# Industrial Heat Pumps, Second Phase

IEA Heat Pump Technology (HPT) Programme Annex 48

## Task 4:
## Training materials for industrial heat pumps

**Final Report**

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Prepared by
A. Arnitz, R. Rieberer
Graz University of Technology
Institute of Thermal Engineering
Inffeldgasse 25/B, 8010 Graz, Austria
Contact: rene.rieberer@tugraz.at

V. Wilk
AIT – Austrian Institute of Technology GmbH
Center for Energy
Giefinggasse 2, 1210 Wien, Austria
Contact: veronika.wilk@ait.ac.at

# Contents

# 1 Integration of heat pumps in industrial processes

Heat pumps allow for waste heat recovery, increase of energy efficiency and emission reduction. With heat pumps, low grad waste heat is upgraded into valuable process heat. The application examples elaborated in Task 1 show several well-suited heat sources for industrial heat pumps, such as waste heat from chillers (ca. 30°C), waste heat from process cooling (cooling water, ca. 50°C), waste water (20 – 40°C, also contaminated), off gas (60 – 80°C, may contain high humidity and contaminants).

Heat pumps in industry are currently most commonly used to provide hot water for internal process needs or space heating. Heat pumps that supply heat around 80°C, which is required for these applications have been available on the market for many years. Heat pumps that use industrial waste heat and supply heat in the MW range generally feed into district heating networks. The number of heat pumps in district heating networks is increasing as a result of the further development of heat pumps to higher heat supply temperatures using new refrigerants. In current installations, the flow temperature of the district heating systems is between 60 and 95°C.

A structured guideline how to select suitable heat sources and sinks for industrial heat pumps is available in Task 3. In this report, the next steps are presented in detail. When integrating a heat pump into an industrial process, certain decisions have to be taken carefully to maximize the benefits. During the design phase, the appropriate output must be determined. Furthermore, the hydraulic integration of the heat pump into the industrial process must be defined and has to be combined with a suitable control strategy. In addition to that, techno-economic evaluation of industrial heat pumps is presented. It includes different approaches for estimating the capital expenditure of heat pumps and the expected operating costs, as well as calculation of CO2 emissions and primary energy consumption. It is used to compare industrial heat pumps to other heat suppliers to quantify the benefits.

This report is intended to inform planners of energy supply systems, energy managers, consultants working in the energy sector and anyone wishing to familiarise themselves with the integration, design and control of heat pumps for industrial processes.

## 1.1 Design

When using heat pumps for industrial applications, it must be determined at the beginning of the design process whether the heat pump should be designed for a certain heat source (e.g. available heat from a process to be cooled) or a certain heat sink (e.g. required useful heat for a process to be heated). Usually, the capacity of the heat pump will be limited thereby. The heat pump will not produce more power than can be taken from the heat sink or supplied by the heat source. Seasonal variations in capacity must also be taken into account.

Figure 1-1 shows the results for two different designs. A COP of 5 is assumed for the heat pump, it is a compression heat pump that uses electrical energy to convert process heat at low temperature into medium temperature heat.

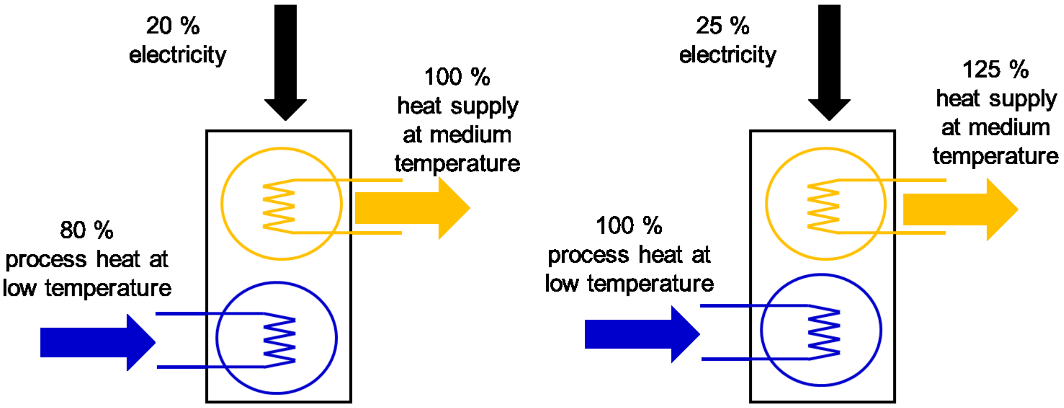


Figure 1-1: Energies to be supplied and discharged according to the design for a specified heat source or heat sink capacity

