APPLICATION NOTE
HEAT PUMPS FOR LARGER BUILDINGS

Keeran Jugdoyal, revision by Nic Wincott

February 2018

ECI Publication No Cu0179

Available from www.leonardo-energy.org

Document Issue Control Sheet

Document Title:	Application Note – Heat Pumps for Larger Buildings
Publication No:	Cu0179
Issue:	02
Release:	Public
Content provider(s)	Keeran Jugdoyal, Nic Wincott
Author(s):	Keeran Jugdoyal
Editorial and language review	Bruno De Wachter (editorial review)
Content review:	Nic Wincott

Document History

Issue	Date	Purpose
1	April 2013	First publication, in the framework of the Good Practice Guide
2	February 2018	Second edition, re-written after a review
3		

Disclaimer

CONTENTS

SUMMARY

Heat pumps are increasingly being used in medium and large buildings to provide both heating and cooling. If specified and installed correctly they present a very good opportunity to save energy and reduce carbon emissions compared to traditional building heating and cooling technologies. This application note provides an overview of the types of heat pumps available along with the advantages and constraints of installing them in larger buildings.

The main appeal of heat pumps is that they take low grade heat from a renewable, cost-free source and transfer it at a higher temperature to where it is needed, in an energy efficient manner. There is a great deal of flexibility in the heat sources available, for example external air, pipework installed in the earth, water wells and boreholes as well as local watercourses and ponds.

Heat pumps that use external air as the heat source are relatively cheap and easy to install. However, they have higher running costs and are more susceptible to a reduction in their operational efficiency during colder weather compared to other types of heat pumps. With these systems, extra attention should go to perfecting the design, installation and control of the system for maximum efficiency.

Heat pumps which use underground pipework or water courses as their heat source have higher installation costs and may require large areas of land, however they do have more stable operating efficiencies across the entire heating season. With these systems, extra attention should go to mitigation of the installation cost, for instance by combining the installation with other ground works.

Choosing the most appropriate heat source for a building will depend on evaluating the advantages and constraints of the options available and looking at the whole life costs of the installation. The relatively high installation costs compared to gas boilers, especially with ground source heat pumps, needs to be considered against the longer working life, lower running costs and the carbon reduction to be achieved.

There is also a great deal of flexibility in the ways in which heat pumps can be used to heat and/or cool buildings, especially how they can be integrated with traditional building distribution systems. They are suitable for use with air-based systems, such as air handling units as well as water based systems such as fan coil units, under floor heating and chilled beams. Heat pumps operate at lower output temperatures than traditional gas boilers and radiant electric heaters. For this reason, the heat emitters need to be physically larger than has been normal in the past. This sometimes requires extra space in the buildings for larger radiators, fan coil units, air handling units and air ducts. Space savings can be made in the plant rooms, because there is no need to provide separate heating and cooling plant. The lower output temperatures of heat pumps mean the building fabric must be designed and built to a high standard to ensure that insulation levels and air tightness are as good as is practicable.

Heat pumps can also be used for dehumidification in larger buildings. Dehumidification can be undertaken for many reasons including improving thermal comfort, protecting the building fabric and stored goods, and for drying processes.

A heat pump will in most cases save on carbon emissions compared to a fossil fuel boiler, but the exact carbon savings that can be achieved will depend on several factors. The heat source should be closely matched with the building's heat requirements, and the most energy efficient components should be used in both the heat pump and the distribution system. The control systems should be set up to ensure that heating and cooling is only provided where and when required and the building fabric should be designed to ensure heat loss is minimized.

It is only by taking a holistic view of the entire heating and cooling systems for a building that a proper assessment of the suitability for heat pumps can be made.

Introduction

Heat pumps are being used more and more to provide heating and/or cooling for buildings of all types and sizes. They are specified for several reasons, most notably to reduce energy consumption and thus cost, and to reduce carbon emissions when compared to traditional combustion based equipment.

Heat pumps are a well-established technology. They collect low grade heat from the environment and upgrade it for use in buildings or local heat networks. Heat pumps are also used for cooling by absorbing heat from inside the building and rejecting it into the ground, air or water. They can be used to recover and reuse heat which would otherwise have been wasted from server rooms, ventilation ducts or even sewers into an alternative heating load, for example to provide domestic hot water.

Heat pumps are very versatile machines found in all types of domestic or industrial chillers, freezers and refrigerators or in the air conditioning systems used in vehicles and offices. Traditionally they have been used mainly for cooling purposes in medium and larger sized buildings, but this is changing as heat pumps are shown to be reliable and cost effective as heat generators. They work best at low flow (delivery) temperatures and work in conjunction with air handling units, low temperature radiators, fan coil units, surface and under floor heating and chilled beams.

Heat pumps have few moving parts which makes them robust and reliable, but their key appeal is in their relatively small energy use (typically 25 to 30% of the energy delivered). Moreover, unlike fossil fueled boilers, electrically driven GSHP's do not require an air supply or flue, which saves installation and maintenance costs and means that the plant room can be in any part of a building.

A heat pump operates most efficiently when delivering both heating and cooling simultaneously.

Why install a heat pump?

Heat pumps can provide an efficient and low carbon means of using renewable heat from the air and ground, as well as surface and groundwater e.g. rivers, canals and lakes. Although heat pump systems are nearly always more expensive to install than conventional oil or gas combustion technology, they are efficient, reliable and long lived and so deliver a cost-effective return on investment, with significant potential benefits to the owner/developer/operator of the building.

Types of Heat Pump

There are two main types of heat pump: vapour compression and 'sorbtion (a**b**sorption or a**d**sorption). Vapour compression cycle units use a motor driven compressor (usually an electric motor). Heat pumps using a 'sorption process are becoming increasingly common, especially where waste heat is available.

This application note does not discuss the engineering behind the different heat pump technologies in detail, nor their specific advantages and disadvantages. A basic overview is given in the Annex.

Heat Pump Efficiency

The performance of vapour compression cycle heat pumps can be varied by using different refrigerants or combinations of refrigerants which perform differently and according to the temperature range required (recent climate legislation has resulted in many changes to the refrigerants available but suitable alternatives are gradually evolving). There are also some “add on” devices and techniques which may be used to enhance or modify performance, for example desuperheaters and hot gas injection.

Heat always moves through a heat pump in the same direction, it is absorbed at the evaporator and rejected at the condenser. When heat is required, the “useful” end is the hot one, while for cooling it is the cold one. If both heating and cooling are required simultaneously, the overall efficiency increases because less additional energy is required to drive the process (or even no energy at all).

The efficiency of the Heat Pump is expressed as the ratio between the energy input required to run the machine and the energy moved at a set temperature. In heating mode, this is called the Coefficient of Performance (CoP). It is an instantaneous and dimensionless measure.

Coefficient of performance (COP)

Heat resulting from the work done by the drive motor is added to the heat collected from the environment. For example, if a given heat pump has a COP of 4 this means that for every unit of electrical energy input, 3 units of “free” heat are collected from the environment and “pumped” or moved through the machine from the evaporator to the condenser. This has to be compared to electric resistance heating, where 100% of the energy input is delivered as heat, or 100% of the heat is delivered electrically. Following the same logic, a heat pump with a CoP of 4 is 400% efficient.

The COP of a heat pump will fall as the temperature difference between the heat source and heat sink increases. For example, suppose a heat pump delivers a COP of 5 when the heat source temperature is 10°C and the output is at 45°C. When working with a heat source of 0°C, the COP of the same heat pump will fall to be closer to 2.75. Figure 1 shows a typical relationship between COP and the temperature difference between the source and sink. Therefore, it is important when assessing the performance of heat pumps to understand how its COP varies with changes in input and output temperatures.

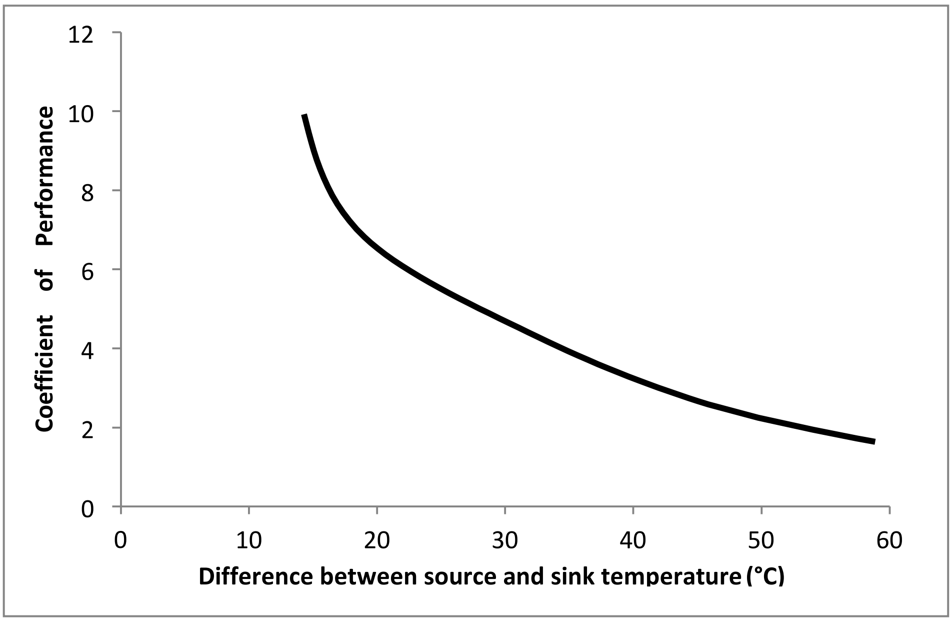

Figure 1 – Example of how the COP changes with source temperature for a typical electric heat pump.

