MODULE 4: RENEWABLE ENERGY

1 HEAT PUMPS

1.1 BASICS OF HEAT PUMP TECHNOLOGY

Heating systems of buildings that use fossil fuels (natural gas, oil) as heat sources operate in a quite straightforward way. The chemical energy stored in the energy carrier is being released during the combustion process that takes place in the boiler. The use of renewable energy sources often requires an additional technology which makes the renewable energy source available for heat utilisation.

Geothermic heat sources, underground or surface lakes and rivers, waste heat from industrial processes or merely the vast heat capacity of the atmosphere are available on temperature levels lower than the target temperature of a heating system. Therefore, additional performance input is necessary to raise the temperature of the source to that of the utilisation.

With the use of a heat pump one can exploit heat sources of lower temperatures and utilise their heat in heating systems operating on higher temperatures. The heat pump elevates temperature from the source to that of the utilisation by a refrigerant circuit. A seen in Figure 1, the heat source medium – may it be external air, brine or groundwater – is lead into one of the heat exchangers of the heat pump, while the target medium – usually secondary heating or cooling water – is connected to the other one. Depending on the type of operation (heating or cooling), the role of the heat exchangers can vary.

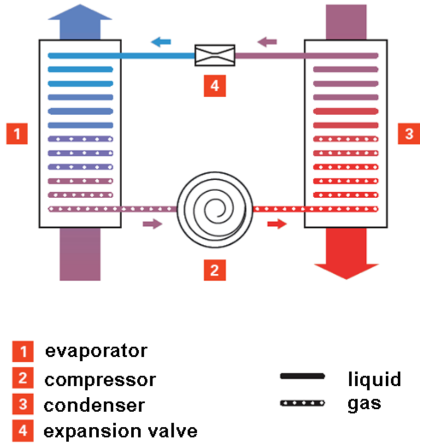

Figure 1: Components and cycle of a heat pump [1]

In Figure 1 the heating operation is shown, where the heat from the heat source is extracted through the evaporator and the heating performance is transferred to the heating system through the condenser. The refrigerant has to evaporate entirely in the evaporator so that it can enter the compressor in a fully gaseous state of matter. There – as a result of the compression – its pressure and temperature are being elevated to the level of the heating system. The external electric power is introduced into the system in the compressor. The heat, which can be now directly utilised, is transferred to the heating system through the condenser. During this process, the heating water gets heated up and the refrigerant condenses. After this stage, it releases pressure while streaming through the expansion valve. From this stage, the process is being repeated from the evaporator.

1.2 HEAT SOURCES

Heat sources of heat pumps can vary in a wide range. Therefore, it is not necessarily the right approach to list the environmental heat sources used in the heat pump technology, rather one should reflect on the variety of environmental and industrial low-temperature heat sources which can be utilised in heating systems as renewable sources of energy by the use of a heat pump. It shall not be overlooked that industrial processes produce a remarkable amount of waste heat which are released into various heat sinks (the atmosphere, the ground or even the sky) by further use of non-renewable energy. The utilisation of these is not directly associated with renewable use of energy, however, they come to be permanently and therefore offer a renewable alternative for the energy household.

1.2.1. Air-to-water heat pumps

Air-to-water refers to the heat source ambient air and water as the secondary medium on the side of the heating or cooling system. In cooling systems, this medium can be a mixture of water and glycol as well. Air-to-water heat pumps are the cheapest to install, because the access to the heat source does not require special equipment, only a heat exchanger, cased in the external unit of the heat pump.

The ambient air contains heat in vast quantities, however the availability of this heat does not coincide with heating and cooling needs of buildings. The temperature of the heat source varies significantly over the course of the year. Low temperatures of the heat source and high heating demand come equally at the same time as high temperatures of the heat sink and high cooling demand. Therefore, air-to-water heat pumps can reach the lowest COP values, although they are the easiest and cheapest to install.

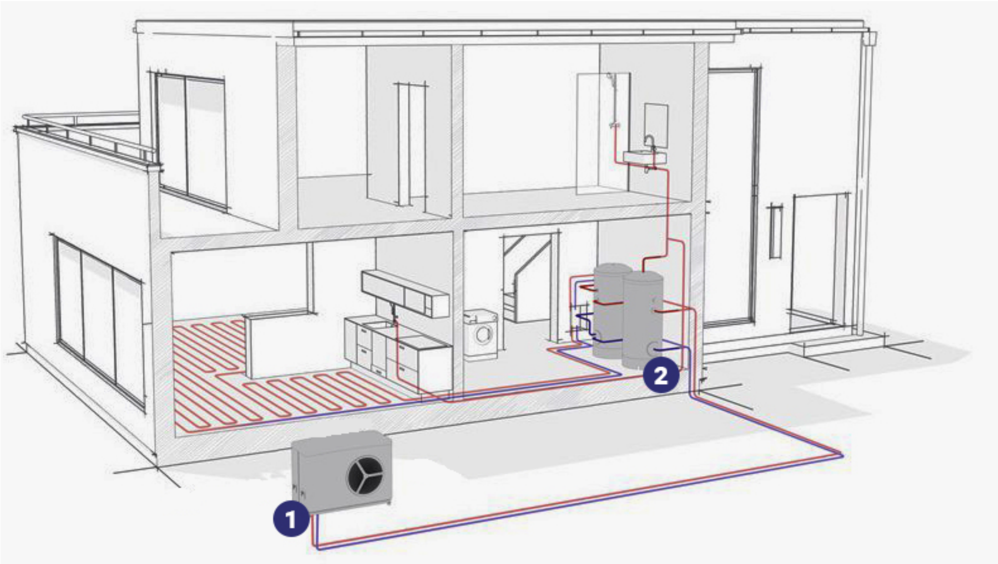

Figure 2: Ait-to-water heat pump system supplying a single-family house with heating and DHW [2]

However, the advantages on the cost and installation side do not come without negative aspects. Special attention has to be paid on the noise pollution the external unit of the air-to-water heat pump can cause, as this can disturb the users of the system and even the neighbours. Shielding constructions can help minimise the noise pollution, but the streaming of air into and out of the external unit cannot be hindered.

Air-to water heat pumps can be either of split or monoblock construction.

- Split system: a connection between the outdoor and indoor unit is made using the refrigerant circuit pipeline, in which the refrigerant transfers the heat generated to the exchanger in the indoor unit. In the case of split heat pump heating, due to the connection of the refrigerant circuit of the outdoor and indoor units, the installation cost will be higher compared to the monoblock heat pump, which work can only be performed by a specialist authorized to install the cooling circuit. No danger of frost in the external unit. [3]

- Monoblock system: no refrigerant authorization is required for installation, i.e. no refrigerant circuit work is required. This results in cost saving, because a heating system installer can also install the unit. In the case of a monoblock heat pump, as the cooling circuit is built into the outdoor unit in the factory, a possible refrigerant leakage can be almost ruled out. Frost protection must always be provided for the monoblock heat pump. In the event of a prolonged shutdown, the outdoor unit recirculates the required heat from the heating buffer tank to the outdoor unit, or even activates a factory-installed heating cartridge. Assuming a longer power outage, the most accurate solution is to disconnect the primary monoblock heat pump from the secondary heating system inside the building with a properly sized heat exchanger and fill the external primary (heat source) system with antifreeze. [3]

1.2.2. Heat pumps using Ground Heat

Geothermal energy, given its continuous availability, is one of the most reliable of renewable energy sources. Heat from the ground can be utilised in various ways. Depending on how deep the level of heat extraction is one can distinguish between shallow and deep use of geothermal energy. Deep geothermy is not being considered in the current chapters, as it supplies systems on the larger scale individual buildings. Shallow geothermy can be further divided into subcategories.

