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# Optimal usage of low temperature heat sources to supply district heating by heat pumps

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**Abstract:**

This paper presents a theoretical study on the optimal usage of different low temperature heat sources to supply district heating by heat pumps. The study is based on data for the Copenhagen region. The heat sources were prioritized based on the coefficient of performance calculated for each hour. Groundwater, seawater and air heat sources were compared with each other as well as to a scenario consisting of a combination of these heat sources. In addition, base load and peak load units were included. Characteristic parameters were the coefficient of performance, the number of full load hours and the covered demand of each heat source as well as required peak unit capacity. The results showed that heat pumps using different heat sources yield better performance than a heat pump based on a single one. The performance was influenced by the composition of the different heat sources. It was found that 78% groundwater, 22% seawater and 0% air resulted in highest COP of 3.33 for the given heat demand. Furthermore, the implementation of rule based short term storage made peak units redundant. The variation in base load capacity showed that heat pumps utilizing the analyzed heat sources could perform very efficiently without the presence of base load with a COP of 3.43.

**Keywords:**

District heating, Heat pumps, Low temperature heat sources.

## 1. Introduction

District heating (DH) dominates the heat supply in Denmark. More than 60% of residential buildings are supplied in this way from which already 50% is based on sustainable sources [1]. Denmark's goal however is to become independent of fossil fuels by 2050 [2]. For achieving a 100% sustainable energy system, DH networks in Denmark will have to undergo major changes. Currently, DH supply temperatures in Denmark vary between 70 °C and 90 °C with a few exceptions [3]. Lund et al. [4] defines the fourth generation of district heating (4GDH), which operates at supply temperatures between 30 °C and 70 °C. They state that reducing the DH supply temperature to such range has several advantages. Among others, heat losses in the grid are reduced and available low temperature heat sources can be exploited. This leads to higher utilization of renewable energy sources, because more potential heat sources can be used either directly or by use of a heat pump (HP). Ommen et al. [5] and Elmegaard et al. [6] document that the benefit differs significantly depending on whether the DH network is able to supply hot water directly or heat pumping is required. Apart from that, the coefficient of performance (COP) of a HP increases when the temperature lift between heat source and heat supply decreases.

Integration of HPs in the DH network can be done in different ways: One option is to install distributed HPs of small size at each building. Zvingilaite et al. [7] propose to reduce the DH supply temperature to 40 °C. In this way, space heating (SH) can still be supplied without any supplementary device when floor heating is installed. In addition, the return pipe of traditional DH networks can be used as heat source. Different configurations of the consumer substations are investigated for domestic hot water (DHW) preparation. They conclude that a micro booster HP increasing the temperature from 40 ˚C to 53 ˚C is most beneficial from an exergetic point of view and with lowest electricity consumption in comparison to an electric heater for the investigated configurations.

Another way of integrating HPs in the DH network is using centralized, large scale HPs. By doing so, it has to be ensured that sufficient amounts of heat sources are available. In order to identify the most suitable heat sources for HPs, one study [8] was conducted for the whole Denmark investigating the following heat sources: low temperature industrial waste heat, supermarkets, waste water, domestic water, ground water, rivers, lakes and sea water. Only sources located within 500 m of existing DH networks are considered. Furthermore, sources above 100 ˚C are disregarded, because they can be used directly without a HP. Each heat source is analyzed and its capacity estimated. The outcome of the study is a map of Denmark giving the heating capacity of heat sources available in comparison to the heat demands. It is noted that heat sources are distributed all over Denmark, but that the heating capacity of sources is not proportional to the heating demand, which means that some regions are more suitable for HP installations than others. Lund and Persson [8] conclude that groundwater has the highest potential to serve as heat source for HPs in Denmark due to its geographical availability and potential heat capacity. Another study with a more detailed focus on waste heat from industrial processes estimates the energy potential of various low temperature heat sources in Denmark [9]. They find that the largest potential for waste heat comes from the industrial sector with 103 PJ per year followed by the transport sector with 76 PJ, the utility sector with 58 PJ and the building sector with 25 PJ.

Focusing on the capital region of Copenhagen, the city council agreed on a climate plan to become the first $CO_2$ neutral capital in the world [10]. In Copenhagen, DH supplies 98% of the heat demand in the municipality [11]. In 2015, 53% of the supplied heat was $CO_2$ neutral [12]. This indicates the need of transferring the current DH network further. Investigating potentials of integrating large scale HPs is one of the possibilities [13].

In Bach et al. [14] integration possibilities of large scale HPs into the Greater Copenhagen area are analyzed from a technical and private economic perspective using the energy model Balmorel [15]. They investigate whether HPs should be integrated into the transmission or distribution grid. In the study HPs are introduced as base load in a current and a future energy scenario of 2025. The outcome of the study was that approximately 3500 and 4000 full load hours (FLH) of HP operation can be achieved for the investigated scenarios when connected to the distribution grid. The connection to the transmission grid results in a reduction of approximately 1000 FLH due to the higher temperature level of the network. For their analysis, the following heat sources are considered: sewage water, drinking water and seawater with certain capacity limits originating either from the heat source or from the heat demand. The COP is calculated on a seasonal level for one week in each month in order to investigate how its change would influence the results. This is different compared to other studies where a constant COP during the entire year is assumed for the integration of large HPs in the Greater Copenhagen area, e.g. [11].

The purpose of the present study was to investigate how the variation in COP on hourly basis influences the choice of using different heat sources for HPs to supply heat to the DH network. Groundwater, seawater and air were considered to demonstrate the influence of hourly changes in COP on the overall performance. A scenario considering all heat sources was compared to scenarios using only one heat source. Furthermore, rule based short term storage was implemented in order to investigate options for peak shaving.

## 2. Method

In order to investigate the optimal choice between HPs using different heat sources to supply DH more efficiently a model was developed in MATLAB [16]. The model carried out calculations on an hourly basis. Each heat source has different characteristics in terms of temperature profiles and media properties that vary during the year and day. This motivated an investigation on how these variations result in changes of the COP. By combining a number of HPs with different heat source characteristics, the unit with the highest COP may be prioritized. In this way, an overall improvement in performance may be achieved compared to a scenario with a single heat source. Three heat sources with different characteristics were considered for a case study, to represent the functionality of the developed model.

## 2.1. Comparison of HPs using different heat sources

HPs based on groundwater, seawater and air were analyzed for supplying the total dimensioning heat load individually. These scenarios were compared to a scenario combining the three different heat sources to supply in total the same design load as one of the HPs using a single heat source. In the following, this scenario is referred to the *Scenario with various heat sources*.

The model chose base load first to cover the heat demand, which could be waste incineration or biomass. Afterwards, HPs for each heat source were prioritized by highest COP, until the full demand was covered. If the demand could not be covered utilizing the full capacity of base load and all HPs, a peak load unit based on e.g. natural gas was used to cover the remaining demand in that hour. The HPs using single heat sources were compared with each other and to the *Scenario with various heat sources* based on the COP, the required additional units to cover the peak demand, the number of equivalent full load hours (FLH) during a year and the demand covering factor (DCF).

