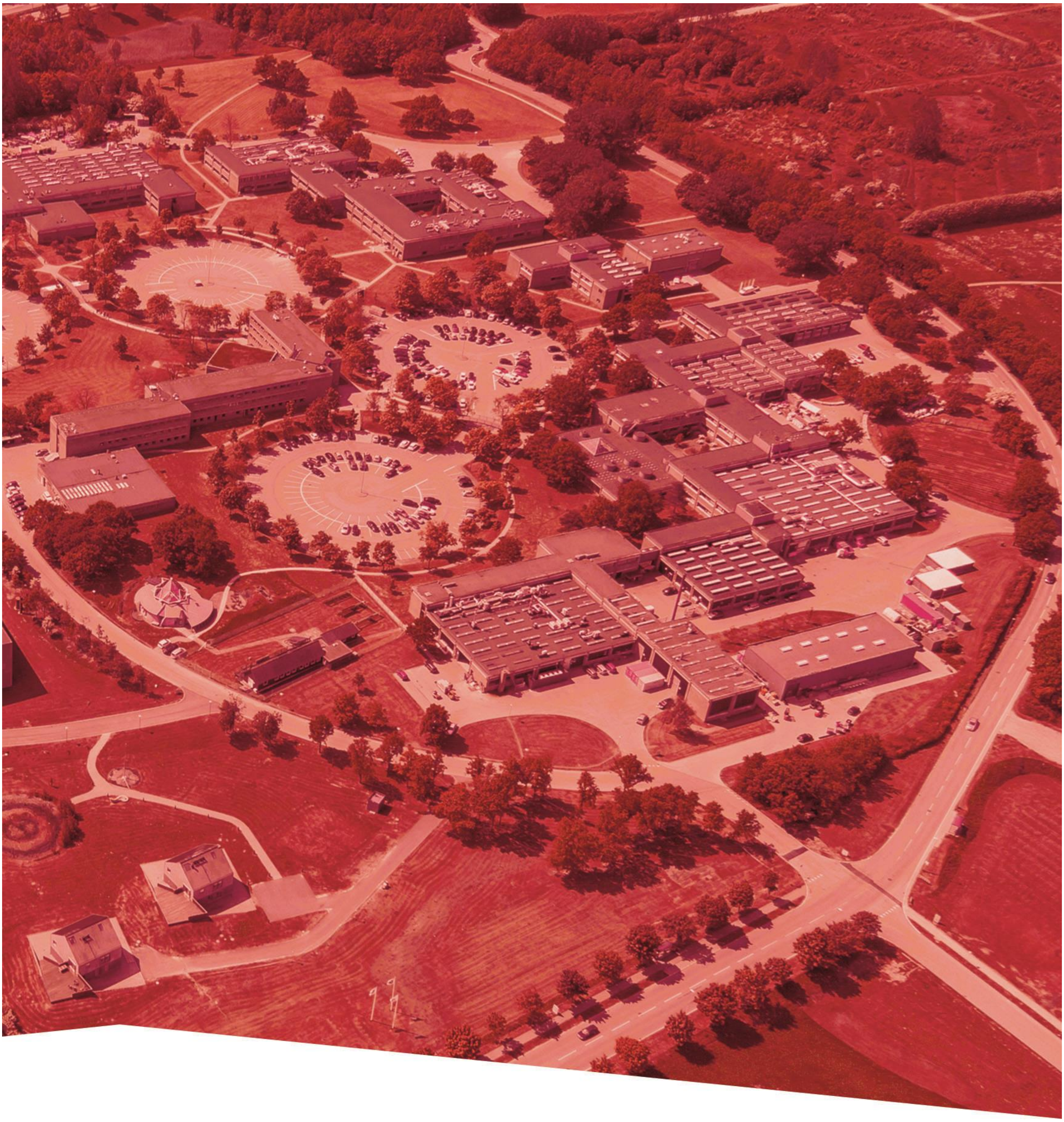

Danish participation in IEA HPT Annex 48 “Industrial Heat Pumps”

Final report

DANISH TECHNOLOGICAL INSTITUTE

Danish participation in IEA HPT Annex 48 ”Industrial Heat Pumps”

Final Report

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Content

1. Project details

Project title	Danish Participation in IEA HPT Annex 48 "Industrial Heat Pumps"
Project identification (program abbrev. and file)	64016-0090
Name of the programme which has funded the project	EUDP 2016
Project managing company/institution (name and address)	Danish Technological Institute Kongsvang Allé 29 DK-8000 Aarhus C CVR 56976116 Contact: Benjamin Zühlsdorf, bez@teknologisk.dk
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CVR (central business register)	CVR 56976116
Date for submission	01/2020

2. Short description of project objective and results

English

Annex 48 aimed to improve the knowledge base for industrial heat pumps (IHP) with a focus on identifying measures to facilitate a higher number of installations. The activities comprised a collection and analysis of IHP installations and best practice examples, the creation of material and recommendations to support the integration of industrial heat pumps and a summary of communication means in the field of IHP. In total, 69 cases were identified with 47 cases supplying to district heating. Four best practice examples were explained in detail and recommendations for realizing successful IHP installations were derived. Developments that are improving the process integration of industrial heat pumps and technical advances to allow higher supply-temperatures were identified as promising to facilitate the number of installations.

Dansk

Formålet med Annex 48 har været at skabe bedre viden om industrielle varmepumper (IHP), og der har i projektet været fokus på at identificere, hvordan man bedst kan øge antallet af installationer. Aktiviteterne omfatter indsamling og analyse af industrielle varmepumpeinstallationer og best practice-eksempler, udarbejdelse af materiale og anbefalinger, som støtter integrationen af industrielle varmepumper, samt en oversigt over tilgængeligt kommunikations- og informationsmateriale om industrielle varmepumper. I alt er der identificeret 69 cases, hvoraf de 47 cases handler om installationer, der leverer til fjernvarmenettet. Fire best practice-eksempler er blevet grundigt undersøgt og præsenteret, og ud fra denne viden er der udarbejdet anbefalinger til, hvordan man laver en vellykket installation. Udvikling, der forbedrer procesintegrationen af industrielle varmepumper, samt tekniske fremskridt, der muliggør en højere forsyningstemperatur, vurderes at være vigtige i forhold til at øge antallet af installationer.

3. Executive summary

Annex 48 as part of the Technology Collaboration Programme for Heat Pump Technologies of the International Energy Agency (IEA TCP HPT) aimed to summarize more profound information about industrial heat pumps, with a focus on everything that implies the potential to decrease application barriers and facilitate the uptake of further installations. This work comprised an analysis of the state of the art, a collection of realized installations including non-technical experiences, an overview of methods for the integration of industrial heat pumps and an analysis of communication material.

Task 1 focused on the analysis of the collection of existing cases and aimed to discuss these in the context of the technical potential and the economic boundary conditions. The collection of realized installations comprised 69 installations with a total capacity of 119 MW, of which 47 with a capacity of 100 MW were installed in district heating and 22 with an installed capacity of 19 MW in industrial applications. The capacity of the installations in district heating accumulated around 1 MW to 2.5 MW, while the capacity of the installations for supply of industrial process heat was more evenly distributed between 250 kW and 2.5 MW. Most of the installations used R717 (ammonia) as refrigerant. The mapping was complemented with an analysis of the technical potential in the industry and in district heating. The industrial heat demand and sources of excess heat were mapped, and the integration of industrial heat pumps was evaluated. A considerable potential for industrial heat pumps over a wide range of temperature levels and applications was found. In cases where not all heat could be recovered for internal utilization, it was found to be promising to consider supplying the excess heat to district heating networks.