Ground collector systems use pipelines laid in 1-1.5 metres depth underneath the ground level as seen in Figure 3. Therefore, it is clear that it does not use geothermal heat directly, as this would be not perceivable in such a low depth. Rather it utilises the solar heat stored in the upper ground layers. Compared to air-to-water heat pumps, systems with ground collectors rely on a much more balanced heat source. The thermal capacity of the ground layer ensures that temperature peaks in the depth of the collector stay higher in winter and lower in summer compared to the ambient. Additionally, peaks come to be with a certain delay. To avoid frost related damage, an antifreeze-mixture (water+glykol) is to be used in the pipeline. Attention has to be paid that no trees or bushes, can be grown above the pipes, as roots would harm the pipelines. Furthermore, the any kind of shading of the utilised area decreases the efficiency of the system.

Figure 3: Pipelines of a Ground Collector System laid in 1-1.5 metres depth [4]

Downhole heat exchangers are U-tube heat exchangers installed inside a borehole that goes down to approx. 100 m depth, where effect of the geothermal gradient can be perceived and the geothermal heat can be utilised. A seen in Figure 4, the temperature in the ground is independent of the seasons under 30 m depth. This makes downhole geothermal applications very reliable in terms of constant heat source temperature.

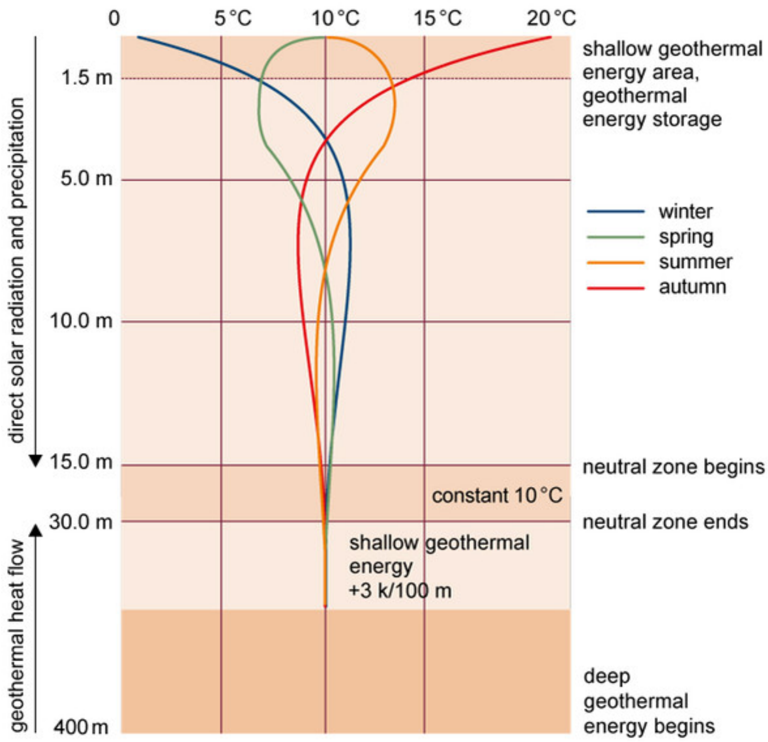

Figure 4: Ground temperatures over the vertical [1]

The site-specific thermal properties of the geological medium play an important role in the design and installation of a system. That is why their knowledge is vital. From the early 1990s, determining the thermal properties of the soil was very time and cost consuming. In practice, the necessary tests were carried out only for large investments, and it was common to use estimated values when designing smaller geothermal systems. The necessary safety factors that were taken into account in the design usually meant significant additional costs. [5]

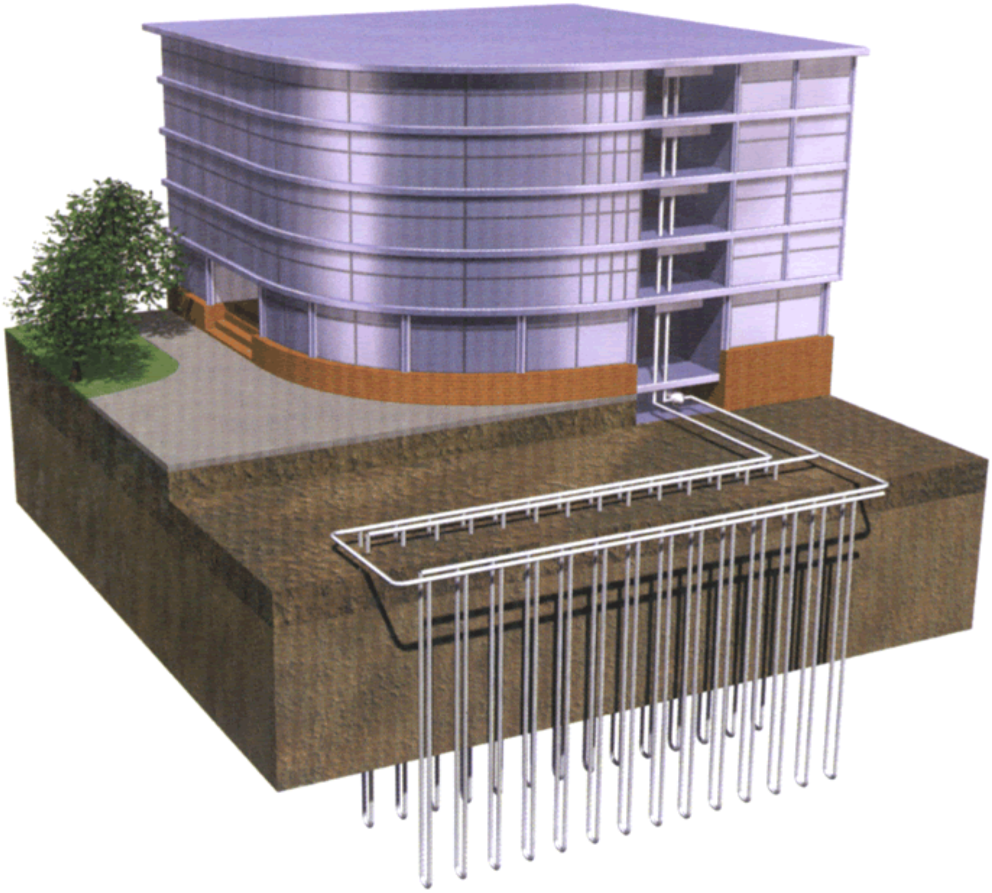

Figure 5: Downhole heat exchangers [6]

Today, a thermal response test is a quick and easy-to-use method for determining local geothermal properties of ground. The main advantage of the geothermal probe test over other methods is that the measurement is performed in situ in the pre-installed geothermal probe, as opposed to the traditional method where rock samples are measured under laboratory conditions. The resting temperature of the soil varies along the borehole. These are determined during the thermal response test. During the test, the test equipment is hydraulically connected to the geothermal downhole heat exchanger. In a closed system, water circulates and is heated to a specified heat output. This heat flows into the ground through the geothermal downhole heat exchanger. During the measurement, the flow and return temperatures and the mass flow are recorded. Based on the temperature curves, the thermal conductivity of the ground is determined by the Kelvin line source (line thermal conductivity) method. [5]

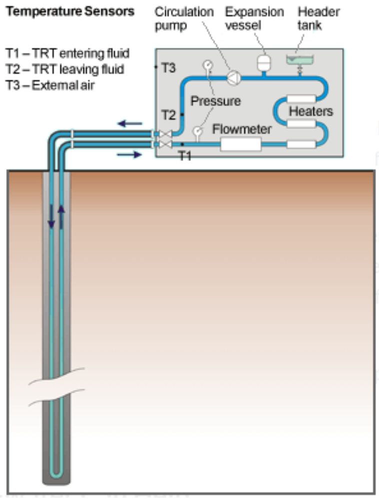

Figure 6: Thermal response test procedure [1]

