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Integration of Air to Water Heat Pumps into Industrial District Heating Substations

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The paper aims to evaluate a potential of integration of air to water heat pumps in existing district heating substations, especially for supply of heat in an industrial sector. Facts and data from the literary search support the idea that the air source heat pumps (ASHP) should be more often used as a supplementary source of heat in district heating substations. Heat pump is fully integrated in the system and thus efficient for the industrial practice only if the actual return on investment (ROI) is positive. The ROI depends especially on investment cost, average COP, on prices of electrical energy and on the price of heat from district heating. The paper presents a case study of effective integration of 25 kW ASHP into an industrial district heating substation. Sensitivity analysis is conducted to study all the above mentioned aspects of the integration.

1. Introduction

The paper focuses on air to water heat pumps, often called air source heat pumps (ASHP). ASHP units have found wide-spread application in recent decades, thanks to their high energy efficiency. Common applications of ASHP in the residential sector include space heating and water heating. In the commercial sector, the basic technologies used are similar to those in residential sector, although usually on a larger scale (IEA, 2011). Efficiency, or coefficient of performance (COP), is the most important operating characteristic of a heat pump. COP of today's ASHP exceeds 4, which means 4 units of heat produced for each unit of electrical energy consumed (that is 1 kWh_e consumed provides 4 kWh_t of output heat).

Heat pumps are more and more often discussed as a part of district heating systems (DHS). Main function of a DHS is to supply energy for heating and for production of domestic warm water for customers. The system may involve only few houses as well as large municipalities. District heating is suitable for residential as well as for commercial buildings. In many cases, district heating systems also satisfy low-temperature industrial heat demands. The main idea behind the use of district heating for low-temperature industrial heat demands is to utilize the surplus heat and to better organize the heat production so that it is more efficient than individual production (Euroheat and Power, 2011).

The older concept of centralized plants has been gradually replaced by a number of heat sources. Heat pumps are also an integral part of the latest concepts of DHS. However, papers in expert journals often tend to deal only with high-power heat pumps (Lund and Persson, 2016). And yet, the integration of ASHP may be fully justified, as this paper argues. The authors here discuss the financial aspects of ASHP from the perspective of the heat consumer that is the industrial business. The authors further aim to evaluate the potential of integration of air to water heat pumps in existing district heating substations with a specific configuration: ASHP is integrated into the existing DH substation as a supplementary source to cover part of the hot water supply. DHS is still the main heat source in this proposed configuration. Water from ASHP covers supply of low-temperature water (< 50 °C) and/or supply of hot water outside working hours.

Integration of ASHP has to face technological and operational restrictions. Actual operational COP is reduced by various factors, including supply of high-temperature hot water and lower ambient air temperature. But these setbacks may be compensated if the heat pumps are part of the DH substation. Heat pump is fully integrated into the system and efficient for the industrial practice only if the actual return on investment (ROI)

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is positive. The ROI depends especially on COP, investment cost, prices of electrical energy and price of heat from district heating. Sensitivity analysis of ROI for COP, investment cost, prices of electrical energy and price of heat from district heating is presented in this paper.

