared, from [1] (response time is the time to heat up).

Infrared heating can both be an individual heating process or act as assisting heating process in e.g. drying. Infrared heating is commonly used in drying processes in the paper industry.

1) Energy services

Infrared heating installations are considered direct heating. Infrared heating is assumed to be able to substitute currently indirect heated processes and is therefore also included as having an application potential as an indirect energy service.

Table 1: Energy services

Energy services	Indirect	Direct
High temperature	*Yes*[25]	*Yes*[1]
Medium temperature	*Yes*	*Yes*

2) Sector relevance

Table 2: Sector relevance

[25] Could theoretically be used for high temperature energy services, but no high temperature end-uses in Denmark are considered relevant for Infrared heating

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
Di	***Medium***	**yes**	**yes**	**yes**	**yes**	**yes**
In	***Medium***	**yes**	**yes**	**yes**	**yes**	**yes**

3)

4) End- use relevance

Infrared heating can be used melting purposes, but it is not considered relevant in Danish manufacturing industries.

The end-uses with far largest application potential are drying and heating processes.

Table 3: End-use relevance

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firering / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Infrared heating	Yes	Yes	No	No	No	No	No	No

Typical capacities

Typical capacities are from 10 kW to 200 kW, [4].

Infrared heating systems most often consist of modular build heating elements, making the capacity vary flexible.

Typical annual operation hours and load pattern

Typical annual operation hours and load pattern for infrared heating can vary to a great extent depending on the application.

Infrared heating technology can be either batch or continuous production. The annual operation hours are estimated to be in the span 1000-8000 hours.

Regulation ability
Infrared heating elements are either on or off, however infrared heating system can be modular consisting of many heating elements, which enable part load regulation and the possibility of a low load level. Regulation down to 10 % is not uncommon, but most typical regulation is on/off.

Advantages/disadvantages
Advantages:

Infrared heating systems heats objects rapidly. For some common materials the heating times is 7 to 40 times faster than gas ovens [1].

The technology has a very fast response time, it heats up and cools down in seconds.

The system is often more compact than traditional alternative systems.

Infrared heating is precise and able to control target temperature +/- 0,5 °C [1].

Modular design, which is easy to integrate into existing production systems.

Provides clean production as it has no contact with the product on the contrary to convective heating which can cause contamination [1].

Disadvantages:

Infrared heating is a line-of-sight technology, which can be a challenge if the product has complex curved parts.

The heating elements has a limited lifetime of 10.000 hours, before they need to be replaced. This increases planed outrage time could lead to reduced time in operation.

The investment cost is high, and each infrared installation often requires individual dimensioning.

Lack of reference plants.

Environment
Not relevant.

Potential for Carbon capture
Not relevant.

Research and development perspectives
The technology is well known and tested. The main focus is how to incorporate infrared heating technology in relevant processes and expand the horizon of application potential.

Examples of market standard technology
The infrared heating itself is a well-known and standard heating element. As shown in Figure 2, four types of infrared heating element and tubes are common.

- Ceramic elements – best for processes requiring even & gentle heat, and need of zone control [6]
- Quartz elements – best for instant on/off with high watt density [6]
- Quartz tungsted tubes – best for instant on/off such as heat sensitive materials [6]
- Quartz halogen tubes – best for high watt density

More information on different types of infrared emitters can be found at [7].

Even though the infrared heating emitters are well known, a standard for application utilization is not a present. The infrared heating elements are often built to the specific case.

Examples of applications are:

Case story - Queen City Forging, heating billets
Preheating of aluminum billets to 425 °C prior to hot-forging. The electric infrared heating elements are tungsten halogen quartz lamps.

Figure 4: Queen City Forging - heating billets, from [1]

This system Figure 4 achieved energy savings of 65 % compared to convection gas heating. Decrease of preheating time from 6 hours to 18 minutes. Heat treatment time reduced from 10 hours to 1 hours. Even the product quality increased. [1]

Case story - Outdoor South, curing paint
A US metal fabricator makes painted cargo racks**.** Before implementation of infrared system, the paint was cured in a gas oven, in batch operation. After implementation the system operates with continuous flow, and the cures the paint in 4 minutes. The production speed increased by eight-fold, which also increased the production capacity. Also, here the quality increased. [1]

Prediction of performance and costs

No significant reduction in cost and performance are expected. This is due to well-known technology and specially designed and dimensioned systems for each application. The lack of standard systems decreases the possibility for cost reduction as function of installed systems.

The infrared heating technology itself are classified as a category 4, *Commercial technology with large deployment*. It is important to emphasize that the classification is meant for the infrared technology itself and not the systems in industrial processes, as these does not have large deployment and are classified as a category 2.

(xxxv) Direct and in-direct investment costs

Not relevant, systems are installed at the of heating demand, and an additional in-direct investment cost will not increase the application potential.

(xxxvi) Related benefits and savings

Related benefits and savings are energy savings from shorting the production time and thereby the heat loss.

Decreases processes time, which can increase the production capacity.

In some cases, an important benefit is improved product quality.

Uncertainty

The uncertainty of the investment cost is high, ± 50% can easily be expected. The large uncertainty originates from sparse information on investment cost as the technology is not widely used in industrial processes. Furthermore, it is difficult for manufactures to estimate the investment cost. An infrared heating system for industrial processes vary to a great extent, this also impact the share of the infrared heating element of the total investment cost.

The cost of the heating element itself is fairly certain, but the amount of subsystems around the heating element vary, make the specific cost highly uncertain.

Additional remarks

None.

References

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Quantitative description

See separate Excel file for Data sheet and Application matrix

310 Electric boilers (industrial process heating)

Contact information

- Contact information: Danish Energy Agency: Jacob H. Zeuthen, jhz@ens.dk; Steffen Dockweiler, sdo@ens.dk
- Author: Niklas Bagge Mogensen, Viegand Maagøe

Brief technology description

This chapter describes electric boilers in the MW size range 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], 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 boilers. Electrode systems are used for larger applications. Electrode boilers (larger than a few MW) are directly connected to the medium to high voltage grid at 10-15 kV (depending on the voltage in the locally available distribution grid).

The chapter describe boilers used for high-pressure hot water and for steam production and the difference between these two types.

From [1], 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*** *flow through the upper chamber and the power that is led through, thus enabling output to be controlled between 0 and 100 %.* The heat production and power outtake also depends on the temperature of the water and the conductivity of the water.

In a similar technology, the heat output is varied, by varying the contact area between water and electrodes, by covering the electrodes in control screens. Thus, the contact area between water and electrodes can be varied by varying the water level around the electrodes." This type of boiler is no longer on the marked.

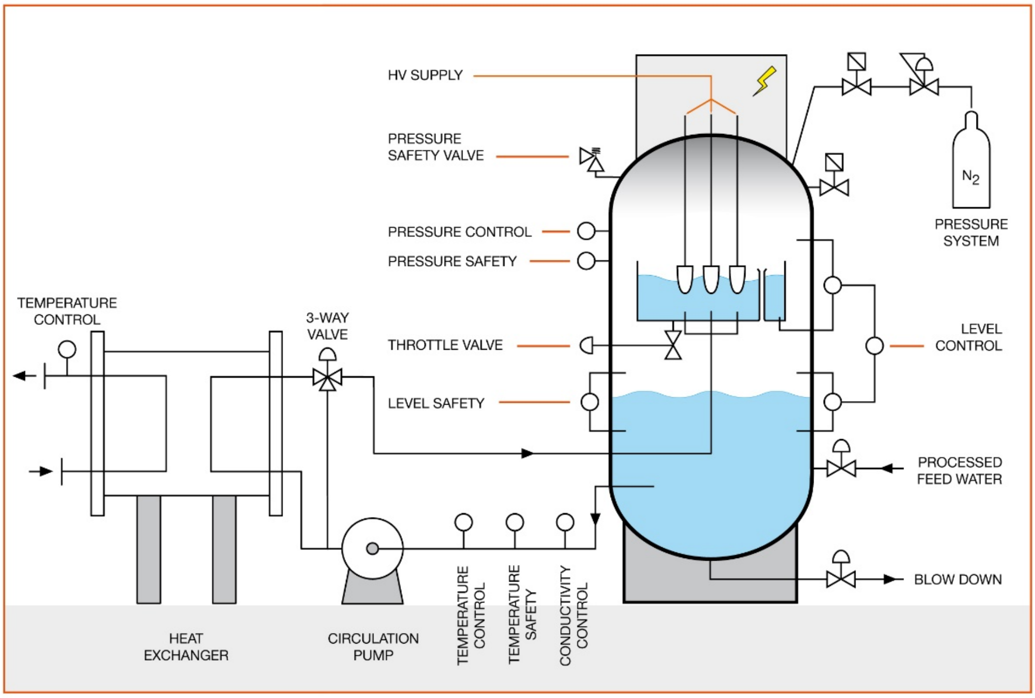

Figure 1: Schematic illustration of an electrode boiler for hot water production, [2]

Figure 1 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 circulation pumps.

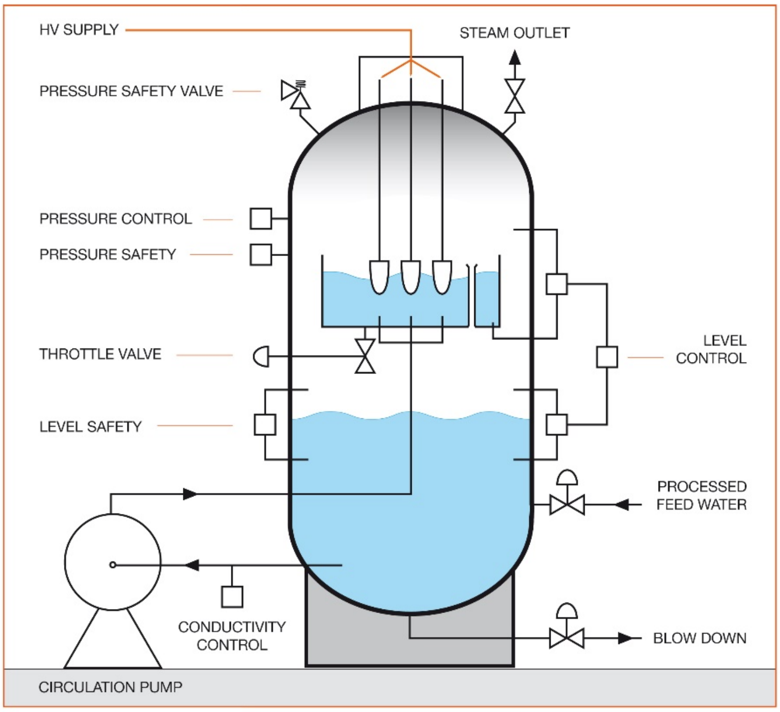

Figure 2: Schematic illustration of an electrode boiler for steam production, [2]

Figure 2 illustrates the production of steam. This system does not have a heat exchanger and the steam produced in the boiler is supplied directly to the steam system. The feed water needs water treatment before inlet to the boiler. The **optimal** conductivity of the feed water should be less than 2 µS/cm. Higher concentrations can be used but will result in more blow-down water.

Input
Input is electricity at medium to high voltage 6.3-22 kV.

Output
Steam or high-pressure[26] hot water.

(xxxvii) Applications

1) Energy services
Table 1 shows the energy service for steam boilers.

Table 1: Energy services, electric steam boiler

Energy services	Indirect	Direct
High temperature	*Yes*	*No*
Medium temperature	*Yes*	*No*

Table 2 shows the energy service for hot water boilers.

Table 2: Energy services, electric hot water boiler

Energy services	Indirect	Direct
High temperature	*No*	*No*
Medium temperature	*Yes*	*No*

2) Sector relevance
Table 3 shows the sector relevance for steam boilers.

Table 3: Sector relevance, electric steam boiler

[26] Typically 2-13 bar

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
in	***Medium***	**yes**	**Yes**	**yes**	**yes**	**yes**
in	***High***	**yes**	**yes**	**yes**	**yes**	**yes**

Table 4 shows the sector relevance for hot water boilers.

Table 4: Sector relevance, electric hot water boiler

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
in	***Medium***	**yes**	**Yes**	**yes**	**yes**	**yes**
in	***High***	**no**	**no**	**no**	**no**	**no**

3)

4) End- use relevance

Table 5 shows the end-use relevance for steam boilers.

Table 5: End-use relevance, electric steam boiler

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firering / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Technology n	Yes	Yes	Yes	Yes	No	No	Yes	Yes

Table 6 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.
Hot water boiler will only be able to cover an insignificant share of *Other processes > 150 °C,* and is therefore not included as end-use relevancy.

Table 6: End-use relevance, electric hot water boiler

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firering / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Technology n	Yes	Yes	No	Yes	No	No	Yes	No

Typical capacities
Electrode boilers are available in the seamless span 0-60 MW/unit, with typical appliances being 5- 50 MW/unit [1].

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.

Regulation ability
See [1]

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].

Potential for Carbon capture
Not relevant

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]

Prediction of performance and costs
The electric boilers are very similar to the one described in [1], and the prediction of cost and performance follows the same trend. The cost of high-pressure hot water boilers is identical to the one described in [1]. The cost of steam boilers is slightly higher due to larger boilers [2], but it also follows the trend of [1].

(xxxviii) Related benefits and savings
Not relevant

Uncertainty
See [1]

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 could also be installed as a supplement and only operate a favorable electricity price.

References
[1] Danish Energy Agency, Technology Data - Energy Plants for Electricity and District heating generation, 2016, Version 5.

[2] AS:SCAN Industries, Personal communication, webpage: http://www.as-scan.com/, 2019

Quantitative description
See separate Excel file for Data sheet and Application matrix

311 Traditional Steam and Hot Water Boilers

Qualitative description

Contact information

- Contact information:
- Author: Niklas Bagge Mogensen, Viegand Maagøe

Brief technology description

This chapter focus on different types of boilers in industry, with main purpose of steam or hot water production. 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 boiler is that they include a furnace which heats pressurized water and produces steam or hot water distributed across an industrial site for multi-purpose heating demands.

Condensing the flue gas from gas fired boilers can increase the efficiency with up to ~11.8% [1], by utilizing the latent heat of the water vapor in the flue gas. As coal does not produce water, this cannot be done in this process. Flue gas from oil combustion contains pollutants that would heavily corrode the heat exchangers surface if condensed and is thus not an option.

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 is depicted. Hot water and steam can be produced on both types. Wood and coal, if not pulverized, are most suited for water tube boiler. Oil and gas can be used in both.

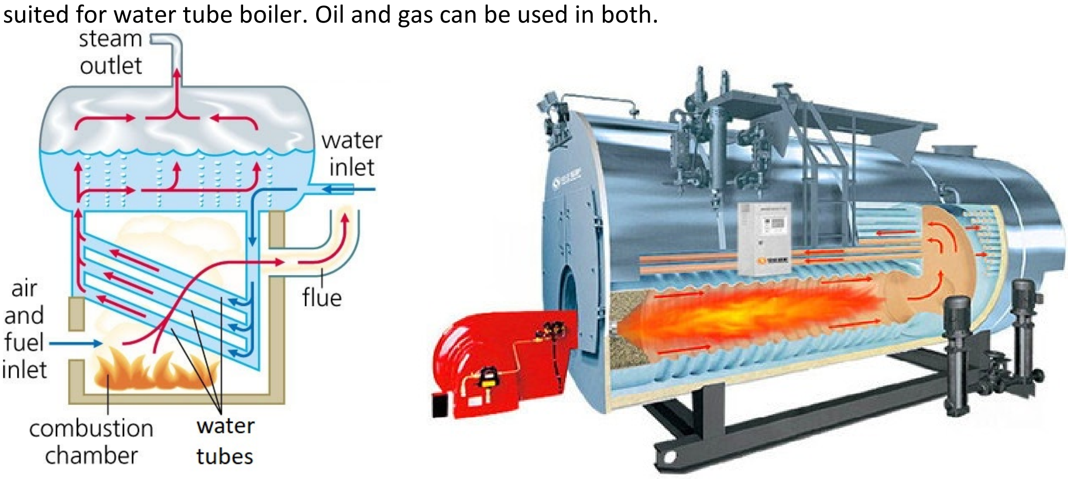

Figure 1: Schematic of a furnace producing steam or hot water. (Left) is a water tube boiler and (Right) is fire tube boiler.

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

The boilers used for hot water and steam are almost identical in working principle [4].

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 equal 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 2-60 bar, but most typical in the range 7-25 bar. Resulting in temperatures in the range of 125-300 °C.

(xxxix) Applications

The boilers can be used to produce steam or hot water. The application potentials are described in the AP matrix as *Current application potential* and *Full application potential. Current application potential* is relevant for hot water boilers, as these are not as widely used as steam boilers. If hot water boilers are to be installed on a site with existing steam system an additional investment cost for pipe installation must be expected (in-direct investment cost). To increase the application potential from *Current application potential* to *Full application potential,* the indirect investment cost must be included, see Direct and in-direct investment costs.

1) Energy services

Table 1 shows the energy service for steam boilers.

Table 1: Energy services, steam boiler

Energy services	Indirect	Direct
High temperature	*Yes*	*No*
Medium temperature	*Yes*	*No*

Table 2 shows the energy service for hot water boilers.

Table 2: Energy services, hot water

Energy services	Indirect	Direct
High temperature	*No*	*No*
Medium temperature	*Yes*	*No*

2) Sector relevance

Table 3 shows the sector relevance for steam boilers.

Table 3: Sector relevance, steam boiler

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
in	***Medium***	**yes**	**Yes**	**yes**	**yes**	**yes**
in	***High***	**yes**	**yes**	**yes**	**yes**	**yes**

Table 4 shows the sector relevance for hot water boilers.

Table 4: Sector relevance, hot water boiler

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
in	***Medium***	**yes**	**Yes**	**yes**	**yes**	**yes**
in	***High***	**no**	**no**	**no**	**no**	**no**

3) End- use relevance

Table 5 shows the end-use relevance for steam boilers.

Table 5: End-use relevance, steam boiler

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firering / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Steam boiler	Yes	Yes	Yes	Yes	No	No	Yes	Yes

Table 6 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.

Hot water boiler will only be able to cover an insignificant share of *Other processes > 150 °C* and is therefore not included as end-use relevancy.

Table 6: End-use relevance, hot water boiler

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firering / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Hot water boiler	Yes	Yes	No	Yes	No	No	Yes	No

Typical capacities

The typical capacity is in the range 1-50 MW.

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 does not include a buffer tank (the boiler itself act as a buffer to some extend). 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 %[27]	15 %

Advantages/disadvantages

The advantages/disadvantages for coal, natural gas and biogas and wood boilers are described in [3] and will not be elaborated further in this chapter.

The advantages/disadvantages for oil boilers are described in [2] and will not be elaborated further in this chapter.

Environment

The environmental aspects for coal, natural gas and biogas and wood boilers are described in [3] and will not be elaborated further in this chapter.

The environmental aspects for oil boilers are described in [2] and will not be elaborated further in this chapter.

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 having net zero CO_2 emission, 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 new type of the technology is to utilize updraft gasification and gas combustion of biomass. This makes the plant much simpler and possible 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 biogas, additional sulphur cleaning may be required.

