

# Industrial Heat Pumps in the Danish Energy System – Current Situation, Potentials and Outlook

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Heat pumps are considered to be a key technology in the transition of the Danish energy system. The technology was successfully demonstrated by several installations in district heating, while the number of industrial applications is limited. In the context of district heating, the focus of R&D is shifting to issues of upscaling and operation as well as to exploiting further benefits. For industrial applications the focus lies on simplifying the optimal integration of heat pumps and enabling higher supply temperatures. This article summarizes the current situation and gives an overview of current and future developments in the field of industrial heat pumps.

## Introduction

Denmark aims to reduce the greenhouse gas emissions (GHG) by 40% by increasing the renewable energy production to 55% of the total demand and by increasing the energy efficiency by 33% by 2030, as well as other actions. The share of renewables in the electricity production in 2017 was 64% with 43% wind power, while heat supply to a large extent is based on biomass and waste incineration, but also on fossil fuels, such as gas, oil and coal. This yielded a 33% share of renewables in the total energy consumption. These boundary conditions result in a high potential reduction of GHG emissions associated with the implementation of electricity-based heat pumps, in addition to the improvements in overall energy efficiency.

Accordingly, heat pumps play an important role in the Danish energy scenarios and there are many projects aiming to enhance the number of applications. This article gives an overview of the situation of heat pumps in district heating and industry and describe areas with requirements for further developments.

## Heat pumps in district heating

77 industrial heat pump installations with a total supply capacity of approximately 120 MW were identified, out of which 66 were in district heating. The wide distribution and the currently increasing request of heat pumps in district heating can be associated with several different factors.

Certainly, a main aspect is that district heating operators are legally obliged to consider the socioeconomic cost as the main criterion. In addition, it may be noted that the boundary conditions are becoming more beneficial for heat pumps. The electricity prices are decreasing due to the ongoing phase-out of the public service obligation and the reduction of taxes on electricity used for heating purposes. Heat pumps in district heating systems are furthermore eligible for subsidies for energy efficiency improvements.

Another aspect contributing to heat pumps being widely requested is that the technology has reached the status of being known and acknowledged by all involved par-

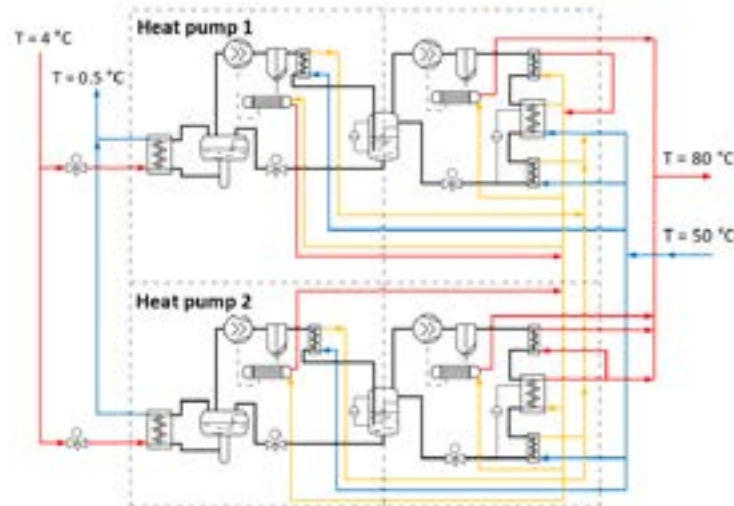


Fig. 1: System layout for the two two-stage R-717 heat pumps in the SVAF project in the configuration in which the source side uses seawater and the two heat pumps are connected in parallel

ties. The district heating network operators know the peculiarities of heat pumps and how to integrate them in the most beneficial way. The integration process is supported by publicly available information material, such as detailed guidelines and catalogues with realized cases for inspiration and planning tools [1].

Also, the solutions provided by heat pump suppliers are becoming more standardized, which reduces the engineering efforts.

It may be concluded that heat pump technology has become an established technology in district heating, and it is expected that several projects will follow during the coming years. The expected increase of applications is associated with certain challenges that translate into demand for further research and development. In the following we provide an overview of expected challenges and introduce corresponding development projects.

