Heat Pump Systems

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1 Technical Introduction

1.1 General function

A heat pump is an electrical device that extracts heat from one place and transfers it to another. Heat pumps use environmental energy, e.g. from the ground, the air or from water. Heat is being extracted from the environment and then transferred to a heat distribution system or to warm drinking water. → Heat pumps are based on renewable energies.

Heat pumps basically work like refrigerators, but reversed:

➔ While refrigerators conduct the heat to the outside, the heat pump transfers energy out of the air or soil via the heating system into the rooms of a building.

Heat pumps can be used for new buildings and also when old buildings are being modernized.

But heat pumps can also be used for cooling, the heat pump cycle is fully reversible. For this the refrigeration cycle is internally reversed or the external primary and secondary connections are switched. The heat pump now transfers the heat from the inside of the building onto the soil probe.

1.1.1 The heat pump cycle step by step:

- Heat is generated by depriving heat from the nature and then using this heat to evaporate a refrigerant with it.
- The compressor compresses the gas that is produced in this process and brings it to a higher level by doing so.
- A heat exchanger then transfers the energy from the heated gas to the heating cycle.
- The pressurized refrigerant is being liquefied again and thereby brought back into its initial state.

1.1.2 Heat pump components

Refrigerant: The refrigerant is a liquid or gaseous substance that circulates through the heat pump. The refrigerant is alternately absorbing, transporting and releasing heat.

Reversing valve: The direction of the refrigerant flow in the heat pump is controlled by the reversing valve. The valve changes from heating to cooling mode or vice versa.

Coil: The coil is a loop, or loops, of tubing where the heat transfer takes place.
Evaporator: The evaporator is a coil in which the refrigerant absorbs heat from its surroundings and boils to become a low-temperature vapour. When the refrigerant passes from the reversing valve to the compressor, the accumulator collects any excess liquid that didn’t vaporize into a gas.

Compressor: The compressor squeezes the molecules of the refrigerant gas together. By doing so the temperature of the refrigerant is increased.

Condenser: The condenser is a coil in which the refrigerant gives off heat to its surroundings and becomes a liquid.

Expansion: The expansion device lowers the pressure created by the compressor which causes the temperature to drop, and the refrigerant becomes a low-temperature vapour or liquid mixture.

Plenum: The plenum is an air compartment that forms part of the system for distributing heated or cooled air through the building.

1.1.3 Performance of a heat pump

For the evaluation of heat pumps, the COP of a heat pump can be used, which represents a coefficient of performance of a heat pump determined under fixed test conditions and is defined as follows according to DIN EN 14511:

\[ \text{COP} = \frac{Q_{\text{el,WP}}}{W_{\text{el,WP}}} \]

The larger the COP, the more efficient the heat pump works. A heat pump with a COP of 4 indicates that you can generate a total of 4 kWh of heating energy with the electrical input of 1 kWh.

<table>
<thead>
<tr>
<th>HEAT PUMP</th>
<th>COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-source heat pump</td>
<td>~5</td>
</tr>
<tr>
<td>Ground-source heat pump</td>
<td>~4</td>
</tr>
<tr>
<td>Air-source heat pump</td>
<td>~3</td>
</tr>
</tbody>
</table>

Tab. 1 shows the respective COPs that can be achieved by different types of heat pumps. However, these are only estimations.
1.1.4 Heat pumps and renewable energy

In order to make a heat pump system completely renewable, the electricity input should come from a renewable source, such as solar energy. For example, a heat pump can be combined with PV-Panels on the roof providing solar energy.