Examples of market standard technology

Examples of market standard for coal, natural gas and biogas and wood boilers are described in [3] and will not be elaborated further in this chapter.

Examples of market standard for oil boilers are described in [2] and will not be elaborated further in this chapter.

- [27] [3], Wood Chips, HOP,6 MW feed

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].

(xl) Direct and in-direct investment costs

The indirect investment cost represents additional piping installation needed if increasing the *Current application potential* to *Full application potential.*

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 purpose (output) but overall description and working principle are similar.

Coal is seldom used 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.

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Quantitative description

See separate Excel file for Data sheet and Application matrix

312 Direct Firing

Qualitative Description

The qualitative description consists of a technology and application review.

Contact information

- Contact information: Danish Energy Agency: Jacob H. Zeuthen, jhz@ens.dk; Steffen Dockweiler, sdo@ens.dk
- Author: Niklas Bagge Mogensen, Viegand Maagøe

Brief technology description

Direct firing consists of a heating element either burning fuel or electrically heating a process stream directly, in comparison to indirectly heating with a media e.g. steam. The unit will consist of a fan, and a burner or an electric heater. Fuel will be supplied either via an electrical cord, a fuel pipe or, for solid fuels, a more complex feed and milling system. Today the simplest and widest used burners are for gaseous or liquid fuels, an example can be seen in Figure 1. These can be used for almost all purposes and direct firing technology is spanning wide in terms of areas of usage.

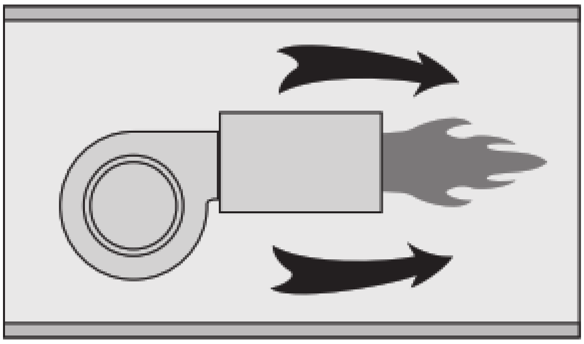

Figure 1: A burner in a duct [10].

A variety of fuels can be used depending on the process, and burners can be flexible to burn multiple different fuels. See an example in Figure 2.

Figure 2: Multifuel burners.

Left: Multifuel burner from FLSmidth (JETFLEX). "It fires rotary kilns with pulverised coal or coke, oil, natural gas, or any mixture of these fuels. Alternative fuel firing of plastic chips, wood chips and sewage sludge can also occur through the same common fuel channel" [11].

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" [12].

Due to the variety in the application and thus the variety in the adaption 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 present in an airstream, which will always be the case for oxidizing burners but not always the case for electricity. Changing a directly fired glass furnace to an electric would involve changing major components and installing electrodes directly in the melt, see Figure 3.

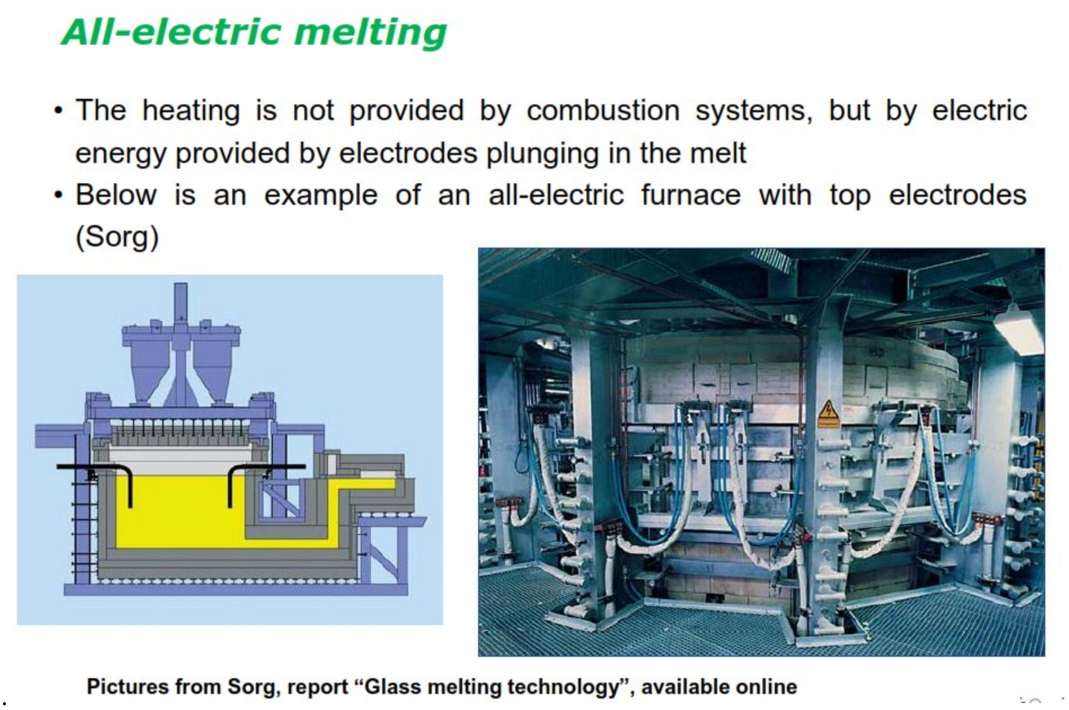

Figure 3: Electric glass furnace - slide from [8].

This is not comparable investment wise with other electrically "direct fired" process. Another example is rotary kilns which, depending on process, can be converted to electricity. This will also require considerable funds in the form of a new kiln, compared to changing a burner. An example of an electrically powered kiln can be seen in Figure 4.

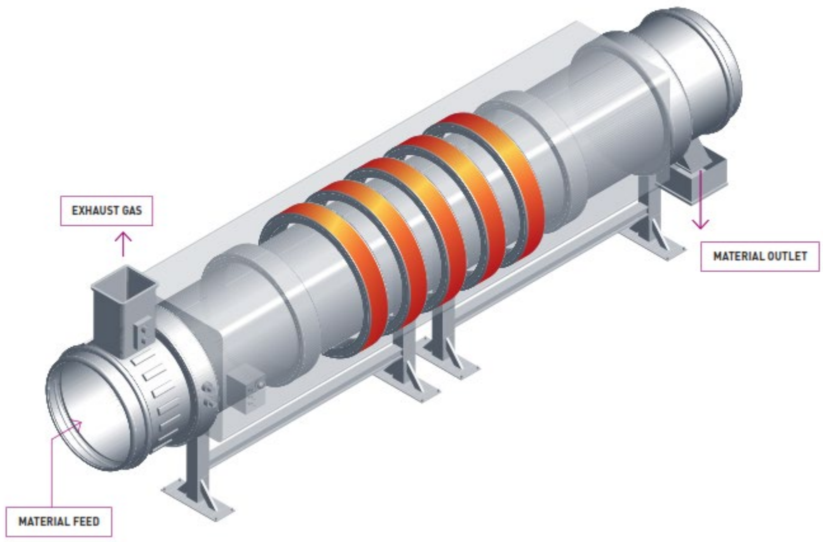

Figure 4: Electrically heated Kiln [9].

Depending on the process the efficiency will vary, however since it is direct firing, it the combustion is total all of the available energy in the fuel will enter the air stream. What determines the overall efficiency of the system is how the flue gas is utilised to preheat inlet air and product streams. The hotter the flue gas is discharged to the surroundings the greater the loss.

For some processes using electricity could be advantageous as a fresh supply of oxygen to burn the fuel is not necessary and the flue gas loss 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 is set to 100% (in relation to lower heating value).

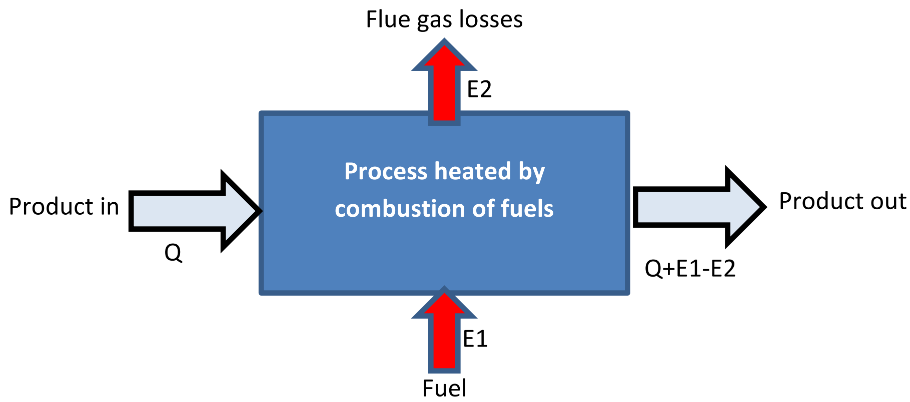

Figure 5: Energy balance of a direct firing process.

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 a low temperature (<100 °C) whilst cement industry will take place at >1000 °C and a glass furnace at upwards of 1500 °C.

(xli) Applications

Direct firing can be used in any processes that requires direct heating. The process will determine which type of fuel can be used.

1) Energy services

Direct Firing is as the name indicates only applicable in processes which can accept direct heating from flue gas or heated air stream. The energy services are shown in Table 1.Table 1: Energy services

Table 1: Energy services

Energy services	Indirect	Direct
High temperature	*No*	*Yes*
Medium temperature	*No*	*Yes*

(xlii) Sector relevance

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

Natural Gas: Can be used for any process at any temperature, one exception is made to some plastic molding equipment, which is fully electric.

Multifuel Burner: Solid fuels such as coal will produce pollutants like NO_x and SO_x, and sometimes mercury and are thus not suitable for introducing directly in food and beverage production. Furthermore, the complexity of feed system of solid fuel direct burners makes them impractical for smaller applications. Generally, manufacturers do not sell burners below 7-10 MW.

Electricity: Is the cleanest form of direct heating as the "flue gas" (heating media) is pure air. The temperature is a limiting factor as the current maximum with standard materials is 600-800 ˚C [3]. This will rule out some of the potential in the high temperature applications.

It will however be possible to create a hybrid setup with electric preheating of the process air and a subsequent burner that raises the temperature to the desired level. Preheating the air will depend on the integration of heat recovery. If a process is already preheating the air by heat recovery, there is little to no potential in preheating with electricity.

Table 2: Sector relevance, Natural gas

Energy service		Any Sector potential				
Firing direct/ indirect	***Temperature***	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
Di	***High***	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Di	***Medium***	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

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(xliii) End- use relevance

Any direct end-use is of relevance, the end-uses: Boiler and distribution loss, Dewatering and Distillation are excluded as these are purely indirect processes. The fuel choice will determine the actual end use relevancy.

Table 3: End-use relevance

	End-use relevancy							
	Heating / Boiling	Drying	Dewatering	Distillation	Firing / Sintering	Melting / Casting	Other processes <150C	Other processes >150C
Direct firing	Yes	Yes	No	No	Yes	Yes	Yes	Yes

(xliv)

(xlv) Application potential

The characteristics of Table 1, Table 2, and Table 3 are combined into one sheet which provides an overview of the application potential in percentage of the total demand for the sector. The sheet is published in the quantitative part of the technology chapter and in the data sheet.

The overlap between the three different fuels has been estimated and is plotted in Figure 6. The intervals are:

- Electricity [0%;39%]
- Solid fuels [29%;84%]
- Natural Gas [2%;100%]

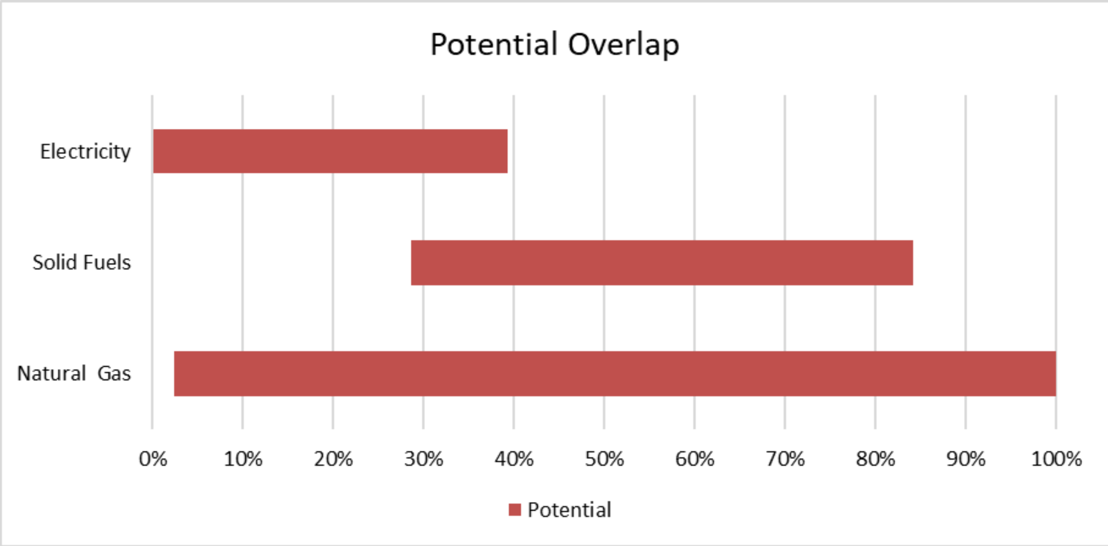

Figure 6: Potential Overlap

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 [1]. 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 [1] [2].

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 problem going down in load. However, low air flows 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.
- **Solid Fuels:** Will depend on the fuel mix.

Potential for Carbon Capture (CC)
All of the fuels included, result in CO_2 emissions, which enable the possibility of carbon capture (except for electricity). Additional information can be found in [7].

It is assumed that wood and biogas are carbon neutral and therefore having net zero CO_2 emission, this does not mean 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-known technology that has been used for a long time. For electricity however there is still a potential for research and development. Currently the maximum air temperatures with commercial equipment is 600-800 °C [4]. With new alloys there might be a potential to expand the temperature range of the technology.

For Cement industry specifically the CemZero project is of interest as it seeks to develop a fully electric cement manufacturing process by 2030 [13].

Examples of market standard technology
Natural Gas: Danish Crown A/S, singeing furnace.

Solid Fuels: Aalborg Portland A/S, multiple rotary kilns with mixed fuel firing.

Electricity: Arla Foods amba HOCO and AKAFA, spray drying.

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

(xlvi) 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 [3] [4] [5]. The unit price only covers the burner itself. Auxiliary costs have been estimated by Viegand Maagøe as a general average. Auxiliary costs cover the fuel supply system, such as gas piping for a gas burner or electric installations and grid connection for an electric heater.

Table 4: 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. 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 therefor left out of the analysis.

(xlvii) 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.

(xlviii) 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.

(xlix) 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.

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

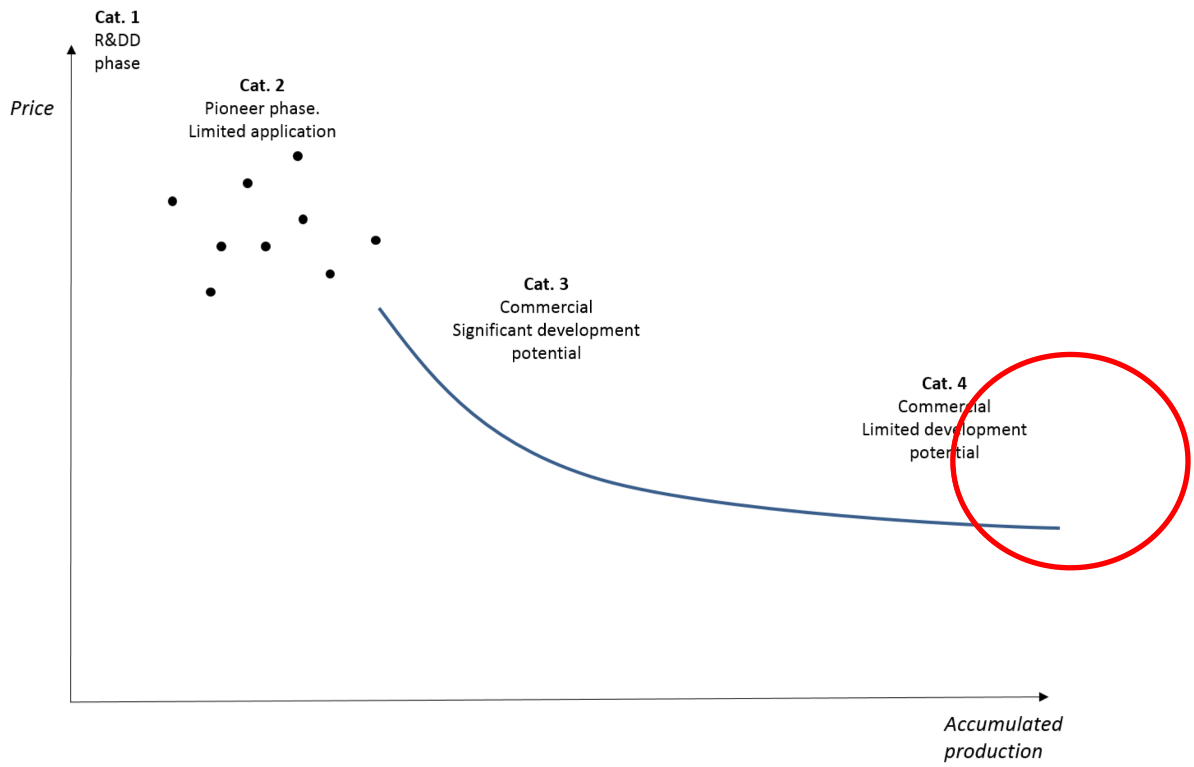

Figure 7: Technological development phases. Correlation between accumulated production volume (MW) and price.

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.

Additional remarks

None

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Quantitative Description

See separate Excel file for Data sheet and Application matrix

i Introduction to Carbon Capture Technologies

Contact information

- Contact information: Danish Energy Agency: Filip Gamborg, fgb@ens.dk; Laust Riemann, lri@ens.dk
- Author: Jacob Knudsen and Niels Ole Knudsen from COWI

i.1 Abbreviations

Abbreviation	Definition
ASU	Air Separation Unit
ATEX	ATmospheres EXplosives
CC	Carbon capture
CHP	Combined Heat and Power
CPU	CO_2 purification Unit
CFB	Circulating Fluidized Bed
DAC	Direct Air Capture
DH	District Heating
ECRA	European Cement Research Academy
FGR	Flue Gas Recirculation
MWh_e	Mega Watt hour electric
ORC	Organic Rankine Cycle
PC	Pulverized Coal
P2X	Power to X

i.2 Carbon Capture technologies

Carbon capture (CC) is a process that recovers CO_2 from a source (e.g. flue gas) and turns it into a concentrated CO_2 stream. Following the CC process, the concentrated CO_2 stream can be used as input to CO_2 utilisation processes e.g. P2X, urea production, etc. or compressed/liquefied and transported to geological underground formation with the purpose of permanent storage. In the context of CC from energy plants or other combustion plants, the CO_2 source is nearly always flue gas, hence the CC technology will be a gas separation technology.