2. Heat pumps as a part of centralized district heating systems

Heat pumps provide space heating (and cooling), and hot water in building. They are tested, commercially available technologies, but their share in the global heating market is small (IEA, 2011). They are highly efficient. In contrast to water-to-water heat pumps, advantages of ASHP include easier integration into the system at lower performance since installment of expensive ground or water loops is not necessary. Common operational COP of existing ASHP reaches excellent values of 4, and the most advanced units reach for 5 or even 6. Performance improvements have been achieved through advances in individual components (heat exchangers, compressors or defrosting system) and better overall system integration (IEA, 2011).
COP is affected by many aspects; and users may, to a certain degree, adjust ambient air temperature (that is low-potential heat source) and required output water temperature. Maximum output water temperature must be 50–60 °C to maintain a plausible COP (Wiltshire, 2016). Integration of the unit has to further consider the differences between input and output temperature, the so called temperature lift. The higher the difference, the lower the efficiency of the system (IEA, 2011).
ASHP is a technology that may efficiently expand the DH substation. Low temperature water leaving the ASHP complies with the concept of the so called Fourth-generation district heating systems (4^{th} GDH, Lund et al., 2014). This new generation of DHS brings decreased temperature of heating water, which results in reduced heat loss, compared to previous generations. The system may use diverse sources of heat, including low-grade waste heat, and may allow consumers to supply heat as well (UNEP, 2014). Heat pumps are an integral part of the 4^{th} generation systems also thanks to their ability to convert electricity to heat at high efficiencies in times of surplus electricity generation. Customers with hourly variable electricity pricing may experience significant savings since the heat pumps, combined with storage tanks, may use cheaper electricity, for example during night (Laveyne, 2014). Concept of the 4^{th} GDH systems includes integration of heat pumps in district heating substations to increase temperature of domestic hot water by cooling down the return temperature (Lund et al., 2014).
However, the new generation of DHS has to find wide application in the industrial practice and meanwhile, we need to decrease energy intensity in existing DHS. District heating represents 12 percent of heat demand in the EU (Connolly, 2012). The share is much higher in Russia and China. Existing DHS use ca. 100 °C water; 120 °C pressurized water systems or steam distribution are no exception either. District heating is suitable for residential as well as for commercial buildings. But it is often a source of heat for industrial businesses, too. The high energy intensity of industrial consumers makes them ideal to connect to district energy. Numerous current industrial customers demand high-temperature water (> 90 °C).
These above mentioned conditions are no obstacle for efficient integration of the heat pumps. High water temperature from DHS does not have to cover processes that can do more efficiently with low-potential sources. Processes that require 50 °C water may be efficiently covered with heat pumps. ASHP units could be further employed for preheating of cold water. Also, the DH substation may be shutdown during outside working hours period, and ASHP units may then function as the main source of heating and of hot domestic water.
Profitability of the ASHP is evaluated in this paper in terms of a typical industrial business complex that has a district heating substation supplying 100 °C water. The business is further the end-user of the heat. However, the conclusions made in this paper are valid for any type of industrial business with centralized heat production that is able to determine its heat production costs per GJ of heat.

3. Integration of ASHP into District Heating Substations

3.1 Types of Configuration

There are three basic types of ASHP configuration using ambient air as a low-potential heat source in district heating systems:

- Heat supplied into input pipe DHS (SF)
- Heat supplied into return pipe DHS (SR)
- Heat supplied to the consumers/process (SD)

Figure 1 illustrates, in compliance with Ommen's methodology (2014), all three configurations where the white arrows indicate the temperature lift from T_{Source} to T_{Sink}. The configurations are termed with the initial letter of both the source and the sink temperature level as SF, SR and SD.

ASHP in the SF configuration uses ambient air (T_{Source} = 5 – 25 °C) to heat the water to the temperature required in the district heating substation. This configuration is employed when the temperature of supplied water from the DHS is required to be low; it will surely be applied in 4th GDH. If the supplied temperature is required to reach ca. 90 °C, the said configuration is not plausible since the common ASHP do not supply high temperature output water.
In terms of standard ASHP, SR configuration makes more sense. Heat pump is used to preheat the return line, for example to 50 °C; the COP may be high. Benefits of this design for the customers comes from decrease of total consumption. However, for DHS, initial temperature increase of the return line is not desired. Part of the energy is likely to be wasted in line loss. Decrease in main source efficiency is also likely.
The last SD configuration employs ambient air (T_{Source} = 5 – 25 °C) for preheating of water to the temperature required by a given device or process. SD does not require a DH network in order to operate. The location of a heat pump is decentral as the heat is delivered directly to the consumer (Ommen, 2014). This configuration presents highest flexibility to the operators. However, integration of the units must comply with specific operating conditions. Key factor here is to identify processes that will consume the produced heat of the given temperature.

