# Industrial Heat Pumps, Second Phase

IEA Heat Pump Technology (HPT) Programme Annex 48

## Task 2:
## Danish Report

**Final Report**

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# Contents

# 1 Introduction

This report summarizes the activities of the Danish consortium related to task 2 of Annex 48 about industrial heat pumps. Task 2 derives and summarizes conclusions and recommendations for a successful application, based on available materials developed during the last five years. The work is furthermore supported with a detailed description of best practice examples selected from Task 1.

In Denmark there are two main drivers behind the implementation of industrial heat pumps (IHP). The first, and perhaps also the most dominant for the time, is the development in the district heating sector. The Danish district heating sector consists of approximately 400 local district heating companies and covers 1.7 million households, which corresponds to a coverage of 64 %. The vision presented by the Danish District Heating Association is to supply 75 % of the households with district heating and to be $CO_2$ neutral by 2030 (Dansk Fjernvarme, 2019). District heating is in a Danish context a non-profit utility and is obliged to supply the cheapest possible heat from a socio-economic perspective.
The other main driver is related to energy savings and economic benefits in industry. The energy consumption of the Danish industry has for a long time been subject to different political initiatives. As also concluded from Chapter 5, Country report Task 1 (Benjamin Zühlsdorf et al., 2019a), taxes, tariffs, subsidies and, grants are continuously up for discussion, with an increasing focus on facilitating energy efficiency and electrification, which in turn benefits the implementation of industrial heat pumps.

In the following, recommendations, best practice examples and experiences with the implementation of IHP from the perspectives of the DH sector and the industry will be presented.

# 2 Heat pumps in district heating applications

The implementation of large-scale industrial heat pumps in the district heating network has been promoted through different initiatives during the last 5 years. Two of the first important initiatives were a combination of a task force of experts helping the district heating companies with the implementation of heat pumps and a grant scheme supporting the investments. The purpose was to promote the knowledge about large-scale heat pumps and facilitate the implementation. The motivation was partly related to the environmental benefits of electrification as the share of renewables in the electricity mix is continuously increasing, and partly economical motivated due to changes in the fixed annual amount of subsidy given to combined heat and power (CHP) plants (Danish Energy Agency (Danish: Energistyrelsen), 2019).
The task force has been working from 2015 to 2018 collecting valuable experiences from the field about barriers and needs. Based on this work, a book of information and recommendations for successful implementation titled "Guidebook" (In Danish: "Drejebogen") (Kortegaard Støchkel et al., 2017a) has been published. This publication was further supported by publishing the "Inspiration Catalogue" (In Danish: "Inspirationskataloget") (Kortegaard Støchkel et al., 2017b) describing the economic and technical details of 22 cases.
As an extension of the work done by the aforementioned task force, the Green Energy Association (a policy institute connected to the Danish district heating association) has published a report summing up on the experience from 23 different installations in (Rambøll et al., 2019).

The recommended approach for district heating companies in the initial phase is outlined by three steps:

1) Take a look at the available examples of existing installations and get an overview of the technology and related topics in "Guidebook".
2) Identify potential heat sources in the local area.
3) Use the calculation tool (see section 2.1.3) with data from your company.
4) Contact a consultant for a feasibility study to support an investment decision.

In the following a summary of different parts of the above work and the given steps will be given.

## 2.1 Integration in conventional district heating systems

### 2.1.1 Selection of heat sources

All heat sources have their advantages and disadvantages in terms of availability, flow, temperature level and variation during the year. Specific local conditions can have an additional impact with respect to the feasibility. For this reason, a screening of the available heat sources and their potential is an important step in the initial phase. The screening should end up with a preliminary ranking of available heat sources considering the following criteria within a yearly time frame (Clausen, 2018):

- Temperature – A high source temperature is basis for a high COP.
- Available flow – The flow will give an indication of the available capacity.
- Availability – More hours of availability during the year, increases the possible number of operation hours.

- Simultaneity – preferable, the availability should be aligned with the heating demand, to avoid losses associated with short term or seasonal storage.
- Accessibility – Are there any big investments related to the heat source?

The recommendations for the selection of the heat source are shown in Figure 2-1. The main ranking of the heat sources is determined by the heat source temperature and its availability. The decision tree includes also which criteria are to be fulfilled by the heat source in order to become a viable alternative.

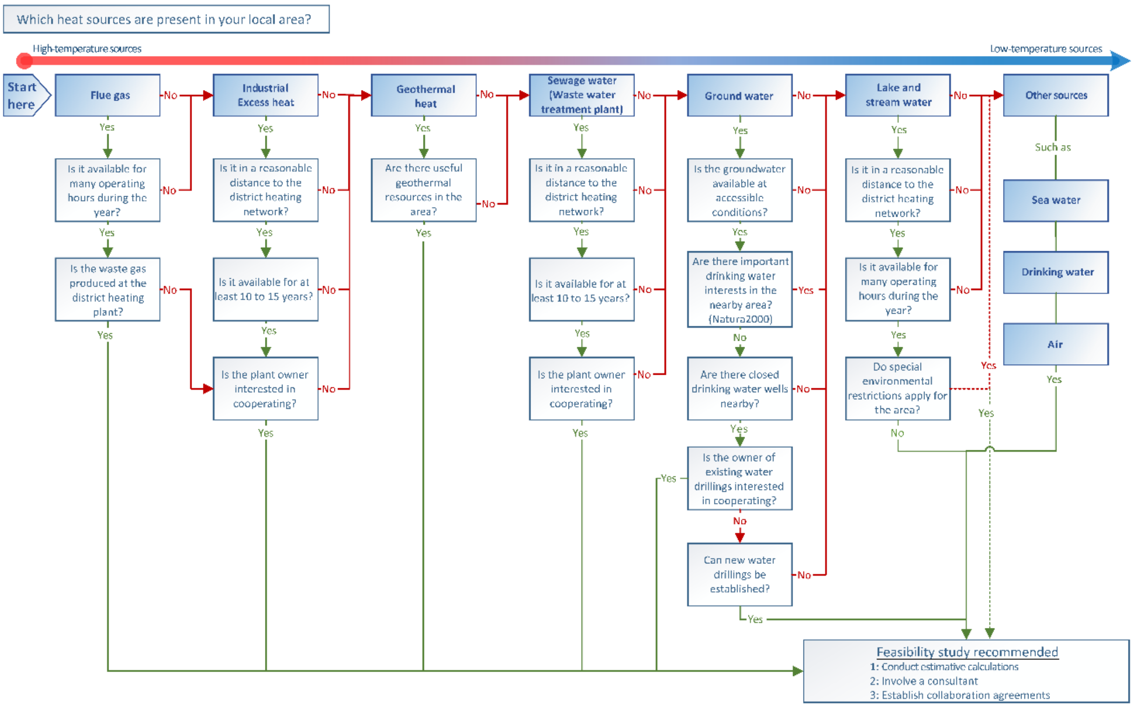

Figure 2-1: *Heat sources for heat pumps, ranked according to temperatures. Translated based on* (Kortegaard Støchkel et al., 2017)

In Figure 2-1 the category "Industrial excess heat", can both be interpreted as waste heat from a process, as well as the excess heat related to the production of cooling. This can again, both be in terms of cooling produced for a single industrial site or from a central plant providing cooling to a district with more consumers.

### 2.1.2 Utilization of multiple heat sources

Since the characteristics of different available heat sources differs during the year, it may for larger areas be feasible to exploit more than one heat source. The optimal combination of more heat sources including the investment cost and the following operation, has been investigated in (Pieper et al., 2019). The method includes an analysis of the yearly variation in COP for different heat sources, based on the heat sources temperatures in Nordhavn, Copenhagen. An example from the analysis is shown in Figure 2-2. The color indicates the seasonal coefficient of performance (SCOP) at the given share of the three different heat sources: Air, seawater and groundwater, indicated by the colored lines and the respective axes. For achieving high system performance in this case, it was found that the groundwater heat pump capacity should be between 50 % and 80 %, the seawater heat pump capacity between 0 % and 35 % and the air heat pump capacity between 5 % and 40 %.

The total investment cost of a heat pump project varies among other things with the heat source (see Section 4.2). For this reason, the economic optimum, might not be found at the exact same share as the optimal SCOP was found. However, an optimal SCOP will give a fair estimation of the best share between heat sources.

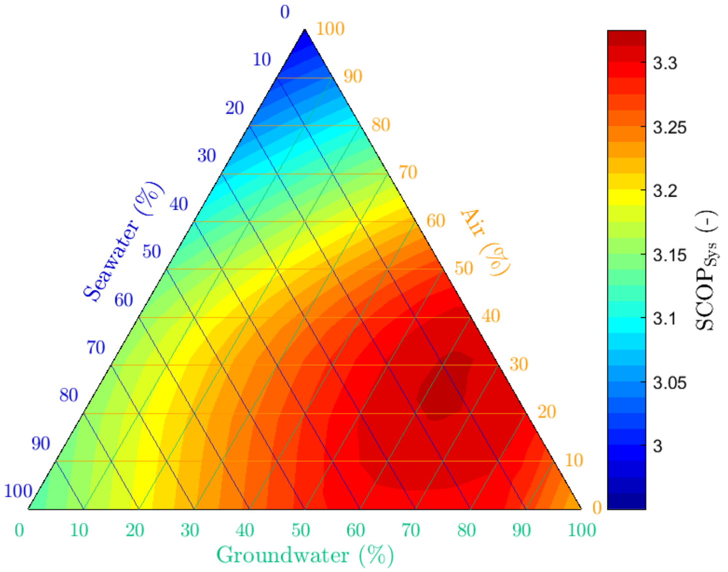

Figure 2-2: Seasonal coefficient of performance of a system utilizing multiple heat sources. Source: (Pieper et al., 2019).[1]

### 2.1.3 Calculation tool for the integration of heat pumps in existing district heating systems

In addition to “Guidebook” (Kortegaard Støchkel et al., 2017a) and ”Instiration Catalogue” a simple excel-based tool “Heat pump calculator” (In Danish: “Varmepumpeberegner”) was developed to support the initial considerations by a utility company in a potential heat pump project. The tool was publised for free download at the Danish Energy Agency homepage (Danish Energy Agency (Danish: Energistyrelsen), 2019), and a user guide was given as a chapter in the “Guidebook”. The purpose of the tool is to calculate the company economy with a heat pump implemented in a district heating system with up to four existing production units. The tool shows the impact on the duration curve and economic figures incl. simple pay back time as well as individual and average marginal cost of production. The tool can be used to test the influence on the capacity, the heat pump COP and different aspects of the eonomy. The calcuations should always be validated by further feasibility studies.