**Heat sources**

The increasing propagation of heat pumps for district heating supply comes with a demand for heat sources of considerable size. Copenhagen plans to become carbon-neutral by 2025 and expects a capacity of district heating supply of up to 300 MW to be covered by heat pumps. In general, there are different heat sources available with a variety of characteristics:

- » Flue gas
- » Industrial excess heat
- » Geothermal sources
- » Wastewater
- » Groundwater
- » Water from lakes and rivers
- » Seawater
- » Air

These heat sources have different characteristics regarding installation and operation [2,3] and may be dependent on geographical conditions or constrained in quantity. Flue gases from boilers and industrial excess heat are often available at comparably high temperatures and therefore constitute a promising source if located in the vicinity of the network. Geothermal sources are constrained by their location while the installation implies a certain investment risk at the current state of development. The utilization of groundwater is associated with large initial costs for pre-studies and is subject to concerns regarding the impact of the groundwater quality. Utilizing water from lakes, rivers and especially the sea is promising in Denmark, as seawater is available in abundance around all large Danish cities. Air is another potential heat source and especially used by smaller networks with limited access to other sources. However, it is often associated with large area demands, noise from the evaporator fans, and needs defrosting during cold periods.

In order to explore the possibilities with cleaned wastewater and seawater as heat sources for heat pumps with a capacity up to 100 MW, the R&D project SVAF on large heat pumps in district heating [4] was initiated. A demonstration plant as described in Figure 1 and Table 1 with a heat supply of 5 MW was constructed. The plant is configured with two two-stage heat pump units with

Table 1: Design specifications of the heat pump in the SVAF project

System	Two serially connected two-stage R-717 heat pumps with screw compressors		
Source	Medium	Seawater	Wastewater
	Temperatures	4 °C → 0.5 °C	10 °C → 4 °C
	Heat flow	3672 kW	3732 kW
Sink	Medium	District heating	
	Temperatures	50 °C → 80 °C	
	Heat flow	5194 kW	5177 kW
Performance	Power	1635 kW	1552 kW
	COP <sub>h</sub>	3.2	3.3

ammonia as refrigerant. The heat pumps are connected serially on the sink side and may be operated both in parallel and in series on the source side. The project aims to collect operating experiences with these heat sources while developing strategies to ensure an optimal operation throughout the plant's lifetime. The plant was taken into operation in spring 2019 and is undergoing performance tests at a range of capacities and temperatures, including supply temperatures of up to 90 °C.

**Tuning of operating parameters and predictive maintenance**

The large-scale heat pump tested in SVAF is subject to varying boundary conditions, e.g., seasonal variations of the supply temperatures and the heat source temperatures, as well as to shifting component performances, e.g., due to fouling in the heat exchangers. The heat pump system is relatively complex, and its control system implies 18 set points, such as desired temperatures and intermediate pressures of the cycle. Finding the optimal operating conditions is accordingly demanding and two strategies are tested.

Firstly, a validated numerical model is used to study the sensitivities and to adjust the set points [5]. This may further require a continuous tuning of the component parameters to account for the ongoing fouling, and is numerically demanding. Secondly, it is tested to analyze the sensitivities by variations of the operating plant. This gives more accurate results while a direct impact on the operation is inevitable.

The heat pump operating parameters are furthermore intended to be monitored and compared to numerical simulations to observe the conditions of selected components. These observations enable the prediction and scheduling of the required cleaning and maintenance downtimes, caused by the fouling of the heat exchangers as well as typical component wear.

**Exploiting secondary benefits of heat pumps**

Another unit, which has recently been installed in district heating in Copenhagen is located in the new development area of Nordhavn for heat supply for a warehouse and terminals for cruise ships. The unit is an 800 kW heat pump unit supplied by Johnson Controls/Sabroe. It is combined with 200 kW direct electric heating units and a heat storage of about 5 MWh. The system will supply the demand in an island configuration without connec-