In analogy to compression heat pumps, the same design considerations can also be applied to absorption heat pumps. Absorption heat pumps use thermal driving energy at high temperature to convert process heat at low temperature into medium temperature heat supply. If the heat pump is integrated into an existing process, it must first be determined whether the heat output of the heat source or the heat output of the heat sink limits the size of the heat pump. If an existing heat generator is used to provide the driving energy for the heat pump, the limitation of the heat pump size can also be limited by the available driving heat output. The influence of the design on the heat input and output of a heat pump with an assumed $COP_h$ of 1.8 is shown in Figure 1-2.

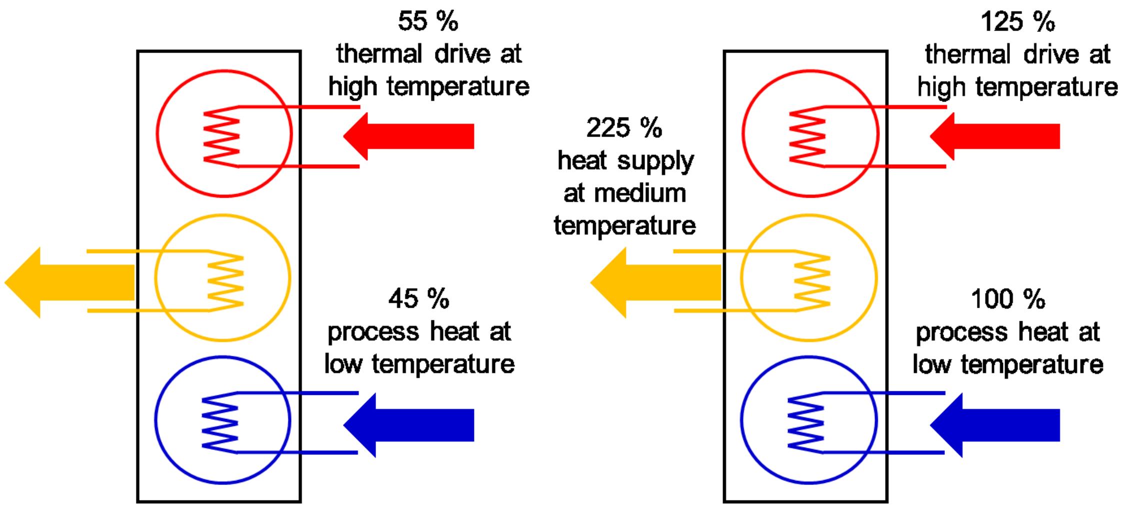


Figure 1-2: Energies to be supplied and dissipated according to the design for a specific heat source or heat sink capacity

## 1.2 Hydraulic concepts

When integrating the heat pump hydraulically, different requirements must be considered. The following requirements can be met by the heat sink or heat source.

- A certain minimum heat sink outlet temperature for the process to be heated
- A certain maximum heat source outlet temperature for the process to be cooled
- A certain minimum heat source outlet temperature (risk of freezing)
- High temperature difference on the source or sink side
- Use of several heat sources
- Combination of the heat pump with other heat suppliers
- Separation of the heat source and heat sink circuit of the heat pump from the heat transfer medium of the heat source or heat sink (prevention of contamination in the condenser and evaporator)

When selecting a suitable hydraulic concept, the requirements of the heat pump must also be taken into account in some cases. Most heat pump manufacturers set limits for the volume flows on the source and sink side, which must be met, otherwise the heat pump switches off. The compressor also has defined operating limits that are illustrated in operating envelop diagrams provided by the manufacturers, such as:

- Heat sink temperature: If the high heat sink temperature is too high, it can lead to an overload of the motor due to the too high pressure ratio. In addition, an excessively high temperature of the refrigerant can occur at the compressor outlet, which can lead to problems with seals and the oil. Furthermore, the component strength of the compressor is designed for a maximum pressure, which must not be exceeded.
- Heat source temperature: If the heat source temperature is too high, it can lead to a higher evaporation pressure and thus a higher suction gas density. As a result, a larger mass flow is conveyed by the compressor and there is a risk of overloading the motor. Furthermore, in the case of suction gas-cooled engines, engine cooling is no longer guaranteed if the suction gas temperatures are too high.
- Evaporation temperature: Too low evaporation temperatures leadsto a lower density, which leads to a reduced cooling capacity, especially with suction gas-cooled compressors, and can therefore also cause the engine to overheat.