## 2.2 Flexible operation of heat pumps

One of the main challenges of the future energy system is the increasing share of fluctuating power in electricity production. This requires flexible electricity consumers with the possibility

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[1] Reprinted from Energy, 176 (2019), Pieper, H., Ommen, T., Elmegaard, B., Markussen, W. B., Assessment of a combination of three heat sources for heat pumps to supply district heating, 156-170, Copyright (2019), with permission from Elsevier.

to operate according to the availability of the electricity and thereby to balance the fluctuating electricity production and enable efficient use of the energy. Integrating the heating and transportation sector with the power sector implies a considerable potential for demand side flexibility but requires the utilization of suitable technologies for the energy conversion. Large scale heat pumps are expected to play a key role to efficiently integrate large amounts of renewable energy into the system.

Different aspects of flexible operation of large-scale heat pumps are investigated in the research and development project *EnergyLab Nordhavn – New Urban Energy Infrastructures* (www.EnergylabNordhavn.dk) and tested at a heat pump application in the development area of Nordhavn in Copenhagen, Denmark. The test facility, fully described in Section 5.1.
Figure 2-3 shows four levels of system integration characterized by the mode of operating the heat pump system. The heat pump is gradually used more intelligently to integrate the heat- and electricity market with the benefit of reducing the heat production cost of the heating system.

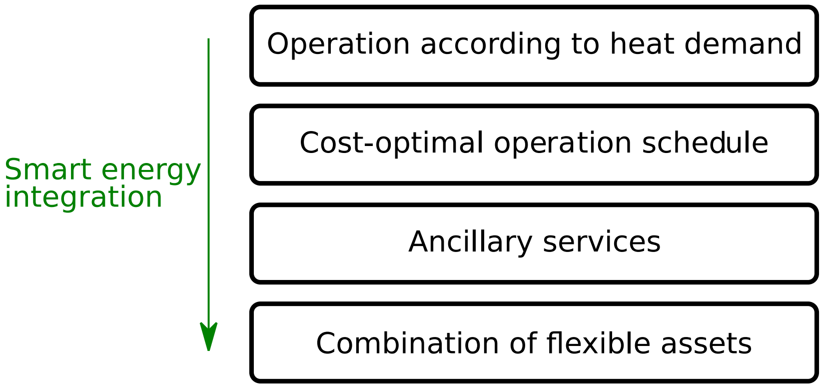

Figure 2-3: Integration towards the electricity sector by supplying the flexibility from the district heating sector. Modified from (Meesenburg, 2019).

The four steps summarize the Smart Energy integration:

**Step 1:** The heat pump is operated according to the heat demand of the consumers. The flexibility of the storage tank is only exploited to allow for start-stop operation of the heat pump.

**Step 2:** The flexibility of the tank is exploited to run the heat pump and electric boiler primarily when the electricity prices are the lowest and utilize the stored heat in the tank when the prices are higher.

**Step 3:** The system is used to help the local distribution grid by ramping the heat pump up or down. If the distribution grid experiences a surplus of electricity production, which could be due to in-feed from solar- or wind power, the system could ramp up and consume extra electricity for a period. If there is a shortage of electricity on the grid, the system can ramp down for a period. The system can also be used to help the transmission grid. This is done by frequency-regulation services, which can help on a higher level of the grid.

**Step 4:** is a combination of other assets, for example, large-scale battery systems used for grid control or electric vehicles. This will potentially give additional income from frequency regulation that cannot be delivered by the single systems in separated configuration, i.e. either the heat pump or the electric vehicle.

It has been identified that full integration of such heat pump system requires a rather comprehensive optimization model, control strategy as well as iterative testing and validation. Furthermore, technical challenges with the heat pump system were addressed when reaching step 3 and 4. These challenges were related to the time requirements for different ancillary services, as shown in Figure 2-4.

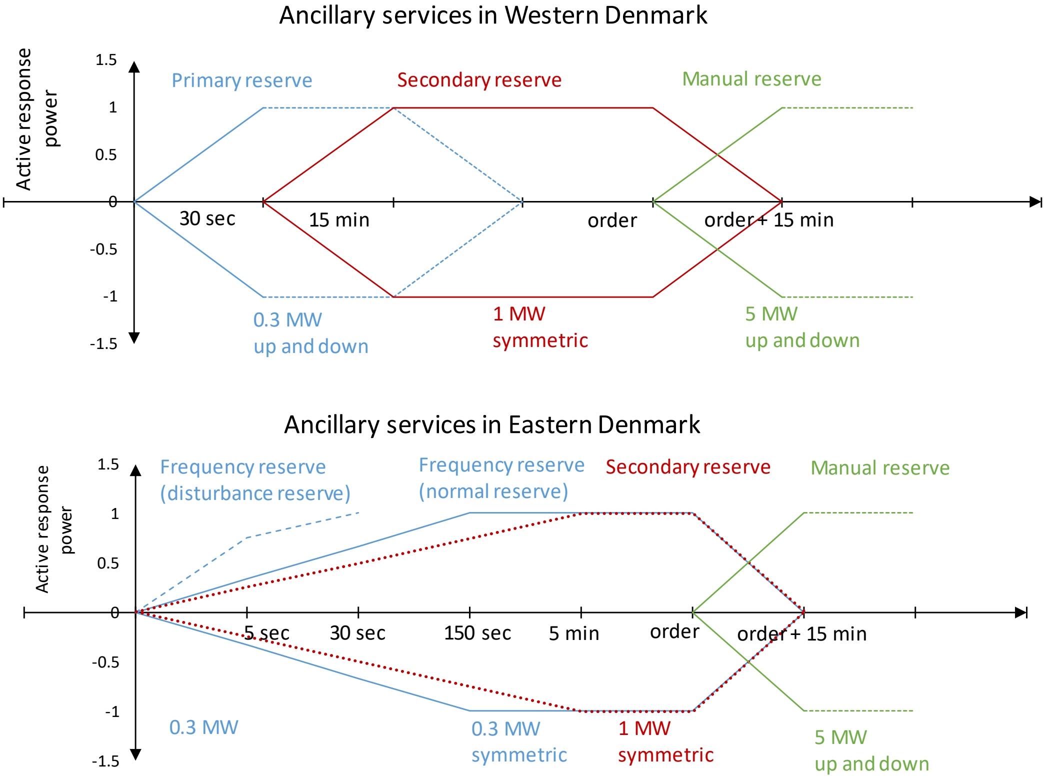

Figure 2-4: Ancillary services in Western and Eastern Denmark. Source: (Meesenburg, 2019).

For reaching the frequency reserve (normal reserve) and secondary reserve for Eastern Denmark, it was found by tests and modelling of the dynamic behavior, that the standard control scheme used for the heat pump, was a limiting factor (Meesenburg et al., 2019, 2018). For this reason, a collaboration with the heat pump manufacturer was established in order to challenge the limits and to find solutions on the technical issues that occurred. The work illustrates the benefits of test and demonstration projects that both involve end users, researchers, consultants and the manufactures. Preliminary tests indicate that the heat pump is able to regulate 50 % capacity within 90 seconds – this allows the system to participate on the normal reserve power market of Eastern Denmark, and it is an important result in the pursuit of designing heat pumps to support the electricity grid, and thus allowing integration of more renewable and intermittent electricity.

# 3 Integration of heat pumps in industrial applications

As described in Report 1 chapter 2 and 3 (Benjamin Zühlsdorf et al., 2019a), the amount of excess heat and potential for industrial heat pumps utilizing excess heat are well investigated for the Danish industry. The decision of implementing a heat pump at an industrial site, should be based on an overall assessment of the energy efficiency of the processes and utility systems. Different political initiatives to invest in such an assessment has been implemented on both European level and national level. It may be concluded that an energy efficiency assessment could be beneficial if one or more of the following processes occur in a production company:

- Heating/boiling
- Drying
- Evaporate
- Distillation
- Melting/casting
- Refrigeration
- Use of compressed air
- Wastewater

This chapter presents an outline of the different steps in an energy efficiency assessment, highlighting the context of heat pumps in process integration (Section 3.1) and the technical and economic feasibility of heat pumps utilizing natural refrigerants (Section 3.2).

## 3.1 Recommendations for implementing industrial heat pumps

The following steps are based on a step-by-step guide made for industries in Denmark (Gate 21 and Viegand Maagøe, 2017), the Ph.D. thesis of F. Bühler (Bühler, 2018) and the European standard for Energy Audits (EN 16247-3:2014).

The overall aim of an energy efficiency assessment is to investigate the opportunities to minimize the amount of energy use in industrial processes, by investment in process equipment, for modification or extension of the industrial site. The assessment must be approached with a rigid method, for a complete overview of all energy demands and supply systems. This will provide a strong basis for prioritizing between the different investments in energy efficiency measures (EEM).

1) **Energy mapping**
   The first step is an energy mapping, where all processes with a heating and cooling demand, as well as the possible excess heat sources and the utility system, are systematically collected or estimated and analyzed at a sufficient level of accuracy. In addition, the time schedule of the different processes should be carefully mapped, as this aspect will be crucial for further investigation of integration and needed storage capacity. Based on this, relevant energy performance indicators should be calculated on a theoretical level and compared to the actual values and relevant sector references. This will give an overall indication of the savings potential.

2) **Identify opportunities of energy efficiency measures**

Figure 3-1: Figure 3-1 shows an exemplifying industrial site and different opportunities for energy efficiency measures (EEM). The site consists of a thermal process (e.g. heating, distillation or evaporation). The process is supplied with energy from a conversion technology (e.g. burner or boiler) supplied with a given source (e.g. natural gas). The desired output of the thermal process is the energy service provided to the product (e.g. separation, pasteurization, melting). As undesired, but consequential, output both the conversion technology and the thermal process rejects energy, either as usable excess heat or non-useable excess heat/waste heat. If no action is taken, to utilize the excess heat, both streams end up in the surrounding environment. The company can decide to reduce the amount of waste heat and excess heat by improving the efficiency of the conversion technology (EEM Utility) and/or thermal process (EEM process). This will lead to a reduction in energy consumption, without compromising the energy service.
If undesired excess heat is practically unavoidable, the heat can be recovered for internal or external use. In both cases, this will require an investment in intermediate recovery equipment, such as heat exchangers, piping, control equipment, and heat pumps. For internal use, the recovered heat can be delivered to the thermal process, or to a bigger internal distribution system if more process can be supplied.