1.2 Different Heat Pump Systems

The best heat source depends on the local conditions and the individual heat demand. Different heat sources can be used with different heat pump models:

- Sole-water heat pump
- Water-to-water heat pump
- Air-to-water heat pump
- Hybrid heat pumps

1.2.1 Sole-to-water heat pump

The source for a sole-water heat pump is geothermal. The natural heat of the soil is being used to heat a building. Geothermal heat can be obtained in different ways, although the most common are vertical heat probes or horizontal geothermal collectors. Vertical heat probes need to reach a depth of about 10 m. At this depth the heat is almost constant the whole year around, which provides optimal conditions for the efficient use of a heat pump. In general, the depth of the probe depends on the heat demand and the thermal conductivity of the soil. If vertical heat probes can’t be used, horizontal geothermal collectors are a good alternative.
Sole-water heat pumps are considered the best option for cold climates, because of the natural supply of warmth by the ground, even during low air temperatures. Usually plastic pipes (PE 80 or PE 100) are used for the probes and geothermal heat collectors. From the outside diameters the exchanger surface and thus the transfer capacity of the pipe are derived.

**Design of earth probe systems**

The determination of the extraction capacity of probes depends on the local geological strata and can vary up to 100%. 50 W/m can be assumed as a first approximate value. With the help of geological maps, the extraction rate can then be estimated more accurately for the respective location. The detailed calculation and definition of the probe system must be carried out by a specialist company. When determining the required extraction capacity, the annual heat load is taken into account in addition to the actual heat pump capacity. Thus, a heat pump in a bivalent parallel system achieves a considerably higher annual heat load than a monovalently operated heat pump for the same heat output. The probe must then be dimensioned larger. The following factors must be taken into account for the hydraulic dimensioning of the pipe network and its connection lines:

- Uniform flow through all probes
- From three probes upwards, use a probe distributor with control valves to enable hydraulic balancing
- Low pressure losses in the entire probe system (affects the required electric pump capacity of the primary pump)
- The material and the heat transfer medium must be compatible with each other
- When the pipe lengths are known, the pressure loss and the brine pump can be calculated

**Design of ground collector systems**

Horizontal ground collectors use the uppermost layer of earth as a heat source. They should be laid at least 20 cm below the frost line to a depth of approx. 1.5 m. The amount of usable heat available
in this layer depends strongly on the thermophysical properties of the soil and the climatic conditions (radiation energy of the sun and the climatic conditions (precipitation). Earth collectors are not sealed. A maximum length of 100 m per pipe circle has proven to achieve the lowest possible pressure loss in the system.

**Heat transfer medium**

For smooth operation of the heat pumps a glycol-based antifreeze is used in the primary circuit. It must ensure frost protection for at least -15 °C and contain suitable inhibitors for corrosion protection. Transfer medium mixtures with integrated antifreeze ensure an even distribution. To determine the required quantity of the heat transfer medium, the contents of the individual probes or ground collector circuits, the connecting pipes and the fittings are added together.

**Volume flow and pressure loss in the brine circuit**

In addition to the system temperature in the secondary circuit, the dimensioning of the heat source system is very important for the efficiency of a heat pump system – this applies in particular to the determination of the volume flow in the primary circuit. The smaller the temperature difference in the brine circuit, the higher the source temperature at the evaporator – this in turn increases the efficiency of the machine. In the case of probe and ground collectors, a temperature difference of 3 K is recommended for calculating the volume flow; a maximum of 5 K is permissible. At 3 K this results in a volume flow in the brine circuit of 184 l/h per kW for a mixture of 85 % water and 15 % glycol. This value underlines the importance of the lowest possible pressure loss of the primary circuit for the overall efficiency of the system.

In order to be able to make a statement about the usefulness of a borehole for the development of geothermal energy, it is worthwhile to search the internet for specially designed portals that provide information. Such a portal exists, for example, for Hamburg and the surrounding area and can be found under the website geoportal-hamburg.de

![Figure 4: Conditions of use of geothermal, source: geoportal-hamburg.de](image)

The illustration on the terms of use of geothermal energy shows whether the use of geothermal energy at this location is inadmissible, must be examined in individual cases or is permissible.
The illustration borehole register shows the boreholes evaluated for Hamburg geothermal energy after different drilling depths of 30 to 1000 m.