The analysis of the economic boundary conditions indicated the project's economy to be strongly dependent on the fuel cost. The fuel cost was subject to a considerable share of taxes, while it may be noted that the taxes for electricity are lower when being used for space heating purposes than for industrial process heating. The ratio of the specific cost for natural gas to electricity was however steadily decreasing. The ratio is expected to approach 1.5 for district heating applications and to stabilize at 1.7 for industrial process heating in 2030. The more favorable fuel cost was found to be one of the reasons for the higher number of installations in district heating.

Task 2 summarized recommendations, tools and methods considered as best practice for industrial heat pumps. It comprised general recommendations for installations in district heating and industrial applications and methods for estimating performance and economics. It concluded with a detailed presentation of four best practice examples for different applications.

The analysis of the realized installations indicated a higher number of installations in district heating than in industrial applications. This is substantiated with a good knowledge basis for installations in district heating. The "guidebook" represents a suitable guideline for district heating companies that are considering the installation of a heat pump comprising information covering the phases from idea to the more detailed project initiation. In addition to the guidebook, studies were presented that analyzed the combination of multiple heat sources for reaching optimal seasonal performances. And finally, the possibility of operating the heat pump flexibly in order to benefit from lower electricity tariffs of supplying ancillary services was discussed.

For industrial applications, the situation was found to be more diverse with respect to the possible boundary conditions. The industrial sites are complex thermal systems with specific characteristics for both heat sources and heat sinks. The integration process often requires a comprehensive process integration study, and the successful implementation might require buffer tanks and secondary heat transfer loops. In order to guide potential end-users through the process of integrating industrial heat pumps, a step-by-step guide was formulated. In addition, the concept of working domains was presented, which may be a suitable support for identifying the most promising heat pump configuration for a given application.

In addition to these relatively comprehensive methods, an approach was presented to estimate the heat pump COP using a Lorenz efficiency. This allows the estimation of the COP solely based on the temperature levels of heat source and sink and an estimated Lorenz efficiency. This estimate is based on experiences and allows a performance estimation at an early stage of the feasibility study. It was outlined how the Lorenz efficiency differs from the Carnot efficiency and elaborated why the Carnot efficiency is insufficient for most heat pump cases.

Furthermore, two methods for estimating the investment cost for large scale heat pumps were presented. The first approach was a capacity-based approach, accounting for the different heat sources in district heating applications. The second one was an approach based on the purchased equipment cost of the components. Both methods are based on experiences and have to be validated with realized systems in similar environments.

As a final part of task 2, four best practice examples were selected and presented in detail. The summary comprised data about the system and the boundary conditions, the project handling, non-technical experiences and economics. These cases were considered as best practice and served as the basis for the derivation of recommendations for successful applications.

Task 3 was mainly covered by Switzerland with inputs from the other countries, including Denmark. The task focused on the application of methods and tools for the integration of heat pumps in industrial processes. The Danish working group contributed with an overview of the developments in Denmark comprising developed methods and models for heat pump design, pinch analysis and utility integration on- and off-site. In addition, a tool for providing a first assessment of the heat pump feasibility “HP FAT” was developed as part of the Annex. The tool aims to provide a very first assessment without the requirement of detailed knowledge about heat pump systems.

Task 4 aimed at improving the knowledge base with respect to industrial heat pumps. Various information materials and tools about industrial heat pumps were summarized, an overview about the organizations working with industrial heat pumps was given and relevant events and courses were presented.

The generated results were found to be a substantial contribution to the knowledge base of industrial heat pumps in Denmark and internationally. Besides the overview of the state of the art and the summary and generation of information material, important conclusions could be made regarding drivers and barriers for industrial heat pumps. Regarding the technical developments, it may be concluded that the number of installations for supply of industrial process heat may be enhanced by developments in the field of process integration and high-temperature heat pumps.

4. Project objectives

The main objective of Annex 48 was to provide a more profound information about industrial heat pumps, including state of the art, best cases and best practices, an overview of integration methods and tools as well as a summary of available information material.

The overall project objectives were structured and approached by 4 tasks. Task 1, 2 and 4 were conducted separately by each participating country, while task 3 was solely conducted by Switzerland.

- Task 1: Analysis of the collected case studies and successful applications of industrial heat pumps
  Task 1 was based on a collection of existing industrial heat pump installations and a detailed analysis of the respective collection. The collection comprised information about the system and the application and was conducted for all participating countries. The work of task 1 was documented by [1].

- Task 2: Structuring information on industrial heat pumps and preparation of guidelines
  Task 2 prepared guidelines for the implementation of industrial heat pumps and presented best practice examples for heat pump applications in various applications, that were selected based on task 1. The work of task 2 was documented by [2].

- Task 3: Application of existing models for integration of industrial heat pumps
  Task 3 continued the developments of Annex 35, in which methods for process integration of industrial heat pumps were developed, by focusing on the application of the previously developed methods. This task was solely conducted by Switzerland, while the Danish consortium contributed with a summary of Danish activities in this field [3].

- Task 4: Communication
  Task 4 focused on summarizing the existing information material about industrial heat pumps as a basis for potential stake holders. The different information materials and activities were furthermore discussed in an international context to evaluate the effectiveness and appropriateness in other countries. The work of task 4 was documented by [4].

The Danish participation was conducted by country reports for task 1, 2 and 4 that were submitted to the operating agent, who considered them for the overall report.

5. Project results

This chapter summarizes the activities of the Danish consortium as part of the annex, which are documented by separate detailed reports for task 1, 2 and 4 [1,2,4]. Parts of this summary are directly taken from the reports and the reader is referred to the original reports for a more detailed description.

In addition to the activities of the Danish consortium, DTI was actively involved in the activities in the international IEA Annex consortium and coordinated the national and international activities with the other partners. This involved participation in several annex meetings as well as presentations at international workshops.

5.1. Task 1: Analysis of the collected case studies and successful applications of industrial heat pumps, [1]

Task 1 started with an analysis of the collected cases, including the system characteristics and the boundary conditions. The analysis of the existing situation, including the number of installations in different sectors, were supplemented with an analysis of the process heat demand and the potential for implementing large-scale heat pumps. Finally, the economic boundary conditions and political strategies for industrial heat pumps were summarized and related to the results.

5.1.1. Existing industrial heat pump installations

The collection of cases from Annex 35 was updated and the collection comprised in total 69 installations of industrial heat pumps, of which 47 were supplying heat to a district heating network and 22 to industrial processes. Table 1 shows an overview of the cases, indicating a total installed capacity of 119 MW of which 100 MW are found in district heating and 19 MW in industrial applications.

Table 1: Overview of collected cases by 2018

	Cases	Capacity
District heating supply	47	100 MW
Industrial heat supply	22	19 MW
Total	69	119 MW

Figure 1 shows the distribution of the installed heat pump capacity and it may be noted that the capacity of district heating installations accumulates around the category between 1 MW to 2.5 MW, while the number of installations in industrial applications are more evenly distributed ranging from 250 kW to 2.5 MW.
Figure 2 shows an overview of the working fluid used in the heat pump installations, and it may be noted that the >99 % are using natural refrigerants. Ammonia (R717) accounts for 93 % of the installations, which is mainly associated with the typically high thermodynamic performances and low investment cost.