Energy Efficiency Ratio (EER)

The Energy Efficiency Ratio (EER) of a cooling device is the ratio of output cooling to input electricity. Heat resulting from the work done by the drive motor is added to the heat collected from the cooling load, meaning more heat must be rejected to the environment. For example, if a given heat pump uses one unit of electrical energy to collect 4 units of heat from a building it will need to reject 5 units of heat at the condenser.

System efficiency

CoP and EER are measurements used to compare the performance of the heat pump unit. However, heat pumps are part of a system used seasonally if not annually. The average performance of a heat pump over the entire heating season is referred to as the Seasonal Performance Factor (SPF).

The methodologies used for assessing the efficiency of heat pump systems in the building sector are laid out by SEPEMO (SEasonal PErformance factor and MOnitoring) for heat pump systems in the building sector. It developed a universal methodology for the field measurement of heat pumps systems and calculation of SPF to reflect the conditions in real installations.

The standardized methodology of measuring the SPF makes it possible to compare the heat pump system with fossil fuel heating systems like oil or gas. By this comparison, it is also possible to calculate the CO_2 emissions and primary energy reduction potential from different heat pump systems compared to other heating systems.

SPF is a measure of the efficiency of a heat pump system and can be used to accurately compare different heat pump installations across different climates, and to compare the CO_2 emissions and primary energy reduction heat pump systems with fossil fuel heating systems.

The main parameters influencing a heat pump systems' performance are:

- the heat pump unit
- the quality of installation (design and execution)
- type, design and temperature level of the heating and/or cooling system
- the building energy demand (heat load)
- user behaviour
- climatic conditions.

There are various ways that SPF can be established, which use different systems boundaries, see figure 2. The system boundaries and the SPF-calculation methodology are separate for heating and cooling.

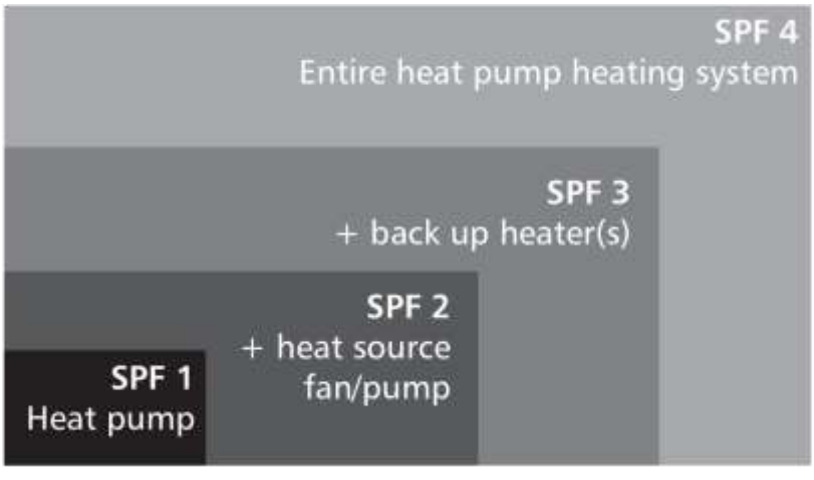

Figure 2 – Boundaries used for calculations of system efficiencies (as defined by the SEPEMO project).

TYPES OF INSTALLATIONS

Heat Pumps use the air or the ground as a mechanism to collect or reject heat.

- Air Source Heat Pumps (ASHPs) use air, normally but not always from the outside, simply by passing it across a heat exchanger, usually directly and by means of a fan
- Ground Source Heat Pumps (GSHPs) extract the heat from or reject heat into the earth using a Ground Heat Exchanger (GHE)

Common Ground Source options are:

- Pipework buried horizontally or drilled vertically into the ground
- Pipework embedded into the piling foundations of the building
- Pipework placed into a body of water such as a pond or river
- Raw groundwater abstracted from an aquifer or surface feature

Other techniques for accessing heat for a GSHP can been deployed. Structural piles modified to also act as GHE's (so called "thermal piles") are increasingly being used in large building since they require only minor, low cost modification to utilizes an existing structural building element and need no additional space, see figure 3.

Figure 3 –Thermal Pile cage ready for installation (reproduced with the permission of Nic Wincott).

The key benefit of an ASHP over a GSHP is that they are easier to install as they do not require any additional research, design, excavations or drilling. However, on the coldest days when most heat is needed, an ASHP has the least heat available, leading to inefficiencies and on the warmest days when cooling is required, the opposite applies.

A key benefit of a GSHP over an ASHP is its performance is less weather dependent. With a relatively constant ground temperature, a GSHP does not have to work harder in any season. Put another way, GSHPs tend to have a higher performance factor than ASHP's and have therefore lower running costs than an equivalent ASHP.

The ground temperature at 15 meters remains constant, approximating to the average annual air temperature at that location, see Figure 4.

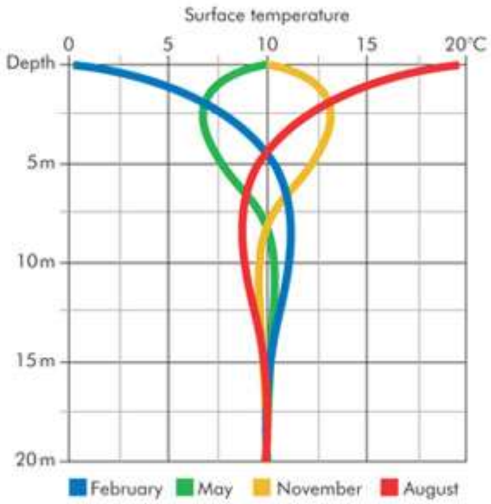

Figure 4 –*Table to indicate ground temperatures throughout a typical year (example).*

Therefore, in a continental climate that is not moderated by the proximity of the sea or other large water body, where there is a large differential between summer and winter temperatures, GSHP's work extremely well due to the large delta T (temperature differential) between the source and sink temperatures.

For Example, Climate data for Munich shows an annual daily mean of 9.7°C with a max of 37.5°C and min of -25.4°C [1].

The ground source will be close to 9.7°C being the annual average air temperature at the location. Thus, on the coldest day the ground source temperature is 35.1°C higher than the source air temperature. Put another way, to reach the target temperature in the building of 21°C, an ASHP will have to raise the temperature by 46.4°C and the GSHP by only 11.3°C.

HEAT PUMP NOTATIONS

Both ASHPs and GSHPs can be used with water or air as the heat sink. Therefore, ASHPs are commonly referred to as either 'air to air' or 'air to water' heat pumps, and GSHPs are commonly referred to 'water to air' or 'water to water' heat pumps depending on the configuration used.

Table 1 refers to the simple notations used to aid understanding within the heat pump community.

Notation	Heat Source	Delivery Medium
A/W	Air	Water
W/W	Water	Water
B/W	Brine	Water

Table 1 – Heat Pump notations.

Please note: brine (a salt solution usually made of calcium chloride) is hardly ever used today but remains the common name for all low temperature (<5°C) thermal transfer fluids whatever their chemistry. *Alternative notations used for 'brine':* W_{af} or $W_{(<5^{o}C)}$.

Characteristics of different heat pump installations

With ASHPs the main unit is usually installed with the evaporator unit outside the building, either mounted on an external wall, the roof or on the ground close by. The evaporator is usually enclosed in a protective housing and an integral fan used to blow air over them.

Figure 5 – 4 x 60kW Dimplex Air Source Heat Pumps providing heating, cooling and domestic hot water to an old people's home in the UK (reproduced with the permission of Nic Wincott).

In GSHP systems, the heat pump unit is typically installed within the building and the evaporator is connected to a pipework system filled with a Thermal Transfer Fluid, usually water based, which runs to the external heat source. For buried pipework systems, the size of the ground required will depend on the heat demand from the building. Car parks and school playing fields are often an ideal location to install large buried pipework systems. Vertical boreholes containing necessary pipework are also an option where space is limited.

An alternative is to install Direct Expansion (DX) copper pipework collectors in the ground. In these systems, the heat pump evaporator is the buried pipework through which the refrigerant flows. This is not considered ideal because corrosion of the collector could cause pollution and the potential for compressor lubrication problems.

Heat pumps are available as 'single stage' and 'two stage' units. Two stage units contain two heat pump circuits combined into a single unit. They are typically used with ASHPs, with a single stage being used during mild weather and the second stage being switched on during periods of extreme cold or heat.

Two stage heat pumps can also be used when retro-fitting a heat pump to an older heating system to produce higher output temperatures. The maximum output temperature of a single stage heat pump is typically around 45°C – 52°C. This is perfectly adequate for many types of heating systems; however, many older radiators require input temperatures of up to 90°C. Two stage heat pumps have the potential to produce these higher output temperatures; the first stage boosts the temperature up to around 45°C – 55°C and the second stage can raise the temperature up to the required higher output temperature. These higher source temperatures are also more suitable for the generation of domestic hot water.

Many larger buildings are split into separate zones, each of which can be controlled to its own temperature set point. In certain situations, one zone will require heating while another requires cooling. This is especially common in buildings with large glass facades where the solar gains can heat up part of a building very quickly. To meet this simultaneous demand for heating and cooling, there are heat pumps available with two or more refrigeration circuits. One circuit can provide the heating, whilst the other provides the cooling. An advantage of this arrangement is that the heat rejected from the cooling circuit can be used as the heat source for the heating circuit. This improves the COP of the heat pump installation, see figure 6.