FLH [h] represent the number of hours the HP would operate on its full capacity during the year for the calculated heat supply. FLH were defined as the ratio of the supplied heat of a HP for a given heat source and its maximum possible heat supply in each hour, summarized over the year:

$$\mathrm{FLH} = \sum_{t=1}^{n=8760} \frac{\dot{Q}_{\mathrm{sink},t}}{\dot{Q}_{\mathrm{sink},t,\mathrm{max}}} . \qquad (1)$$

The DCF [%] was defined as the ratio of total supplied heat by a given heat source and the total supplied heat from the entire system:

$$\mathrm{DCF} = \frac{1}{\dot{Q}_{\mathrm{s,tot}}} \sum_{t=1}^{n=8760} \dot{Q}_{\mathrm{sink},t} . \qquad (2)$$

## 2.2. Calculation of COP

The COP of each heat source was calculated for every hour based on (3), (4) and (5) [17]:

$$\overline{T}_{\mathrm{lm},h,t} = \frac{T_{h,o,t} - T_{h,i,t}}{\ln T_{h,o,t} - \ln T_{h,i,t}} , \qquad (3)$$

$$\overline{T}_{\mathrm{lm},c,t} = \frac{T_{c,o,t} - T_{c,i,t}}{\ln T_{c,o,t} - \ln T_{c,i,t}} , \qquad (4)$$

$$\mathrm{COP}_{\mathrm{HP},t} = \eta_L \cdot COP_{\mathrm{HP},L,t} = \eta_L \cdot \frac{\overline{T}_{\mathrm{lm},h,t}}{\overline{T}_{\mathrm{lm},h,t} - \overline{T}_{\mathrm{lm},c,t}} . \qquad (5)$$

Equations (4) and (5) calculate the logarithmic mean temperature of the heat sink and heat source, respectively. $\mathrm{COP}_{\mathrm{HP},L,t}$ represents the COP of an associated Lorenz cycle, which is multiplied by the Lorenz efficiency as stated in Table 2. An average $\mathrm{COP}_{\mathrm{avg}}$ was calculated for the entire year taking the mean of the individual $\mathrm{COP}_{\mathrm{HP},t}$ of each hour. However, such COP does not take into account when the HP was in operation. Therefore, a weighted annual $\mathrm{COP}_{\mathrm{HP},w}$ considering the operating hours of HPs was defined, which may be seen in (6):

$$\mathrm{COP}_{\mathrm{HP,w}} = \frac{1}{\dot{Q}_{\mathrm{sink},tot}} \sum_{t=1}^{n=8760} \left( \sum_{j=1}^{\mathrm{j,max}=3} COP_{j,t} \cdot \dot{Q}_{\mathrm{sink},j,t} \right) . \qquad (6)$$

The $COP_{HP,w}$ was calculated by taking the sum of the COP for each HP multiplied by their heat supplies for every hour, summarized over the year and divided by the total supplied heat from all HPs.

## 2.3. Calculation of dimensioning conditions

The dimensioning capacity $\dot{Q}_{\text{source},d}$ of a heat source was calculated using (7) for the specific hour during the year that met the design heat pump capacity $\dot{Q}_{\text{sink},d}$ :

$$\text{COP}_{\text{HP},d} = \frac{\dot{Q}_{\text{sink},d}}{W_{\text{HP},d}} = \frac{\dot{Q}_{\text{sink},d}}{\dot{Q}_{\text{sink},d} - \dot{Q}_{\text{source},d}}. \qquad (7)$$

Heat losses and transient conditions over the HP were neglected [18]. The dimensioning source mass flow rate $\dot{m}_{\text{source},d}$ for a HP was calculated by (8):

$$\dot{Q}_{\text{source},d} = \dot{m}_{\text{source},d} \cdot c_{p,\text{source},d} \left( T_{\text{source},i,d} - T_{\text{source},o,d} \right). \qquad (8)$$

The capacity of each heat source and the corresponding heat loads that could be supplied at each hour were calculated with the dimensioning source mass flow rate and hourly temperature levels of demand and supply side.

## 2.4. Storage implementation

A rule based short term storage was implemented for further analysis in the model. Whenever the results showed a peak demand that could not be covered by base load and HPs, the model looked back in time hour by hour before the actual peak demand occurred in order to use remaining capacity from different heat sources. 23 hours before the occurrence of a peak demand were considered for the calculations. The reduced peak boiler unit, the weighted $COP_{HP,w}$, the required storage size, FLH and DCF were investigated. The required storage size was calculated by taking the maximum of the additional net heat supply of the HPs before the peak demand until the peak demand occurred. This includes discharging by the actual peak demand.

## 2.5. Case description

The case is representative for a new residential and commercial development area in Copenhagen, Denmark called Nordhavn. This area is one of the largest development districts in Europe that should demonstrate how sustainable living can be achieved [19]. Nordhavn gradually expands over the next 50 years to accommodate approximately 40,000 inhabitants and 40,000 jobs [19]. The heat demand considered for this study aimed at representing the existing part of Nordhavn and building phase stage II starting in 2018 with approximately 669,600 $m^2$ floor area in total [20,21]. It was assumed that this area only consists of residential buildings complying with the Danish Building Regulation 2015 [22]. The SH demand was calculated based on one of such apartments located in Nordhavn using the software IDA ICE [23]. An hourly simulation was performed over one year using the Danish Design Reference Year (DRY) for the region of Copenhagen to represent typical weather conditions [24]. DHW consumption was based on a tapping profile for an European family with shower use consuming 100 l at 60 °C [25]. Since it is very unlikely that every family consumes DHW at the same time, a normal distribution was assumed for the total number of 5151 apartments with a standard deviation of 60 min. By doing so, the DHW consumption accounts for different inhabitant behavior. An overview of the differences in DHW consumption for the entire area is shown in Fig. 1.