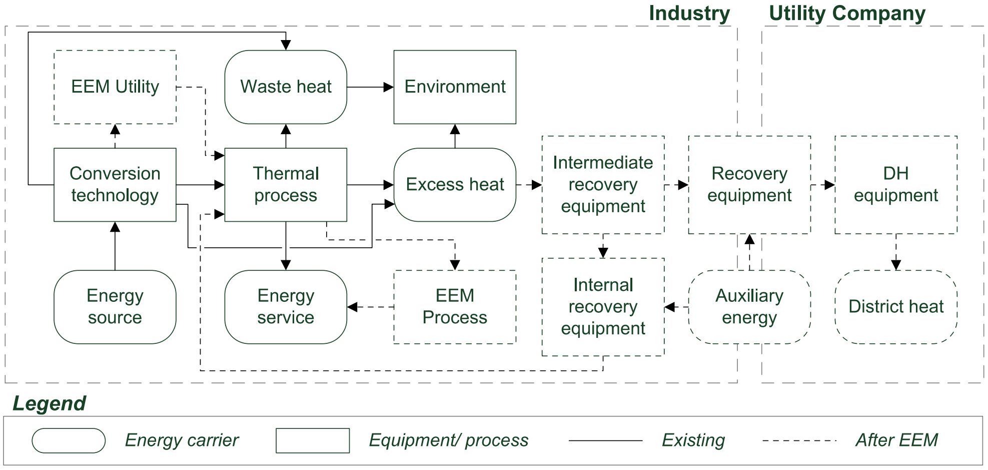

Figure 3-1: Opportunities for energy efficient measures for process, utility system and utilization of excess heat indicated by the dotted lines and boxes (Bühler, 2018).

The optimization opportunities should be investigated in the following order:

- Challenge and question the actual process needs and chosen technology/method. (Is thermal pasteurization needed or could it be done with e.g. ozone, UV etc.)
- Challenge and question the process parameters and equipment design, to reduce energy needs.
- Investigate the opportunities for process integration within the same process.
- Investigate the opportunities for process integration across the production site.
- Optimize the utility system.
- Investigate the opportunities for external heat recovery, by providing the remaining excess heat to an external buyer. This could be the local utility company or another local company.

A proven approach for investigating and optimizing process integration is *pinch analysis*. The general approach and main steps of pinch analysis are well described in the literature, origining from the book *Pinch Analysis and Process Integration* (Kemp, 2006) and also outlined in Report 3, Section 2.1.1 and 2.1.2 (Wallerand et al., 2019).
The potential for implementation of heat pumps can be found in all levels of process integration. The implementation should naturally apply to cases where temperatures do not allow heat recovery by direct heat exchange, and furthermore, also follow the "heat pump rules and belonging exceptions" as outlined in Report 3 section 2.1.3 and 2.1.4 (Wallerand et al., 2019).
The current state-of-art of heat pump implementation combined with process integration, a review of cases and development of methodology can be found in the Ph.D. thesis of H. C. Becker (Becker et al., 2012).
The optimal placement is additionally influenced by non-technical parameters for a specific process site. Heat pumps may for example be integrated at different levels of integration, more specifically:

- Direct integration in processes, such as mechanical vapor recompression
- Integration on unit level with or without interaction of different units
- Utility level

Although the highest performances are expected at the highest level of integration, solutions with less required modifications of the actual processes may be the preferred choice. This may result from less required process modifications but also improved utilization of the equipment at utility level. (Bühler et al., 2019) studied the level of integration by considering different strategies for electrification of a dairy site and (B. Zühlsdorf et al., 2019) presented different heat pump systems that are suitable as utility systems. It is accordingly recommended that end-users are developing a strategy for the transition to sustainable energy supply in order to follow the most reasonable investment strategy and avoid technology lock-in. The development of such strategies may be supported by respective R&D activities.

### 3) Evaluation of economic feasibility

The investment and operating cost of a heat pump depend on many factors, such as the sink and source temperatures, temperature glides, working fluid, compressor technology and number of operating hours. Different methods for estimation of investment cost and operation efficiency will be given in Section 4.1 and 4.2.

Even though internal utilization of the recovered heat should always be prioritized, it might be an option to provide it to external customers, presuming no meaningful internal heat sink may be determined. With a potential for selling excess heat, and an interested buyer identified, the following questions should be clarified:

- How much heat can be utilized over the year?
- What price will cover the cost?
- How should/can the investment cost be split between the partners in the project?

A guide highlighting options and reflections in a Danish context upon the above questions is published as part of the project *Grøn Kollektiv Varme* (English: Green collective heat) (Niras, 2018). A case study included in the guideline identified six different models of ownership between the external buyer and the company holding the excess heat. The choice of ownership model had a significant impact on both the share of the investment cost, possible grants and saving potential for both partners. The general conclusion recommended that both partners were included early in the process, in order to increase the mutual understanding of the pros and cons within the different business cases.

4) **Detailed planning of prioritized projects**

The final design calculations should be handed over to a consultant specialized in energy-related projects. The consultant should calculate the precise amount of excess heat, temperature relations, investment cost and operation cost. The consultant will also investigate the final feasibility of the investment.

## 3.2 Feasible and optimal working domains for natural refrigerants

Due to Danish legislation, natural working fluids have for a long period been the only allowed solution for large-scale industrial heat pumps. However, a large amount of operational and economic constraints limit the applicability. In (Ommen et al., 2015) the possible working domains for several natural working fluids in a single stage vapour compression heat pump, considering temperature lift and sink temperatures relevant for industrial application, were investigated.

The working domains for each working fluid were constrained and compared using both economic and technical constraints. In Figure 3-2 the working domain of ammonia utilized in low-pressure equipment (LP R717) and high-pressure equipment (HP R717), respectively, are shown. The working domains shown are valid for a temperature glide of 10 K on both sink and source. The considered constraints indicated on Figure 3-2 are: a positive net presents value (NPV) of the system (proposed to replace a natural gas burner), the maximum allowable discharge temperature ($T_H$) and pressure ($p_H$) with the available refrigeration equipment on the current market. Furthermore, the outlet of the source was limited to 0 °C, and $T_{sink,in} < T_{source,in}$, as direct heat exchange otherwise would be preferred. Additionally, lines for a payback time (PBT) of 4 and 8 years are shown.

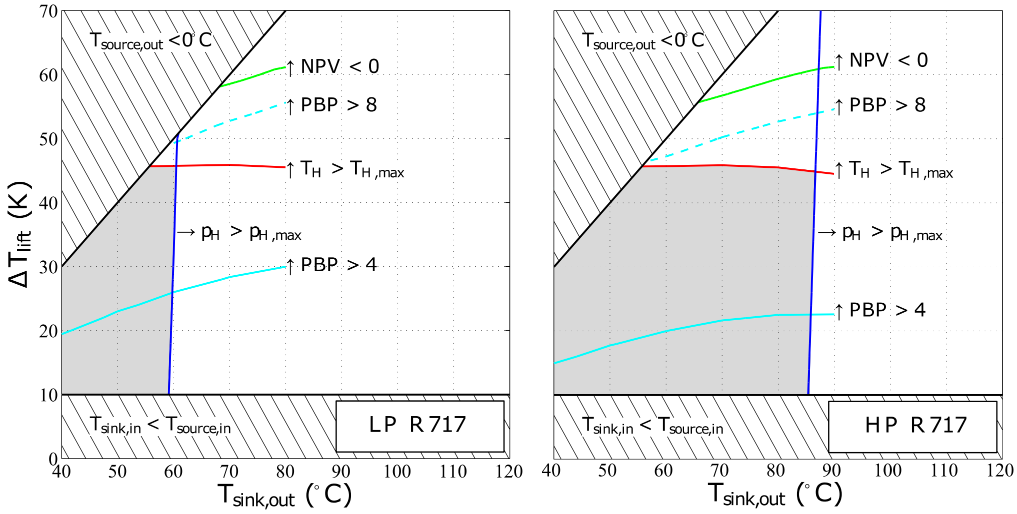

Figure 3-2: Working domains for two different heat pumps with $\Delta T_{sink}$=10 K / $\Delta T_{source}$=10 K. Source: (Ommen et al., 2015)[2].

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[2] Reprinted from International Journal of Refrigeration 55, Schmidt, T.O., Jensen, J.K., Markussen, W. B., Reinholdt, L., Elmegaard, B., Technical and economic working domains of industrial heat pumps: Part 1 – single stage vapour compression heat pumps, 168-182, Copyright (2015), with permission from Elsevier.

In addition to the two working domains shown in Figure 3-2, similar working domains are shown for R290, R600a, R744 and R134a. R134a is included in the study for a comparison of the feasibility of natural working fluids. In addition to the case of $\Delta T_{sink}$=10 K / $\Delta T_{source}$=10 K the working domains were also investigated at $\Delta T_{sink}$=40 K / $\Delta T_{source}$=10 K, $\Delta T_{sink}$=20 K / $\Delta T_{source}$=10 K and $\Delta T_{sink}$=20 K / $\Delta T_{source}$=20 K.

For the case of ΔTsink=10 K / ΔTsource=10 K, a full comparison of working domains and compilation for all heat pump systems is presented in Figure 3-3 (left). The optimal system among these, based on the highest NPV are shown in Figure 3-3 (right).

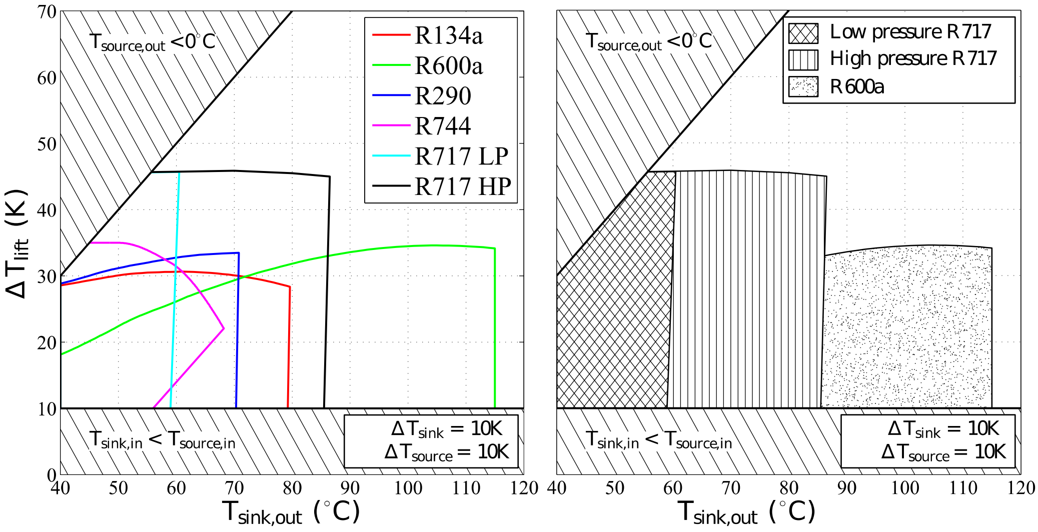

Figure 3-3: Left: Compilation of all heat pumps system. Right: Optimal system based on NPV. Source: (Ommen et al., 2015)[3].

