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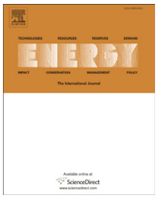

# Heat pumps in combined heat and power systems

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ABSTRACT

Heat pumps have previously been proposed as a way to integrate higher amounts of renewable energy in DH (district heating) networks by integrating, e.g., wind power. The paper identifies and compares five generic configurations of heat pumps in DH systems. The operational performance of the configurations is investigated at both local and system level considering different DH network temperatures, different fuels and different production technologies in the DH network. The results show that in terms of system performance and cost of fuel one or two configurations are superior for all of the considered cases. When considering a case where the heat pump is located at a CHP (combined heat and power) plant, a configuration that increases the DH return temperature proposes the lowest operation cost, as low as 12 EUR $MWh^{-1}$ for a 90 °C − 40 °C DH network. Considering the volumetric heating capacity, a third configuration is superior in all cases. Finally, the three most promising heat pump configurations are integrated in a modified PQ-diagram of the CHP plant. Each show individual advantages, and for two, also disadvantages in order to achieve flexible operation.

## 1. Introduction

DH (district heating) systems are used as a means to increase overall energy efficiency and reduce consumption of fossil fuels in urban areas [1,2]. Such systems are implemented in many cities of northern Europe where CHP (combined heat and power) plants provide low carbon intensive heat from co-production with electricity. In order to further reduce the fossil fuel dependency of domestic heating, the use of renewable energy sources must be considered.

Heat pumps driven by electricity from renewable sources are proposed as a step to replace fossil-fuelled boilers [3–5]. The heat pump units can be installed in individual dwellings or as production units in DH networks. An advantage of implementing heat pumps in the DH networks is that they can be used to decouple the production constraints of the co-produced products at the CHP plants. This is especially important in systems with a high heat-to-power demand [6]. Using this ability, a higher amount of intermittent renewable power production can be integrated in energy systems with CHP plants, without further reducing the possibilities for efficient production in the thermal plants [7]. In this case, a reduction in carbon emissions can be achieved by utilising renewable energy sources for the heat pump compressor and evaporator.

For optimal utilization of the renewable energy and for economic reasons, the thermodynamic performance of the heat pump technology is of major interest. In liberalized energy markets, the installed utility technologies are optimized in an effort to reduce total production cost for each individual hour of production. Thus, a unit with low production cost and synergies with base load power production equipment will experience a higher amount of operating hours than that of a unit with higher heat price or a negative impact to the system operation. The fuel consumption of operating the heat pump and the derived effects in the system will thus have a major impact on the operation.

Only a few previous works discuss the optimal operation distribution between thermal power production, co-production of heat, and heat pumps: Blarke and Lund [8] discuss the impact of two different heat sources for a parallelly coupled HP at a small decentral CHP plant considering optimal operation of the units. In Malinowska and Malinowski [9] a study of exergetic efficiency is performed on a serially coupled HP and small-scale CHP plant. Lowe [10] assesses the heat production capabilities of a CHP by considering the combination of a conventional steam turbine cycle and an HP at varying condensing temperatures of the CHP plant. He finds that heat production of CHP plant is highly effective with a performance advantage in the order of a factor of 3 when compared to the coefficient of performance of heat pumps. In contrast, Dagilis [11] discusses the possibility of combining traditional power plants

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and HP to obtain cost efficient CHP plants. None of these previous works discuss more than one configuration, or mentions the possibility of other plausible configurations.

In this paper, five basic configurations of heat pumps in district heating systems are identified. The operational performance of the configurations are investigated for different DH network temperatures, assuming that the network is supplied by a CHP plant and the heat pump is operated by electric motors. The analysis focusses on four key performance factors chosen to indicate the performance from a system perspective and differences between system performance and the performance of the heat pump. The target figures are the COP (coefficient of performance), COSP (coefficient of system performance), the VHC (volumetric heating capacity), and the cost of fuel. The five configurations are additionally examined considering the shaft power delivered by an ICE (internal combustion engine) operating on natural gas.

As another case, the DH network can be fed by surplus heat in stack gases or from various renewable sources. This case is also considered in the paper in order to make a fair comparison for the configurations where lower return temperatures may have a significant effect on the main production technology of the DH network.

### 1.1. Heat pumps in finite reservoirs

In industrial processes, and similarly in DH networks, the heat capacity of the reservoirs are finite and thus the difference in temperature between inlet and outlet of a stream, the temperature glide, may be of high importance for the efficiency of the new solutions. For heat pumps in such processes, it is important to consider the temperature glide of both sink and source in order to achieve optimal integration of the technology [12,13].

A schematic diagram of a single stage vapour compression heat pump is presented in Fig. 1. The nomenclature used matches that of several studies, e.g., Refs. [14,15]. The operating conditions of a heat pump can be evaluated based on four variables, considering the case where a fixed temperature difference is assumed for the two heat exchangers. The required variables are: the temperature of the sink process stream leaving the condenser $T_{\text{sink}}$, the temperature lift $\Delta T_{\text{lift}}$ and the process stream temperature glides from inlet to outlet in both heat exchangers ($\Delta T_{\text{sink}}$ and $\Delta T_{\text{source}}$).