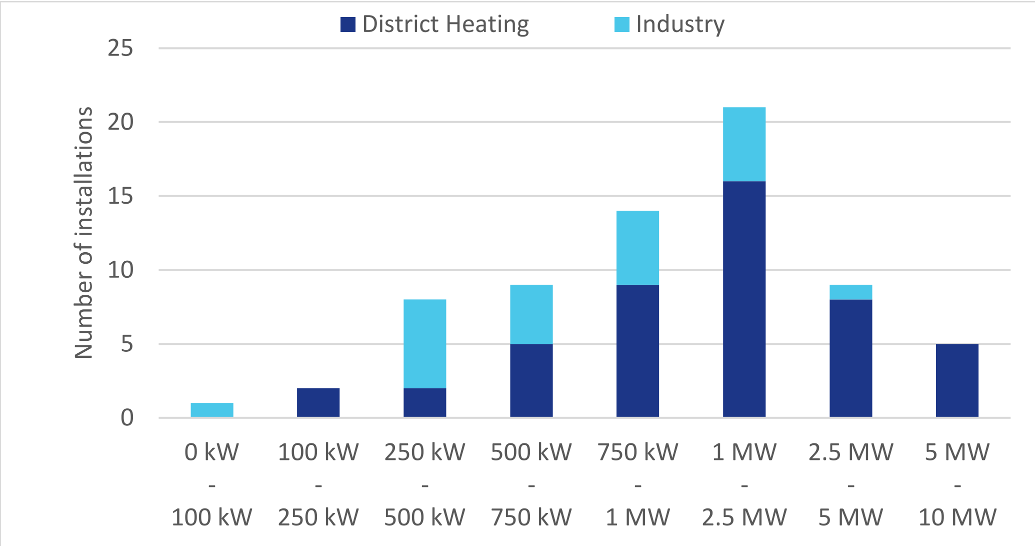

Figure 1: Overview of heat pump installations for industry and district heating by number of installations

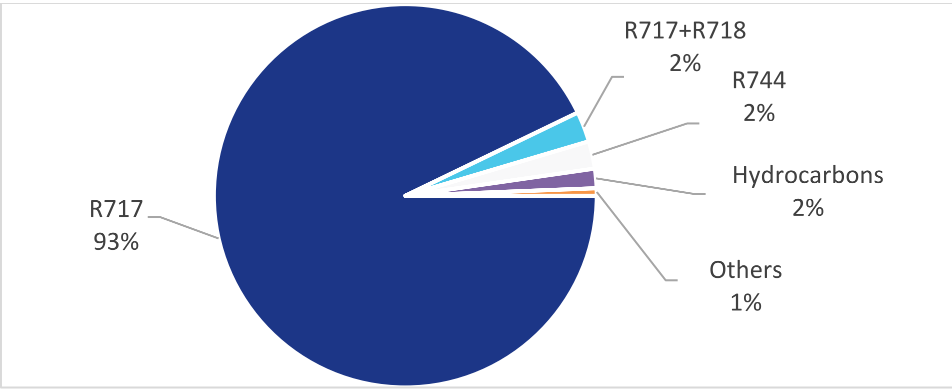

Figure 2: Installed capacity of heat pump installations for industry and district heating by refrigerant type

5.1.2. Industrial energy demand and excess heat

Furthermore, the industrial energy demand and excess heat was analyzed as a basis for the evaluation of the potential of industrial heat pump applications.

The gross energy consumption of the Danish industry sector was 166.3 PJ in 2017, which corresponds to 22 % of the country's total energy use. Within the industry sector, the manufacturing industry accounted for 70 % of the final energy use [5].

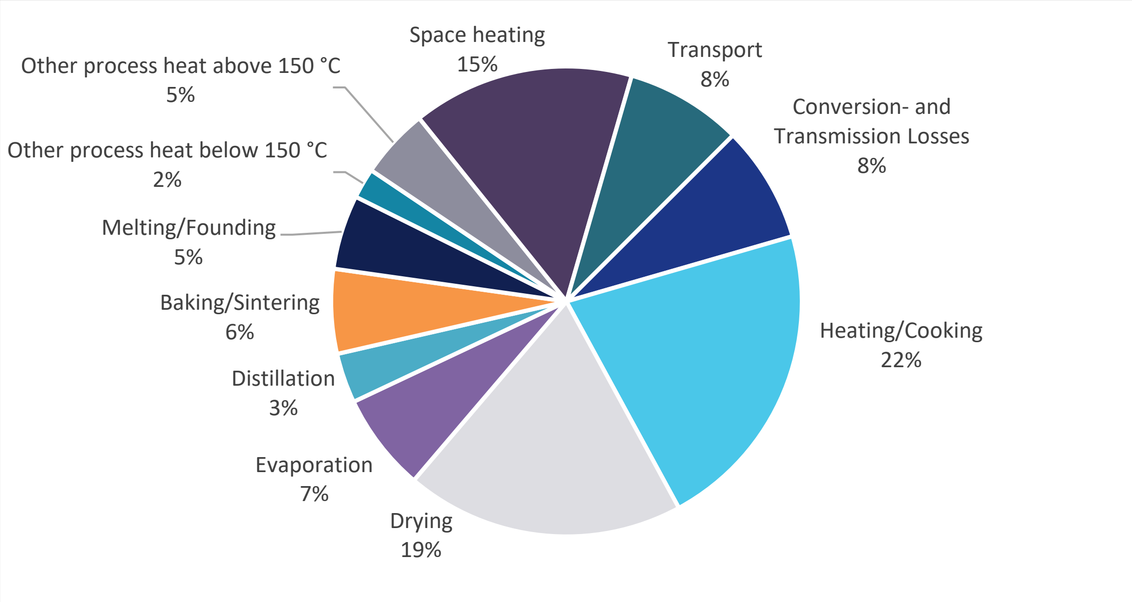

Figure 3: Distribution of fuel use in the manufacturing industry by final energy user in Denmark. Based on data from [6] using the 2012 final energy use from [7].

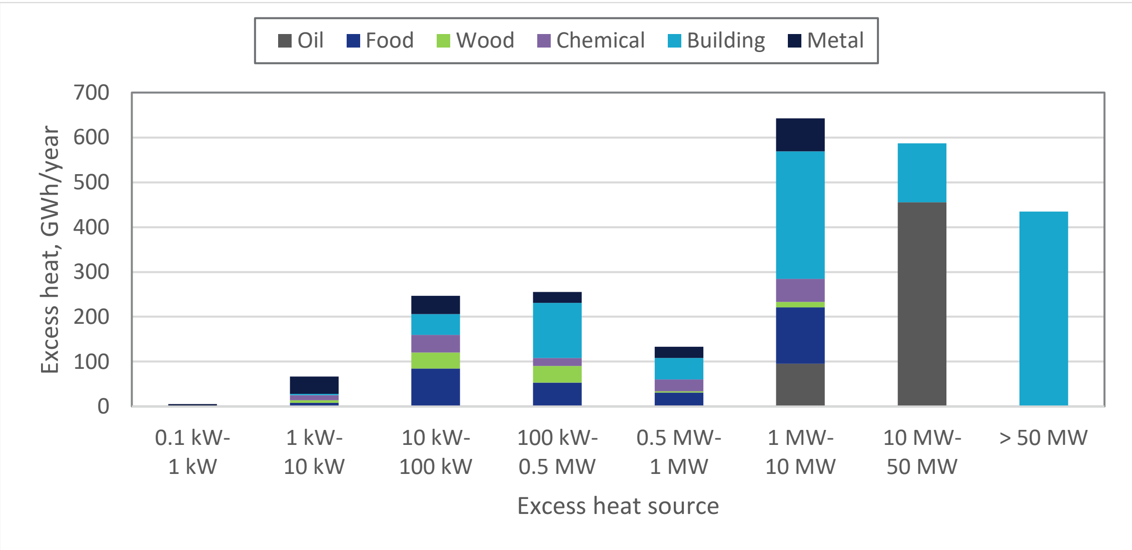

Figure 4: Distribution of industrial excess heat potentials by capacity and industry sector, [8].

Figure 3 shows the distribution of fuel use in the manufacturing industry by final energy use in Denmark. The highest share of fuels is used for process heating and drying operations. In total, 86 % of the fuel is used for thermal operations while 14 % is used for transport.

The thermal processes were analyzed in more detail in [8], which allowed the estimation of capacities of the different excess heat sources. The distribution of the heat sources may be seen in Figure 4 and indicates the potential for the required heat pump capacities in the different industry sectors.