The study concluded that all six considered heat pump systems showed working domains where the net present value was positive when compared to the fuel cost of a natural gas burner. In operation areas covered by several systems, it was found that LP R717 and HP R717 allowed the optimal NPV. By investigating the working domains at different temperature conditions, it was found that sink temperatures up to 115 °C and temperature lift up to 40 K can be achieved with four of the considered heat pump systems.

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[3] Reprinted from International Journal of Refrigeration 55, Schmidt, T.O., Jensen, J.K., Markussen, W. B., Reinholdt, L., Elmegaard, B., Technical and economic working domains of industrial heat pumps: Part 1 – single stage vapour compression heat pumps, 168-182, Copyright (2015), with permission from Elsevier.

# 4 Heat pump performance and economy

The feasibility of a heat pump project, depends on both the investment cost and the operating costs. Different approaches to conduct an economic evaluation are found in the literature. The following section 4.1 will address how the performance of a heat pump system can be evaluated. Section 4.2 presents two different approaches to estimate the investment cost.

## 4.1 Evaluating Coefficient of Performance (COP)

The performance of a heat pump is usually evaluated in terms of the Coefficient of Performance, COP, defined as the supplied heat divided by the compressor power consumption.

$$\mathrm{COP} = \frac{\dot{Q}_{\mathrm{supply}}}{\dot{W}}$$

The value of COP may be used to compare the power consumption of a heat pump to the fuel cost and efficiency of a boiler solution.

If any heat loss from compressor and piping is neglected, the heat supply equals the sum of the heat input from the lower-temperature source and the power consumption:

$$\dot{Q}_{\mathrm{supply}} = \dot{Q}_{\mathrm{source}} + \dot{W}$$

Accordingly, the COP values for heating, COP, and cooling, $\mathrm{COP}_c$, are related as

$$\mathrm{COP} = \mathrm{COP}_C + 1$$

For the cycle illustrated in the log *p-h* diagram in Figure 4-1 operating between the evaporator temperature of 20 °C and the condenser at 80 °C, the heat pump COP is determined to be 4.0.

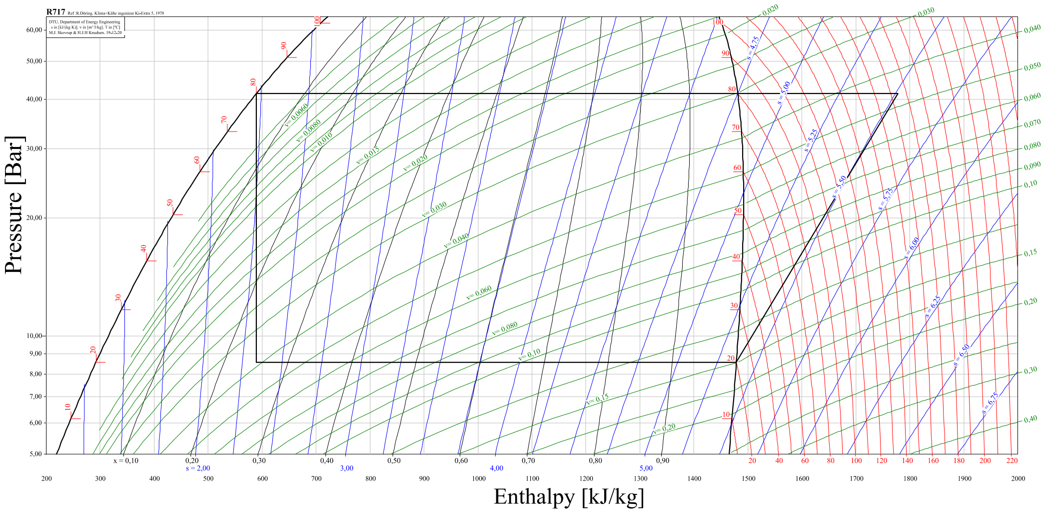

Figure 4-1: R717 heat pump cycle.

The COP may be related to the limits given by the basic laws of thermodynamics. The limit of performance for the thermodynamic cycle is given by the Carnot cycle, which is defined by reversible compression and expansion, and by isothermal heat absorption and rejection at the evaporator and condenser temperatures on an absolute scale [K].

$$\mathrm{COP}_{\mathrm{Carnot}} = \frac{T_h}{T_h - T_L}$$

For the R717 heat pump cycle, the Carnot COP is 5.9. The cycle has a *Carnot efficiency* of 4.0/5.9=67 %.

However, heat pumping often utilizes a lower-temperature reservoir of finite heat capacity to provide a higher-temperature reservoir also of finite heat capacity. The finite heat capacities are indicated by a temperature glide. Taking this into account it can be determined that the thermodynamic limit of the COP is *not* given by the Carnot cycle between the maximum and minimum temperatures, but by the Lorenz cycle operating between the source and sink temperature variations. Figure 4-2 illustrates the difference between the heat source and sink and the respective process temperatures. Furthermore, it indicates the potential of using zeotrpic mixtures as working fluids to match the temperature glide.

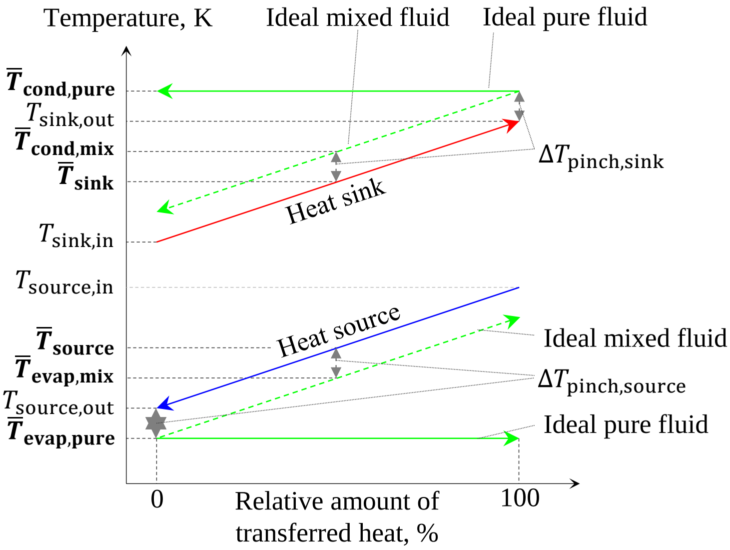

Figure 4-2: Illustration of heat pump operating between finite capacity reservoirs, source: (Benjamin Zühlsdorf et al., 2019b).[4]

The COP of the Lorenz cycle is determined by thermodynamic average temperatures of source and sink, which correspond to the logarithmic average temperatures for streams of constant heat capacity:

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

For a cycle operating between a sink cooled from 45 °C to 25 °C and a sink heated from 55 °C to 75 °C, the Lorenz COP is 11,3 which shows that the apparent limit given by the Carnot cycle only account for the cycle-internal irreversibilities – not for inefficiency related to temperature mismatches in heat transfer. The Carnot limit does not provide a true limit for the performance and the Carnot efficiency does not show the full potential for improvement of the heat pump solution.

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[4] 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.

The *Lorenz efficiency* of the ammonia cycle is only 36 %, and far better heat pump configurations may be introduced. These include multistage cycles, serial heat pumps, use of zeotropic mixtures, and minimizing irreversibilities in the system components.

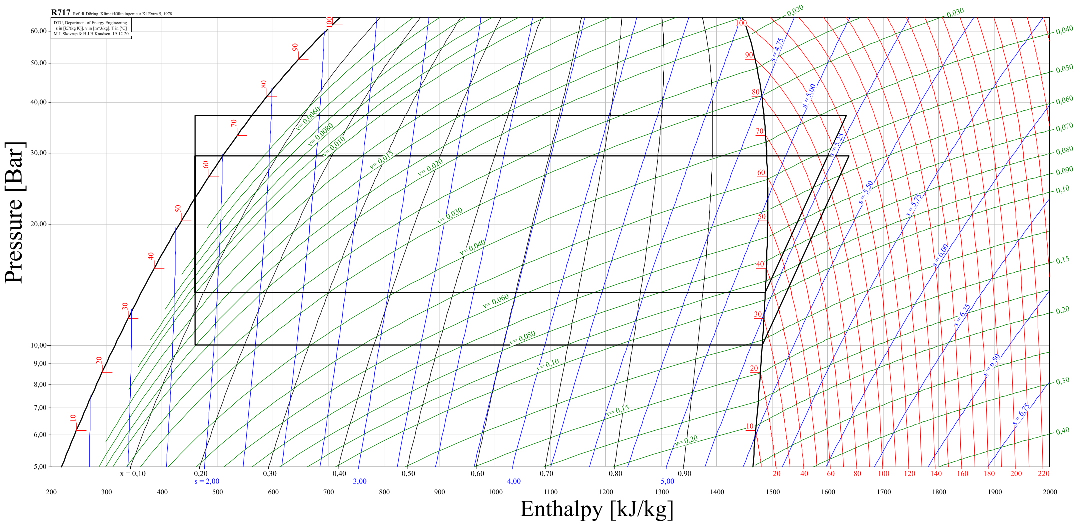

Figure 4-3: Illustration of two heat pump cycles to be installed in series for optimizing COP and minimizing thermodynamic irreversibility

As an example, a serial connection of the two ideal cycles illustrated in Figure 4-3 each providing half of the temperature lift would results in a COP of 6.8. Hence, heat pumps with COP exceeding the Carnot limit may be developed, while not violating the thermodynamic limits. The Lorenz efficiency is in this case 60 %.

Further the *exergy efficiency* may be introduced e.g., to account for incomplete utilization of the excess heat source by not cooling it to the ambient temperature.

In some cases, *System COP* is used. This does, however, not have a single well-defined definition and should be defined in each case in order to evaluate its value in relation to a thermodynamic limit. It may usually be used as a means for comparison to boiler solutions.

For heating and cooling cogeneration, the combined COP, accounting for both products, may also be introduced to show the total benefit of the solution. Both System COP and cogeneration COP are useful for economic evaluation, but they can hardly be compared to thermodynamic limits. In this case exergy efficiency is the most reasonable means for evaluating the potential for performance improvement.