The figure extraction performance indicates where in Hamburg up to a depth of 100 m, which heat output can be extracted.

### 1.2.2 Water-to-water heat pump

This heat pump system uses near-surface groundwater resources, with only small seasonal temperature fluctuations. The water-water heat pump is working in an open water system, where the groundwater is extracted via a well pump from the intake well, usually from depths of up to 20 meters. With the help of the heat exchanger, the thermal energy of the groundwater is transferred to the refrigerant in the pipes inside the heat pump.

The efficiency of a water-to-water heat pump depends on the quality and temperature of the
ground water and also on the height of the ground water level. Since the water quality varies a lot, it is recommended to use a DC heat exchanger to protect the plate heat exchangers within the heat pump. Bolted stainless steel heat exchangers have proven to be suitable for this purpose.

The height of the ground water is an important factor considering the economical aspects. Especially for buildings that already have a groundwater well, a water-to-water heat pump can be a good economical option compared to ground-to-water heat pumps.

**Water source heat pump - open loop system (well based)**

![Diagram of a water source heat pump - open loop system (well based)](http://www.ashireporter.org/HomeInspection/Articles/Warming-Up-to-Heat-Pumps/15064)

**DC Link**

Soldered plate heat exchangers are common in today’s heat pumps for transferring heat from the primary to the refrigeration circuit. These heat exchangers are exposed to high energy loads, they are in constant contact with the medium serving as a heat source in the primary circuit. In the case of water-to-water heat pumps, the primary medium is water with a wide variety of dissolved chemical substances. This leads to a risk of corrosion and deposits on the copper-brazed plate heat exchangers.

**Groundwater**

If groundwater is used directly as a heat source, at least two wells are required. Planning and execution of this well system must be carried out by an approved well construction company. The use of groundwater is subject to approval according to the Water Resource Act. Water-to-water heat pumps can achieve very high annual performance factors due to the high primary temperatures if properly planned and executed. However, various factors must be taken into account during planning:

- A quantity of 250 l/h per kW cooling capacity of the heat pump should be permanently...
available, the flow rate should be verified by a pump test.

- The maximum temperature change of the ground water must not exceed +/- 6 K.
- The chemical composition and quality of the ground water must be taken into account (electrical conductivity, oxygen, iron and manganese content). Depending on the chemical composition, there is a risk of corrosion for pipelines and plant components as well as the risk of ochre formation in suction and absorption wells. A chemical analysis of the ground water is therefore recommended.

As with brine-to-water heat pumps, the temperature difference in the primary circuit is of great importance for the efficiency of the overall system in water-to-water machines. Due to the somewhat higher source temperature, a volume flow based on temperature difference of 3 K is recommended for water as the primary source; a maximum of 6 K is permissible. This maximum value should never be exceeded. In winter, a groundwater temperature of 8 °C is to be assumed; higher temperature differences could lead to freezing at the heat exchanger.

1.2.3 Air-to-water heat pump

Air-to-water heat pumps extract thermal energy from the outside air and transfer it to a water-based heating system within the building. Depending on the local climate the air-to-water heat pump might not be able to provide enough heating during the coldest months and the lowest outdoor temperatures. Because of this fact, hybrid-solutions with a back up system can be an option (see below).

![Diagram of an air-to-water heat pump system](image)

*Figure 8: Air-to-water heat pump system, source: Viessmann*

The primary source air has two properties, which must be given special attention when planning an air-to-water heat pump: The high temperature fluctuations between winter and summer affect the performance and the efficiency of the system. The necessary fans cause noise, which requires an acoustic assessment of the installation site.
**Air-to-water heat pumps with unregulated compressor**

Heat pumps are used both with power-controlled and non-controlled compressors.

Under certain operating conditions, uncontrolled, so-called fixed speed compressors achieve a better annual performance factor.