An important factor in the design of a geothermal probe heat pump system is the thermal wellbore resistance, which expresses the heat transfer between the heat transfer medium flowing in the geothermal downhole heat exchanger and the geological environment. The thermal resistance between the heat transfer medium and the borehole wall gives a temperature difference, which is the difference between the temperature of the liquid flowing in the geothermal downhole heat exchanger and the temperature of the borehole wall for a given specific heat removal rate. The so-called thermal borehole resistance depends on the location of the geothermal downhole heat exchanger in the borehole, the thermal properties of the filling material and the quality of the filling, as well as the bore diameter. The thermal borehole resistance has a significant effect on the operation of the system and should be kept as low as possible. [5]

Determining an undisturbed ground temperature is an essential element of a geothermal downhole heat exchanger system design. The temperature rises with depth due to the geothermal gradient. Seasonal changes in ground temperature due to changes in outside air temperature can be detected up to a depth of about 15-30 meters, depending on location. [5]

The size of the probe field is determined by the following characteristics:

1. the energy characteristics of the building (determined by the building service engineer),
2. thermal conductivity of the soil (characteristic value of the construction site, determined by measuring procedure using the previously mentioned method)
3. resting temperature of the soil along the entire length of the downhole heat exchanger (determined with a measuring device)
4. thermal wellbore resistance. [5]

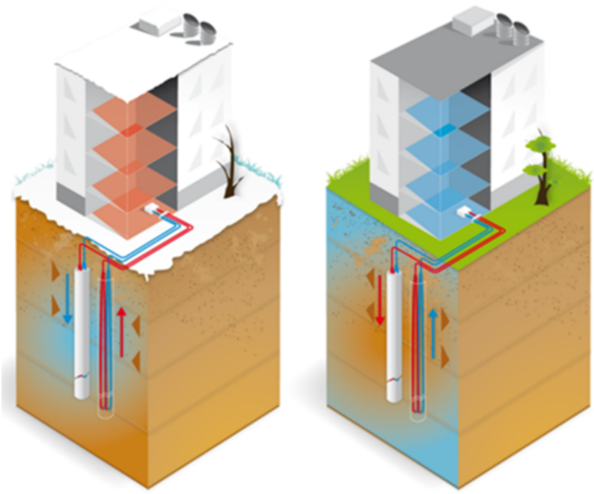

Figure 7: Heating and cooling operation helps not deplete the geothermal source [7]

It is recommended to use a geothermal downhole heat exchanger filed for both heating in winter and cooling in summer. Heat withdrawal in winter may be of higher intensity than the strength of the local geothermal heat source, which would lead to the depletion of the source. Cooling operation in summer charges back the ground with heat, making it into a long-term thermal storage medium.

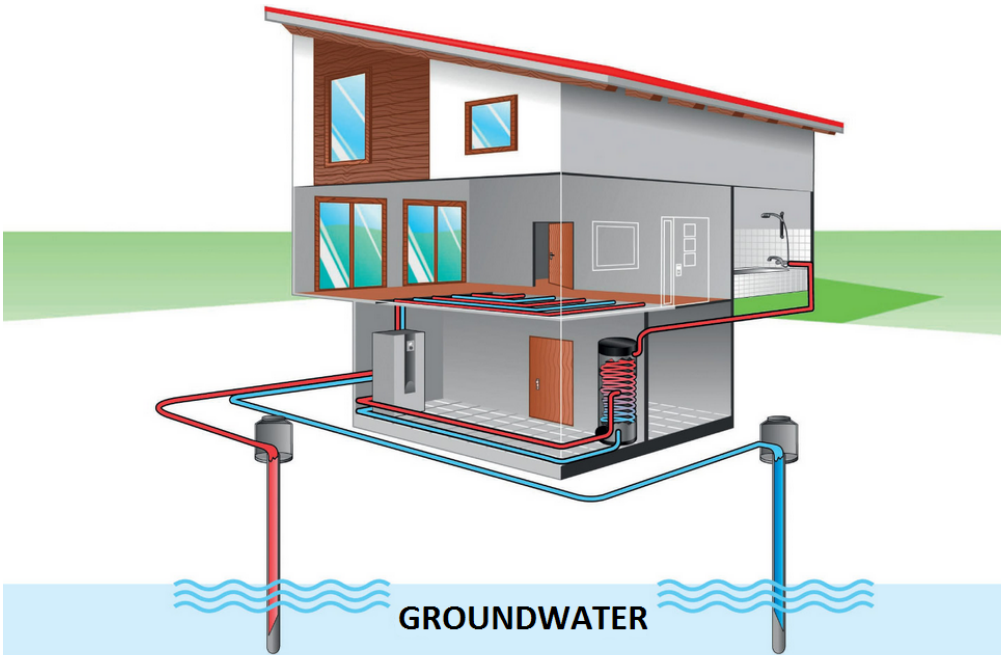

Figure 8: Groundwater heat utilisation with two wells [8]

The heat of the deep layers is brought to the surface by the geothermal fluid. In addition to water, the main components of the fluid are dissolved salts, gases and possibly suspended solids. At the selected location, it must be examined whether it is geologically possible to bring thermal water of the required and usable quantity to the surface. The heat content of the thermal water must be used up to the lowest possible temperature level. Heat utilization depends on the surface temperature of the water and on the mass flow of the thermal water well. Due to the re-injection of thermal water, only its thermal energy is utilized, and the amount of water is returned to the aquifer. [9]

1.3 OPERATIONAL PRINCIPLE

The operational principle of the heat pump is based on the Carnot-cycle of a refrigerant. The subtasks of the cycle are as follows:

- 1-2: The refrigerant evaporates, absorbing ambient energy.
- 2-3: The compressor raises the refrigerant vapour pressure and temperature using the absorbed electricity.
- 3-4: The refrigerant condenses, releasing the absorbed ambient energy and the introduced electricity.
- 4-1: During expansion, the refrigerant pressure and temperature return to the initial state.

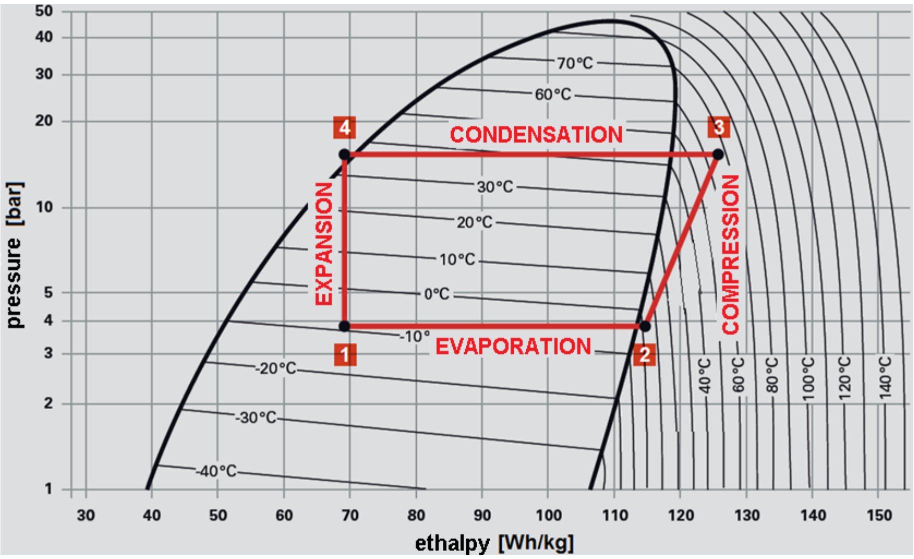

Figure 9: Carnot cycle of a heat pump in logp-h diagram [1]

The higher the temperature of the heat source and the lower the temperature of the heating system, the higher coefficient of performance (COP) can be achieved. If the heating flow temperature is 1K lower, the COP is 2.5% higher. If the temperature of the source medium is

1K higher, the COP is 2.7% higher. The smaller the temperature difference between the heating flow and the source medium inlet temperature, the higher the COP. Therefore, higher source temperatures (ground heat, groundwater, waste heat) are favourable, such as low temperature heating systems, such as surface heating.