A vast number of different carbon capture technologies have been proposed and investigated in the scientific community since the early nineties. Many of the technologies have not made it past the research stage and have failed to gain commercial attractiveness. A few technologies such as amine based CC and oxy-fuel technology have been demonstrated in large scale. The following section will provide a brief overview of the more significant CC technologies and explain the pros and cons in a Danish context.

i.2.1 Post combustion capture

Amine based

Amine based CC technology is the more mature and more widely demonstrated CO_2 capture technology available today. The technology works by scrubbing CO_2 out of the flue gas with an amine solvent and subsequent thermal regeneration of the amine solvent to yield a pure CO_2 stream. The technology is flexible with respect to CO_2 source and capacity. Amine CC may capture 90% or more of the CO_2 from the source.

Amine scrubbing has been used in smaller scale in the food and beverage industry for several decades to recover CO_2 from a flue gas/process gas stream and turn it into a high purity concentrated CO_2 stream. Amine scrubbing processes are also known within gas treatment (gas sweetening) and various chemical industries to remove CO_2 from process gasses e.g. natural gas, biogas, hydrogen, etc. The amine scrubbing process for upgrading biogas is described further in the chapter Biogas Upgrading in Technology Catalogue for Renewable Fuels.

For capture of CO_2 from flue gas streams, the capture plant is installed in the tail end of the combustion plant with minimal impact and interfaces to the combustion plant/point source. For these reasons the amine based CC process is very suitable for retrofitting to existing heat and power plants as well as to other industrial combustion processes. Amine CC technology may also be heat integrated with the steam cycle of boilers and the district heating network to obtain improved overall energy efficiency. Drawbacks with the amine technology is the use of substantial amount of heat, which may reduce heat output from a Combined Heat and Power (CHP) plant and/or result in large penalty in electrical efficiency. The capital cost today of the amine process is also significant.

The more recent years development of amine technology in a CO_2 capture context has focused on scale-up and optimization of the process with respect to energy requirement, capital investment and harmful emissions. There are several vendors offering amine based CC on commercial basis. The technology is further elaborated in section 0.

There is also research and development work ongoing regarding use of the classic amine CC process with alternative solvents such as amino acid salts, ionic liquids, non-aqueous solvents etc. This may lead to future improvements in energy requirements and investment costs of solvent CC processes, but these alternative solvents are still at low Technology Readiness Level (TRL).

Chilled ammonia/carbonate process

Chilled ammonia (or ammonium carbonate process) technology is relatively similar to amine CC process except that a solution of ammonium carbonate is used instead of amine. Due to the volatile nature of ammonia the process must be chilled to below ambient temperature to limit ammonia slip. The chilled ammonia process is proprietary process of Baker Hughes (former part of Alstom).

The advantage of the chilled ammonia process is supposed to be reduced heat consumption, CO_2 recovery at relatively high pressure (5-25 bar) and no emission of amine and degradation products. However, slow absorption kinetics, increased process complexity as well as challenges with handling of solid precipitation of carbonates have proven to be significant disadvantages. In addition, the heat requirement has proven higher than initially anticipated. The process has been demonstrated at relatively large scale (100,000 tpa). The process will be more relevant for more concentrated CO_2 sources.

Another carbonate process (Benfield process) has been applied for CO_2 removal in the process industry for decades. This process applies a solution of potassium carbonate instead of ammonium carbonate. As potassium carbonate is non-volatile the process does not require chilling. However, the very slow reaction kinetics and unfavourable equilibrium conditions will limit the application of this process to high pressure gas streams hence it is not suitable for CO_2 capture from flue gas.

Other solvent systems

Post combustion processes with alternative solvents such as non-aqueous solvents, ionic liquids, amino acid salts, enzymatically enhanced solvents, phase change solvents, etc. are also under development [1-4]. The aim with these alternative solvents is to achieve lower energy consumption and reduce the cost of CC technology. Most of the processes involving more novel solvents have not been demonstrated at large scale and are thus at relatively low TRL. Therefore, what energy and cost reductions these alternative solvents may bring relative to amine solvents remain uncertain.

Solid sorbents

Post combustion processes with use of solid sorbents instead of liquid solvents are under early stage development. Both solid adsorption processes working at low temperature suitable for tail-end retrofitting (similar as for amine technology) as well as high temperature processes working at the calcination temperatures of inorganic carbonates (600-900°C) exists.

For the low temperature process research focuses on developing solid sorbents with good properties for CO_2 capture and high process durability. Examples of sorbents are support materials of carbon, zeolite, metal organic framework (MOF), etc. loaded with amine functional groups [7]. Challenges relate to low cyclic loading of the solid i.e. need to circulate large amounts of solid, relatively rapid deactivation of solid sorbent, and difficulty in developing a robust industrial scale process.

The high temperature sorbent process also referred to as calcium looping applies lime (CaO) or modified lime with other metal oxides to capture CO_2 at high temperature (500-650°C) [1]. The formed solid carbonates are then calcined/regenerated to yield a pure CO_2 stream around 900°C [1]. Thus, the process requires heat input at high temperature, which may be delivered by direct oxy-firing in the regenerator (hence it may be regarded as oxy-fuel technology) or indirect heating. The main advantage of the process is the potential of high energy efficiency as the heat of absorption is released at high temperature (500-650°C) where it can be turned into power or used for process/district heating. If used as post combustion technology, calcium looping needs to be significantly integrated with the boiler, which in turn makes it non-suitable for retrofit. Challenges are also related to relatively low lifetime of the sorbent which implies relatively large mass streams of fresh and spent limestone will have to be handled [7]. In the case of a cement kiln where limestone is a major raw material, the short lifetime of the CaO sorbent is not an obstacle as spent CaO sorbent can be used as raw material. Calcium looping can also be applied in gasification plants to remove CO_2 from the gas prior to combustion. This makes the process a pre-combustion capture technology.

Solid sorbent technology is at low TRL and not relevant for near or midterm retrofit projects.

Membrane technology

Membrane technology is used in the industry today for gas separation. As a CO_2 capture technology, CO_2 selective membranes are under development and have been tested in pilot scale with some success [8]. The main challenge with membrane CC technology is the low partial pressure of CO_2 in flue gas, which make it difficult to obtain adequate driving force (i.e. CO_2 pressure gradient) for transport of CO_2 through the membrane. This is solved by compressing the flue gas and/or maintain high vacuum on the permeate side (CO_2 side) of the membrane. Both methods result in substantial electricity consumption [9]. Moreover, as the membrane area required for separation is inversely proportional to the driving force, there will always be trade-off between membrane area and driving force. In addition, membrane technology will be sensitive to dust and pollutants in the flue gas. Membrane CO_2 capture is at low TRL for flue gas and is more ideal for high pressure gas separation.

Cryogenic separation

Processes for CO_2 capture by freezing out CO_2 from the flue gas i.e. cryogenic separation, are also under development. The low CO_2 partial pressure in flue gas implies that the flue gas will have to be chilled to very low temperature (<-100°C) for the CO_2 to separate (freeze) from the gas. Therefore, the flue gas may also have to be compressed to avoid too low temperature. Handling of pollutants in the flue gas and use of expensive compression and chilling machinery are challenges to this technology. A process is being developed by Sustainable Energy Solutions. The technology may have some potential but is regarded as low TRL with only relatively small-scale pilot plant trials conducted. [10]

i.2.2 Oxy-fuel combustion

In oxy-fuel carbon capture, the oxygen required for combustion is separated from air prior to combustion, and the fuel is combusted in oxygen diluted with recycled flue-gas rather than by air.

This oxygen-rich, nitrogen-free atmosphere results in a flue-gas consisting mainly of CO_2 and H_2O (water), so producing a more concentrated CO_2 stream for easier purification.

In order to keep the temperature down and ensure the flue gas flow in the boiler, 60-70% of the cooled flue gas, which primarily consists of CO_2 and water vapor, is recirculated.

After the boiler, water vapor is removed from the flue gas which then typically consists of 70-85 vol% CO_2. CO_2 can then be further purified and compressed, ready for reuse or disposal.

The oxy-fuel technology is further elaborated in section 0.

i.2.3 Chemical looping combustion

Chemical looping combustion is a novel combustion concept with integrated carbon capture. Oxygen is carried to the combustion process in the form of a solid carrier e.g. metal oxide. The oxygen carrier will be reduced through reaction with the fuel and is hereafter regenerated in a separate oxidizing reactor with air. In principle, the technology is a kind of oxy-fuel process as nitrogen is eliminated from the combustion atmosphere. The concept will eliminate the costly air separation unit of oxy-fuel processes, hence offers a cost saving potential. The working principle of the technology has been demonstrated in pilot plant scale however, the concept has received little commercial attention and is therefore at low TRL level. The technology is not relevant for retrofit to existing emission sources.

i.2.4 Pre-combustion capture

Pre-combustion capture covers many different technology concepts. Common for all concepts is that the carbon from the fuel is separated from the combustible gases prior to combustion or use. The concept is only relevant for gasification/reforming plants where fuel is converted to CO_2 and H_2 prior to combustion. The concept is used today for hydrogen plants in the fertilizer industry to remove CO_2 from the feed stream to ammonia plants. Typically, the feed stream is at high pressure hence capture technology with physical solvents (pressure swing absorption) or less reactive amine (chemical) solvents can be applied. The concept is not relevant for flue gas from existing boilers but may be relevant for new-built energy plants based on gasification. Likewise, it will be relevant for production of emission free hydrogen from natural gas.

i.2.5 Direct air capture

The Direct Air Capture (DAC) technology captures CO_2 from ambient air and recovers a concentrated CO_2 stream like other CC technologies. Because of the low content of CO_2 in the atmosphere (~400 ppm) compared to that of typical flue gas, DAC processes have substantially higher energy requirements compared to CC from flue gas. Likewise, the capital expenditure per tonne captured CO_2 will be higher.

The DAC technology is still in its infancy and there are many different concepts under development. Most of the technologies and methods for DAC are still being developed in the laboratory and are thus at low TRL. A few technologies have been demonstrated in pilot- and/or commercial plants, but at relatively small scale (up to a few tonnes per day).

As DAC in the combination with renewable energy can be used to generate emission free CO_2 for use in CO_2 utilisation processes e.g. Power to Fuel, or carbon negative solutions in combination with geological CO_2 storage it may be a relevant technology despite the obvious obstacles. Another advantage with the DAC technology is it will be able to recover CO_2 at any location independently on an emission point source. The two most mature and relevant types of DAC technology for near to mid-term deployment are described further in section 0.

i.3 CO_2 post treatment

The CO_2 stream, i.e. raw CO_2, recovered by the different capture technologies typically requires further treatment/conditioning before it can be transported or used by other utilization technologies.

Most CC technologies (including amine CC and oxy-fuel) will recover a concentrated CO_2 stream at fairly low pressure and saturated with water vapour. For oxy-fuel, the CO_2 purity is low and more extensive treatment is required. This will be further explained in the oxy-fuel technology section.

i.3.1 CO_2 compression and dehydration

If CO_2 is to be transported in pipeline from capture site to a geological storage or a utilisation site it will have to be compressed and dried to meet suitable conditions for pipeline transport.

Typical CO_2 pipeline pressures will be 80-180 bar to avoid two-phase region and obtain acceptable densities.

The moisture content of the CO_2 will be required to below 50-400 ppmv (depending on specifications) to avoid carbonic acid corrosion and/or hydrate formation. Dehydration processes such as mole sieve adsorption drying or glycol absorption drying is applied for drying of CO_2 gas. Table i-1 summaries expected cost and performance of CO_2 compression from 1 to 150 bara.

Table i-1. Energy consumption and cooling for CO_2 compression from 1 to 150 bara and dehydration to <50 ppmv moisture. Values estimated based on 8 stage internally geared compressor with inter-cooling to 30°C.

	Estimated value	comment
Compression electricity	~0.10 MWh_e/ton CO_2	0.09-0.12 depending on compressor design
Cooling requirement	~0.16 MWh/ton CO_2	30-100°C, possible to recover part of the heat
Dehydration electricity	~0.005 MWh_e/ton CO_2	
CAPEX CO_2 compression & dehydration	0.2 - 0.5 mill €/(t CO_2/h)	Depending on capacity

i.3.2 CO_2 liquefaction

CO_2 may be liquefied at various temperature and pressure conditions (-56 to 31°C and pressure of 5.2 to 74 bara). Typical conditions for transport, interim storage and trading of industrial CO_2 is in the order of -28°C and 15 bara.

In a standard industrial CO_2 liquefaction solution, concentrated CO_2 is compressed to 15-20 bara and liquefied by chilling at -25 to -30°C. The CO_2 is dehydrated prior to chilling. The requirements for CO_2 dryness for liquid CO_2 will be even more stringent due to greater risk of ice or hydrate formation at the lower temperatures (<30 ppm). Non-condensable gases will also have to be removed to low level as these will change the physical properties of the liquid CO_2. A standard liquefaction plant will include a stripping unit to remove non-condensable gasses, CO_2 dryer and activated carbon (or similar) filter to remove traces of organic compounds from the CC plant. A small loss of CO_2 in the liquefaction process through purging about 1% should be expected.

Typical energy requirement and CAPEX values of industrial CO_2 liquefaction plants are provided in Table i-2.

Table i-2. Energy consumption and cooling requirement for CO_2 liquefaction to -28°C and 15 bara. Values based on today's standard industrial solution for CO_2 liquefaction.'

	Estimated value	**comment**
Liquefaction electricity	~0.16 MWh_e/ton CO_2	Includes chillers, CO_2 dehydration and compression
Cooling requirement	~0.26 MWh/ton CO_2	~50% of cooling is through chiller air cooler, rest cooling water/cooling tower
CAPEX CO_2 liquefaction	0.4 - 0.8 mill €/(t CO_2/h)	Depending on capacity.

ii 401 Amine post combustion carbon capture technology

Contact information

- Contact information: Danish Energy Agency: Filip Gamborg, fgb@ens.dk; Laust Riemann, lri@ens.dk
- Author: Jacob Knudsen and Niels Ole Knudsen from COWI

ii.1 Brief technology description

The amine carbon capture technology is based on cyclic absorption and desorption (stripping) processes. The CO_2 (which is an acidic gas) is absorbed from the flue gas by a circulating aqueous amine solution (alkaline solution) and released as a concentrated CO_2 stream through thermal regeneration of the amine solution i.e. applying heat to the solution, in a desorber. The CO_2 capture process is thus driven by thermal energy. The working principle of the process and its basic units are illustrated in Figure ii-1.

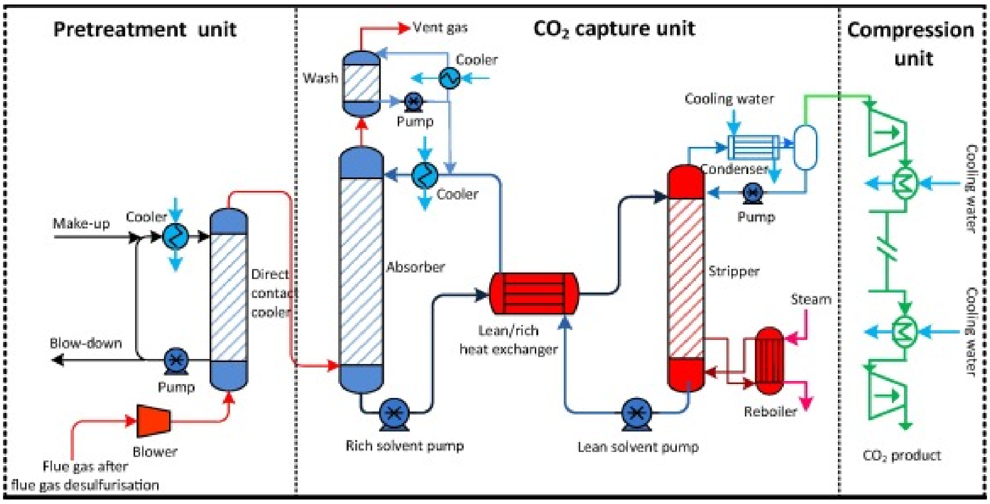


Figure ii-1. Schematic illustration of amine based CO_2 capture process as reported in [11]. Flue gas is cooled in a pre-treatment unit prior to entering the CO_2 capture unit where CO_2 is washed out by an amine solution. The CO_2 gas is stripped of the amine solution whereby it is regenerated by applying heat in a stripper (desorber). The recovered CO_2 may be compressed and dehydrated for transportation.

As outlined in Figure ii-1, a typical amine based CC plant will be composed of the following units:

Flue gas pre-treatment

Amine based CO_2 processes requires that the flue gas is relatively cool and clean i.e. low dust and acidic pollutants, before contacted with the amine solution. A too warm flue gas stream will disfavour the CO_2 absorption equilibria resulting in increased energy demand of the capture process. The presence of flue gas pollutants such as SO_2, HCl and NO_2 will inactivate the amine by irreversible absorption or degradation. This may in turn lead to excessive amine consumption, emission of amine degradation products, corrosion in the amine process as well as create more chemical waste. Furthermore, the presence of significant mass loadings of submicron particles in the flue gas e.g. acid mist, may lead to formation of amine aerosol emission.

Typically, the flue gas is preconditioned in a pre-scrubber or direct contact cooler. The pre-scrubber will quench the flue gas to typically 30-40°C and scrub out most remaining acidic pollutants and fly ash. Caustic solution is typically applied to remove the acid pollutants and keep the scrubbing water close to neutral pH. Because the flue gas is cooled below its dewpoint a bleed stream of condensate containing the absorbed pollutants is produced. Depending on the purity of the flue gas the condensate requires some level of treatment before discharged to public sewer. The cooling of the flue gas below its dew point requires also significant heat removal. This heat may also be upgraded with heat pump technology to be useful for district heating.

In case of a thermal power plant or other industrial emission source that is equipped with flue gas condensation it is likely that the described preconditioning unit may be omitted as the flue gas is already cooled to 30-40°C and polished for pollutants of dust, SO_2 and HCl. This will give small cost reduction for CC retrofitting.

Amine absorption loop

Following pre-treatment, the flue gas is led to a packed bed absorption column, where the CO_2 is scrubbed out through contact with the amine solution (solvent). The absorber will be the largest structure of the CC plant and may be 25-50 m tall. The absorber tower will be fitted with emission control sections in top (water wash and demisters) to minimize emissions of amine and degradation products with the treated flue gas. Significant heat will be released in the absorber due to the heat of absorption of CO_2. This will increase flue gas temperatures with 25-35°C. Cooling is therefore applied to maintain efficient absorption equilibrium and limit the evaporative loss of amine with the treated flue gas.

The CO_2 loaded amine solution (rich amine) is pumped to a regeneration tower (desorber) after pre-heating with hot regenerated amine solution. A reboiler – the device that heats the solvent - driven by low pressure steam (typically at 3-5 bara and 130-150°C) is installed in the bottom of the regeneration tower to supply the heat for releasing the CO_2 and regenerating the amine solution. The hot CO_2 and water vapours from the top of the desorber will be cooled in a condenser and the condensate will be refluxed. The concentrated CO_2 stream leaving the condenser is the product from the CC process. Typical operating conditions of the desorber is around 120°C and 2 bara in the bottom/reboiler and 100°C and 2 bara in the top. The condenser will cool the CO_2 to normally 30-40°C. The conditions will vary somewhat with the specific technology and there is also some flexibility in the design to adjust parameters.