If source temperatures are constant (such as exhaust air) or if there is a high heat demand in summer (such as for heating outdoor swimming pools), the use of controlled compressors is not necessary. However, heat pumps with unregulated compressors usually require a buffer storage tank in order to operate efficiently.

**Heat pump capacity**

When using the air as a heat source, the heat output of the heat pump changes ambivalently with outside temperatures. Very large systems would therefore be required for monovalent operation. This would mean that the heat pump would be oversized for most of the time. For this reason, air-to-water heat pumps are predominantly operated bivalently.

**Dimensioning of the connecting lines**

Since the output of an air-to-water heat pump is so sensitive to temperature fluctuations, the connecting pipes to the heating system are designed to the point of maximum possible heat output of the heat pump. It must be ensured that the thermal energy is safely transferred to the downstream system. The bivalence point should be between -3 °C and -10 °C outdoor temperature so that the pump can cover a large part of the annual heat load.

**Air flow for internally installed air-to-water heat pumps**

With internally installed air-to-water heat pumps, the outside air is supplied to the heat pump via a duct network. It is therefore necessary to perform a pressure loss calculation for the piping network. The technical data sheets of the heat pump specify the maximum permissible pressure loss a fan can overcome. The planned duct system must be checked on the basis of this value. The pressure losses of the air ducts depend on the air volume flow, in the data sheets of the components the individual resistances are assigned to different heat pump types.

1.2.4 Hybrid heat pumps

Hybrid heat pumps combine the heat pump with another non-renewable heat source, such as a gas boiler for example. This is also known as a dual fuel system. Both heat generators are being monitored by an intelligent control unit, that aims for an intelligent and efficient use of energy at all times. It takes aspects such as the exterior temperature and the current energy costs from the grid into consideration. Therefore, hybrid heat pumps can guarantee a flexible and efficient heat production independent from exterior circumstances.

One disadvantage of hybrid systems is that fossil fuels are used for the heat production, even if its only partly. For climate mitigation the use of a heat pump alone is the better option. Hybrid heat pumps are often used in buildings that already have a traditional system in place. The installation of both systems in a new building comes with high investment costs at the beginning.
1.2.5  Low temperature district heating

Low temperature district heating are innovative heat infrastructures based on networks with low temperatures (20 to 95 °C). The heat supply is carried out under criteria of climate protection and perspective cost-effective heat supply mainly based on renewable energies and waste heat.

The quality of heating networks is determined by the degree of innovation of individual components, as well as the optimized interaction of these in an overall system. This includes innovative heat generation, cross-seasonal storage concepts such as seasonal large-scale heat storage facilities, efficiency-promoting network optimisation measures, integration of fluctuating heat generation or energy sources, efficient sector coupling, use of digitization strategies, measures to improve economic efficiency or institutional innovations.

Low temperatures offer the following advantages:

- Development of additional local heat sources (this includes above all fuel-free technologies, such as solar collectors, waste heat recovery, and large heat pumps)
- Increasing the yield of solar collectors and the efficiency of heat pumps
- Reduction of network losses especially in areas with low heat density
- Reduction of thermal stresses in the pipe materials leads to less degradation
- Potential contribution to cost reduction through intensified development of renewable energies with economies of scale and other systemic advantages

1.2.6  Cold heating network

Cold heat networks operate at an even lower temperature level (8 to 20 °C). The energy supply is provided in several units, which combine different heat sources. Usually heat pumps access groundwater or soil. Advantages of cold local heating compared to conventional heat networks are a possibly lower heat loss during distribution, the possibility of using inexpensive materials, transport over longer distances as well as better step-by-step expansion. Heat pumps in the refrigeration network can be operated with a higher COP than decentrally installed heat pumps.