To comply with the requirements of the compressor, a mixing circuit is usually installed upstream of the evaporator. For this purpose, the inlet temperature of the cold water into the evaporator is reduced on the side of the heat source, thus avoiding an excessively high temperature at the inlet to the evaporator (see Figure 1-3).

It may also be useful to install a mixing circuit upstream of the condenser (see Figure 1-3). For example, fluctuating return temperatures occur, and the heat pump manufacturer requires a minimum water volume flow through the condenser. Then a mixing circuit can increase the inlet temperature of the water into the condenser and ensure that the desired temperature is reached at the outlet from the condenser.

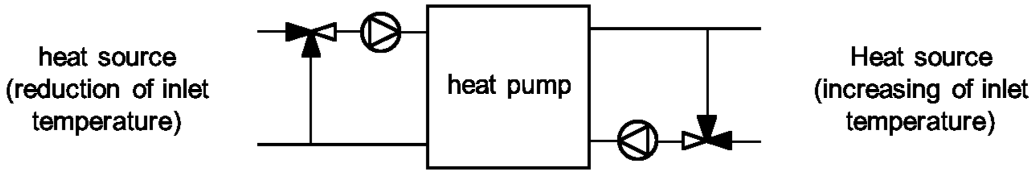


Figure 1-3: Use of mixing circuits to maintain the maximum evaporator inlet temperature or to ensure a minimum useful temperature of the cooling water at the outlet from the condenser.

Large temperature differences of the heat source or heat sink can be achieved if several heat pumps are connected in series (see Figure 1-4). If both the heat sink and the heat source require a large temperature difference, the two condensers and the two evaporators of the heat pumps can be connected in series. The water flow is countercurrent, (see Figure 1-4, left), as this results in approximately equal temperature differences between the condensation and evaporation temperatures in the respective heat pumps. If a large temperature difference is only required for the heat sink or the heat source, only the condensers or the evaporators are arranged in series, the other heat exchangers are used in parallel. In addition to that, a subcooler can be used, if a large temperature difference is only required for the heat sink.

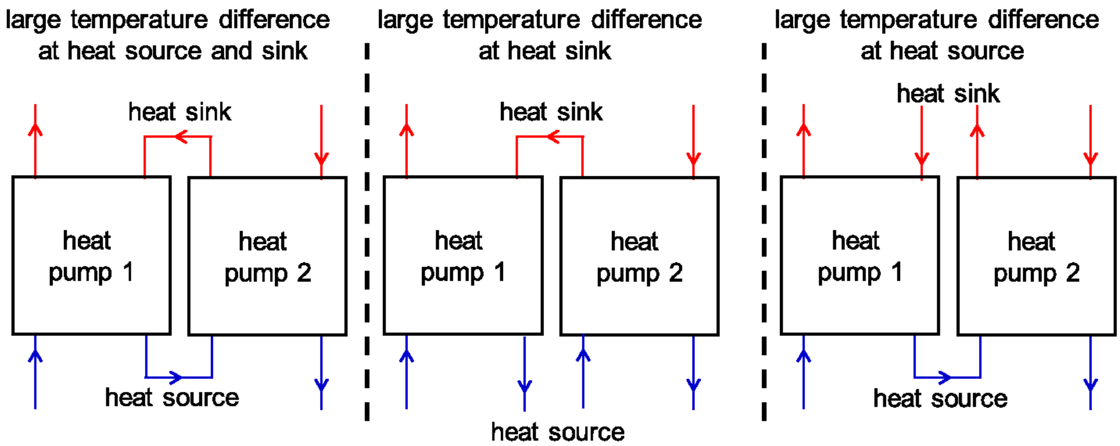


Figure 1-4: Connection of several heat pumps for a high spread on the heat source and/or heat sink

If the heat transfer medium of the heat source or heat sink is contaminated, it is advisable to install a separating heat exchanger to avoid frequent maintenance work on the heat pump or replacement of the evaporator and/or condenser due to damage (Figure 1-5). However, it should be noted that the heat pump is operated at a higher temperature lift due to the temperature differences of the heat exchangers. This reduces the $COP_h$ and thus increases the operating costs.

