Preparatory Studies for Ecodesign Requirements of EuPs (III)

ENER Lot 21 – Central heating products that use hot air to distribute heat
Task 4: Technical analysis of existing products

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Task 4: Technical analysis of existing products

This Task presents the technical analysis of existing products and appliances covered in the scope of ENER Lot 21 preparatory study for central heating products that use hot air to distribute heat. To analyse a product in terms of environmental impacts means to examine its complete life cycle, starting with the amount of raw materials used for manufacturing, its energy consumption during use and finishing with how it is discarded at the end of life. Therefore this Task is divided into subtasks according to the life cycle of a product:

- Production phase
- Distribution phase
- Use phase of the product
- Use phase of the system
- End-of-life phase

The product categories treated in this section are defined in the Task 1 report of this study and will also be revisited in this Task from a technical point of view. The results are based upon data received by stakeholders and manufacturers of these products, who responded to questionnaires. Additional data were taken from public information sources, technical literature as well as standards and legislation.

The aim of this Task is to examine the different technologies and components of the product categories included in this study from a life cycle perspective. This will form a technical basis for defining base–cases and determining their environmental impacts, which will be further elaborated in Task 5 of this study.

4.1 Technical basics and thermodynamics

According to the definition stated in Task 1, air-based central heating products[1] are "*appliances that convert electricity, gaseous or liquid fuels into heat (up to 1200 kW), or extract heat from a medium, and then distribute the hot air via ducts to one or several indoor spaces in buildings.*" From this it is apparent that air-based central heating products can be operated with a variety of fuels. Nevertheless, the functional principle can be categorized into two fundamental kinds of heat production:

- Heat production through electricity
- Heat production through combustion

[1] In the report, **Air-Based Central Heating Products** may be abbreviated as **ABCHPs**.

For heat pumps it is not correct to speak of heat production as such, as a heat pump extracts thermal energy from one place and transmits it to another. Therefore, it is more appropriate to speak of "heat transportation". Whatever the case energy is still needed to transmit the heat and this is enabled either by electricity or other energy sources, e.g. gas.

4.1.1 Heat production through electricity

Heat production through electricity means that heat is generated through the transformation of electricity into thermal energy. This process is also called resistive heating, Ohmic heating or Joule heating, as the passage of an electric current through an electric resistance releases heat. The effect was mathematically described by Georg Simon Ohm (1827) and later independently researched by James Prescott Joule (1849). According to these laws, the amount of heat dissipated by a resistor is mathematically described as

$$Q = I^2 \cdot R \cdot t$$

where (Q) is the heat generated by a constant current (I) flowing through a conductor of electric resistance (R), for a time (t). In other words, this physical law states that the rate of heat dissipation in a resistive conductor is proportional to the square of the current through it and to its resistance. Manufacturers choose highly resistive materials suited for electric heaters.

The principle of resistive heating is used in all electric heating devices. Depending on the principle of heat transfer, there are different conductor materials and techniques used. These will be explained in more detail in the corresponding product sections.

The energy efficiency of electric heating elements may at first appear to be 100% since the electric energy is almost completely transformed into heat. However, the efficiency of the electric power generation and distribution has to be taken into account. The efficiency of electric heating elements in terms of primary energy consumption is far lower than 100%.

In most EU countries, coal is still used as the major source for generation of electricity. The efficiency of electricity generation of conventional coal power plants in the EU is about 30%. Additionally, the combustion of coal produces more CO_2 than other energy sources. Table 4-1 presents the different energy sources and the amount of electricity they generate in the EU.

Table 4-1: Electricity generation in EU-27 in 2008[2]

Energy source	Generated electric energy [GWh]	% of Total
Coal	940,260	27.9
Nuclear Power	937,236	27.8
Gas	786,472	23.3
Hydro	358,672	10.6
Wind	118,734	3.5
Oil	105,107	3.1
Biomass	78,802	2.3
Waste	31,677	0.9
Solar Photovoltaics	7,433	0.2
Geothermal	5,732	0.2
Other Sources	2,418	0.1
Tide	513	0.0
Solar Thermal	16	0.0
Total	3,373,072	100.0

The exact thermal efficiency of electric heating elements can only be estimated, as it depends on the energy mix of the individual Member State, the efficiencies of the conversion processes and the conduction losses.

In order to estimate the efficiency of electric heat generators in this study, the electricity consumed by these heaters is multiplied by a primary energy conversion factor. The resulting primary energy consumption is used as the energy input value for the determination of thermal efficiency.

4.1.2 Heat production through combustion

The second fundamental functioning principle of heat generation is the process of combustion. The combustion of fuels such as oil, gas and solid fuels generate heat that can be used for space heating by using a heat transfer medium such as air or water. When the combustion is used in an engine (e.g. for engine gas heat pumps) it can provide work for refrigerant compression. In this case, the heat generated in the combustion can also be recovered for heating.

[2] International Energy Agency (IEA); Electricity/Heat in European Union - 27 in 2008. www.iea.org/stats/electricitydata.asp?COUNTRY_CODE=30

Figure 4-1: Combustion triangle [3]

A simple example for this process is the oxidation of methane (CH_4) with pure oxygen (O_2).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + energy$$

In this case, methane is the fuel and oxygen is the oxidizer of the reaction. The result is carbon dioxide (CO_2) and water (H_2O) accompanied by the production of energy. This energy is either transferred to the surroundings or it remains in the combustion products (e.g. flue gas) in the form of elevated internal energy (temperature).

Fuels are evaluated based on the amount of heat generated per unit mass through complete combustion of the fuel. This value is also known as the calorific value (formerly known as the "upper heating value").

Generally the chemical reaction of combustion only happens in the gas-phase of a fuel, which means that liquid and solid fuels do not burn directly, but the vapours of the combustible compounds do. The fuels for combustion can be classified into three categories with different technological characteristics

- Gaseous fuels

Gaseous fuels like methane or liquefied petroleum gas (LPG) can be combusted directly. This is possible because all relevant combustible compounds for the process are in gas-phase already. The gas is mixed with the adequate amount of oxidant and is ignited by an ignition source. Since there is no need to transfer the fuel to a different phase state, the combustion of gaseous fuels can be obtained with comparatively low efforts.

LPG has a higher calorific value (94 MJ/m^3 equivalent to 26.1kWh/m^3) than natural gas (methane) (38 MJ/m^3 equivalent to 10.6 kWh/m^3), which means that LPG cannot simply be substituted for natural gas. In order to allow the use of the same burner controls and to provide for similar combustion characteristics, LPG can be mixed with air to produce a synthetic natural gas (SNG) that can be easily substituted.

- Liquid fuels

Liquid fuels include fuel oil, paraffin/kerosene and ethanol fuels. Kerosene and ethanol are available in bottles, cartridges (which allow for easy storage), and fuel oil is also delivered by truck. Therefore, kerosene and ethanol are commonly used in portable heating appliances, in

[3] www.cablesystems.co.uk/fire-triangle.php

locations without access to piped natural gas or as an alternative backup fuel supply. In air-based central heating products kerosene and ethanol are not commonly used.

- Solid Fuels

Solid fuels include wood, charcoal, coal, peat, and pellets made from wood, as well as some grains including corn, wheat and rye. The use of solid fuels is increasing as heating technology and the availability of good quality fuel improves. The greatest disadvantage is that some solid fuels such as coal emit significantly higher levels of toxic emissions than natural gas or oil. Some furnaces for solid fuels also require regular maintenance, as more combustion residues, such as ash and soot, are produced.

As the combustion of solid fuels is not relevant for the heaters considered in ENER Lot 21 study, they will not be further explained in this context. For more detailed information on solid fuels used for space heating, please see the DG TREN Lot 15 preparatory study on Solid fuel small combustion installations[4].

- Requirements for a complete combustion

There are several requirements that have to be fulfilled for a complete combustion process. The major influencing factors on the combustion process are: Temperature, Turbulence and Time, also referred to as "the three T's of combustion".

- Temperature: higher combustion temperatures accelerate the reaction speed and the degree of burn of the combustion process.
- Turbulence: to enhance the contact of the fuel with the oxidizer, the reactants have to be mixed properly. This can be achieved through higher turbulence in the reaction zone.
- Time: The fuel-oxidant mix has to stay in the reaction zone for a sufficient time range so that there is enough time for the complete combustion process to take place.

Although there are many different principles to generate heat through combustion, the fundamental working principles always stay the same. A more detailed look at the respective functional principle will be examined in the corresponding product sections of this Task.

4.1.3 Heat pump cycles

The heat pump process is a closed thermodynamic cycle. It refers to the Carnot cycle, which is a theoretical process to determine the combustion efficiency of a given fuel that was proposed by Nicolas Léonard Sadi Carnot in 1824 and expanded by Benoit Paul Émile Clapeyron in the 1830s and 40s.

When a system is taken through a series of different states and finally returned to its initial state, a thermodynamic cycle is said to have occurred. There are different process-cycles used in heat pump technology.

[4] www.ecosolidfuel.org/

- Vapour-compression cycle

The vapour-compression cycle is the most relevant one for heat pumps and consists of the following steps:

Step 1 to 2: The gaseous refrigerant enters the compressor. The vapour is compressed, reducing its volume and causing it to heat up. The high-temperature vapour exits the compressor superheated.

Steps 2 to 4: The superheated vapour travels through the condenser which first cools and removes the superheat and then condenses the vapour into a liquid. The heat caused by this phase change is subsequently emitted to the surroundings.

Step 4 to 5: The liquid refrigerant goes through the expansion valve (also called a throttle valve) where its temperature and pressure are lowered while the volume increases. The liquid refrigerant is changed to a low-pressure liquid/vapour mixture.

Step 5 to 1: The cold liquid refrigerant travels through the evaporator and is completely vaporised due to heat absorption from the heat source. The resulting low-temperature vapour returns to the compressor inlet to complete the thermodynamic cycle.

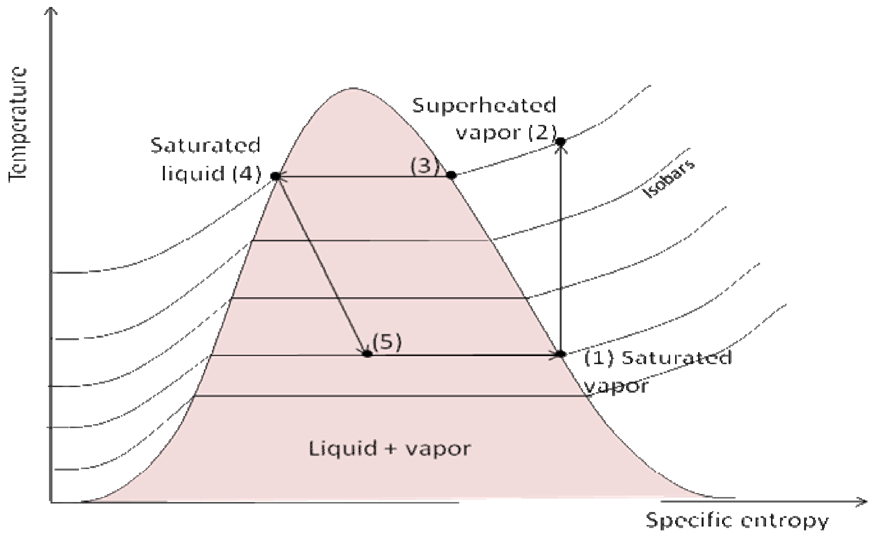

Figure 4-2: Vapour compression cycle

- Vapour-absorption cycle

The vapour absorption cycle is relevant for all absorption heat pumps. The absorption cycle is similar to the compression cycle, except for the method of raising the pressure of the refrigerant vapour. In the absorption system, the compressor is replaced by an absorber which dissolves the refrigerant in a suitable liquid. A liquid pump raises the pressure and a heat generator (electric heater, combustion, solar- or geothermal-heated water) evaporates the refrigerant from the high-pressure liquid. Some work is required by the liquid pump, but for a given quantity of refrigerant, it is much smaller than what is needed by the compressor in the vapour compression cycle. Absorption heat pumps for air-heating purposes are a niche product with a very small market share.

4.1.4 Heat distribution

As all air-based central heating products use air as a heat transportation medium, all heat is distributed to the application by convection. Heat transfer by radiation can be neglected in this context.

Convective heat transfer is the technical term for transportation of heat within a fluid (i.e. liquids and gases). Free (or natural) convection occurs when the fluid motion is caused by buoyancy forces that result from density variations due to a temperature difference in the fluid. Forced convection occurs when the fluid is forced to flow over the surface by external means (such as fans, stirrers, and pumps), creating an artificially induced convection current. Physically, the mechanism of convection heat transfer is a combination of conductivity and fluid flow. Convective heat transfer depends on many factors including fluid properties, flow velocity, geometric configuration, and any fluid phase change that may occur as a result of heat transfer. Both methods, natural and forced convection are used in heating technology, depending on the functional design of the heater.

The heat flow between a heated surface and the transporting fluid is given by:

$$\dot{Q} = h \cdot A \cdot \Delta T$$

- $\dot{Q}$ is the heat flow, expressed in $[W]$
- h is the heat transfer coefficient, expressed in $[W / m^2 \cdot K]$
- A is the surface area of the heat being transferred, expressed in $[m^2]$
- ΔT is the temperature difference between the heating surface and the flowing medium temperature, expressed in $[K]$

4.2 Main components

The following section will give a broad overview of the main components used in ABCHPs.

4.2.1 Warm air heaters

Warm air heaters are generally composed of a heat generation element and fans, air intake and air outlet, dampers and other air handling components. Additionally, warm air heaters may include heat exchangers, capacity controls, etc.

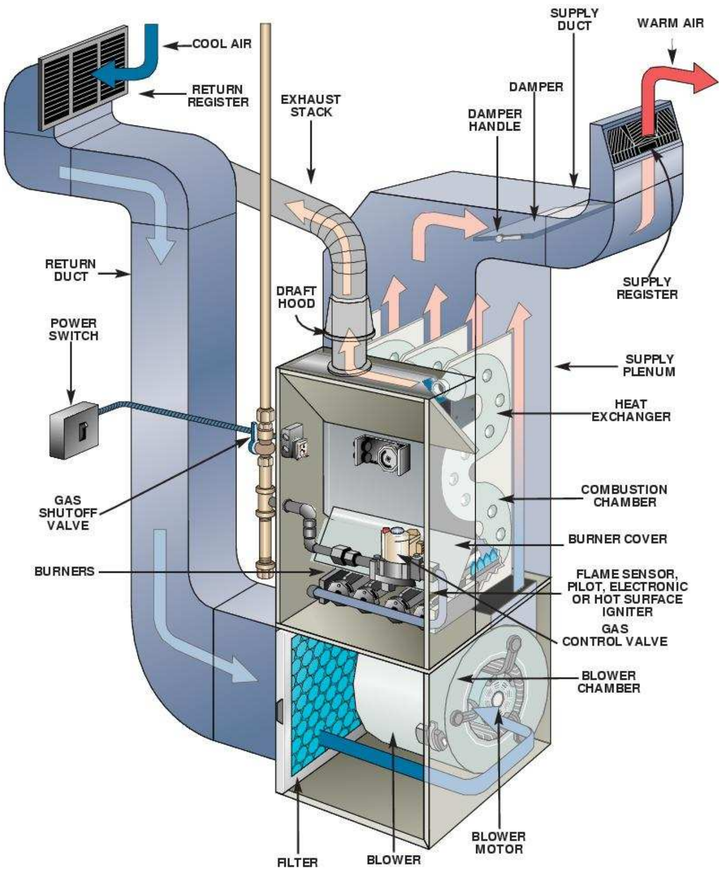

Figure 4-3: A typical gas fired warm air heater[5]

4.2.1.1 *Oil burners*

Oil burners are heat generators that produce heat by combustion of oil. Generally the supplied oil is pre-processed inside the burner, mixed with supply air and then ignited and burned safely. According to the burning process, oil burners can be differentiated into:

- Vaporising burners

Vaporising burners contain a shell- or pot-like vessel in which the oil is continuously heated. At a certain temperature level the oil will start vaporising. Mixed with combustion air, the oil vapours form a combustible gas which is ignited and burned above the oil vessel. Vaporising burners are also used in oil ovens, older kitchen stoves as well as tiled stoves. A basic form of a vaporising burner is also used in ethanol fireplaces.

- Atomizing burners

As the name indicates, atomizing burners atomize the supplied oil into very small oil droplets (size 40 to 200 µm) that are subsequently mixed with combustion air. By atomizing the oil the surface area is increased, which simplifies the gasification process necessary for combustion. The atomized gas/air mixture is sprayed into the combustion chamber and is ignited simultaneously. The atomization can be reached with different techniques like pressure atomization, injection

[5] www.pinnaclepropertyinspection.com/blog/archives/1065

atomization, rotary atomization, air atomization and ultrasonic atomization. Atomizing burners are the most common type of oil burners used today.

4.2.1.2 *Gas burners*

Compared to oil burners, gas burners have the advantage that the fuel does not need to be vaporised before combustion, since it is already in this phase. Gas burners are categorised according to the type of gas/air mixture and the functioning principle into the following subcategories:

- Diffusion burners (fan burners)

A diffusion burner mixes and burns the reactants simultaneously without premixing. This corresponds to the same principle like pressure atomizing oil burners. For diffusion burners a combustion air fan is generally necessary. Due to this reason, these kinds of burners can be used for all available types of gas. As a result of the great flexibility of use, diffusion burners are very wide spread on the gas burner market.

- Premix burners (fan assisted)

Premixing burners produce a premixed combustible gas/air mixture. The necessary combustion air is drawn in by a fan and lead into a mixing device. The gas is atomized by a gas nozzle into the mixing device. The resulting turbulent air stream enables the mixing of combustion air and gas. The mixture is then led to the burner surface, usually a perforated steel plate, woven metal fibre or a perforated ceramic material. Each hole in the burner surface serves as a flame holder. The geometry of the holes together with the supply flow and pressure of the gas/air mixture determines the shape and the size of each individual flame. Three kinds of flames can be distinguished:

- free flame - the flame hovers over the burner's surface;
- radiation burner - the flame sits at the burner's surface;
- flameless burner - the combustion takes place inside the flame holders.

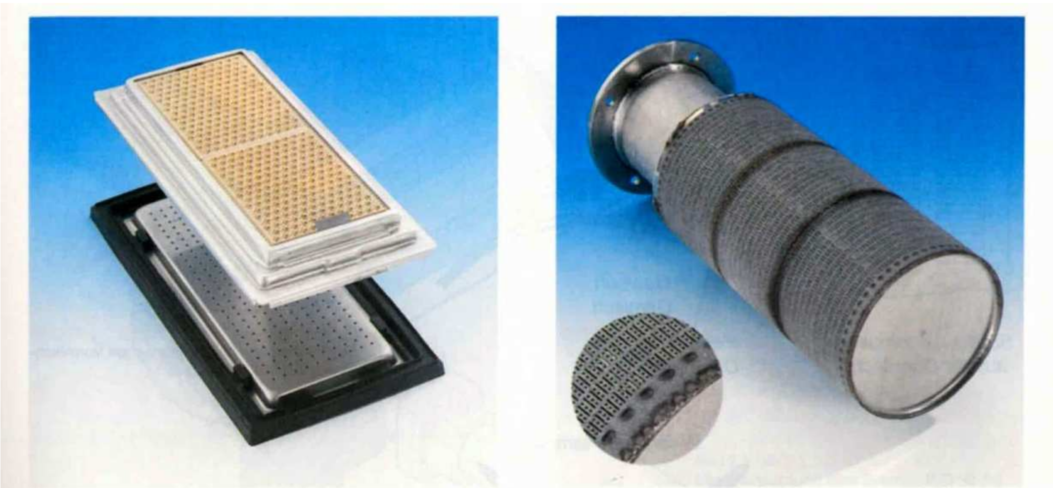

Figure 4-4: Different premix burner surfaces[6]

[6] Buderus Heiztechnik (2002) Handbuch für Heizungstechnik; 34. Auflage.

- Atmospheric burners (fanless injector burners)

Atmospheric burners may be classified as premixed burners as well, as the mixing of gas and supply air is conducted before the combustion. In contrast to premix burners, this mixing is achieved without additional combustion air fans. The gas is atomized by a gas nozzle into a combustion rod under common gas supply pressure. This combustion rod is usually a round, oval or cylindrical metal pipe with an integrated venturi nozzle and perforations on the top side. As the gas is sprayed into the venturi nozzle, primary air is drawn in by the impulse force of the gas stream. Subsequently, due to the venturi nozzle, the gas mixes with the primary air and enters the combustion rod. The premixed gas/air mixture streams through the perforations on the top of the rod and gets ignited. The necessary secondary combustion air is drawn in by the flame automatically. Some appliances with atmospheric burners contain an additional flue draft fan, which supports the mixing with secondary air.