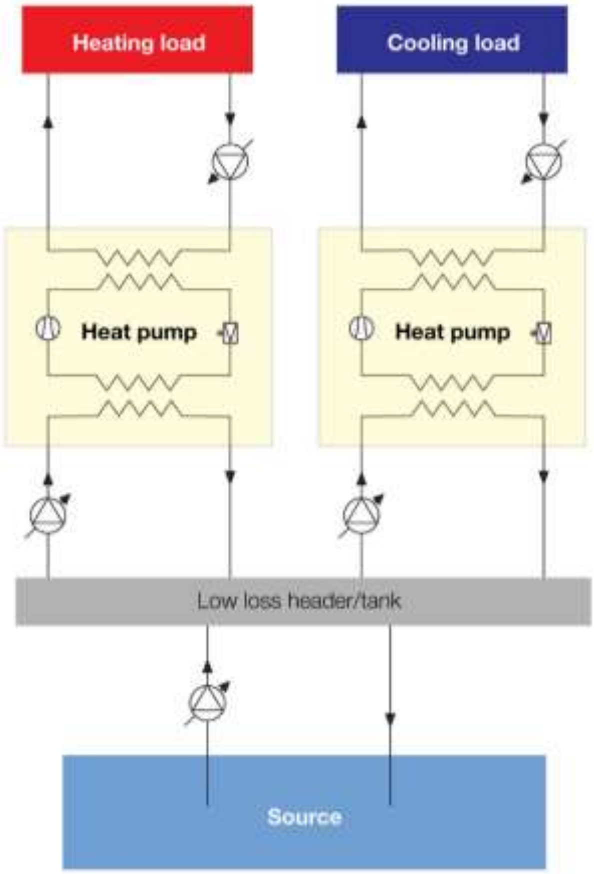

Figure 6 – Simultaneous heating and cooling provided by paired (non-reversible) heat pumps with a low loss header (taken from CP2: Surface water source heat pumps: A Code of Practice for the UK. Permission granted by CIBSE).

ECONOMIC AND ENVIRONMENTAL EVALUATION

CARBON EMISSIONS COMPARISONS

Table 3 shows a comparison of the carbon emissions of traditional heating methods versus a number of heat pump installation types. The figures for the carbon emissions of heat pumps presented here are on the conservative site and can be significantly lower, for two reasons:

1) For comparison, an average efficiency/SPF has been used, based on a typical plant available on the market, rather than the 'best in class' performance. This means that under favorable circumstances, the carbon emissions of a well-chosen and well-installed heat pump will fall even further below the emissions of a natural gas heating system.

2) The carbon emission factors used in the table are the average for the EU in 2015. The carbon emissions for electricity are expected to continue their steady decrease across Europe in the coming years, as more low carbon electricity sources will come into use, implementing the EU target of 20% renewable electricity by 2020. This will cause the average emissions associated with heat pumps over their life-cycle to be lower than the figures presented here. Once electricity generation has become entirely carbon emission free, this will also be the case for heat pumps.

	Direct electric heating	Natural gas heating	GSHP	ASHP
Annual heat (kWh)	200,000	200,000	200,000	200,000
Typical average efficiency	100%	90%	340%	260%
Annual energy consumption (kWh)	200,000	222,222	58,824	76,923
European average CO_2 emissions (2015) **($kgCO_2/kWh$)**	0.326	0.202	0.326	0.326
Annual carbon emissions ($kgCO_2$)	**64,200**	**44,889**	**19,177**	**25,077**

Table 2 – Comparison of typical carbon emissions for direct electrical heating, gas boilers and heat pumps.

The figures presented in this table will also depend significantly on the country in which the heat pump is installed. For example, in the UK, where electricity carbon emissions are relatively high, the natural gas carbon emissions are relatively low, and the winters are comparatively cold, the relative advantage in carbon emissions for heat pumps is smaller. Conversely in countries with very low electricity carbon emission factors and relatively mild winters, such as France, which has a significant amount of nuclear power, heat pumps offer higher carbon emission reductions.

Relative Life Cycle Costs

A key barrier to the installation of heat pumps, especially GSHPs is the initial capital costs. For example, traditional gas boilers typically cost between €80 - €150 / kW for a full installation. The typical installed cost is approximately €250 - €300 /kW for an ASHP, and approximately €1,000 - €1,500 / kW for GSHPs [2]. If ground works are integrated into other ground works that must be executed for the construction of the building, it should be possible to reduce the installation cost to approximately €800 / kW. Financial incentives from governments are available in many countries to assist with the initial costs of installing a heat pump.

The following table shows the estimated life cycle costs of various heating systems for a building, assuming an annual energy demand of 200,000 kWh, a peak heat demand of 150 kW, and a plant life of 30 years. Note: the SPF for both GSHP and ASHP will improve in time as the technology and installation practices improve. Therefore, it is likely that the whole life cost of ownership for new heat pumps will continue to decrease.

	Gas boiler				GSHP				ASHP			
Annual heat load (kWh)	200,000				200,000				200,000			
Plant power output (kW)	150				150				150			
Assumed fuel cost (€/kWh) [3]	0.055				0.16				0.16			
Installation costs (€)	**Low scenario** 12,000		**High scenario** 22,500		**Low scenario** 120,000		**High scenario** 225,000		**Low scenario** 37,500		**High scenario** 45,000	
Seasonal efficiency / SPF (low/high scenarios)	**80%**	**90%**	**80%**	**90%**	**3.0**	**4.0**	**3.0**	**4.0**	**2.0**	**3.0**	**2.0**	**2.0**
Annual energy consumption (MWh)	250	222	250	222	67	50	67	50	100	67	100	67
Annual running costs (€,000)	13.8	12.2	13.8	12.2	10.7	8.0	10.7	8.0	16.0	10.7	16.0	10.7
Total cost after 30 years (€,000)	**422**	**377**	**433**	**387**	**438**	**359**	**543**	**464**	**515**	**356**	**522**	**363**
Total cost after 30 years, with incentives	422	377	433	387	*249*	*209*	*288*	*249*	*267*	*187*	*193*	*267*

Table 3 – Example of a Life Cycle Cost comparison for gas boilers and heat pumps (discount rate of 4% assumed. Electricity inflation rate of 3.96%, source EuroStat data code nrg_pc_204).

The last line of table 4 shows the life cycle cost in case of a 25% reduction on the purchase and installation cost of the heat pump (through a direct grant or tax reduction) combined with a 50% reduction on the price of electricity used for the heat pump. This represents an approximation of the more favourable regimes of government incentives to promote heat pumps that exist in the EU.

There are several different types of incentives in individual member states, taking the form of:

- **Heat pump tariffs for electricity** – These are common in countries such as Germany and Austria. They offer reductions of around 40 – 60% on electricity prices when used with a heat pump. Some are offered with 100% green electricity.

- **Direct grants** – Grants are available in several member states including Finland and Germany. In Finland up to 25% of the heat pump and its installation costs are available when a heat pump is installed in an existing building.

- **Tax based incentives** – These can take many forms including deductions from taxable income, reduction of tax burden and VAT re-imbursements. In France, for example, 40% of the cost for eligible units can be deducted from the income tax burden.

- **Preferred interest** – These loans can be offered by governments or private banks. They often come with conditions surrounding the technology to be used and the savings to be achieved.

- **Feed-in–tariffs (FITs)** – In certain member states an incentive is available which is payable for the heat generated by a qualifying heat pump. In the UK this Renewable Heat Incentive (RHI) is currently GBP (£) 0.0909 kWh for Ground Source and £0.0261 kWhr for Air Source heat pumps. [4]

These incentives are intended to fill the gap in life cycle cost between heat pumps and traditional gas boilers, to yield the carbon emission reductions that heat pumps bring about. As heat pump technology improves and capital costs reduce, the need for these incentives reduces.

Table 4 shows the gap in life cycle cost between a GSHP and a gas boiler per tonne of CO_2 saved, with different SPFs and installation costs.

Euro / ton CO_2 emissions saved	GSHP Low installation cost (€800 / kW)	GSHP Average installation cost (€1,000 / kW)	GSHP High installation cost (1,200 kW)
SPF = 3.1	113	178	244
3.2	86	148	210
3.3	64	123	182
3.4	45	101	157
3.5	29	83	136
3.6	15	67	118
3.7	2	52	102
3.8	-	40	88
3.9	-	28	75
4	-	18	64

The LCC of the installation is lower than that of a gas boiler, so no financial incentives are needed

Below €50 / ton CO_2

Between €50 and €100 / ton CO_2

Above €100 / ton CO_2

Table 4 – Cost per tonne of carbon emissions saved compared to a gas boiler for a range of GSHP costs and SPFs (a 150kW gas boiler, 90% efficiency, 200,00 kWh output per year, €12,000 capital costs, 30 year life, a discount rate of 4% and an inflation rate of 3.96%).

Table 4 shows that as GSHP costs fall to the region of €800/kW and the SPF improves to 3.7, then they have a lower life cycle cost than an equivalent gas boiler, and so incentives of any form are not required.

The high installation costs are still a big hurdle to overcome. Attention should go to mitigating those costs. For instance, the viability of GSHP installations increases significantly if the ground work costs can be incorporated into those of other ground work being undertaken for the building.