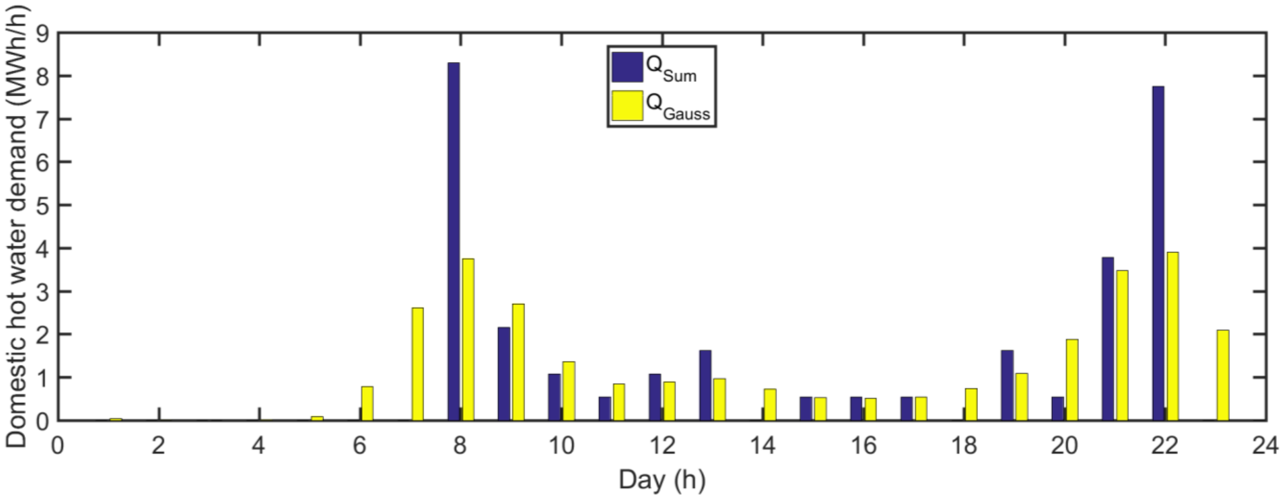


*Fig. 1. DHW demand for entire area*

The dark columns in Fig. 1 indicate DHW consumption for all inhabitants if hot water would be tapped at the same time in every apartment. The light columns take into account a standard deviation of the tapping profile. The latter consumption pattern was used for the calculations. Thereby, the peak demands were reduced. In addition, seasonal variations of DHW consumption were taken into account based on Frederiksen and Werner [26]. Their findings are based on measurements in Swedish residential multi-dwelling buildings. The relative hot water flow demand for every month considered for the calculations in this study may be seen from Table 1.

*Table 1. Relative hot water flow demand*

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor | 1.1 | 1.1 | 1.1 | 1.1 | 0.9 | 0.85 | 0.7 | 0.75 | 1.0 | 1.0 | 1.1 | 1.1 |

The heat demand profile was used to represent the entire area, which resulted in a peak demand of 12.38 MWh/h and an energy consumption of 37.43 kWh/m$^2$. A base load capacity of 20% of the peak demand was assumed, which could be supplied using e.g. waste incineration or biomass. The capacity of a HP using a single heat source was assumed 60% of the peak demand. For the *Scenario with various heat sources*, a HP for every heat source was assumed with a total capacity of the HPs equivalent to the one using a single heat source. The capacities of the HPs using groundwater, seawater and air were assumed 60%, 30% and 10% of the single HP capacity, respectively. Furthermore, a weather compensation curve was applied, which changed the DH supply and return temperatures based on the ambient temperature as presented in Fig. 2. This accounts for the variation of heat demand with ambient temperature.

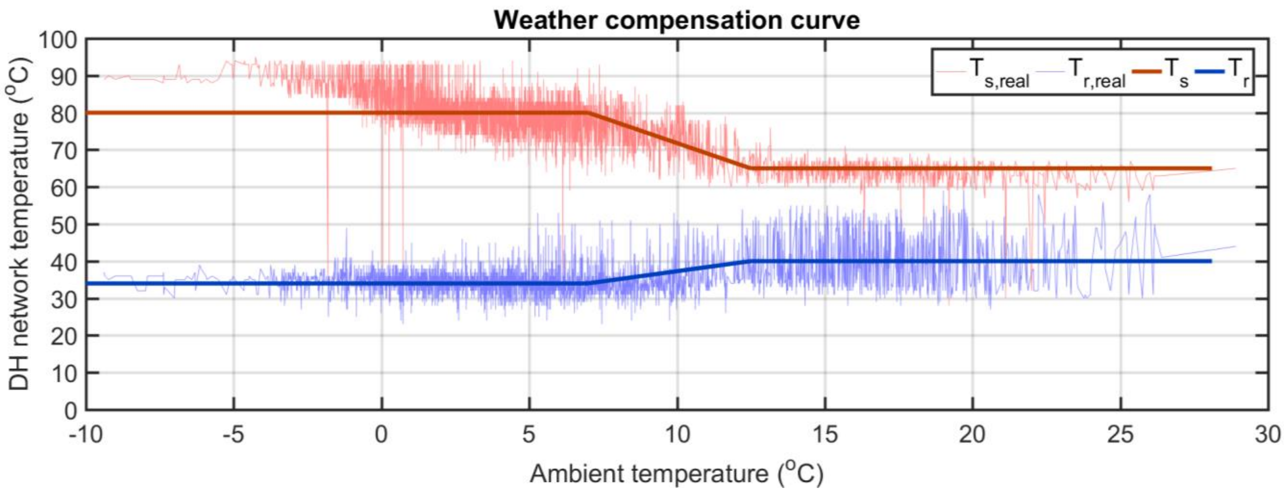


*Fig. 2. Weather compensation curve for DH network temperatures*

The temperatures shown in Fig. 2 are supply and return temperatures from a building in Nordhavn. Thick lines indicate the temperature settings of DH network supply and return temperatures considered for the calculations. As shown in (9), heat losses of the DH network were assumed and varied based on the logarithmic mean of supply and return temperatures:

$$\dot{Q}_{\mathrm{loss},t} = 0.05 \cdot \frac{\dot{Q}_{s,tot}}{n} \left( \frac{T_{s,t} - T_{r,t}}{\ln T_{s,t} - \ln T_{r,t}} \right) \Big/ \max \left( \frac{T_{s,t} - T_{r,t}}{\ln T_{s,t} - \ln T_{r,t}} \right). \quad (9)$$

Heat losses in storage, pressure losses as well as electricity consumption of auxiliary equipment such as of pumps and fans were neglected. Especially, considering pumps and fans would result in a reduced COP of HPs. The assumptions and inputs to the model are summarized in Table 2.

*Table 2. Assumptions and model inputs*

| Inputs | Assumptions and model inputs |
|---|---|
| Space heating | 21.31 kWh/(m$^2$ yr); hourly simulation in IDA ICE of a 2 story apartment of 130 m$^2$ for a single family; building standard based on [22] |
| Domestic hot water | 16.12 kWh/(m$^2$ yr); hourly tapping profile for an European family with shower use, 100 l at 60 °C [25] |
| Total floor area | 669,600 m$^2$, only residential [20,21] |
| Peak demand | 12.38 MWh/h |
| Base load capacity | 2.48 MWh/h, 20% of peak demand, not covered by HPs |
| Seawater | Hourly values based on DRY, station 30336 [24] |
| Groundwater | $T_{\mathrm{source,GW}}$=9 °C [27] |
| Air | Hourly values based on DRY, station 6136 [24] |
| Total heat pump capacity | 7.42 MW, 60% of peak demand |
| Groundwater heat pump capacity | 4.45 MW, 60% of total heat pump capacity |
| Seawater heat pump capacity | 2.23 MW, 30% of total heat pump capacity |
| Air heat pump capacity | 0.74 MW, 10% of total heat pump capacity |
| Lorenz efficiency $\eta_L$ | 0.5 [28] |
| $\Delta T$ of heat sources | 5 K |
| Minimum allowed seawater temperature | $T_{\mathrm{sea,min}} = -1$ °C |
| Media properties | Calculated for each hour using Engineering Equation Solver (EES) [29] |
| Not included | Heat losses in storage, pressure losses, auxiliary electricity consumption |

# 3. Results

First, the HPs based on the single heat sources seawater, groundwater and air were compared with each other and to the *Scenario with various heat sources*. Second, rule based short term storage was implemented in the model in order to shave the peak demand. Finally, a sensitivity analysis was conducted. The base load capacity was varied to investigate the effect on different key parameters for a HP using a single heat source and for the *Scenario with various heat sources*. Furthermore, the distribution of capacities between the different heat sources was varied in order to analyze the performance of the HP system.