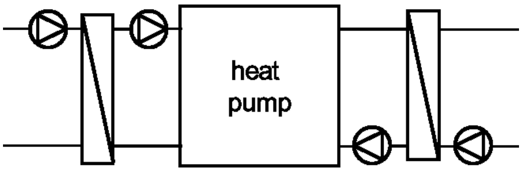


Figure 1-5: Using a separating heat exchanger to avoid contamination of the condenser and evaporator of the heat pump

Heat pumps often use several heat sources or supply several heat consumers together with another heat supplier. In this case, the use of a thermal water storage tank as a hydraulic separator is recommended (see Figure 3 6). By using a hydraulic separator, the volume flows can be adapted to the requirements of the respective heat source, heat sink, heat pump or additional heat supplier. Mutual interference is avoided.

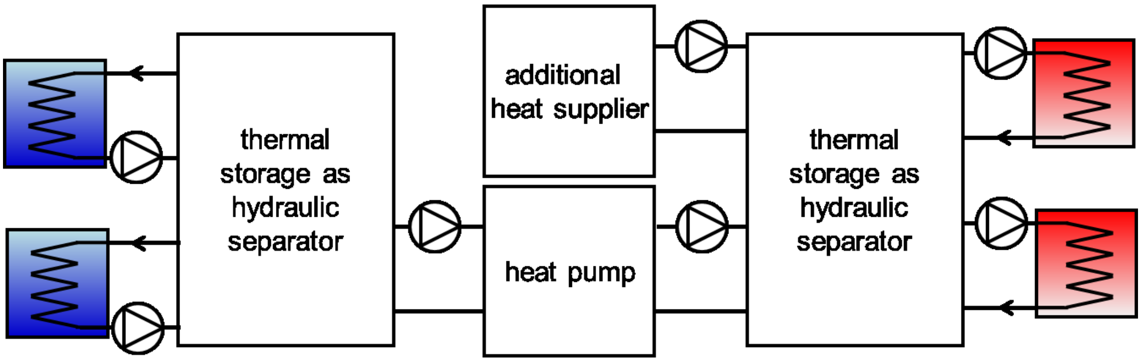


Figure 1-6: Use of several heat sources or heat sinks by hydraulic separators

## 1.3 Control strategies

Conventional heat pumps are typically controlled by clocking to adjust the provided heating capacity (on/off control). Now, frequency converters that change the speed of the compressor are gaining importance.

Frequency converters will also be the most frequently selected control for industrial heat pumps. It should be noted that either the heat source or the heat sink water outlet temperature can be selected as the controlled variable. When heat pumps are used in industrial processes, however, the heat source and sink outlet temperatures must usually follow a certain setpoint. For the temperature that is not controlled by the speed of the compressor, a different control option must be selected, such as:

- Influencing the inlet temperature by means of a mixing circuit (see Figure 1-3)
- Change the volume flow of the heat source or heat sink

With absorption heat pumps, the following control variables can be used to control the output. If the volume flow and temperatures in the cooling and cold water circuit are specified by the process conditions, the solvent volume flow, the hot water inlet temperature and the hot water volume flow are available for controlling the heating capacity.

# 2 Techno-economic evaluation

## 2.1 Capital expenditures

Manufacturer information on capital expenditure on industrial heat pumps is not publicly available. The main reasons are the individual designs with regard to refrigerant cycle, size of installed components, refrigerant used, hydraulic connection and control.

### 2.1.1 Capital expenditures of the heat pump

The data available in the literature are based on individual research and indicate specific investment expenditure in EUR/$kW_{th}$ as a function of the nominal heating capacity ($\dot{Q}_{th,nom}$) in kW. Table 2-1 gives an overview of the available approaches and Figure 2-1 shows the specific capital expenditures as a function of the nominal heating capacity. Most approaches were obtained by persons from the Institute for Energy Economics and Rational Use of Energy (IER) in Stuttgart (Wolf et al., 2017; Wolf et al., 2014; Wolf, 2017); in addition, approaches from an online publication of the Federal Ministry of Transport, Building and Urban Affairs (BMVBS, 2012) are listed.