Euro / ton CO2 emissions saved	ASHP Low installation cost (€200 / kW)	ASHP Average installation cost (€250 / kW)	ASHP High installation cost (€300 kW)
SPF = 2.50	145	176	207
2.55	105	133	162
2.6	72	98	125
2.65	45	69	94
2.7	21	45	68
2.75	2	23	45
2.8	-	5	26
2.85	-	-	9
2.9	-	-	-
2.95	-	-	-

The LCC of the installation is lower than that of a gas boiler, so no financial incentives

Below €50 / ton CO_2

Between €50 and €100 / ton CO_2

Above €100 / ton CO_2

Table 5 – *Cost per tonne of carbon emissions saved compared to a gas boiler for a range of ASHP costs and SPFs (a 150kW gas boiler, 90% efficiency, 200,00 kWh output per year, €12,000 capital costs, 30 year life, a discount rate of 4% and an inflation rate of 3.96%)*

Table 5 shows that for ASHPs, the life cycle cost is much less affected by the installation cost. Consequently, the impact of the SPF on the life cycle cost is much higher. Only a small change in the SPF of ASHPs can have a significant impact on the savings that can be achieved. This highlights why it is very important to ensure that ASHPs are correctly specified, installed and operated.

HEAT PUMP APPLICATIONS

Heat pumps are used in larger buildings to provide:

- Space heating and cooling
- Heat recovery & dehumidification
- Potable Water Heating and Cooling (for domestic hot water, swimming pools & spa's)

HEATING

When heat pumps are used for heating buildings, the wider heat distribution systems and building fabric need to be carefully considered to ensure they are designed or adapted to make effective use of the relatively low temperatures at which most heat pumps work most efficiently. The building fabric needs to be as air tight and insulated as is practicable. The distribution equipment (radiators, air handling units and fan coil units) when used with water temperatures of 35°C–55°C will be physically larger than traditional high temperature units. Designers and Architects will need to take this into consideration. For larger spaces, active beams, air handling units or surface heating (e.g. underfloor heating) is always recommended over radiators.

The arguably the most effective method of maximizing the benefit of heat pumps with a water based (hydronic) heating system is using surface heating because their large active area enables them to be used with exceptionally low entering water temperatures (35°C or less). This improves the SPF of the heat pump and reduces running costs accordingly.

However, the "as installed" thermal performance of the distribution system selected must be considered in detail as this can influence response times. This is particularly important in buildings with high air change rates, for example schools and older buildings where windows are open and shut for ventilation and/or cooling purposes. There can be an issue installing under floor heating systems in some larger buildings where electrical and communications services are recessed into the floor.

COOLING

ASHPs have been used in air conditioning systems for many years and their application in large buildings is well established and understood. GSHPs are a less well-known technology for cooling operations but can save operational costs against ASHP and offer other advantages when integrated with heat recovery or storage.

Heat pumps can be used to provide cooling to buildings via the same system used to distribute heat e.g. air handling and fan coil units, DX units, chilled ceilings and active (chilled) beams. If conventional radiators are employed in the building, then separate cooling systems will be needed.

If the pipework is installed in the appropriate way, heat pumps installations can be used for 'free cooling'. This is where the ground or external air is used directly, i.e. without running the refrigeration cycle. It is not completely 'free', as any circulating pumps and cooling fans will still need to operate.

HEAT RECOVERY

Heat pumps can be used in large buildings to recover heat which would otherwise be wasted. They are commonly employed in ventilation extract ducts before the warm "extract" air is expelled to the atmosphere. In this situation, the heat pump evaporator can be installed in the duct and the heat collected used to heat the incoming air or to pre-heat water for heating or other purposes. Since the internal air within a building is typically maintained to a set-point temperature throughout the year, ventilation heat recovery systems are not affected by seasonal variations in the same way as conventional ASHPs.

Medium and large buildings often have operations which produce waste heat. This can include plant rooms, data centres and cafeterias. Installing a heat pump in these areas is a very effective method of improving efficiency by collecting and using low grade heat that would otherwise be wasted. The amount of heat that can be recovered and the associated carbon saved will depend on the available waste heat and a suitable heat demand (e.g. domestic hot water).

Some heat pumps incorporate a desuperheater to boost part of their output to a higher temperature specifically to facilitate the production of domestic hot water.

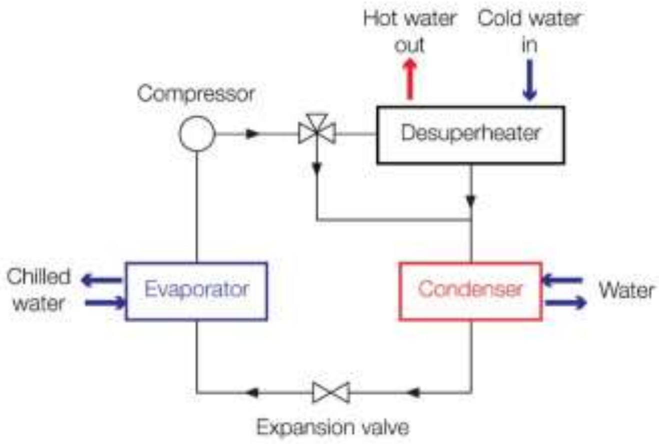

Figure 7 – Use of a heat pump fitted with a desuperheater to provide heating (*Taken from CP2: Surface water source heat pumps: A Code of Practice for the UK. Permission granted by CIBSE*)

DEHUMIDIFICATION

Dehumidification is the process of reducing the amount of water in the air. It is sometimes employed in larger buildings to improve the comfort conditions and protect the building fabric from damage and mould growth. Heat pumps are well suited to dehumidification applications especially when the latent heat is recovered and directly recycled into spa's and pool rooms. This can substantially reduce operating costs.

DOMESTIC HOT WATER

Heat pumps can be used to produce domestic hot water at scale. This is particularly cost effective when using waste heat or recovered heat. However, there are issues concerning the temperature at which it is produced and stored that need to be carefully considered.

Domestic hot water temperatures are usually held at 60°C or above to prevent the growth of microorganisms, in particular Legionella, in the pipework and storage tanks. Although it is possible to have output temperatures this high from a heat pump, this is likely to result into a low COP, which is not ideal. However, some refrigerants can achieve higher temperatures, notably CO_2.

When the output temperature is lower, the heat exchanger coils inside the storage tank will need to be significantly larger than those used in conventional domestic hot water tanks.

Some systems pre-heat the incoming water with a heat pump and then use a desuperheater, a hot gas injection gas or electric resistance heaters to reach the required delivery temperature. If extra Legionella precautions are taken, the water can be stored at lower temperature than the usual 60°C, which means the storage tank can be placed between the heat pump and the additional heating system.

ADVANTAGES AND LIMITATIONS OF HEAT PUMPS IN LARGER BUILDINGS

There are advantages and limitations to consider when investigating the use of heat pumps instead of conventional heating and cooling systems for use in larger buildings. Some of these are discussed in further detail below.

ADVANTAGES

HEATING AND COOLING IN A SINGLE UNIT

Both GSHPs and ASHPs can be used for heating in winter and cooling in summer. There are several ways this can be provisioned. Some heating and cooling installations are completely independent, and others combined. Of the combined units, some allow alternate operation and others may only be used in parallel. There are space and capital savings to be made as only one system needs to be installed and maintained.

Buildings with separate heating and cooling systems can find themselves in a situation where the two systems are operating at the same time in the same zone. This is surprisingly common and very wasteful and results in significantly increased energy bills. Having the heating and cooling distribution system integrated prevents this from occurring.

During operation, a heat pump reduces the temperature at the evaporator and increases the temperature at the condenser. It literally pumps heat from one to the other, producing heating and cooling simultaneously. This means that a heat pump uses the same amount of electricity whether heating **or** cooling, or heating **and** cooling. Consequently, heat pumps providing heating and cooling simultaneously are operating very efficiently.

Alternatively, heat pumps may be connected in tandem so they share a heat source. However, with this arrangement, the heat rejected by one unit can become the heat source for the other. In this configuration, even though it requires two compressors, the ability to directly recycle heat internally still leads to substantial saving.

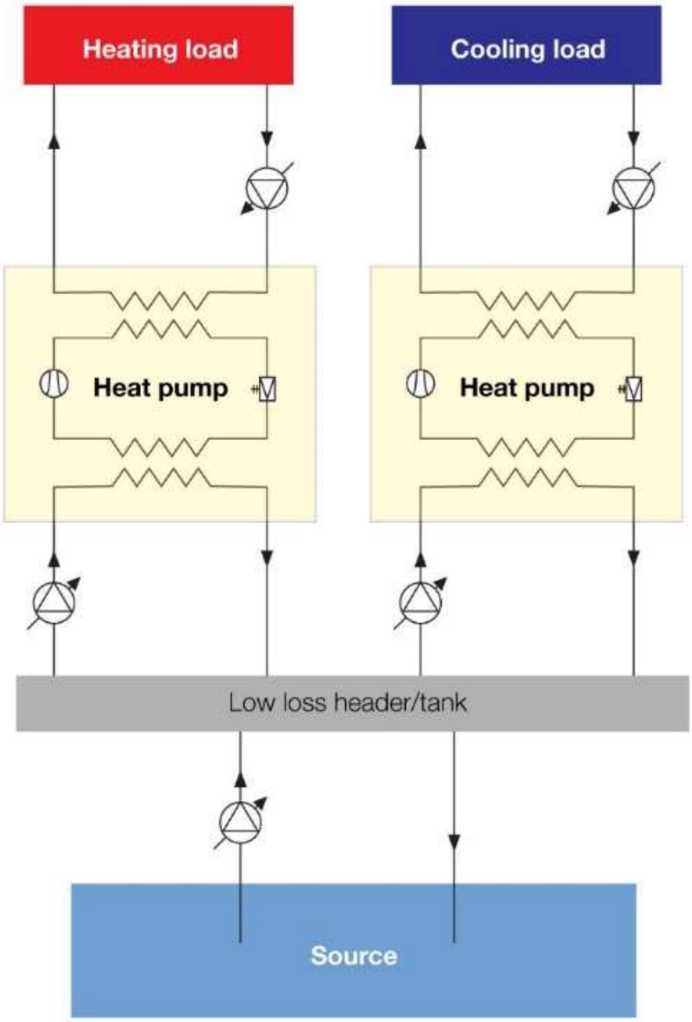

Figure 8 – Simultaneous heating and cooling being supplied by a non-reversing heat pump (taken from CP2: Surface water source heat pumps: A Code of Practice for the UK. Permission granted by CIBSE).