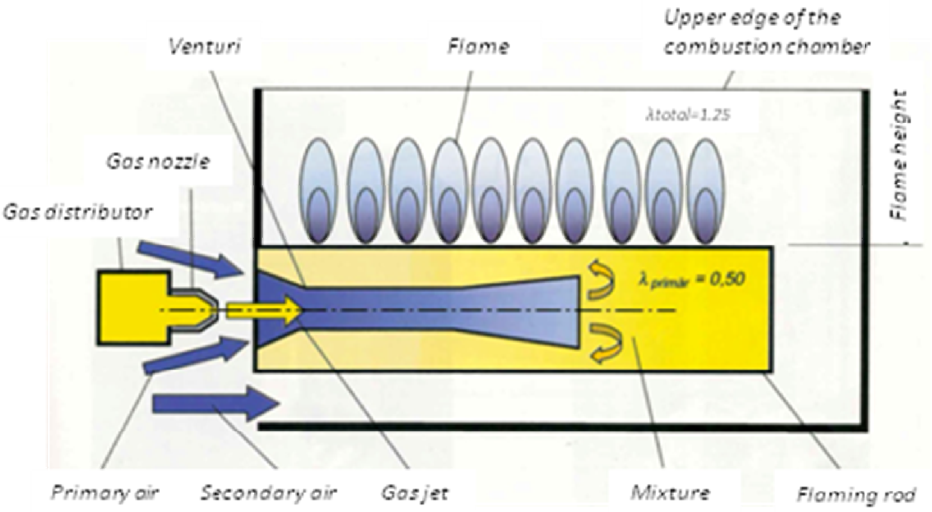

Figure 4-5: Atmospheric gas burner[7]

4.2.1.3 *Electric heat generators (resistive conductors)*

Electric heat generators are not commonly used in ABCHPs. They work by electric resistors that transform electricity into radiation and thermal energy. If an electric current is passed through such a resistive conductor the surface temperature rises and it will start emitting thermal energy and visible light (glowing). In ABCHPs, electric heaters generally use one of the following electric heat generator techniques:

- Heating wires

Heating wires are resistive wires or ribbons that can be produced in a straight or coiled form. They are usually made of iron-chromium-aluminium (FeCrAl) wire, nickel-chrome (NiCr) wire or strip as well as Cupronickel (CuNi) alloys. Similar heating wires can be found in common items such as toasters or hair dryers, as well as in residential fan heaters or electric floor heating systems.

[7] Buderus Heiztechnik (2002) Handbuch für Heizungstechnik; 34. Auflage.

- Tubular heating elements

In these kind of electric heating elements, a resistive heating wire (mostly a coil of nickel-chrome wire) is embedded in an insulating binder like magnesium oxide (MgO), sealed inside a tube made of steel, stainless steel, aluminium or brass. If a current is passed through the heating wire, it warms the surrounding binder and therewith the surrounding tube.

4.2.1.4 Solid fuel burners

Solid fuel burners are not commonly used in centralised air heaters. The combustion of solid fuels strongly depends on the type of fuel used, as there are remarkable differences between fuels in terms of their size and characteristics. A typical solid fuel burner contains a steel or cast-iron grate, on which the fuel is placed, and a combustion chamber where the fuel combustion occurs. These two components usually form a unit, meaning that the grate is embedded in the bottom of the combustion chamber. Combustion chambers are usually made of steel, cast-iron or masonry, which is lined with a refractory material such as pyrolite or similar. The solid fuel is ignited and primary combustion air is introduced over the grate to the combustion chamber. The hot flue gases are introduced to a heat exchanger, where the contained heat is transferred to the supply medium. Solid fuel burners may be equipped with additional start-up burners. These ignite the solid fuel and can generate heat in case of insufficient fuel supply.

4.2.1.5 Combustion air supply

Depending on the method how the combustion air is lead to the burner, air-based central heating products are divided into two main categories.

Room sealed devices take the combustion air from the outside over a separate combustion air supply line. These appliances are recommended for rooms with an insufficient fresh air supply.

Open flue appliances take the air needed for combustion directly from the surrounding environment. To avoid a lack of combustion air, which may lead to a decrease of the efficiency, the room has to be fitted with sufficient fresh air supply openings. If the intake air is not heated up, it might cause a drop in the room temperature, which would cause an increase of the energy consumed by the heater in order to maintain the desired temperature. The heated air can be continuously renovated or partially re-circulated. Recirculation increases the efficiency since the air coming from the room has a higher temperature than outside air.

4.2.1.6 Exhaust gas system (flue)

A flue is a duct, pipe, or chimney for conveying exhaust gases from combustion processes to the outdoors. They usually operate by buoyancy, also known as the stack effect, or the combustion products may be 'induced' via an additional blower. Buoyancy occurs due to a difference in indoor-to-outdoor air density resulting from temperature and moisture differences. The result is either a positive or negative buoyancy force. The greater the thermal difference and the height of the structure are, the greater the buoyancy force is, and thus the stack effect. The stack effect is also referred to as the ‘chimney effect’.

As combustion products contain carbon monoxide and other dangerous compounds, proper 'draft', and admission of replacement air is imperative. Building codes, and other standards, regulate their materials, design, and installation.

4.2.1.7 Ignition system

The ignition system is responsible for igniting the burner of fuel-fired heating appliances. A common ignition system is the pilot light. A pilot light (or pilot) is a small gas flame, which is kept alight in order to serve as an ignition source for a more powerful gas burner. The pilot light is fired by natural gas or liquefied petroleum gas and constantly uses a small amount of fuel, regardless of the operational state of the main burner. Recent gas burners in residential heating appliances use electric spark igniters instead of pilot lights, which do not consume any fuel.

4.2.1.8 Blower fan

The air circulation blower is an essential component for any forced warm air heater, as it is responsible for the circulation of hot air throughout the housing and the connected ductwork.

While in older warm air heaters the fan was often belt-driven, today’s warm air heater blowers use belt-less centrifugal fans. Centrifugal fans have a moving component (called an impeller) that consists of a central shaft about which a set of blades, or ribs, are positioned. Centrifugal fans blow air at right angles to the intake of the fan, and spin the air outwards to the outlet (by deflection and centrifugal force). The impeller rotates, causing air to enter the fan near the shaft and move perpendicularly from the shaft to the opening in the scroll-shaped fan casing. Centrifugal fans produce more pressure for a given air volume, and are typically noisier than comparable axial fans. The fan blades on the hub can be arranged in three different ways: forward-curved, backward-curved or radial.

- Forward-curved blades use blades that curve in the direction of the fan wheel's rotation. These are especially sensitive to particulates. Forward-curved blades are for high flow, low pressure applications.
- Backward-curved blades use blades that curve against the direction of the fan wheel's rotation. The backward curvature mimics that of an airfoil cross section and provides good operating efficiency with relatively economical construction techniques. These types of fan wheels are used in fans designed to handle gas streams with low to moderate particulate loadings. Backward-curved fans are much more energy efficient than radial blade fans. Therefore radial fans with backward-curved blades are often used in warm air heaters.
- Radial fan blades extend straight out from the hub. A radial blade fan wheel is often used on particulate-laden gas streams because it is the least sensitive to solid build-up on the blades, but it is often characterized by greater noise output. Radial fans are for high speed, low volume and high pressure applications.

The Commission Regulation (EU) No 327/2011 of 30 March 2011 established efficiency requirements for fans from 125 W to 500 kW across the following types:

- Axial fan
- Centrifugal forward curved fan and centrifugal radial bladed fan
- Centrifugal backward curved fan without housing
- Centrifugal backward curved fan with housing
- Mixed flow fan
- Cross flow fan

4.2.1.9 Motors

Electric motors are used for driving the fans in warm air heaters and air heat pumps. Depending on the motor technology, the electricity consumption can be very different. The classic division of electric motors is according to the power type they are designed to run on. Thus, there exist alternating current (AC) and direct current (DC) motor types. Every motor consists of both a rotor (the part that rotates), and a stator (the fixed part of the motor) that generally includes the motor's housing assembly and windings. Concerning warm air heater blowers and heat pump condenser/evaporator fans, there are usually two types of motors used;

- The **permanent split capacitor (PSC)** motor is a single phase AC motor traditionally used in air handlers, blowers and fans. A PSC motor's rotor spins due to changing the magnetic poles on the magnet mounted to the rotor. Standard PSC motors are single speed motors with an additional speed controller. This speed controller is an inefficient way of varying the supply voltage of the motor in order to regulate the rotating velocity. As PSC motors are less cost intensive than BPM motors, they are still used in many standard applications.
- The **brushless permanent magnet (BPM)**[8] motor design differs from that of PSC motors. BPM motors are brushless DC motors that use a built-in inverter.[9] This means, that an AC current is connected to the motor and transformed into a DC current. Additionally the BPM has a permanently poled magnet (permanent magnet) mounted on the rotor and electronically varies the polarity of stator magnetic fields, causing a rotating magnetic field to be generated. Compared to PSC motors, BPM motors maintain their efficiency regardless of rotation speed, which means that there are no slip losses occurring. The ECM's efficiency can be as high as 82% which is a 20% greater efficiency at full load and 30% better efficiency at

[8] BPM motors are also known as Electronically Commutated Motors (ECM), which is registered trademark of General Electric.

[9] Nailor Industries Inc.; The ECM Motor Story; Available at: www.nailor.com/pdf/ecm_1.pdf

part load conditions than a PSC motor.[10] Besides this, there are a lot of additional advantages like constant airflow over a range of downstream static pressures, radial ramp-up to set-point flow rate at start-up, a longer motor life and less motor noise.

In summary it can be said that with BPM motors it is possible to reach significantly higher efficiencies compared to PSC motors as well as better control This is especially significant while running at full load until turndown. The efficiency of BPM motors is higher than in PSC motors, which makes them a favourable choice for high efficiency applications.

The Commission Regulation (EC) No 640/2009 of 22 July 2009, established efficiency requirements for electric motors equipped with variable speed drives and motors integrated into other products – apart from motors completely integrated into a product (for example gear, pump, fan or compressor) of which the energy performance cannot be tested independently from the product. The regulation is therefore not applicable to products or components covered in ENER Lot 21, as motors are either small and single-phase (for use as fans) or integrated into hermetic compressors in heat pumps.

4.2.1.10 Heat exchangers

All indirect-fired warm air heaters contain heat exchangers to transfer the generated heat from the flue gases to the circulating air. Depending on the fuel used there are different heat exchanger designs.

- Heat exchangers for indirect-fired gas warm air heaters

Indirect-fired gas warm air heaters contain at least one heat exchanger. Condensing warm air heaters contain an additional secondary heat exchanger.

Primary heat exchangers are usually made of aluminized steel tubes, or profiles that were crimped together. Aluminized steel has very unique properties like corrosion resistance without losing its steel base properties and is therefore often used for heat exchangers. Depending on the heat output of the warm air heater there are three or more parallel exchanger tubes or plates that go directly through the circulating air stream.

Secondary heat exchangers are responsible for condensing the water vapour that is contained in the flue gas after combustion which results in an additional heat gain and therefore an increase of efficiency. Secondary heat exchangers are usually built as finned tube exchangers and are made of stainless steel.

Primary and secondary heat exchangers are connected, so that the flue gas that leaves the primary exchanger directly enters the secondary heat exchanger. In it, the flue gas transfers additional heat until its temperature falls below the dew point. The water vapour is then condensed and latent heat is released. The negative pressure in the flue gas route is created by a draft inducer.

[10] ASHRAE Transactions (2007) Use of electronically commutated motors (ECMs) in air terminal units. www.pwaengineering.com/articles/?article=9

- Heat exchangers for indirect-fired oil warm air heaters

Heat exchangers in oil warm air heaters may differ from those in gas warm air heaters. Usually heat exchangers for oil warm air heaters are constructed in a more robust manner from heavy gauge steel. The thicker the metal is, the more durable and corrosion resistant the heat exchanger. This is necessary as fuel oil contains higher sulphur values, which means that occasionally formed condensation water is highly acidic and will corrode metal surfaces. The metal thickness is usually described in gauge numbers; the lower the gauge number, the thicker the steel. Most heat exchangers for indirect-fired oil warm air heaters are crimped or welded together from 18 (1.02mm) to 13 (approx. 1.82mm) gauge steel plates. The basic form for heat exchangers in oil fired warm air heaters is square, round or octagonal in shape, making it easier to manufacture and therefore less cost intensive.

Some oil warm air heaters also contain secondary heat exchangers made of aluminized steel. They are in most cases applied only for reasons of additional heat transfer and not for condensing, as the usage of condensing technology is more difficult to achieve for oil fired appliances. Another problem is that due to the chemical composition of fuel oil, more combustion residues are formed, i.e. soot, ash, sulphur, etc. These residues are gathered in the heat exchangers and can restrict the flow of the combustion gas which leads to a decrease in efficiency and requires regular cleaning.

4.2.1.11 *Flue draft inducers*

Flue draft inducers are small radial fans located in the gas burner compartment of a warm air heater. The flue draft inducer is responsible for inducing a draft in the flue gas route (heat exchanger) and for escorting the flue gas to the outside of the warm air heater housing. As they also influence the fuel-air ratio, they have an impact on the combustion quality and the energy efficiency of the warm air heater. Additionally draft inducers purge the heat exchanger of gases that may have remained in that area during the warm air heater's previous heating cycle. This makes the surrounding air cleaner at the time of combustion and also prevents warm air heater burners from getting clogged with soot.

4.2.1.12 *Heat controls (actuators)*

- Burner control

The heating capacity of fuel-fired air warm air heaters depends on the burner technology used and can be controlled by modulating the heating output of the contained burner.

Single-stage burners offer only two operating stages (off and on – running at full load). The heating demand can be reached by intermitting operation of the burner, which means that the burner is switched continuously on and off. Two-stage burners offer three operating stages (off, stage 1, stage 2). Stage 1 covers the base load and stage 2 covers the maximum load. The third type is modulating burners. Modulating burners can be operated anywhere between their minimal/maximal load range and can control the heat output without switching the burner on and off. These burners offer the highest efficiencies, as they adapt the heating capacity to the actual heating demand. Additionally they are more reliable as there is no continuous switching.

The disadvantage of modulating burners is that the design is more complex thus they are more expensive than single- or two-staged burners.

- Electric capacity control

The heating capacity of an electric warm air heater is controlled by modulating the supply voltage of the resistive heating elements. The higher the voltage, the more heat is produced and delivered to the circulating air. Due to the basic principles of resistive heating, electric heating elements are easier to control than burner-fired warm air heaters.

- Fan control

The flow rate of circulation air can be controlled by modulating the rotation speed of the motor that drives the blower fan. Therefore the energy efficiency of the fan control depends on the kind of motor used, as they have different abilities to control the rotation speed (see chapter 4.2.1.9.- Motors). Older warm air heater motors usually have only one or two fan speeds while recent air warm air heaters contain variable speed or modulating speed fans. The advantage of modulating fans is that they always deliver the exact amount of air required, which has a positive impact on energy efficiency.

4.2.1.13 Room temperature control (sensors)

Room temperature controls are part of every air-based central heating product as they have the function to control the heating capacity and therewith the temperature in the application area. There is a big variety of room temperature control systems which can roughly be divided into the following categories.

- Room thermostats

Room thermostats measure the actual room temperature with a temperature sensor, and then compare this measured value with a desired value given by the user. The heating output is then adjusted according to the difference between desired and actual state.

Room thermostats can be built as mechanical, electric or digital devices and are usually mounted to a wall in the supplied area. These control types are often combined with zone controls and programmable timers to help saving energy.

- Zone controls

Many warm air heaters are equipped with zone temperature controls. This means that dampers are placed in the duct passages of the different supplied zones and are controlled with separate room thermostats in the specific areas.

- Programmable thermostats

Programmable thermostats are designed to adjust the temperature according to various programmed parameters that take effect at different times of the day. For example newer digital thermostats allow setting different temperatures for different zones, over the day (morning, day, evening, night) and the week.

More expensive models of programmable thermostats may have additional built-in controllers, so that the thermostat learns how the system reacts to its commands. Learning from the past behaviour of the room, these devices automatically decide when the systems should be operated to reach a specific temperature for a given time.

- Remote control thermostats

ABCHPs can be equipped with remote controls to increase the ease of use. In its simplest form only the heat output can be set individually by remote control. Switching the device on and off is done manually. More comfortable remote control solutions allow the complete control of the device. In some cases a temperature sensor is built in the remote control, so it can act as a room thermostat. In addition, a manual mode and timer functions are usually available, allowing a time-defined special operation (e.g. night subsidence or reduced operations during the day).

4.2.1.14 *Safety devices*

- **Thermal cut-out**

In the occurrence of overheating such as heat accumulation, a thermal cut-out, will protect the device from the excessive heat and shut it off. Usually thermal cut-outs are bimetallic contacts made out of copper, beryllium or steel, located in the power circuit of the heating device. Once a thermal cut-out is activated, the device may not be able to restart automatically even if a safe temperature is reached. This needs to be done manually or be replaced, which depends on the type of the thermal cut-out used. Thermal fuses are single use cut-outs, while thermal switches can be used over and over again.

- **Flame supervision device (FSD) or flame failure device (FFD)**

Appliances where combustible fuels are used, a flame supervision device (FSD) is installed in order to cut off the fuel supply in case the flame is extinguished. This avoids hazardous unburned fuel being released into the room or flue pipe. There are a great number of different FSDs in the market, but typically when the fuel supply is cut off, the device/appliance has to be reset manually. The most common FSD technologies are thermoelectric FSDs, flame rectification FSDs and optical FSDs. One of the simplest FSD devises is a *flame sensor* in the form of a small metallic cylinder located directly above the flame sending a signal to the circuit board when a problem is detected[11]. An FSD is an important safety feature, as it helps prevent the accumulation of dangerous gases within the dwelling, which would pose great health risks to the user.[12]

  - Thermoelectric FSD (Thermocouple)

A typical thermoelectric flame supervision device contains a safety valve and a thermocouple tip, which is connected to the safety valve over a wire. The thermocouple tip is heated directly by the flame and creates an electric current, which flows down the wire to the valve. Inside the valve, the electric current passes through a coil that generates a magnetic field to hold open the spring-loaded gas safety valve. If the flame goes out, the thermocouple cools, the magnetism created by electricity is cut off and the valve closes, thus stopping the flow of fuel to the burner.

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[11] www.asi-heating-airconditioning.com/A_Simple_Fix_Gas_Furnace.html

[12] BIO Intelligence Service (2012) DG ENER Lot 20 preparatory study

▷Flame rectification / ionisation FSD

Flame rectification FSDs detects flame failure by conducting electric current through the flame. Flames contain freely moving charged particles called ions, which allow the flame to conduct an electric current. A circuit board passes a current through the flame using two electrodes. If the flame is extinguished, the circuit board will detect that current flow has stopped. It may then try to reignite the flame at the burner. If this does not work after a specified time (e.g. 30 seconds), the circuit board can shut down the appliance completely so that it will have to be manually reset.[13]

- **Optical FSD**

▷Infrared FSD

An infrared FSD monitors the infrared radiation emitted by a flame. An infrared-sensitive diode receives the emitted radiation and converts it into an electric signal. If the flame is extinguished, the signal changes and the safety valve is shut off.

▷Ultraviolet (UV) FSD

Similar to the infrared FSD, ultraviolet FSDs use a UV-sensitive cell to monitor the flame. When exposed to UV radiation emitted by a flame, the UV cell converts it to an electric signal. UV FSDs work like infrared FSDs, but monitor a different part of the electromagnetic spectrum.

- **Spill switch or Limit switch**

A spill switch or limit switch is a switch that is usually mounted on the manifold of the warm air heater. Its purpose is to detect unwanted flames or heat escaping the burner tubes inside the gas burner. If such flames or heat are detected the main gas valve will be turned off. Depending on the age and model of the warm air heater an error message or light will be displayed notifying the user of the problem.

- **High limit switch or Plenum Thermostat**

The purpose of high limit switches or plenum thermostats is to monitor the temperature of the airstream at or close to the heat exchanger. It is typically located at the back wall of the gas burner chamber above the main gas burner. It is set to work in a specific temperature range, and once it detects too high temperature the heating system is turned off by turning off the main gas burner.

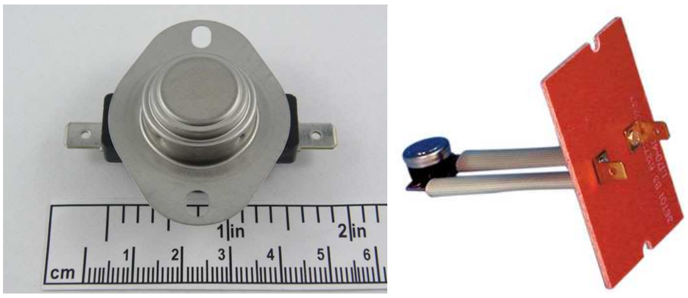

Figure 4-6 A limit switch[14] (left) and a Plenum Thermostat[15] (right)

[13] www.radmidlands.co.uk/ControlsDom.pdf

[14] www.fire-parts.com/replacement-parts/limit-switches-discs/large-300f-150c-limit-switch.html

4.2.2 Heat pumps

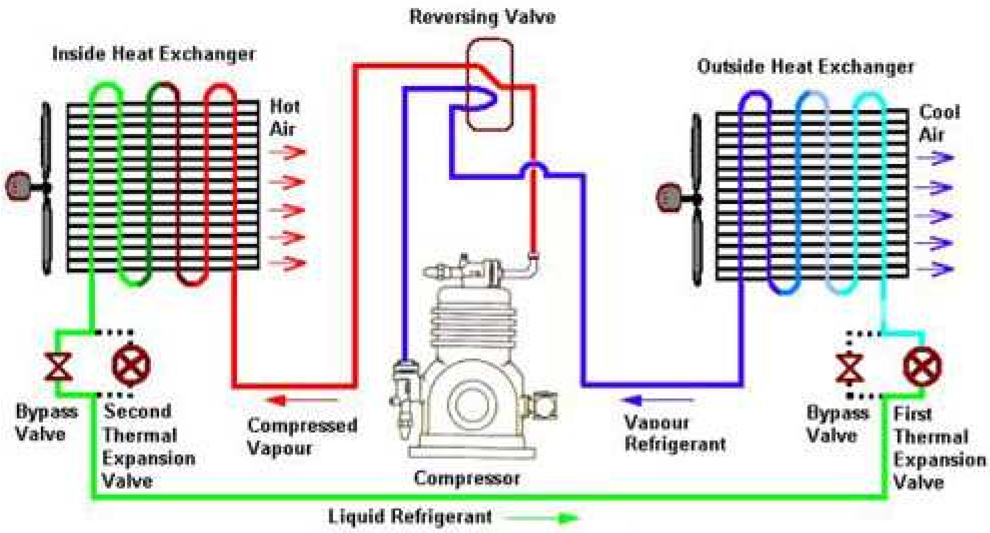

Figure 4-7: Reversible air-to-air heat pump in heating mode[16]

4.2.2.1 *Compressor*

The compressor is the centrepiece of every heat pump device, as it is the only mechanically driven component that needs an external power source. Because of this, the compressor type has a major influence on the energy efficiency of a heat pump system. Technically a compressor is a device that increases the pressure of gas by reducing their volume. As a result of this, the density and temperature of the gas increases as well. This change of condition is achieved through mechanical work of the compressor, which is powered by an electric motor or a gas fired engine.