5.1.3. Potential for industrial heat pumps in district heating and industrial applications

District heating provided heat to approximately 64 % of all households in Denmark in 2018 [9] and plays an accordingly large role in the national energy system. District heating companies are striving to increase the share of renewables in heat generation, and large-scale heat pumps are a key-technology in this transition. The ongoing promotion of heat pumps requires the availability of heat sources, which may be obtained from the environment or from industrial excess heat.

An analysis of potential heat sources for heat pumps in district heating applications was conducted by [10]. Within a 500 m radius around district heating areas, there was found a national potential for some sources including:

- 3.4 TWh of industrial excess heat
- 0.4 TWh from supermarkets
- 2.9 TWh from wastewater treatment
- 0.8 TWh from drinking water
- 6.9 TWh from ground water
- 3.2 TWh from rivers
- 0.7 TWh from lakes.

Additionally, it is expected that a substantial share may be covered by sea water, if accessible, and by air.

A more detailed analysis of the geographic distribution and utilization potential of industrial excess heat sources in Denmark was done in [11,12]. It showed that the majority of excess heat sources found in the industry are relatively small (< 100 MWh per year), while there are a few large sources primarily found in the main industrial areas of Denmark (Kalundborg, Fredericia, Aalborg).
The energy outlook from the Danish Energy Agency [13] projects approximately 10 % of the expected complete district heating supply in 2030 (135 PJ) to be covered by heat pumps and electric boilers (14 PJ). This corresponds to an installed capacity of large-scale heat pumps in district heating between 600 MW to 1000 MW in 2030.
Furthermore, the potential for heat pumps in industrial processes was studied. The specific potential is strongly varying based on the assumptions, but it may be noted that industrial heat pumps were found to be able to cover a large share of the industrial process heat while improving the overall energy efficiency considerably.
In order to study the potential in more detail, a study was conducted in which the heat sources and sinks were matched as a basis for the evaluation of the possibility for an industrial heat pump. The heat pump performance is dependent on the temperatures of both source and sink, while there is sometimes a lack of sufficient data. Typically, the required process heat supply temperature is known, while it is not known at which temperature the heat transfer fluid returns from the heat consumer. This requires an estimation of the return temperature, and two cases were considered. The first evaluation assumed that the total amount of heat is supplied at the maximum heat supply temperature, while the second evaluation assumed that the heat is provided while heating a stream up from the source inlet temperature to the maximum process heat temperature. Figure 5 shows the results for the first evaluation. It may be seen that the process heat demand that can be covered increases steadily up to 120 °C, while the amount to be supplied at higher temperatures is slightly lower.

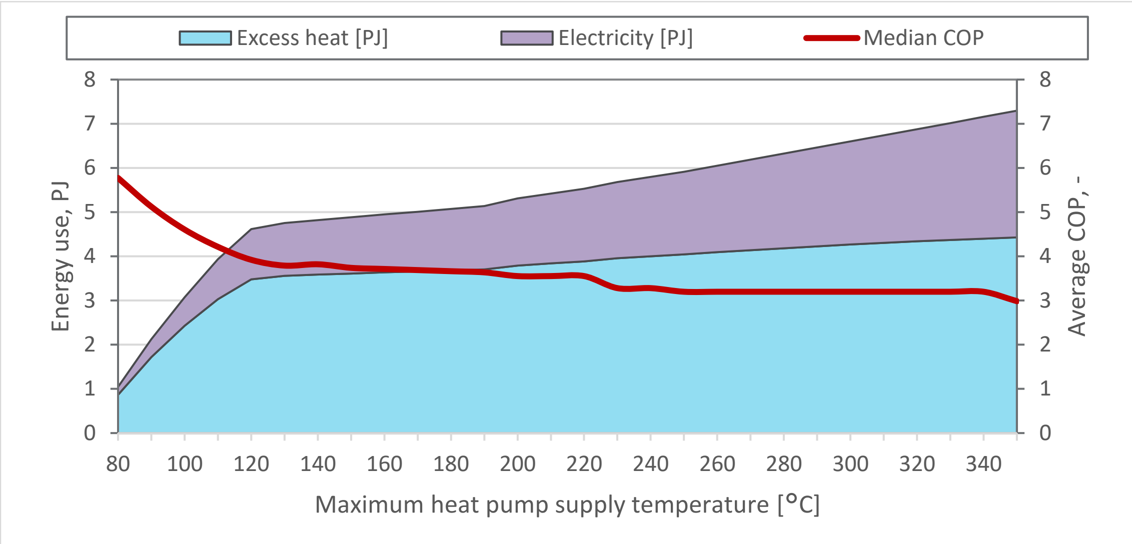

Figure 5: Utilization potential of excess heat with heat pumps and average COP in the Danish manufacturing industry assuming the heat pump sink is heated from the excess heat temperature to the maximum supply temperature [8].

5.1.4. Economic boundary conditions and political strategies for heat pumps in Denmark

The economic boundary conditions for the implementation of heat pumps in industry and district heating were summarized and compared. The taxation schemes were found to have a considerable impact, and in general it may be noted that the boundary conditions are more favorable when used for space heating than for process heating.

Figure 6 shows the ratio of electricity to gas prices, which may be seen as the minimum performance of a heat pump installation to cover the operating expenses. The ratio is lower for space heating purposes than for process heating. Both curves are dropping in close future and are approaching 1.4 for space heating and 1.7 for process heating towards 2030. The strong decreases until 2023 are expected to result in a faster uptake of industrial heat pump installations and enable economically feasible installations at higher supply temperatures.

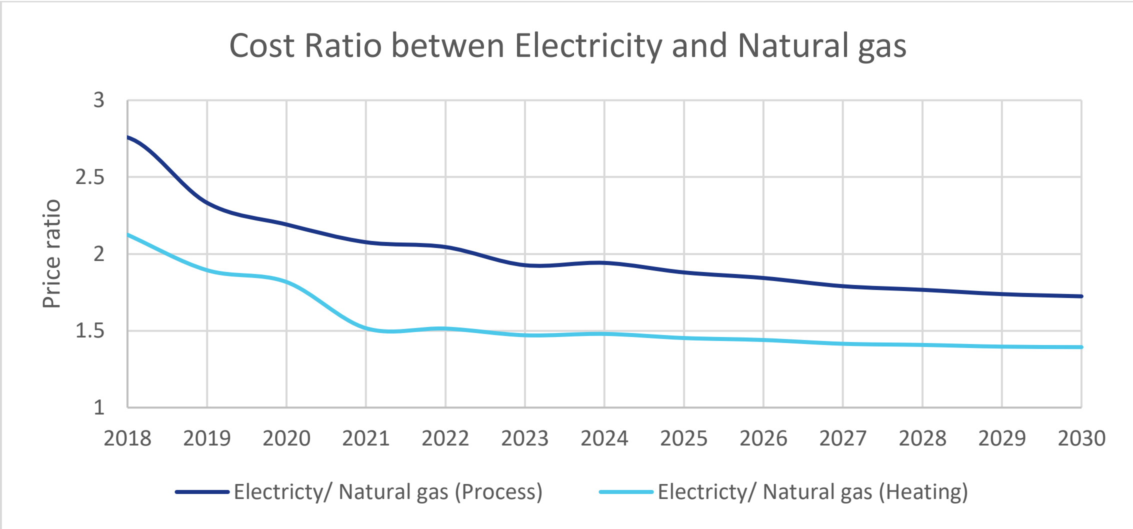

Figure 6: Ratio of electricity prices to natural gas prices for process heating and space heating.

Besides the economic boundary conditions, there are a range of factors that are impacting the feasibility of industrial heat pump projects. Such drivers and barriers were collected as part of the project and are summarized in Table 2.