Reduced Maintenance Compared to Combustion Boilers

Although both heat pumps and combustion boilers require maintenance to ensure their continued safe and efficient operation, the maintenance requirements for heat pumps are less onerous. This is because the operation of combustion boilers is more complex and there is an inherent risk of fire or explosion and Carbon Monoxide poisoning. Combustion boilers also have fresh air requirements which need ventilation systems that themselves require maintenance.

Compared to boilers, heat pumps used in larger buildings have fewer moving parts, are electrically powered and consequently require no fresh air or flue. This means that they have lower maintenance requirements.

It is important to note however that heat pumps are included in Article 9 of EC Directive 2002/91/EC on the Energy Performance of Buildings, which sets out a mandatory inspection regime for heat pumps over 12 kW. The purpose of the inspection is to assess the efficiency of the system and provide appropriate advice on possible improvement or replacement of the system. The inspections must be carried out by independent experts. In addition to this, heat pumps may require mandatory inspections under the EU Regulation 842/2006 on Certain Fluorinated Greenhouse Gases, commonly referred to as the F-gas Regulations. The purpose for these inspections is to reduce the likelihood of harmful greenhouse gases being emitted to the atmosphere.

The larger the heat pump, the more regular the inspections need to be. These F- gas inspections can be avoided by using heat pumps with refrigerants that are not included in the regulations.

Higher Efficiency than electric resistance heating

Electric resistance heating systems are often used in areas which are not on the mains gas network or where the use of gas is not safe or practical. They do not require fuel deliveries, nor a combustion plant. The main disadvantage of electric resistance heating systems is that they are costly to run. Heat pumps, with their high SPF, provide the potential to significantly reduce the energy consumption of electrically heated buildings.

Recovery of Waste Heat

As mentioned in the previous section, an advantage of heat pumps is that they can use low grade waste heat. For example, if a server room is emitting a constant output of heat at 25°C, this can be efficiently used by a heat pump to provide hot water.

Thermal Energy Storage (TES)

Considerable efficiency improvements can be achieved by storing thermal energy for later use by GSHPs either diurnally, periodically or even inter-seasonally. This thermal energy may be stored conventionally by heating or chilling water, or by other storage media. It may also be stored in the ground, which is then called Underground Thermal Energy Storage (UTES).

Both Borehole Thermal Energy Storage (BTES) and Aquifer Thermal Energy Storage (ATES) have been successfully deployed in a variety of projects (especially larger ones) over the last 20 years (see Figures 9 and 10 of the Aquifer Thermal Energy Storage installed at Arlanda Airport, Stockholm).

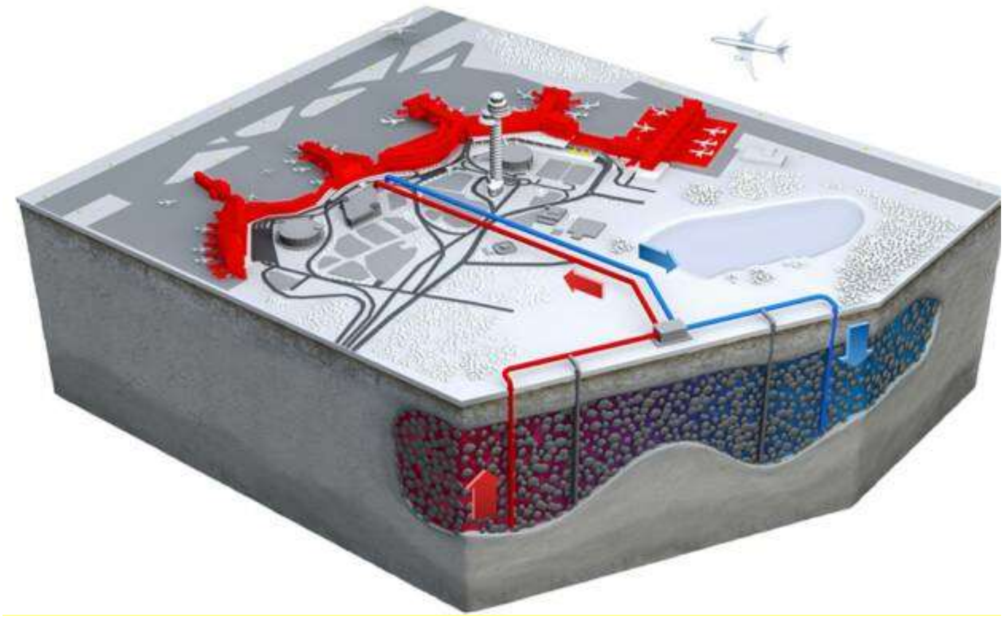

Figure 9 – Arlanda Airport – Winter condition.

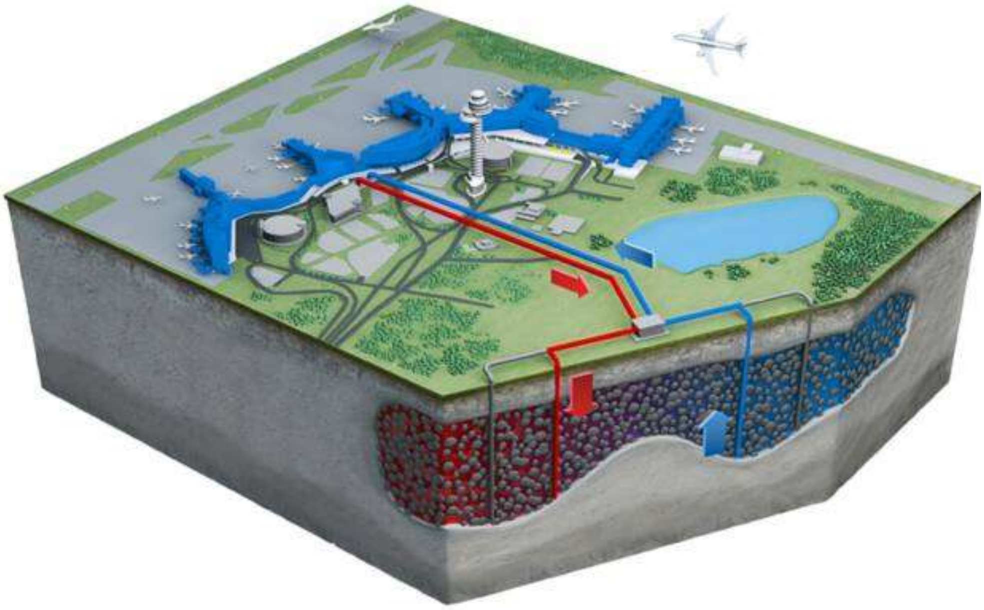

Figure 10 – Arlanda Airport – Summer Condition.

Constraints

Low Output Temperatures

As discussed in the previous sections, heat pumps are typically restricted to providing output temperatures of around 50°C – 55°C. This means they are unsuitable for directly retro-fitting onto most of the older style heating systems which have been designed for higher temperatures unless these are modified or replaced. This also means that the heat emitters used with heat pumps must be physically larger than those traditionally used in buildings. Building designers need to take this into consideration.

Increasingly high temperature heat pumps are being developed to overcome this restriction. One example can be found at Drammen in Norway, where heat pumps using the adjacent fjord have been installed to deliver heat to an existing network at 90°C.

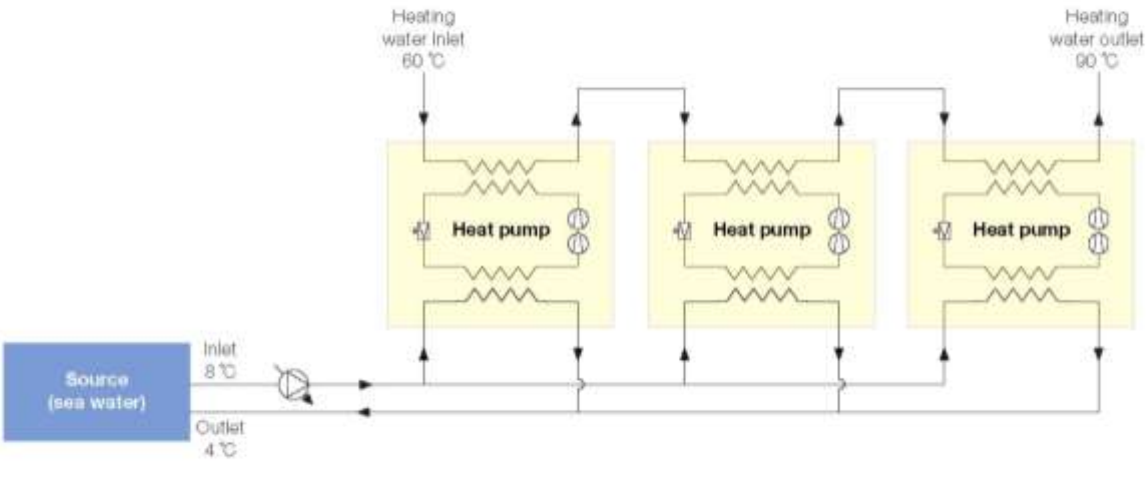

Figure 11 – Heat pumps operating in series, as used at Drammen (taken from CP2: Surface water source heat pumps: A Code of Practice for the UK. Permission granted by CIBSE).