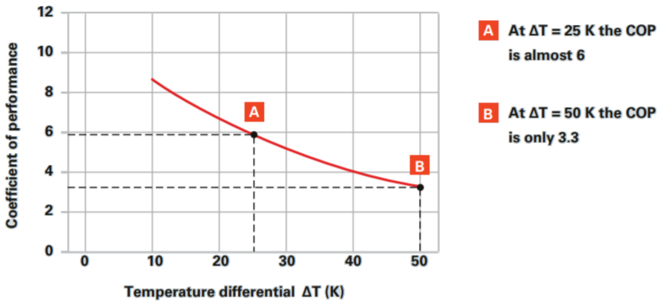

Figure 10: COP drops with higher the temperature difference between heat source and heating flow [1]

Determination of COP by Measurement [10]

The DIN EN 14511 standard defines the standard conditions for measuring the COP value of heat pumps. This is based on the establishment of stationary measuring points, which form the basis of the comparability of devices, and can be taken as a starting value during design.

Heat sources:

- Outside air, exhaust air for ventilation (A: air)
- Surface or groundwater (W: water)
- Ground heat (B: brine)

The nominal operating temperatures for both the heat source and the heating flow are as follows:

Heating flow temperatures:

- Low temperature: 35 ° C: W35
- Average temperature: 45 ° C: W45
- High temperature: 55 ° C: W55
- Very high temperature: 65 ° C: W65

For air as heat source:

- -15°C: A-15
- -7°C: A-7
- 2°C: A2
- 7°C: A7

- 12°C:	A12

For exhaust air as heat source:

- 20°C:	W20

For ground heat as heat source:

- -5°C:	B-5
- 0°C:	B0
- 5°C:	B5

For water as heat source:

- 10°C:	W10
- 15°C:	W15

One can observe that the standardised testing conditions are given as the source temperatures would naturally occur.

1.4 MAIN HEAT PUMP COMPONENTS

THE COMPRESSOR

The compressor is designed to compress the gaseous, fully evaporated refrigerant, the entry of a liquid phase leads to failure. The steam is slightly superheated before it enters the compressor. The degree of overheating is controlled by the expansion valve. Constructional varieties are:

- Scroll compressor (low to medium power)
- Reciprocating compressor (low power)
- Screw compressor (for high performance)

Scroll Compressor [11]

The operational principle of the scroll compressors is fundamentally different from conventional reciprocating compressors. Scroll compressors marked a radical breakthrough in technology that significantly changed structure, performance, and lifespan. During compression, the upper Archimedean spiral is motionless, the one below moves eccentrically on the drive shaft along an orbital trajectory. In this way, the refrigerant is forced into the constriction slots, which effectively close as soon as they reach the centre of the coil and thus compress the gas. When these gaps reach the centre of the coil, the gas reaches its final pressure and leaves the compressor on the central discharge port in the stationary coil. Characteristic features:

1. Lack of suction and discharge valves. This has two important advantages over a reciprocating compressor: it eliminates the pressure drop across the valves which means a significant increase in the cycle power factor and eliminates the noise caused by the valve.
2. Due to the elimination of dead space, the volumetric efficiency is close to 100%.
3. Fewer parts cause fewer failures.

Taken together, these factors mean that scroll compressors represent a significant improvement in energy delivery efficiency over conventional reciprocating compressors. In general, the COP value is 10-20% higher than for reciprocating compressors in the 1.5-15 hp range.

In the case of EVI scroll compressors, an additional heat exchanger – called an economizer – is built into the refrigeration circuit with its own expansion valve, through which a refrigerant with increased enthalpy but significantly lower than the final compression temperature is introduced into the compressor. This has a double effect: on one hand, it cools the final compression temperature, and on the other, it increases the evaporation capacity, thus the COP value of the compressor, with powerful aftercooling.

COMPRESSOR PERFORMANCE REGULATION

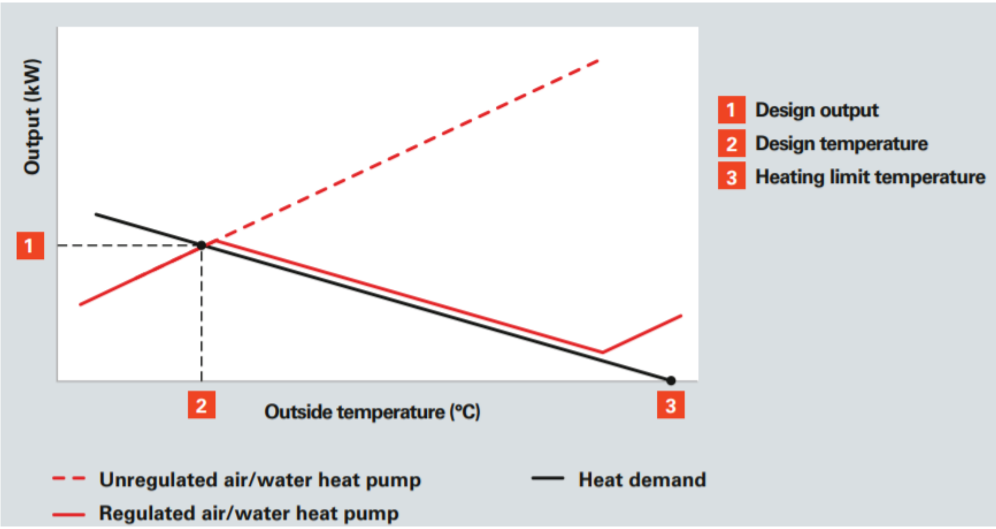

Figure 11: Heat pump performance regulation against the natural output rise with higher outside temperature [1]

In Figure 11 one can observe that if the heat source is the external air, the output performance would rise with the rising outside temperature. However, heat demand drops with rising outdoor temperature, so the heat pump would be forced into extremely disadvantageous low output rates without proper performance regulation. Therefore, precise performance regulation against this natural output rise is especially important for air to water heat pumps, where the temperature of the heat source changes the most during the year.

Compressor Performance Regulation with Inverter

The mains voltage (230 V ~) is converted to direct current. Depending on the frequency, the compressor speed varies, so does the power of the heat pump. It is very effective, especially at part load.

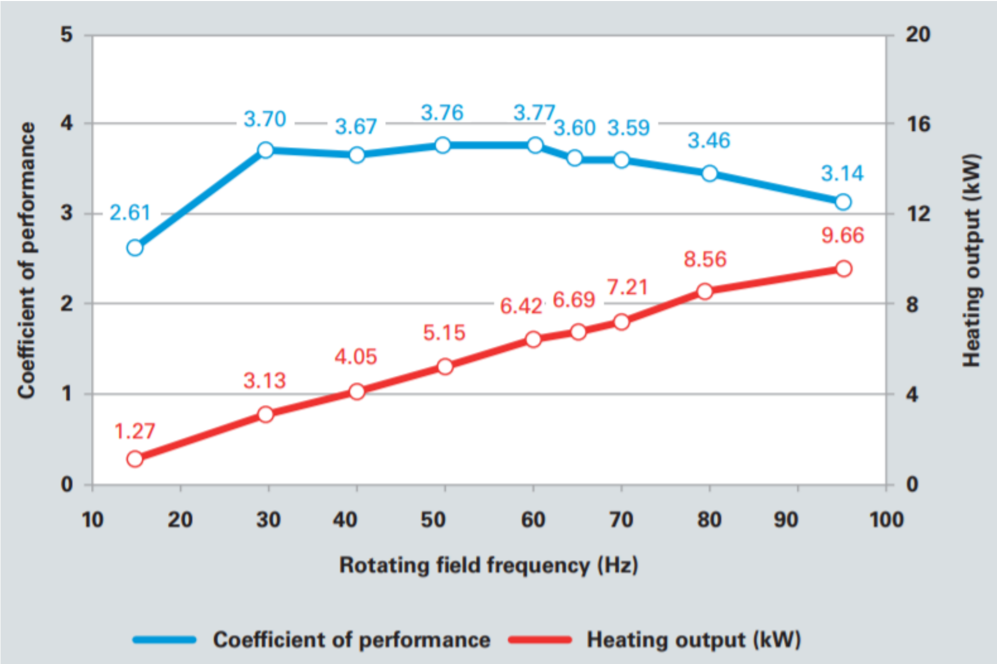

Figure 12: Performance regulation with inverter [1]