Table 2: Overview of main drivers and barriers for the implementation of heat pumps in industry and district heating

Drivers	• Subsidies for energy saving applicable to heat pump projects (Sale of energy savings to utility/ energy saving obligation). • Reduction in electricity taxation for heating use and phase out of the public service obligation (PSO). • Simplification of excess heat taxes. • Legal obligation to consider socioeconomic cost as main investment criteria for heat pumps in district heating.
Barriers	• Relative low price/ taxation for alternative combustion fuels, including natural gas and biomass, is promoting the use of natural gas boilers instead of heat pumps. • Energy saving obligation scheme will stop in 2020, uncertainty of new support scheme. • Currently there are obligations for certain heating areas to be connected to the natural gas grid. • Uncertainty and complicated rules. • Rather short required Payback periods for feasibility in industry. • High investment cost. • Lack of technologies or low TRL for applications with high source and sink temperatures.

5.2. Task 2: Structuring information on industrial heat pumps and preparation of guidelines, [2]

Task 2 condensed the experiences from realized installations, case studies, theoretical considerations and other information materials into recommendations for successful applications. The presented guidelines were furthermore based on different publicly available information material. Finally, four best practice examples were presented.

5.2.1. Heat pumps in district heating applications

Task 1 indicated that there is a large number of heat pump installations, which indicated the availability of sophisticated information material and supporting tools, as well as a good experience-based knowledge basis.

For district heating applications, a well-structured guideline is available as the "Drejebog til store varmepumpeprojekter i fjernvarmesystemet" [14]. This available guideline was summarized in English. An important parameter for the implementation of heat pumps is the availability of heat sources. Figure 7 gives an overview for the evaluation of heat sources and the respective actions to take in the project handling.

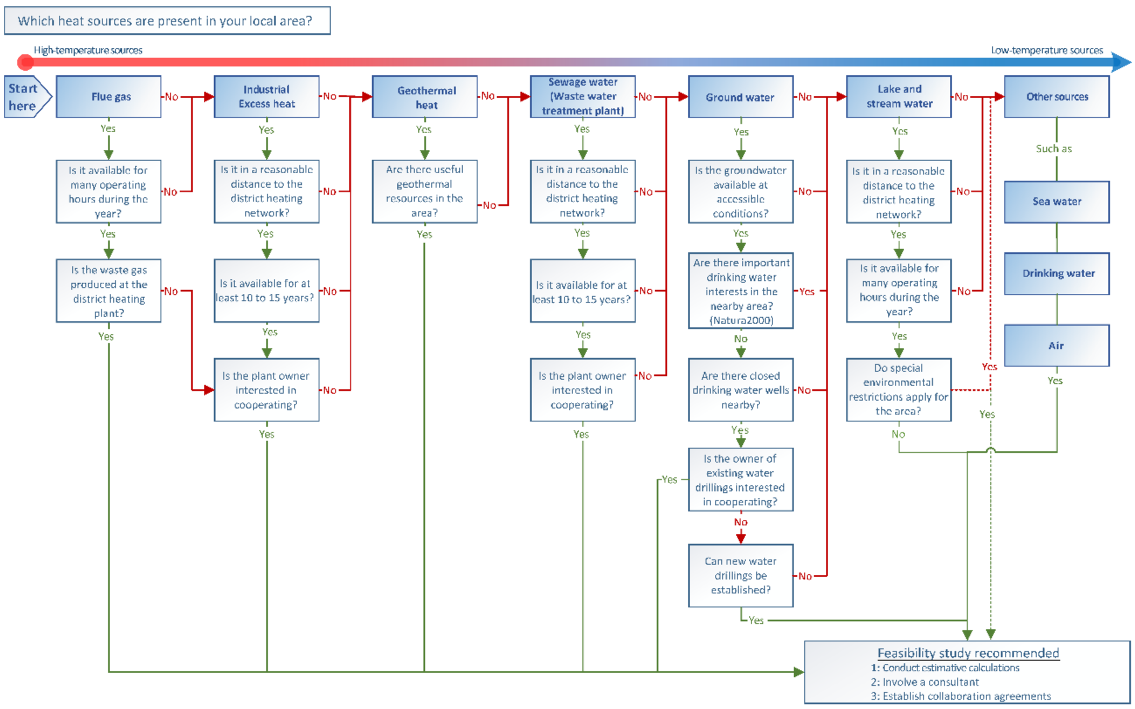

Figure 7: *Heat sources for heat pumps, ranked according to temperatures. Translated based on* [14].

The heat sources for large-scale heat pumps are often limited in capacity and varying over time and during one season. Reaching optimal performances does therefore often require combining several heat sources. In the report of task 2 [2], this aspect was addressed by discussing and presenting an example from Pieper et al. [15], who presented the optimal composition of heat sources in a case study in the Nordhavn area, considering seasonal variations in performance.

Heat pumps in district heating applications are typically operated according to the heat demand. However, a more flexible operation and an increased integration with the power sector may lead to financial benefits due to reduced electricity tariffs or the provision of ancillary services. In the report, different options for operating large-scale heat pump systems were presented, as originally analyzed in [16].

5.2.2. Integration of heat pumps in industrial applications

The integration process for heat pumps in industrial processes is often more comprehensive than for applications in district heating. The processes are more diverse and finding the optimal placement does often require a comprehensive process integration study.

As part of task 2, recommendations for a successful implementation of heat pumps were derived based on [17], the Ph.D. thesis of F. Bühler [18], and the European standard for Energy Audits (EN 16247-3:2014).

The step-by-step guide comprised the following steps:

- Energy mapping
- Identify opportunities of energy efficiency measures
- Evaluation of economic feasibility
- Detailed planning of prioritized projects.

The steps are substantiated with more detailed explanations and examples in the report of task 2 [2].

Even though the optimal placement of an industrial heat pump is determined, there is a variety of different heat pump types that may be suitable. In order to determine the most promising heat pump technology for a given system, the guidelines about the working domains for natural refrigerants [19,20] may be utilized.

5.2.3. Heat Pump performance and economy

The integration process of industrial heat pumps requires the estimation of the heat pump performance and the investment cost at an early stage of the project. Therefore, a method for estimating both the thermodynamic performance and the investment cost was presented.

Based on the thermodynamic maximum, described by the Lorenz cycle, the actual performance may be estimated. The COP of the Lorenz cycle is determined by thermodynamic average temperatures of source and sink, which corresponds to the logarithmic average temperatures for streams of constant heat capacity:

$$\mathrm{COP}_{\mathrm{Lorenz}} = \frac{\bar{T}_h}{\bar{T}_h - \bar{T}_L}, \text{where } \bar{T} = \frac{T_{\mathrm{in}} - T_{\mathrm{out}}}{\ln\left(\frac{T_{\mathrm{in}}}{T_{\mathrm{out}}}\right)}$$

The Lorenz cycle receives and rejects heat at the thermodynamic average temperatures of the heat source and the heat sink and operates with a reversible compression and expansion processes. The real cycle will always imply some efficiencies and require some temperature differences (see Figure 8) as well as irreversibilities in the expansion and compression process.

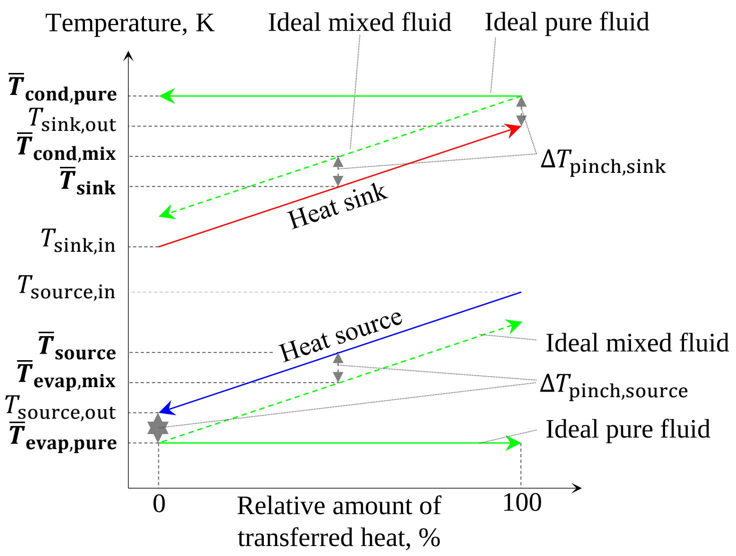

Figure 8: Illustration of heat pump operating between finite capacity reservoirs, source: [21][1].