Surface Heating systems are idea for use with heat pumps as they are designed for low temperature operation. Of these, underfloor heating is the most common, but wall or ceiling heating is gaining ground, especially for retrofit where it is easier and less disruptive to install.

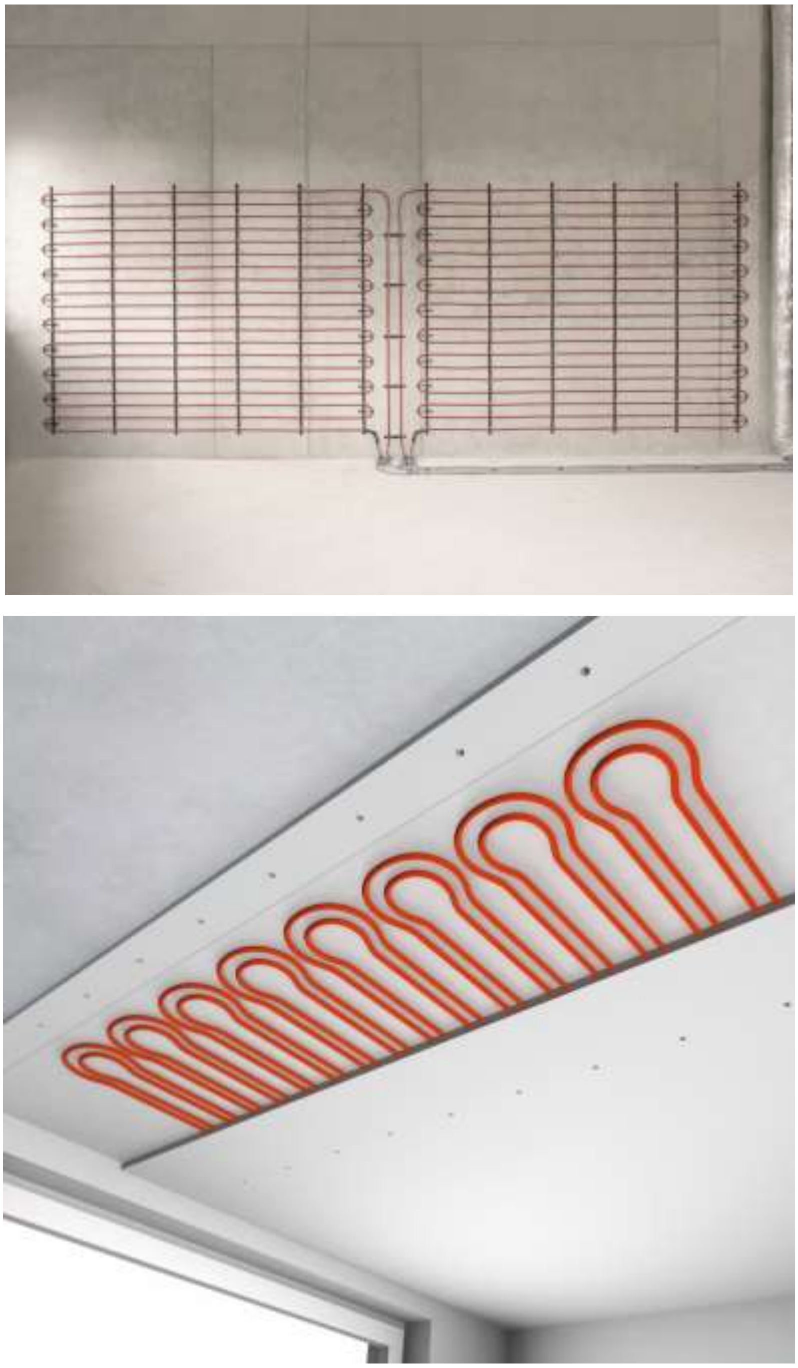

Figure 12 – Examples of Wall and Ceiling Low Temperature Surface Heating – (reproduced with the permission of REHAU Limited).

REDUCED EFFICIENCIES WHEN LARGE TEMPERATURE DIFFERENCE BETWEEN SOURCE AND OUTPUT

The efficient operation of a heat pump is dependent on there being a relatively small difference in temperature between the heat source and heat sink temperature. This can lead to high costs and carbon emissions that are much higher than expected if the system is not correctly specified.

If ASHPs are being installed, it is particularly important to understand the heat pump's performance across the whole heating season, as they are more susceptible to changes in the source temperature than GSHPs. It is important to take this into consideration when weighing up the relative benefits and drawbacks of the proposed heating systems.

If there will be large fluctuations in the source temperature, such as when ASHPs are used in colder countries, then it is recommended that a low temperature emitter is specified. Such an emitter is designed for use with output temperatures of 35°C – 40°C, rather than systems with 55°C output temperatures. This helps to reduce the efficiency drop on colder days.

Retrofitting older buildings

Retrofitting heat pumps to older buildings presents various challenges. Firstly, the building is likely to have been designed for heating devices at a higher temperature than is optimum for a heat pump. The physical size of any radiators or heating coils will have to be increased to overcome this issue, requiring more space. It may also involve an upgrade of the building fabric to improve the air tightness and insulation, especially around openings. This is because heat emitters with relatively high output temperature are better at countering the cold draughts caused by poorly performing building fabric.

When heat pumps with relatively low output temperatures are used with existing air handling units designed for higher output temperatures, the air flow rates may have to be increased to maintain the same heat output. This may cause sound issues in the ducts and may also cause cold draught complaints from people who have to work close to air outlet grilles. To overcome this, larger ducts and low velocity air outlets may be required.

There can be issues with retro-fitting a GSHP to older buildings with regards to installing the ground collector pipework. This can involve disruptive excavation work on large areas of the site, which may have existing services buried in it. This is less of an issue when the heat pump is being installed as part of the construction of a new building, as the work can be programmed as part of the ongoing excavation work and the GSHP ground collector pipes can be coordinated with the other utility pipework and cabling being installed at the same time. The local ground conditions should be assessed when considering the location and installation of ground collector pipework, as excavating hard ground could be considerably more expensive than soft ground. The ground should also be scanned to detect if any existing services.

A useful strategy for retrofitting heat pumps is to install a hybrid or multivalent system. In addition to the heat pump a combustion boiler capable of producing the original higher design temperatures is fitted (or retained). Under normal conditions the heat pump operates alone, but once the temperature falls below a defined balance point the boiler is fired either in place of the heat pump (alternate operation) or as well as the heat pump (parallel operation).

Note: Because of the reduced workload, the life of a mature combustion boiler could be extended by many years, making this a simple but effective approach.

IMPROVING HEAT PUMP INSTALLATION EFFICIENCY

There are several measures which can be taken to ensure maximum efficiency from a heat pump installation. Some of these relate to the heat pump itself, and others to the wider system or the building. The following section discusses and provides details of a few of these measures.

HIGH EFFICIENCY COMPRESSORS AND MOTORS

The compressor in a heat pump, or rather the motor which drives the compressor, consumes most of the electricity used by the machine. Therefore, it is important that it is as energy efficient as possible. The compressor unit should:

- Be **sized correctly** according to the expected maximum load
- Be **of the right type**, matching for the expected load pattern
- Have a **high energy efficiency**

Heat pump manufacturers often offer a choice in compressors to match the application. There are three main types:

- **Centrifugal compressors** offer higher full load efficiency but can only operate down to around 20% of the full load. They are the best option if there is a constant load.
- **Scroll compressors** maintain good efficiency when running at part load and operate between 0 – 100% of the full load. They should be selected if there is likely to be a varying load.
- **Reciprocating compressors** remain an energy efficient option up to around 50 kW although there can be noise or vibration issues.

Some larger heat pumps may have several smaller compressors arranged in parallel which may cascade to meet an even wider range of loads.

Smaller compressor-motor combinations are constructed as a single integrated and sealed unit, while larger ones tend to have an electric motor that is specified separately.

- If the motor can be separated from the compressor, it is subject to the Ecodesign Directive (2009/125/EC), mandating Premium Efficiency IE3 as a minimum. An exception was made for motors combined with a Variable Speed Drive (VSD), which only have to comply with efficiency level IE2 (a rule which is likely to disappear in the next regulatory round). Apart from regulation, however, motors with a VSD will have a lower life cycle cost (TCO) if they comply with IE3 instead of IE2 in the large majority of cases.

- Compressor-motor combinations that are constructed as a single integrated unit do not (yet) apply to any EU Minimum Efficiency Performance Standards. A preparatory study is ongoing for a new Ecodesign chapter (Lot 32) that applies to these types of machines. Also for these integrated compressor-motor units, investing in a high energy efficiency category pays off, with pay-back times which are often less than a year.

REFRIGERANT CHOICE

Heat pumps are available in a range of refrigerant choices. An ideal refrigerant will

- Have a boiling point significantly lower than the source temperature
- Be able to absorb a relatively large amount of energy during evaporation
- Have appropriate densities in both the gas and liquid form

- Require a relatively low operating pressure

Several fluids traditionally used as refrigerants have been found to have a significant global warming potential (GWP) and therefore have already been banned or are likely to be added to this list.

Fortunately, many refrigerants, including natural gases such as ammonia and CO_2, remain commonly available. When specifying a heat pump, ensure that the refrigerant is well matched to the heat source and sink temperatures used in the building. Heat pump manufacturers can advise on this issue.