Table 2-1: Capital expenditures for different types of heat pumps

| Type | Heating capacity, $kW_{th}$ | Capital expenditures, EUR/$kW_{th}$ | Reference |
|---|---|---|---|
| Compression heat pump | 500 | 450 - 700 | Wolf et al., 2017, S. 28 |
| Compression heat pump | 10.000 | 250 - 400 | Wolf et al., 2017, S. 28 |
| Absorption heat pump | 500 | 500 - 800 | Wolf et al., 2017, S. 28 |
| Absorption heat pump | 10.000 | 300 - 450 | Wolf et al., 2017, S. 28 |
| Compression heat pump (brine/water) | 10 - 180 | $2610.2 \cdot \dot{Q}_{th,nom}^{-0,558}$ | Wolf et al., 2014, S. 37 |
| Compression heat pump (water/water) | 10 - 180 | $1520.7 \cdot \dot{Q}_{th,nom}^{-0,363}$ | Wolf, 2017, S. 24 |
| Compression heat pump (air/water) | 10 - 160 | $2717.1 \cdot \dot{Q}_{th,nom}^{-0,435}$ | Wolf, 2017, S. 24 |
| Gas engine heat pump (air/water) | 25 - 90 | $3533.8 \cdot \dot{Q}_{th,nom}^{-0,454}$ | Wolf, 2017, S. 24 |
| Absorption heat pump | 25 - 350 | $902.9 \cdot \dot{Q}_{th,nom}^{-0,172}$ | Wolf, 2017, S. 32 |
| Compression heat pump (water/water, reversible) | 20 - 300 | $3221.5 \cdot \dot{Q}_{th,nom}^{-0,306}$ | BMVBS, 2012 |
| Compression heat pump (water/water) | 20 - 300 | $1140.3 \cdot \dot{Q}_{th,nom}^{-0,174}$ | BMVBS, 2012 |

The specific capital expenditures for heat pumps were collected for heat pumps with different nominal outputs. Wolf (2017, p. 24) cites stagnating specific capital expenditure in the range 150 to 200 EUR/$kW_{th}$ for heat pumps in the large output range (> 300 $kW_{th}$). For two-stage heat pumps, Wolf (2017, p. 24) recommends using an additional factor of 1.2 to 1.4 to take account of the higher system costs.

