9 Heat pumps

[H.J. Laue]

9.1 Introduction

Sustainable development for a more efficient energy use and the protection of the environment is of ever increasing importance, challenged by the obvious admonitions of the consequences of the greenhouse effect, the ozone depletion in the stratosphere, the air pollution as well as the finite resources of fossil energy presently covering around 90% of the ever increasing world energy demand. In Europe, besides the energy and transport sector, the space and process heat demand is of specific importance for the reduction of CO_2 and other greenhouse gas emissions with more than 50% of the total final energy consumption and around 80% dependence on fossil fuel.

Heat pumps represent one of the most practicable solutions of the greenhouse effect as the only known process that recirculates environmental and waste heat back into a heat production process offering energy-efficient and environmentally friendly heating and cooling in applications ranging from domestic and commercial buildings to process industries. Studies and practical experiences have shown that heat pumps are able to drastically reduce greenhouse gas – in particular CO_2 – emissions in space heating and heat generation depending upon the type of heat pump and the energy-mix and efficiency of driving power used. Energy savings and the associated further reduction of emissions will even be higher with the presently developed high performance heat pumps and optimized heating and cooling systems.

9.2 Historical development

In 1852, the British physicist William Thomson (Lord Kelvin) described for the first time the working principle of “pumping” heat with a thermodynamic cycle [1852Tho] and in 1856/57, Peter Ritter von Rittinger built the first functioning “heat pump” with a capacity of 14 kW in Ebensee/Austria for the energy supply of the salt production [1855Rit].

Around 1930, more than seventy years after Lord Kelvin and von Rittinger, the first small and large heat pumps were tested in Great Britain and the USA and in 1938, the first European large-scale heat pump for the heating and cooling of the City Hall in Zürich/Switzerland was installed, still in operation today [38Egl]. Since the beginning of the fifties reversible heat pumps for cooling in summer and heating in winter have been booming in the USA and Japan.

In Europe, a mentionable market developed in the middle of the seventies, in particular caused by the first and second oil crisis, but the following drop in energy prices negatively influenced the slim European heat pump market with a slow down in some countries at the beginning of the nineties. The new renaissance in Europe in the middle of the nineties was initiated by the already mentioned understanding of sustainable development for a more efficient energy use and the related protection of the environment. Until the end of the year 2005, around 120 million heat pumps have been installed worldwide for heating only or heating and cooling applications. In addition the world’s air conditioning and air-cooled heat pump population is approximately 250 million units and about 60 million room and packaged air conditioners for heating and cooling are produced annually. The European heat pump market, with only less than 5% of the worldwide installed heat pumps, is still far behind the USA, Japan and China, which are the largest markets for heat pumps today.

9.3 Basic principles

The heat pump is a thermodynamic cycle that transports heat from a low to a high temperature level, which – in accordance with the second law of thermodynamic – is not possible without additional energy input to drive the process. This driving energy input is much smaller than the heat energy delivered at the higher temperature level. This is the fundamental difference compared to a conventional combustion device which always has a heat output lower than energy input supplied by the fuel.

A heat pump is essentially a heat engine operating in reverse between two temperature levels (see Fig. 9.1). A heat engine produces work W by extracting heat Q_2 from the high temperature T_2 and delivering heat Q_1 to the temperature T_1, whereas a heat pump delivers heat Q_2 at the high temperature T_2 by extracting heat Q_1 from the low temperature T_1 and requiring a work input W. A refrigerator operates in exactly the same way as a heat pump, with the exception that the desired effect is not the heat Q_2 delivered at T_2 but the heat Q_1 extracted at the temperature T_1. The first law of thermodynamics gives the relation between heat and work involved in these processes by

$$Q_2 = Q_1 + W \,.$$

The second law of thermodynamics states that the work output (W) continuously produced by the heat engine can never be greater than the work input (W) required by a heat pump when operating between the same temperature levels. This results in the following relationship between the temperatures and the transferred heat:

$$Q_1 / T_1 = Q_2 / T_2 \,.$$

The efficiency of these processes is defined as the ratio of the useful heat or work output, respectively, to the necessary input. In the case of a heat pump the efficiency is called the Coefficient of Performance *COP* and is defined as

$$COP_\mathrm{H} = Q_2 / W \,.$$

For engine and thermally driven heat pumps the performance is indicated by the primary energy ratio *PER*. For electrically driven heat pumps a *PER* can also be defined by multiplying the *COP* with the power generation efficiency.