HEAT EXCHANGER SIZE AND MATERIALS

Heat exchangers come in many sizes, materials and configurations and have many applications. However, they all operate by transferring heat, usually between two fluids, across a conductive "wall" or separator. The factors which govern the effectiveness of heat exchangers are the surface area of the separator and the conductivity of the separating material. Although heat exchangers are available in a range of materials, copper is ideal due to its high heat conductivity and corrosion resistance. Aluminium is often used as a cheaper alternative but doesn't perform as well. To increase a heat exchangers surface area, they often have fins, corrugations or ridges in one or both directions. These increase surface area and may channel fluid flow or induce turbulence to improve performance.

Figure 13 – Large Heat Exchanger used to deice the aircraft stands and to pre-heat or pre-cool incoming air to the terminal buildings at Arlanda Airport Stockholm ((reproduced with the permission of Nic Wincott).

MATCH HEAT SOURCES AND SINKS

Heat pumps are most efficient when the temperature difference between the heat source and sink is small. To facilitate this, efforts should be made to select heat sources which are relatively warm and stable. In some cases, a solar thermal collector can be used to boost source temperatures immediately before the heat pump evaporator.

In colder climates, GSHPs may be selected in preference to ASHPs. If ASHPs are used, the evaporator preferably should be put in a protected area, such as in a garage or on the south facing side of the building where it can benefit from daytime solar gains. Care must be taken to ensure an uninterrupted airflow around the unit.

In terms of heat sinks, low temperature emitters such as surface or underfloor heating or low input temperature radiators should be used. For cooling purposes, chilled beams are preferable to fan coil units and air handling units as they have a higher working temperature.

IMPROVE BUILDING FABRIC

Whether a building has a high or low thermal mass creating a stable internal temperature is always the objective and improving the building fabric will go a long way to achieving this. It should be as air tight as possible to prevent warm air from leaking out and cold air from coming in during the winter and vice versa in the summer.

The walls and roof should be well insulated and low heat loss doors and windows fitted. Cracks, chimneys and unnecessary penetrations in walls should also be sealed. Ventilation systems should be fitted with heat recovery systems. South facing windows should be provided with blinds or shading to reduce summer cooling loads. These will all reduce the load on the heat pump and consequently its running hours.

Great care should be taken to maintain or improve indoor air quality as reduced air change rates can quickly lead to a build-up of toxic elements in the indoor air.

USE INTELLIGENT CONTROLS

Even the most efficient heat pump being used in a well-insulated building can waste significant amounts of energy without good controls.

These range from the original basic BMS (Building Management System) which in many cases only sent a simple signal calling for either heat or cold, over BEMS (Building Energy Management Systems) to SCADA (Supervisory Control And Data Acquisition) software which allows a far more sophisticated control environment capable of working with multiple heat generators, energy storage and even energy price data. Improved measurement devices and sensors as well as applying artificial intelligence to controls is expected to further improve performance, see Figure 14.

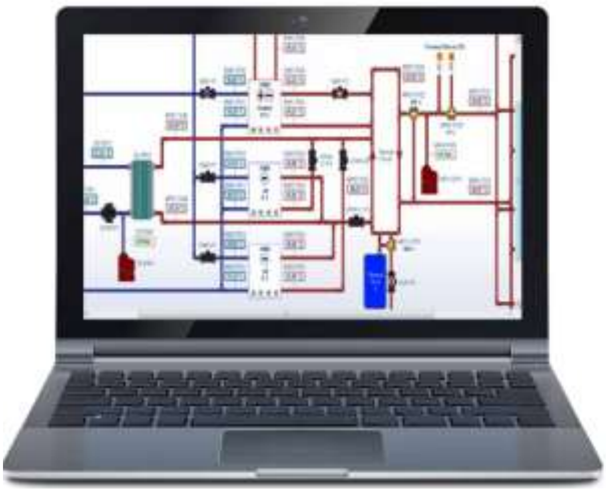

Figure 14 – Visual display of SCADA monitoring and control information (reproduced courtesy of Energy Machines SA, Luxemburg (taken from CIBSE CP2: Surface water source heat pumps: A Code of Practice for the UK)

The controls should be configured to match the occupancy. Intelligent controls can learn to switch on the heat pump just in time for the start of the working day based on the external temperature. Therefore, on warmer mornings, the heating would be switched on later than on colder mornings.

Larger buildings should always be separated into discrete zones for heating and cooling. This will prevent simultaneous heating and cooling and allow unused areas to be switched off completely. It also allows different areas to be maintained at different temperatures according to the activities taking place. For example, areas where people engaged in physical activity can have a lower heating set point temperature than areas where people are sitting working at desks.

With the appropriate heat pump, intelligent controls can adjust the refrigerant working pressure. The pressure is reduced when the source temperature is close to the sink temperature. This reduction in pressure means a reduced load on the compressor, which in turn results in lower energy consumption.

CONCLUSION

Heat pumps are a versatile and practical solution for heating and cooling larger buildings. They are available in a range of options. Before specifying a heat pump for a building, it is important to consider the following factors:

- **Understand the heating and cooling demand for the building.** For example, will there be a demand for heating above 55 °C which a heat pump might struggle to achieve? Or will there be a need for simultaneous heating and cooling, which will necessitate at least two heat pump circuits? Can the building be divided into separate zones for regulating temperature?

- **Decide on the most appropriate heating and cooling distribution system within the building.** For example, under floor heating systems potentially have the lowest operating costs in the winter due to the low output temperature, however they have a relatively high installation cost, are only suitable for certain flooring types, and a separate cooling system needs to be installed. Air handling units, fan coil units and chilled beams have the benefit that they can be used to provide both heating and cooling. If using a low temperature heat emitter, be sure to consider the fresh air requirements and air change rates as the heat recovery times may be unacceptably long.

- **Decide on a heat source.** If using an ASHP, consider the effect that changes in the outside temperature is likely to have on the efficiency across the whole heating and cooling season. Remember that the COP of a heat pump reduces as the outside temperature falls. Beware of the stated performance of a heat pump as this tends to be based on an external temperature of 7°C, as specified in the EN 14511 test standard for heat pumps. If there are big changes in winter temperature then consider using a two-stage heat pump, or even a supplementary heating source to be used on the very coldest days. If using a GSHP, consider if there is sufficient space to install horizontal ground collectors or whether a local water course or borehole could be utilized.

- **Ensure the building is well insulated and air tight.** Heat pumps are particularly susceptible to a reduction in efficiency due to cold draughts entering buildings.

- **Decide on a control philosophy for the building.** Consider how different zones can be individually controlled. Will there be any form of monitoring and targeting to ensure the continued efficient operation of the system?

Once all this has been agreed, the life cycle cost and the carbon emission reduction cost can be compared with other alternatives. It is especially important to consider local factors, such as:

- Capital and labour costs,
- Building size and use,
- Available access to suitable ground, aquifers or water courses,
- Fuel prices
- The carbon emission intensity of grid electricity
- Financial incentives for heat pumps (tax reductions, grants, special electricity tariffs, etcetera)

When specifying the heat pump, ensure that the heat exchanger materials, compressor, motor and refrigerant are selected on whole life cost and energy efficiency grounds rather than low initial capital costs.

For GSHP, special attention should go to a mitigation of the installation cost, for instance by combining the ground works with other ground works for the building. For ASHP, the operating costs are more important and therefore special attention should go to optimizing the design and installation for maximum efficiency.

For new buildings, if care is given to selection, installation and operation, the difference in Life Cycle Cost (LCC) (over 30+ years) against traditional heating systems is already reasonable and sometimes excellent. Financial incentives available from some governments improve the viability of many heat pump installations even more to well below the LCC of traditional heating systems. Further, as heat pump technology improves with time and installation best practices are widely adopted, the LCC and carbon emission savings will continue to improve.

ANNEX: THE BASIC PRINCIPLES OF A HEAT PUMP

VAPOUR COMPRESSION

Vapour compression cycle units include a compressor which is (usually) driven by an electric motor. All vapour compression heat pumps are made up of four main components:

- A heat exchanger to reject heat, the condenser
- A compressor, driven by an electric motor
- A heat exchanger to absorb heat, the evaporator
- An expansion valve

These components are connected via pipework through which a refrigerant is circulated.

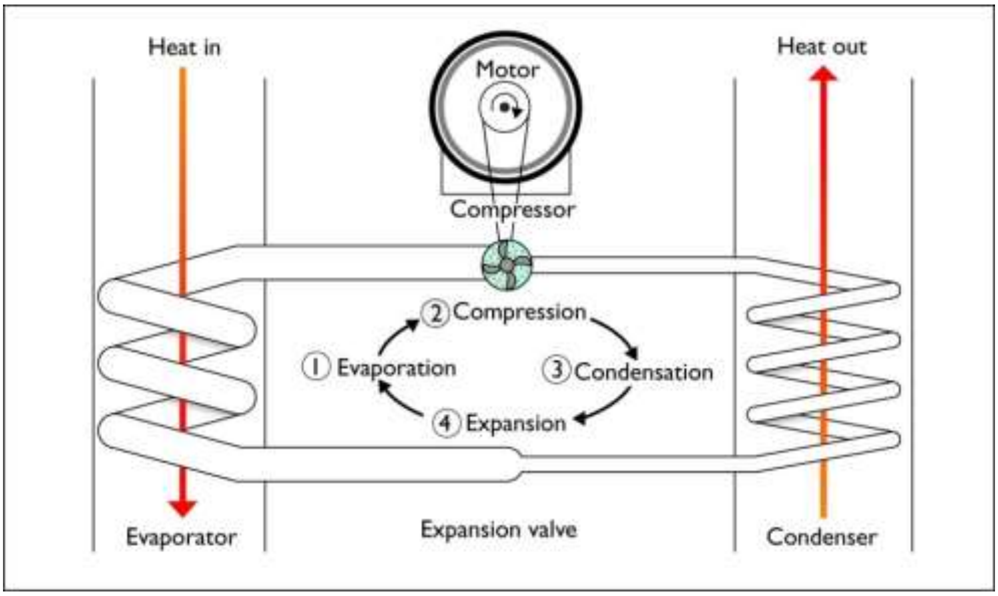

Figure 15 – Schematic diagram of the main components of a vapour compression heat pump.