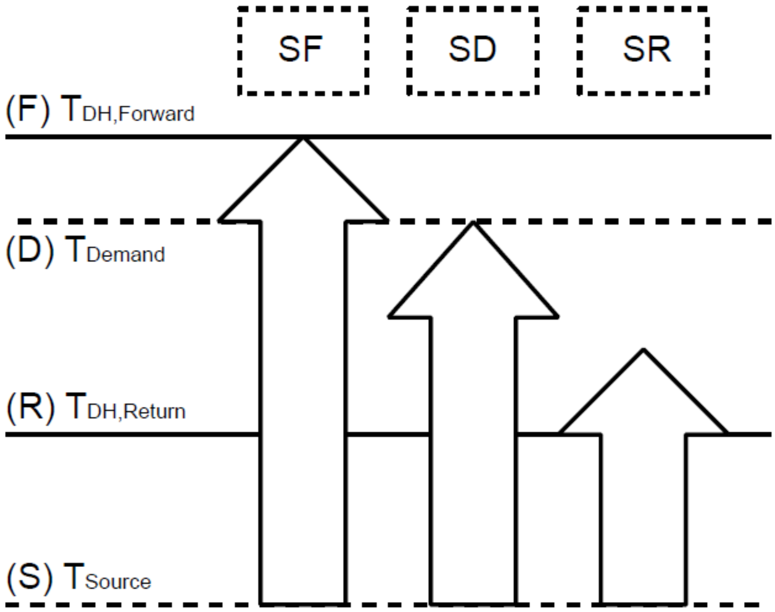

Figure 1: Possible configuration of ASHP into a district heating substation (Ommen, 2014)

In order to analyze economic aspects of ASHP integration into DH substation, a case study was performed. This case study shows efficient integration of ASHP in an industrial facility.

3.2 Case study

The case study analyses an industrial facility in the Czech Republic; its annual heat energy consumption equals 420,000 kWh_t (1,512 GJ). Let's assume that the facility consumes heat from the DHS and its energy system is to be extended with a 25kW ASHP. Ambient air is used as a low-potential heat source for the heat pump. Expected annual operating time of the heat pump (1,680 h/y) is 8 hours a day for the period of 10 months. The heat pump is running only when the facility is operating. The ASHP is shutdown for the coldest 2 months of the year so that the COP remains acceptable. Under these conditions, the ASHP covers 10 percent of the total annual heat consumption of the facility. ASHP is integrated into the system as a stand-alone circuit, and supplies 45 °C hot water into the technology (Figure 2). The most universal SD configuration was selected.
For SD configuration, consumers/processes must consume the produced heat of the given temperature. This type of heat consumption is present in most facilities. Washing and cleaning processes are just some of the examples.