To judge whether it is better to utilise an on-off scroll or inverter compressor to a particular heat pump type, it is important to know that an inverter heat pump achieves the best efficiency at 70% of the compressor speed. Thus, in normal operation, this means that heat pumps with inverter technology usually operate in the less efficient range, i.e. above or below the optimum compressor speed. In contrast, on/off heat pumps (with scroll compressor) always operate in the optimum operating range and have basically been optimized for this ideal operating point. Constantly variable speed, variable speed compressors are subject to greater wear and tear, as a result of which they reach the end of their service life sooner. In contrast, a heat pump with an on/off scroll compressor has three times the life of an inverter compressor. On/off devices have a consistently low noise emittance level. In addition, the noise reduction in these devices is also optimized for the frequency spectrum emitted during operation. [12]

Compressor Performance Regulation with Pressure Reduction Valve

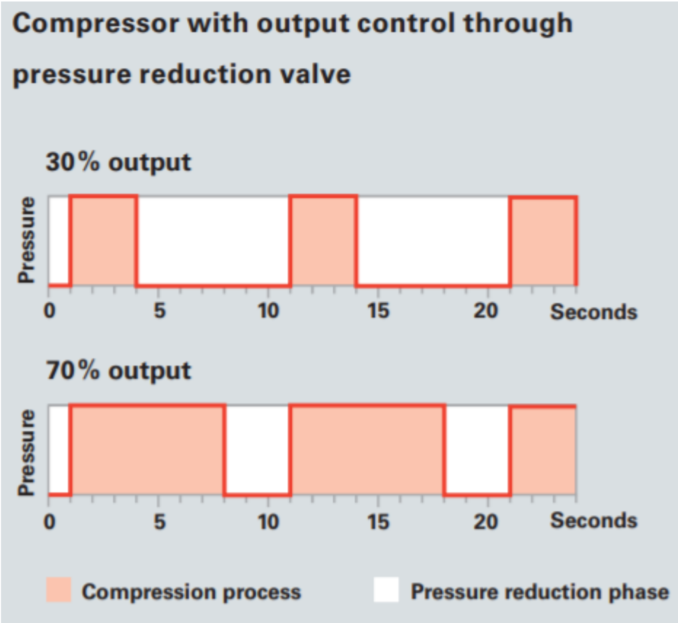

Figure 13: Compressor with output control through pressure reduction valve [1]

The compressor is equipped with a relieving. When the solenoid valve opens, the compressor runs depressurized. In this case, the heating output is paused. Based on the division of the periods, the power can be regulated between 30-100%.

Compressor Performance Regulation with Enhanced Vaporised Injection (EVI)

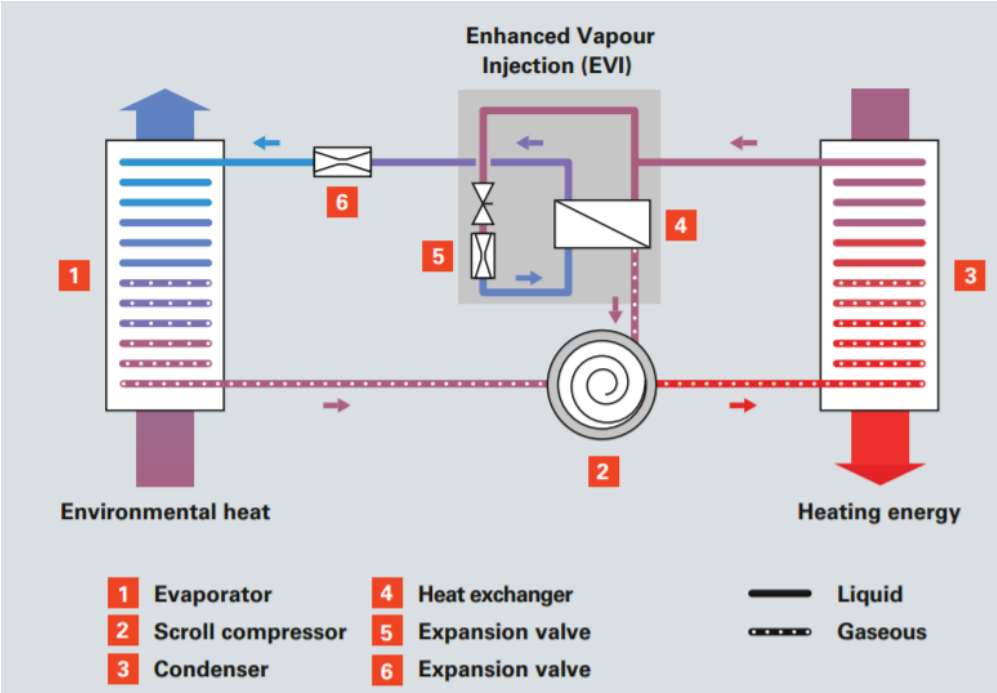

Figure 14: Compressor Performance Regulation with Enhanced Vaporised Injection [1]

It is basically nothing more than an additional built-in circuit in the cooling circuit of the heat pump. With EVI technology, higher inlet flow temperatures can be achieved at lower source temperatures - especially in winter with an air-to-water heat pump. EVI is automatically activated during periods when a higher heat pump capacity is required (this is especially the case in winter), which increases the heating capacity of the heat pump, so the heat pump provides a higher flow temperature. The intermediate circuit includes a separate heat exchanger and an (electronic) expansion valve. Once the heating energy has been transferred to the heating system, a small portion of the refrigerant (about 10-25%) is passed to the intermediate circuit, which evaporates there, and then this is returned to the compressor. Refrigerant is only "injected" at extremely high head temperatures of the compressor, which evaporates immediately upon contact with the surface. During high compressor loads (low source temperature, e.g., -7 °C air and high secondary heating flow temperature, e.g., 65 °C), "injecting" low temperature refrigerant cools the compressor, allowing increased performance. The EVI process is constantly active and its effect will only be perceived in situations where the compressor is under high load (DHW production and winter heating operation). The control of the intermediate circuit is demand-dependent, which means that the higher the demand on the compressor, the higher the amount of refrigerant introduced into the compressor through the intermediate circuit. For example the lower the source temperature, e.g. the downhole circuit cools from 3 ° C to 0 ° C and/or the secondary heating flow temperature rises from 35 °C to 55 °C. This results in an increase in the amount of refrigerant in the compressor. An increase in the refrigerant injected increases the pressure in the compressor and allows the compressor to provide higher heating performance. However, the compressor will have to work harder and consume more energy if the amount of refrigerant injected and the pressure increases. Compared to conventional compressors, EVI technology keeps inlet flow temperatures and heating output constant. In the case of conventional compressors, the heating capacity would be reduced, so that the inlet flow temperature of 65 ° C would not be possible via the refrigeration circuit, only with electric booster heating. [12]