Compressors can be classified by the compression type:

- positive displacement compressors
- dynamic compressors

[15] http://stspartsupply.com/Supco-SHL503-Limit-Plenum-Thermostat-Range-150-190F-Supco-SHL503.htm
[16] Image property of TrueHVAC.com. Website: www.truehvac.com/php/how-heat-pumps-work.php

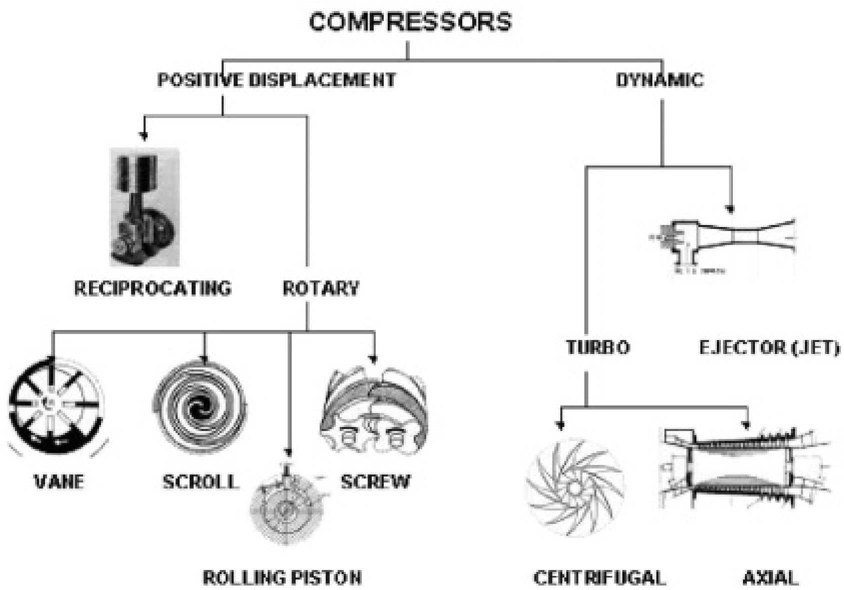

Figure 4-8: Types of compressors

- **Positive displacement compressors** confine fixed volumes of refrigerant within a closed space at high pressures. The fluid pressure increases when the volume of refrigerant decreases. Reciprocating, screw, and scroll are common positive displacement compressors.

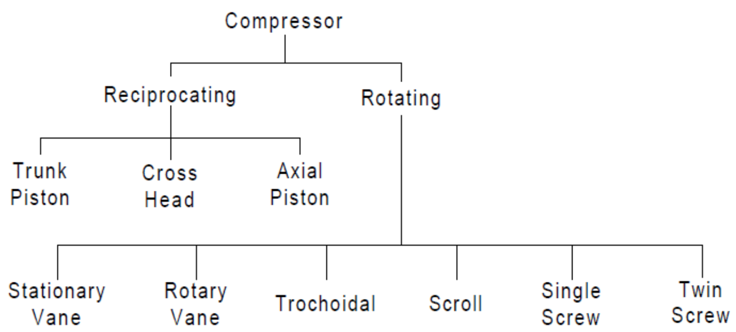

Figure 4-9: Classification of positive displacement compressors

- **Dynamic compressors** confine large volumes at low pressures. They use rotating vanes or impellers to increase the pressure of the refrigerant. Centrifugal compressors are the most popular compressors of this category.

Furthermore compressors may be classified by their motor configuration:

- **Open compressor**, the compressor motor is located in a separated casing from the compressor, which is convenient for maintenance since it allows easy access to the components. But this configuration can cause refrigerant leaks and only used in remote refrigeration systems. Open compressors are used when ammonia is used as the refrigerant as the copper contained in the electric motor would otherwise have a corrosive effect.

- **Hermetic compressor**, the motor and compressor are installed in a closed space, which helps prevent refrigerant leakages. Refrigerant is also used to cool the motor. Hermetic compressors are typically used in power ranges less than 40 kW[17].
- **Semi-hermetic compressor** includes the motor and compressor in a common casing, but allows access to key components such as valves and connecting rods. They have an improved tightness to avoid leakages compared to open compressors, but they are not as tight as hermetic compressors. The refrigerant is used to cool the motor.

All of these compressor types can be used for heat pump appliances and offer different advantages. Generally the most used compressors for heat pumps are reciprocating piston compressors (e.g. piston compressor), scroll compressors and rotary compressors. The design of the heat pump and selection of compressor and refrigerant line is usually optimised for the specific characteristics of the heat pump: cooling, heating or reversible function; operating temperatures, capacity and size of the system; number of connectable units; etc.

- Reciprocating piston compressor

In reciprocating piston compressors the compression is achieved by a reciprocating movement of pistons in combination with inlet and outlet valves. The intake gas enters the suction manifold, then flows into the compression cylinder where it gets compressed by a piston driven in a reciprocating motion via a crankshaft, and is discharged subsequently through the outlet valve. Reciprocating piston compressors have been used in heat pumps for years; typically in small and medium sized heat pumps.

As it is not practical for the piston to be in close contact with the valve plate, there is always a small "dead" space in the cylinder leaving a small amount of refrigerant uncompressed. This effect influences the average flow and reduces the efficiency of the compressor. Other disadvantages of reciprocating piston compressors are high vibrations and noise due to the pulsating movement of the pistons.

- Scroll compressor

A scroll compressor uses two interweaving scrolls to compress the fluid or gas. Often, one of the scrolls is fixed, while the other moves eccentrically in relation to the fixed scroll without rotating, thereby trapping and pumping or compressing pockets of fluid between the scrolls (see Figure 4-10). Another method for producing the compression motion is co-rotating the scrolls, in synchronous motion, but with offset centres of rotation.

Conventional scroll compressors have only two capacity settings – "on" and "off" which makes it impossible to vary the output of the compressor. Scroll compressor technology has however evolved in recent years, and new modulation concepts exist which allow continuous control of the compressor capacity without any intermitting operations.

The main advantages of scroll compressors are high operation smoothness, low noise, higher reliability than reciprocating piston compressors and compact design. As a result of these advantages, scroll compressors are used in many small residential heat pump systems. Especially

[17] Source: Hydro Québec (1994) Guide technique, systèmes de compression et de réfrigération.

capacity controlled scroll compressors are found in recent heat pump systems as they combine the typical scroll advantages with good output modulation abilities.

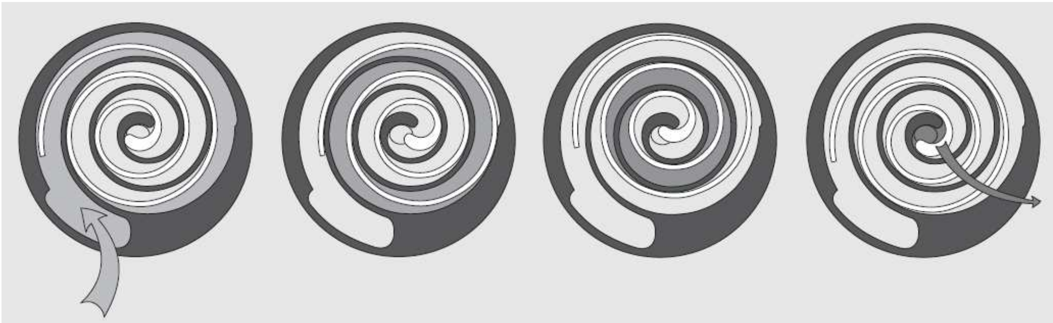

Figure 4-10: Scroll compressor, compression process[18]

- Screw compressor

Rotary screw compressors use two meshing helical screws, known as rotors, to compress the gas. In a dry running rotary screw compressor, timing gears ensure that the male and female rotors maintain precise alignment. In an oil-flooded rotary screw compressor, lubricating oil bridges the space between the rotors, both providing a hydraulic seal and transferring mechanical energy between the driving and driven rotor. Gas enters at the suction side and moves through the threads as the screws rotate. The meshing rotors force the gas through the compressor, and the gas exits at the end of the screws.

The main advantage of screw compressors is the operation smoothness as well as a consistent flow rate, due to the steady movement of the screws. Additionally, the screws work frictionless, which results in greater reliability and low maintenance efforts. Other advantages are resistance to moisture and good capacity controllability. Screw compressors are mainly used in medium and large appliances of non-residential heat pump systems.

- Rolling piston compressor

Rolling piston compressors consist of a cylindrical housing with an eccentrically mounted piston rolling on the inner wall of the cylinder. One or more vanes installed on the inside of the cylinder wall separate the cylinder space into a pressure chamber and a suction chamber. Scroll compressors can include more than one piston that work in parallel and can reach higher pressure levels than a single compressor. Rolling piston compressors offer a low noise level and low vibrations during operation but are more sensitive to moisture.

Recent rolling piston compressors can be output controlled with the help of inverters that can vary the motor's speed. Due to their compact design and their relatively small delivery volume rolling piston compressors are usually used in smaller residential heat pump systems.

[18] Bitzer; Application Manual, Hermetic scroll compressors. Website: www.bitzer.de/ger/products/docu/doc_det/35

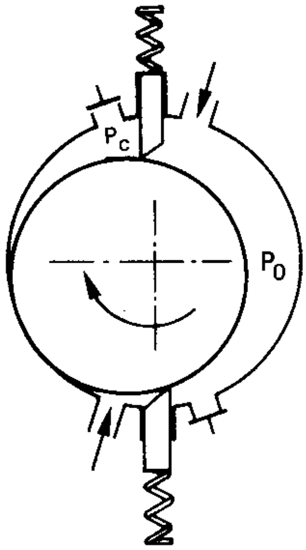

Figure 4-11: Rolling piston compressor[19]

- Compressor motors

As in most cases electric motors are used for powering heat pump compressors. The most commonly used motor types are the permanent split capacitor motor (PSC) and the recent brushless permanent magnet motor (BPM). These motor types are already explained in chapter 4.2.1.9 -Motors.

- Compressor oil

The main purpose of the compressor oil is to lubricate the moving parts of the compressor, to reduce the friction so that a smooth and silent operation is ensured. Additionally it protects the compressor from both corrosion and pollution, and is responsible for heat evacuation and for the sealing of the compression process.

As compressor oils get into direct contact with the refrigerant they have a lot of secondary functional characteristics. Depending on the type of refrigerant used and the type of heat pump, the oil can either be mixed with the refrigerant or not. It has to maintain its properties throughout all occurring temperature levels and keep its durability in order to reduce oil replacement intervals.

Due to the compressor type, oil may get mixed with the refrigerant fluid and additional issues may occur. The oil/refrigerant mixture becomes viscous on the cold evaporator side, which will lead to oil adherence on the inside of the evaporator. As a result the heat transfer is affected and little oil returns to the compressor.

As observed, the selection of the compressor oil may have an influence on the heat pump's efficiency and on the reliability of the compressor.[20]

[19] Recknagel, Sprenger, Schramek; Taschenbuch für Heizung + Klimatechnik 09/10

[20] www.oelcheck.de/wissen-von-a-z/uebersichten-und-tabellen/elementbestimmung-oel-und-kraftstoff-reinheitsklassen/oelcheck-analysen-halten-kaeltemaschinen-fit.html

4.2.2.2 *Evaporator/Condenser*

The evaporator in a heat pump system is responsible for evaporating the liquid refrigerant fluid into a gaseous state by extracting latent heat from the heat source. To achieve this effect, a good thermal conduction is necessary between the two separated media streams (heat source and refrigerant cycle). For this reason, evaporators are heat exchangers with a high surface area, mostly made of high thermal conducting metals like copper, aluminium or stainless steel.

Evaporators are classified according to the method of refrigerant liquid feed. The dry method features complete evaporation of the liquid and superheats the refrigerant vapour after its evaporation. The flooded method is totally immersed with liquid refrigerant. This classification is of great importance as some compressors can handle moisture while other compressors can be damaged due to moisture exposure.

Evaporators and condensers can both be seen as heat exchanging components. Evaporators transfer heat from the heat source to the refrigerant, while condensers exchange heat from the refrigerant to the heat sink. A condenser liquefies the hot vaporised refrigerant and thereby delivers latent heat to the application area (heat sink). The refrigerant is cooled and condenses completely back to the liquid phase. Under certain conditions evaporators and condensers can be used interchangeably as the technical aspects are basically the same. The choice of the design and functional principle of evaporators and condensers have a major influence on the COP (coefficient of performance) of heat pumps.

Evaporators can be built using different designs. The most relevant designs are presented in the following paragraphs.

- Plate heat exchanger

A plate heat exchanger consists of a series of thin, corrugated plates that are held together by gaskets, welded or brazed together depending on the application of the heat exchanger. The plates are compressed together in a rigid frame to form an arrangement of parallel flow channels with alternating hot and cold fluids. This has the major advantage that the surface area for heat transfer is much higher than in other heat exchanger types. Because of this large heat transfer area, the size of the plate heat exchanger is smaller for the same amount of heat exchanged. The greatest disadvantages of plate heat exchangers are a relatively high pressure drop as well as the risk of oxide and sludge particles in the refrigerant clogging the inside chambers. This is due to the narrow chambers between the exchanger plates. Plate heat exchangers are usually manufactured of aluminium or stainless steel metal plates and offer a wide range of capacity, i.e. from 0.5 to 5,000 kW for brazed heat exchangers and up to 25,000 kW for gasketed heat exchangers. However, heating and cooling heat pumps rarely reach more than 200 kW of capacity. For higher heating and cooling demands, a combination of several outdoor units is a common solution.

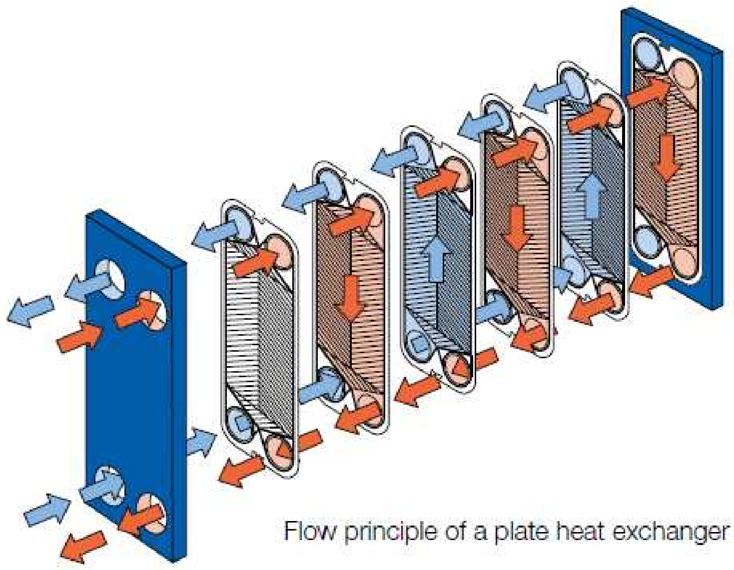

Figure 4-12: Flow principle of a typical plate heat exchanger[21]

- Shell and tube heat exchanger

Shell and tube evaporators/condensers consist of a shell (a large pressure vessel) with a bundle of tubes inside. One fluid runs through the tubes, and another fluid flows over the tubes (through the shell) to transfer heat between the two fluids. The set of tubes is called a tube bundle, and may be composed of several types of tubes: plain, longitudinally finned, etc. Shell and tube devices are characterized by a large diversity of materials, a low sensitivity to dirt and frost, and sluggish control behaviour. Because of these parameters they are very widespread in large industrial appliances and offer very high capacities up to 70,000 kW. However, these capacities are not common in heating and cooling heat pumps and the size of this kind of heat exchangers prevents them from being used in the products covered in this preparatory study.

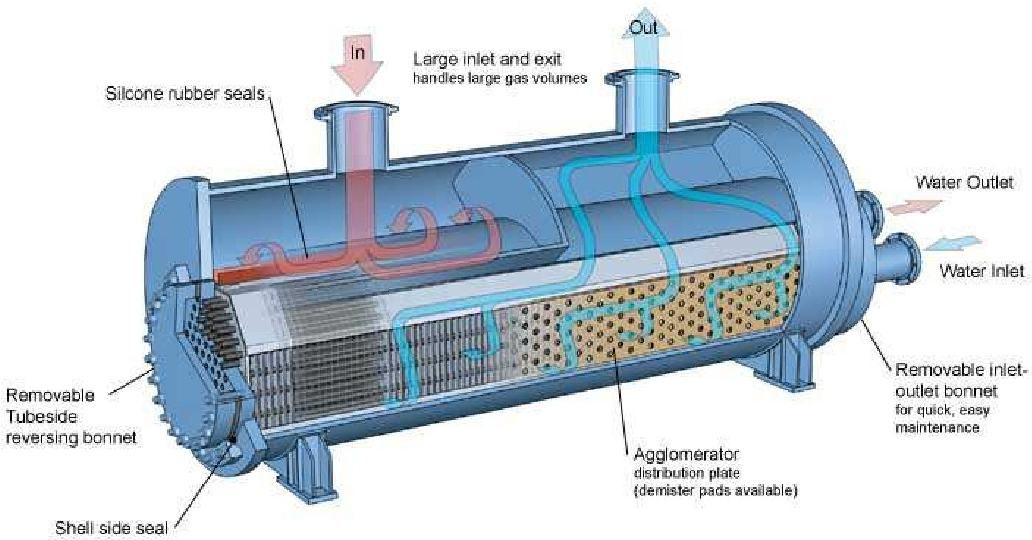

Figure 4-13: Shell and tube heat exchanger[22]

[21] Image property of Alfa Laval Corporate. Website:www.alfalaval.com

- Coaxial heat exchanger

Coaxial evaporator or condenser devices consist of one or more inner tubes and a surrounding outer tube. This tube bundle is coiled in a spiral shape and hard-soldered at the ends with T-fittings. Usually the inner tubes are specially optimised with additional fins or corrugated surfaces. Most coaxial heat exchangers are made of stainless steel, copper or copper alloys.

The advantages of coaxial devices are high frost-resistance, a long lifetime, low system fouling and possible reversible operation. Coaxial evaporators or condensers are predominantly used in small residential appliances due to design considerations.

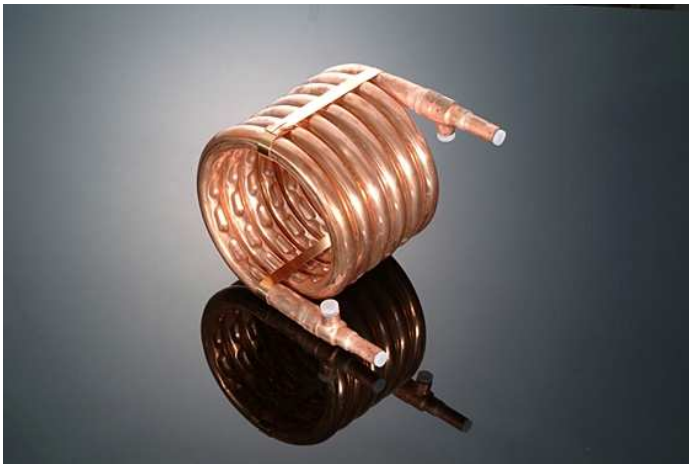

Figure 4-14: Coaxial heat exchanger [23]

- Finned tube heat exchanger

Finned tube heat exchangers are typical air/fluid heat exchangers often used in air conditioners and air-to-air or water-to-air heat pumps. They contain tube coils, mostly made of copper, with several rows of fins mounted to the tube. These fins are mostly made of aluminium and are mounted in a metal frame. As the heat transfer coefficient of air is many times lower than the coefficient of water, the heat transfer area must be proportionally higher. This is why the fin design is used as it offers a large surface area. The fins can be arranged in various arrays depending on the intended application.

4.2.2.3 Expansion device

The expansion valve of the heat pump is the counterpart to the compressor. The fundamental functions of the expansion device are to reduce the pressure of the condensed refrigerant before it enters the evaporator and to regulate the refrigerant flow into the evaporator. Depending on the evaporator type, different expansion device types can be used. There are several kinds of expansion devices used for heat pumps; i.e. capillary tubes, automatic expansion valves, thermostatic expansion valves, electronic expansion valves and float type expansion valves. As the most relevant device for heat pump systems are thermostatic expansion valves and electric expansion valves, they are reviewed in more detail.