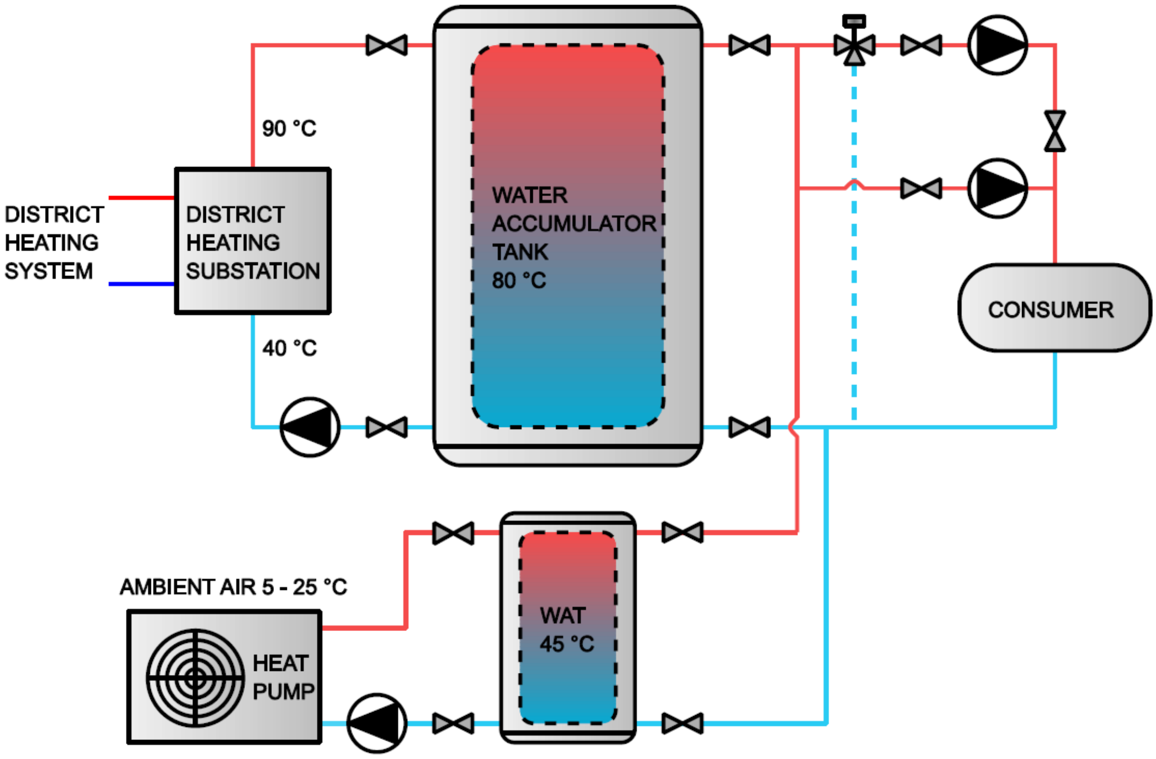

Figure 2: Diagram of the proposed configuration of ASHP with heat stored in a storage tank (WAT)

Heat may be used for preheating of cold water or for heating of hot domestic water. Initial data of the case study are given in Table 1, and input data for calculation of ROI are given in Table 2.

Table 1: Main data characterizing the installation – input data for the case study

Parameter	Value
Heat consumption of the industrial facility [kWh_t/y]	420,000
Supplied temperature from DH substation ($T_{DH,Forward}$) [°C]	90
Return temperature into DH substation ($T_{DH,Return}$) [°C]	40
Cost of purchasing energy from DHS [€/GJ]	20.53
Cost of purchasing electrical energy [€/kWh_e]	0.082
Heat pump performance [kW]	25
Average ambient temperature [°C]	15
Required temperature from the heat pump [°C]	45
Average COP [°C]	3
Operating time of ASHP system [h/y]	1,680
Electrical energy consumption [kWh_e/y]	14,000
Heat supplied from ASHP [kWh_t/y]	42,000

Quoted prices apply to large-scale consumers of electrical energy who required more than 500 MWh/y of electrical energy in the Czech Republic in 2014 (Eurostat, 2015). Heat price from DHS was determined as an average market price of the heat produced by various Czech heat sources, VAT exclusive (MPO, 2015).

Table 2: Input data for the ROI calculation

Parameter	Value
Total ASHP plant investment costs [€]	11,000
Income from production of heat energy in ASHP [€/y]	3,108
Operating costs of ASHP system (electricity consumption) [€/y]	1,148
Annual revenues from ASHP system [€/y]	1,960
ROI [y]	5.6

Calculation of the payback period (ROI) was based on average exchange rates of euro in 2015. All the prices are VAT exclusive. Final payback period was ca. 5.6 years; this value seems to be plausible for the investors. Until the heat pump is fully paid up, it will be in operation for 9,400 h, which is a quarter of the expected total life cycle.
It is clear that the calculated ROI significantly depends on concrete operating conditions at the installation site as well as on heat pump parameters. Key factors affecting the ROI include COP of the heat pump and investment costs of the integration of the unit into the system. Economic factors, such as prices of electrical energy and prices of heat from district heating in the facility, cannot be neglected either. The following part presents sensitivity analysis for the above mentioned factors.