The heat that must be removed from the desorber and absorber may be used for district heating.

Amine reclamation unit

Over time amine degradation products and traces of flue gas pollutants will build-up in the amine solution. To maintain the performance of the solvent, a reclamation process is applied where the active amine is recovered, and degradation products and pollutants are rejected as chemical waste. The reclamation process can be a thermal process that requires steam (6-10 bar) and caustic solutions. Alternatively, ion-exchange processes can be used which consumes more chemicals and water. [12] Some processes will also have continuous activated carbon filtration of the amine solution to remove some degradation products.

ii.2 Input

The energy consumption for amine CC processes is significant and typically the largest element in the OPEX for the technology. The main energy consumption for the process is in the form of thermal energy, typically low-pressure (LP) steam (3-5 bara and 130-150°C) for regeneration of the solvent in the reboiler/desorber system. Depending on the specific technology (vendor), the CO_2 concentration in the flue gas and the flue gas temperature the thermal energy demand is typically reported to be within the interval listed in Table ii-1. For flue gases with CO_2 concentration above 6-8 % the specific energy requirement will only decrease marginal with increasing CO_2 concentration. At lower concentrations e.g. gas turbine exhaust (3-4% CO_2) there could be an energy penalty about 10-15%. Different options exist for reducing the thermal energy consumption of the CC process such as mechanical vapour compression, inter-cooling in absorber, internal heat integration, etc. [14] All these options will however increase the investment cost and may not necessarily be economically attractive.

The electricity demand for the amine based CC process is relatively modest as shown in Table ii-1. Electricity is mainly required for various recirculation pumps and the flue gas fan (increased pressure drop). Electricity for cooling water circulation is included. If a CO_2 post treatment process is included, where CO_2 is compressed to pipeline transport pressure or liquefied, the electricity consumption will be substantially higher as further described in section i.3.

Amine make-up needs to be added to the process to compensate for degradation and losses. This number is highly amine specific hence, it depends on the specific vendor technology. Typically, the variation range is as listed in Table ii-1. The classic amine process based on monoethanolamine (MEA) will see an amine consumption in the higher end whereas processes with more advanced amine solvents such as MHI's KS-1 or Aker Solutions S26 [13] solvents will be in the lower end.

Typical range for caustic soda consumption for flue gas pre-cooling and reclaiming is shown in Table ii-1. Other consumables such as activated carbon, lube oil, etc. are required in minor quantities. Caustic soda and the other minor consumables will typically constitute less than 1% of OPEX and can be ignored for initial evaluations.

Table ii-1. Typical main inputs for amine based CC processes. *Estimated from pumping works. ** Estimated based on 0-20 ppm SO_2 in flue gas + 0.1-0.3 kg/ton CO_2 for reclaiming use.

Parameter	Typical variation	Ref.	Comment
Reboiler LP steam demand	2.5-3.5 GJ/t CO_2 or 0.7 – 1.0 MWh/t CO_2 output (3-5 bara and 130-150°C)	[13, 16, 17, 18]	Depending on vendor technology
Electricity demand	25-35 kWh/t CO_2 output	*	Excluding CO_2 compression/liquefaction
Amine consumption	0.2 – 1.6 kg/t CO_2 output	[13]	Depending on vendor technology
Caustic soda consumption	0.1-0.5 kg/t CO_2 output	**	Depending on flue gas quality e.g. SO_2, HCl, and specific amine

ii.3 Output

Main output of the process is the concentrated CO_2 stream i.e. the captured CO_2. Typically, 90% of the CO_2 content in the flue gas is captured, the remaining CO_2 is led to the stack through the flue gas stream. The capture rate can be increased to 95% or higher on the account of increased specific steam demand for regeneration and/or increased CC plant investment cost.

The CO_2 recovered from amine CC plants is highly pure. The CO_2 will normally be saturated with water vapour at the conditions it leaves the process (30-40°C and 1-3 bara), which corresponds to 2-3 %-vol. On dry basis the CO_2 purity will typically be 99.95 %-vol or higher. Main pollutants will be O_2 and N_2 as well as traces of volatile degradation products from the amine solvent.

For CO_2 storage and most technical applications the CO_2 from amine CC plants will have adequate quality. The requirement for post treatment of CO_2 is therefore mainly limited to conditioning of the CO_2 to meet conditions (pressure, temperature and dryness) for pipeline transport or ship/truck transport. In this context the water content will be an issue as CO_2 is very corrosive in the presence of water (forms carbonic acid).

As the captured CO_2 will normally have to be transported to storage/utilisation site, the amine CC plant will typically include a CO_2 compression plant (for pipeline transport) or liquefaction plant (for road or boat transport) with integrated dehydration plant. This is further described in section i.3.

Other main output from the amine process is low grade heat as listed in Table ii-2. Approximately the same amount of heat that is supplied to the CC process in the reboiler needs to be removed by cooling or used for district heating. This will be available at two or more distinct temperature levels, typically around 80°C in the desorber and around 50°C in the absorber. If flue gas pre-cooling is required, significant additional cooling is needed. This can be estimated from flue gas inlet conditions. As an example, if flue gas at 90°C with 20%-vol moisture and 13%-vol CO_2 is cooled to 35°C, approx. 0.5 MWh/t CO_2 output additional cooling is required and 0.5 m^3/t CO_2 output flue gas condensate needs to be discharged.

Minor outputs from the process are chemical waste from reclaimer, spent activated carbon, etc. which may be ignored in the initial OPEX estimate.

Table ii-2. Typical main outputs from amine based CC processes. * Estimated values based on typical inlet conditions for CHP flue gas.

Parameter	Typical variation	Ref.	Comment
CO_2 capture	85-95% (of flue gas CO_2 content)	[13, 16]	most studies are based on 90%
Heat output excl. flue gas pre-cooling	0.7–1.0 MWh/t CO_2 output 20% available at ~80°C 80% available at ~50°C	*	Cooling duty approximately similar to reboiler heat input
Heat output (cooling) flue gas pre-cooling	0-0.5 MWh/t CO_2 output Heat available at ~40°C	*	Depending on flue gas composition and inlet temperature
Flue gas condensate from pre-cooling	0-0.6 m^3 H_2O/t CO_2 output	*	Depending on flue gas composition and inlet temperature

ii.4 Energy balance

An energy balance for a CO_2 capture facility with CO_2 compression and dehydration, which is treating a flue gas stream from a 100 MW_{th} biomass-fired energy plant, is illustrated in Figure ii-2. The biomass fired energy plant is assumed to be equipped with flue gas condensation (as in the data sheet), hence no additional pre-cooling of flue gas included. Electricity to pump cooling water/heat output stream from CC and compression plant is included.

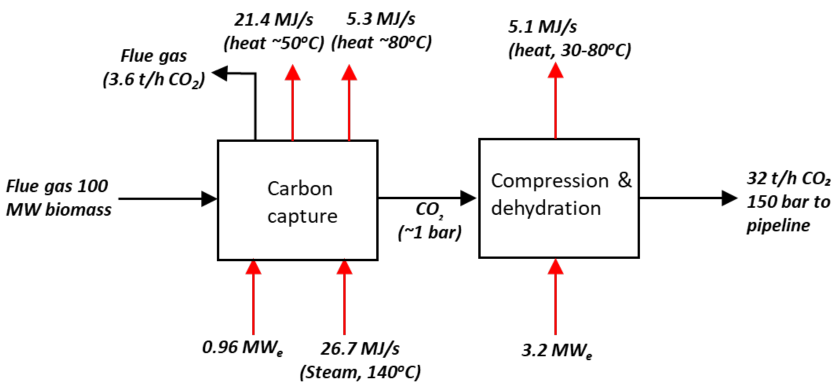


Figure ii-2. Illustration of energy balance for a CO_2 capture and compression plant treating all flue gas from a 100 MW_{th} biomass boiler that is equipped with flue gas condensation. 90% of the CO_2 in the flue gas is captured corresponding to 32 t CO_2 output per hour. Black arrows: Mass streams. Red arrows: Energy streams.

ii.5 Application potential

The amine based CC process is very suitable for retrofit to existing heat and power plants as well as to other industrial combustion processes. Clearly installing a large process unit to an existing site in operation is always complicated. Typically, there may be challenges with space availability, tie-ins to existing plants, adequacy of existing utilities, etc.

For retrofitting an amine CC to power generation boilers, the LP steam for the amine plant can in many cases be extracted from the steam turbine of the power plant on account of an increased parasitic load. Thereby also investment in additional utility boiler for supply of steam to the CC plant is avoided.

Combined heat and power plants

A retrofit case of amine CC to an existing CHP plant is illustrated in Figure ii-3. The CC plant will typically have tie-in to the CHP plant in the tail-end just before the flue gas stack. Amine CC may therefore be applied to nearly all kinds of combustion technologies and fuels such as biomass CHP, Waste to Energy or fossil fuel fired plants. A CO_2 flue booster fan is typically included in the scope of the amine plant to overcome the increased pressure drop. The treated CO_2 lean flue gas (wet conditions) may be vented directly from the top of the absorber in a dedicated stack or alternatively routed back to the power plant's stack (more costly). Depending on local legislation, reheat of flue gas may be required.

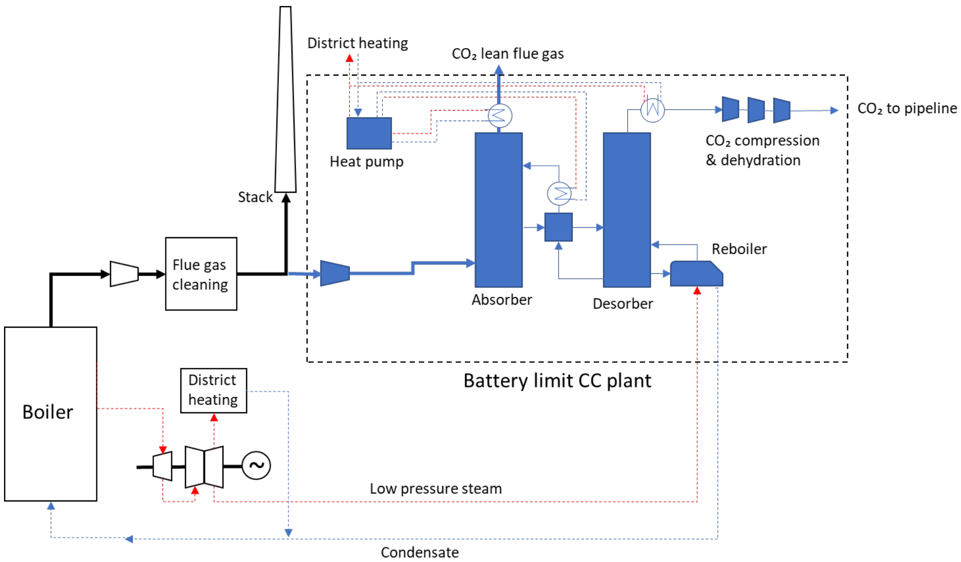


Figure ii-3. Illustration of amine CC retrofit to CHP plant. The CC plant includes a booster fan and CO_2 compression plant. The pre-scrubber has been omitted as the CHP has flue gas condensation and excellent flue gas cleaning. As an option heat pumps may be used to upgrade low value heat from CC plant to district heating.

In the CHP case it will typically be attractive to extract steam at low pressure from the turbine to drive the reboiler in the CC process as shown in Figure ii-3. This of cause depends on the specific steam turbine design as some turbines will not allow for steam extraction or not at correct pressure level. A major turbine modification may be required or even turbine replacement. To compensate for the reduced LP steam availability for district heating (DH), waste heat from the amine process and/or CO_2 compression may be integrated with the district heating network. However, about 80% of the waste heat will be available at relatively low temperature (about 50°C in average) that requires upgrade with heat pumps if to be used in the DH network. Heat pumps for upgrade of low temperature heat is not included in the energy numbers and CAPEX estimate in the data sheet (can be estimated from Technology Catalogue chapter regarding Technology Data for DH heat pumps), 20% of waste heat is available around 80°C, hence may be exchanged directly against DH water.

Depending on the possibility for heat integration with DH network and the available cooling capacity at the CHP, new cooling water capacity may need to be erected as part of the CC project.

As mentioned in section ii.1 if the CHP is equipped with flue gas condensation, the pre-scrubber may be omitted from retrofit scope.

Other industrial emission sources

Amine CC will also be relevant for decarbonising emissions from other industries such as refinery emission sources, cement kilns, reforming plants, steel industry, large industrial utility boilers and more. In a Danish context, the largest industrial emission sources besides energy plants are cement kilns and refineries.

For cement kiln the tie-in will again be close to the existing stack downstream flue gas cleaning equipment. The CO_2 content of cement flue gas is typically higher (20-30%-vol) than for power plants (10-15%-vol), implying that the absorber part will be more compact. At cement kilns there is normally not steam available, hence a steam boiler or other heating plant will have to be included in the scope for an amine CC retrofit, which will increase costs and emissions to be captured. On the other hand, some cement kilns may have waste heat available after the preheating tower or in the clinker cooler excess air vent. Part of the heat demand of the amine CC process may therefore be covered by installation of Waste Heat Recovery Units (WHRUs) in the cement processing lines. Some cement kilns have already exploited this heat in a steam cycle for cogeneration of power. In this case it will presumably be cost efficient to use the produced steam for the CC plant instead of power generation.

The required cooling water capacity for a CC plant (Table ii-2) is unlikely to be present at the cement plant, hence this must typically be established as part of the CC project.

Refinery emission sources typically consist of several smaller point sources from fired heaters, crackers, auxiliary boilers, etc. The point sources may be combined and fed to a common capture plant for cost saving. At refineries several heat integration options would typically be available. It is however likely that an additional steam boiler will be required if a high share of the CO_2 emission should be captured.

ii.6 Typical capacities

Amine based CC plants are today available from small scale 0.1 t CO_2 output/h in the food and beverage industry to large scale in the energy sector 200 t CO_2 output/h. This as single train units although plants at the higher end of the capacity interval will consist of multiple equipment units for heat exchangers and reboilers.

The biggest equipment in the amine CC plant are the absorber, desorber, pre-scrubber and reboiler. These will be tailormade equipment. Pumps, heat exchangers will be standard sizes.

The data sheet for "Post combustion - small biomass " is based on a 32-34 t CO_2 output/h capacity, whereas "Post combustion - large biomass" and "Post combustion - cement kiln" are based on 150-170 t CO_2 output/h.

CO_2 compressors are tailormade equipment and are available as single train units for the highest CC capacities.

ii.7 Space requirement

An amine CC plant in the size range from 25 to 200 t CO_2 output/h is estimated to occupy an area of 40 m^2/[t CO_2 output/h], i.e. a 100 t CO_2 output/h CC plant will occupy 4000 m^2. This will include the basic CC process including chemical storage tanks and substation.

Additional area will be required for cooling towers or air coolers if no cooling water is available. For CO_2 compression and dehydration approximately 12 m^2/[t CO_2 output/h] additional is required. If liquefied CO_2 is produced, additional space should be allocated for CO_2 storage tanks and CO_2 export facilities.

ii.8 Regulation ability

Amine based CC plants have good regulation ability. Turn-down to 20-30% of nominal capacity is possible.

In most retrofit projects, the CC plant will be integrated hence it is possible to bypass or partially bypass on the flue gas side. This will allow the energy plant or industrial emission source to operate without the CC plant in operation or with the CC plant at limited capacity.

Starting-up the process from cold conditions may involve slowly heating the system over 2-4 hours. If the CC plant is kept in hot standby conditions i.e. maintained at operating temperature, the CC plant will be able to start-up to full load in less than 0.5 hour.

It is also possible to regulate load up and down relatively fast by adjusting steam flow to the reboiler. In practice it may be the downstream transport and utilization processes of CO_2 i.e. compressor, pipeline, injection well, that will be the limiting factor as these processes do not cope well with fast load changes.

ii.9 Advantages/disadvantages

The main advantages and disadvantages by amine based CC can be summarised as follows:

Advantages:

- Can facilitate deep CO_2 emission reductions (+90%) from an emission point source
- Proven technology used in the industry for many decades
- Technology offered commercially by multiple vendors in a large capacity range
- Flexible with respect to flue gas source (biomass, waste, coal, oil, NG, etc.) and composition (CO_2 content typically 3 to 30 %)
- Very suitable for retrofit because of low impact on upstream combustion process and few tie-ins. An amine CC plant can be erected while the host plant remains in operation. In principle, only a few short stops are required to establish tie-ins. This will however be site specific.
- Possibility to heat integrate with steam cycle and district heating network (reduce OPEX and production loss). Both concerning heating and cooling requirement of the CC process.
- Possible to implement for partial capture (slip stream) from a CHP/emission source to meet demand for CO_2.
- Bypass mode is possible (i.e. low risk for primary plant). Flexible with respect to load changes.

Disadvantages:

- Requires high standards for upstream flue gas cleaning (low concentration of SOx, NOx, HCl, particulates (in particular submicron). Typically, a pre-scrubber is required.
- Amine degradation and emission of degradation products with flue gas may be an issue with large-scale plants. This can normally be solved with good design of emission control systems.
- High energy demand for thermal regeneration of amine solution

ii.10 Environmental

Some of the amines applied in CC processes may be harmful to the environment due to high pH, low biodegradability, toxicity, secondary reactions such as reactions with NO_X to form harmful nitrosamines. [19]

Emissions of amine and amine degradation products to air with the treated flue gas is the largest environmental concern with amine CC technology. Reducing emissions has been a focus point in recent years R&D work. This has resulted in improved emission control technology and today several vendors claim low emissions of harmful components. [13, 16]

Most amine CC processes will not have emissions to water (only from pre-cooling of flue gas) from the amine loop. Risk of spillage and leakage of amine solution from the rather large hold-up in the process needs to be mitigated in the design as many of the used amine chemicals may have low biodegradability.

The consumption of amine due to degradation may also be significant for some amines, in particular monoethanolamine (MEA), Table ii-1. This will in turn generate substantial amounts of chemical waste for disposal/incineration (0.2-1 kg/ton CO_2).

Finally, the significant energy consumption of the CC technology has an indirect environmental impact.

ii.11 Research and development perspectives

Over the past couple of decades, a lot of research has been conducted concerning development of new improved amine solvents which require less energy for regeneration, have higher cyclic capacity (smaller equipment), are more resistant to degradation, have better environmental properties, etc. The energy consumption and chemical consumption of the amine CC process have also decreased substantially with nowadays advanced solvents and amine processes. Development of amine processes and solvents which can provide a CO_2 stream at higher pressure i.e. saving expensive compression work/cost, is also underway [58]. It is likely that amine solvents with even better performance and properties may be identified, however further refinements are unlikely to provide a step change in terms of the energy consumption. Research is also being conducted into radically other kinds of solvents e.g. non-aqueous solvents, special engineered compounds, etc. which may provide a breakthrough in the future in terms of reducing energy consumption. However, this is very uncertain at present.