Knowing the maximum thermodynamic performance allows to estimate the expected real performance by use of an efficiency that relates the optimal and the real performance to each other.

The investment cost of industrial heat pump installations is always dependent on a range of factors. Figure 9 shows the breakdown of the investment cost associated with the actual heat pump, the heat source, the construction, the electricity and the consultancy services. It may be seen that the distribution of the cost varies considerably for the different heat sources.

The investment cost of the heat pump may furthermore be estimated by a range of methods that were summarized in the report of task 2 [2].

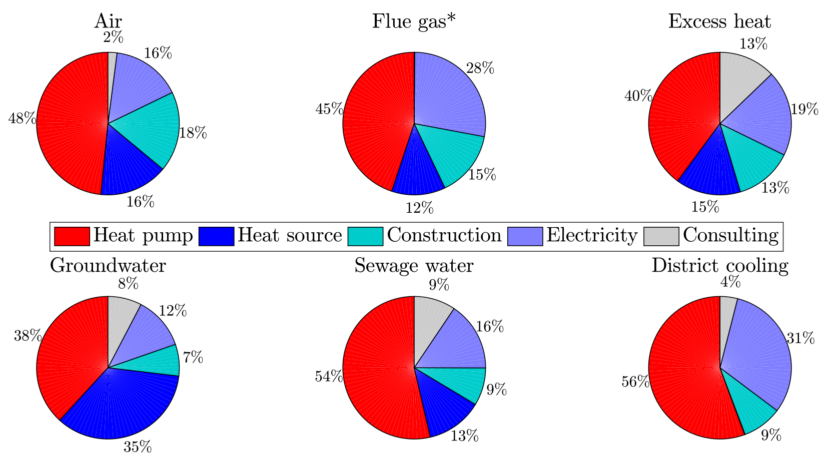

Figure 9: Breakdown of investment cost in five different categories considering 6 different heat sources [22].

[1] Reprint from International Journal of Refrigeration 98, Zühlsdorf, B., Jensen, J.K., Elmegaard, B., Heat pump working fluid selection – economic and thermodynamic comparison of criteria and boundary conditions, 500-513, copyright (2018) with permission from Elsevier.

5.2.4. Best practice examples

Four examples were chosen based on the list from task 1 as best practice examples. These examples were selected as sophisticated, realized installations that are demonstrating the benefits of industrial heat pumps in different applications. The installations were mainly different by their heat sources and sinks, and the following combinations were selected:

- Natural heat source to district heating
- Industrial excess heat to district heating
- District cooling to district heating
- Industrial process to industrial process.

The examples were summarized including 1) the project background and characteristics, 2) economics and environmental effects, 3) experience from planning and operation and 4) specifications of the heat pump system. The experiences included inputs from different parties and were included in the formulation of the step-by-step recommendations for the integration of industrial heat pumps.

In the following, the key information for the four heat pump installations are presented, while the reader is referred to the report of task 2 [2] for more detailed information.

Groundwater heat pump to island DH network

Table 5-3: Project Information, summary

Company/end user	HOFOR A/S
Location	Nordhavn, Copenhagen
Process application	District heating
Type of heat pump	Vapor compression 2-stage
Refrigerant	Ammonia R717
Capacity	800 kW
Running hours	2,150 h/year
Year of operation	2018
Primary energy savings	889 MWh/year
Reduction in CO_2 emissions	425 tons/year
Maintenance cost per supplied heat	3.2 €/MWh
Manufacturer/contractor/consultant	Johnson Controls/COWI

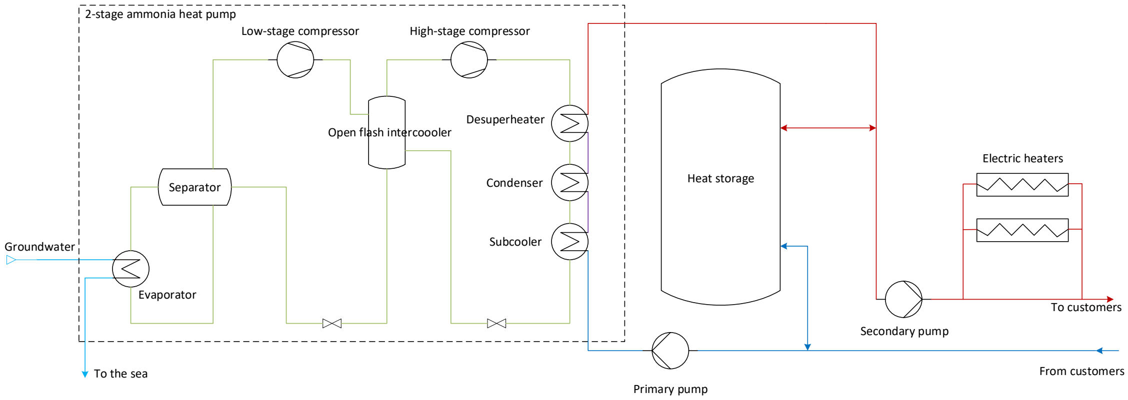

Figure 10: Sketch of the heat pump and the system configuration. Source: [16].

Table 5-4: Specifications of the heat pump installation in Nordhavn, Copenhagen

Refrigeration circuit configuration	Two-stage with open intercooler
Refrigerant	Ammonia
Compressor type	Piston, with variable speed drive
Heat exchanger type	Plate HEX, Shell and plate HEX
Heating capacity	800 kW
Power consumption, compressor	213 kW
Heat sink (type/temp)	Water, 40 °C → 70 °C
Heat source (type/temp)	Salt containing groundwater, 10.5 °C → 4.5 °C

From waste heat to district heating

Table 5-5: Project Information, summary

Company/end user	CP Kelco ApS
Location	Lille Skensved, Denmark
Process application	District heating production
Type of heat pump	Vapor compression
Refrigerant	Ammonia
Capacity	48,860 MWh/year
Running hours	8,600 hours/year
Year of operation	2017
Primary energy savings	48,860 MWh
Reduction in CO_2 emissions	10,000 tons/year
Maintenance cost per supplied heat	Approximately 2 €/MWh + fixed maintenance cost of 7,000 €/year
Payback time	2.1 years

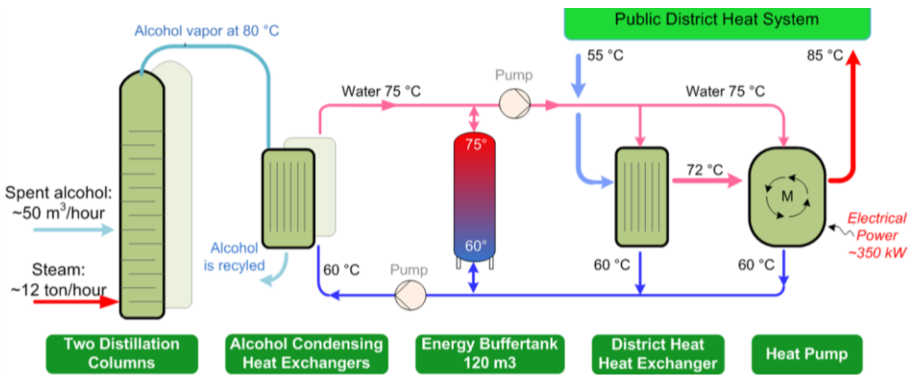

Figure 11: Design of heat recovery system.