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[22] http://heatexchanger-design.com/2011/01/14/tube-heat-exchangers/

[23] Picture property of Wieland-Werke AG, www.wieland-thermalsolutions.de

- Thermostatic expansion valve (TEV)

A thermostatic expansion valve does two things. First, it acts as an expansion device for the refrigerant. That is, it allows the liquid refrigerant to move from the warm, high-pressure side of the condenser output to the cold, low-pressure environment of the evaporator input. It does this by restricting the refrigerant flow by lowering the flow diameter. The second function of the TEV is to regulate the amount of refrigerant that flows through the evaporator (see Figure 4-15). A temperature sensing bulb (1), filled with a similar fluid as contained in the system, is attached to the refrigerant line exiting the evaporator. The pressure of the fluid in the sensing bulb is at the saturation pressure corresponding to the temperature at the evaporator exit. This pressure is led to the valve through a capillary tube and is exerted on top of a metal diaphragm (3) which is connected to the valve needle. Due to an internal equalizer (4) the evaporation pressure acts from below to the diaphragm. As the temperature on the bulb increases, the pressure on the diaphragm increases, causing the valve to open against a spring with a preset spring force. As the temperature after the evaporator decreases, so does the pressure in the bulb and on the spring, causing the valve to close.[24] As long as the saturation pressure and evaporation pressure are equal, the valve keeps the refrigerant flow rate equal as well. Besides internally equalised TEVs there are externally equalised TEVs, which are needed for larger evaporators.

Each TEV is designed for a particular refrigerant and a particular refrigeration load, and comes preset from the factory to keep the refrigerant slightly above the vaporization temperature (superheated evaporation). Liquid refrigerant leaving the evaporator can damage the compressor so the refrigerant at the evaporator output must always be in gaseous form. The thermostatic expansion valve represents the most often used expansion device in heat pumps today because they are often more energy efficient than other designs in which they are not employed.[25]

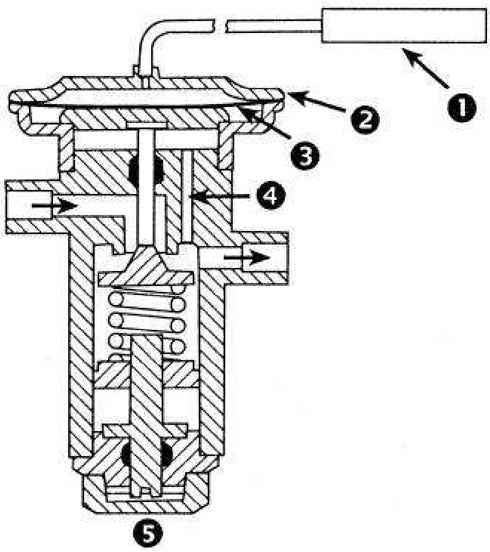

Figure 4-15: Cross section of a typical Thermostatic Expansion Valve[26]

[24] www.wisdompage.com/SEUhtmDOCS/SEU10.htm
[25] Whitman, Johnson & Tomczyk (2005) Refrigeration & air conditioning technology; 5th Edition.
[26] www.wisdompage.com/SEUhtmDOCS/SEU10.htm

- Electronic expansion valve

Electronic expansion valves (EEVs) use a small step motor to control the valve port and thereby the amount of refrigerant entering the evaporator. The step motor drives a gear train and a lead screw to position a piston. The piston is used to modulate flow through the valve port. EEVs do this in response to signals sent to them by an electronic controller. The controller gets an actual temperature and pressure value from a sensor installed at the evaporator exit and permanently sends a control input to the step motor. Thus, the refrigerant gets superheated exactly to the point where there is no liquid is left, even in part load operation. Generally, EEVs react faster to changing evaporator conditions than conventional TEVs.

4.2.2.4 *Refrigerant fluid*

The refrigerant fluid is the working fluid of every refrigeration or heat pump system. Its main purpose is to allow multiple phase changes from liquid to gas and vice versa, where the actual latent heat gain and heat sink happens. Different refrigerants offer a wide range of characteristics, e.g. different boiling point and dew point, so that the refrigerant always has to be appropriately chosen for the specific demands of the application. Due to the environmental impacts of some refrigerants like ozone layer depletion, global warming potential and toxicity, the choice of the refrigerant has become an important issue. Additionally, a lot of important practical issues such as the system design, component size, initial and operating costs, safety, reliability, and serviceability depend very much on the type of refrigerant selected for a given application.

Refrigerants can be classified according to their chemical composition into natural refrigerants (water, ammonia, propane, CO_2) and synthetic refrigerants (Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Hydrofluorocarbons (HFCs)). Most of the synthetic refrigerants contribute significantly to either the ozone depletion or the global warming. For these reasons some refrigerant fluids, like the formerly wide spread CFCs or R-22 (Chlorodifluoromethane), are nowadays prohibited by EU-legislation[27]. It is still a big challenge for the chemical industry to find suitable substitutes that combine the required characteristics of refrigerants with environmental sustainability. The following table contains an overview of common refrigerants.

[27] Regulation EC No. 2037/2000 on substances that deplete the ozone layer and Regulation EC No. 842/2006 on certain fluorinated greenhouse gases

Table 4-2: Overview of refrigerant groups

CFCs Chlorofluorcarbons	HCFCs Hydrochlorofluoro-carbons	HFCs Hydrofluorocarbons	Natural refrigerants
R-11 R-12 R-502 …	R-22 R-123 R-124 R-401A R-402A …	R-134a R125 R-404A (blend) R-407C (blend) R-410A (blend) …	R-717 (ammonia) R-718 (water) R-744 (CO_2) R290 (propane) R1270 (propene) …
Prohibited for new appliances, extension and modifications.	Prohibited for new appliances, extension and modifications.	Permitted in the EU. Regulation EC No. 842/2006 has to be followed.[28]	Permitted for all kinds of appliances.

Nowadays only HFCs and natural refrigerants are used in heat pumps. The most common refrigerant fluids are:

- **R-134a** (1,1,1,2-Tetrafluoroethane)
- **R-404A** (blend of 52 wt.% R-143a, 44 wt.% R-125, and 4 wt.% R-134a)
- **R-407C** (blend of 23 wt.% R-32, 25 wt.% R-125, and 52 wt.% R-134a)
- **R-410A** (blend of 50 wt.% R-32 and 50 wt.% R-125)

Natural refrigerants like ammonia, propane or water cause low global warming potential, but have other negative characteristics like high combustibility, toxicity or high vapour pressures. Due to these reasons, heat pumps with natural refrigerants are still a minority on the market. The right refrigerant selection is important for energy efficiency, as it can affect the energy consumption of the equipment. The thermodynamic properties of the refrigerant have a significant impact on the heat transfer and therefore on the performance of the system. However, the choice of the appropriate refrigerant is a compromise between its environmental, thermodynamic and safety properties. A good comparison of environmental and efficiency properties can be done using TEWI (Total Equivalent Warming Impact) values, which include the warming impact due to energy consumption and of refrigerant emissions. For example, the efficiency of a heat pump system can be improved by choosing multiple smaller outdoor units, but this configuration requires a higher refrigerant charge, which could increase the potential GHG emissions.

4.2.2.5 *Fans*

The purpose of fans in heat pumps is to transfer heat by blowing the air through the heat exchangers when either extracting heat from the condenser, or transferring heat to the

[28] In some non-EU countries, the use of HFCs is prohibited.

evaporator. This can be achieved with axial, cross-flow or centrifugal fans. Axial fans are most commonly used for air-to-air outdoor systems and the airflow can be adjusted through a variable speed electrical motor or other mechanisms. Centrifugal fans with backwards curved blades are also commonly used and are predominately placed on walls and windows[29].

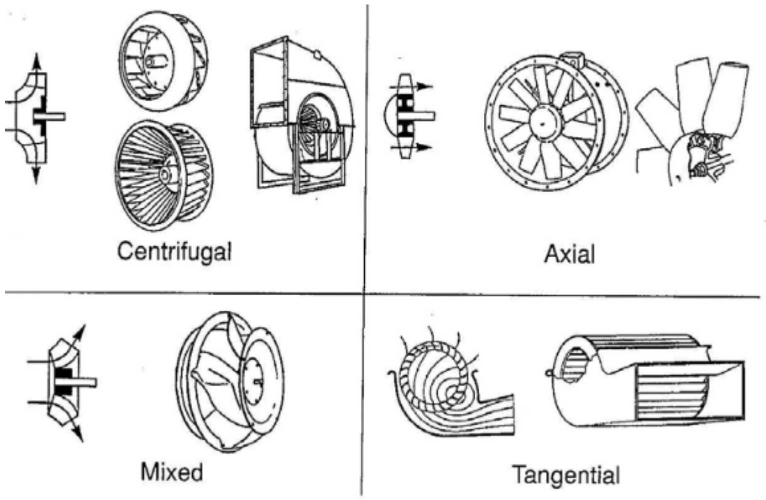

Figure 4-16: Classification of different types of fans (Cory, 1992)[30]

The airflow of axial fans are in a parallel direction to the axis of the fan, while centrifugal fans have a radial airflow, which blow the air perpendicular to that of the intake. Usually axial fans are of lower costs, lighter weight and more compact to that of centrifugal ones. However, centrifugal fans with backwards-curved airfoil-shaped blades can perform better than axial ones, as they can reach efficiencies of up to 90%[31].

With cross flow or tangential fans, the air flow is tangentially. They are also a good option for transferring heat as they are relatively efficient. Due to the particular shape, they also emit less noise and can handle big flows compared to their size.

4.2.2.6 *Auxiliary heater*

Auxiliary heaters are used to cover peak loads in heat pumps systems, when the heating capacity of the heat pump is not sufficient. This may be the case for heat pumps with low heat source temperatures, i.e. air-source heat pumps.

In the context of auxiliary heaters, it is necessary to introduce two terms; *monovalent* and *bivalent* heat pump operation. Monovalent heat pumps meet the annual heating (and cooling) demand alone, without the support of auxiliary heaters. Bivalent heat pumps are sized for 20-60% of the maximum heat load and meet around 50-95% of the annual heating demand (in a building in Europe). The peak load is met by an auxiliary heating system, often a gas or oil boiler

[29] ARMINES (2008) DG ENER Lot 10 preparatory study on residential air conditioning and ventilation.

[30] Fraunhofer, Karlsruhe (2008) EuP Lot 11: Fans for ventilation in non residential buildings. Final report.

[31] ARMINES (2011) Air Conditioning and Ventilation Systems DG ENTR Lot 6, Draft Report Task 5 Technical Analysis Ventilation Systems for non residential and collective residential applications, BAT and BNAT, Study commissioned by the European Commission - DG Enterprise.

or an electric heater. In larger buildings the heat pump may be used in tandem with a cogeneration system (CHP).[32]

4.2.2.7 *Safety devices for heat pumps*

Safety devices are essential to ensure a safe operation and installation of heat pump systems. The most common safety devices are:

- Safety pressure limiter

The purpose of the safety pressure limiter is to protect the compressor and all components on the high pressure side from excessive pressures. It stops the compressor if a set maximum pressure value is exceeded.

- Low pressure protection

If the pressure level on the low pressure side of the heat pump drops below a certain value, operation has to stop to avoid damage to the compressor and other components.

- Frost protection

The purpose of a frost protection is to cut-off the operation if the heat source temperature drops below a set minimum value to avoid freezing damage of the evaporator. This is common in air source heat pumps, as the air temperature may fall below 0°C in winter.

- Oil pressure supervision

Oil pressure surveillance devices monitor the oil pressure in lubricated compressors. It will stop the compressor in case the lubricant oil pressure drops to prevent damage to the compressor.

- Hot gas monitoring

The temperature of the hot refrigerant gas is monitored. If this temperature exceeds a set maximum value then operation cut-off is triggered.

- Refrigerant level surveillance

The purpose of a refrigerant level surveillance is to prevent overfilling or lack of refrigerant fluids well as to recognise system leakages. This can be achieved by automatic refrigerant level monitoring devices or manual control devices like sight glasses.

- Flow surveillance

A flow surveillance switches off the appliance when the secondary flows (air flow on the outside and in the application area) are too low to prevent icing (evaporator) or overheating (condenser).

4.2.2.8 *Capacity controls (actuators)*

As the heating demand of a building varies with changing indoor and outdoor conditions, heat pump systems must be able to control their heating capacity to meet the actual heat demand and avoid energy losses.

[32] IEA Heat Pump Centre; Sweden; www.heatpumpcentre.org/en/aboutheatpumps/heatpumpsinresidential/Sidor/default.aspx

- Compressor control

The heating capacity of a heat pump can be controlled by modulating the capacity of the compressor. Depending on the compressor type, there are several methods such as intermittent operation (on/off), hot gas bypass, evaporator temperature control, multiple compressor control and variable speed control. As proven by several investigations, the variable speed control is the most energy efficient continuous capacity control method.[33]

The variation of a compressor's rotation speed can be achieved by using a frequency inverter that changes the frequency of the electric supply to the motor. Therefore, heat pumps that use this kind of technology are often called inverter heat pumps. Frequency inverters however have their own electric losses, and increase manufacturing costs and reliability concerns. Smaller compressors in heat pumps use brushless permanent magnet motors (BPM) with built-in inverters that can be speed controlled without significant energy losses (see Section 4.2.1.9 - Motors).

Recent scroll compressors are able to modulate their capacity without using additional devices like inverters. With this technology it is possible to continuously control the compressor capacity from approximately 10% to 100%.

- Capacity controls of fans and pumps

When modulating the compressor capacity it is also necessary to control fans and pumps that transport the heat source and heat sink media. This can also be achieved by variable speed motors like BPM motors.

4.2.2.9 Rooms temperature controls (sensors)

Heat pump control systems use specially designed thermostats to control the heating capacity. Generally the type of thermostat depends on the available functions of the heat pump (heating, cooling, heating and cooling)

- Programmable thermostats

Programmable heat pump thermostats are available today from most heat pump manufacturers and their representatives. Unlike conventional thermostats, these thermostats achieve savings from temperature setback during unoccupied periods, or overnight. Although this is accomplished in different ways by different manufacturers, the heat pump brings the building back to the desired temperature level with or without minimal supplementary heating.[34]

- Conventional thermostats

Conventional room thermostats for air-based heat pump heating systems are two-staged indoor thermostats. Stage one calls for heat from the heat pump if the temperature falls below the

[33] Frederik Karlsson (2007) Capacity Control of Residential Heat Pump Heating Systems.

[34] Natural Resources Canada; Thermostats for heat pumps;

http://oee.nrcan.gc.ca/residential/personal/thermostats-controls.cfm?attr=4#electronic preset level. Stage two calls for heat from a supplementary heating system (if available) if the indoor temperature continues to fall below the desired temperature.

Additionally, there are two types of outdoor thermostats used with these systems. The first type controls the operation of the electric resistance supplementary heating system. It turns on various stages of heaters as the outdoor temperature drops progressively lower. This ensures that the correct amount of supplementary heat is provided in response to outdoor conditions, which maximizes efficiency and thereby also saves money. The second type simply shuts off the air-source heat pump when the outdoor temperature falls below a specified level.

Thermostat setback may not yield the same kind of benefits with heat pump systems as with more conventional heating systems. Depending upon the setback and temperature drop, the heat pump may not be able to supply all of the heat required to bring the temperature back up to the desired level within a short time period. This may mean that the supplementary heating system operates until the heat pump "catches up." This will reduce the savings that could be expected when installing the heat pump.[34]

4.2.2.10 *Other components*

- Reversing valve

A reversing valve is a type of valve usually used in heat pump systems that changes the direction of refrigerant flow. By reversing the flow of refrigerant, the heat pump refrigeration cycle is changed from cooling to heating and vice versa. The cycle reversion is initiated by a small solenoid pilot valve that triggers the movement of a slide. This slide can block and release the different flow routes and is therefore responsible for inverting the flow direction. Reversing valves can cause pressure drop and undesired heat exchange that leads to a decrease of the heat pump's performance.

- Filter-drier

A filter-drier is used to remove dirt, moisture and other contaminants from the refrigerant to avoid damage to the compressor and other components in the heating system. The filtering is achieved by filter pads while the drying is accomplished by a hygroscopic desiccant contained in the filter-drier.

- Sight-glass

A sight glass is used to do a visible check of the refrigerant condition. Gas-bubbles, colour and filling level can give a good impression of whether the refrigerant is in good condition or not.

- Liquid receiver

A liquid receiver is occasionally built into the bottom of the condenser and serves to accumulate liquid refrigerant, to provide storage for off-peak operation, and thus avoids refrigerant shortage in the system. The receiver also serves as a seal against the entrance of gaseous refrigerant into the liquid line.

- Economiser

Economisers are mechanical devices used in heat pump and refrigeration systems to increase the performance. In simple terms, it is an additional heat exchanger. As can be seen in Figure 4-17, an economiser uses a part of the total refrigerant flow leaving the condenser to cool the rest of the refrigerant flow that leaves the condenser. The evaporated refrigerant part flow (m1) then enters the compressor at an intermediate pressure level. The cold gas from the economiser can also be used to provide extra cooling for the compressor. The sub-cooling of the main refrigerant flow (m2) changes the quality of the inlet vapour to the evaporator, which increases the cooling capacity. Since economiser systems require extra components, such as piping and a compressor with an economiser entrance, they usually add to the manufacturing costs.

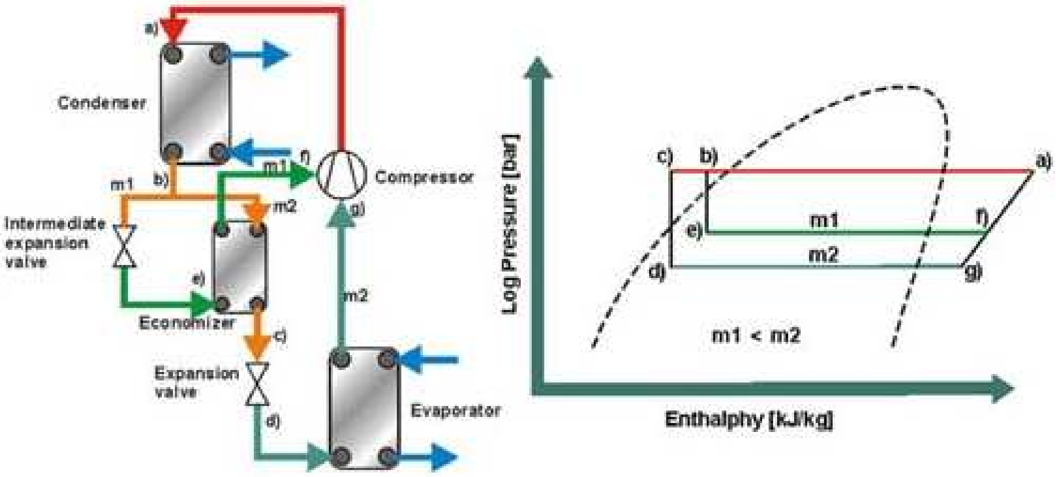

Figure 4-17: Economiser process diagram[35]

4.2.2.11 Noise

The noise generated by heat pumps can be a great concern to customers' comfort and the local environment. Usually heat pumps (particularly those used in domestic applications) do not emit high levels of noise and are considered to reproduce the same noise as a large refrigerator [36].A direct co-relation can be established between the power output and the noise level. However, there does not appear to be a direct relation between energy efficiency and noise levels[37]. The outdoor noise levels for multi split units are always considerably higher than indoor units. On the other hand, the difference between indoor and outdoor noise levels for single split units are not that high. For units bigger than 35 kW the noise is actually either the same or higher indoors[38].

Most of the heat pumps manufacturers publish noise data for the cooling function of their heat pumps. No big differences can be detected between the noise levels of the cooling and the heating function (in the range of +/- 2 dBA)[39]. The main sources of noise from electric heat pumps come from the motors, the indoor/outdoor fans and the compressor. The condenser fan is

[35] Picture property of SWEP International. Website: www.swep.net/index.php?tpl=pageo&lang=en&id=313
[36] www.ecoheatpumps.co.uk/heat_pump_faq.htm#1
[37] ARMINES (2008) DG ENER Lot 10 preparatory study on residential air conditioning and ventilation.
[38] ARMINES (2011) DG ENER Lot 6 preparatory study on Air Conditioning and Ventilation Systems.
[39] ARMINES (2008) DG ENER Lot 10 preparatory study on residential air conditioning and ventilation.

typically the noisiest of all[40]. For gas engine heat pumps, the combustion engine is also a source of noise.

There are a number of standards regarding the evaluation of noise and related issues:

- EN 12102 Air conditioners, liquid chilling packages, heat pumps and dehumidifiers with electrically driven compressors for space heating and cooling – Measurement of airborne noise – Determination of the sound power level
- ISO/NP 13261-3 Sound power rating of air-conditioning and air-source heat pump equipment - Part 3: Ducted equipment
- DIN ISO 3744 resp. DIN EN ISO 9614 Determination of sound power levels of noise sources using sound intensity

These can be found described in more detail in Task 1 of this preparatory study.

4.3 Common configurations & technologies

In the following section, common air-based central heating products are analysed in terms of their configurations and general technologies. The aim is to present an overview of the available technologies and also to provide information on the suitability of the different technologies for air-based central space heating.

4.3.1 Gas and liquid-fuel warm air heaters

4.3.1.1 Indirect-fired warm air heaters

Indirect-fired warm air heaters use an internal air circulation fan to suck in the circulation air that needs to be heated. These fans or blowers are typically direct driven centrifugal (radial) fans, with a speed modulating electric motor. Before entering the warm air heater housing, the air is usually passed through a filter to remove any particles like dust or pollen. Then the air is passed over the flue gas heat exchangers. There are two separated, circulating air paths:

- the combustion path carries the hot flue gas from the burner to the primary heat exchanger/secondary heat exchanger and then finally to the flue gas exhaust
- the ventilation air path transports the air that is to be heated

Today, most indirect-fired warm air heaters contain either gas in-shot burners or oil retention burners. The fuel is burned and the hot flue gas is passed through a primary heat exchanger, which is installed directly in the ventilation air flow. The heat is transferred from the flue gas to the ventilation air.