Also, more advanced process flowsheets with higher extent of heat integration have been developed, which reduces the energy requirement of CO_2 capture. Some suppliers are starting to implement these solutions in their design e.g. the Petra Nova plant by MHI.

On the integration side between the CC plant and the energy plant research is also ongoing. The availability of increasingly sophisticated heat pump technology may improve total energy efficiency of an integrated CC solution, where waste heat can be exploited to a greater extent.

Process equipment suppliers are also starting to develop optimised solutions for carbon capture e.g. Sulzer Chemtech has developed optimized absorber packing for CC. The potential here for CAPEX reductions is likely to be significant in the mid- to long-term as the suppliers are still reluctant to invest in improvements because the large-scale CC market is yet to take off.

ii.12 Examples of market standard technology

Work on scale-up and improvement of amine based CC technology gained momentum during mid 2000s due to the growing commercial interest for CC. Several technology vendors (GE, Cansolv/Shell, Aker Solutions, MHI, Hitachi, Fluor, Linde/BASF, etc.) have erected large scale pilot plants in conjunction with power plants and demonstrated their technology. A few vendors have also delivered commercial plants for CO_2 utilisation in the chemical industry.

Below is listed some of the main amine based CC demo plants that has been erected. The Global Carbon Capture Institute also publishes an annual status reports on CCS projects which provides an overview of projects (not limited to amine CC technology) [22].

- Boundary Dam 1 Mtpa CO_2 capture demonstration plant, Canada (operational 2014 - present). First full-scale post combustion amine plant retrofitted to a commercial operating boiler. About 90% of CO_2 is captured from a refurbished 150 MWe coal-fired unit at Saskpower's Boundary Dam power station. The CO_2 is compressed and transported in pipeline to a nearby oil field where it is sold for EOR. The amine carbon capture technology is provided by Shell Cansolv. The project also included a SO_2 removal process with amine, which is heat integrated with the CO_2 removal process. The net power output of the unit declined by 13.6 % with the CC (and SO_2 removal) retrofit, however this number includes the gains by turbine and boiler refurbishments. The project claimed negative media coverage from cost overruns and delays [23]. Following start-up, the plant suffered some issues with fly ash deposition and plugging of equipment as well as excessive amine degradation. This resulted in low availability in the first years and short deliveries of CO_2 to the oil companies, which triggered large penalties. Most of these issues have now been rectified and the plant performs stable although the captured amount is somewhat below design (May 2020, CO_2 capture past 12 months was 732.000 tons [24]).

Figure ii-4. Photo [59] of Saskpower 800 MW$_e$ Boundary Dam coal-fired power station where one of the four units was retrofitted with amine CC in 2013.

- Petra Nova, 1.6 Mtpa CO_2 capture demonstration plant, USA (operational 2016-2020). The amine plant captures 90% of CO_2 from a 240 MW slipstream of flue gas from the coal-fired WA. Parish Unit 8. This is the world's largest amine based capture plant in operation. The CO_2 is compressed and transported in pipeline to a nearby oil field where it is sold for EOR. The CC technology is provided by MHI. Separate heat recovery boilers fitted to a gas turbine supplies the heat to the capture plant. MHI have implemented novel heat integration in the CC process to obtain low energy numbers. The plant was delivered on budget and schedule [28]. The published results indicate the facility performs as designed. The first million-ton CO_2 was captured 10 months after commencement of commercial operation and in Dec. 2019 (3 years anniversary) 3.5 million metric tons CO_2 had been captured. This is somewhat below target capacity (17%). The reasons for being below target are mainly related to outages of steam plant and other balance of plant systems as well as the load factor of the coal power station. It has recently been announced [29] that the plant has been mothballed due to low offtake price/volume of CO_2 following the collapse in crude oil price.

Figure ii-5. Petra Nova amine CC plant retrofitted to a slip stream of flue gas (equivalent to 240 MWe) from the WA Pariash unit 8 coal-fired power plant. Source: https://www.nrg.com/case-studies/petra-nova.html

- Technology Centre Mongstad (TCM), Norway (operational 2012-present). Large pilot facility established next to the Equinor's Mongstad refinery. The test facility operates a 80.000 tpa amine CC plant delivered by Aker Solutions and a 40.000 tpa sized Chilled Ammonia Plant delivered by ALSTOM (now Baker Hughes). The captured CO_2 is not used but released back to the atmosphere. Originally CO_2 could be captured from two different sources a) natural gas combined cycle CHP and b) a fluidized catalytic cracker (FCC). The amine plant has been used by several vendors (Aker Solutions [13], Shell, Carbon Clean Solutions, ION Engineering and Fluor corp.) to test and qualify their technology in semi-commercial scale. The chilled ammonia plant was only operated for test campaigns during 2012-2014 and has since been out of operation.

- Danish Experience. Esbjergværket 1 t/h CO_2 capture plant (operational 2005-2011), Ørsted (DONG Energy). World's first large pilot plant installed on a coal fired power station. The plant was used to demonstrate the feasibility of CC on coal derived flue gas and to test optimised solvent and process configurations. [30]

Several amine CC plants are also in the planning in Europe. The Norwegian national CCS demonstration project is currently moving towards final investment decision (expected autumn 2020) to realise a full carbon capture, transport and storage value chain. FEED studies have been conducted for two CO_2 capture projects both based on retrofit of amine CC plants:

- 400,000 tpa CO_2 capture from Norcem's cement plant in Brevik, Norway. The project includes waste heat recovery and heat integration with the cement plant as well as CO_2 liquefaction plant and liquid CO_2 export terminal. The 400.000 tpa constitutes approximately half of the total CO_2 emission from the cement kiln. This is evaluated to be the maximum feasible CO_2 capture capacity as the plant is solely to be driven by waste heat from the cement kiln and the CO_2 compressor. The technology provider for the amine capture plant is Aker Solutions. [33]

- Approx. 400,000 tpa CO_2 capture from Waste to Energy plant at Klemetsrud, Oslo. The project includes heat integration with WtE plant and upgrade of low-grade heat to district heating (compensate for heat loss with CC). The project also includes CO_2 liquefaction plant as well as 10 km truck/pipeline transport of CO_2 to CO_2 export terminal at harbour. The technology provider for the amine capture plant is Shell Cansolv. [32]

In the Netherlands two medium scale carbon capture and utilisation projects are in construction/planning based on amine CC from WtE plants and CO_2 use for greenhouse fertilization. Dutch WtE company AVR has completed construction of 60,000 tpa amine based capture and liquefaction plant [20] at their Duden site. Dutch WtE company Twence has announced installation of a 100,000 tpa capture amine plant at their Hengelo facility [21]. Furthermore, the project Porthos aims to establish a large CCUS hub around the Rotterdam harbour area with intended investment decision in 2021 [25]. In the first phases 2-2.5 MTPA CO_2 shall be captured from several industrial sites in the area and stored off the coast in abandoned oil and gas reservoirs as well as used for CO_2 utilisation.

In the UK several large-scale CCS demonstration projects have been far in the planning but they have all been cancelled for financial reasons. More recently Drax Power Station has installed a pilot plant to capture CO_2 from a biomass fired unit (BECCS) and plans exist to build full-scale at one of the units at Drax by 2027 [26]. Tata Chemicals is working on a CCU project and is about to install an amine based CC plant to recover 40,000 tpa CO_2 from a natural gas fired CHP plant. The captured CO_2 will be used for manufacturing of food and medical grade sodium bicarbonate [27].

Considering that a number of large-scale amine CC plants are in operation and that the technology is supplied by different vendors, the amine CC technology can be regarded as commercially available.

ii.13 Prediction of performance and costs

CAPEX

The total capital cost of retrofitting an amine unit to an existing emission source will in addition to the cost of the CC plant itself consist of various integration costs. The integration costs are substantial and may vary significantly from case to case depending on the scope included. The following typical cost elements may be included in retrofit projects in addition to the CC plant costs:

- Boiler for generating low pressure steam to CC plant or modification of steam turbine/new steam turbine to allow for steam extraction to CC plant
- CO_2 compression and dehydration or CO_2 liquefaction plant
- Liquid CO_2 tank farm and export facilities
- Extensive heat integration
- Additional flue gas cleaning e.g. desulfurization plant
- Utilities such as cooling tower, water treatment plant, etc.
- Owners cost, contingency

Because of the different scope included and the general uncertainty on cost estimation significant scatter is seen in CAPEX estimates reported in the literature for retrofit cases. Moreover, because only few CC projects have been realised there is a general lack of as built capital cost data.

Table ii-2 lists the public available cost data for the two existing large-scale post combustion retrofit projects Boundary Dam and Petra Nova. To supplement also recent cost estimates for a retrofit case study for Saskpower's Shand power plant and the Norwegian National CCS Demonstration project. For these projects, the cost data is based on significant level of engineering and therefore of higher credibility than miscellaneous high-level studies in the literature.

Table ii-3. Cost of specific amine CC retrofit projects based on engineering estimates or actual costs. * Realised cost for total project is 1.5 bill USD but the total project also included other works e.g. power plant refurbishment. ** although realised, the reported cost is an engineering estimate, total project cost is reported to 1 bill. USD, but includes pipeline cost. ***costs adjusted to 2018 level using 2% escalation rate similar as in study.

Project	Boundary Dam	Petra Nova	Shand feasibility study	Klemets-rud CCS	Norcem CCS
Project type	Commercial plant in operation	Commercial plant in operation	Feasibility study	Concept study	Concept study
Emission source	Coal-fired power plant	Coal-fired power plant	Coal-fired power plant	Waste to Energy	Cement kiln
Capacity (t CO_2 output/h)	135	200	272	52	55
CAPEX reported	800 mill USD*	635 mill USD**	876 mill USD***	3500 mill NOK	3100 mill NOK
Scope included in CAPEX besides capture plant	CO_2 Compression, stretch of pipeline	CO_2 Compression, steam plant, cooling tower	CO_2 Compression plant,	Liquefaction, 4 days storage, export of CO_2, transport, heat pumps	Liquefaction, 4 days storage, export of CO_2, WHRUs, host modifications
Year of cost data	2015	2016	2018	2018	2018
Reference	[23]	[28]	[31]	[32,34]	[34, 33]

As shown in Table ii-3, the scope included in the capital cost is not identical. All cases however include costs for integration and CO_2 compression/liquefaction, which are major addons. Total actual cost of the Boundary Dam project has been reported to 1.5 billion USD, but about half of this was related to refurbishing of old coal-fired boiler including new turbine and generator as well as an amine based desulphurisation plant. The Petra Nova total actual project cost has been reported to about 1 billion USD, which is more than the predicted engineering cost. The cost also included utilities and a steam plant. The Norwegian projects include CO_2 liquefaction and liquid CO_2 storage tanks for 4 days production as well as CO_2 export pier, which is more costly than CO_2 compression for pipeline transport. Also, the Norwegian projects included extensive heat integration with heat pumps, steam compression and waste heat recovery units.

To obtain a more equal basis for the CAPEX the scope and cost adjustments to the Norwegian projects as shown in Table ii-4 have been applied. The CAPEX reported for CC retrofit will then include CO_2 capture plant, CO_2 compression to pipeline pressure, utility systems (cooling water, electricity, steam, etc.), integration costs (hook-up to main plant) and owners cost.

Table ii-4. Specific CAPEX of CC retrofits with estimated scope adjustments.

Project	Boundary Dam	Petra Nova	Shand study	Klemetsrud CCS	Norcem CCS
Scope adjustment	-	-	-	Site preparation, CO_2 storage & export, truck transport, heat pumps	CO_2 storage and export, heat integration, Site preparation & relocation of equipment
CAPEX adjustment	0	0	0	-500 MNOK	-400 MNOK
Specific CAPEX (mill EUR/[t CO_2 output/h]	5.3 mill	2.9 mill	2.9 mill	6.0 mill	5.0 mill
Exchange rate applied	0.90 EUR/USD	0.90 EUR/USD	0.90 EUR/USD	0.10 EUR/NOK	0.10 EUR/NOK

Rubin et al. [35] compared cost estimates of 6 different case studies for new built coal fired power plants (capacity 3-4 MTPA, generic cases) with amine CC and found that the specific CAPEX varied from 1600 to 2300 USD/kWe generating capacity, which translates to approximately 2.1-2.9 mill EUR/(t CO_2 output/h). This is lower than any of the cases reported in Table ii-3, but the capture capacity is significantly higher, and the case covers newbuilt.

The Global CCS Institute has released an update on its predicted global cost of carbon capture in 2017 [36]. This shows estimates on cost of carbon capture implemented in different industries. For coal fired boilers specific capital costs of 1.6 mill EUR/(t CO_2 output/h) for CC installation can be deduced. This includes compression and transport of CO_2 and is related to newbuilt power station in USA with capacity of 480-550 t CO_2 output/h.

It is clear from the studies referenced above that many desktop studies of generic plants provide substantially lower CAPEX estimates compared to specific projects where the costs are based on some level of engineering. Also, the fact that most desktop studies concern newbuilt facilities will contribute to significantly reduced integration costs.

Figure ii-6 shows a comparison of the different CAPEX estimates in Table ii-4 and in the referenced studies vs. the CC plant installed capacity. It is apparent that the effect of scale on specific CAPEX shown in Figure ii-6 is quite pronounced even if the two data points from generic studies are omitted. However, it is also clear from the scatter in Figure ii-6 that the CAPEX of CC retrofit project is difficult to generalise and there will be considerable uncertainty on such generalised cost estimates. The CAPEX estimates for 2020 in the Data Sheets are based on the cost level indicated in Figure ii-6.

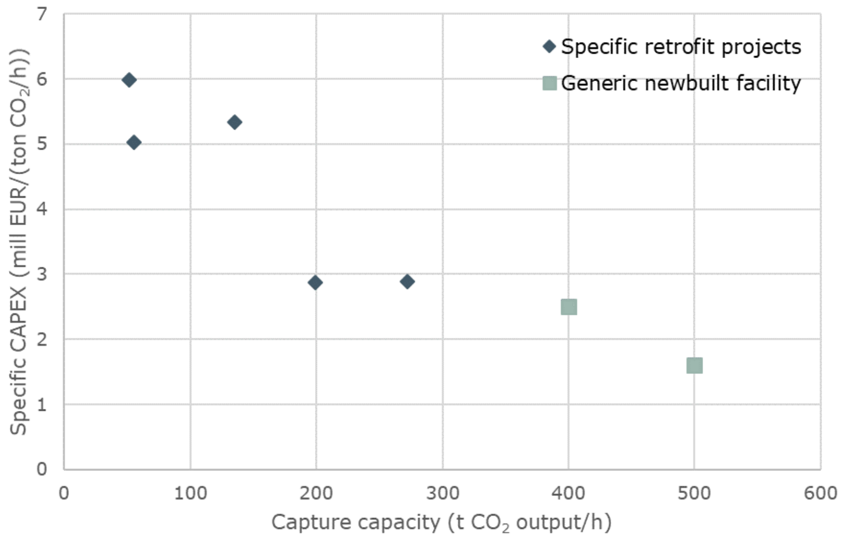


Figure ii-6. Specific CAPEX cost of complete CC plant installations including CO_2 compression, integration and utility costs vs. CC plant capacity (data from Table ii-4).

Figure ii-7 shows a rough estimate of the share of total CAPEX for a retrofit CC project that is related to respectively the capture plant, utilities incl. flue gas supply, CO_2 compression, Owner's cost and heat integration e.g. turbine refurbishment, steam plant and waste heat recovery. The estimate is amongst other based on data from [28]. Figure ii-7 can be used to correct the CAPEX estimate if not all scope is relevant to the investigated CC project.

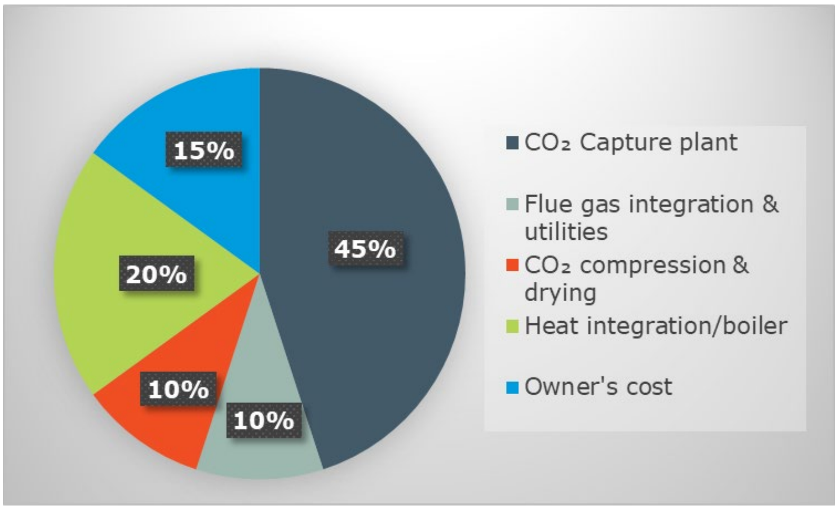


Figure ii-7. Estimated CAPEX distribution of a complete CC plant retrofit installation based on data from [28].

OPEX

Fixed O&M for amine CC includes staffing, maintenance, service agreements. As the amine CC plant will be an addon to an existing facility, the need for additional operating staff is reduced. 7 to 15 additional staff (depending on size and the site's existing organisation) for O&M is expected for a commercial plant including CO_2

compression and drying. Other fixed O&M such as service agreements and maintenance. Annual fixed O&M is calculated as 3% of CAPEX.

Variable OPEX for amine CC plants are dominated by cost of heat and electricity. Many reported variable OPEX in the literature includes cost of energy. Excluding heat and electricity (listed separately) the variable OPEX is mainly related to costs of make-up of amine, caustic soda for flue gas pre-treatment, waste disposal costs and the variable part of maintenance costs.

The cost of make-up amine may range from 1.5-12 EUR/kg depending on the specific amines applied. The consumption rate is as provided in Table ii-1. Based on this, a cost of 2 EUR/(t CO_2) is included in variable O&M.

Other consumables such as caustic soda, activated carbon, etc. are required in minor quantities. These consumables will typically constitute less than 1% of OPEX. Disposal cost of chemical waste from reclaimer is typically also comparatively small. A cost of 0.5 EUR/(t CO_2) is included in variable O&M to cover all these small consumables.

ii.14 Uncertainty

The uncertainty on cost data for larger scale plants i.e. > 20 t CO_2 output/h, is relatively significant today as few of these plants have been erected. Although several large-scale projects have been in the planning, no large CC installations have been erected in Denmark or EU hence there will also be uncertainty related to the permitting process.