By using these four temperature variables and defining an expression for heat transfer in each of the heat exchangers, state points can be found for both heat exchangers using properties of sink, source and heat pump working fluid. We define the heat transfer of the condenser and evaporator by a pinch temperature difference, $\Delta T_{\text{pinch}}$. An example of a the heat exchange processes for a pure refrigerant using finite temperatures of the reservoirs is presented in Fig. 2.

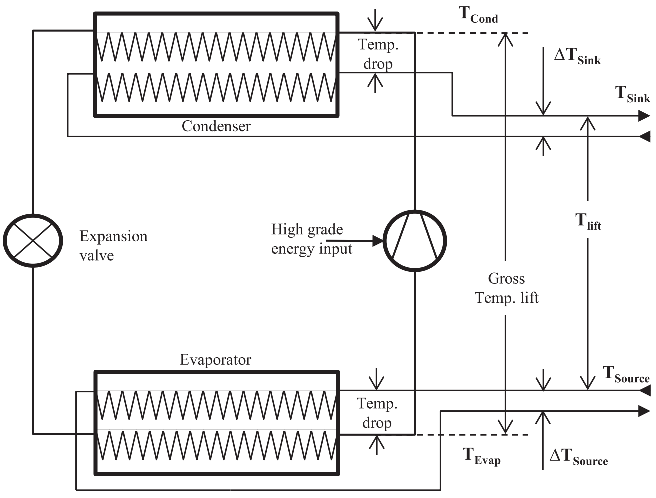

**Fig. 1.** Schematic diagram of a single stage heat pump system.

### 1.2. Heat pump configurations in a district heating network

District heating networks are not uniform in sizes or technology. The networks are built according to a large variety of specifications: temperature of demand, pressure levels, direct or indirect installations, with or without transmission lines etc. Thus, when considering the temperature levels of forward and return lines in DH networks, a span is needed rather than a fixed temperature. In a Danish context the forward temperature ($T_{\text{DH,Forward}}$) varies from 70 °C to 120 °C [16,17] mainly depending on size of the network and its commissioning year. The corresponding network return temperatures ($T_{\text{DH,Forward}}$) range from 35 °C to 55 °C. For the present study three different temperature levels of the network have been chosen as representative of the full range of temperatures. The temperature data is presented in Table 1.

Besides the temperature levels of the DH network, additionally two temperatures can be considered: the highest temperature of the available renewable heat source and the temperature of the demand of heat, which may be considered as the highest temperature of a finite heat capacity flow.

The temperature of the source is dictated by the type and location of the installation [18]. Smaller systems operate with source temperature according to the available media at the location of the heat demand. By using a DH network, larger installations can be located near heat sources of elevated temperatures (compared to ambient conditions), such as sewage water, industrial waste heat, power plants etc. Most of these heat sources tend to have a low yearly temperature variation and a finite heat capacity rate of the stream. In some cases the heat source can also be ocean or lakes

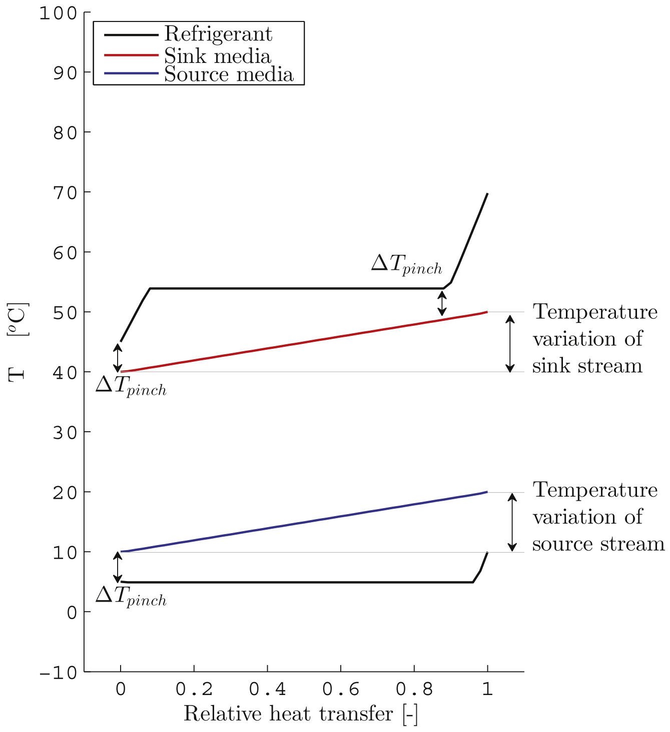

**Fig. 2.** Schematic diagram of condenser and evaporator in a single stage heat pump system. The transferred heat is normalised for each of the heat exchangers.