[40] ARMINES (2011) DG ENER Lot 6 preparatory study on Air Conditioning and Ventilation Systems.

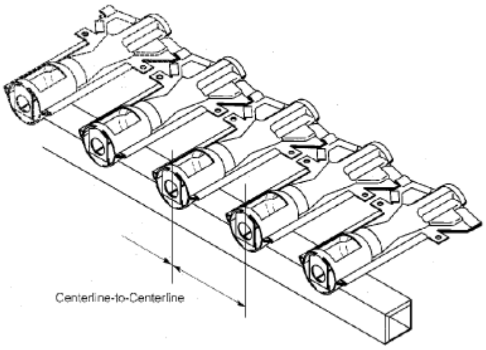

Figure 4-18: In-shot burners[41,42]

Most recent indirect-fired gas warm air heaters are condensing, which means that they condense the water vapour that is contained in the flue gas and use the achieved condensation heat. The accumulated condensate is diverted to an external condensate drain.

Gas warm air heaters contain a flue draft blower (or draft inducer), which is a fan that creates a negative pressure in the flue gas route and creates the necessary positive pressure for the flue gas exhaust side. Oil warm air heaters do not contain such draft inducer fans, as they make use of the barometric draft over the flue gas exhaust/chimney system.

All warm air heaters are defined by the direction of circulation airflow through the heater. Horizontal warm air heaters are used in a reclining position. The airflow is from side to side. This style of furnace is usually installed in crawl spaces with a shallow ceiling height. Upflow warm air heaters are the most commonly installed type of heaters. The airflow is directed upward. Downflow warm air heaters have the air flowing downward over the heat exchanger. This type of heater is mostly used when the ductwork is installed into access floors. Additionally, heaters are categorised into "lowboy" and "highboy", depending on the height resulting from the component arrangement. A highboy is a tall furnace with the blower arranged under the heat exchanger. A "lowboy" is shorter and usually has the blower in back of the heat exchanger. Warm air heater housings are usually made of steel sheet metal that is further treated for durability and rust resistance. The combustion chamber and blower compartment is fully insulated to enhance thermal efficiency and noise reduction.

4.3.1.2 Direct-fired warm air heaters

In direct-fired air warm air heaters, the heat generation through combustion takes place directly in the ventilation air stream. Direct-fired warm air heaters may solely be fired with natural gas or liquefied petroleum gas (LPG), as the flue gas emissions of other fuels (e.g. oil) are higher and more harmful to health.

[41] Image property of Invensys Controls. Website: www.invensyscontrols.com www.toolbox.invensyscontrols.com/appliance/linkedElements/InshotBurners.pdf

[42] www.steam-boilers.org/boiler/gas-burners.html

The greatest advantage of direct-fired systems is that, compared to indirect-fired systems, a very high thermal efficiency can be reached (up to 100% net calorific value) while there are no cost- and maintenance-intensive heat exchangers needed.

Otherwise direct-fired air heaters resemble indirect-fired ones, containing a blower compartment with preceding filter unit, a combustion chamber, and insulated steel sheet metal housing.

Direct-fired central heating products are mainly used in the commercial and industrial sector. There are indirect-fired air heating systems like air make-up units (AMUs) and furnaces for industrial processes available on the market; these are however considered outside the scope of this study, since they are covered by the preparatory studies ENTR lot 6 and ENTR lot 4, respectively.

4.3.1.3 Solid- and multi-fuel-fired heaters

Solid and multi-fuel heaters are not commonly used as air-based central heating systems, and usually are part of boilers and water heaters. While solid fuel-fired heaters are centralised heating systems designed to burn solid fuels exclusively, multi-fuel-fired heaters can burn more than one kind of fuel. These warm air heaters contain one or more combustion chambers where the combustion takes place. The produced hot flue gases are led through a heat exchanger, where the heat is transferred to the circulating air or water. The heat is distributed in a similar way to conventional gas or oil-fired warm air heaters, with heated air radiating through air ducts.

Multi-fuel fired warm air heaters usually can be fired with solid fuels like wood, pellets and coal, and are additionally equipped with an oil or gas burner. The heat generation method can be switched depending on the availability of fuels. At heater start-up, the oil- or gas-burner generates heat and also ignites the loaded solid fuel (e.g. wood logs). After a while, the burner shuts off and the combustion of the solid fuel takes over. If the amount of refilled solid fuel is insufficient, the warm air heater will automatically switch back to oil/gas combustion until more solid fuel is delivered.

4.3.1.4 Electric heaters

Electric heaters are not commonly used as air based central heating systems, and are usually part of local room heaters with lower heating capacities. Electric heaters generate heat through an array of electric heating elements (resistance heating). These heating elements are installed directly in the ventilation air stream. A single heater usually contains several heating elements that are arranged in a cascade. Every single heating element can be activated or deactivated individually to match the actual heat demand and prevent overheating of the supplied area.

A ventilation fan (usually a radial fan) sucks in surrounding air or return air from the heated location and passes it over the electric heating elements. Thereby the ventilation air is heated and is led into the plenum. Preceding the fan, the sucked air is passed through an air filter, to trap dust particles or lint.

Electric heaters can be combined with air-to-air heat pumps. In these cases the condenser of the heat pump acts as the heating element for the warm air heater.

4.3.2 Heat pumps

The heat pumps considered in this study can be classified in several ways:

- By heat source:
  - Air-to-air heat pumps
  - Heat recovery heat pumps
  - Water-to-air heat pumps
  - Ground-to-air heat pumps
- By energy source
  - All-electric heat pumps
  - Gas engine heat pumps
  - Gas absorption heat pumps
- By configuration
  - Packaged heat pumps
  - Single split heat pumps
  - Multi split heat pumps
  - VRF heat pumps

4.3.2.1 Air-to-air heat pumps

For outside air-to-air heat pumps the evaporator coil is placed on the outside of the building. It can be mounted on a wall or stands on the ground, where it absorbs heat from the surrounding air. As explained in section 4.2.2, heat pumps use a vapour compression cycle to extract heat from the air and release it in the room to be heated.

The German Geothermiezentrum Bochum conducted a study of the available heat pumps in Germany market and their efficiencies. According to this study, air-source heat pumps have a lower COP compared to water-source heat pumps.[43] This means that they gain less heat from the heat source using the same amount of electric power. This is due to:

- The specific heat capacity (amount of heat required to change a substance's temperature by a given amount) of air is approximately four times lower than that of water. This means that four times the amount of air is needed to gain the same amount of heat compared to water with the same temperature.
- The heat transfer coefficient of air is many times lower (factor 50 to 100) compared to that of water. This signifies that when using air as a heat source

[43] Geothermiezentrum Bochum (2010) Analyse des deutschen Wärmepumpenmarktes.
Website: www.geothermie-zentrum.de/projekte/marktstudien/analyse-des-deutschen-waermepumpenmarktes.html

the flow rate has to be significantly higher and/or the heat exchanging surface of the evaporator has to be increased.

- In colder seasons air source heat pumps regularly run into icing danger, which can further mitigate the heat transfer. A frost protection or regular defrosting consumes additional energy and thereby lowers the efficiency.
- The higher the source temperature, the more heat can be gained. In wintertime the amount of heat gained is low, due to cold temperatures. On the other hand, the heating demand of a given building is very high. This often results in the installation of auxiliary heaters to cover peak loads, which consume additional electric energy.

Nevertheless, air-source heat pumps are often used as a replacement for installed heating systems as outside air can be accessed easily and inexpensively compared to water source heat pumps that require additional constructional operations (e.g. drillings for a ground probe) and usually need special permissions.

Most outside air-to-air heat pumps are reversible, which means that they may be used for heating and cooling purposes. Therefore, a reversing valve is needed to reverse the complete working mechanism. This means that the condenser works as an evaporator and the evaporator works as a condenser.

4.3.2.2 Heat recovery heat pumps

In modern buildings, where the desired high tightness of the building envelope prevents an air infiltration from the outside (e.g. passive houses), controlled ventilation may become necessary. To minimise the heat losses caused by such ventilation systems, especially during winter, a heat recovery system is essential.

Heat recovery heat pumps are exhaust-air-source heat pumps, which extract heat from the exhaust air of such buildings and retransfer the heat to the supply air stream. By doing this, the heat loss to the outside is reduced.

4.3.2.3 Water-to-air heat pumps

As the name implies, water-to-air heat pumps use water as the heat source. It is possible to use ground water, well water or surface water (lakes, etc.) as sources that have temperatures high enough to evaporate of the refrigerant. The water is pumped into the evaporator where it evaporates the working fluid by transferring its heat. In most appliances, coaxial heat exchangers are used on the water/refrigerant side. The vapour compression cycle is similar as in air-to-air heat pumps.

Most water-to-air heat pumps are reversible, which means that they may be used for heating and cooling purposes. Therefore a reversing valve is needed, which can reverse the complete working mechanism so that the condenser works as an evaporator and the evaporator works as a condenser.

4.3.2.4 *Ground-to-air heat pumps*

A ground source heat pump (GSHP) is a heat pump system that uses the earth as a heat source (in the winter) or a heat sink (in the summer). Geothermal heat pumps are also known by a variety of other names, including geoexchange, as well as earth- or ground-coupled. Ground source heat pumps harvest a combination of geothermal energy (from the Earth's core) and solar energy (heat absorbed at the Earth's surface) when heating, but work against these heat sources when used for air conditioning.[44]

Ground-source systems are among the most energy efficient technologies for providing conditioned air and water heating. One major reason for this is that the source temperatures remain nearly constant over the year. Depending on the latitude, the upper three metres of Earth's surface maintains a nearly constant temperature between 10 and 16°C.[45] Seasonal variations drop off with depth and disappear below seven meters due to thermal inertia.[44]

Ground source heat pumps must have a heat exchanger in contact with the ground or groundwater to extract or dissipate heat. This component accounts for a third to a half of the total system cost. Several major design options are available for these, which are classified by fluid and layout. Direct exchange systems circulate refrigerant underground, closed loop systems use a mixture of anti-freeze and water (brine), and open loop systems use natural groundwater.

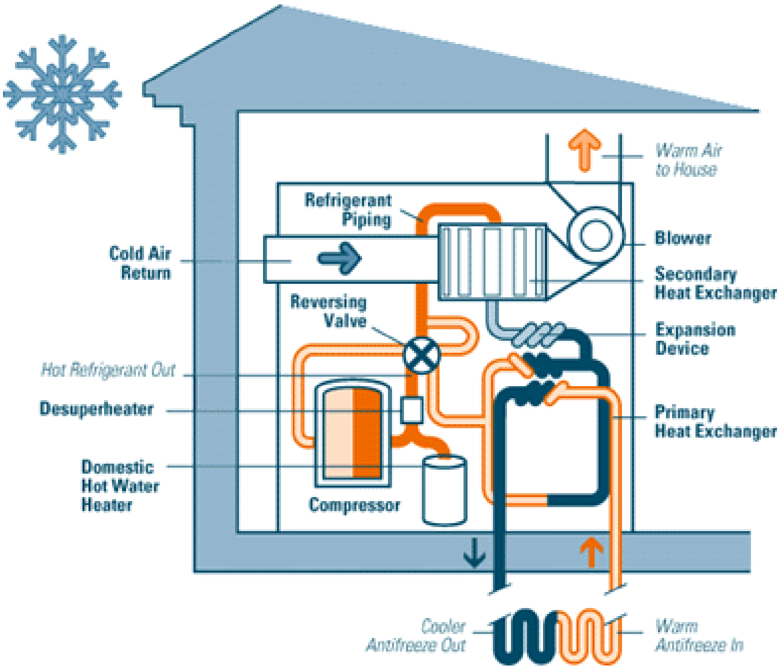

Figure 4-19: Ground source heat pump system[46]

[44] Hanova, Dowlatabadi (2007) Strategic GHG reduction through the use of ground source heat pump technology. http://iopscience.iop.org/1748-9326/2/4/044001/pdf/erl7_4_044001.pdf

[45] www1.eere.energy.gov/geothermal/geothermal_basics.html

[46] Natural Resources Canada; http://oee.nrcan.gc.ca/publications/infosource/pub/home/Heating_and_Cooling_with_a_Heat_Pump_Section4.cfm

4.3.2.5 All-electric heat pumps

As explained in section 4.1.3, the principle behind a heat pump is the vapour compression cycle. In an electric heat pump the compressor is driven by electricity and thus, there is no need for another energy source. Electricity is used to deliver the required mechanical work to increase the pressure of refrigerants (through the compressor) and to move the air to improve the heat exchanger processes (through the fans).

4.3.2.6 Gas engine heat pumps

Gas engine-driven heat pumps (GEHPs or GHPs) use a gas-fired combustion engine instead of an electric motor to drive the compressor of the heat pump and represent one of the most practicable solutions which offer high energy efficiency and environmental benefits to heating and cooling applications. Figure 4-20 shows a diagram of a gas engine-driven heat pump system. One major difference with all-electric heat pumps is that part of the heat released by the engine is recovered and usually used for additional heating purposes like hot-water heating. A further advantage of GEHP systems is that they offer high thermal efficiency at part load with simple control of the engine speed. This eliminates the need of an additional inverter. Heat recovery of the engine can be achieved by cooling the engine with water or by using flue gas heat exchangers. As can be seen in Figure 4-21, the average COP at rated cooling and heating conditions has improved in recent years from 0.9 to approximately 1.6. These high performances have been reached by using more efficient heat exchangers, the use of scroll compressors and improvement of the gas engine. The refrigerant fluid used today is R410A.[47] Generally, it can be stated that GEHPs are more efficient when being operated in low ambient temperatures and when used with integrated warm water heating.[48] GHEPs are usually available as packaged systems or as multi-split-systems, and are predominantly used in the commercial and industrial sector.

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[47] Thonon. Promotion of efficient heat pumps for heating (ProHeatPump). Deliverable No. 19. Available at: www.proheatpump.eu/

[48] Hepbasli et al. (2007) A review of gas driven heat pumps (GEHPs) for residential and industrial applications.

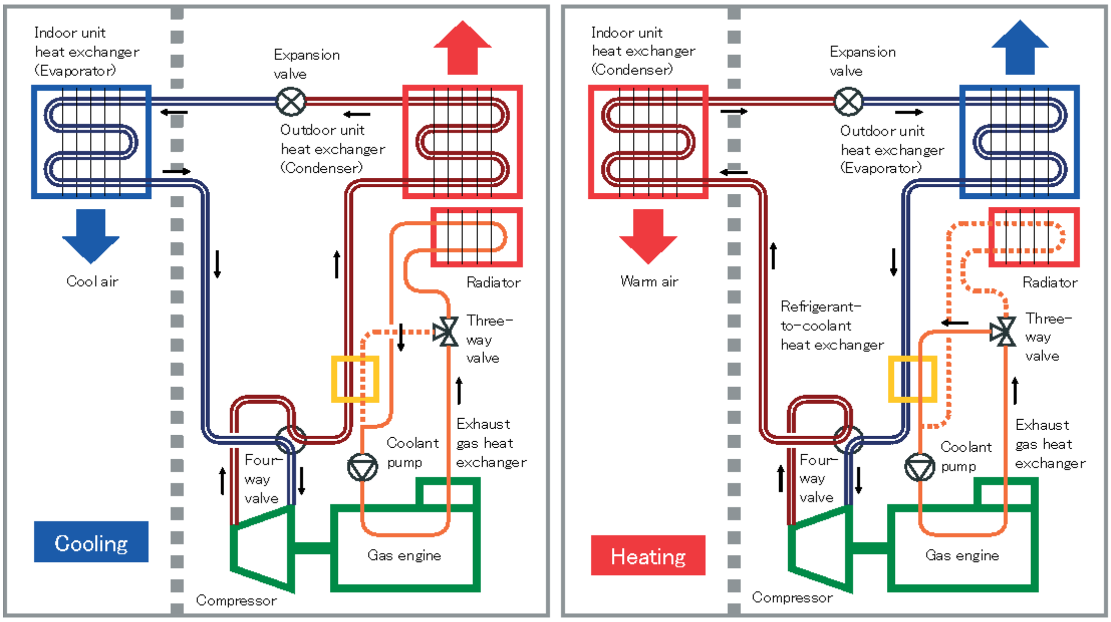

Figure 4-20: Diagram of a gas engine-driven heat pump system[49]

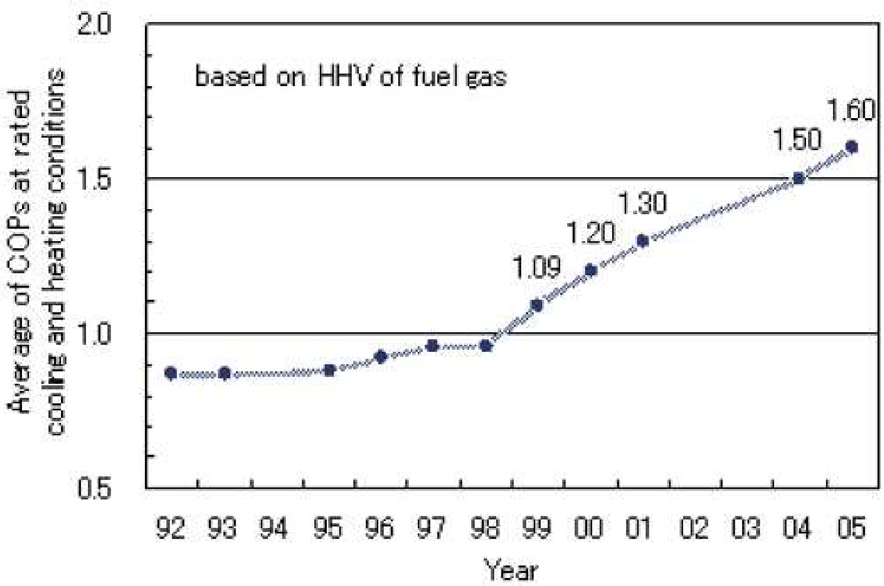

Figure 4-21: Progress in COP of top-rated GEHP Systems[49]

Another type of GEHP's is the biogas engine-driven heat pump, which include a biogas driven combustion engine. First test results of biogas engine-driven heat pumps (BEHP, BHP or BHPAC) show that BEHP's can save more energy than the all-electric heat pump. In summer, the minimum for percentage of primary energy saving for BEHPs is over 25%. In winter, the minimum for percentage of primary energy saving for BEHP is 37%. BEHPs have good partial load characteristic and good effects of energy saving.[50]

[49] International Energy Agency (IEA). Heat Pump Centre, Newsletter Vol. 24, 1/2006

[50] Zhenjun Xu et al. (2010) Energy consumption and performance for biogas heat-pump air condition

4.3.2.7 *Gas absorption heat pumps*

As previously described, absorption heat pumps are not driven by electricity (unlike all-electric heat pumps), but by other heat sources such as fuel-fired burners. The liquid refrigerant is led through the evaporator and is completely vaporised due to heat absorption from the heat source (for example outside air). The resulting low-temperature vapour enters an absorber. The gaseous refrigerant in the absorber is taken up by an absorbent fluid, meaning that it is dissolves completely. Then the liquid solution of refrigerant and absorbent is pumped into the generator. This absorber pump represents the only relevant consumer of electricity in absorption heat pump systems. In the generator, the absorbent/refrigerant mix (often known as the "rich solution") is heated by a gas burner, which separates the refrigerant from the absorbent through evaporation by increasing its temperature and pressure. This functional principle is therefore often called "thermal compression". The remaining absorbent is led back into the absorber, where it again absorbs refrigerant vapour, and thus closes the absorber cycle.

The high-pressure and high-temperature gaseous refrigerant leaves the generator and enters the condenser, where it condenses and transfers its latent heat to an external fluid (water or air). Afterwards, the condensed liquid refrigerant is passed through an expansion device (usually a restrictor) to reduce its temperature and pressure from where it is returned to the evaporator.

Because the working principle strongly depends on the refrigerant and the absorbent characteristics, usually pairs of working fluids are used in specific combinations. The most relevant pairs of working fluids are water (refrigerant) and lithium bromide salt (absorbent), or ammonia (refrigerant) and water (absorbent).

Absorption heat pumps represent an alternative to regular heat pumps where electricity is unreliable, costly, or unavailable; where noise from the compressor is problematic; or, where surplus heat is available (e.g. from industrial processes or from solar plants). Additionally, ammonia in particular is a convenient refrigerant for air source heat pumps, as it allows flawless operation and evaporation under temperatures from 0°C to -20°C[51].