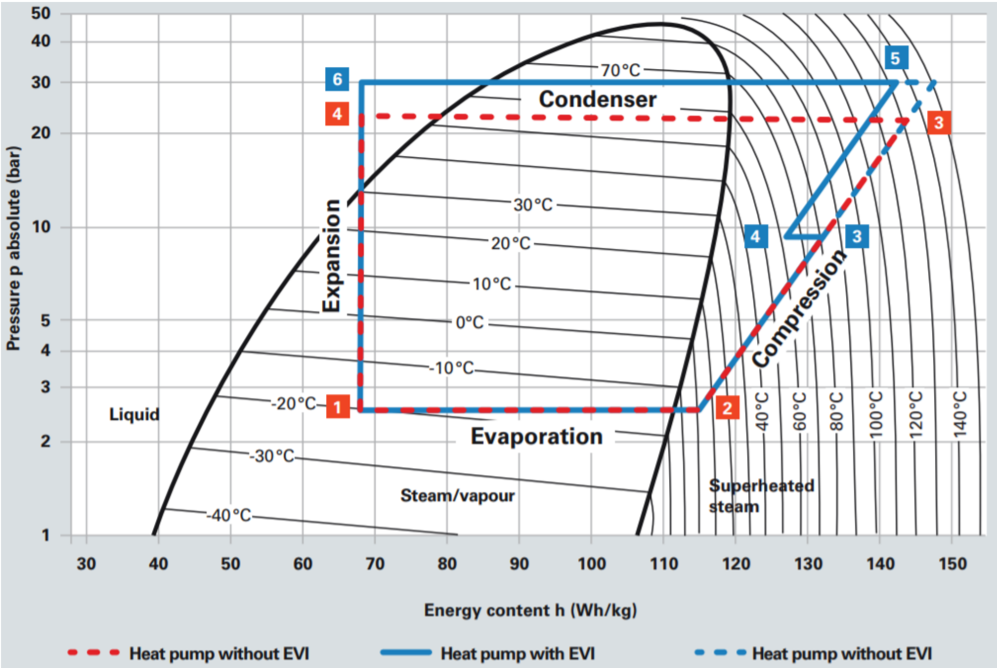

Figure 15: EVI process in logp-h diaram [1]

EXPANSION VALVE

Its function is to reduce the pressure of the liquid-phase refrigerant after it has transferred the heat to the heating system. The refrigerant is then ready to absorb ambient energy again.

The purpose of the expansion valve is to control the mass flow of refrigerant in the evaporator so that no liquid-phase refrigerant enters the compressor. Continuous changes in source temperature require the use of controlled expansion valves.

Thermostatic Expansion Valve

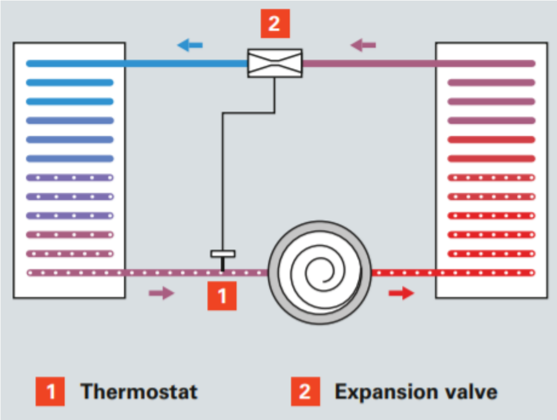

Figure 16: Thermostatic expansion valve [1]

The temperature controlled control valve measures the temperature in the suction line to the compressor and adds the refrigerant to the evaporator accordingly.

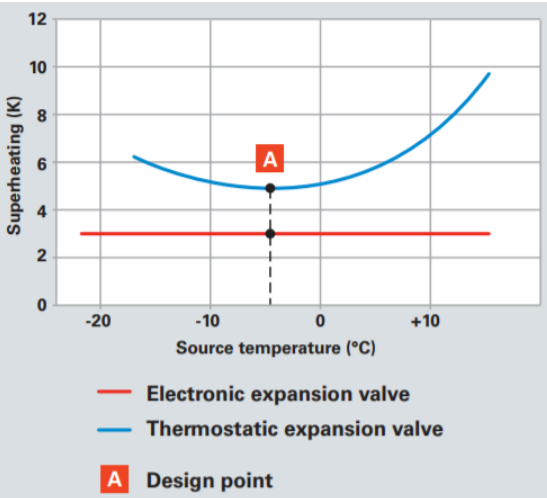

Figure 17: Overheating with thermostatic expansion valve [1]

Thermostatic expansion valves produce the minimum required overheating only in the sizing state, the degree of overheating is higher in all other states. The higher the refrigerant overheating, the lower the maximum achievable temperature on the condenser. With an electronic expansion valve, the output flow temperature can be maximized.

<u>Electronic Expansion Valve</u>

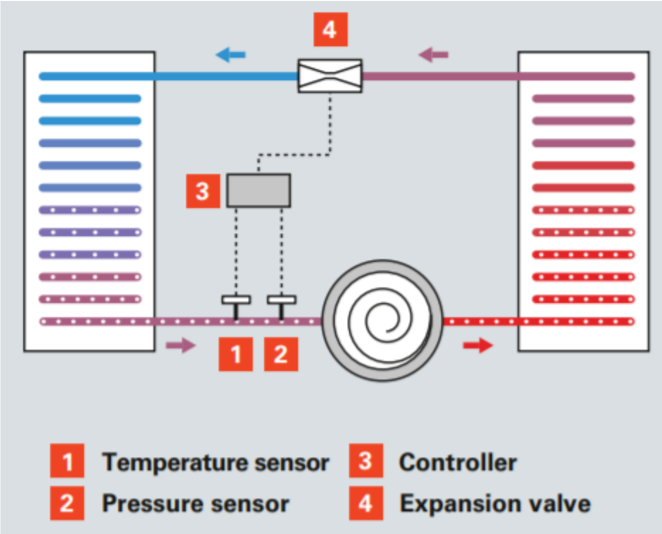

Figure 18: Electronic expansion valve [1]

Today's modern, monoblock or split air-to-water heat pumps include an electronically controlled expansion valve within the cooling circuit, as this is the only way to use heat pump equipment for active cooling in summer. However, the electronically controlled expansion valve also has additional benefits because their use constantly optimizes overheating, higher COP and safer system, no liquid droplets in the compressor. These benefits can also be exploited with ground source heat pumps, so more manufacturers are starting to switch to this principle today. Although thermostatic expansion valves are basically maintenance-free, their disadvantage is overheating optimized for a single operating point, and heat pumps with this type of expansion valve cannot be reversed. It measures both temperature and pressure in front of the compressor. With the help of an electric controller, the overheating can be kept constant throughout the power range of the compressor. An electric motor in the valve can quickly change the amount of medium dispensed. [12]

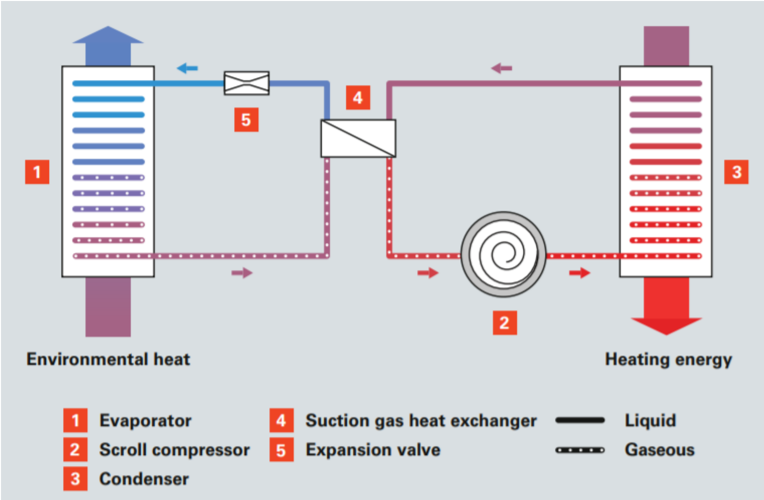

Figure 19: Heat exchanger in front of the compressor [1]

In multi-component refrigerants, perfect evaporation of all components can be ensured with a heat exchanger fitted in front of the compressor.