As an estimate industrial heat pumps may in practice reach Lorenz efficiencies between 30 % and 65 %. The value depends on the system configuration, but also on temperature lift and glides.

## 4.2 Economy

Heat pump projects differ in size, configuration, components, heat source, and performance. All these different factors have an impact on the investment cost, which makes it difficult for both the district heating companies and the industrial companies to estimate expected costs and to plan new heat pump projects. Considering different studies from literature (Kortegaard Støchkel et al., 2017; Ommen, 2015), it was found that the investment costs contribute with 1/3 to the levelized production cost of heat for district heating, which makes a good estimate of these costs important.

In the following sections, two different approaches to estimate the investment cost is presented. The method in Section 4.2.1 is based on information from realized or planned projects and presents the specific cost per MW heat pump capacity. Section 4.2.2 presents a method based on the purchased equipment cost of the individual components and from this a simplified relation to the total capital investment cost.

### 4.2.1 Economic evaluation based on based realized or planned heat pump projects

This section presents an analysis of large-scale heat pump projects connected to the district heating networks in Denmark, conducted by H. Pieper, DTU Mechanical Engineering (Pieper et al., 2018). The aim was to provide a better estimate of the total investment cost and how these may vary depending on the capacity, heat source or others, with a higher level of details. The results may be used for energy system modelling or by consultants and energy planners.

The study investigates the investment cost for 26 HP projects. The selection criteria were that they were vapor compression machines above 0.2 MW, connected to the district heating network, utilized a natural refrigerant and either were built or were planned to be built in Denmark. In addition, the study also included 12 heat pumps utilizing excess heat as heat source from (Bühler et al., 2018).

Figure 4-4 shows the composition of the investment cost by five different categories: The heat pump itself, costs related to connecting the heat source, construction cost, connection to the electricity grid, and consulting cost. From Figure 4-4 it is clear that a considerable amount of investment cost, accounting for all heat sources, was placed on other parts than the heat pump itself.

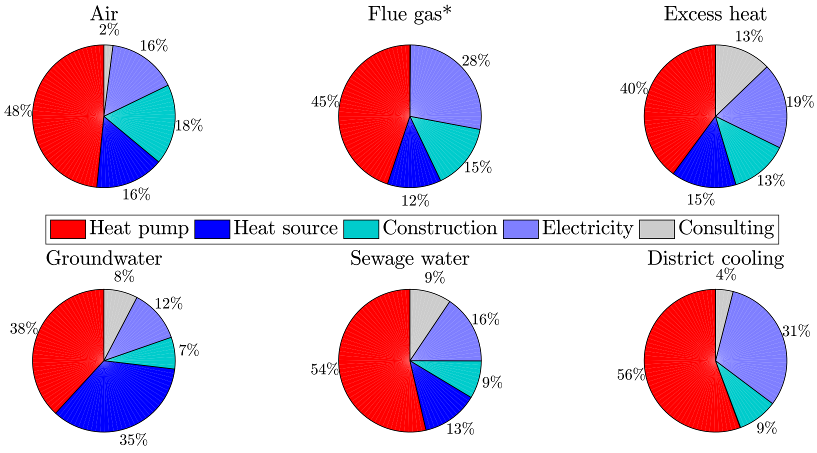

Figure 4-4: Breakdown of investment cost in five different categories considering 6 different heat sources (Pieper, 2019).

A cost correlation based on the heating capacity of the heat pumps was established for each category. Adding the contributions of each category resulted in the specific total investment cost, presented in Table 4-1.

Table 4-1: Specific total investment cost for heat pump projects, depending on the heat source and heat pump capacity ($HP_{cap}$). Source: (Pieper et al., 2018)[5]

| Specific cost,<br>million €/MW | Flue gas | Sewage water | Excess heat | Ground-water | Air |
|---|---|---|---|---|---|
| 0.5 MW ≤ $HP_{cap}$ < 1 MW | 0.63 to 0.53 | 1.91 to 1.23 | 1.30 to 0.97 | 1.72 to 1.18 | 1.12 to 0.90 |
| 1 MW ≤ $HP_{cap}$ < 4 MW | 0.53 to 0.46 | 1.23 to 0.72 | 0.97 to 0.72 | 1.18 to 0.77 | 0.90 to 0.73 |
| 4 MW ≤ $HP_{cap}$ < 10 MW | 0.46 to 0.44 | 0.72 to 0.62 | 0.72 to 0.67 | 0.77 to 0.69 | 0.73 to 0.70 |

As presented with the numbers in Table 4-1 it was found that the specific investment cost decreased for larger capacities.

### 4.2.2 Economic evaluation based on cost estimation of individual components and additional cost

In the method presented in the above section 4.2.1, the cost of the heat pump itself is based on the total heating capacity of the installation and omitting other details of the system configuration. The method for cost estimation is fully valid when only an estimation is needed, which in many cases will be sufficient information. However, it was also seen from the collected data that different heat pumps with the same total capacity, could have a deviation in the specific cost. A reason for this is, of course, related to the price difference between different suppliers, but could also be related to choices made in the design phase, to decrease the exergy destruction and improve the system performance. The most common examples include a smaller pinch temperature difference in the heat exchangers, additional heat exchangers and compression in two stages.

For a given system, the total capital investment (TCI) can be estimated as suggested in (Bejan et al., 1996) and shown by Eq (1) with a fixed multiple $f_{\mathrm{TCI}}$ of the total purchased equipment cost (PEC).

$$\mathrm{TCI} = f_{\mathrm{TCI}}\,\mathrm{PEC} \qquad \text{Eq. (1)}$$

The factor accounts for all remaining expenses and is often experience-based. In (Bejan et al., 1996) two different factors of 4.16 or 6.32 are suggested, depending on whether the system is an expansion of an existing installation or a new system. With this method, the PEC of the included components become very important and should rely on cost correlations with high accuracy.

The cost of purchased equipment can be based on vendor quotations, past purchase orders or cost databases incl. estimating charts. From any of these, it can be necessary to take the effects of the size on the equipment into account. (Bejan et al., 1996) suggests Eq. (2),

$$C_{\mathrm{PE},Y} = C_{\mathrm{PE},W}\left(\frac{X_Y}{X_W}\right)^{\alpha} \qquad \text{Eq. (2)}$$

---

[5] Reprinted from Energy Procedia, 147 (2018), Pieper, H., Ommen, T., Bühler, F., Paaske, B. L., Elmegaard, B., Markussen, W. B., Allocation of investment cost for large-scale heat pumps suppling district heating, 358-367, Copyright (2018), with permission from Elsevier.

Where $C_{\mathrm{PE},W}$ is the base cost associated with the dominating size or capacity $X_W$, and $C_{\mathrm{PE},Y}$ is the cost of a component with the size or capacity $X_Y$. The scaling exponent $\alpha$, is for thermal process equipment less than unity and can be assumed 0.6 in absence of other information.

Considering heat pump systems, examples of the total investment cost calculation for both heat exchangers, compressors, electric motors, pumps, receiver, and liquid-vapor separators can be found in e.g. (Jensen et al., 2015) and (Zühlsdorf et al., 2018).

This method is accordingly suitable for comparison of different systems with various layouts and working fluids. It may however be noted that the method is strongly dependent on the availability and consistency of raw data. It is recommended that any cost estimation based on this method is validated with other cost estimation approaches.

# 5 Best practice examples

In this chapter, best practice examples are presented in order to give examples of successful applications. The cases were selected from Task 1 considering a wide range of applications. The best practice examples are categorized according to their heat source and heat sink with the following combination:

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

In addition to the cases described here a catalog with the description of 22 installations can be found in the "Inspiration Catalogue" (Energistyrelsen, 2014) and a follow up report on operation experiences from 24 different installations (Rambøll et al., 2019).

## 5.1 Groundwater heat pump to island DH network

### 5.1.1 Summary

"Flexheat" is a heat pump located in the outskirts of Nordhavn, Copenhagen. This facility is established as a part of the "EnergyLab Nordhavn" project. The heat pump has a capacity of 800 kW, and utilizes groundwater to supply a local island district heating network, with a forward temperature of 68 °C to 74 °C and a return temperature of 40 °C. Besides the heat pump, the system consists of a stratified storage tank of 100 m$^3$ and two electric boilers of 100 kW each. In addition to the heat supplied to the district heating grids, it is tested if the system can provide ancillary service to the electricity grid, on a local level as well as on the overall level. This means that the system, acts as a controllable load in the power system, i.e. the heat pump electricity consumption changes according to signals from the power system operator. This corresponds to the second highest level of integration as presented in Chapter 2.2.

Table 5-1: 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 CO2 emissions | 425 tons/year |
| Maintenance cost per supplied heat | 3.2 €/MWh |
| Manufacturer/Contractor/consultant | Johnson Controls/COWI |

### 5.1.2 Project background and characteristics

The “Flexheat” system is designed to supply three terminals and a large UNICEF warehouse with heat for space heating and domestic hot water.

Figure 5-1: Left: The bulding in Outer Nordhavn, located next to the storage tank. Right: the heat pump from Johnson Controls before installation. Source: HOFOR

The heat pump has a heating capacity of 800 kW. Besides the heat pump, the system consists of a stratified storage tank of 100 m$^3$ and two electric boilers of 100 kW each. A sketch of the system is shown in Figure 5-2.

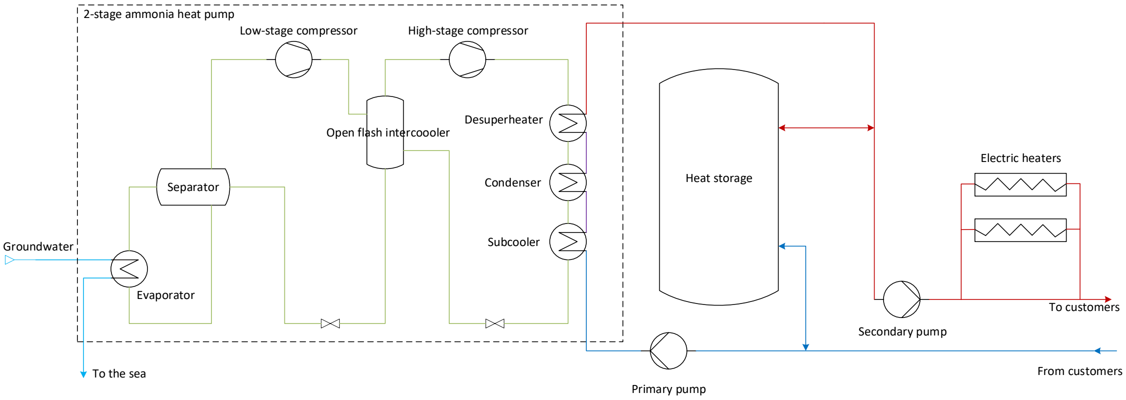

Figure 5-2: Sketch of the heat pump and the system configuration. Source: (Meesenburg, 2019).