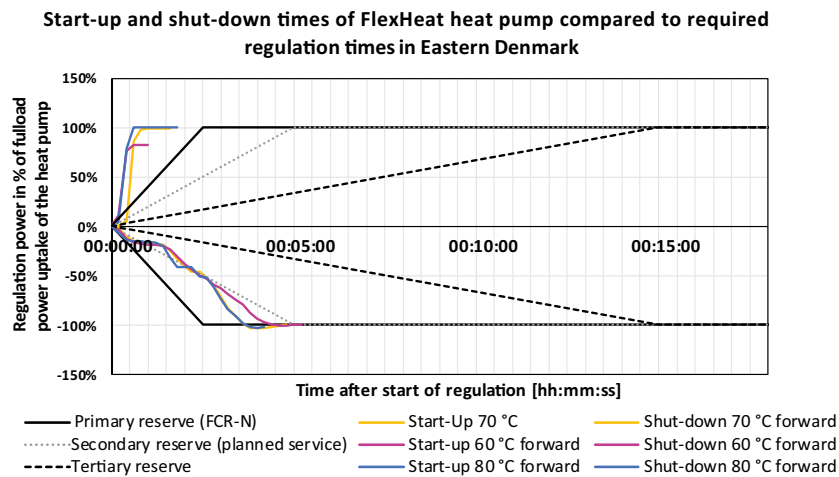


Fig. 2: Realizable and required regulation power of the heat pump in the Nordhavn Project

tion to the remainder of the city network. This makes the system well suited for testing flexible operation and thereby exploit secondary benefits, such as cost optimal operation, peak shaving of the district heating demand and delivery of ancillary services to the power system. Initial tests have been made and have shown that it is possible to deliver secondary and tertiary reserve power, as presented in Figure 2. Further development is expected for the heat pump to enable faster regulation and avoid any risks of surpassing operating limits provided by the supplier.

### Heat pumps in industry

The integration of heat pumps in industrial applications is found to be rather challenging. The boundary conditions are more diverse, there is an additional degree of freedom in the level of integration and the available technologies do not cover the entire range of applications.

### Level of integration

In addition to the diversity of the processes, there is also a certain degree of freedom in the level of process integration. The implementation of energy efficiency measures and electrifying process by means of heat pumps may be categorized by the following levels:

1. Integration on the process level without interaction among sub-processes
2. Integration on the process level with potential connection between different sub-processes
3. Integration on the utility level with different levels of interaction with the processes

Bühler et al. [6] studied the different possibilities and found that the system on utility level with a high degree of interaction with the process, i.e., different heat recovery loops and process heat supply at different temperature levels, showed the highest thermodynamic and economic performance. The integration at the process level does, however, enable a gradual implementation and may be more appropriate for integration in existing plants. The optimal placement of the heat pump unit is thereby not only dependent on technical and economic

constraints, but also on the company's strategy to implement energy efficiency measures.

### High-temperature heat pumps

In addition to the challenging integration of industrial heat pumps, there are technological challenges in the development of high-temperature heat pumps. An analysis of the demand identifies several processes that require heat at temperatures above 100 °C. Examples are sterilization processes with heat demands above 120 °C, drying processes with heat demands at up to 200 °C or higher, and chemical processes and refineries with demands of up to 300 °C. However, readily available heat pump systems are limited to supply temperatures of 100 °C to 150 °C. While natural gas boilers including a compensation for the emissions are considered as medium-term alternatives, biomass boilers and electrical boilers are considered as long-term alternatives. This raises the question what role high-temperature heat pumps are going to play in future energy scenarios.

Zühlsdorf et al. [7] analyzed the technical and economic feasibility of heat pump-based utility systems for process heat supply. The study evaluated two technologies for two case studies considering different fuel cost scenarios. There were three scenarios corresponding to the fuel cost in Denmark, Germany and Norway in 2020 and one scenario corresponding to operating own renewable electricity generators, such as windmills or PV. Both a reversed Brayton cycle using CO<sub>2</sub> and a cascade multi-stage steam compression system were considered. The two case studies were a spray dryer application for milk powder production with a supply of 8.2 MW at 210 °C and an alumina production case study with a supply of 50 MW at up to of 280 °C.

Figure 3 shows the specific levelized cost of heat for both cases and both technologies as well as for the alternative heat supply technologies. The levelized cost of heat is broken down to the contributions for investment, fuel cost, electricity cost, and an exemplifying tax for CO<sub>2</sub> emissions. The results indicate that the heat pump solutions using electricity from renewable sources are