4. Conditions for acceptable payback period

Four basic factors affecting ROI have been analyzed using sensitivity analysis (Figure 3):

- COP of ASHP
- total investment cost of ASHP
- prices of electrical energy
- price of heat from district heating

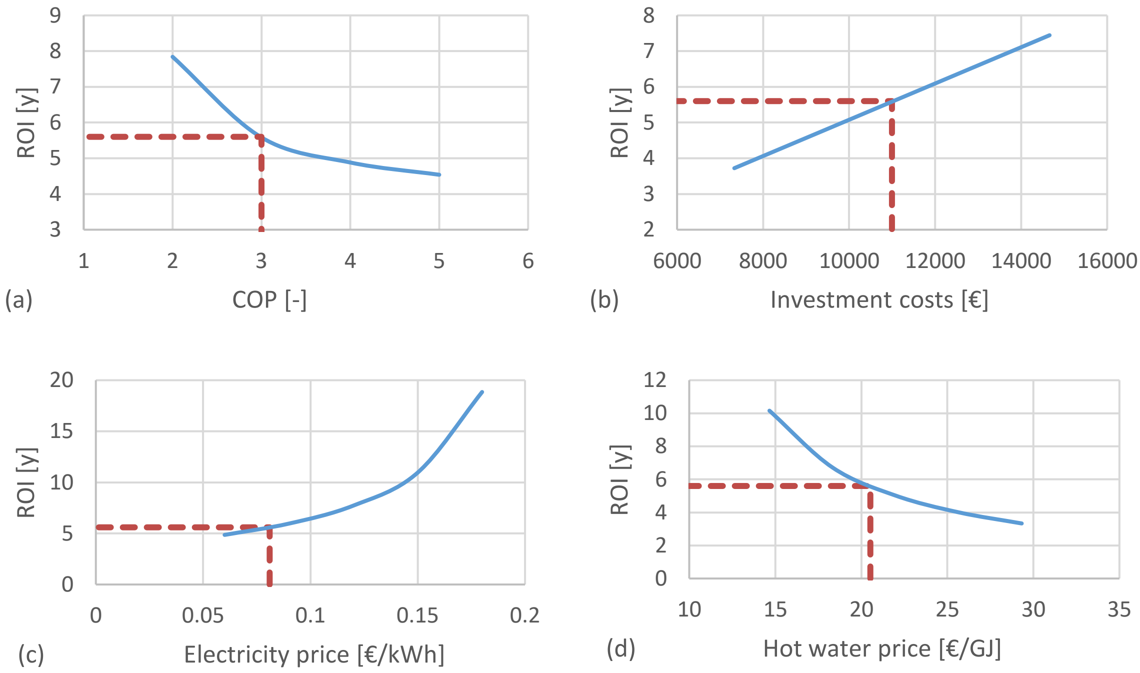

Figure 3: Sensitivity analysis for ASHP payback period (ROI) for: a) COP, b) investment costs, c) electricity prices and d) hot water price.

Average annual COP of ASHP is affected especially by ambient temperature and required temperature of the water leaving the ASHP. COP that can be achieved in relation to these two factors is commonly given in the specifications of every product. High ambient air temperature and low temperature of water leaving the ASHP are good for plausible COP. If the limit value set for ROI is 10 years, then the average annual COP should not drop below 3 (Figure 3a). Lower values of COP result in increase in ROI. COP is further commonly associated with investment costs. Low-end units with less efficient compressors and heat exchangers made from poor materials usually mean lower COP than COP of high-end products. In terms of ROI, the investment costs may not be a significant factor (Figure 3b). More expensive products have a longer life.
On the other hand, prices of electrical energy have a major impact on economics of the facility (Figure 3c). Prices notably differ in relation to the concrete siting of the facility and its size. Range of axis x on the chart in Figure 3c covers the whole scale of electrical energy prices for large industrial plants in EU countries in 2014. Electricity is considerably cheap in Sweden (0.067 €/kWh$_e$), while Italy has some of the highest prices (0.174 €/kWh$_e$) (Eurostat, 2015). If the acceptable ROI is 10 years, the boundary value for electricity price is 0.14 €/kWh$_e$ (Figure 3c). Electricity prices fluctuate under this line in most of the European countries. Price of heat

from existing sources is another economic factor to be considered. This may be DHS or an in-house boiler house. Payback period under 10 years requires heat prices from DHS not lower than 15 €/GJ (Figure 3d).