Table 5-6: Specification of the heat pump installation at CP Kelco.

Refrigeration circuit configuration	Single stage compression with flooded evaporator
Refrigerant	Ammonia (NH3)
Compressor type	Reciprocating
Heat exchanger type	Plate heat exchangers
District heating capacity	6 MW / 8 MW (summer / winter)
Heat pump heating capacity	3.35 MW
Heat pump cooling capacity	3 MW
Power consumption, compressors	150 kW and 190 kW
Heat sink (type/temp)	District heating water / 85 °C
Heat source (type/temp)	Cooling water loop / 60 °C

District cooling to district heating

Table 5-7: Project Information, summary

Company/end user	Høje Taastrup Fjernvarme
Location	Copenhagen Markets, Taastrup
Process application	District cooling/District heating
Type of heat pump	Vapor compression
Refrigerant	Ammonia
Capacity	Heating: 2.3 MW, Cooling: 2.0 MW
Running hours	1,800 hours/year
Year of operation	2016
Primary energy savings	-
Reduction in CO_2 emissions	-
Maintenance cost per heat supply	2 EUR/MWh
Manufacturer/Contractor/consultant	GEA/ICS Energy
Payback time	Estimated: 5.4 years

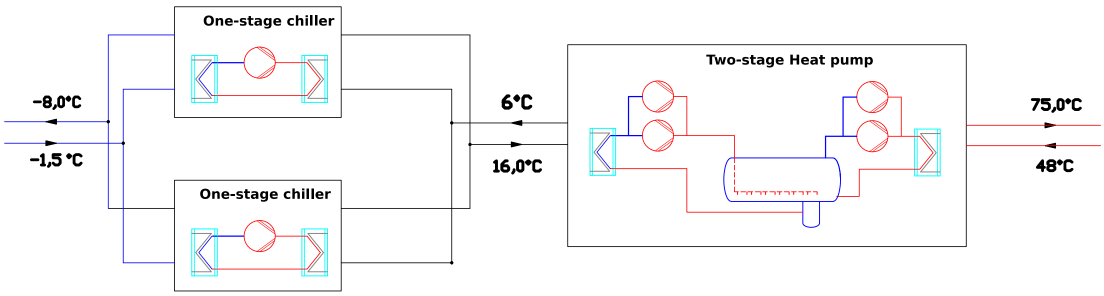

Figure 12: System and heat pump configuration of the district heating and district cooling co-production. Source: Høje Taastrup Fjernvarme amba.

Table 5-8: Specifications of the heat pump installation at Copenhagen Markets

Refrigeration circuit configuration	Heat pump: A two-stage cycle, with two compressors in parallel at each stage. Chillers: two one-stage cycles operated in parallel.
Refrigerant	Ammonia
Compressor type	Screw compressors
System configuration	One heat pump and two parallel chillers
Heat exchanger type	
Heating capacity	3.1
Power consumption, compressor	0.98 MW
Heat sink (type/temp)	District heating network, 46 °C → 73 °C
Heat source (type/temp)	District cooling network, -1 °C → -8 °C

Process cooling to process heating

Table 5-9: Project Information, summary

Company/end user	Arla Foods amba
Location	Rødkærsbro, Denmark
Process application	Process heating and cooling
Type of heat pump	Vapor compression
Refrigerant	Ammonia
Capacity	1 MW cooling, 1.5 MW heating
Running hours	7,800 hours/year
Year of operation	2014
Primary energy savings	16,010 MWh/year
Reduction in CO_2 emissions	2,980 tons/year
Maintenance cost per heat supply	Approximately 4 €/MWh
Payback time	6.1 years

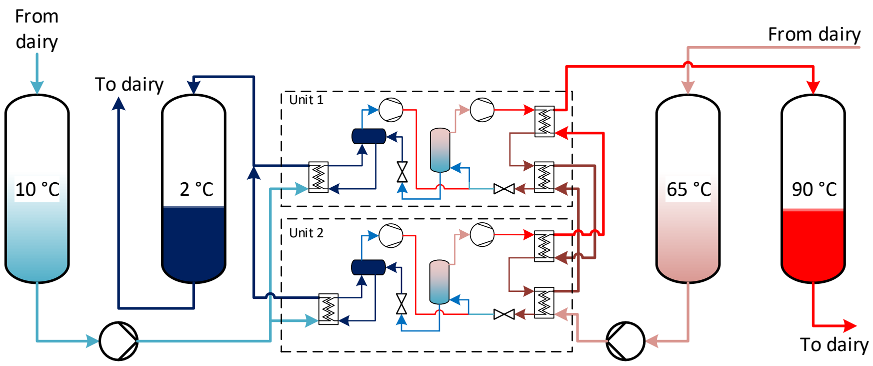

Figure 13: Two two-stage heat pumps were installed that simultaneously delivered heating and cooling for the utility loops. The system of heat pumps can deliver 2 MW of cooling and 3 MW of heating.

Table 5-10: Specification of the heat pump installation at Arla Foods, Rødkærsbro.

Refrigeration circuit configuration	Two-stage compression
Refrigerant	Ammonia
Compressor type	Reciprocating
System configuration	Open flash tank at intermediate pressure and flooded evaporator
Heat exchanger type	Plate heat exchangers
Heating capacity	2 x 1.5 MW
Cooling capacity	2 x 1.0 MW
Power consumption, compressor	2 x 510 kW
Heat sink (type/temp)	Hot water, 90 °C
Heat source (type/temp)	Cooling water, 2 °C

5.3. Task 3: Application of existing models for integration of industrial heat pumps

Task 3 focused on the application of numerical tools and models to support the integration of industrial heat pumps. Task 3 was conducted solely by Switzerland and supported with input from the Danish consortium. The input from the Danish working group comprised an overview of methods and models developed within the scope of heat pump design, pinch analysis and utility integration from a broader perspective and with more focus on the heat pump cycle design and its integration with the heat sink and source. All models are developed at the Technical University of Denmark, Section of Thermal Energy, and published in scientific journals or conferences. The models are all available for use by others. Some are published on open source repositories.

In addition, a first assessment tool for evaluating the thermodynamic and economic feasibility of industrial heat pumps, HP FAT, was developed. The tool is based on second law efficiencies for an estimation of the thermodynamic performance and supplemented with economic calculations to enable first estimations of the economic feasibility. The tool is available at [23] and was furthermore presented as an article at the Gustav Lorentzen conference in Valencia [24].

5.4. Task 4: Communication [4]

Task 4 focused on communication and information material for various target groups. In the Danish report for task 4 [4], an overview was prepared, comprising:

- Information material and tools about industrial heat pumps
- Organizations working with industrial heat pumps
- Events and courses about industrial heat pumps.

This overview is summarized in the following, while a detailed description may be found in the respective report [4].

5.4.1. Information material and tools about industrial heat pumps

The following information material and calculation tools were found to be effective in the field of industrial heat pumps in Denmark:

- Guidebook on large heat pump projects in the district heating sector – December 2017 (Danish: Drejebog til store varmepumpeprojekter i fjernvarmesystemet) [14]
- Inspiration Catalogue on large heat pump projects in the district heating sector – December 2017 (Danish: Inspirationskatalog for store varmepumpeprojekter i fjernvarmesystemet) [25]
- Heat pump calculator (Danish: Varmepumpeberegner) [14]
- Heat Pump – First Assessment Tool (HP-FAT) [23]
- Technology Catalogues (Danish: Teknologikataloger) [26]
- Map of existing heat pump installations [27]
- Simulation tools available from IPU website
    - Coolpack [28]
    - Pack Calculation Pro [29]
    - Simple one-stage CO_2 [30].