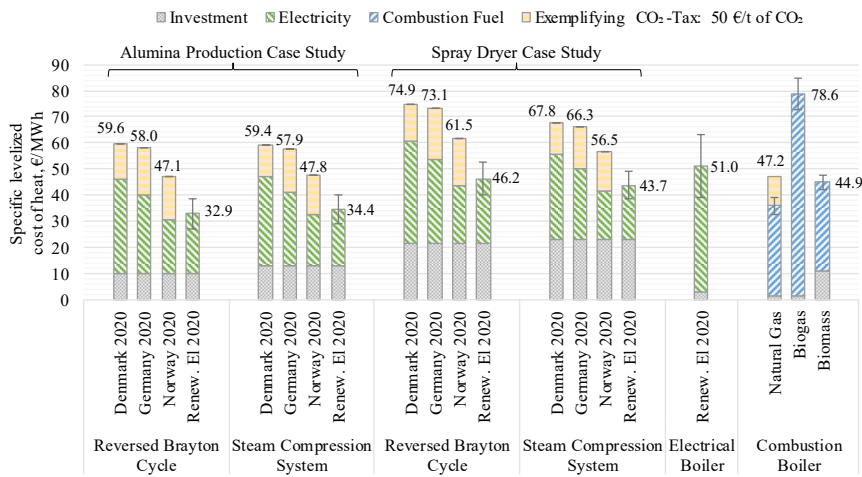


Fig. 3: Levelized cost of heat for an alumina production case study (heat source: 110 °C → 60 °C, heat sink: 140 °C → 280 °C & 50 MW) a spray dryer case study (heat source: 50 °C → 25 °C, heat sink: 64 °C → 210 °C & 8.2 MW) for a cascade multi-stage steam compression system and a reversed Brayton cycle using R-744, in comparison to electrical and combustion based boilers [7]

economically competitive compared to natural gas boilers (with a CO<sub>2</sub> tax of 50 €/ton) as well as biomass in the spray dryer case. Further, similar heat pump solutions outperform both biomass and gas boilers in the case of the alumina production.

The considered concepts were based on components from oil and gas industries that are commercially available but that were not demonstrated in the suggested concept.

## Conclusions

The number of heat pump installations in district heating is increasing significantly. The technology was successfully demonstrated in many applications and the development focus shifts to the upscaling, operational issues and exploitation of secondary benefits. In the context of industrial applications, the increasing complexity of the systems as well as technological constraints with respect to high-temperature heat supply are considered as limiting factors. However, it is expected that ongoing developments and the shifting boundary conditions will contribute to an increased number of demonstrations and enable similar dissemination as that observed in district heating.

## References

- [1] Danish Energy Agency (Energistyrelsen). Working group for large heat pumps (Rejsehold for store varmpumper). Drejebog for Store Varmepumper, Inspirationskatalog for Store Varmepumper, Varmepumpeberegner 2019. <https://ens.dk/ansvarsomraader/varme/rejsehold-store-varmpumper> (accessed May 27, 2019).
- [2] Pieper H, Ommen T, Bühler F, Lava Paaske B, Elmegaard B, Brix Markussen W. Allocation of investment costs for large-scale heat pumps supplying district heating. *Energy Procedia* 2018. 147:358–67. doi:10.1016/j.egypro.2018.07.104.

- [3] Pieper H, Ommen T, Elmegaard B, Brix Markussen W. Assessment of a combination of three heat sources for heat pumps to supply district heating. *Energy* 2019. 176:156–70. doi:10.1016/j.energy.2019.03.165.
- [4] HOFOR A/S, CTR, VEKS A/S, Innoterm A/S, Dansk Miljø & Energistyring A/S, Alfa Laval Aalborg A/S, et al. Store elvarmepumper til fjernvarme (Large heat pumps for district heating) SVAF, Phase 2 n.d. [https://energi-forskning.dk/en/projects/detail?program=All&teknologi=All&field\\_bevillingsaar\\_value=&start=&slut=&field\\_status\\_value=All&keyword=svaf&page=0](https://energi-forskning.dk/en/projects/detail?program=All&teknologi=All&field_bevillingsaar_value=&start=&slut=&field_status_value=All&keyword=svaf&page=0).
- [5] Jørgensen PH, Ommen T, Markussen WB, Elmegaard B. Performance Optimization of a Large-Scale Ammonia Heat Pump in Off-Design Conditions. *Proceedings of the 8<sup>th</sup> IIR Conference: Ammonia and CO<sub>2</sub> Refrigeration Technologies*, 2019, p. 8.
- [6] Bühler F, Zühlsdorf B, Nguyen T-V, Elmegaard B. A comparative assessment of electrification strategies for industrial sites: Case of milk powder production. *Applied Energy* 2019. 250:1383–401. doi:https://doi.org/10.1016/j.apenergy.2019.05.071.
- [7] Zühlsdorf B, Bühler F, Bantle M, Elmegaard B. Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C. *Energy Conversion and Management: X* 2019. doi:10.1016/j.ecmx.2019.100011.

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