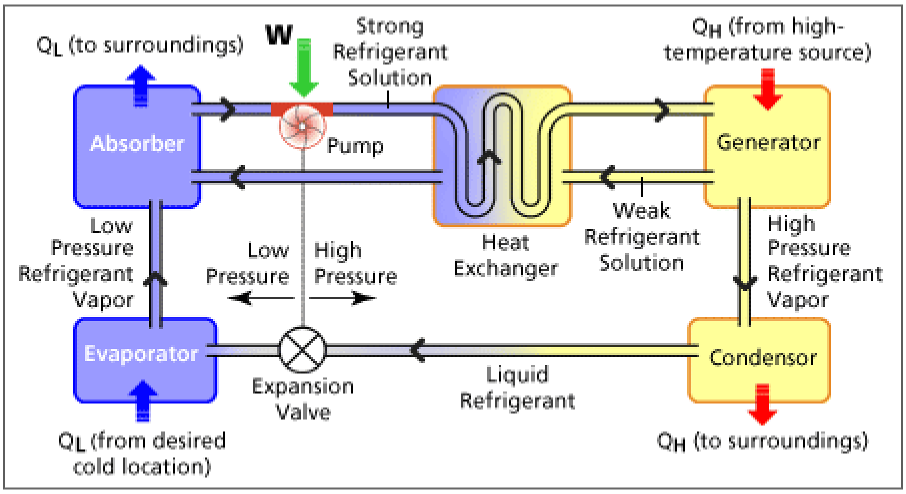

Figure 4-22: Absorption heat pump system (cooling mode)[52]

[51] IKZ Haustechnik; Issue 03-2007. Available at:www.ikz.de/uploads/media/IKZH_200703_751_Heizungstechnik.pdf

[52] www.energygroove.net/heatpumps.php

4.3.2.8 *Packaged heat pumps*

Packaged heat pump systems contain all necessary heat pump components (evaporator, condenser, compressor, etc.) in one space-saving unit (see Figure 4-23). Therefore, package heat pumps are also known as self-contained units. Packaged heat pump units are typically installed outdoors at ground level or on the roof, making them versatile for both horizontal and down-flow designs. Packaged units require ductwork for return and supply air distribution. Packaged units are ideal for situations in which indoor space is limited.

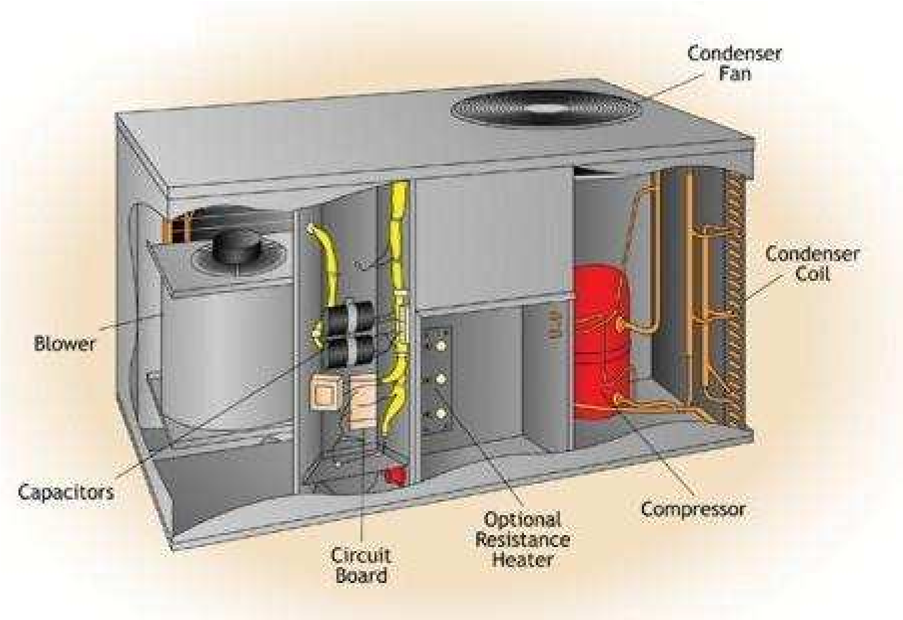

Figure 4-23: Packaged heat pump unit[53]

4.3.2.9 *Single-split heat pumps*

Heat pumps, especially in the non-residential sector, are often built as split systems, where the evaporation (heat source) and condensation (heat sink) takes places in separated or "split" appliances and locations.

The liquid or gaseous refrigerant is led to the different locations through a system of pipes. Ducted single-split heat pumps are heat pump systems that consist of two separated appliances, the evaporator unit (outside coil) and the condenser unit (inside coil). The blower draws in returning or surrounding air, passes it over the condenser and introduces it to the ducted air distribution system. The units are connected by small diameter, insulated refrigerant lines that transport the liquefied or gaseous refrigerant. Ducted single-split heat pumps (or ducted mini-split heat pumps) can provide heat or air conditioning to a single house.

[53] Source: www.coopersheatingandair.com/104864.html

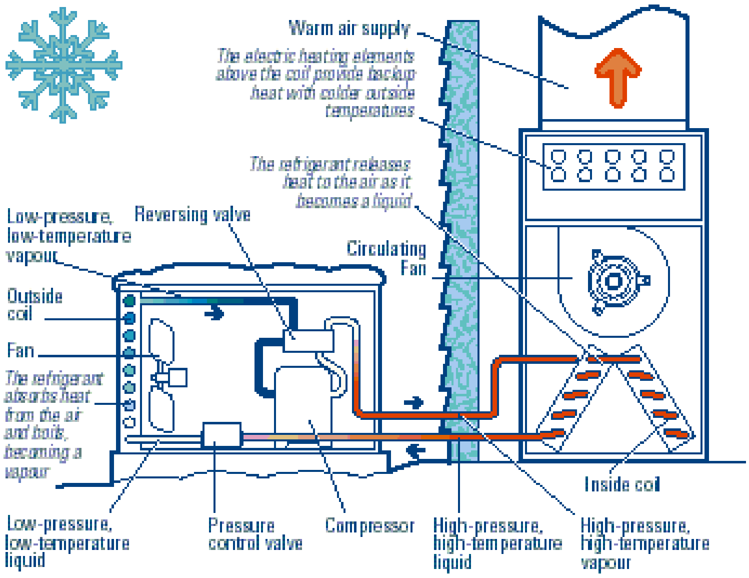

Figure 4-24: A ducted single-split heat pump system in heating mode[54]

Ductless single-split heat pumps (or ductless mini-split heat pumps) are split heat pump systems specifically designed for cooling and/or heating single rooms.

Ductless single-split heat pumps provide air-heating and/or air-conditioning without requiring ductwork. Therefore, they are often used as retrofitted cooling or heating devices. The main advantage is that they offer a high variety of indoor installation designs (floor-standing, wall-mounted, ceiling-suspended, etc.) and do not require large wall breaches for installation of the refrigerant lines. The space required by the refrigerant lines is lower than the space occupied by air ducts, and the noise emitted by the system is lower due to the smaller and fewer fans used.

4.3.2.10 Multi-split heat pumps

Multi-split heat pump systems became feasible with the introduction of capacity-controllable compressors. Besides single-split heat pumps, which contain one external unit and one internal unit, multi-split systems use one external unit which is connected to several indoor units[55]. As a result, multi-split heat pumps can supply heat to multiple rooms without requiring ductwork. Typically, up to 8 indoor units may be connected to one outdoor unit. This limitation results from pressure losses in the refrigerant pipework that has to be compensated for by the compressor. Each outdoor unit has a specific maximum refrigerant pipe length, which is usually specified by the manufacturer.

Multi-split heat pumps can provide heat (or cooling) to more than one room or zone, with each their different heating (or cooling) demand (depending on the type of room (office, bathroom, kitchen, etc.) and the user's heating/cooling behaviour). This is done with the following control designs.

[54] Natural Resources Canada; http://oee.nrcan.gc.ca/publications/infosource/pub/home/heating_with_electricity_chapter2.cfm?attr=4

[55] Mike Hardy; A Practical Guide to Multi-split Systems and Variable Refrigerant Volume (VRV) Systems. www.ambthair.com/multisplit_and_vrv_systems.html

- Master/slave heat pump systems

In a master/slave controlled system, one representative indoor unit is provided with a room thermostat and acts as a "master" and all other units act as "slaves", meaning that they are all controlled according to the master's thermostat settings and its room conditions.

Master and slave units are suitable for large single areas with more than one indoor unit or multiple rooms with very similar heat gains and losses. They are not suitable for individual areas or rooms, which have different heat demands as they may lead to overheating or overcooling of these areas.

- Zoned control heat pump systems

With zoned control systems, each indoor unit has a temperature controller and the operation and temperature can be controlled individually. The major drawback of zoned control multi-split heat pumps is that if cooling is required in one area it is not possible to provide heating in a different area at the same time, as the compressor in the outdoor unit will function only in cooling mode or heating mode.

- Variable refrigerant flow (VRF) heat pump systems

VRF systems are able to provide total versatility because each indoor unit may cool or heat independently according to the demand. If part of a building requires cooling and other areas require heating, the heat rejected for the required cooling contributes or is recovered to provide heating in the other area.

4.3.2.11 VRF heat pumps

As previously mentioned, variable refrigerant flow (VRF) heat pump systems are a specific type of multi-split heat pumps with one external unit and several connected indoor units. With VRF systems, each indoor unit can be operated independently, either in cooling or in heating mode. As a result, VRF heat pumps have a more complex construction and need additional components. Usually an additional refrigerant line and a special separation unit are required. The separation unit is placed before the indoor coils and changes the operation of the indoor unit by changing the refrigerant cycle.

The capacity control of the VRF heat pump systems is achieved by modulating the compressor capacity, while the capacity of the individual indoor unit is controlled by electronic expansion valves.

4.3.3 Air handlers

4.3.3.1 Air handling units

An air handling unit (AHU) conditions and circulates air as part of a heating, ventilating, and air-conditioning (HVAC) system. An air handler is a factory made encased assembly that consists of a fan or fans and other necessary equipment to perform one or more of the following function: circulation, filtration, heating, cooling, heat recovery, humidification, dehumidification and mixing of air. The unit should be capable to be used with ductwork[56]. Sometimes AHUs discharge (supply) and admit (return) air directly to and from the space served without ductwork.

Only AHUs with heat generation components within the assembly are considered within the scope of this study.

4.3.3.2 *Rooftop units*

Rooftop units (RTUs) are air handling units that usually include a gas fired or electric air heater, a cooling coil, and other functional equipment like fans, economizers and filters. As their name implies, they are specifically designed for outdoor use, mainly on rooftops. Other names for rooftop units are unitary air heaters or packaged units. RTUs are available in sizes ranging from 3.5 kW to more than 350 kW of air-conditioning capacity.[57]

4.3.3.3 *Fan coil units*

Fan coil units (FCU) are decentralised air conditioning devices, consisting of a heating and/or a cooling coil and a fan to circulate the air. They are usually part of an HVAC system found in residential, commercial, and industrial buildings. Typical FCUs are hydronic systems, which means that the heat is delivered or withdrawn by hot or chilled water, that is led through the heating respectively the cooling coils inside the unit.

They are usually not connected to a ductwork, and are used to control the temperature in the space where they are installed. Unit configurations are numerous including horizontal (ceiling mounted) or vertical (wall mounted).

Fan coil units are decentralised heating products that are not connected to ducts, even though they may be used as a part of the heat distribution system, e.g. in air handling units.

4.3.3.4 *Small Duct High Velocity Devices (SDHV)*

Small duct high velocity devices are similar to traditional split-system air conditioners and heat pumps, incorporating an outdoor unit with an indoor blower-coil unit. What differentiates SDHV systems from conventional split systems is the use of compact ductwork and specialized diffusers designed to accommodate high air velocities, combined with a specially designed indoor unit. Because of this reason, SDHV devices are also known as "mini-duct systems".

Since these space constraints only affect the indoor portion of the system, the outdoor portion of SDHV systems is a conventional model, selected from a manufacturer based on the desired performance specifications of the system.

The inherent system design constraints prevent SDHV systems from achieving the same efficiencies as conventional split-system heat pumps without placing a disproportionate burden on consumers and manufacturers.[58]

[56] Source: Eurovent Certification Programme. www.eurovent-certification.com

[57] www.reliant.com/en_US/Page/Generic/Public/esc_purchasing_advisor_packaged_rooftop_air_bus_gen.jsp

[58] www1.eere.energy.gov/buildings/appliance_standards/residential/small_duct_ac.html

4.3.4 Condensing technology

Condensing technology is a wide-spread technology to increase the overall efficiency of combustion processes. A condensing appliance uses the latent heat of water produced from the burning of fuel in addition to the standard sensible heat.

In conventional heaters, fuel is burned and the hot flue gases are passed through heat exchangers to heat a transport-medium like air or water. After passing through the heat exchanger, the flue gases are released to the outside. As every fuel contains elementary hydrogen, water vapour can be found in the flue gas, which is formed due to burning the contained hydrogen. A condensing appliance extracts additional heat from the flue gases by condensing this water vapour to liquid water, thus recovering its latent heat. For example the AFUE (Annual Fuel Utilisation Efficiency) rating for a condensing warm air heater can be much higher (by more than 10%) than a non-condensing warm air heater.[59]

To use condensing technology, an appliance usually needs an additional heat exchanger (often described as a secondary heat exchanger). This technology has been explained in section 4.2.1.10.

The condensate produced is slightly acidic (pH 3-5), so the choice of materials used for secondary heat exchangers must be suited to this purpose. Most commonly used are aluminium alloys and stainless steel. The production of condensate also requires the installation of a condensate drainage system.

The additional energy that can be obtained is determined by the amount of hydrogen contained in the fuel. With fuel-oil containing approximately only half the hydrogen of natural gas, the potential for efficiency improvements by condensing is lower compared to natural gas appliances. Furthermore, the dew point of oil flue gases is lower than in the case of natural gas, so the work required to condensate the gases is higher. Also, with higher sulphur levels compared to natural gas, the condensate is more corrosive, so that any condensing heat exchanger for oil has to be more corrosion-resistant than in the case of natural gas.

4.4 Production phase

In order to calculate the environmental impacts and costs of materials and production processes, 'bill of materials' (BoM) of typical air-based central heating products were gathered from manufacturers. BoMs list all the types and quantities of materials and components used to produce one product unit. This section compiles the information received from different stakeholders. The data does not necessarily reflect the market situation, but provides an idea of the range of values.

[59] www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12530

4.4.1 Indirect-fired gas warm air heaters

- Bill of Materials

Table 4-3: Bill of Materials for indirect-fired gas warm air heaters

	Content				
	Mean	Median	Minimum	Maximum	Std. Deviation
Max. heating output [kW]	56.8	17.50	9.50	250.00	94.4
Product weight [kg]	82.43	62.85	54.00	150.00	45.82
Packaging weight [kg]	5.75	4.75	1.50	12.00	4.44
Product	**Content [%]**				
Steel	72.14	70.76	60.00	87.04	12.16
Cast Iron	0.50	0.00	0.00	2.00	1.00
Other ferrous metals	0.00	0.00	0.00	0.00	0.00
Non-ferrous metals	11.00	11.82	1.85	18.52	7.93
Plastics	5.94	4.29	1.85	13.33	5.08
Coatings	1.33	1.50	0.46	1.85	0.62
Electronics	6.65	7.52	0.46	11.11	4.51
Other materials	2.43	0.70	0.00	8.33	3.99
Packaging	**Content [%]**				
Plastics	4.17	0.00	0.00	16.67	8.33
Cardboard	43.33	36.67	0.00	100.00	41.63
Paper	0.00	0.00	0.00	0.00	0.00
Wood	52.50	63.33	0.00	83.33	36.35

*Bills of materials received: 4

4.4.2 Single split heat pumps

▶ Bill of Materials

Table 4-4: Bill of Materials for single split heat pumps

	Content				
	Mean	Median	Minimum	Maximum	Std. Deviation
Max. heating output [kW]	15.00	15.00	14.00	16.00	1.41
Product weight [kg]	130.53	133.00	123.00	135.60	6.65
Packaging weight [kg]	11.50	11.50	10.00	13.00	2.12
Product	**Content [%]**				
Steel	38.08	45.00	24.24	45.00	11.99
Cast Iron	0.00	0.00	0.00	0.00	0.00
Other ferrous metals	0.00	0.00	0.00	0.00	0.00
Non-ferrous metals	21.77	30.00	4.30	31.00	15.14
Plastics	20.88	15.00	12.00	35.63	12.86
Coatings	0.00	0.00	0.00	0.00	0.00
Electronics	7.05	8.00	2.16	11.00	4.50
Other materials	12.23	2.00	1.00	33.69	18.59
Packaging	**Content [%]**				
Plastics	17.50	17.50	30.00	5.00	17.68
Cardboard	60.50	60.50	70.00	51.00	13.44
Paper	0.00	0.00	0.00	0.00	0.00
Wood	21.50	21.50	0.00	43.00	30.41
Other	0.50	0.50	0.00	1.00	0.71

* Bills of materials received: 3

4.4.3 VRF heat pumps

- Bill of Materials

Table 4-5 : Bill of Materials for VRF heat pumps

	Content				
	Mean	Median	Minimum	Maximum	Std. Deviation
Product weight [kg]	499.84	499.84	411.45	588.22	125.00
Packaging weight [kg]	61.15	61.15	50.80	71.5	14.64
Product			**Content [%]**		
Steel	55.47	55.47	56.13	54.80	0.01
Cast Iron	2.77	2.77	2.65	2.88	0.00
Other ferrous metals	1.80	1.80	1.72	1.89	0.00
Non-ferrous metals	17.90	17.90	18.34	17.46	0.01
Plastics	0.00	0.00	9.33	0.00	0.00
Coatings	9.63	9.63	0.94	9.93	0.00
Electronics	0.96	0.96	4.90	0.99	0.00
Other materials	4.64	4.64	5.98	4.39	0.00
Packaging			**Content [%]**		
Plastics	5.69	5.69	5.51	5.87	0.00
Cardboard	77.07	77.07	76.38	77.76	0.01
Paper	0.00	0.00	0.00	0.00	0.00
Wood	8.18	8.18	0.00	16.36	0.12
Other Materials	9.06	9.06	18.11	0.00	0.13

* Bills of materials received: 2

4.5 Distribution phase

Air-based central heaters are typically packed in cardboard boxes to ensure maximum protection of the product. The proportion of plastic in the packaging usually does not exceed 10%. However, some products are packaged in boxes entirely made of plastic or partly made of styrene foam.

Depending on its type and model, the weight of the packaged product is between 50 and 500 kg. The variation is due to different configurations for air-based central heating appliances, or the number and size of the ducts for example. Warm air heaters need air ducts to distribute the hot air to different rooms, whereas heat pumps distribute refrigerant through pipes instead of air ducts. However, heat pumps are also designed and installed using multiple indoor and outdoor units, depending on the heating capacity needed. This configuration considerably increases the weight of the product.

The volume of a packaged product typically ranges between 0.2 m^3 (i.e. 200 L) and 1.3 m^3. As can be expected, the heaviest appliances are also usually the largest in volume.

No data have been received from manufacturers for electric warm air heaters and liquid fuel-fired warm air heaters. The data obtained from manufacturers are summarised in Table 4-6.

Table 4-6: Summary of distribution data (volume and weight of packaged product)

Type of ABCHP	Weight [kg]			Volume [m3]		
	Mean	Min	Max	Mean	Min	Max
Indirect-fired gas warm air heater	98.1	56	462	0.7	0.4	1.3
Single split heat pump	139.5	136	143	0.77	0.66	0.87
VRF heat pump	560.99	462.25	659.72	4.96	4.96	4.96

More detailed data on the volume, weight and Bill of Materials of ENER Lot 21 products are presented in Task 5.

4.6 Use phase (product)

The following section gives an overview of resources consumed during the use phase of air based central heating products and of the factors that influence consumption. The existing energy-related standards at EU-level for the products covered in this preparatory study are presented in Task 1:

- **EN 13253**: Ducted air-conditioners and air-to-air heat pumps – Testing and rating for performance
- **EN 14511:** Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling.
- **prEN 14825**: Air conditioners, liquid chilling packages and heat pumps, with electrically compressors, for space heating and cooling- Testing and rating at part load conditions and calculation of seasonal performance
- **EN 12309:** Gas-fired absorption and adsorption air-conditioning and/or heat pump appliances with a net heat input not exceeding 70 kW
- **EN 1020:** Non-domestic forced convection gas-fired air heaters for space heating not exceeding a net heat input of 300 kW incorporating a fan to assist transportation of combustion air or combustion products.
- **EN 1319:** Domestic gas-fired forced convection air heaters for space heating, with fan-assisted burners not exceeding a net heat input of 70 kW
- **EN 13842:** Oil-fired air heaters. Fixed and transportable for room heating

4.6.1 Fuel consumption

The fuel consumption of air-based central heating products is determined by two major factors: heat demand and system efficiency.

- Heat demand

The heat demand is mainly influenced by climate conditions, the building environment and personal preferences of consumers. In case of feeling cold, operators of ABCHPs most often try to match the heat demand by switching the appliance on or increasing the power stage or indirectly by increasing the desired temperature value of the thermostat.

The temperature difference between the indoor and the outdoor environment and the building insulation determine the amount of heat loss to the environment. The heat loss of buildings increases with the temperature difference between outside temperature and room temperature. The climate conditions of the EU MS are analysed in Task 3 - Consumer behaviour and local infrastructure.

The building shell affects the fuel consumption of air-based central heating products as every constructed part of a building (e.g. walls, windows, doors, etc.) has its own heat transfer coefficient. The higher the coefficient, the more heat passes through the building element. As a result, the heat loss and the heat demand increase.

Another issue that has major influence on the fuel consumption of air based central heating products are internal heat gains. An internal heat gain is the amount of heat brought into a room or a building due to direct sunlight, people, technical equipment and lighting. The higher the internal loads, the less energy the heating systems need to provide during the heating season, resulting in reduced fuel consumption. In contrast to this, high internal heat gains may lead to overheating in summertime which raises the cooling energy demand and will increase the fuel consumption.

- System efficiency

The definition of "system efficiency" depends on the technique used for the air-based central heating. For all fuel-fired ABCHPs, it can be defined as the heat output to an indoor space in relation to the energy input required.

When talking about heat pumps, the word "efficiency", which has a very specific thermodynamic definition, might not be very accurate. The term "system performance" is more precisely, as the coefficient of performance (COP) is used to describe the ratio of useful heat movement to energy (work for compression heat pumps, heat for absorption heat pumps) input.

Both system efficiency and system performance depend on many product aspects and system factors. System efficiency is analysed in more detail in Section 4.7.