## 3.1. Comparison of HPs using different heat sources

### 3.1.1. COP of HPs using different heat sources

The hourly $\mathrm{COP}_{\mathrm{HP},t}$ obtained by the use of each heat source as well as the daily heat demand are shown in Fig. 3.

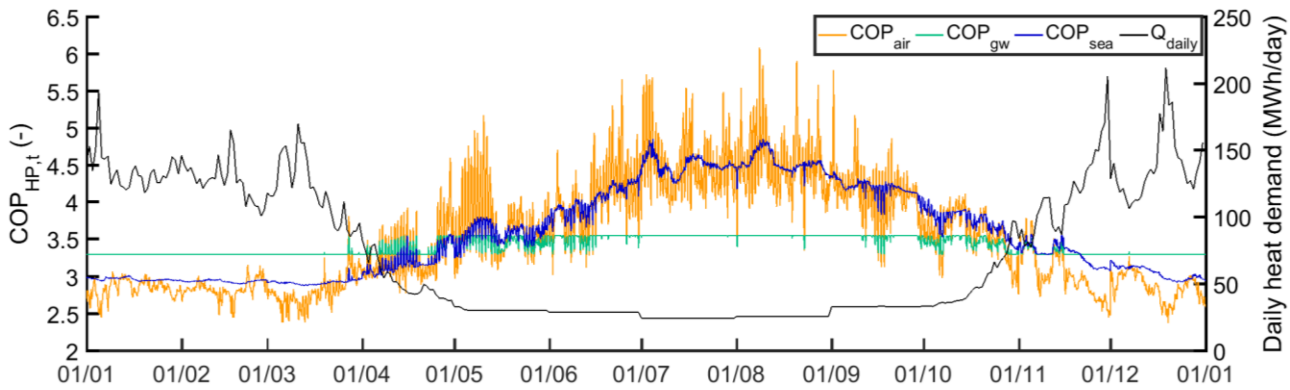


*Fig. 3. Hourly $COP_{HP,t}$ of HPs based on individual heat sources and daily heat demand*

It can be seen from Fig. 3 that the COP of air fluctuates the most. It has its highest values during summer with some significant peaks at high ambient temperature. On the other hand, the COP of air is low during winter when the ambient air is cold. The COP of seawater has similar characteristics as air, but with smaller amplitude. The reason for that is moderate seawater temperatures compared to air. Typically, the seawater in the area around Copenhagen does not cool below −0.5 °C during winter and will not increase above 22 °C during summer [24]. The COP of groundwater is rather flat due to its constant temperature [27]. Its change in COP occurs due to the weather compensation curve, resulting in varying sink temperatures. This results in small temperature lifts during summer and requires high temperature lifts in winter.

The daily heat demand is high during the heating season (October until May) with a few significant peaks. During the non-heating season, only DHW has to be covered. This is why seawater and air can only be utilized to a limited extent since there is little demand. Groundwater on the other hand has high COP when the heat demand is high. Therefore, groundwater should be the preferred heat source to use during the heating season.

### 3.1.2. Prioritization

The functionality of the model and the prioritization of heat sources are shown in this section. Two days during winter (a) and summer (b) were chosen to represent the optimal choice of heat sources as presented in Fig. 4 for the *Scenario with various heat sources*.

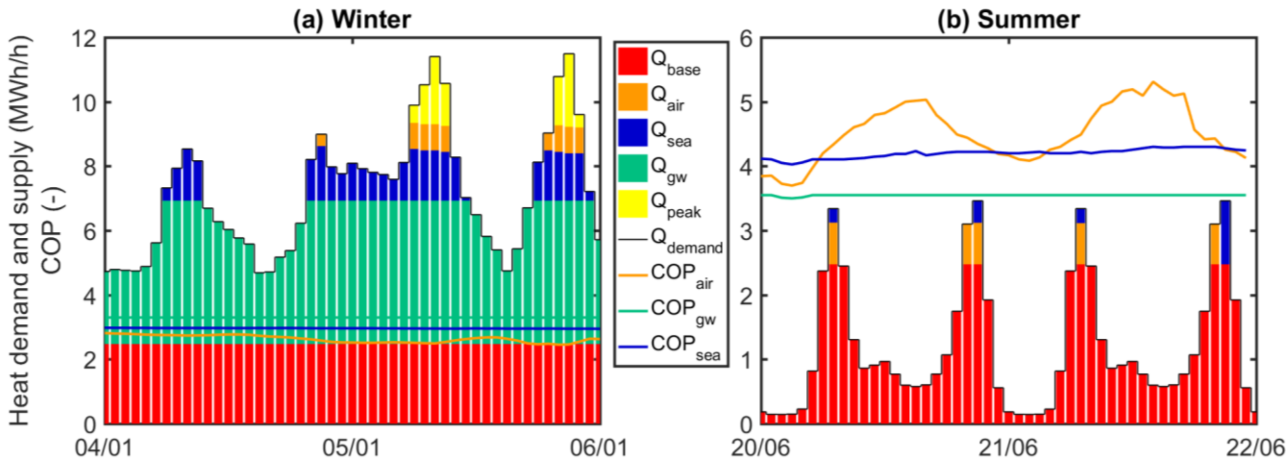


*Fig. 4. Prioritization of heat sources during winter (a) and summer (b)*

It may be seen in Fig. 4 (a) that the HP using groundwater is prioritized, because of its high COP. Whenever the full capacity of the groundwater HP is reached, the HP using seawater is chosen next, because it has the second highest COP. The air HP is only used during periods with such a high demand that it cannot be covered by the HPs using the other heat sources. In this way, the system consisting of different HPs always operates at highest possible efficiency. In addition, a peak boiler has to run during few hours with very high heat demand.

It may be seen from Fig. 4 (b) that the heat sources during summer can only be utilized during the morning and evening peaks. The air HP is prioritized due to its high COP followed by the seawater HP. During the last evening peak, the COP of the HP utilizing seawater is higher than the one using air and therefore prioritized. During the day when the COP of the air HP is much higher, the heat demand is so small that it is covered by base load. The result would look differently if the heat demand had a different profile or if the base load capacity was reduced.

### 3.1.3. Key parameters of HPs using different heat sources

An overview of key parameters is presented in Table 3 comparing HPs using the different heat sources with each other as well as to the *Scenario with various heat sources*.