March-Hugstetten: The cold heating network has been implemented by EnBW Regional AG since 2009 and is intended to supply 55 low-energy buildings with a total output requirement of 760 kWTh. The network operator pumps groundwater with a temperature of 10 to 12°C all year round from seven extraction wells and conducts the water to the customers through a 2.5 km long uninsulated pipe network. The customers use the water to operate their decentralised heat pumps: they extract heat energy from the groundwater and use it to supply their buildings (underfloor heating). The cooled water is fed into the network return and runs into absorption wells. The transfer point is one meter after the property boundary is crossed. The EnBW Regional AG sells the house owners extracted groundwater, the development of the heat source was carried out at the risk of EnBW, the house owners use electricity to provide heat from the low temperature source. A cooling operation is also conceivable.
2 Implementation

2.1 Heat pumps in new buildings

Most heat pumps are installed in new buildings. This is because the work required to access the heat sources for brine/water or water/water heat pumps is easier to carry out in new buildings. Because of the necessary earthworks, the construction required for integration in existing buildings is usually quite extensive. For this reason, air-to-water heat pumps are often used for the renovation of existing systems, because tapping the "air" energy source requires very little construction work.

These requirements are to be implemented in a system taking into account the regulations for energy saving applicable in the respective country and the structural conditions. Also, the desires of the building’s owner and the user behaviour should always be considered.

When planning a heat pump system, it is essential that all components are a good fit for each other. This assures economical operation and the low consumption and operation-related costs compared to all other heating systems.

2.2 Heat pumps in old buildings

The use of a heat pump is particularly recommended for the renovation of buildings, when a very favorable energy consumption figure is desired.

The funding programmes of the respective country should be used. In Germany, the refurbishment of existing buildings and the modernisation of old heating systems are supported by the “Kreditanstalt für Wiederaufbau” (KfW-Bank) with a variety of programmes.

The conditions depending on the application should be checked. A fundamental distinction must be made between the replacement of older heat pumps and the conversion of heating systems to heat pump technology.

Depending on the heat source used so far (air, water, ground), the measures and the required effort differ. The replacement of an air-to-water pump is easy to implement.

If water was previously used as the energy source, the well system must always be checked. In doing so, the flow rates, the water quality and the condition of the absorption well must be taken into account. The submersible pump should also be urgently included in the inspection. If the examinations lead to a positive result, the existing heat pump can simply be replaced by a new unit.
2.3 Current state in the Baltic Sea Region

Figure 9: Price Ratio: Heat pump energy vs. oil in Europe

Figure 9 shows the price ratio of heat pump electricity to heating oil in Europe. The most favourable ratio occurs in Hungary, followed by the Scandinavian countries, Poland, France, Italy and Portugal.

The price ratio is the quotient of electricity price to oil price for an equivalent amount of thermal energy. As electricity consumed in Germany, for example, is relatively expensive due to levies and charges, this results in correspondingly high price ratios of up to more than 4.

This ratio can be interpreted as a value that indicates the COP that a heat pump has to operate with in order to ensure economical operation compared to fossil heat supply.

This means that different economies are created depending on the country.
Figure 10 illustrates the sales figures for four different types of heat pump in Germany from 2000 to 2018. The highest increase took place in 2006, when a total of 32,000 heat pumps was added.
3 Conclusion

Disadvantages

- The installation of a heat pump system is usually associated with higher investment costs compared to conventional fossil systems. Special expenditures arise for example with earth drillings.
- If the heat pump system is not combined with a PV system, it is 100% dependent on electricity prices on the market. If electricity prices rise in the future, this would definitely be a disadvantage.
- The environmental balance of a heat pump varies depending on the electricity consumption and the origin of the electricity.

Advantages:

- If a heat source with a high temperature level is available and can be developed at low cost, short amortization periods are achieved.
- Especially in combination with photovoltaic systems, an extremely high flexibility of the overall system can be achieved.
- Heat pumps represent a sustainable energy solution which renders renewable heat sources accessible within an economic and ecological framework.
- Heat pumps can be used for both cooling and heating, which is a clear advantage over conventional solutions.
Sources:

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