4.6.2 Electricity consumption

The electricity consumption of ABCHPs is influenced by several factors like which components are used and operational procedures. The main electricity consuming components are:

- Electric motors (heat pump compressor, fans, pumps)
- Electric heating elements (heaters, auxiliary heating for heat pumps)
- Ignition systems
- Controls

The overall electricity consumption is mainly determined by the appliance type and the heat source used.

- Warm air heaters

A study[60] compared the electricity consumption of two typical residential warm air heaters: a single-stage, non-condensing warm air heater with a PSC motor was compared to a two-stage non-condensing warm air heater with a BPM motor under equal conditions.

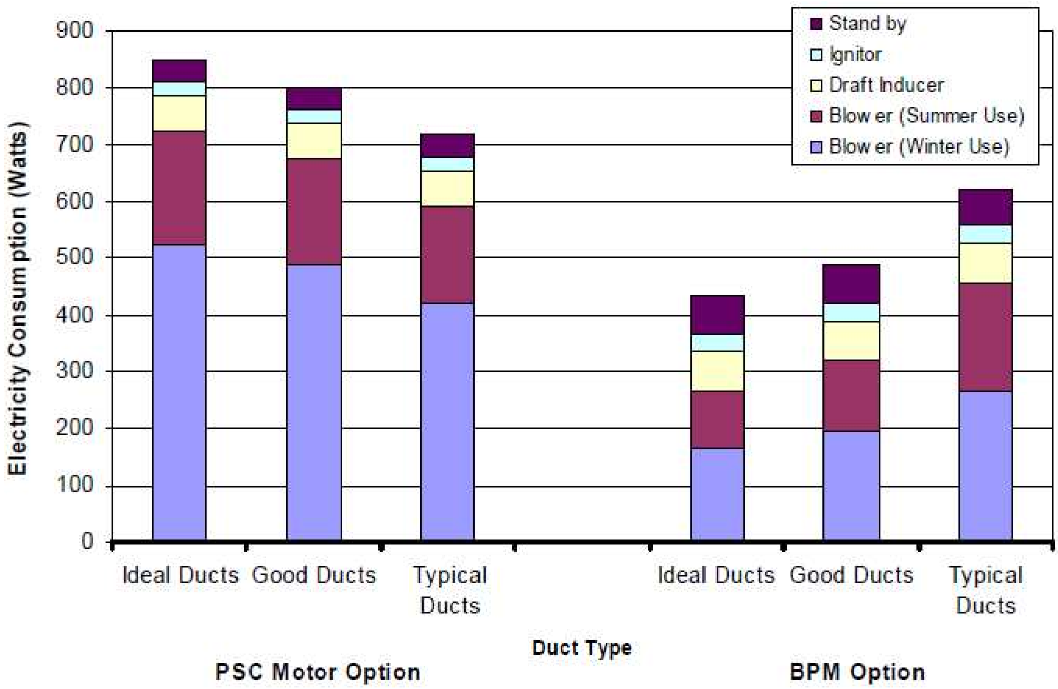

Figure 4-25: Electricity use by component for warm air heaters with PSC and BPM motor[60]

As can be seen in Figure 4-25, a PSC motor's electricity consumption accounts for about 80% of the total electricity consumption, while a BPM motor consumption accounts for 60-70%. Thus, the motor for the heater blower is the major electricity consuming component followed by the draft inducer and the ignitor. Another interesting point is that that standby consumption is lower for PSC motors than for BPM motors.

[60] Florida Solar Energy Center (2008) Furnace Blower Electricity: National and Regional Saving Potential. Available at: www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1774-08.pdf

- Heat Pumps

The German Fraunhofer Institute for Solar Energy Systems (ISE) conducted a field study [61] with approximately 110 heat pumps (air-to-water and brine-to-water) that were installed in new residential buildings. In this study the electricity consumption of the heat pumps was measured and evaluated. Table 4-7 shows the electricity consumption of air-to-water and brine-to-water heat pumps. Although these specific types are hydronic heat pumps and therefore not relevant for ENER Lot 21, the general component based electricity consumption can be transferred to the heat pumps within the scope of this study.

Table 4-7: Electricity consumption of heat pump components[61]

Heat pump	Fan	Brine pump	Compressor	Electric supplementary heater
Air-to-water	7%	-	89%	4%
Brine-to-water	-	6%	92%	2%

As it may be seen, the main power consumers in heat pumps are the electric motors for the various components. Particularly the compressor consumes the major part of total electric energy. Fan motors (air-to-air heat pumps) and pump motors (water-to-air and ground-to-air heat pumps) consume only a minor part of the total electricity. Electric supplementary heaters play a very important role for electricity consumption as their part depends on the frequency and length of operation. All other electric consumers such as controls, etc., use only a small part of the total electric energy and are negligible.

4.6.3 Other consumptions

Besides the fuel for combustion and electricity, there are other resources consumed over the use phase of air-based central heating products.

- Lubricants

Most mechanical devices that contain moving parts need lubricants to work properly over a long time. In most compressors this is achieved by using special compressor oils. Besides the lubrication of the moving parts, the oil also inhibits corrosion, seals the pressure chambers and cools the moving parts by carrying away the heat.

Most compressors in heat pumps are delivered with an initial oil filling and so do not need regular oil replacement. Some compressors are even oil free. Due to the wearing and pollution of the lubricant oil as well as oil losses, it may be necessary to replace the lubricant oil.

- Refrigerant

Depending on the length of refrigerant carrying pipes, every heat pump system contains a certain amount of liquid refrigerant. Usually the manufacturer states which type and amount of

[61] Marek Miara (Fraunhofer ISE), published in SBZ, Sanitär, Heizung, Klima, issue 03-2011; www.sbz-online.de/SBZ-2011-3/Effizienzmessungen-im-Feld,QUlEPTMwNTAxNCZNSUQ9MTAxOTAy.html

refrigerant is used for their device. As a general rule of thumb, it can be said that from 0.3 kg [62] to 1 kg [63] of refrigerant is needed for 1 kW of cooling capacity. This value may depend on many different factors such as the heating/cooling capacity, the installed pipe length, the type of used refrigerant and the compressor type. The amount depends on the type and size of the heat pump. Due to leakages in the refrigerant lines it may become necessary to refill the refrigerant during regular maintenance practices.

The contribution of refrigerants to climate change is characterised by the GWP (global warming potential) indicator. The impact of refrigerants to global warming is not only an issue if the refrigerant leaks, or if the treatment is not appropriate at the end-of-life stage, but also during production. Some of the key requirements to reduce environmental impacts are the reduction of refrigerant charges and the control during use. When comparing the GWP of systems running with different types of refrigerant, the global warming potential is often characterised by the TEWI, Total equivalent Warming Impact, which also takes into account the emissions of greenhouse gases from the electricity consumption of the system.

The F-Gas Regulation EC 842/2006 requires the recovery of HFC refrigerants during service and at end-of-life. It establishes standard inspection requirements, and indirect and direct leakage measurements for refrigeration systems (among others).Emissions

Every combustion process is accompanied by the formation and emission of different pollutants. These pollutants have different characteristics regarding environmental impacts and toxicity. For these reasons, it is of great importance to analyse the emissions of air-based central heating products.

The amount of formed pollutants depends on the characteristics of the used fuel and the type and quality of the combustion process. Generally, the combustion of natural gas emits lower quantities of greenhouse gases and pollutants per unit of energy produced than do other fossil fuels. This occurs in part because natural gas is more easily fully combusted, and in part because natural gas contains fewer impurities than any other fossil fuel.[64] Figure 4-26 gives an impression on the amount of emissions by fuel type. The following section gives an overview on pollutants and their environmental impacts.

[62] Johnson, E.P. (2011) Air-source heat pump carbon footprints : HFC impacts and comparison to other heat sources. Energy Policy, doi:10.1016/j.enpo.2010.12.009

[63] Defra (2009) F-gas support information sheet GEN 5 – refrigerant quantity.

[64] Environmental impacts of different types of central heating boilers taken from EcoReport (VHK, 2005)

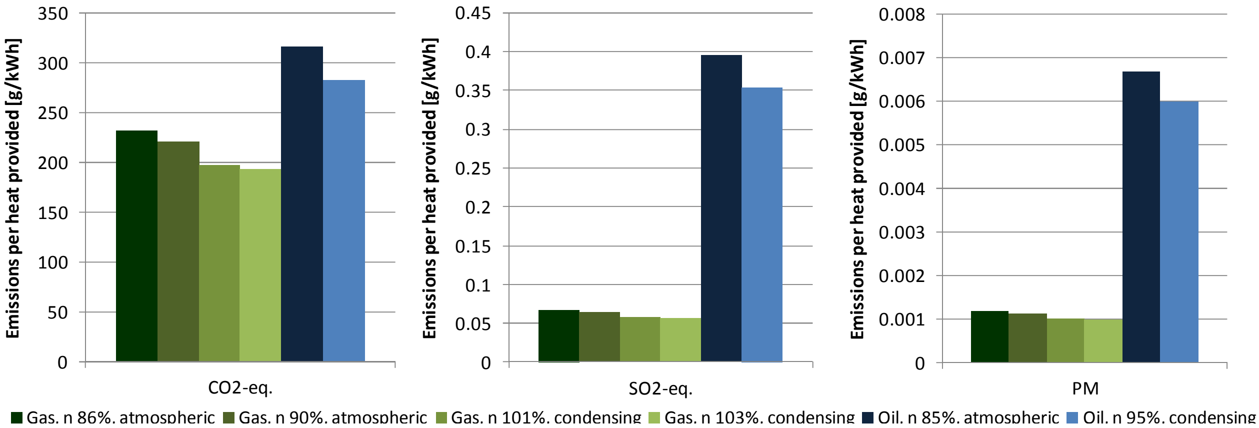

Figure 4-26: Comparison of emitted pollutants of gas and oil[65]

- CO_2 - carbon dioxide

Carbon dioxide is a greenhouse gas that leads to global warming. In a properly tuned heating appliance, nearly all of the fuel carbon (over 99 percent) in natural gas and oil is converted to CO_2 during the combustion process. Fuel carbon not converted to CO_2 results in methane (CH_4), CO, and/or VOC emissions and is due to incomplete combustion[66]. Thus the amount of emitted carbon dioxide depends on the amount of carbon contained in the fuel. It can be seen in Figure 4-26, natural gas contains the lowest amount of fuel carbon, followed by oil and coal.

- NO_X - nitric oxides

NO_X is a generic term for mono-nitrogen oxides NO and NO_2 (nitric oxide and nitric dioxide). Both gases participate in ozone layer depletion while NO is also responsible for acid rain.

NO_X is a by-product of combustion and the result of partial oxidation of fuel nitrogen. The greatest amounts of nitric oxides are emitted as NO (>90%) and the smaller amounts as NO_2 (<10%). The emissions of NO_X increase with increasing nitrogen contents in the fuel, excess air ratio, and higher combustion temperature. Heavy oils contain between 0.1% and 0.8% of nitrogen, fuel oils between 0.005% and 0.07%. Natural gas contains no organically bound nitrogen.[67]

- CO - carbon monoxide

Carbon monoxide is a highly toxic gas in addition to promoting the formation of ground-level ozone, which has negative impacts on the environment. Carbon monoxide is found in combustion of all carbonaceous fuels, as an intermediate product of the combustion process and in particular a result of under-stoichiometric combustion[68]. The emission level is influenced by the excess air ratio as well, the combustion temperature and residence times of combustion products in the reaction zone.[67]

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[65] Environmental impacts of different types of central heating boilers taken from EcoReport (VHK, 2005)
[66] Office of Air Quality Planning And Standards, Office of Air And Radiation, U.S. Environmental Protection Agency; Compilation Of Air Pollutant Emission Factors, Chapter 1.3 to 1.5; January 1995; www.epa.gov/ttnchie1/ap42/
[67] Kubica, Paradiz, Dilara (2007) Small combustion installations: Techniques, emissions and measures for emission reduction; European Commission.
[68] Understoichiometric combustion signifies that there is less oxygen available for combustion than potentially should be available to ensure complete combustion.

- PM - particulate matter

Particulate matter can be described as the amount of fine particle emissions in flue gas. It might also be described as carbon, smoke, soot, stack solid or fly ash. The amount of particulate matter released mainly depends on two factors: combustion quality and fuel composition. For these reasons the main measures to prevent high PM emissions are an optimal design of the combustion process to reach a complete combustion and increasing fuels quality.[67] PM emissions cause severe impacts on environment, most notably an increase of global warming in addition to causing adverse effects on public health.

- SO_2 - sulphur dioxide

Sulphur dioxide is a major air pollutant and has significant impacts on health and the environment. It is mainly formed through the combustion of sulphur-containing fossil fuels like coal, oil or natural gas. The quantity of emitted sulphur dioxide directly depends on the sulphur content of the burned fuel, while the sulphur content itself varies locally.

- NMVOC - non-methane volatile organic compounds

NMVOC is a generic term for a large variety of chemically different compounds, like for example, benzene, ethanol, formaldehyde, cyclohexane, 1,1,1-trichloroethane or acetone. Similarly, as for CO, the emission of NMVOC is a result of an inferior combustion temperature; an insufficient residence time in oxidation zone; and/or, insufficient oxygen availability during the combustion process.

- HM - Heavy metals

Most of the heavy metals considered (As, Cd, Cr, Cu, Hg, Ni, Pb, Se, and Zn) are generally released as compounds associated with and/or adsorbed on particles (e.g. sulfides, chlorides or organic compounds). Hg and Se are at least partly present only in the vapour phase. Less volatile elements tend to condensate onto the surface of smaller particles in the exhaust gases. Therefore, the emission of heavy metals strongly depends on their concentrations within a given fuel. Coal and its derivatives normally contain heavy metals concentrations that are several orders of magnitude higher than oil (most exceptionally for Ni and V in heavy oils) and in natural gas (about 2-5 µg/m^3.

- PAH - Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons are potent atmospheric pollutants that consist of fused aromatic rings and do not contain heteroatoms or carry substituents[69]. PAHs occur in oil, coal, and tar deposits, and are produced as by-products of fuel burning (whether fossil fuel or biomass). Emissions of all polycyclic aromatic hydrocarbons results from incomplete (intermediate) conversion of fuels. As for CO and NMVOCs, emissions of PAH depend on the quality of the combustion process, especially on combustion temperatures (too low temperatures increases their emission), the residence time in the reaction zone and the

[69] Fetzer (2000) The Chemistry and Analysis of the Large Polycyclic Aromatic Hydrocarbons. Polycyclic Aromatic Compounds.

availability of oxygen[70]. As a pollutant they are of concern because some compounds have been identified as carcinogenic, mutagenic, and teratogenic.

- PCDD/F - Polychlorinated dibenzodioxins and -furans

Polychlorinated dibenzodioxins and -furans are commonly referred to as dioxins and furans for simplicity because every PCDD molecule contains a dioxin - and every PCDF molecule contains a furan skeletal structure. The emissions of dioxins and furans are highly dependent on the conditions under which combustion and exhaust gas cooling is carried out. Carbon, chlorine, a catalyst and oxygen excess are necessary for the formation of PCDD/F[6]. Members of the PCDD/F family are known teratogens, mutagens, and confirmed human carcinogens.

4.6.4 Efficiency ratings

Heating is the process to provide a room with required thermal comfort independent from outer climate conditions. Before efficiency figures of heaters or components are considered, the the energy efficiency of the system in relation to the building must be considered. Integral efficiency perspective incorporates:

- heating system in interaction with the building, building structure and usage
- heater or heating system performance in reference to the actual heat demand (locally and temporarily)

As there are several different methods for measuring the energy efficiency of heating products, the following section gives an overview and an analysis of the relevant efficiency ratings for air-based central heating products.

4.6.4.1 *Thermal efficiency*

Thermal efficiency (η_{th}) is a performance measure (in %) of devices that use thermal energy. In general, thermal efficiency is the ratio between the useful output (Q_{out}) of a device and the input (Q_{in}), in energy terms. Accordingly, when considering heating appliances, thermal efficiency is the ratio of the heat output divided by the heat-content of the consumed fuel.

$$\eta_{th} = \frac{Q_{out}}{Q_{in}}$$

Thermal efficiency always necessitates a restating of the heating value of the used fuel. Net thermal efficiency indicates that the net heating value (lower heating value) was used for efficiency calculation while gross thermal efficiency is based on the higher heating value.

All electric resistance heaters have a thermal efficiency close to 100%. As mentioned earlier, the efficiency losses for generation of electricity have to be taken into account. Therefore, the consumed electric power will be multiplied with a primary energy conversion factor of 2.5 (same

[70] Kubica, Paradiz, Dilara (2007) Small combustion installations: Techniques, emissions and measures for emission reduction; European Commission.

as for all Ecodesign preparatory studies). The resulting primary energy consumption is treated as the energy input value for the determination of thermal efficiency.

4.6.4.2 COP (Coefficient of Performance)

The Coefficient of Performance (COP) expresses the efficiency of a heat pump and is the quotient of useful heating output (at the heat reservoir of interest) and the power input.

$$COP = \frac{Q_H}{W}$$

- Q_H is the heat supplied to the hot reservoir
- W is the work consumed by the heat pump

Thus, the COP for heating and cooling are different because the heat reservoir of interest is different. However, for heating, the COP is the ratio of the heat removed from the cold reservoir plus the heat added to the hot reservoir by the input work divided by the input work.

$$COP_{heating} = \frac{|Q_C| + W}{W}$$

- $|Q_C|$ is the heat supplied to the cold reservoir

The highest possible COP is determined by the Carnot cycle efficiency, given by the following equation:

$$COP_{max,heating} = \frac{T_{hot}}{T_{hot} - T_{cold}}$$

- T_{hot} is the absolute temperature of the hot reservoir in Kelvin
- T_{cold} is the absolute temperature of the cold reservoir in Kelvin

De facto installed heat pumps can reach a COP of up to 4, while a theoretical upper limit of approximately 7.8 is determined by the Carnot cycle efficiency.

4.6.4.3 SCOP (Seasonal Coefficient of Performance)

The Seasonal Co-efficient of Performance is equivalent to SEER but it refers to the heating mode of heat pumps. SCOP is determined by the relation between the annual heating capacity and the annual electricity consumption based on the standard prEN14825. It depends on the heat pump and determined by building characteristics, compressor type and meteorological data.

4.6.4.4 GUE (Gas Utilization Efficiency)

The efficiency of gas heat pumps is usually measured by the Gas Utilisation Efficiency (GUE). This is the ratio of the energy that is supplied (i.e. heat transferred to the medium to be heated) to the energy consumed by the burner.

4.6.4.5 EER (Efficiency Utilization Ratio)

According to US standards, the Energy Efficiency Ratio (EER) is the ratio of output cooling (in Btu/h) to input electric power (in Watts) at a given operating point (indoor and outdoor temperature and humidity conditions). In some MS the EER is used equally to the COP, which can lead to the wrong assumption that they are equal. As the EER only expresses the cooling efficiency of a heat pump, it is not further reviewed in this study.

4.6.4.6 SEER (Seasonal Energy efficiency Ratio)

The Seasonal Energy Efficiency Ratio (SEER) is related to the EER and has the same units of Btu/(W*hr), but instead of being evaluated at a given operating point, it represents the expected overall performance for a typical year's weather in a given location. The SEER is defined by the US Air Conditioning, Heating and Refrigeration Institute (AHRI) in its standard ARI 210/240. As the SEER only expresses the cooling efficiency of a heat pump, it is not further treated in this study.

4.6.4.7 APF (Annual Performance Factor)

The Annual Performance Factor is a performance factor for air conditioners and heat pumps that was introduced by Japanese Industrial Standards (e.g. JIS B8616:2006). It is the ratio of the total heat quantity required to cool and heat a room during both the cooling and heating period to the total power consumption during the same period. The calculation of the APF allows an efficiency figure that more closely approximates the figure during actual use.

$$APF = \frac{Q_{Cooling} + Q_{Heating}}{W_{Cooling} + W_{Heating}}$$

- Q is the heat or cooling load at actual period
- W is the power consumption at actual period

4.6.4.8 AFUE (Annual Fuel Utilization Efficiency Rating)

The Annual Fuel Utilization Efficiency (AFUE) is a US measure of thermal efficiency for combustion equipment such as warm air heaters, boilers, and water heaters expressed in percent. The AFUE differs from the true 'thermal efficiency' in that it is not a steady-state, peak measure of conversion efficiency, but instead attempts to represent the actual, season-long, average efficiency of a product that piece of equipment, including the operating transients.[71] The method for determining the AFUE for residential furnaces is the subject of ASHRAE Standard 103.

[71] ASHRAE (2004) ASHRAE Handbook, Systems and Equipment.

4.6.4.9 HSPF (Heating Seasonal Performance Factor)

The Heating Seasonal Performance Factor (HSPF) is specifically used to measure the energy efficiency of air source heat pumps over one heating season while the cooling efficiency is measured with the Seasonal Energy Efficiency Rating (SEER) over one cooling season. In detail, the HSPF is calculated with the total heating output (supply heat) in Btu (including electric heat) during heating season divided by the total electricity energy consumption of the heat pump (in W/h) in the same season. The higher the HSPF of a unit, the more energy efficient it is.

4.6.4.10 Efficiency ratings used in this study

As can be seen, there are various energy efficiency ratings for air-based central heating products, depending on the type and working principles of the product. For this study, the following efficiency ratings are relevant for an assessment of energy use during the heating operation.