*Table 3. Comparison of key parameters for different heat sources*

| Parameters | Unit | Seawater | Groundwater | Air | *Scenario with various heat sources* Sea/GW/Air |
|---|---|---|---|---|---|
| Average $COP_{avg}$ | (-) | 3.59 | 3.41 | 3.52 | 3.48 |
| Weighted $COP_{HP,w}$ | (-) | 3.09 | 3.31 | 2.88 | 3.32 |
| Peak unit capacity | (MW) | 7.69 | 2.48 | 1.65 | 3.56 |
| FLH peak unit | (h) | 280 | 14 | 5 | 32 |
| FLH HP | (h) | 1993 | 1534 | 1506 | 960/2088/359 |
| DCF HP | (%) | 39 | 42 | 43 | 7/35/1=43 |

As shown in Table 3, the average $COP_{avg}$ using seawater is the highest, followed by air, the *Scenario with various heat sources* and then groundwater. This picture changes looking at the weighted $COP_{HP,w}$ considering the operating hours of HPs. In this case, HPs using only seawater and only air encounter significant drops in COP by 14% and 18% to 3.09 and 2.88, respectively. The $COP_{HP,w}$ of the HP utilizing groundwater only decreases by 3% to 3.31 due to its rather constant value during the year, compare Fig. 3. The weighted $COP_{HP,w}$ for seawater and air decreases that much compared to the average $COP_{avg}$, because of the observations made in Fig. 3 and Fig. 4 regarding high COP and given heat demand. The *Scenario with various heat sources* has the highest $COP_{HP,w}$ of 3.32, which is only marginal larger than for the HP based on groundwater. However, it shows that combining HPs using different heat sources with each other instead of choosing only one heat source can result in an increased performance.

Seawater requires a high peak unit of 7.69 MW, because of restrictions on the minimum temperature seawater can cooled down to ($T_{sea,o} \geq -1$ °C). Therefore, the available capacity of the heat source below a seawater temperature of 4 °C reduces significantly compared to other situations with a fixed temperature difference of 5 K. This can be seen from the available heat capacity for every hour calculated based on (8). The effect of reduced capacity available for seawater is shown in Fig. 5. Groundwater (a) is able to supply more of the heat demand during peak hours than seawater (b).

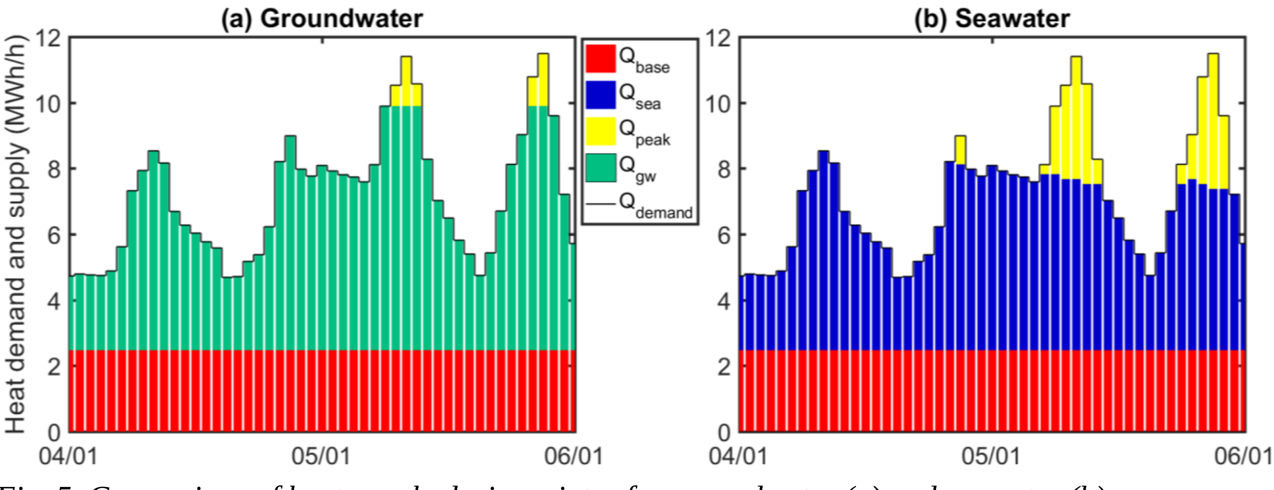


*Fig. 5. Comparison of heat supply during winter for groundwater (a) and seawater (b)*

The FLH for the HPs are in general quite low at 1500 h to 2000 h. The reason for this is described in section 3.1.2 and Fig. 4. Seawater seems to have better utilization, because of its high number of FLH. This is due to the limited capacity available during hours below a seawater temperature of 4 °C. Other heat sources operate in part load during such periods with heat demands above base load capacity. Seawater however runs on limited full capacity during these hours. This results in a high capacity of a required peak boiler unit and an increased operation of 280 FLH for that unit. Groundwater and air cover a higher share of the demand, which results in lower operating hours of the peak boiler. The DCF for seawater is with 39% lower than for the other scenarios, where the heat sources cover 42% to 43% of the heat demand.

For a HP using a single heat source, groundwater was chosen as the *Reference scenario* for comparison with the *Scenario with various heat sources*, because it has a higher COP than seawater and air as well as it does not require a large peak boiler unit.

### 3.1.4. Load duration curves

The load duration curves for the *Scenario with various heat sources* are shown in Fig. 6 for the different heat sources, peak unit and base load.