The operating cycle is as follows:

- Liquid refrigerant passes into the **Evaporator** and the combined operation of the **Compressor** and the **Expansion valve** causes the pressure in the **Evaporator** to drop.
- This decrease in pressure causes the refrigerant to evaporate. This evaporation process causes heat to be extracted from the **Heat Source** as the refrigerant changes from liquid to gas.
- The heated refrigerant gas is then forced through the **Compressor** into the **Condenser**. The force of the gas pushing on the **Expansion Valve** causes a back pressure to form in the **Condenser**.
- This increase in pressure causes the refrigerant to condense back into a liquid, discharging heat to the **Heat Sink.**
- The cooled liquid refrigerant flows through the **Expansion Valve** back into the **Evaporator**.

This process pumps heat away from the evaporator thus lowering its temperature, to the condenser, so raising its temperature. It does not create heat.

A heat pump can be used to provide heating or cooling separately or simultaneously. When heating is required, the heat available at the condenser is used. When cooling is needed, the cooling effect of the evaporator is used. If both are used simultaneous, no additional electricity is required to run the compressor and the effect is magnified.

Reversible heat pumps

A vapour compression heat pump may be reversed within the unit by means of an integrated valve which allows the functions of the evaporator and condenser to be swapped.

Figures 16 and 17 illustrates how the reversing valve changes the flow of refrigerant, so the same unit can heat or cool, depending on the position of the reversing valve. It switches the function of the evaporator and condenser depending on which way you want to move heat.

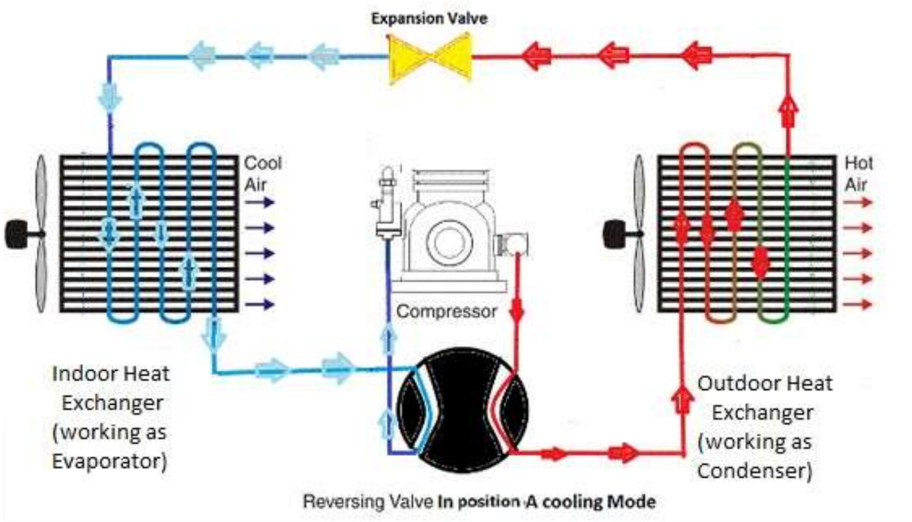

Figure 16 – Reversing Valve in Cooling Mode.

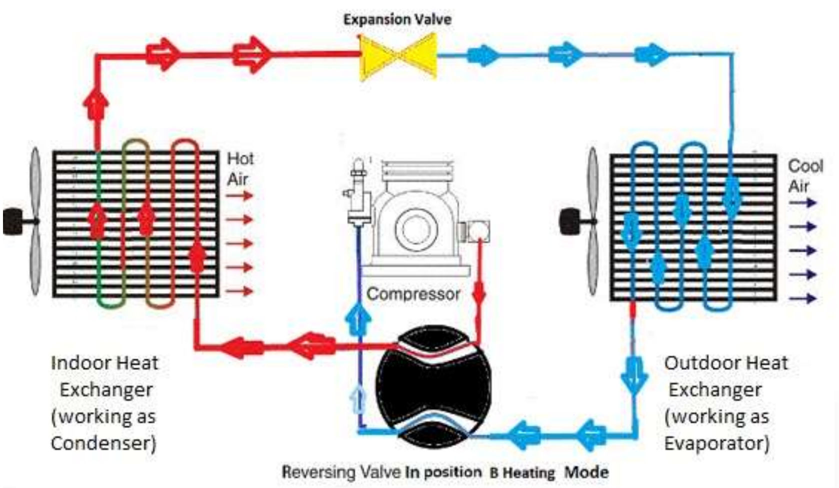

Figure 17 – Reversing Valve in Heating Mode.

'Sorption Heat Pumps

'Sorption heat pumps use heat as their primary motive energy, this can be derived from fossil fuels e.g. Oil or Gas, Electricity, Solar or recovered heat.

There are two types:

Ad*sorption* transfers heat by using the changing temperature/pressure relationship between two chemicals that do not chemically combine (e.g. water/zeolite), see figure 18.

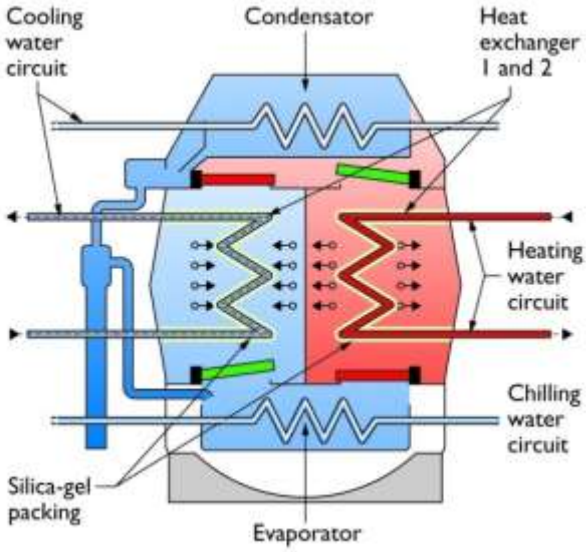

Figure 18 – How an adsorption heat pump works (Taken from CU0155, permission granted by BSRIA).

Ab*sorption* transfers heat by using the changing temperature/pressure relationship between two chemicals which can chemically combine and be separated again (e.g. lithium bromide/water or ammonia/water), see figure 19.

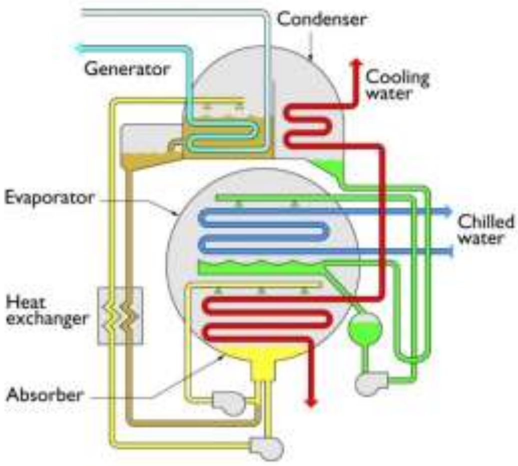

Figure 19 – How an absorption heat pump works (Taken from CU0155, permission granted by BSRIA).

In larger buildings, 'sorbtion heat pumps are found as an integral part of trigeneration systems, also called cogeneration or combined cooling, heat and power (CCHP).

Table 1 highlights the various types of heat pump technology and what should be considered when selecting an appropriate heat pump installation for your building.

Heat Pump Type	Typical Application	Considerations
Vapour Compression Low Temperature Heat Pump	Space heating with low temperature heat emitters	Domestic Hot Water storage temperatures will need a disinfection strategy
Vapour Compression High Temperature Heat Pump e.g. Cascade dual refrigerant; Vapour Injection	Space heating with ordinary or high temperature heat emitters and Domestic Hot Water	May not be economical for low temperature space heating applications without Domestic Hot Water (DHW); suitable for existing network temperatures
Gas Absorption (e.g. lithium bromide/water)	High temperature, ground source	Reverse cycle (heating & cooling), ground source
Gas Adsorption (e.g. zeolite)	Higher temperature applications *N.B. technology not fully developed*	High efficiency applications

Table 6 – Types of heat pump and where they may or may not be used.

The output temperature of a heat pump is influenced by the properties of the refrigerant used, the heat source temperature and the energy introduced into the system. The more energy input, the greater the increase in temperature between the heat source and the heat sink. This means the energy consumed by a heat pump increases when either the temperature of the heat source drops, or the temperature required by the heat sink increases. It is important to remember this when using external air as a heat source because on very cold days, the energy consumption of a heat pump will be significantly greater.

References

[1] https://en.wikipedia.org/wiki/Munich#Climate

[2] "SPON'S M&E 2010 Price book" Spon Press, 40th Edition. 2010 ISBN 13: 978-0-203-87242-0

[3] www.energy.eu/ May 2012 average retail natural gas and electricity costs for Europe

[4] https://www.ofgem.gov.uk/environmental-programmes/non-domestic-rhi/contacts-guidance-and-resources/tariffs-and-payments-non-domestic-rhi