The system supplies the network with 68 °C to 70 °C in forward temperature and 40 °C in return temperature at the design conditions. The forward temperature from the heat pump can change from 60°C to 82 °C. The heating load can vary down to 30 % of the design capacity.

The heat pump utilizes salt-containing groundwater from two different wells as heat source. The ground water is cooled from 10.5 °C to 4.5 °C in design conditions. The depth of the wells is approximately 120 meters. The water is discharged to the sea after cooling it down.

In addition to the heat supplied to the district heating grids, it is tested if the system can provide ancillary service to the electricity grid. This means that the system acts as a controllable load in the power system, i.e. the heat pump electricity consumption changes according to signals from the electricity markets (see Figure 2-4).

It was found that the provision of ancillary services requires a sophisticated control strategy as well as iterative testing and validation. From tests and modelling of the dynamic behavior, it was found that the standard control scheme used for the heat pump, was a limiting factor

(Meesenburg et al., 2019, 2018). For this reason, a collaboration with the heat pump manufacturer was established in order to challenge the limits and to find solutions on especially the risk of condensation on the suction line.

### 5.1.3 Economics and environmental effects

Including all losses, the yearly heat supply from the heat pump is 2,000 MWh per year. The system replaces an oil boiler, with a yearly consumption of 200,000 liters fuel oil. The heat pump has around 2,150 full load hours and an electric consumption of 634 MWh per year. The COP of the heat pump is 3.3. The maintenance cost related to the heat pump is approx. 3.2 EUR/MWh. The yearly savings are estimated to 131,000 € and 425 tons of $CO_2$-emissions.

The system is established as part of “EnergyLab Nordhavn” project. The total project investment was 2.04 mio. €, and was supported by the Danish research fund EUPD with 200,000 € and further a sale of energy savings of 67,000 €. It is expected that the heat pump can reduce the cost of heat by 5 % to 10 % with flexible operation of the heat pump and participation on the electricity market.

### 5.1.4 Experience from planning and operation

The heat pump has a COP of approx. 3.3 in the design conditions. The COP of the heat pump has been mapped with tests in different operating conditions, in order to include this is the prediction model of the system. The test showed that the COP increases with a lower forward temperature and to some extent when operating in part load. The peak in COP due to part load operation, was found at a capacity of approx. 60 % to 70 % for forward temperatures around 58 °C to 62 °C. For higher forward temperatures the peak in COP was found at 80 % to 85 % of the design capacity.

In relation to the flexible operation of the heat pump, it was found that the heat pump could be used for manual reserves (see Figure 2-4), without any changes in the system. This service could be reached also from complete shut down and start-up from zero capacity. Providing the secondary and primary reserve (Eastern DK), was possible by going into part-load operation, however it was found that the control scheme should be optimized. Further, it was identified that condensation in the suction line occurred during fast ramp down. Different possibilities to avoid this was investigated in (Meesenburg et al., 2019).

### 5.1.5 Specification of the heat pump

Table 5-2: 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 |

## 5.2 From waste heat to district heating

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### 5.2.1 Summary

A project was carried out to convert excess heat from the company CP Kelco into district heating, to be distributed by VEKS (district heating company). Heat from an alcohol condensation process was being rejected by cooling towers via a cooling loop, but the temperatures available, showed promise to be recovered for district heating. The cooling towers operated with forced convection and the noise caused complaints from the neighbors. CP Kelco was interested in a solution that could both eliminate the noise issues and recover the waste heat.
Viegand Maagøe was hired to uncover the potentials of heat recovery and for eliminating the use of the cooling towers. The initial thought for heat recovery was the application of a heat pump to be directly applied to the current cooling loop and deliver district heating into the district heating network.
However, thorough mapping and analysis of the energy flows and consumption and a quite different solution was proposed. The mapping showed that the condensation of the alcohol occurred at a temperature of 80 °C, but the cooling loop had forward/return temperatures of 30 °C/45 °C. Thus, the following was proposed; a redesign of the cooling loop and alcohol condenser turning it into a heat recovery system that could be utilized for supplying district heating while ensuring redundancy with cooling towers and a buffer tank.

The new heat recovery system supplies district heating throughout the year with district heating supply temperatures varying throughout the year from 75 °C to 85 °C. During summer the heat recovery system can even supply district heating without the heat pump. This setup yields system COPs (incl. direct heat exchange) ranging from 15 to 50 depending on the conditions and weather. By systematically mapping the energy flows and usage, the original project was expanded to integrate additional parts of the factory thereby improving upon the business case proposal of 40 GWh to deliver up to nearly 50 GWh of district heating each year.

Table 5-3: 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 +<br>fixed maintenance cost of 7,000 €/year |
| Manufacturer<br>Contractor<br>Consultant | Mayekawa Europe SA<br>Svedan Industri og Køleanlæg A/S<br>Viegand Maagøe A/S |
| Payback time | 2.1 years |

### 5.2.2 Project background and characteristics

Initially, CP Kelco discharged their excess heat through large cooling towers. The fans of the cooling towers made enough noise to receive complaints from the neighbors. CP Kelco was interested in a solution to reduce the load on the cooling towers to reduce their noise issues. Viegand Maagøe was hired to map the energy consumption and determine the feasibility of recovering a part of the heat rejected by the cooling towers. The waste heat rejected through the cooling towers came from the condensation of alcohol from distillation columns. The condensers were cooled by a cooling system and initially the idea was to simply apply a heat pump directly to the current cooling system to deliver district heating.

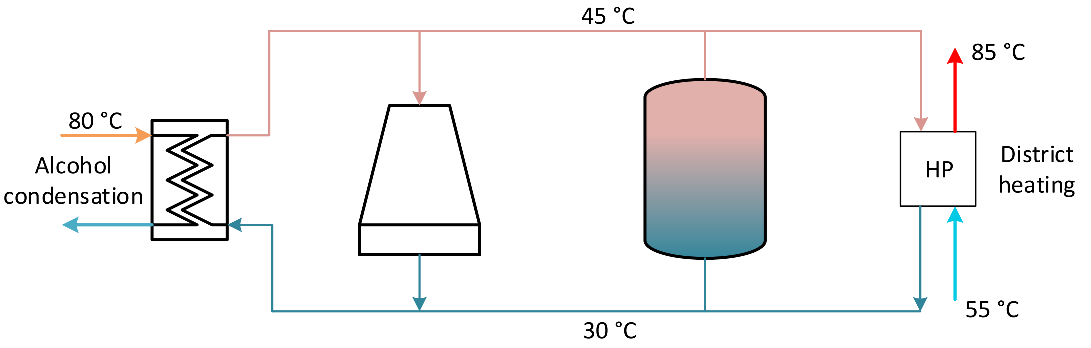

Figure 5-3: Initial configuration. On the left side, the alcohol condenser. On the right side, the district heating receives energy from the heat pump.

It was, however, determined that the primary energy service for the process was the condensation of the alcohol at temperatures in excess of 80 °C, but the cooling systems had forward/return temperatures of 30 °C/45 °C. It was proposed to redesign the condensers and increase the integration of the heat recovery system with the already existing systems and piping while ensuring redundancy. Thereby the temperatures of the heat recovery system could be increased to forward/return temperatures of 60 °C/75 °C.

The new design of the heat recovery system simultaneously increased the COP by higher evaporation temperatures and a lower temperature lift, but also through preheating the district heating water allowing for a much higher system COP. The heat recovery system enters the alcohol condensers at 60 °C and leaves the condensers at 75 °C. The public district heating system has a return temperature of 55 °C, which is initially preheated by the heat recovery system before the heat pump increases the temperature up to the forward temperature of 85 °C, while cooling the heat recovery system to its forward temperature of 60 °C. A buffer tank is in place which ensures the stability of the system and the heat recovery system is also connected to the cooling towers to ensure redundancy.

The heat pump system design can deliver upward of 8 MW of district heating with an electrical input of roughly 350 kW. During summer the district heating capacity is limited to 4 MW due to demand and during winter the capacity varies with the demand up to the maximum capacity. In the heat pump evaporation takes place at 60 °C and condensation at 87 °C. By preheating the district heating water directly from the heat recovery system, the heat pump only needs to deliver up to 2 MW of the heating, while the district heating heat exchanger supplies 3 MW to 6 MW.

The installed heat pumps are specially designed for low pressure ratios between the suction and discharge side, meaning high evaporation and condensation temperatures with a relatively small temperature lift, which results in a higher COP. Additional safety is implemented with a throttling valve to ensure a suitable pressure ratio.

During summer the district heating forward temperatures are lower, and the heat recovery system discharges its heat directly to the district heating system.

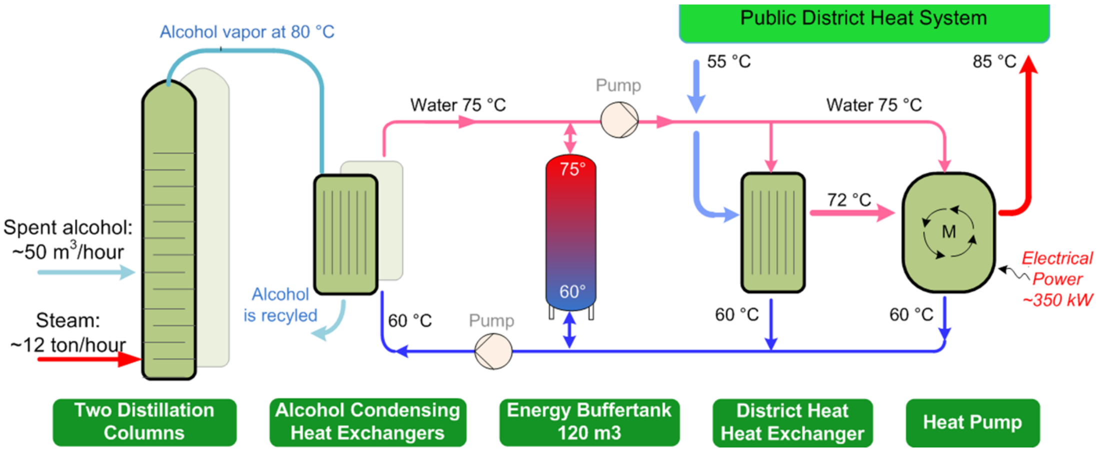

Figure 5-4: Design of heat recovery system

An important factor for the feasibility of the project was the support from the district heating company, VEKS. VEKS was eager to cooperate and assist in the project development as well as accommodating CP Kelco’s supply into their district heating network. The interests and cooperation between CP Kelco and VEKS ultimately made the project feasible.