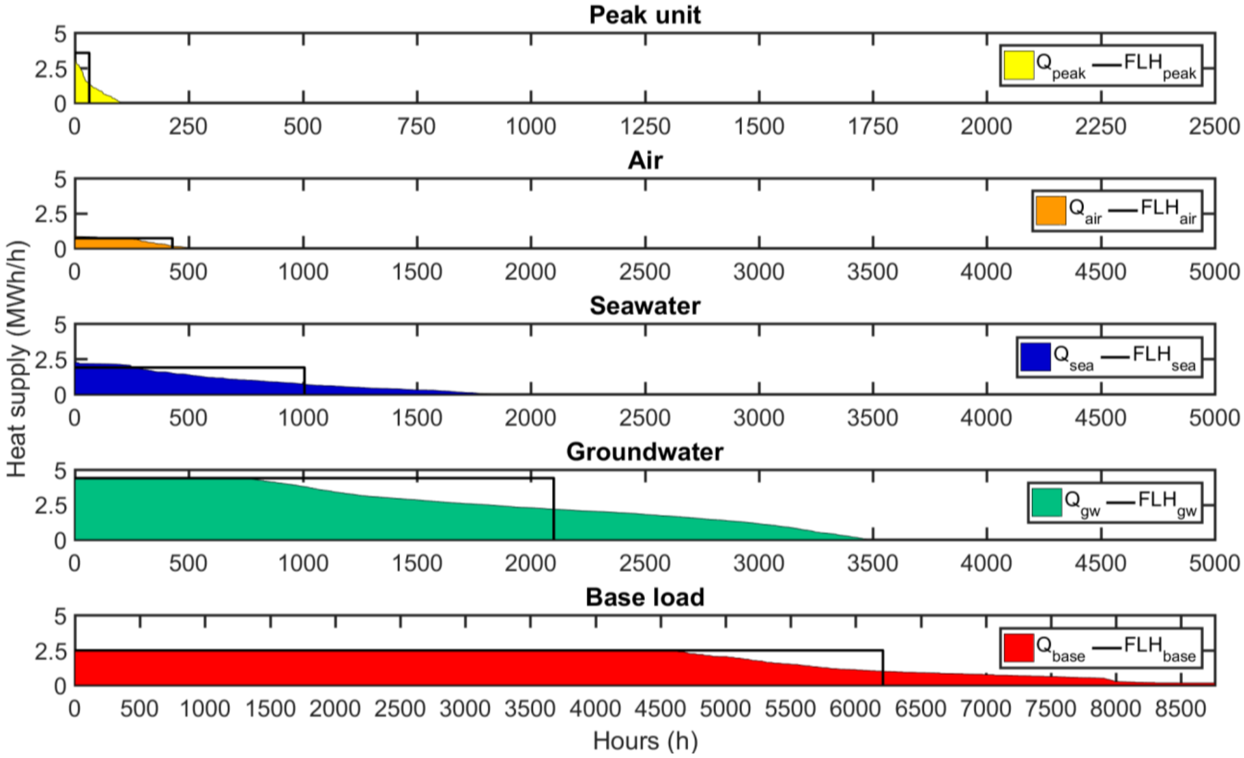


*Fig. 6. Load duration curves for the Scenario with various heat sources*

It may be seen from Fig. 6 that groundwater is the most utilized heat source even though it has highest capacity compared to the other HPs. This was also indicated by the highest DCF of 35% for groundwater, compare Table 3. It is used 2088 equivalent FLH during the year. The HP using seawater has a DCF of 7% and 960 FLH. The air HP is only in operation at rare occasions. It has a small capacity, but is used either during peaks in summer when its COP is high or during peak hours when the capacity of the remaining heat sources is not sufficient. The DCF of the air HP is 1% and it has 359 FLH. Base load is prioritized over HPs and therefore covers most of the heat demand with a DCF of 57%. The FLH for base load are accordingly high with 6210 FLH. The peak unit on the other hand is only used for 32 FLH. However, it is still required to have such peak unit of 3.56 MW size. A possibility of making the peak unit redundant is by introducing a rule based short term storage as described in the next section.

## 3.2. Peak shaving by introducing storage

This section presents how the implementation of rule based short term storage into the model helps to make a peak boiler unit unnecessary. Whenever a peak demand occurred, the model considered the previous 23 hours to utilize remaining capacity of the heat sources. The heat demand as well as a comparison of the supply profile for the case with and without storage for two winter days with peak demand is shown in Fig. 7.

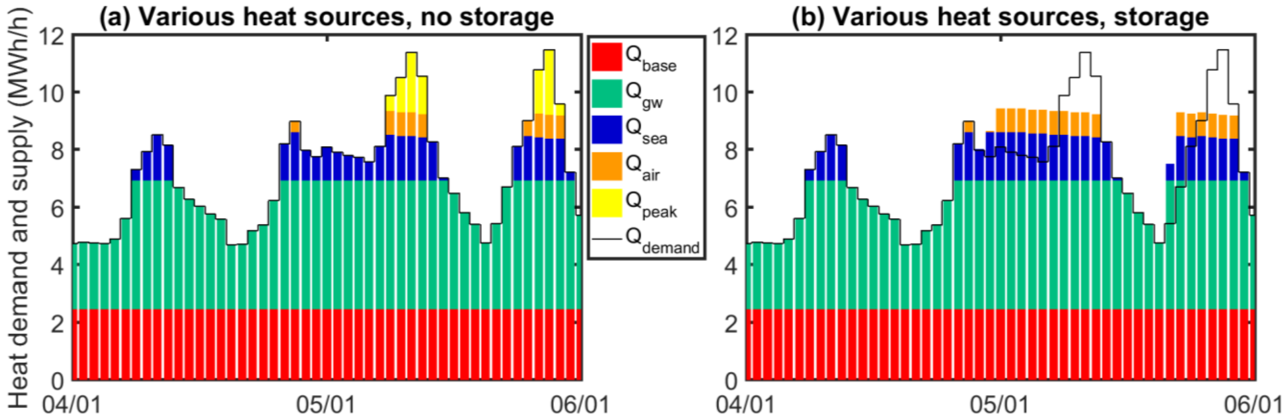


*Fig. 7. Comparison of the Scenario with various heat sources with (b) and without storage (a)*

It can be seen from Fig. 7 (a) that the heat demand can only be completely covered using a peak boiler during 7 hours. In the same time, the base load as well as the heat supply using HPs with various heat sources are illustrated. When storage is introduced as shown in Fig. 7 (b), the peak unit becomes redundant. HPs cover the peak demand by operating in the previous hours depending on their COP and remaining capacity. Comparing the peaks and the previous hours in Fig. 7 (a) and (b), the capacity of the groundwater HP has already been fully utilized except for two hours. This is indicated by the presence of seawater already at the case without storage before the occurrence of the peak demand. Since the capacity of seawater was not reached yet, the peak demand can partly be compensated by that heat source. The HP using air as heat source cover the remaining part of the peak demand.

It should be noticed that this storage implementation optimized the operation of each individual hour, not from the entire day. Looking for instance at the previous hours before the second peak, it can be seen that seawater and air are used in the two hours immediately before the peak. However, groundwater with higher COP has still remaining capacity in the hours 3 to 6 before the peak. An overview of key parameters for the case with and without storage is presented in Table 4.

*Table 4. Key parameters for variation of considered hours for storage before peak demand*

| Sea/GW/Air | Unit | *No storage* | *Storage* |
|---|---|---|---|
| Weighted $COP_{HP,w}$ | (-) | 3.32 | 3.31 |
| Peak unit capacity | (MW) | 3.56 | 0.00 |
| FLH peak unit | (h) | 32 | 0.00 |
| FLH HP | (h) | 960/2088/359 | 1007/2101/428 |
| DCF HP | (%) | 7/35/1=43 | 7/35/1=43 |
| Storage size | (MWh) | 0.00 | 15.30 |

As shown in Table 4, the annual weighted $COP_{HP,w}$ does not change much. It is influenced by the additional supply for compensating the peak demands. Looking at characteristic peaks like in Fig. 7 it can be seen that the HP with highest COP was often already used to its full capacity. Instead, a HP with a lower COP supplies the additional heat, which explains the small reduction in the weighted $COP_{HP,w}$. The peak boiler unit becomes redundant when adding storage. Instead, a storage of 15.30 MWh in size has to be implemented. If a hot water tank is used, it will require a size of approximately 300 $m^3$ under typical conditions. This storage size is necessary, because of many hours in a row with high peak demands. When comparing the FLH, it is noticed that air and seawater are influenced the most. This is because the capacity of the groundwater HP with high COP has already been used before peak hours. Air and seawater are the heat sources that would be used the most to compensate the peak boiler unit.