EVAPORATOR

In heating operation, the evaporator is the heat exchanger in which the heat is extracted from the heat source and lead into the refrigerant cycle. The construction of the evaporator is a plate heat exchanger in ground heat and water-to-water heat pumps. Due to this, it has compact design, high heat transfer performance. For contaminated water source medium, a coaxial heat exchanger ensures no blockage.

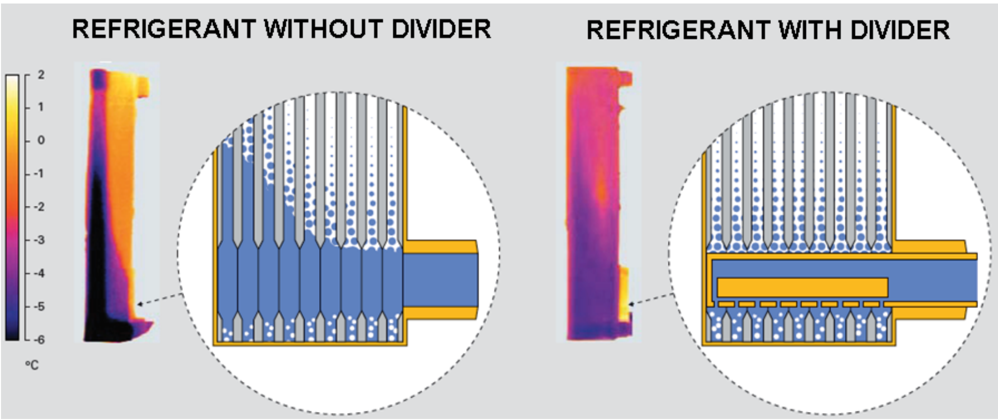

Figure 20: Evaporator streaming homogenised with a divider [1]

For the optimal use of the heat transfer surface, an even distribution of the refrigerant in the heat exchanger is targeted. Lamellar heat exchangers in air to water heat pumps have large surface on the primary side due to the low heat capacity of the air. At sub-zero temperatures, the moisture content of the air freezes on the slats. With a wider distance between the slats, this can be reduced, but not completely prevented.

Figure 21: Primary temperature incensement with unglazed solar thermal collectors [1]

Increase of Heat Source Temperature

Several methods have been used to increase the temperature of the heat source in order to reach higher COP. Transparent uncoated absorbers are one, but they make the performance highly weather dependent with increasing the temperature of the primary side with solar energy.

CONDENSER

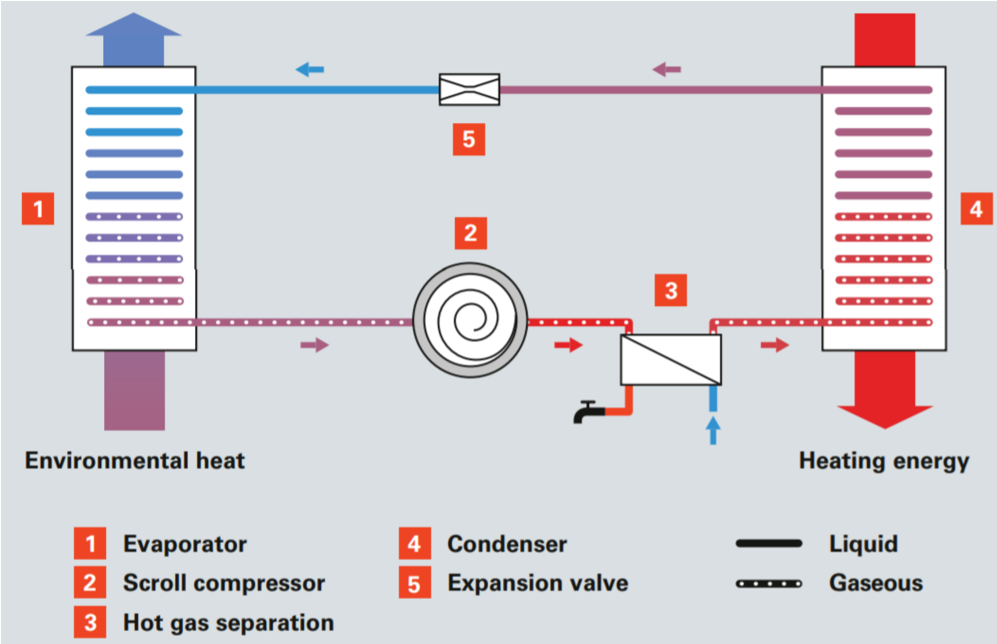

Figure 22: Hot gas separation for DHW production [1]

Primarily plate heat exchangers are used on the condenser side. Other designs only appear above 100 kW. Hot gas separation can be applied to produce domestic hot water (DHW) and reduce the hot gas temperature in before entering the condenser.

Refrigerants and their requirements

- It should have a low boiling point if possible.
- Small specific vapor volume.
- High specific heat capacity.
- You must not attack the heat pump components and the lubricants used.
- Must not be toxic.
- Must not be flammable or explosive.

1.5 OPERATIONAL MODES IN BUILDING HEATING

MONOVALENT OPERATION [13]

The heating demand is only ensured by the operation of the heat pump. The temperature conditions of the heat supply system must be designed so that the heat pump can provide the heat demand on its own. Low temperature heating systems, such as surface heating helps realise this. Heat pump inverter control: as the outside temperature rises, the power of the heat pump decreases.

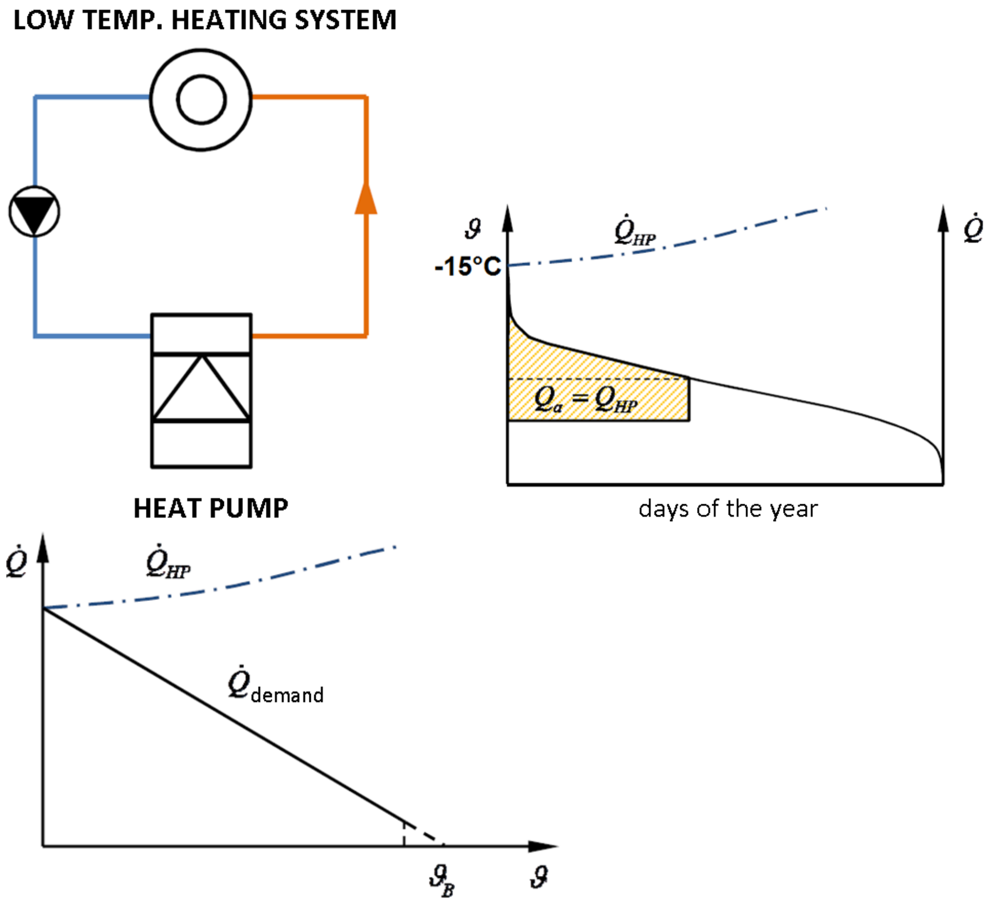

Figure 23: Monovalent operation of a heat pump [13]