In a 2050 perspective there will be significant uncertainty predicting the performance and cost of technology as it will depend on how and when the market will develop. As the cost data at 2020 level is based on first-of-a-kind plants, it is however likely that costs will decrease substantially in the future.

ii.15 Quantitative description

Three data sheets have been provided for amine based CC technology (separate Excel file). The sheets cover the following emission sources and capacities:

- CC plant (32 t CO_2/h) retrofit to 100 MW_{th} waste or biomass fired CHP
- CC plant (164 t CO_2/h) retrofit to 500 MW_{th} biomass fired CHP
- CC plant (152 t CO_2/h) retrofit to 4500 tpd clinker cement kiln

iii 402 Oxy-fuel combustion technology

Contact information

- Contact information: Danish Energy Agency: Filip Gamborg, fgb@ens.dk; Laust Riemann, lri@ens.dk
- Author: Jacob Knudsen and Niels Ole Knudsen from COWI

iii.1 Brief technology description

iii.1.1 Oxy fuel combustion at Pulverized coal (PC) and Circulating Fluid Bed (CFB) fired units

Oxy-fuel combustion is a relatively new technology. The first proposals for commercial use of the technology originated in 1982 when oxy-fuel combustion was proposed as a technology to provide CO_2 for EOR. This chapter will be based on oxy-fuel retrofit to existing energy plants and emission sources.

Conventional boilers use atmospheric air for combustion, where the 79% nitrogen in air dilute the CO_2 in the flue gas. To avoid post-combustion capture, nitrogen is removed before combustion, resulting in a flue gas consisting primarily of water vapor and carbon dioxide.

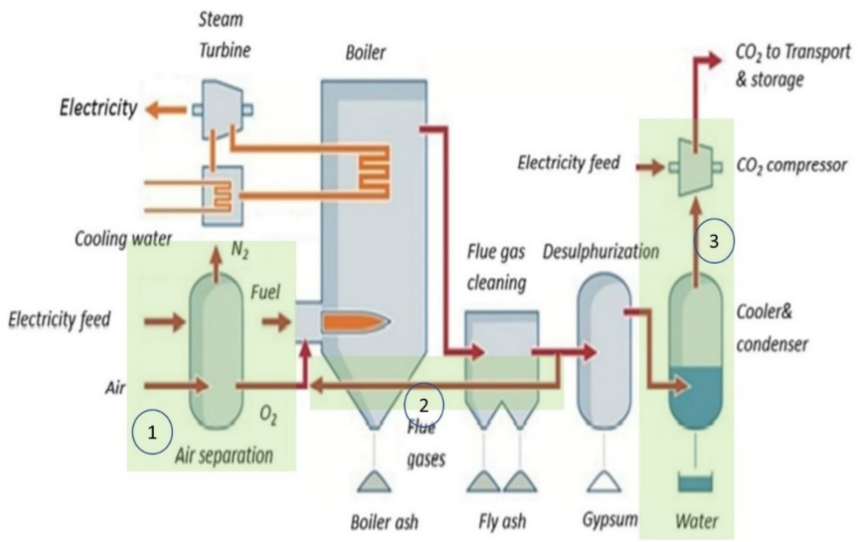


Figure iii-1 Schematic illustration of oxy-fuel combustion (25).

In principle, there are only three differences between a conventional power plant and an oxy-fuel power plant

1. A oxygen source typically an air separation unit (ASU)
2. Flue gas recirculation (FGR)
3. CO_2 purification (and compression) (CPU)

Theoretically the difference between the two combustion concepts seems limited, however, as gas properties and the thermodynamic framework conditions changes, the combustion zone, heat-transfer, etc. must be adapted.

The major differences are: The heat capacity of H_2O and CO_2 is higher than for N_2. The oxygen concentration must therefore be kept at 27-30%, instead of the atmospheric 21%, in order to maintain the same adiabatic flame temperature. This also means that approx. 60% of the flue gas must be recycled as the oxidant is pure oxygen.

Due to the higher heat capacity of H_2O and CO_2, the flow through the boiler after recirculation of flue gas is slightly reduced, while the flue gas flow out of the plant is reduced by approximately 80% as it primarily consists of H_2O and CO_2.

Both CO_2 and H_2O have a higher thermal radiation than N_2. If O_2 is kept below 30% in the burners, unchanged heat transfer in the radiation part of the boiler can be maintained. In the convection part of the boiler, (approximately after the first superheater) thermal transmission is lower, therefore additional (retrofitted) surfaces may be necessary.

The flue-gas outlet from an oxy-fuel boiler consists primarily of CO_2 and H_2O. However, due to air ingress, necessary O_2 surplus, argon in the O_2-input stream, nitrogen in the fuel etc. the final dry CO_2 concentration at full load lies between 70 - 90% where 70% can be reached at PC and CFB retrofit units and 80-90% at new plants.

iii.1.2 Oxy-fuel at grate-fired units

At grate-fired units, air leakages are crippling for use of the oxy-fuel technology. As grate-fired boilers are small, notoriously leaking air at fuel-feeding and ash outlets etc., it will be very challenging to retrofit an existing grate boiler to oxy-fuel conditions. No demo plants for oxy-fuel firing of grate boilers have been erected. No relevant literature or reports on experimental work for oxy-fuel combustion in grate-fired units exists.

iii.1.3 Oxy-fuel firing at cement plants

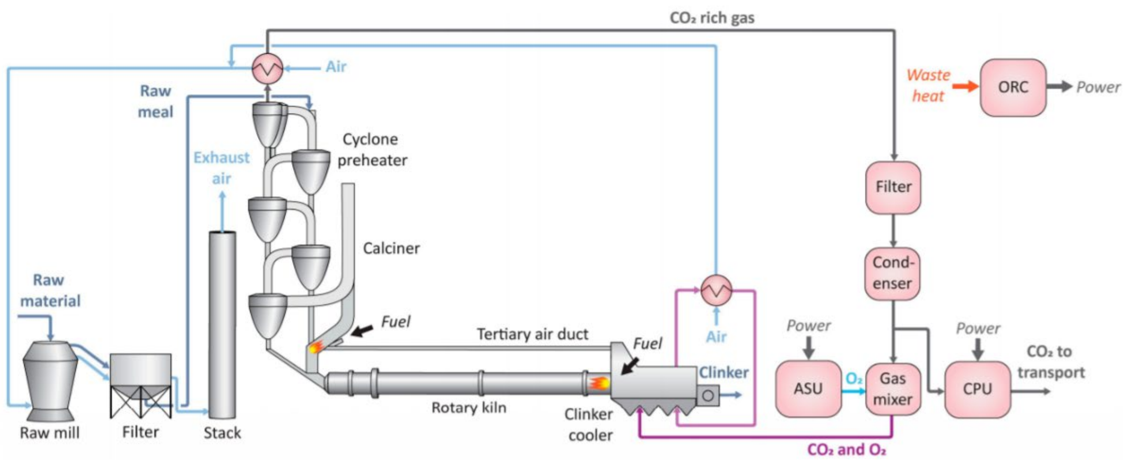
In cement plants it is possible to obtain a concentrated CO_2 flue gas by oxy-fuel firing like in power plants, however due to the much more integrated process (calcination, clinker burning, clinker cooling etc.) retrofitting a cement plant is substantially different from retrofitting a power plant.

Around two-thirds of the CO_2 emissions from the cement industry are process related, originating from the calcination of limestone where $CaCO_3$ is converted to CaO and CO_2, while one-third of the emissions come from combustion of fuels in the cement plant's calciner and rotary kiln. A measure such as fuel switch can therefore only remove one-third of the CO_2 emissions, which make CC a necessity to become close to CO_2 emission free. The CO_2 contribution from calcination results in higher CO_2 content of cement kiln exhaust gas, which is typically 20-30%-vol.

In the oxy-fuel process, combustion is performed with an oxidizer consisting mainly of oxygen mixed with recycled CO_2, to produce a CO_2 rich flue gas which allows a relatively easy purification with a CPU.

Additional power is required for the oxy-fuel process compared to a plant without capture, mainly by an ASU providing oxygen and the CPU. Some of this power demand can be covered by a waste heat recovery system. As an example, an organic Rankine cycle (ORC) can be installed, or surplus heat can be reused for district heating.

Figure iii-2: Cement kiln system converted to oxy-fuel firing. The reddish coloured blocks are new process units [49].



Conversion to oxy-fuel firing might seem uncomplicated, however the cement kiln process itself must be modified. The gas atmosphere in the clinker cooler, the rotary kiln, the calciner and the preheater is changed, and some of the flue gas is recycled.

Air that is heated by hot gases from the preheater and the clinker cooler is sent to the raw mill to dry the raw material, instead of the flue gas. The direct advantage is that the kiln throughput will be increased, but due to the higher CO_2 partial pressure the calciner shall operate at 60 °C higher temperature, which will increase energy consumption and the choice of construction material shall be re-evaluated, likewise fouling when firing alternative fuels might be an issue.

A list of necessary changes can be seen in the following Figure iii-3.

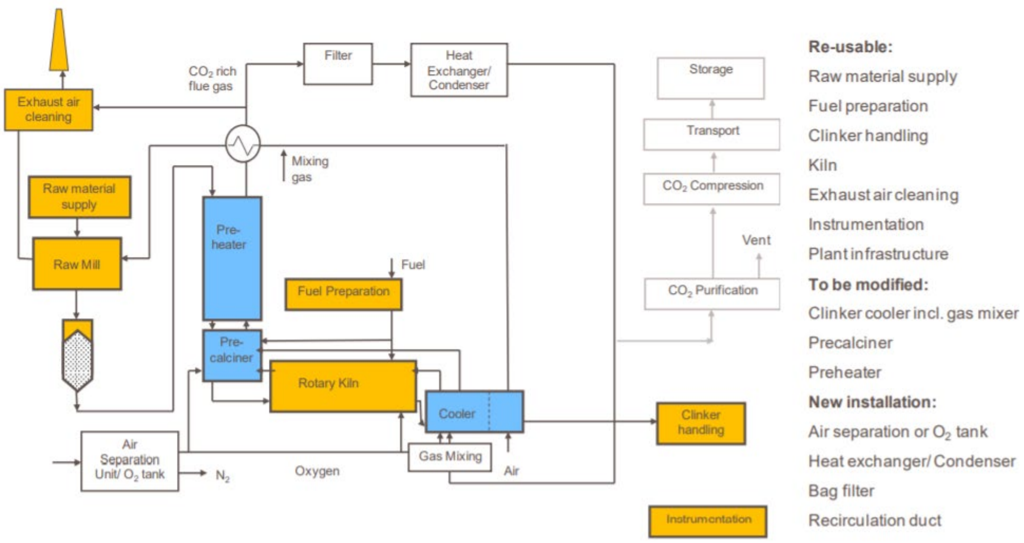


Figure iii-3 General Scheme for an oxy-fuel retrofit concept: White: To be installed new, Blue: To be utilized from existing plant, Yellow: To be modified, Grey: Not needed for proof of concept. [48]

A major drawback for the retrofit process is that the outage period for converting a cement plant to oxy-fuel will last 6 months with resulting lost production revenue.

Another main drawback is that even modern cement plants are leaky. A typical flue gas leaving the preheater chain will contain 15% gases that have entered the plant via leaks. An overview of sources of air-leakages at typical Portland cement plant is shown in Figure iii-4. A study by the European Cement Research Academy (ECRA) reveals that it might be possible to reduce this number to 1% at new plants/totally refurbished plants, but at considerable costs.

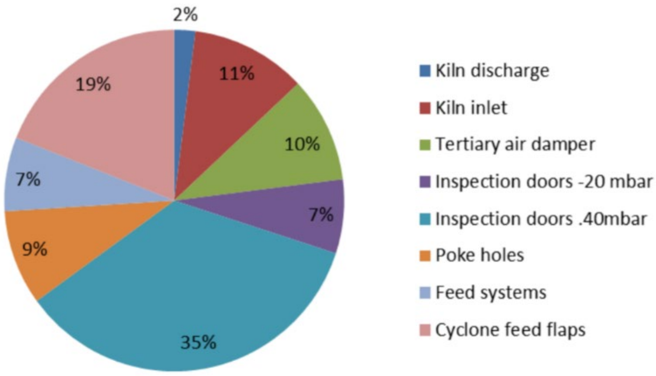


Figure iii-4 Overview of air-leakages at a typical Portland cement plant. [38]

Early phase design studies for an oxy-fuel cement plant have been conducted [60, 55], but demonstration units have not been built.

iii.1.4 Partial oxy-fuel combustion

To reduce the complexity of the oxy-fuel system another option is to perform oxy-fuel combustion on the precalciner, as 80% of the CO_2 is generated here.

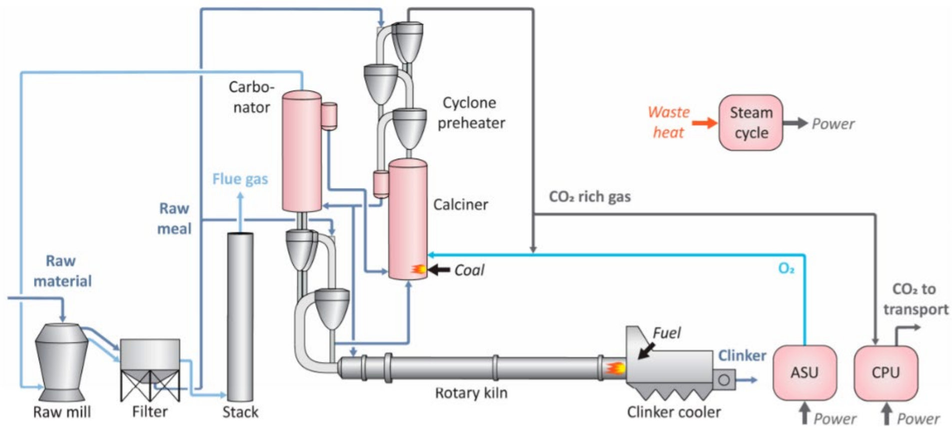


Figure iii-5. Partial oxy-fuel combustion with integrated Calcium looping (49)

The benefit of this system is that the kiln and cooler do not require retrofitting, this reduces the cost of installing CC and the size of the ASU can be reduced by 40%. On the other hand, two cyclone preheater towers are required and the utilisation of heat from hot kiln and calciner flue gases will be reduced increasing net fuel consumption. Feasibility studies of the concept has been conducted but no pilot facility has been constructed. A further simplification is to omit the calcium looping part of the process, thereby reducing CO_2 capture to < 80% as the flue gas from the rotary kiln is still emitted. Despite the simplification, ECRA indicates that the cost of CO_2 capture for the partial oxy-fuel case is higher than for the full oxy-fuel case [60]. This is both related to the increased fuel consumption and that the more expensive units (ASU and CPU) are still required.

iii.2 Input

Compared to conventional combustion, the only differences is that pure O_2 is required as input i.e. from ASU or electrolysis unit. The energy penalty for producing pure O_2 by a standard ASU is around 200-220 kWh/ton O_2.

Instead of installing an ASU unit, it is in principle possible to deliver O_2 from an electrolysis unit producing H_2 and O_2 from e.g. wind power. However, there are technical and commercial challenges in balancing the O_2 production from electrolysis based on volatile renewable energy and the base load operating profile of a cement kiln. Decoupling of O_2 production by electrolysis and the operation of an oxy-fuel cement plant will require storage of large volumes of cryogenic O_2. An O_2 liquefaction plant + regasifying plant including cryogenic O_2 storage tanks for just few days of operation will be an equal sized investment as an ASU.

iii.3 Output

The flue-gas outlet from an oxy-fuel boiler consists primarily of CO_2 and H_2O. The heat produced by the boiler will be the same as in air firing mode with flue gas condensation (and is not included here as an output).

However, due to air ingress, necessary O_2 surplus, Argon in the O_2-input stream, nitrogen in the fuel etc. the final dry CO_2 concentration at full load lies between 70 - 90% where only 70% has been demonstrated for retrofit units and 80-90% at new plants.

Figure iii-6 shows the CO_2 concentration reached on dry basis at the oxy-fuel retrofit plant Callide unit 4 as function of unit load. The overall air ingress was within the design limit of 7 % (mass), the maximum achieved CO_2 concentration reached was 71 vol-%, dry at full load, but at 50% load, only 45% CO_2 Vol-%, dry was achieved due to air ingress which is independent of load.

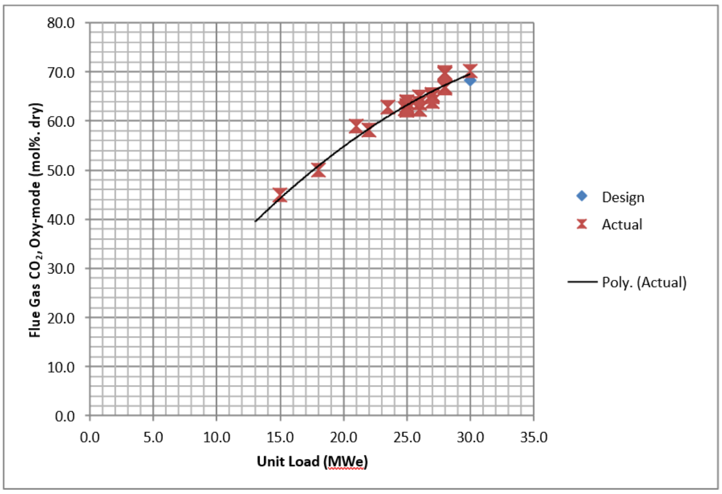


Figure iii-6 CO_2 concentration dependent on load at Callide oxy-fuel plant from [52].

iii.4 Application potential

Technical viable oxy-fuel combustion can be implemented at both power plants and at cement plants if the air ingress can be kept low.

Compared to post combustion amine technology where the resulting CO_2 has a purity above 99%, oxy-fuel carbon capture requires extensive upgrading of the CO_2. System for upgrading CO_2 is shown in Figure iii-7.

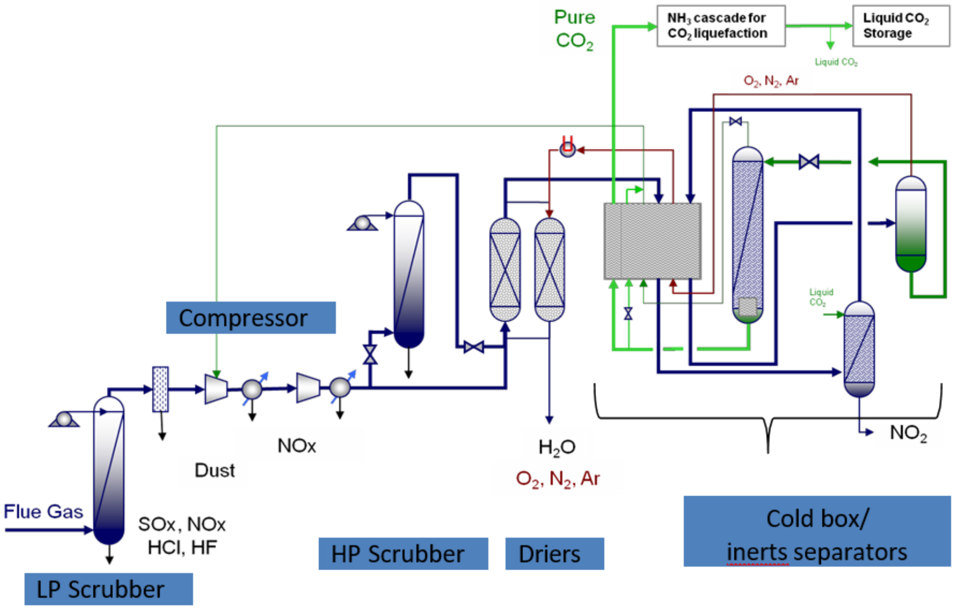


Figure iii-7 Upgrading of raw CO_2 at Callide oxy-fuel CCS. [44]

Due to the lower purity of the CO_2 it is necessary to remove inerts (O_2, N_2 etc. by cryogenic distillation. To reduce CAPEX, OPEX and recovery rate for the CPU part of the plant, it is therefore essential to keep CO_2 content above 60-70%. Also the lower the content of CO_2, the lower CO_2 capture will be obtained as the venting loss increases in the CPU. The CO_2 purification is further described in section iii.12.3. At lower purities post treatment with an amine scrubber becomes more economical, in which case the oxy-fuel combustion makes no sense.

iii.5 Typical capacities

iii.5.1 PC oxy-fuel fired plants

At present no commercial PC fired oxy-fuel plants have been built, but two Demo size projects have been conducted, a retrofit project in Australia and a new built oxy-fuel boiler at Schwarze Pumpe in Germany. As shown in Table iii-1, oxy-fuel has only been demonstrated in relatively small scale e.g. 30-120 MWth.