## 3.3. Sensitivity analysis

In this chapter, the results of varying the base load capacity as well as the capacities between the different heat sources are presented. These variations were conducted for the *Reference scenario* and for the *Scenario with various heat sources* without storage.

### 3.3.1. Variation of base load capacity

The base load capacity was varied from 0% to 40% of the peak demand by steps of 10% points. The original value used in the analysis was 20% corresponding to 2.48 MWh/h. The sensitivity of the results on changes in base load capacity is presented in Fig. 8. The relative change of COP is shown on the right y-axis due to their smaller magnitude compared to other parameter changes.

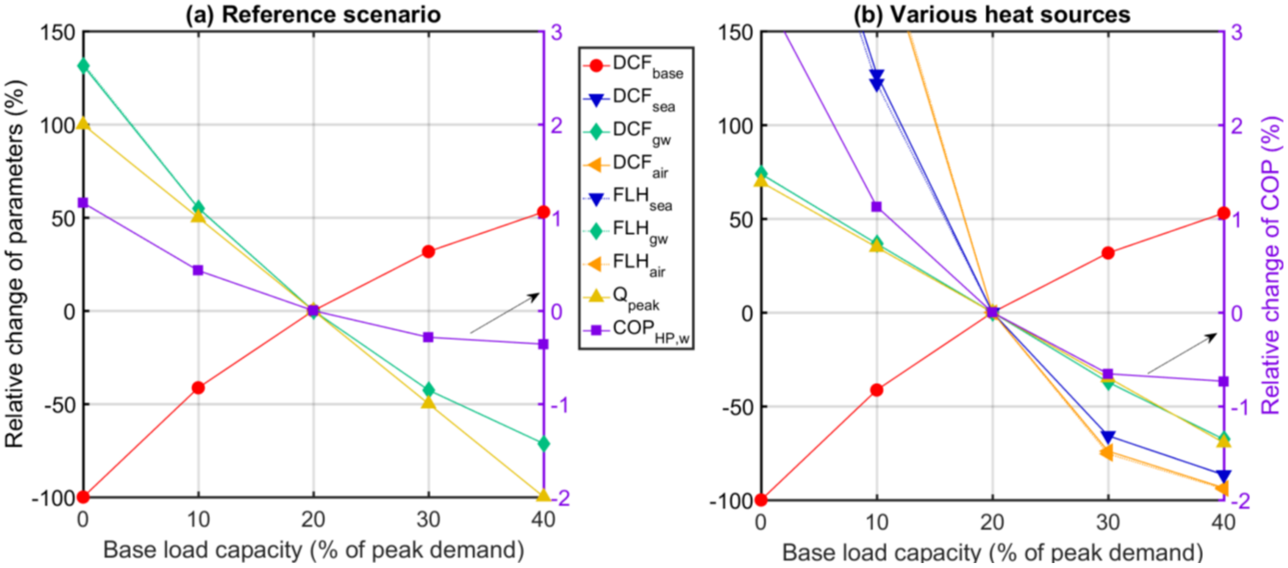


*Fig. 8. Effect on key parameters for changing base load capacity for the Reference scenario (a) and for the Scenario with various heat sources (b)*

The red curves indicate the DCF of base load, which is the same for both, the *Reference scenario* in Fig. 8 (a) and the *Scenario with various heat sources* in Fig. 8 (b). The weighted $COP_{HP,w}$ increases by 1.2% and 3.5% to 3.35 and 3.43 for the *Reference scenario* and the *Scenario with various heat sources*, respectively if no base load is present. The weighted $COP_{HP,w}$ decreases continuously for an increase in base load capacity. If the base load capacity decreases, the HPs will also cover the demand with low and intermediate demands, as it is the case during summer, compare Fig. 4. Small demands during the day can be covered using the air HP, which has a very high COP. Consequently, the weighted $COP_{HP,w}$ increases. Furthermore, groundwater can be used to cover low demands during winter, which were supplied previously by base load. This behavior may also be seen from the changes in DCF and FLH. They are both much higher for all heat sources when the base load capacity is zero compared to the reference point and decrease with an increase in base load capacity. The number of FLH without base load results in 3920 h for seawater, 3632 h for groundwater and 3526 h for air for the *Scenario with various heat sources*. For the *Reference scenario*, the groundwater HP is 3567 FLH in operation. These are significant increases compared to the original FLHs found for both scenarios, compare Table 3. Furthermore, it is noticed that the size of a required peak unit decreases linearly with an increase in base load capacity. The peak demands change by ±100% and ±70% for the given range of base load capacity for the *Reference scenario* and the *Scenario with various heat sources*, respectively. The change in weighted $COP_{HP,w}$ show that a low share in base load capacity is desirable for HPs using low temperature heat sources.

### 3.3.2. Variation of heat source shares

The share of HP capacities for the different heat sources was varied and the results are presented in this section. The base load capacity and the total HP capacity were kept constant at 20% and 60% of the peak demand, respectively. The capacity of the air HP was changed from 0% to 20% of the total HP capacity. The groundwater HP was varied between 0% and 80% to 100% with respect to the share of the air HP and that all HPS together equal 100%. An overview can be found in Fig. 9.