### 5.2.3 Economics and environmental effects

The cost of the heat pump is partly covered by subsidies for energy savings. The economic parameters are presented in the following table. The installation of the heat pump saves upward of 50 GWh, which would otherwise have been largely supplied by VEKS’s other plants. Additional energy savings and heat supplies are found locally within CP Kelco’s facilities due to the integration with other systems. The energy savings translate to a $CO_2$ emission reduction of 10,000 tons/year.

Table 5-4: Economic and environmental effects of the heat pumps installation at CP Kelco.

| | |
|---|---:|
| Investment cost for CP Kelco (heat pump, condenser, building, piping etc.) | 3,920,000 € |
| Investment cost for VEKS (connection to district heating) | 740,000 € |
| Energy saving subsidies | 2,400,000 € |
| Annual operating hours | 8,600 hours/year |
| Annual O&M costs, excluding electricity | 86,000 € |

### 5.2.4 Experience from planning and operation

The expected system COP including direct heat exchange was initially 18.5 with the redesigned system, with the heat pump COP being 8.5. In comparison, the original idea with a heat pump and the old cooling system had a heat pump and system COP of 4.7. Initially, the heat pump had to run continuously throughout the year to secure sufficiently high temperatures, but during the second phase of the project through optimization of the system, the necessary district heating temperatures can be supplied during summer without the heat pump. During summer the forward district heating temperatures are only 75 °C compared to 85 °C.

Through optimization and integration with other parts of CP Kelco's heat recovery system, the system COP for district heating production has been increased with the total capacity having been increased from the business case proposal of 5.5 MW up to 8.7 MW. Thereby the total production capacity has been increased from around 40 GWh to upward of 50 GWh.

The high evaporation temperatures gave rise to problems due to condensation in the suction line despite the insulation of the piping. Heat tracing had to be installed to ensure gas flow to the compressor.

### 5.2.5 Specification of the heat pump

Table 5-5: 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 |

## 5.3 District cooling to district heating

### 5.3.1 Summary

Copenhagen Markets is a large marketplace and distribution center for fruit, vegetables, flowers, and other related food. The market has an area of 67,000 m$^2$, with a yearly cooling demand of 3,500 MWh to 4,000 MWh supplied with district cooling from central units. The main unit is a co-production unit, as the hot side is utilized for district heating in the local distribution network. The operation is based on the cooling demand, which gives approx. 6,500 MWh to 7,500 MWh of heat. The unit is owned by Høje Taastrup Fjernvarme, but as the cooling is sold on a commercial market, the financial accounting is treated separately.

Table 5-6: 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<br>Cooling: 2.0 MW |
| Running hours | 1800 |
| 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 |

### 5.3.2 Project background and characteristics

Copenhagen Markets changed location in 2016, and with the new building a district cooling system was implemented. At the old location individual cooling units supplied the different demands in the building. The new building has an area of 67,000 $m^2$ with up to 55 leases. The local district heating company owns the central cooling unit and utilizes the hot side for district heating. This results in a heat production which corresponds to 2 % to 3 % of the total heat supply of the area. The local utility company primarily buys the heat from the heat transmission company VEKS A/S, but with an increasing share of heat produced by self-owned units.

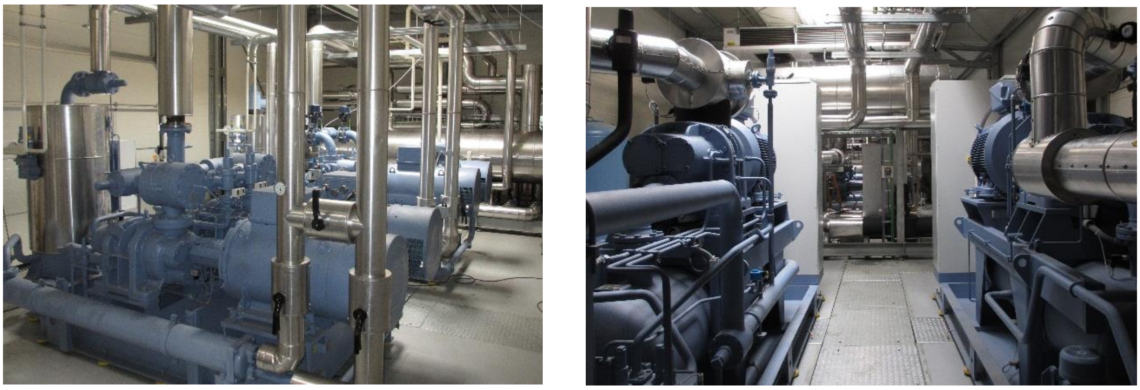

Figure 5-5: The heat pump and chiller installation at Copenhaagen Markets. Source: Høje Taastrup fjernvarme amba.

The system is built up with one main unit and two additional chillers, as shown in Figure 5-6. The main unit's heat sink is utilized as district heating, while the heat source is a connection loop to the chillers. The main unit consists of a two-stage cycle, with screw compressors utilizing ammonia as refrigerant. At each stage two screw compressors are connected in parallel. The unit heats up the heat sink from 46 °C to a supply temperature of 73 °C, with a capacity of 3.1 MW. The connecting loop utilized as a heat source of the main unit and heat sink of the chillers has a temperature 6 °C as the minimum temperature and 16 °C as the maximum temperature. The chillers consist of a single cycle with one screw compressor, also utilizing ammonia as refrigerant. The chillers cool down the district cooling network (water with glycol) from -1 °C to -8 °C, with a total capacity of 2.1 MW.

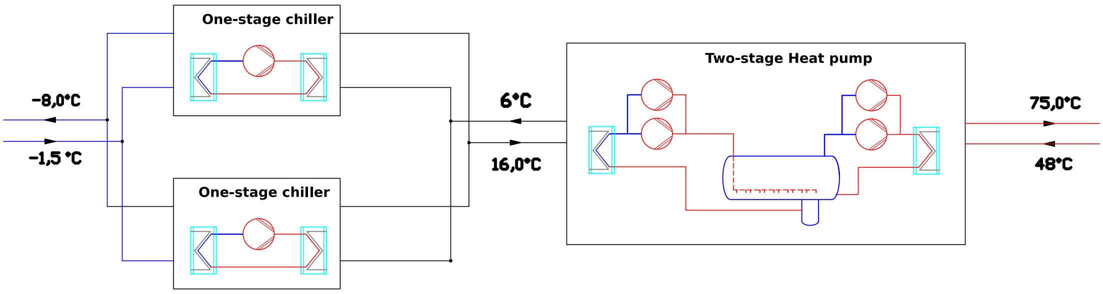

Figure 5-6: System- and heat pump configuration of the district heating and district cooling co-production. Source: Høje Taastrup Fjernvarme amba.

### 5.3.3 Economics and environmental effects

The total investment cost of the system was 3.36 mio. €. In Denmark, district heating is a utility supply, while district cooling is provided on commercial terms, and therefore the investment cost was split into a share for district heating and a share district cooling.

The cost of cooling is settled by a contract between the utility company and Copenhagen Markets, and is not public information. The establishment of the heat pump is based on feasible business case for both Copenhagen Markets and the utility company. The alternative for Copenhagen markets would have been individual chiller units.

For the utility company the cost of heat produced by the heat pump was less than what they normally pay for the heat from the transmission company. The heat from the transmission company is mainly produced by efficient combined heat and power plants, primarily based on wood pellets and waste incineration. This means that the district heating already to some extent has a green profile, and that the strategic goal of implementing a heat pump was more related to a general goal of electrification of the heating sector, and reduced cost of heat.

The cooling varies during the year, due to ambient conditions, but it is present at all times. Due to a realized smaller cooling load than estimated when the system was designed, the units operate mostly in part load conditions. The annual full load hours are approx. 2000 per year, which corresponds to a cooling demand and corresponding heat production of approx. 4000 MWh and 6600 MWh respectively. The system has a heat pump COP of 3.16, and maintenance cost per heat supply of 2 €/MW.

### 5.3.4 Experience from planning and operation

The system performed as expected and the delivery of cooling to the customers has been reliable.

The main challenges were related to the control strategy of the system. The return temperature and pressure from the district heating grid varies during the season. This affects the pressures and temperatures internally in the system, which has to adapt to the changing conditions in order to deliver the cooling at the promised temperature. The problems were solved by increasing the dead time before the control system reacts to changes.

### 5.3.5 Specification of the heat pump

Table 5-7: 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 connected with an intermediate loop. |
| 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 |

## 5.4 Process cooling to Process heating

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### 5.4.1 Summary

A heat pump was integrated into one of Arla Foods' dairies to simultaneously deliver heating and cooling for the facility. Arla continuously works with process and energy optimization at their production facilities and at one of their sites, in Rødkærsbro, a heat pump was found to be a feasible solution with a strong business case.

Viegand Maagøe was hired by Arla to make a mapping of the energy usage within the factory and propose solutions that could reduce their energy consumption. The energy mapping quantified the energy consumption and the corresponding temperature levels and the means by which the energy was supplied or removed. Heating loops at different temperature levels were available in the factory along with an icewater cooling loop with a forward temperature of 2 °C. The temperature of the cooling loop was sustained by large chillers. Most of the high temperature process heating in the factory was supplied by hot water loops which were heated by a natural gas boiler. The temperatures of the hot water loops were as high as 130 °C.

However, through a mapping of the energy usage it was determined that the bulk of the required heating was below 79 °C. After implementation of the optimization proposals, it was required to boost the remaining share of return water at 60 °C to further improve the heat recovery. A solution was thus proposed for simultaneously delivering the bulk of the heating and a significant part of the cooling. The solution is composed of two two-stage heat pumps with evaporation temperatures low enough to deliver icewater to the cooling loop and deliver heat at temperatures of 90 °C to the hot water utility loops. The heat pumps each have a cooling capacity of 1 MW and a heating capacity of 1.5 MW. Stability is ensured with buffer tanks in place and the heat pumps can supply a significant part of the energy consumption. The evaporators of the heat pumps are coupled in parallel and the condensers are coupled in series as indicated in Figure 5-7. The heat pumps reduced the overall natural gas consumption at the factory by 42 %, while increasing the overall electricity consumption by 11 %.