In Denmark a design study at Studstrupværket has been carried out, but it was concluded that due to the chosen boiler steel, boiler configuration, load change ability etc. it would be more beneficial to build a new power plant.

Table iii-1. Overview of main PC oxy-fuel fired demonstration projects and the Danish experience (design study).

Unit scale, Location	Demo scale, Retrofit Callide Australia	Demo scale Brown-field Schwarze Pumpe Germany	Full scale retrofit Design study Studstrup Denmark [62]
Unit thermal power	120 MWth	30 MWth	900 MWth
Years of operation	2008-2012	2006-2014	
Aim of research	Process integration Proof of concept	Process integration Proof of concept	Design study Efficiency Proof of concept
Type of fuel	Bituminous coal	Sub bituminous coal	Biomass
Operators **Main conclusion**	Doable, but project terminated	To expensive	New plant is preferable

iii.5.2 Oxy fuel fired CFB boilers

To date, no commercial-scale (>300 MW_{th}) oxy-fuel CFB boiler has been built despite the technology currently having a TRL of 7–8 [176], however several experimental Oxy CFB units have been built and operated as shown in Table iii-2.

Unit scale, Location	Industrial-scale, CIUDEN, Spain	Industrial-scale, Valmet, Finland	Pilot-scale, CanmetENERGY, Canada	Pilot-scale, University of Utah, USA	Pilot-scale, University of Stuttgart, Germany
Unit thermal power	30 MWth	4 MWth	0.8 MWth	0.33 MWth	0.15 MWth
Years of operation	2011–2014	2013-present	2011–2017	2011- present	2014- present
Aim of research	sulphur capture potential	combustion, heat transfer safety	combustion and pollutant formation	SO3 formation under oxy-fuel conditions	Solid burnout and emission of CO and NOx
Type of fuel	petcoke, coal and biomass	Bituminous coal	Coal, petcoke and lignite	bituminous coal	Bituminous coal
Ref	44	37	40	37	42

Table iii-2 Oxy-fuel CFB experimental units.

iii.5.3 Cement plants

No integrated oxy-fuel cement plants have been erected at any scale. Some of the single unit operations have been proven in lab scale.

iii.6 Space requirements

Limited additional space is required for the modifications at the energy plant or cement kiln. However, the ASU and CPU require relatively extensive area.

CPU: 15 m^2/[t CO_2 output/h]

ASU: 30 m^2/[t CO_2 output/h] for biomass plant and 10 m^2/[t CO_2 output/h] for cement kiln

iii.7 Regulation ability

The main challenges with operation of oxy-fuel combustion systems are:

- Air leakages
- Start-up time for the ASU from ambient temperature
- Load ranges and load changes
- Complexity of operation of ASU, combustion and CPU as one integrated unit

The start-up time for the cryogenic ASU dictates the start-up for the complete plant in CC mode. The start-up time for a cryogenic ASU after long shut-down is around 60-70 hours, but if the stop is less than 24 hours it can be reduced to 2-3 hours due to a very efficient insulation of the cold box. The minimum load range for the ASU is around 30%, The robustness of operation of the complete oxy-fuel combustion and CPU depends on how intimate the heat integration is and on whether adequate buffer storages has been applied. However, optimised heat-integration will reduce the load change ability. Because of the volatile power production from wind and solar plants, thermal power plants operating in the same market are typically required to balance production. It will be challenging to operate oxy-fuel power plants under such fluctuating conditions.

On the contrary, a Portland cement plant normally operates at full capacity with only minor fluctuations, hence an oxy-fuel cement plant will be easier to operate.

At power plants, the purity of CO_2 in the flue gas diminishes at low load. As a rule of thumb, the purity of the CO_2 should be > 60-70% to operate a CPU unit based on standard compression and dehydration, if the purity gets lower it is necessary to go through another purification step such as amine scrubbing, in which case oxy-fuel combustion makes no sense. At Cement plants air leakages are significant at all loads, requiring refurbishment before oxy-fuel combustion is a realistic option.

Basically, CFB boilers are more suitable for oxy-fuel retrofitting than grate and PC boilers as CFB boilers in principle are airtight, however, fans, ash outlets etc. are not completely airtight even if CO_2 is used as sealing air.

For a retrofit boiler, depending on design, it will probably be possible to reach 70-75% CO_2 at full load, but only 50-60% at half load, however an individual design study is needed for each unit to verify the achievable performance.

iii.8 Advantages/disadvantages

iii.8.1 PC and CFB fired boilers

The primary advantage with the retrofit oxy-fuel process are the potential saving on investment cost compared to post combustion capture as the existing boiler can be modified to oxy-combustion.

Nevertheless, both the air separation unit (ASU) for O_2 generation and the CO_2 purification unit (CPU) are expensive and energy intensive units, hence the cost saving potential will be rather limited. However, access to alternative O_2 source e.g. surplus production from electrolysis, will increase the attractiveness of oxy-fuel conversion.

Many of the advantages with the oxy-fuel process that can be achieved with newbuilt oxy-fuel boilers will however disappear with retrofitted boilers. This particularly concerns the issue with excessive air ingress which results in increased CAPEX and OPEX to the CPU. The percentages of air-ingress depend on boiler type in the following order: Grate fired > PC-fired > CFB. CFB boilers therefore have the best potential.

As the recently commissioned 500 MW_{th} BIO4 at Amagerværket is a CFB boiler conversion to oxy firing might be an option and should be considered in line with post amine technology.

iii.8.2 Cement plants

As both the CAPEX and OPEX for the ASU or alternative oxygen generation are high, the mass of recovered CO_2 per ton O_2 produced should be as high as possible. This favour the (partial) oxy-fuel combustion applied at cement plants, as 3-4 times as much CO_2 is captured per unit O_2 consumed compared to that of energy plants.

This is due to the calcination process $CaCO_3 \rightarrow CaO + CO_2$ which releases additional CO_2 without consumption of O_2. Another advantage is that cement plants are operated continuously at full load, hence reducing issues with long start-up times of oxy-fuel process and ASU.

A disadvantage is the rather comprehensive modifications required to the cement plant for oxyfuel retrofit (both full and partial conversion), which will require long downtime for the facility.

iii.9 Environmental

In oxy-fuel combustion no new chemicals are introduced but handling of O_2 requires ATEX zones (from the French: ATmospheres EXplosives) and ATEX equipment, as most organic material ignites spontaneously in pure O_2.

Concerning the flue gas, the high content of CO_2 is a risk factor too. as the density of CO_2 is 60% higher than dry air, CO_2 could be concentrated in basements and other low lying pockets in the plant building

iii.10 Research and development perspectives

At PC fired boilers no major R&D projects are ongoing as the potential is regarded as limited.

At Oxy-CFB the main driver for future plants is the option to reduce the size of the boiler by up to 80% by increasing the oxygen concentration (in the bottom) of the CFB from 21% to 50-80% as shown in Figure iii-8. This requires however, increasing the mass of circulating fluid bed material (sand used for heat transfer etc.) considerably to keep the bed temperature down. I.e. instead of recirculation of flue gas, a larger amount of bed material is recirculated.

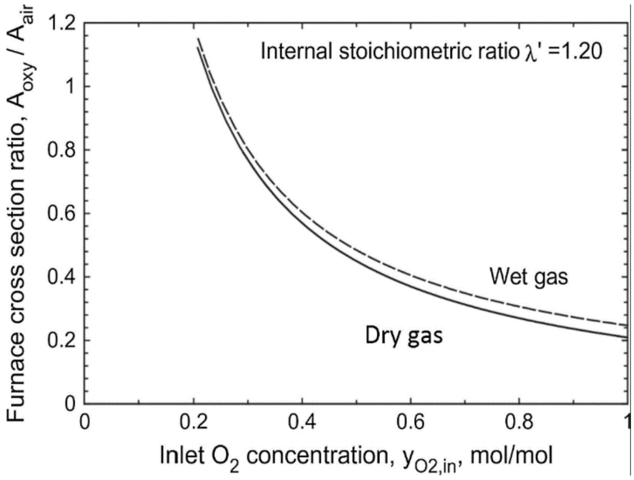


Figure iii-8 Potential to reduce boiler size by increasing O_2 concentration. [45]

With reduced boiler size the capital cost for the boiler is reduced considerably, which might totally offset the cost of the ASU unit making new Oxy-CFB viable.

These 2nd generation oxy CFB´s are still at a very early stage, demonstration units have not been built and commercial plants will not be erected within the next decade.

For retrofit Oxy-CFB, increasing O_2 to 50-80% is not an option, as the furnace size is fixed. The cost of retrofitting a CFB boiler to oxy fuel combustion is therefore more or less comparable to retrofitting a PC boiler. As the three major changes, the ASU, the CPU and the flue gas recirculation are in principle the same.

iii.11 Examples of market standard technology

At present standard market technology does not exist, but several demonstration plants have been built.

iii.11.1 Retrofit of Callide a unit 4

In reality, retrofit of a power plant is more complicated than illustrated in the introduction. As an example, the retrofit of the power plant Callide A, unit 4 is described in the following.

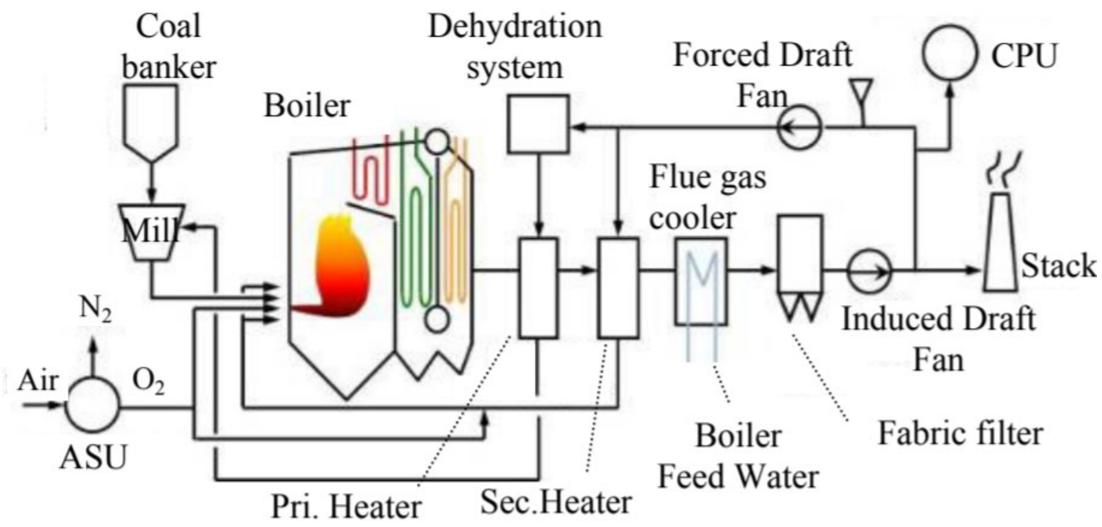


Figure iii-9 Illustration of the rebuilds needed to retrofit Callide A unit 4.[52]

The first step was operation of the boiler in air-fired mode for several months to ensure that the total plant (especially turbine, boiler, and SCADA system) had a residual life of at least 5 years, based on this, the retrofit was designed

Major new equipment included:

- Installation of two x 330 t/day air separation units (ASUs)
- Installation of a 75 t / day CO_2 purification plant (CPU) for the treatment of a side stream (~10%) of flue gas from the Oxy-fuel boiler.

Simultaneously, the retrofit of the boiler system was carried out over a period of 2 years. New boiler components included:

- Replacing the middle burner row with Low NOx burners with two O_2 injection lances per burner
- New flue gas low pressure preheater
- New induced draft fan
- Gas recirculation fan

- Flue gas condensation (dehydration system)

Above are listed the rebuilds that were needed to complete the trial program. If it had been a commercial plant, the plant owners would have considered further improvements which included:

- Improved integration of the ASUs with the oxy-fuel boiler by establishing buffer storage for cryogenic O_2
- Further development of the SCADA concept, including improved transition from air to oxy mode, as well as interaction between ASU, oxy-fuel boiler and CO_2 purification.
- Finally, an improved process and heat integration between ASU, Oxy-fuel boiler and CO_2 purification must be made and the unit operations: ASU, Oxy-fuel boiler and CO_2 purification must each be optimized.

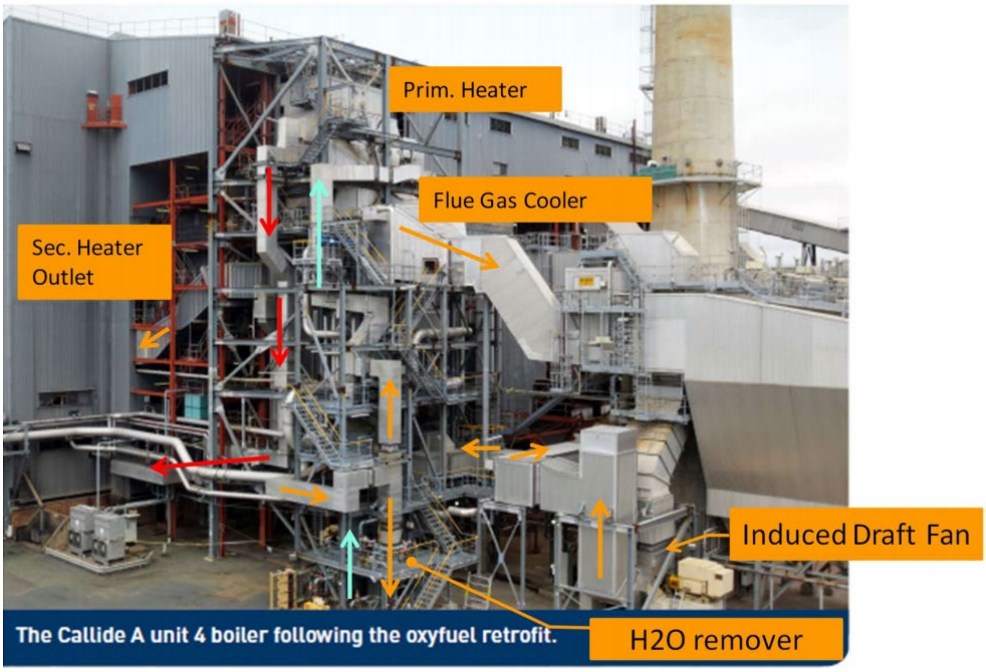


Figure iii-10 Photo of Callide Oxy-fuel boiler from [52] showing retrofit paths (red) and flue gas flue directions (yellow).

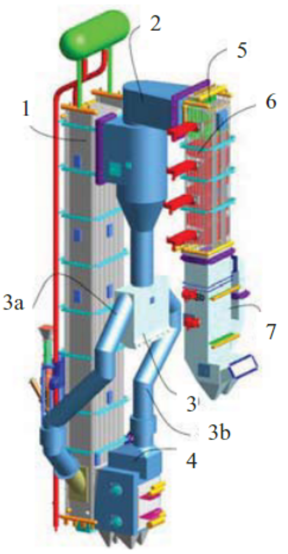
iii.11.2 Oxy-CFB experimental units

The best documented Oxy-CFB boiler is Ciuden's 30 MWth experimental plant at Central térmica Compostilla II in northwestern Spain.

The demonstration unit was established around 2008 and was in operation until 2014. The plant was equipped with flue-gas purification and compression of CO_2. The focus was to prepare for a 330 MWe coal-fired ultra-supercritical Oxy-CFB plant at the nearby power plant.

The test plant was a Foster Wheeler Flexi-Burn® concept that enabled either conventional or oxy combustion operation. Interestingly, the maximum boiler capacity for air combustion was 15 MWth, while the capacity under oxy-fuel conditions was 30 MWth.

The reason for the substantially increased capacity is the high heat capacity in the solid bed material, which allows for additional firing. The fluid bed temperature either can be reduced by flue gas recirculation or alternatively by increased recirculation of bed material.



(1) combustion chamber
(2) solid separator
(3) ash sealing-direction device
(3a) ash duct to the furnace
(3b) ash duct to the cooler
(4) furnace cooler - INTREX™
(5) heat recovery zone
(6) steam cooled walls
(7) economizer

Furnace dimensions (m)	**20x2.8x1.65**
Thermal power (MW_{th})	15 (air mode) 30 (oxy mode)
Max steam flow (t/h)	47.5
Superheated steam T (ºC)	250
Superheated steam p (bar)	30
Feed water T(ºC)	170
Outlet flue gases T (ºC)	350-425

Figure iii-11 Ciuden's 30 MWth experimental plant at Central térmica Compostilla II in northwestern Spain [46].

It was anticipated that a full-scale Oxy-CFB plant should be operational in 2015, however the Ciuden project group have instead focused on further cost reduction to make the project viable. The focus in a newer EU project "Optimization of oxygen-based CFBC technology with CO_2 capture" have been.

1. Reduction of ASU energy consumption to 150 kWh/ton O_2
2. Reduction of Capex by increasing O_2 to 40-50% in the CFB
3. Improved integration of ASU, CFB and CPU

Except for the ASU, these improvements are only relevant for new plants due to the major increase in thermal output if a retrofit is carried out requiring a new turbine and new heat exchangers, and it would also be challenging to implement on a biomass fired unit due to lower ash melting points.

At Ciuden transition from air to oxy mode could be automated and carried out within 30-40 minutes in both directions. The unit was able to achieve 80 vol-% $CO_{2,}$ dry, corresponding to 3% air ingress. Actions are in progress to reduce this number to reduce the CAPEX and OPEX for the CPU.