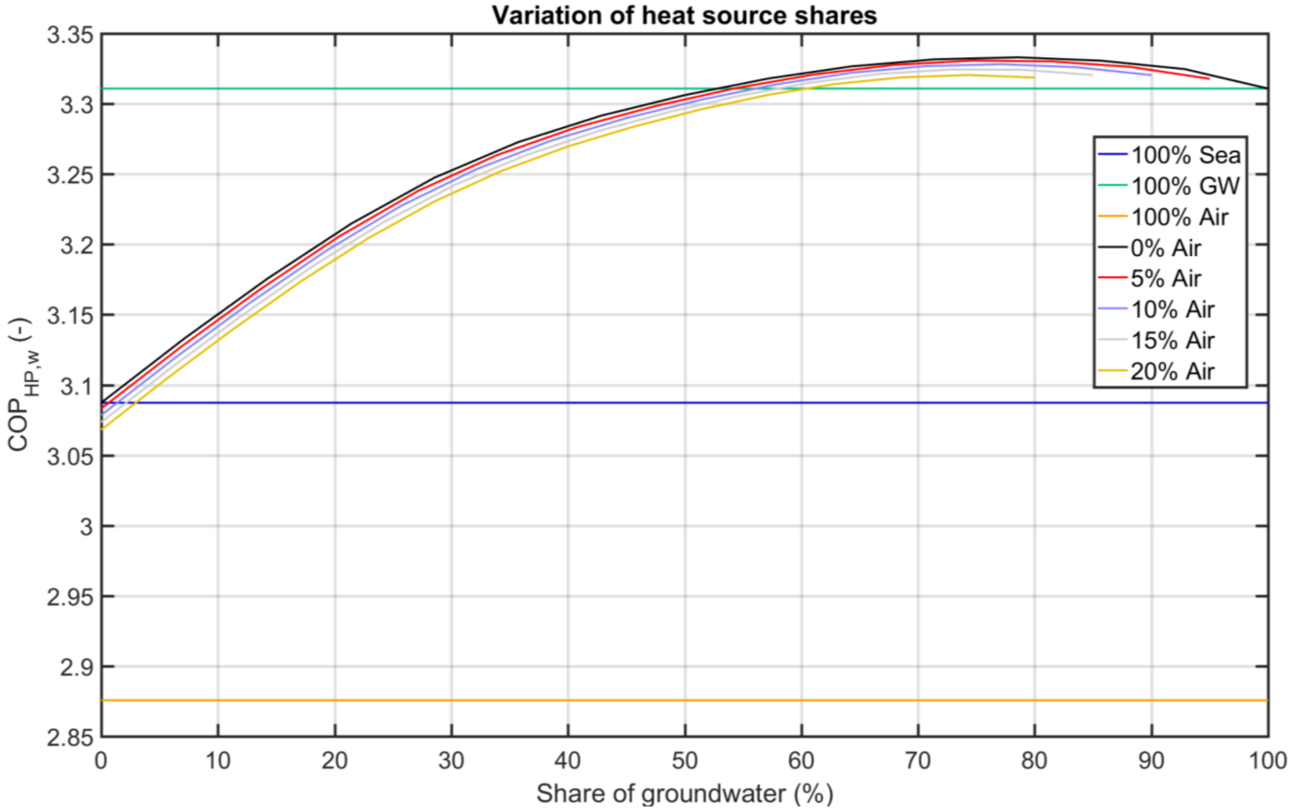


*Fig. 9. Variation of heat source shares*

The horizontal lines in Fig. 9 represent the $COP_{HP,w}$ when a single heat source is used as presented in Table 3. Each curve indicates a different constant share of air. The share of seawater can be determined when the share of the other heat sources are subtracted from 100%. There is an optimum in weighted $COP_{HP,w}$ of 3.33 for a composition of 78% groundwater, 22% seawater and 0% air. Therefore, it may be beneficial to utilize a combination of groundwater and seawater instead of a single heat source. Furthermore, the weighted $COP_{HP,w}$ always decreases if the share of air is increased. Consequently, air is not recommended for the given heat demand, because its benefits cannot be exploited as indicated in Fig. 4.

## 4. Discussion

The results have shown that HPs based on a combination of different heat sources can achieve higher performance than a HP of equivalent design load using a single heat source. This is highly influenced by the composition of the different heat sources and the heating demand. The presented model however also has some limitations that should be kept in mind when looking at the results.

No pressure losses, heat losses in the storage nor electricity consumption for auxiliary equipment such as pumps or fans were considered. This affects the COP and may be different from heat source to heat source. Furthermore, a heat demand of only residential buildings fulfilling the Danish Building Standard 2015 [22] was considered. The demand profile and therefore the results might look differently, when a mixture of an existing building stock, newly built buildings and commercial buildings are considered.

Apart from that, a weather compensation curve was applied with a maximum supply temperature of 80 °C. New buildings do not require such high supply temperature, which could lead to a decrease to e.g. 70 °C or even below. Consequently, HPs would have a better performance, since the temperature lift is smaller. Applying a lower supply temperature would result generally in a higher COP for the HPs of the considered heat sources, but not necessarily in a difference between the choice of using different heat sources.

Another assumption of the model was a constant Lorenz efficiency, which might not be the case for varying temperature lifts and part load operation. In connection to that, the COP was calculated without a HP model only based on temperatures. If a HP was introduced, the model would become more complicated and limited by a specific HP configuration. This was not desired and allows applying the current model to any location when heat demands and temperature characteristics of heat sources and heat demand are known. In addition, a constant temperature difference of 5 K between inlet and outlet of heat source and heat sink was assumed, which might not be the case during the entire year.

The implemented storage was only in operation before peak hours. An overall optimization of prioritizing different heat sources during all hours including available storage capacity was not conducted. This could lead to a higher COP and utilization, since the full capacity of the HPs with highest COP could be operated more often. In addition, the model did not include heat capacities of buildings. The heat demand had to be covered at every hour. The implementation of the storage could also be seen as an indication for the heat capacity of buildings.

The presented method of prioritizing different heat sources was shown based on groundwater, seawater and air. In the future, it could be of interest to implement other heat sources such as solar energy, geothermal or waste heat from industries, as well as to integrate district cooling and other cooling units into the model. At the current state, the model prioritized HPs using different heat sources based on COP. A further development of the model could lead to an optimal choice between heat sources based on economics, considering operating costs and investments.

# 5. Conclusion

The presented results compared HPs using seawater, groundwater and air as heat sources with each other and to a scenario that included all these heat sources. This study has shown that HPs based on a combination of heat sources of equivalent capacity to a HP using a single heat source can perform better on an annual basis for the given conditions. This depends on how the total HP capacity is distributed between the different heat sources. An optimum was found for the given heat demand. It was shown that heat sources with highest COP were prioritized for every hour. In this way, it was possible to exploit the heat sources more effectively. One heat source was preferred over others, which changed during the year. Groundwater was used first during winter, followed by seawater and air. During summer, the trend was the opposite. However, the high COP of air could not be utilized during summer due to the low demand and the presence of base load. This was also the reason why the utilization of heat sources was rather small during the year. Reducing required peak unit capacity was achieved by implementing rule based short term storage. This made a peak boiler unit redundant. Varying the base load capacity has shown that the COP of the HPs in operation increase for a decrease in base load capacity. The smaller the base load capacity, the higher was the utilization of heat sources. In addition, the peak demand not covered by these sources increased.

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## Nomenclature

| | |
|---|---|
| COP | Coefficient of performance |
| $c_p$ | specific heat, J/(kg K) |
| DCF | demand covering factor, % |
| FLH | full load hours, h |
| $\dot{m}$ | mass flow rate, kg/s |
| $\dot{Q}$ | heat capacity, heat supply or heat loss, MWh/h |
| $T$ | temperature, °C |
| $\bar{T}_{\text{lm}}$ | logarithmic mean temperature, K |
| $W$ | Work, MWh/h |

**Greek symbols**

| | |
|---|---|
| $\Delta T$ | temperature difference, K |
| $\eta_L$ | Lorenz efficiency |

**Subscripts and superscripts**

| | |
|---|---|
| $a$ | air |
| $c$ | cold side |
| d | dimensioning |
| loss | district heating network loss |
| GW | groundwater |
| HP | heat pump |
| $h$ | hot side |
| $i$ | inlet |
| j | index for heat source |
| j,max | number of investigated heat sources |
| min | minimum |
| $n$ | number of hours in a year |
| $o$ | outlet |
| $r$ | return |
| $s$ | supply |
| sea | seawater |
| sink | heat sink |
| source | heat source |
| $t$ | current hour of a year |
| tot | total |
| $w$ | weighted |

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