Table 4-8: Relevant energy efficiency ratings for heating operation

Product case	Efficiency rating
Warm air heaters	Thermal efficiency
Compression heat pumps	COP, SCOP
Gas heat pumps	COP, SCOP, GUE

4.6.5 Efficiency losses

4.6.5.1 Warm air heaters

- Air leakage

During a product's normal lifetime, warm air heaters may develop cracks or openings around doors, joints, and other components. The negative pressure created by the natural draft of the chimney or the draft inducer in the warm air heater draws cold surrounding air through the openings (leaks) and into the warm air heater. Depending on the location of the leakage, either the supply air temperature can be lowered (leakage in the plenum) or the efficiency of the internal heat transfer can be diminished (leakage in heat exchanger). In any event, leakages will increase the fuel consumption and thereby reduce the energy efficiency. Additionally leakages might cause excessive oxidation of metals or other materials in the warm air heaters.[72]

- Incomplete combustion

As a result of incomplete combustion, the flue gases of all fuel-fired air warm air heaters may contain combustible substances like CO and hydrocarbons, which were not completely burned during the actual combustion. In other words this means that not all useful energy has been

[72] U.S. Department of Energy (2006) Energy Tips – Process Heating Tip Sheet #5; Reduce Air Infiltration in Furnaces.

taken out of the fuel. In order to achieve complete combustion and to prevent energy loss, it is necessary to adjust the burner with the correct fuel-air-ratio. Electric air heaters are not affected by this issue.

- Flue gas losses

Efficiency reduction due to flue gas losses means that heat is carried away in chimney gases due to high flue gas temperatures. The basic causes for such high flue gas temperatures are insufficient heat transfer surfaces (insufficient heat exchanger size) and fouling of heat exchangers. As a result, too little heat is transferred from the flue gas to the supply air and gets lost through the chimney. To keep the flue gas losses as low as possible it is desirable to take as much heat as possible out of the flue has, without causing condensation and cold end corrosion in the flue gas route.

As electric air heaters are direct-fired (the heat is directly transferred to the supply air, without using heat exchangers) they are not affected by this issue.

- Purge losses

Every heater that generates heat by combustion has to complete a specific cycle of safety operations before and after the actual firing interval is conducted. This cycle contains a pre and post-purge of the heater. In the pre-purge phase, the burner fan operates to force air through the heater's flue gas route, to flush out any combustible residues that may have accumulated. The post-purge performs a similar function. During the purge, heat is removed from the boiler as the purged air is heated. Due to this reason, it is desirable to avoid short cycling of the heater which is usually a result of oversizing. One of the ways to reduce purge losses is to use capacity modulating burners, as they adjust the heating output to the actual heat demand, and thereby avoid short cycling. Most modulating burners can only modify the heating capacity in a specific range. This range is expressed by the turndown ratio, which is the ratio of the burner's maximum capacity to its minimum capacity. If the turndown ratio is too low, it may still result in short cycling of the burner, as the burner cannot adjust its output below the minimum range.

- Jacket losses

Depending on the surrounding temperatures, jacket losses of air heaters may occur. Especially for outdoor units, energy losses to the environment are higher due to the increased temperature difference to the outdoor temperature. As heat always "flows" from the warm side to the cold side, a small heat loss to the environment is inevitable. Therefore it is necessary to insulate the warm air heater housing as completely as possible, especially in outdoor units.

- Thermostats

Modern control devices like electronic thermostats are sealed at the factory to keep out dust and grime. This prevents incorrect temperature sensing. Regardless, thermostats must be installed in representative, non-drafting areas. An improper installation can result in a waste of energy if the thermostat measures a higher or lower temperature than the actual room temperature.

4.6.5.2 *Heat pumps*

- Temperatures

The efficiency of heat pump systems primarily depends on the temperature difference between the heat source temperature and the desired temperature value of the heat sink (room temperature). The lower the desired heat sink temperature and the higher the heat source temperature, the more efficient the heat pump system will be (higher COP rating). On the other hand, this also implies that the lower the heat sink temperature (e.g. during winter) results in lower efficiencies. Thus source temperature of air source heat pumps drops in winter time, while the heating demand increases. Due to this, air source heat pumps usually have lower COP ratings compared to other heat pump systems.

- Refrigerant impurities

Impurities in the refrigerant cycle such as moisture, extrinsic gases and particles may lower the heat transfer and thereby have an influence on the evaporation and condensation process in the refrigerant cycle.

- Refrigerant leaks

For all heat pumps it is very important to always maintain the appropriate refrigerant charge in the heat pump system. A lack of refrigerant fluid will lower the efficiency and will most often lead to operational errors. Furthermore, as some refrigerants are hazardous to the environment it is necessary to check the refrigerant level regularly. For this reason most heat pumps contain a refrigerant sight glass where the condition of the refrigerant can be checked. According to the EU Regulation 842/2006, an annual leakage check for heat pumps containing 3 kg of refrigerant or more is mandatory for the MS.

- Heat exchanger fouling

Fouling of heat exchangers reduces the area to transfer heat, which decreases the heat transfer coefficient. As a result higher flow rates are required for the compensation of the lower heat transfer, which leads to higher electricity consumption and lower energy efficiency. In most cases this energy loss can be avoided by regular maintenance of the heat pumps heat exchangers.

- Sizing and installation

Heat pumps must be sized correctly to meet the heat demand of the building. The result of oversizing a heat pump is that it will start an intermittent operation (continuous on/off switching) which consumes more energy than non-intermittent operation. As a result the COP of an oversized heat pump is lower. Downsized heat pumps cannot meet the heat demand completely. This may result in higher electricity consumption in cases where an auxiliary electric heater is installed. However, variable capacity heat pumps can operate at part loads with a better efficiency than non-variable capacity products, and the negative effects of oversizing are lower for variable capacity products.

Additionally, the heat exchanger surfaces must be sized correctly. This is especially relevant for air- and ground-source heat pumps, as the temperatures of the heat source are not very high. Undersized heat exchangers cannot take up enough heat from the heat source, which, in turn, will lower the efficiency.

- Filters

Air source heat pumps usually have air filters installed near the evaporator or condenser unit. A regular cleaning and replacing of these filters is urgently necessary. Clogged filters restrict the air flow and thereby the amount of heat that is extracted and transferred.

- Thermostats

Please see Chapter 4.6.5.1. – Warm air heaters.

4.6.6 Other functionalities

Besides the heating function, ABCHPs may offer other air handling functions to provide comfort to the provided area. These functionalities are important to this study as they consume additional energy or may have influences to the overall energy efficiency of the products.

- Cooling

Most heat pumps are reversible which means that they can be operated for heating and cooling purpose. In order to do so, heat pumps require additional equipment such as reversing valves (see section 4.2.2.9).

Air heaters may also be retrofitted with a cooling function. In this case an additional cooling coil is installed in the warm air heater housing. These coils are available directly from the warm air heater manufacturers. Besides this, most warm air heater controls are already prepared for additional components, so that they can control the cooling operation as well. Cooling coils for warm air heaters can be operated with cold water (hydronic cooling systems) or in combination with a heat pump or air conditioner.

- Filtering and air cleaning

Filters are installed in every air-based central heating products to remove particles like dust, pollen or lint from the circulating air. Filters need regular maintenance and replacement, otherwise they can become clogged and lower the efficiency. Furthermore, some ABCHPs contain additional air cleaning components, e.g. UV air cleaners.

- Humidification

Some ABCHPs offer the opportunity to install additional air humidifiers or control an externally installed humidifier. Adjusting the humidity in designated areas can reduce static electricity, dried cracked furniture and wood trim, and wilting houseplants. Additional humidifiers consume additional energy.

4.7 Use phase

4.7.1 Overview

There are several factors that can have an influence on the efficiency of air-based central heating products. Besides the product related issues (see chapter 4.6.5. – Efficiency losses) there are other system related factors. These system factors are not a direct part of the product itself, but they are associated with the energy consumption and the efficiency of the product. For these reasons it is necessary to elaborate this system influences further.

4.7.2 Product/System Boundaries

The following section defines the product- and system boundaries of the treated air-based central heating products.

The term product defines the heating appliance and all contained components. The product boundary can therefore be imagined as the housing of the heating appliance including all connections to external lines.

The system boundaries extend the product boundaries to other energy affected parameters, such as properties of the provided area, building environment, climate conditions, controls, distribution grids, etc. Figure 4-27: gives an illustration of the presumed product and system boundaries of this study.

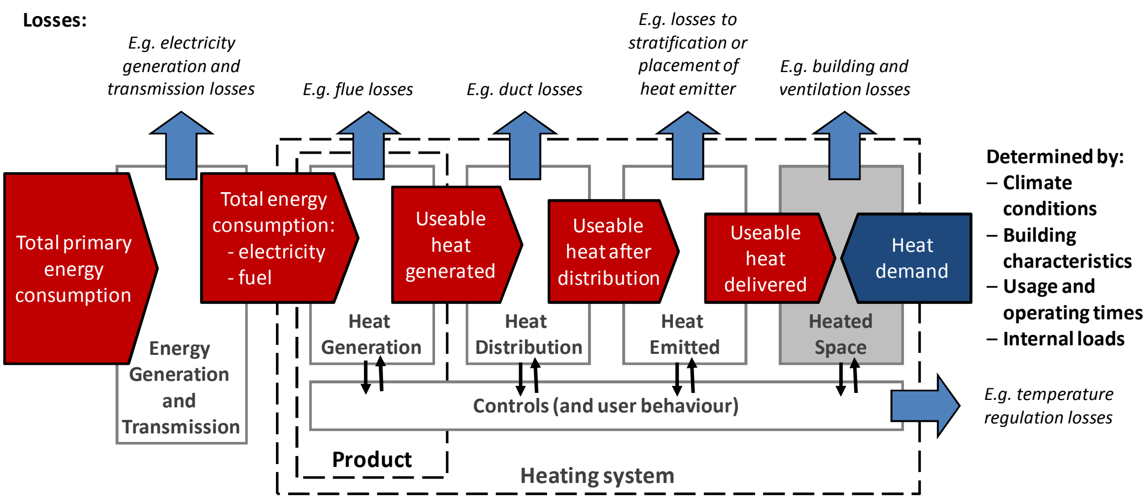

Figure 4-27: Product and system boundaries

4.7.3 System factors influencing thermal efficiency

4.7.3.1 Building environment

Buildings account for around 40% of the EU energy consumption and offer the greatest potential for energy efficiency improvements.[73] This fact shows that building characteristics have a major influence on energy efficiency of heating systems. The energy efficiency is directly linked to the heat demand of a building, as it represents the amount of heat lost through the building surface. Depending on the year of construction, insulation and other conditions, the heating demand of a building can vary strongly. For example, longer established buildings may have a specific heat demand that is three times higher than new buildings.[74] This is a result of improved building methods and improved choice of materials including masonry, windows, doors, insulation materials etc.

The following sections present the main influences of buildings on energy efficiency of air-based central heating products.

4.7.3.2 Distribution system

The location of the appliance has to be adequate in terms of sufficient availability of combustion air and (if necessary) and ambient temperature. Lack of combustion air will inevitably lead to incomplete combustion and thereby to a decrease of combustion efficiency.

4.7.3.3 Flue gas extraction system

The flue gas extraction system can influence the efficiency of air-based central heating products in two ways.

- Flue design

To maintain the stack effect, there are some general requirements that a flue must fulfil. As the stack effect increases with height, a flue has to keep a minimum height in order to create a sufficient draft (approximately 4 to 6 meters). Additionally, the pressure loss inside the flue must be kept as low as possible. The diameter of the flue pipe should not be too small, the material should have a low roughness and bends in the flue should be reduced to an absolute minimum. Incorrect sizing of the flue gas extraction system may result in high pressure losses and thereby to a constrained flue gas flow. Additionally, installation issues may have a negative effect on the heating performance. All flues have to be installed in such a way that wind cannot directly enter the flue.

- External conditions

The external conditions (strong winds, surrounding buildings, etc.) may affect the flue gas extraction rate and thereby the combustion efficiency.

[73] Intelligent Energy Europe IEE; News Review No. 4; February2009; http://ec.europa.eu/energy/intelligent/library/doc/ienr_4_en.pdf
[74] www.dena.de/themen/thema-bau/

It can be seen that the dimensioning of a flue is a very important system factor of flue air-based central heating products. Therefore, the calculation and dimensioning of flue gas systems is described in the European standard EN 13384-1 and -2.

4.7.3.4 Dampers

Dampers are used to control the air flow rate and pressures in air-based central heating and/or cooling systems.

In order to improve efficiency and occupant comfort, HVAC systems are commonly divided into multiple zones. For example, the ground floor of a house may be served by one heating zone while the upstairs bedrooms are served by another. In this way the heat can be directed principally to the ground floor during the day and shift principally to the bedrooms at night, allowing the unoccupied areas to cool down.

A correct setup may increase energy efficiency of air-based central heating products, while on the other hand dampers increase the costs and the maintenance efforts.

4.7.3.5 Fuel supply

All fuel-fired ABCHPs have to be provided with a sufficient amount of fuel under constant conditions. Irregularities in fuel supply may lead to combustion issues, such as flame lifting and flame loss.

Gas fired appliances can be permanently connected to a gas grid, or be supplied with bottled gas. As the gas pressure may influence the combustion efficiency, the gas supply lines must be sized properly. Downsizing may result in a high pressure loss and insufficient fuel supply.

Oil fired appliances usually need to be permanently connected to an oil supply line, and an appropriately sized oil tank. Same as for gas, the oil supply lines have to be sized correctly to avoid high pressure losses.

4.8 End-of-life phase

Air-based central heating systems are not considered to be candidates for significant re-use.

Manufacturers do not have much influence on the end-of-life practices of ABCHPs. Nevertheless, all manufacturers ensured that the printed wiring boards of their products are easy to disassemble, what enables the sorting of materials.

Some manufacturers estimated the fraction of product not recovered (i.e. going to landfill) to be around 5% and pointed out that 100% of metals and plastics can potentially be recycled. This is in line with the landfilling rate of 5% reported in ENER Lot 1 preparatory study on boilers[75]. However, in the ENER Lot 1 study the reuse and recycling of plastics is estimated to be 10% and the thermal recycling 90%.

[75] VHK (2007) ENER Lot 1 preparatory study. Final Report, for DG ENER of the European Commission.

One stakeholder provided recycling and recovery rates for Japan in the year 2010. The ratio of recovered units respect to the delivered units in Japan in that year was of 64.9%, with an average growth trend of 3.5% per year since 2001. Recycling rate of recovered units in Japan is around 88% for 2010, with an average growth rate of 1.11% per year since 2001.

One manufacturer provided detailed information about the recycling rate of its collected scrap units. The waste is shredded, ferrous and non-ferrous fractions are separated by using magnet and flotation enables the separation of the different non-ferrous fractions. At the end of this process, the rest fraction represents only 14% of the original scrap unit waste. 81% of the material collected is ferrous, 4.6% is aluminium, 11.6% copper and 2.3% plastics (PP, ABS and PS).

Some producers are introducing take-back schemes in partnership with installers that go beyond WEEE compliance. Nevertheless, if the goals of the WEEE Directive are fulfilled, the recycling rate of big household appliances should be at least 75% and the total recovery (including energy recovery) 80% by 2009.

Recycling rates of WEEE are calculated as a share of the amount collected, and collected rates are calculated as a share of the weight of the products put on the market in the same year.

The reported reuse and recycling rate in 2006 is quite high in general in the EU[76]: Six countries within the European Economic Area (EEA) achieved reuse and recycling rates above 80% and nine EEA countries achieved rates between 50-80%. However, the overall recycling rate of the entire market depends on the waste collection rate. Among the six countries with recycling rates higher than 80%, two achieved collection rates below 10% in 2006 (compared to the amounts of products put in the market in the same year). Ten of the 21 EEA countries that reported data did not meet the collection target of 4 kg per person per year established in the WEEE Directive. Large household appliances present higher collection rates than small household appliances and electric tools. Fourteen of the 25 countries that reported collection data to Eurostat in 2008 achieved collection rates for large household appliances over 30%. The EU-27 average collection rate is of 37%. These figures may increase in the near future due to the new WEEE Directive targets for collection rate set to 65% for the year 2016.

[76] Tojo N. and Fischer C. Europe as a Recycling Society. European Recycling Policies in relation to the actual recycling achieved. ETC/SCP working paper 2/2011.

Table 4-9 : Collection rate of big household appliances in the EU-27 in 2008, EUROSTAT.

Member States	Collection rate
European Union (27 countries[77])	37%
Belgium	41%
Bulgaria	1106%
Czech Republic	27%
Denmark	47%
Germany	39%
Estonia	18%
Ireland	50%
Greece	25%
Spain	56%
France	20%
Italy	17%
Cyprus	15%
Latvia	22%
Lithuania	26%
Luxembourg	41%
Hungary	40%
Malta	:
Netherlands	1012%
Austria	44%
Poland	7%
Portugal	24%
Romania	6%
Slovenia	:
Slovakia	38%
Finland	39%
Sweden	70%
United Kingdom	71%

* Some collection amounts are higher than the amounts put in the market in the same year

Within the waste classified as WEEE, 75% is recycled, 5% is incinerated with energy recovery, and 20% is going to landfill[78].

[77] The EU-27 average has been weighted with the WEEE waste stream mass in each Member State
[78] Eurostat online database, accessed on 07/09/2011

The waste stream that is not collected as WEEE ends up in the municipal solid waste. At EU level, in 2009, the 37% of the waste collected was deposited into or onto land; 16% was incinerated with energy recovery and 4% was incinerated without energy recovery; 23% was recycled to recover the materials and 17% was recycled in other was such as composting[78]. The 3% left is not reported by Eurostat.

However, the products within the scope of this preparatory study do not fully fall under the scope of the WEEE Directive. Furthermore, the WEEE statistics might not be very accurate for this analysis. There are no other official statistics for ABCHP, and the inputs received from the stakeholders will be taken as the most representative figures for end-of-life practices.

As a summary, Table 4-10 presents the different landfill, recycling and incineration rates discussed above.

Table 4-10 : Landfill, recycling and incineration rates of air-based central heating products

Source	Landfill rate	Recycling rate		Incineration rate	
		Material recycling	Other recycling	Energy recovery	Without energy recovery
Stakeholder's inputs	5%	87% - 97%		3% - 13%	
Eurostat WEEE statistics	20%	75%		5%	0%
Eurostat MSW statistics	37%	23%	17%	16%	4%

In this preparatory study, the inputs provided by stakeholders are used in the environmental analysis in Task 5, assuming that all air-based central heating products are treated in a similar way at their end of life.

4.9 Recommendations on mandates

The products covered in this ENER Lot 21 preparatory study are part of the horizontal mandate of standardisation work in the field of Ecodesign of energy-using products that was given by the Commission to CEN/CENELEC. Standardisation efforts include aspects such as the use of materials derived from recycling activities; the use of substances classified as hazardous; energy consumption throughout the life cycle; ease for reuse and recycling; amounts of waste generated; emissions to air and to water.

4.9.1 Warm air heaters

Concerning heating appliances using gas, new standards are currently being developed for decentralised gas heating appliances by the NAGas working group WG6/TC 180. The Standardisation Committee Gas Technology (NAGas), a part of the DIN Deutsches Institut für Normung e. V., is responsible for standardisation in the field of gas supply and gas utilisation. Technical committee TC 180 is currently working on "Non-domestic, indirect gas-fired air heaters", and among them the working group WG6 is developing a standard for the efficiency of air heating and overhead radiant heating systems. The new standard that will result from this initiative should take into account the system perspective for decentralised space heating. The development of a standard with a similar approach for centralised heating systems will be necessary. This would need to take into account building characteristics and the product-system relationship in order to include the system parameters in efficiency testing of air-based centralised heating systems. This standard or group of standards would apply to gas-fired, oil-fired and multi fuel-fired central heating systems.

4.9.2 Heat pumps

As shown in Task 1, some standards already exist and are used in industry for calculating the efficiency of heat pumps (EN 14511). Test standards have also been developed for several efficiency definitions, such as the coefficient of performance. Other standards are being developed at the time of writing to tackle seasonal performance and climatic conditions in product testing by using efficiency parameters such as heating seasonal performance factor and annual performance factor (prEN 14825; ISO/CD 16358). These test methods include the cooling function as well as the heating function in reversible heat pumps. However, this standard is only applicable to heat pumps for residential buildings up to 12 kW of cooling capacity. Therefore, a similar standard for higher capacities, including VRF heat pumps and non-residential buildings should be developed.

4.10 Conclusions

This Task report presented the different technologies of air-based central heating products. As a summary, two main technologies can be distinguished for centralised space heating using warm air heaters and heat pumps. These two systems differ in the method of heat generation or heat extraction, and in the heat transmission medium. Warm air heaters use oil or gas to heat up air, and ducts and fans to distribute the warm air to the space to be heated. On the other hand, heat pumps use refrigerant fluid to transport heat from one area to another, a compressor to increase the pressure of the gas, and fans to force air to circulate into the heat exchangers. Therefore, the material requirements, components, and resource consumption during the life cycle are different. The two different technologies must therefore be analysed separately in the following tasks. With this aim, some inputs for each life-cycle stage are presented for the different product types in this Task 4 report. The inputs are completed with a more in-depth analysis in Task 5 in order to perform the environmental and economic impact assessment of the representative Base-Cases. The "extended product" approach taken in this preparatory study aims at including an analysis of the aspects of the system that influence the efficiency of the product, such as heat gains and losses, variable heat demands. This way, the environmental analysis and the improvement potential options explored will include not only product-specific issues, but also other possibilities that could provide environmental benefits. However, the objectives and scope of the Ecodesign Directive and the Energy Performance of Buildings Directive (EPBD) are different. This preparatory study will not go beyond the aspects that can be managed from the product perspective.

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