5. Conclusion

Topic of this paper corresponds with IEA objectives to improve heat pump installations for specific applications to achieve higher seasonal efficiency in wider capacity ranges (IEA, 2011). The paper discusses economic factors of ASHP that has been newly integrated in an industrial facility that had been supplied with heat only from DH substation so far. The case study presents an efficient integration of a 25kW ASHP into the energy system of the facility. The purchase price was 11,000 € and operating time was 8 hours a day for the period of 10 months (without the two coldest months of the year). If the average COP equals 3, prices of electrical energy equal 0.082 €/kWh and price of heat coming from DHS equals 15 €/GJ, the payback period is 5.6 years. Sensitivity analysis showed that prices of electrical energy are the decisive factor for economic plausibility of the ASHP as part of the DHS. The prices vastly differ among particular EU states. But they scarcely exceed 0.14 €/kWh; above this line, ROI rapidly rises.

Other factors (COP, purchase price, heat price from DHS) were set in the study so that they may be easily achieved in most European facilities. The sensitivity analysis proved that the ROI may be much lower. The decrease may be attained by increasing the operating time of ASHP or by using waste heat from industrial processes as a low-potential heat source. It is obvious that ASHP has a great potential for integration into industrial facilities.

In compliance with the concept of the 4^{th} GDH, economics of the facilities should be further evaluated in terms of the heat supplier. Some argue that alternative scenarios of heating with ASHP may have a negative impact on existing DHS and may not be that beneficial in terms of CO_2 emissions either (Mashatin, 2014). Their overall primary energy efficiency depends on efficiency of electricity production they use (IEA, 2011).

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Reference

Connolly D. et al., 2012, Heat Roadmap Europe 2050: First Pre-study for the EU27, Euroheat & Power, Brussels.

Euroheat & Power, 2011, District Heating in Buildings, Brussels, Belgium.

Eurostat, 2015, Energy price statistics <ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics > accessed 18.04.2016.

IEA (International Energy Agency), 2011, Technology Roadmap < www.iea.org/publications/freepublications/publication/buildings_roadmap.pdf > accessed 05.04.2016.

Laveyne J. I., Zwaenepoel B., Eetvelde G. V., Vandevelde L., 2014, Increasing Economic Benefits by Load-Shifting of Electrical Heat Pumps, Chemical Engineering Transaction, 39, 1513-1518, DOI: 10.3303/CET1439253.

Lund H., Werner S., Wiltshire R., Svendsen S., Thorsen J. E., Hvelplund F., Mathiesen B. V., 2014, 4th Generation District Heating: Integrating smart thermal grids into future sustainable energy systems, Energy, 68, 1-11, DOI: 10.1016/J.ENERGY.2014.02.089.

Lund R., Persson U., 2016, Mapping of potential heat sources for heat pumps for district heating in Denmark, Energy, 1-10, DOI: 10.1016/J.ENERGY.2015.12.127.

Mashatin V., Link S., Siirde A., 2014, The Impact of Alternative Heat Supply Options on CO_2 Emission and District Heating System, Chemical Engineering Transaction, 39, 1105-1110, DOI: 10.3303/CET1439185.

MPO (Ministry of Industry and Trade of the Czech Republic), 2015, Posouzení potenciálu vysoce účinné kombinované výroby tepla a elektřiny a účinného dálkového vytápění a chlazení za Českou republiku <ec.europa.eu/energy/sites/ener/files/documents/Art%2014(1)%20assessmentCzechrepublic.pdf> accessed 12.04.2016.

Ommen T., Markussen W. B., Elmegaard B., 2014, Heat pumps in combined heat and power systems, Energy, 76, 989-1000, DOI: 10.1016/J.ENERGY.2014.09.016.

UNEP (United Nations Environment Programme), 2014, District Energy in Cities < www.unep.org/energy/portals/50177/DES_District_Energy_Report_full_02_d.pdf> accessed 12.04.2016.

Wiltshire R., 2016, Advanced District Heating and Cooling (DHC) Systems, Cambridge, United Kingdom.