5.4.2. Organizations working with industrial heat pumps

The following independent organizations were identified to play a role in the context of industrial heat pumps in Denmark:

- Danish District Heating Association (Danish: *Dansk Fjernvarme*) [31]
- Grøn Energi [32]
- Task force for large heat pumps from the Danish Energy Agency for the period of 2015-2018 (Danish: *Rejsehold for store varmepumper*) [33]
- GTS institutes [34]
- Universities
- Consultancy companies
- Intelligent Energy (Danish: Intelligent Energi) [35]
- Industrial associations.

5.4.3. Events and courses about industrial heat pumps

Certain events and courses in the field of industrial heat pumps were identified as helpful and effective measures for gathering information and staying up to date regarding industrial heat pumps:

- One-day information events on large heat pumps in district heating
- Member-Networking-Group for large heat pumps in district heating (Danish: ERFA gruppe om store varmepumper i fjernvarme)
- "Symposium on High-Temperature Heat Pumps"
- "Refrigeration and heat pump forum" (Danish: "Køle- og Varmepumpeforum")
- Course on Refrigeration and Heat Pump Technology [36]
- Courses on industrial heat pumps [37].

6. Dissemination of results

The project aimed at providing a more profound information base about industrial heat pumps directed to various stake holders. The results were disseminated in a range of conferences and articles in magazines that were directed to the respective target groups.

An overview of the disseminating activities from the Danish consortium is given in the following.

<u>Reports and articles:</u>

- “Heat pump COP, part 1: Generalized method for screening of system integration potentials”, Reinholdt L., Kristofferson J., Zühlsdorf B., Elmegaard B., Jensen J.K., Ommen T., Jørgensen P.H., in proceedings of Gustav Lorentzen Conference, Valencia, 2018 [24].
- “Heat pump COP, part 2: Generalized COP estimation of heat pump processes and case studies”, Ommen T., Jensen J.K., Jørgensen P.H., Markussen W.B., Elmegaard B., Reinholdt L., in proceedings of Gustav Lorentzen Conference, Valencia, 2018 [38].
- “Industrial Heat Pumps in the Danish Energy System – Current Situation , Potentials and Outlook”, Zühlsdorf B., Meesenburg W., Jørgensen P. H., Elmegaard B., HPT Magazine 2019;37 [39].
- Danish Report of Task 1, Zühlsdorf B., Bühler F., Jørgensen P. H., Elmegaard B., 2019 [1].
- Danish Report of Task 2, Jørgensen P. H.., Elmegaard B., Zühlsdorf B., 2019 [2].
- Addendum to Swiss report of Task 3, Jørgensen P.H., Elmegaard B., Zühlsdorf B., 2019.
- Danish Report of Task 4, Zühlsdorf B., Jørgensen P. H., Elmegaard B., 2019 [4].

<u>Presentations at conferences and workshops:</u>

- Presentation at Heat Pump Summit in Nuremberg 2017 “Higher heat pump COP through temperature match”, Reinholdt L., 2017.
- Presentation at Chillventa Congress 2018 in Nuremberg “Industrial heat pumps in district heating in Denmark”, Reinholdt L., 2018.
- Presentation at Annex 48 Workshop in Tokyo, “Industrial Heat Pumps in Denmark”, Zühlsdorf B., 2019.
- Presentation at the Annex 48 Workshop on industrial Heat Pumps as part of the 25th IIR International Congress of Refrigeration in Montreal, “Heat pumps for district heating and industry in Denmark – Status, perspectives and ongoing developments”, Zühlsdorf B., Bühler F., Meesenburg W., Jørgensen P. H., Elmegaard B., 2019.

<u>Organization of workshops/symposia and courses:</u>

- Organization of the International Workshop on High-Temperature Heat Pumps in collaboration with DTU Mechanical Engineering and SINTEF in Copenhagen in 2017 incl. various presentations from national and international annex participants [40].
- Organization of the 2nd International Symposium on High-Temperature Heat Pumps in collaboration with DTU Mechanical Engineering and SINTEF in Copenhagen in 2019 incl. various presentations from national and international annex participants [41].
- Regular courses about heat pumps in industrial applications and district heating by DTI.

Other information material:

- Homepage incl. various information and dissemination material from the Danish group: https://www.dti.dk/industrial-heat-pumps/41549
- Heat Pump Calculation program HP FAT 2019 [23].

In addition to the contributions from the Danish working group, there are various deliverables, which were published or are in preparation by the operating agent. The Danish working group contributed accordingly to these disseminations.

Other main dissemination deliverables from the international Annex group:

- Homepage incl. various information and dissemination material from the international group: [link to be announced].
- Software models and database for industrial heat pumps.
- Progress reports to the HPC four times annually for publication in newsletters etc. Annual reports to the ExCo and a final report describing the work carried out during the Annex. This report will restate the objectives of the Annex, its findings, a description of the results from the case studies and the demonstration projects, a summary of the workshops and recommendations for further study.
- Scientific summary of Annex results disposable disseminated.
- Two or three workshops with complete proceedings.
- Courses concerning energy efficiency in industry and large-scale heat pumps.
- Contribution to the development of the new VDI Guideline 4646 concerning "Large-scale heat pumps".

7. Utilization of project results

The project results were based on contributions from the Danish working group as well as from the international participants in the Annex. A variety of information material was produced and disseminated. These materials were found to improve the publicly available information material considerably. Thereby, the annex activities contributed to an enhanced understanding of the potentials and challenges associated with industrial heat pumps in district heating and industrial applications.

Furthermore, the developed information material was used in the creation of new guidelines, such as the new guideline of the VDI (Association of German Engineers, German: Verein deutscher Ingenieure) on large-scale heat pumps. The information events, such as conferences, workshops and courses were well perceived and attracted large audiences, substantiating the increasing interest in industrial heat pumps, but also the effectiveness of the developed information material and thereby the annex activities.

In addition, there were various cases from Danish suppliers show-cased in an international context. This substantiated the competitive role of the Danish industry, especially with respect to applications of industrial heat pumps in district heating.

The presented planning tools and information materials are furthermore underlining the role of the Danish R&D partners in the field of industrial heat pumps in an international context. It is expected that the findings from the annex activities will be the basis for various future projects and developments.

The project partners are intending to maintain the use of the developed materials and guidelines in their daily work, as well as a basis for future developments.

8. Project conclusion and perspective

Annex 48 as part of the IEA TCP HPT aimed to summarize more profound information about industrial heat pumps, with a focus on everything that implies the potential to decrease application barriers and facilitate the uptake of further installations. This work comprised an analysis of the state-of-the-art, a collection of realized installations including non-technical experiences, an overview of methods for the integration of industrial heat pumps, and an analysis of communication material.

The annex activities confirmed Denmark to have a leading role in the field of industrial heat pumps for district heating. Denmark was among the countries with most installations in district heating applications, which is associated with the wide distribution of district heating in Denmark as well as the favorable economic boundary conditions arising from the political initiatives. This high number of installations in district heating contributed to the good advances in industrial heat pumps in general.

However, the number of installations in purely industrial applications is still limited, which may be associated with several reasons. The boundary conditions in industrial applications are generally more diverse, and the economic boundary conditions are more challenging. Furthermore, it may be noted that the required supply temperatures in industrial applications are often beyond the maximum supply temperatures that may be reached with state-of-the-art equipment, indicating the need for further developments in the field of high-temperature heat pumps.

In general, it may be concluded that the activities related to this Annex generally increased the perception of the potential and the challenges related to industrial heat pumps by summarizing available and producing new information material, as well as disseminating it. The generated information base enhanced the availability of information material considerably and was of direct use for both project participants and other stakeholders. It may furthermore be expected that the generated results will be relevant contributions to future developments in the field of industrial heat pumps.

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