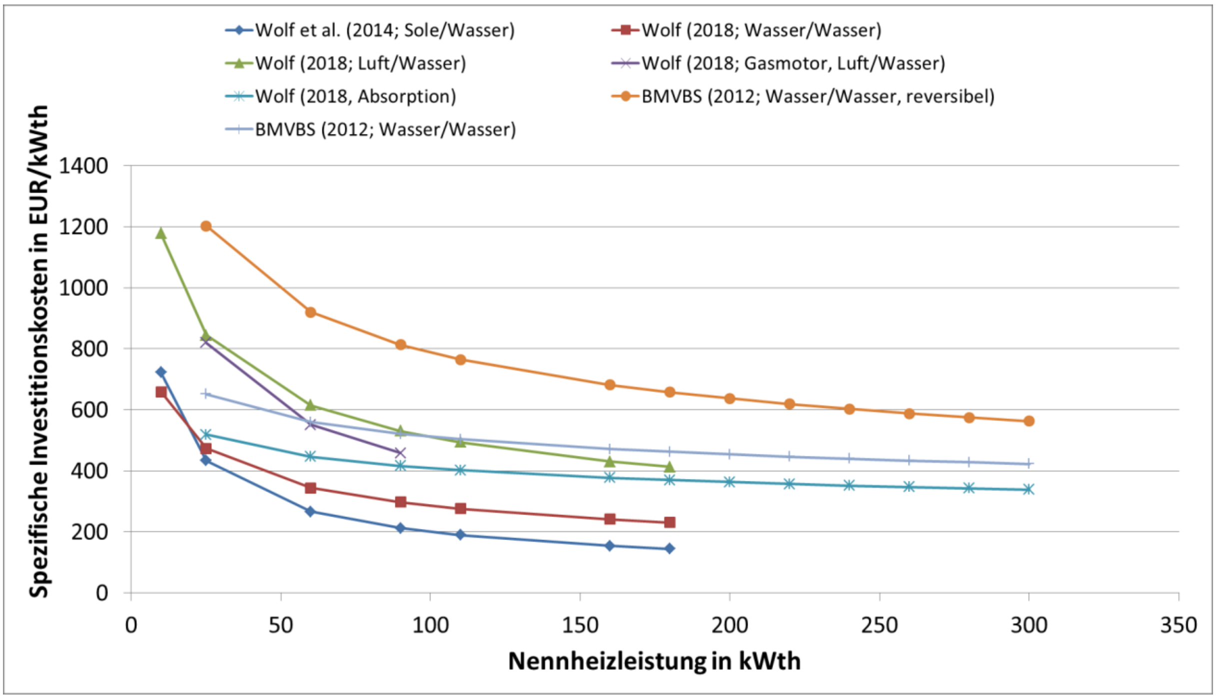


Figure 2-1: Specific capital expenditure of heat pump types from different literature sources (see Table 2-1)

### 2.1.2 Incidental expenditures

In addition to expenses for the heat pump, capital expenditure includes other expenses for the hydraulic connection, costs for electrical installation and costs for planning services. According to Wolf (2017), the incidental expenses for planning, hydraulic components (heat exchangers, storage tanks, piping) and installation can be estimated with a factor of 1.5 to 2 in relation to the acquisition costs of the heat pump system.

## 2.2 Consumption-related costs

In addition to capital expenditure, costs are incurred for operating the heat pump, which are subdivided into energy prices for operating the heat pump (mainly for the compressor) and maintenance and operating costs associated with the operating time of the heat pump.

### 2.2.1 Maintenance and operating costs

According to Arpagaus (2019), operating costs can be calculated from capital expenditures according to Eq. 2-1 as a function of the operating hours. Arpagaus (2019) took this approach from VDI Guideline 2067 (2012). If the heat pump is operated for less than 3024 hours, the factor $f_{service}$ is assumed to be 1.5 and 2.5 %. For a larger number of operating hours, a factor $f_{service}$ of 5.5 - 7.5 % is used.

$$C_{op} = C_{invest} \cdot f_{service} \qquad \text{Eq. 2-1}$$

### 2.2.2 Energy prices

Depending on whether a compression heat pump with an electric motor, a compression heat pump directly mechanically coupled to a gas engine or an absorption heat pump is used, different energy sources can be used to provide the driving energy.

Table 2-2 shows the prices for electrical energy and the electricity price including grid price and taxes for the years 2017 and 2018 for non-household customers. The energy price rose again in 2018, which can be partly attributed to the separation of the electricity price zone of Austria and Germany on 1 October 2018 in the second half of the year. Previously, the price for electrical energy had fallen from 7.01 ct/kWh to 3.70 ct/kWh since 01/2009 (e-control, 2019b). It can be assumed that the slight upward trend shown in Table 2-2 will continue (energyagency, 2019).

Table 2-2: Prices for electrical energy and total electricity price (including grid price and taxes and levies) for non-household costumers (E-control, 2019a)

| Electricity | 2017 | | 2018 | |
|---|---|---|---|---|
| | 1st half | 2nd half | 1st half | 2nd half |
| Energy price, Cent/kWh | 3.93 | 3.81 | 3.89 | 4.23 |
| Total price, Cent/kWh | 11.01 | 10.77 | 11.03 | 11.33 |

Table 2-3 shows the natural gas prices for non-households for 2017 and 2018. The gas price index rose by 27 % in January 2019, thus reaching the previous peak from 2013; experts expect a further increase in gas prices for 2019 (selectra, 2019).

Table 2-3: Energy prices for natural gas and total natural gas price (including network price and taxes and levies) of all non-households (E-control, 2019c)

| Natural gas | 2017 | | 2018 | |
|---|---|---|---|---|
| | 1st half | 2nd half | 1st half | 2nd half |
| Energy price, Cent/kWh | 1.95 | 1.95 | 2.06 | 2.33 |
| Total price, Cent/kWh | 3.37 | 3.41 | 3.46 | 3.72 |

According to Biermayr et al. (2017) large customers pay approx. 3.34 ct/kWh for biomass pellets.