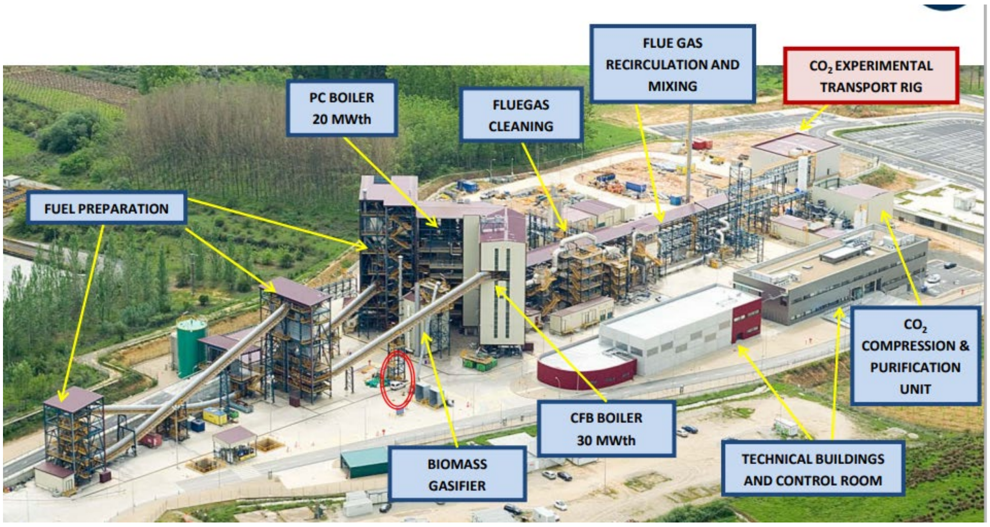


Figure iii-12 Ciuden's Demonstration site. [46]

iii.12 Prediction of performance and cost

iii.12.1 PC and CFB fired units

Retrofit of power plants to oxy-fuel combustion will never be a standard product. Due to the integration with the existing process, individual design studies for each project is needed covering:

- Options to minimize air ingress
- Recalculation of the energy transfer in the boiler and design of new heat-exchangers, O_2 and flue gas mixers, flue gas dehydrators, flue gas recirculation ducts, new fans and blowers etc.
- Based on the above the CPU can be designed

The only completed retrofit conversion of a power plant to oxy fuel firing was the Callide PC power plant and economic data are extrapolation from the number given in the public report. Although the retrofit costs will not be one to one comparable to CFB units, retrofit of either PC or CFB involves many of the same modifications and new installations, hence the cost estimate may be applied as a first estimate for both cases.

The Callide Oxy-fuel Project Capital Costs are summarised below. These data include an escalation to 2017 AUD assuming a CPI of 1.5% per year.

CAPEX	Boiler – Air-firing refurbishment	Boiler – Oxy-fuel retrofit (120 MW_{th})
2017 mill AUD	10	50.8

Figure iii-13 *Summary of Callide Oxy-fuel Capital Costs (rounded) [52].*

The capacity of Callide A from 1965 was 120 MW_{th} (30MW_e), with dry cooling towers etc. this corresponds to a thermal capacity of around 25% of the size of e.g. BIO4 at Amager.

A cost extrapolation for large scale plant was in the project estimated using the “Rule of Six Tenths”.” ($[size_1/size_2]^{0.6}$). For a 500 MW_{th} unit it gives a cost factor of 2.35

At present with the huge uncertainties given, it is anticipated that cost for retrofitting a PC and a CFB boiler are at the same level.

Below is presented the extrapolated costs for a 500 MW_{th} boiler oxy-fuel conversion (excluding CPU and ASU), currency conversion rate 0.67€/AUD, primo 2017, 1,5% CPI.

CAPEX, 2020	Refurbishment	Oxy fuel retrofit (boiler)
Total costs 500 MWth	16 mill. €	83 mill €
Specific investment (mill € /[t CO_2 output/hour])	0.1 mill. €	0.47 mill. €

The uncertainty on the numbers above are quite substantial. The cost of the oxy-fuel retrofit depends on the boiler design.

iii.12.2 Cement plants

Oxy-fuel retrofit to an existing cement kiln will require substantial modifications to the kiln system, clinker cooler and entire flue gas path. As it will impact the gas flow through the preheating tower and downstream process, the heat balance will also be affected. In addition, ASU and CPU units are required.

There are no demonstration plants in operation, no as built data nor any detailed design studies available for oxy-fuel retrofit, hence the CAPEX estimates identified are based on high level studies. The most comprehensive work on oxy-fuel retrofit has been conducted by ECRA.

Table iii-3 shows cost estimates for full oxy-fuel retrofit to respectively a medium and a large cement kiln. The specific investment cost appears to be nearly identical for the two studies. It shall be emphasized that the cost estimates are based on high level studies and thus prone to substantial uncertainty.

Table iii-3. Cost studies for full oxy-fuel retrofit to cement kilns. *Value estimated from ASU cost in section iii.12.4.

Study	ECRA CCS project [60]	Gerbelová et al. [61]
Cement kiln size (t clinker/day)	3,000	5,000
CO_2 captured (t CO_2 output/h)	94.5	162
CAPEX (mill €)	110 - 125	217
CAPEX Excl. ASU (mill €)	92*	162
Specific investment (mill €/[t CO_2 output/h])	0.97	1.0

iii.12.3 CO_2 purification oxy-fuel plant (CPU)

The oxy-fuel process will recover CO_2 at relatively low purity due to the presence of nitrogen and oxygen. The industrial method for purifying the CO_2 is through liquefaction and stripping (distillation) of liquid CO_2 to remove non-condensable gases (O_2, N_2, Ar). This is in principle a similar approach as described under CO_2 liquefaction. If the CO_2 has low purity from the oxy-fuel plant say below 80-85% it may be difficult to liquefy CO_2 in a standard liquefaction process (requires higher pressure and lower temperature). This will increase cost as more advanced chiller or compression process is used. In addition, flue gas pollutants such as NO_X and SO_2 carried with the CO_2 from the oxy combustion may require further purification steps such as activated carbon filtration, NOx Trap and water wash, etc. This will also create minor waste streams depending on the contents of acid contaminants in the flue gas reaching the CPU.

The high share of non-condensable gases (15-20 %-vol) will increase CO_2 liquefaction costs and will imply purging loss or recycle of some of the captured and liquefied CO_2. In the ECRA cement oxy-fuel retrofit study, the CPU is estimated to have 90% CO_2 capture rate i.e. 10% purging loss, at a CO_2 purity about 75 vol-% [60]. The energy consumption for liquefaction of oxy-fuel CO_2 gas will therefore increase substantially.

The CAPEX estimate for CPU is uncertain as no large-scale units have been built. However, one can assume it will be significantly more expensive than a standard CO_2 liquefaction unit which receives >99% pure CO_2 as input. In the Callide oxy-fuel project a CPU with 3.1 t CO_2 output/h was reported to 31.7 mill AUD [52], which corresponds to 6.8 mill EUR/(t CO_2 output/h). In the ECRA cement retrofit study [60] a 94.5 t CO_2 output/h CPU was reported to 0.7 mill EUR/(t CO_2 output/h). Savings due to scale cannot explain the entire cost gap, hence the ECRA estimate seems too optimistic.

Table iii-4. CO_2 purification (99.9%) and liquefaction/compression (to ~150 bar) after an oxy-fuel process.

	Estimated value	Comment
Purification electricity use	~0.16-0.2 MWh_e/ton CO_2	Includes chillers, CO_2 dehydration and compression. depending on CO_2 purity
CO_2 capture	90-95%	Some CO_2 is vented in the purification process
Cooling requirement	~0.3 MWh/ton CO_2	~50% of cooling is through chiller air cooler
CAPEX CO_2 liquefaction/purification	0.7 – 1.8 mill €/(t CO_2/h)	Depending on capacity and CO_2 purity. This is uncertain no large-sale units have been built

iii.12.4 Air separation unit (ASU)

The air separation unit is a very significant part of the cost of an oxy-fuel installation. The CAPEX of large-scale standard ASU plants per unit O_2 produced is given in Table iii-5. This is converted to cost per t CO_2 output both for a biomass-fired unit and a cement plant. The O_2 cost is lower per unit of CO_2 for cement kiln due to the CO_2 released from calcination as explained in section iii.8.2.

Table iii-5. Estimated CAPEX of large-scale Air Separation Unit (100-250 t O_2/h). The cost per unit CO_2 output is higher for biomass than cement because more CO2 is released per unit O_2 in a cement plant as explained in section iii.8.2.

	CAPEX	Comment
ASU CAPEX	0.9 mill EUR/(t O_2/h)	Based on ref. [57]
Cost per unit CO_2 capture for biomass CHP	0.8 mill EUR/(t CO_2 output/h)	Assuming 96% CO_2 is captured
Cost per unit CO_2 capture for cement	0.3 mill EUR/(t CO_2 output/h)	Assuming 96% CO_2 is captured

iii.13 Quantitative description

For oxy-fuel combustion the following two data sheets have been prepared:

- Oxy-fuel CC – Retrofit 500 MW biomass boiler

- Oxy-fuel CC – Retrofit 3,000 t clinker per day cement kiln

The data sheets are shown in separate Excel file.

The cost reported in the datasheet is without ASU, however cost of ASU is specified as an option.

iv 403 Direct Air Capture (DAC)

Contact information

- Contact information: Danish Energy Agency: Filip Gamborg, fgb@ens.dk; Laust Riemann, lri@ens.dk
- Author: Jacob Knudsen and Niels Ole Knudsen from COWI

iv.1 Brief technology description

The Direct Air Capture technology captures CO_2 form ambient air and recovers a concentrated CO_2 stream like other CC technologies. Because the CO_2 content of the atmosphere is only ~400 ppm or 200-300 times lower than that of typical flue gas, huge volumes of air need to be processed per unit of CO_2 captured (Approximately 2.5 mill m^3 air/ton CO_2). Because of the large volumes to be treated and the low concentration of CO_2 DAC processes have substantially higher CAPEX and energy requirements compared to carbon capture form concentrated sources such as flue gas.

The DAC technology is still in its infancy and there are many different concepts under development. Most of the technologies and methods for DAC are still being developed in the laboratory and are thus at low TRL. A few technologies have been demonstrated in pilot- and/or commercial plants, but at relatively low scale (up to a few tonnes per day) compared to CO_2 capture from point sources.

The two most mature and relevant types of DAC technology for near to mid-term deployment are:

- Solid adsorption and low temperature regeneration (temperature swing adsorption or moisture swing adsorption)

- Liquid absorption and high temperature calcination

These are the only technologies that will be described in this catalogue. Other technologies at low TRL level work among others with liquid absorption combined with electrodialysis, ion-exchange or advanced carbon nano materials [40].

The DAC low temperature adsorption process works by adsorbing CO_2 from the air in a contactor device with an activated filter material. The filter material is typically made of polymeric material with amine functional groups that will chemically bind CO_2 to the surface [40]. A forced draft fan will ensure flow of air through the filter. After some hours on stream the filter is saturated with CO_2 and the desorption or regeneration phase is started. Typically, vacuum is applied to assist desorption (vacuum assisted temperature swing adsorption) and the filter is heated to 85-100 °C with a low temperature heat source e.g. hot water. The desorbed CO_2 is collected as a concentrated CO_2 stream with purities of 98-99.9% being reported [40]. Moisture is also adsorbed from air and released during regeneration of the filter hence a stream of pure water is co-produced. After regeneration the filter is cooled to ambient temperature and it is ready for a new cycle. See illustration of working principle in Figure iv-1. A commercial scale DAC plant will consist of multiple independent DAC modules [43].

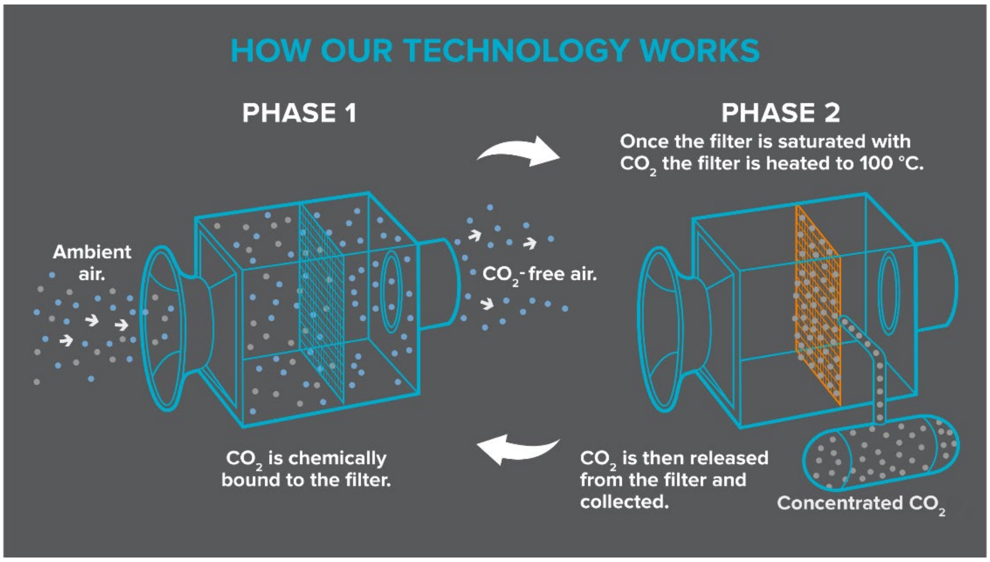


Figure iv-1. Illustration of working principle of Climeworks low temperature adsorption DAC process. Source: www.climeworks.com

The DAC process based on liquid absorption and high temperature calcination is mainly being developed by the company Carbon Engineering. The process involves an air contactor of the scrubber type where CO_2 from the air is absorbed by a circulating caustic solution (potassium hydroxide). Hydrated lime is added to the solution in a causticiser to precipitate captured CO_2 as limestone (CaCO3) and regenerate the caustic solution. Finally, a concentrated CO_2 stream is released by calcination of the solid limestone. The calcination process requires heat at 850-900°C, which in the process of Carbon Engineering is produced by burning natural gas. The burning of natural gas will result in 0.44 ton of CO_2 emission per ton CO_2 captured from the air. Therefore, other CC technology such as amine scrubbing or oxy-fuel combustion is required to make this DAC technology emission free. [40,41,44]. The technology will produce substantial amounts of high-temperature waste heat from the calcination process [44]. This heat will have to be integrated with a power cycle or other industry to obtain acceptable energy efficiency. The heat integration proposed by Carbon Engineering [44] is complex. Furthermore, a waste stream of calcium carbonate will be produced.

In addition to natural gas, the liquid absorption and high temperature calcination process use substantial amounts of electrical energy for air fans, solvent pumps, CO_2 capture/oxy-fuel plant, CO_2 compressor, etc. Make-up of limestone and potassium hydroxide will also be required as well as substantial amounts of water.

As the high temperature absorption process of Carbon Engineering in its current form requires natural gas as input and thereby dependent on fossil energy as well as other CC technologies to become emission free, it is not considered further in this catalogue.

iv.2 Input

The low temperature adsorption process requires air, electrical energy for the air fans, vacuum pumps/compressors, cooling water pumps and possible cooling tower. In addition, heat is required at relatively low temperature (approx. 100°C) to heat the filter module and desorb the CO_2. Values in the literature [40,41,42] for energy requirement vary quite substantially, which may have to do with the level of CO_2 post treatment included in the figure or just a lack of data from pilot plants.

iv.3 Output

The main output of the DAC process is a concentrated CO_2 stream with relatively high purity. The CO_2 is typically available at low pressure and contains moisture. The CO_2 will need to undergo further compression and dehydration to meet specifications for CO_2 transport or utilization as most other CC technologies.

The low temperature process will also produce pure water recovered from the air. Low quality heat from cooling of the filter modules will be available. However, as this is a batch process the quality of heat will vary over time.

iv.4 Examples of market standard technology

The DAC technology is currently under rapid development. The plants that are in operation today are mainly small-scale demonstration and pilot plants. It is mainly the high temperature absorption and calcination process developed by Carbon Engineering as well as the low temperature adsorption technologies developed by primarily Climeworks [43] and Global Thermostat that are under commercial development.

Table iv-1 provides an overview of some of the key DAC plants in operation.

Table iv-1. Overview of selected existing DAC demonstration and pilot plants. [41].
tpd = tonne per day, Power to Gas: the use of electricity to convert CO_2 and water to methane, Air to fuels: capture of CO_2 and moisture from air for fuel production with electricity i.e. P2X.

Plant	Hinwil (Switzerland)	Troia (Italy)	SRI international (Ca, USA)	Squamish (Canada)
Technology provider	Climeworks	Climeworks	Global Thermostat	Carbon Engineering
Type	Commercial	Pilot	Pilot	Demonstration
Capacity	2.46 tpd	0.419 tpd	2.0 tpd	0.6 tpd
CO_2 use	Greenhouse	Power to Gas	Not known	Air to fuels

iv.5 Prediction of performance and cost

The performance and cost data for DAC is based on the low temperature adsorption technology. Mainly data on the technology from Climeworks will be used because performance and investment cost data from Global Thermostat or other companies is not available (only levelized cost of carbon capture).

It shall be stressed that the data reported in the literature for DAC is often from the technology vendors and has not been reviewed by independent party. In particular, the outlook on upscaling and levelized cost of CO_2 capture for future DAC plants appear to be too optimistic in many cases. Furthermore, the assumptions and conditions behind the levelized cost of carbon capture in \$/ton CO_2 captured, reported by some vendors are unclear and not fully published.

Only CAPEX estimate available from a supplier of low-temperature adsorption DAC technology is from Antecy (now part of Climeworks) of 730 EUR/(t CO_2 output/year) or 6.5 mill EUR/(t CO_2 output/h) based on a 360,000 tpa DAC facility [40]. The estimate cannot be verified as no DAC unit of this scale has been erected yet.

O&M is estimated as 3.7% of CAPEX similarly as in [40]. In [42] it is indicated that the individual DAC modules only have a life expectancy of 4 years. Climeworks has clarified that only the sorbent filter part needs replacement. To include this in the O&M cost it is assumed that the DAC sorbent filter makes up 5% of total CAPEX. This is split in 4 years, hence 1.25% of CAPEX is added to the fixed annual O&M cost.

The land use for DAC is also very significant as huge air volumes are required. Viebahn et al. [41] report of 100 x 1000 m² for a 1 million t CO_2 output/year plant. It shall be remembered that there is not any experience with large DAC facilities. One may expect a significant lee-effect when many modules are located in the same area, hence depend

iv.6 Uncertainty

The DAC technology is still in the early development phase hence the uncertainty on both performance and cost numbers are high.

The current energy consumption of DAC is much higher than CC from a concentrated source. It is expected that the energy consumption of DAC will continue to be substantially higher compared to CC from a concentrated source. Very optimistic outlooks for the technology's improvement potential are reported by some vendors e.g. indicating energy performance numbers that is approaching that of CC from concentrated sources. Also the estimated capital cost of a very large DAC plant of 6.5 mill EUR/(t CO_2 output/h) from Antecy as mentioned above is very uncertain as the scale-up is nearly 3 orders of magnitude.

It is difficult to make robust predictions of the future cost of DAC as little information is published on how the technology should improve. DAC modules offer great opportunity for standardisation and mass production, hence it is fair to assume that costs will decrease. Nevertheless, the level of cost reductions will be highly dependent on how the market for DAC develops. A 30% cost reduction to 2050 is assumed in this work well knowing that the starting point (2020 value) is also highly uncertain.

iv.7 Quantitative description

A data sheet for the DAC based on the solid sorbent technology has been produced. See separate Excel file for Data sheet.

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