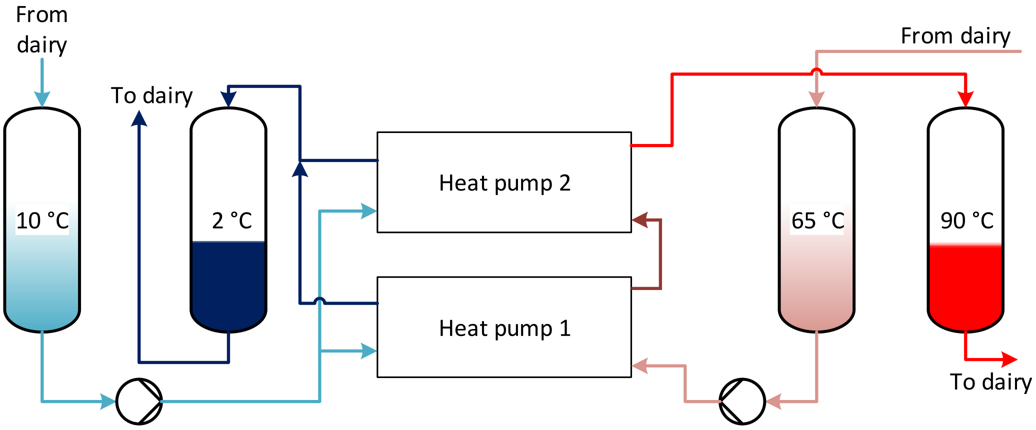

Figure 5-7: Two, two-stage heat pumps supplying both process cooling and process heating.

Table 5-8: 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 CO2 emissions | 2,980 tons/year |
| Maintenance cost per heat supply | Approximately 4 €/MWh |
| Manufacturer<br>Contractor<br>Consultant | Mayekawa Europe SA<br>Svedan Industri Køleanlæg A/S<br>Viegand Maagøe A/S |
| Payback time | 6.1 years |

### 5.4.2 Project background and characteristics

At the dairy owned by Arla in Rødkærsbro, mozzarella cheese is the primary product with whey and cream as secondary products. Raw milk is the primary feed received directly from the farmers. The processing from raw milk to mozzarella cheese requires large amounts of heating and cooling at temperatures up to 125 °C. The heating and cooling were provided by several heating loops, heated by a natural gas boiler, and a cooling loop, cooled by a refrigeration system.

The received raw milk has a temperature similar to the products leaving the factory. This indicates that heat likely only needs to be added at the highest temperatures and cooling for the lowest temperatures. Much of the heating and cooling between these temperatures may be largely recovered by process integration within the factory.

The raw milk goes through several processes as it becomes cheese and both whey and cream are by-products from the factory as the raw milk is turned into cheese. The milk is initially standardized to ensure similar conditions for the cheese production, here cream is removed as a by-product. Culture is then added to the standardized milk and the actual cheese process begins. Rennet is added and the milk coagulates, and as it coagulates, whey is excreted. Throughout the production, the milk is heated and cooled several times for e.g. pasteurization.

A mapping of the energy usage in the factory and to propose solutions that could reduce the energy consumption was conducted. The mapping provided the temperature levels and energy consumption for each step of the cheese production which uncovered potentials for external energy requirements by process and heat integration. The mapping showed that the bulk of the heating was below 79 °C. Many systems were already in place for heat recovery, an example of this is so-called *regeneratives* where the milk to be pasteurized is heated by the milk having just been pasteurized.

Arla had in the original design of the factory implemented an *energy water* loop which was used for low temperature preheating and high temperature cooling. The energy mapping uncovered that this system moved significant energy and proved the usefulness of keeping this system.

Through the proposed optimizations and the quantification of the different systems and their energy flows, an amount of water flows with relatively high temperatures of 60 °C were left. With the heat integration, the regeneratives, and the energy water loop optimized, these water flows were left to be heated by the natural gas-fired boiler. Instead it was proposed to use a heat pump to simultaneously deliver process cooling and process heating. Due to the significant temperature lift, as icewater has to be delivered at 2 °C and process water at 90 °C, the compressor requires a lot of electricity, but with both sides of the heat pump being a product, the overall heat pump COP is favorable.

The heat pump system was designed with two two-stage heat pumps that deliver both heating and cooling to the utility loops in the factory. The evaporators of the heat pumps are coupled in parallel, but to reach the high temperatures and improve the COP the hot side of the heat pumps are coupled in series. The return of the hot water loop is initially heated in the subcooler of both heat pumps and then in the condensers, thereby decreasing the temperature lift and improving the COP. Buffer tanks are installed at either side to ensure stable temperatures at both sides of the heat pump by reducing variability of the return temperatures to the heat pump.

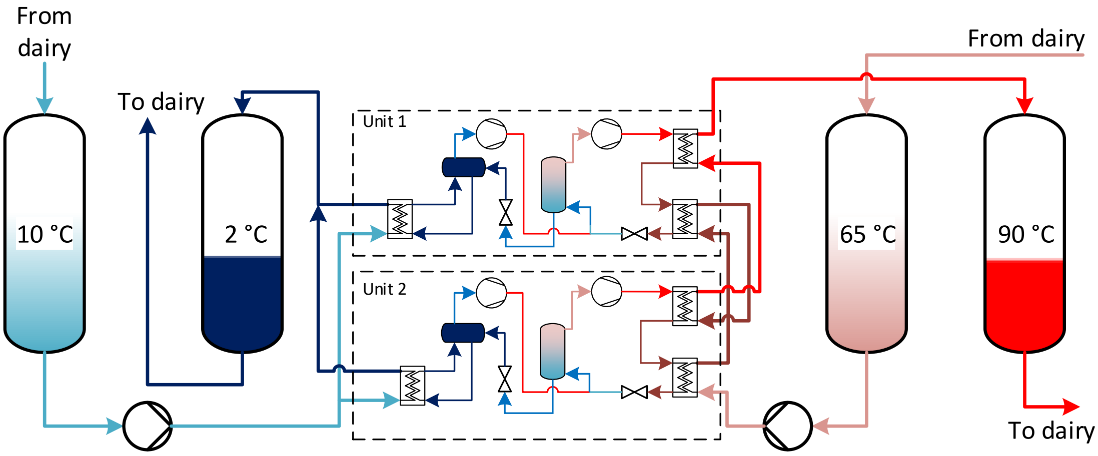

Figure 5-8: Two two-stage heat pumps were installed that simultaneously delivered heating and cooling for the utility loops. The system of heat pumps can deliver 2 MW of cooling and 3 MW of heating.

### 5.4.3 Economics and environmental effects

Due to the size of the heat pumps and filled factory floors, an entirely new building had to be erected. Additionally, buffer tanks were installed for the stability of the system, thereby the heat pumps required considerable auxiliary installations. The overall investment for the heat pump is presented in the following table. The cost of the heat pump is partly covered by subsidies for energy savings.

The installation of the heat pump saves upward of 20,400 MWh of natural gas. However, the energy savings are reduced by the electricity consumption of the heat pump resulting in a reduction of $CO_2$ emissions of 2,980 tons each year. The heat pumps reduced the natural gas consumption of the factory's boilers by 42 %, but due to the electricity requirement of the compressors the electricity consumption increased by 11 %.

Table 5-9: Economic and environmental effects from the heat pump installation at Arla Foods, Rødkærsbro.

| | |
|---|---|
| Investment cost, heat pump | 5,150,000 € |
| Energy saving subsidies | 1,230,000 € |
| Annual operating hours | 7,800 hours/year |
| Annual O&M costs | Approximately 4 €/$MWh_{heat}$ |
| Energy savings | 16,010 MWh |
| $CO_2$ emission reduction | 2,980 tons/year |
| Energy cost savings | 640,000 €/year |

### 5.4.4 Experience from planning and operation

The cheese production is a batchwise process and as such the requirements for heating and cooling vary throughout the day and throughout each batch. However, the requirements for heating and cooling largely coincide allowing the heat pump to deliver a significant part of each when required.

Important lessons include the control of the temperature on both the hot and cold side of the heat pump. Experience from operation shows that fast changes in the temperatures from the variation in the production resulted in undesirably high condensation pressures. Thereby the buffer tanks are necessary to ensure consistent and constant temperatures on each side of the heat pump.

Additionally, early on there were significant issues with the oil and its distribution throughout the heat pump during startup. The oil issues were solved by adding a pump and heating of the oil to ensure oil temperature and pressure during startup. Neither heating nor pumping of the oil is required when the heat pump achieves normal operation conditions.

### 5.4.5 Specification of the heat pump

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 |

# 6 Summary

This reports summarizes recommendations, tools, and methods considered as best practice of industrial heat pump implementation.

The report focuses on four main sections; Heat pumps in district heating applications, integration of heat pumps in industrial applications, evaluation of heat performance and economics and four examples of industrial heat pump installations in Denmark.

The first section gives an overview of different considerations concerning the selection of heat sources and presents an example of the seasonal COP with a combination of three heat sources. The “Guidebook”-tool for integration of heat pumps in the existing district heating system is furthermore recommended, to test the influence on the heat pump COP and different aspects of the economy. Lastly, four steps of Smart Energy Integration of large-scale heat pumps are presented with the current status from a Danish test and demonstration site.

The second section presents a brief recommendation in four steps for the integration of heat pumps in industrial applications. The concept of working domains for industrial heat pumps is introduced and shown in detail for two different heat pump systems. For a given set of temperature glides in the heat source and heat sink it is shown how the optimal heat pump system can be chosen based on the highest net present value.

The third section focused on the evaluation of heat pump performance, by using the Coefficient of Performance (COP) and the related efficiency indicators. The COP defines the heat production in relation to the power consumption. Other indicators such as Carnot efficiency, Lorenz efficiency and exergy efficiency are more useful from viewpoint of thermodynamic performance, but they have different uses. In particular, the Carnot efficiency is not readily applicable for systems with temperature glide.

Two methods for estimating the investment cost of a heat pump installation are presented. One method is based on collected data from 26 heat pump projects. A range on the specific cost per MW in three intervals of installed capacity is given for five different heat pumps systems characterized by the heat source. The other presented method is based on the purchased estimated cost of single components and a fixed multiple-factor to take all other costs into account. It is noted how the final estimate is strongly dependent on the raw data, and that both methods need verification against other approaches.

The fourth section describes four heat pump installations in Denmark. The installations are chosen to cover a wide range of combinations between heat sources and heat sinks. The cases are considered as successful applications due to environmental and economic benefits, smart energy integration and replacement of individual cooling units with a central solution.

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