The energy costs for the operation of a compression heat pump are calculated using Eq. 2-2 and for the operation of an absorption heat pump using Eq. 2-3. The exact variation of the electrical or thermal power consumption over time is usually not known. With a known annual performance factor and known operating hours, it is possible to calculate the energy costs with Eq. 2-4 or Eq. 2-5.

$$C_{heat,chp} = \int_0^{t_{op}} P_{el} \cdot d\tau \cdot c_{el} \qquad \text{Eq. 2-2}$$

$$C_{heat,ahp} = \int_0^{t_{op}} \dot{Q}_h \cdot d\tau \cdot c_{th} \qquad \text{Eq. 2-3}$$

$$C_{heat,chp} = SPF_{chp} \cdot t_{op} \cdot c_{el} \quad \text{Eq. 2-4}$$
$$C_{heat,ahp} = SPF_{ahp} \cdot t_{op} \cdot c_{th} \quad \text{Eq. 2-5}$$

### 2.2.3 Economic comparison of absorption and compression heat pumps

A first assessment as to whether the heat supply with an absorption or compression heat pump is more economical can be made from the COP of the respective heat pump and the energy prices for the respective drive energy.

The specific energy costs incurred during the operation of a compression or absorption heat pump can be estimated as presented by Arnitz et al. (2018) with Eq. 2-6 or Eq. 2-7.

$$c_{heat,chp} = \frac{1}{COP_{chp}} \cdot c_{el} \quad \text{Eq. 2-6}$$
$$c_{heat,ahp} = \frac{1}{COP_{ahp}} \cdot c_{th} \quad \text{Eq. 2-7}$$

If Eq. 2-6 is divided by Eq. 2-7, the specific energy cost ratio according to Eq. 2-8 is obtained. If the specific energy cost ratio results in a value greater than 1, operation with the absorption heat pump is less costly and if it results in a value less than 1, operation with the compression heat pump is less costly.

$$r_{c,heat,chp/ahp} = \frac{COP_{h,ahp}}{COP_{c,ahp}} \cdot \frac{c_{el}}{c_{th}} \quad \text{Eq. 2-8}$$

Figure 2-2 shows this for a COP ratio of 0.36 and two different energy price ratios. In the first case there is an energy price ratio of 2.94 (price for electrical energy of 9.82 ct/kWh and price for thermal energy of 3.34 ct/kWh). The resulting operating cost ratio is 1.06 and in this case the energy costs will be lower if an absorption heat pump is used. In the second case, the energy price ratio is 1.62 (price for electrical energy 5.41 ct/kWh and an unchanged price for thermal energy 3.34 ct/kWh). In this case, the operating cost ratio is 0.58 and the use of a compression heat pump results in lower energy costs.

This example shows that energy prices have a significant influence on the expected operating costs when selecting the type of heat pump.