BIVALENT, PARALLEL OPERATION [13]

Joint operation of boiler and heat pump for medium temperature heating systems (up to 80 °C), e.g. radiator heating. The heat pump remains switched on even at lower outside temperatures. The boiler covers the required additional power. Peak heat demand is covered by the heat pump and the boiler. This operation makes the use of a smaller peak boiler is possible.

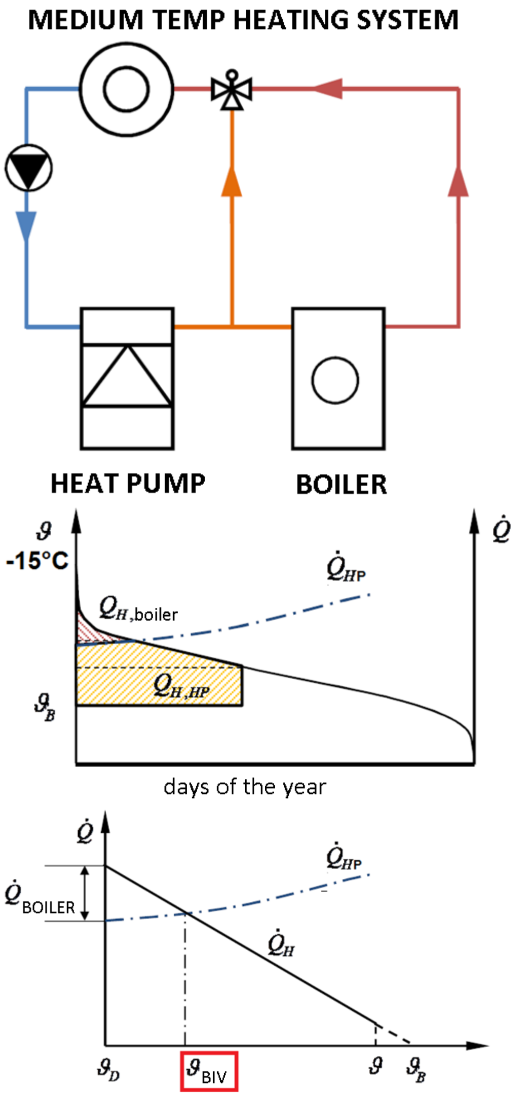

Figure 24: Bivalent, parallel operation [13]

BIVALENT, SWITCHING OPERATION [13]

The heat pump switches off at a lower t_{BIV} temperature and from there the boiler supplies the entire heat demand. This operation can occur when the heat pump has been sized for summer cooling. The heating output results from this choice.

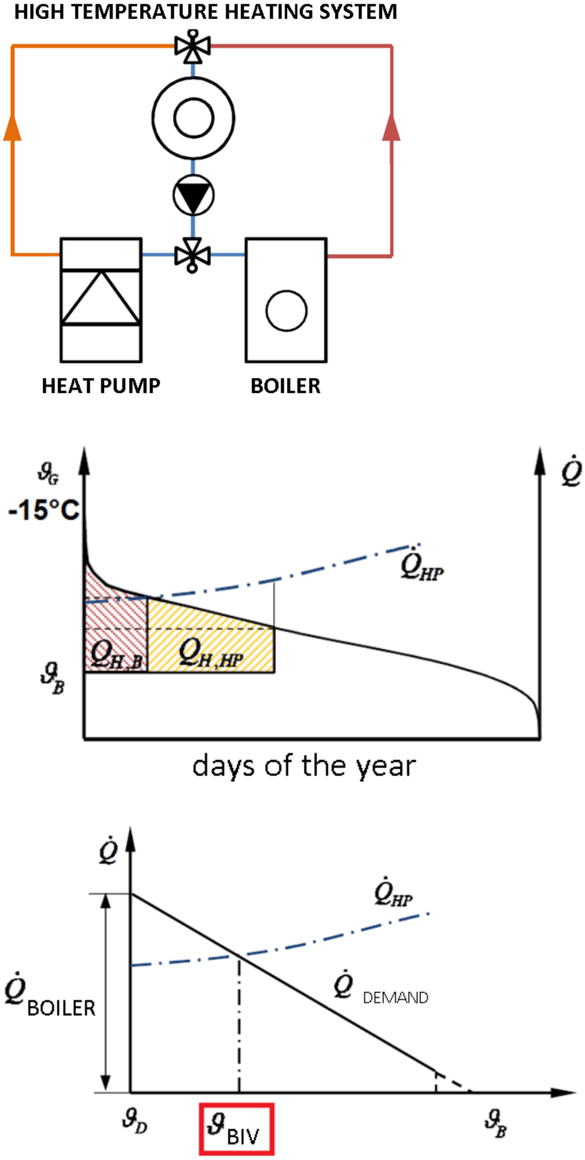

Figure 25: Bivalent, switching operation [13]

SWITCHING BETWEEN HEATING AND COOLING MODES

It is possible to switch the operation of heat pumps equipped with a four-way-valve between heating and cooling operational modes, so that the heat pump can be used the whole year long. Note that the direction of refrigerant circulation does not change at the compressor, as it can compress steam only in one direction. The two heat exchangers are change their roles, as

- in winter the environment is the heat source and the system is the heat sink;
- in summer the system is the heat source and the environment is the heat sink.

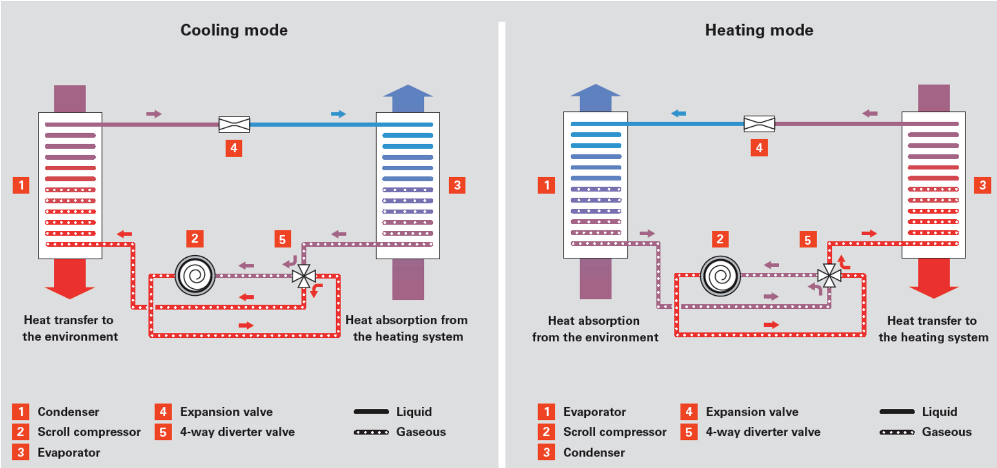

Figure 26: Switching between heating and cooling operation using a four-way-valve [1]

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