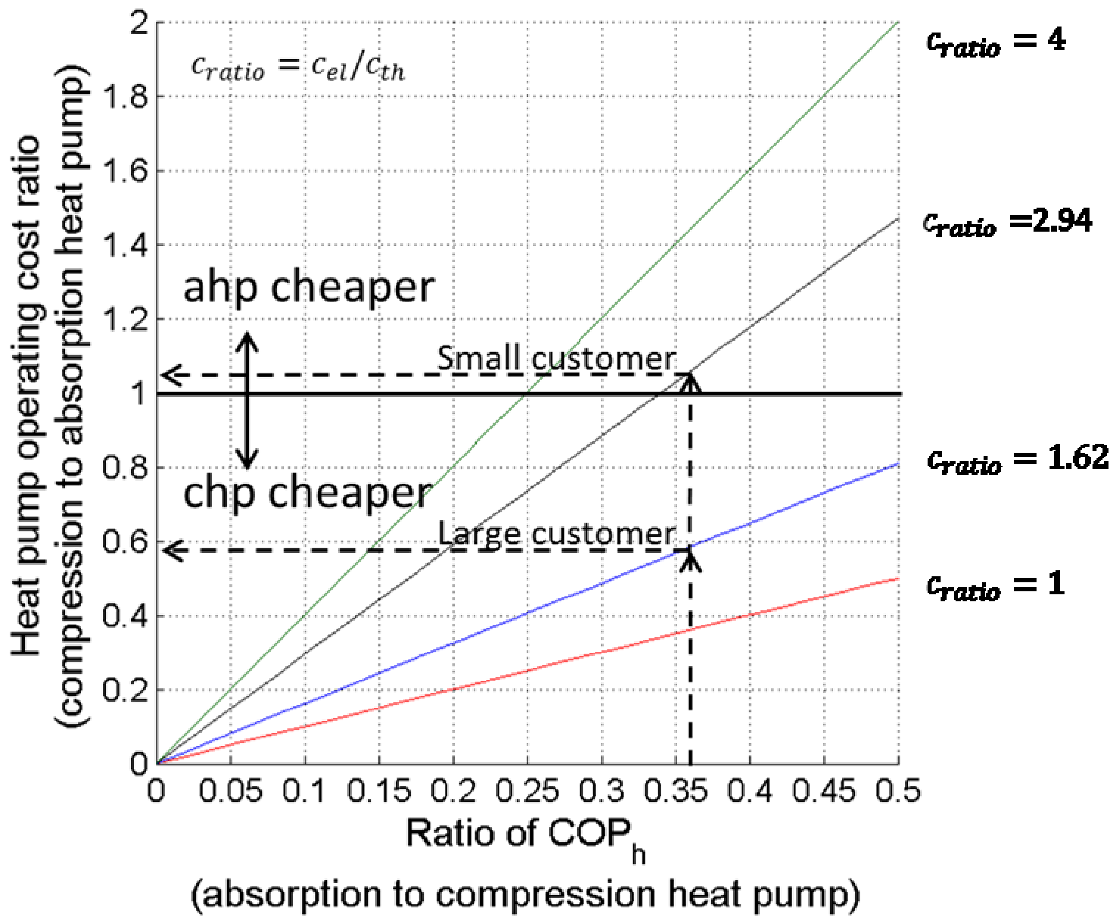


Figure 2-2: Determination of the operating cost ratio of an absorption heat pump to a compression heat pump at a given COP and energy price ratio (Arnitz et al., 2018)

## 2.3 $CO_2$ emissions and primary energy consumption

To consider the environmental impacts, the $CO_2$ emissions and the primary energy consumption of the process before and after the integration of the renewable technology are calculated and compared. Before the integration of a heat pump, process heat is provided, for example, in natural gas-fired boilers. The use of a heat pump reduces the use of natural gas, but requires electricity for the compressor.

The $CO_2$ emission factor (specific $CO_2$ emissions, e) describes how much $CO_2$ per unit of final energy available as process heat is released into the atmosphere. If the $CO_2$ equivalent is given, it also includes other greenhouse gases such as methane.  The primary energy factor (PF) indicates how much energy is needed to provide a unit of final energy. It measures how much energy is needed for extraction, processing, storage, transport, conversion, transmission and distribution. Table 4 4 shows the $CO_2$ emission and primary energy factors of different energy sources.

Table 2-4: $CO_2$ emission factors and primary energy factors by OIB (2015)

| | $CO_2$-emission factor | Primary energy factor |
|---|---|---|
| | g $CO_2$ /kWh | kWh PE/kWh |
| Biomass | 4 | 1,08 |
| Natural gas | 236 | 1,17 |
| District heat | 291 | 1,52 |
| Coal | 337 | 1,46 |
| Fuel oil | 311 | 1,23 |
| Electricity | 276 | 1,91 |

The specific $CO_2$ emissions that can arise during operation of the heat pump ($e_{hp}$) are estimated for known specific $CO_2$ emissions from electricity generation ($e_{elec}$) with the COP according to Eq. 2-9.

$$e_{hp} = \frac{1}{COP_h} \cdot e_{elec} \qquad \text{Eq. 2-9}$$

If the $CO_2$ savings compared to an alternative heat generator are to be calculated, the $CO_2$ emissions of the heat pump and the alternative heat generator shall be compared. According to Wilk et al. (2019), assuming a gas boiler efficiency of 90% and $CO_2$ emissions of 276 g/kWh (OIB, 2015) for electricity generation and 236 g/kWh (OIB, 2015) for natural gas emissions, the use of heat pumps with a COP of 3.5 - 5.5 can save approx. 70 - 81% of $CO_2$ emissions.

The primary energy factor describes the ratio of the primary energy used to the final energy delivered and can be calculated for the heat generated by the compression heat pump ($PE_{hp}$) according to Eq. 2-10.

$$PE_{hp} = \frac{1}{COP_h} \cdot PF_{elec} \qquad \text{Eq. 2-10}$$

By analogy with $CO_2$ emissions, heat pumps with a COP of 3.5 - 5.5 can achieve primary energy savings of 58 - 73% compared to heat generation with natural gas (primary energy factor for electricity 1.17 kWh/kWh, for natural gas 1.91 kWh/kWh).

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