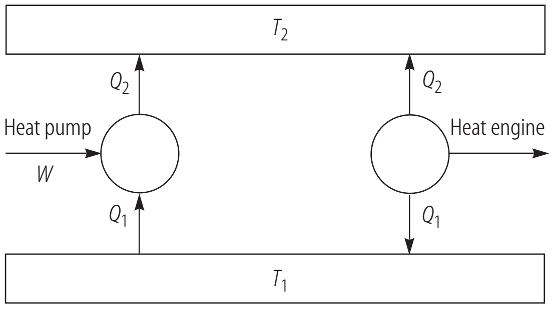

Fig. 9.1. Heat pump and heat engine operating between temperature levels T_2 and T_1.

In theory, the maximum *COP* is given by a Carnot process operating between the temperatures T_1 and T_2; this COP_C only depends on these temperatures as

$$COP_C = \frac{T_2}{T_2 - T_1}\ .$$

In reality, however, it is not possible to operate a heat pump with real working fluids with a completely reversible cycle as ideal conditions can not be realized with real fluids and any technical device operates with loses. This COP_C is therefore often used for comparative calculations as a theoretically maximum *COP* for a given application, only requiring knowledge of the temperature levels. In real heat pumps a number of deviations from the ideal cycle decrease the *COP*. The single most significant deviation is introduced by the compressor. Condensation and evaporation temperatures need to be higher than the heat sink temperature and lower than the heat source temperature to allow heat transfer in limited area heat exchangers. Pressure drops in the refrigerants lines cause further losses. Figure 9.2 shows the *COP* for an ideal heat pump as a function of temperature lift, where the temperature of the heat source is 0°C, as well as the range of actual *COP*s for various types and sizes of real heat pumps at different temperature lifts.

The ratio of the actual *COP* of a heat pump and the ideal COP_C is defined as the Carnot-efficiency η_C, varying from 0.3 to 0.5 for small electric heat pumps and 0.5 to 0.7 for large highly efficient electric heat pump systems. The operating performance of an electric heat pump over the season is called the seasonal performance factor (SPF). It is defined as the ratio of the delivered heat and the total energy supplied over the season.

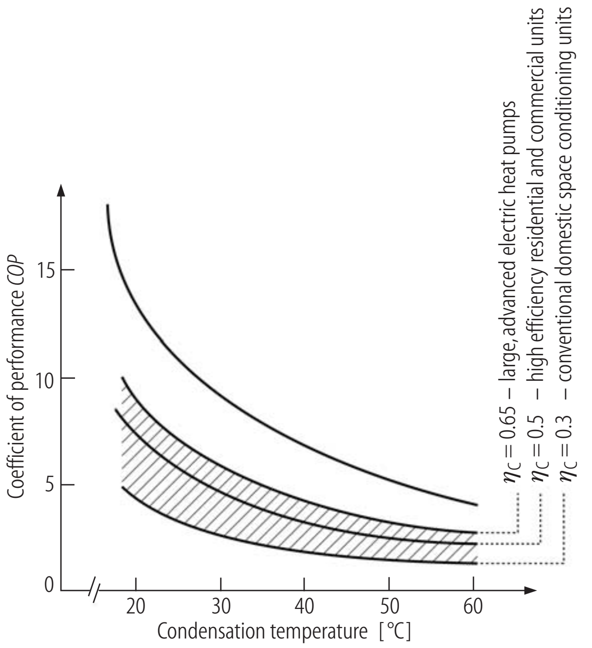

Fig. 9.2. *COP* for an ideal heat pump as function of the temperature lift.

9.4 Heat pump technology

There are mainly two types of heat pumps being used today, the vapor compression heat pump with a mechanical compressor requiring mechanical drive energy and the absorption heat pump using, instead of a mechanical compressor, a thermodynamic cycle requiring thermal drive energy. Theoretically, however, heat pumping can be achieved by many more thermodynamic cycles and processes [02Kru]. These include adsorption systems, Stirling and Vuilleumier cycles, single-phase cycles (e.g. with air, CO_2 or noble gases), solid-vapor sorption systems, hybrid systems (notably combining the vapor compression and absorption cycle) and electro-magnetic and acoustic processes. Some of them are still in an early stage of research and development; some have reached technical maturity but not the necessary economic competitiveness. However, additional RD&D is required to significantly enter the market in the future.

The great majority of heat pumps work on the principle of the vapor compression cycle (see Fig. 9.3), consisting of an evaporator, a compressor with drive energy, a condenser and an expansion valve. A volatile liquid, known as the working fluid or refrigerant, with low evaporating temperature is used to transport the heat in the closed heat pump cycle. The cycle is thermodynamically identical with the household refrigerator, whereby the heat input at the evaporator (heat source) and the heat output at the condenser (heat sink) normally take place at a higher temperature level and it is heat – and not cold – that is used.

In the evaporator the temperature of the liquid working fluid is kept lower than the temperature of the heat source, causing heat to flow from the heat source to the liquid, and the working fluid evaporates. Vapor from the evaporator is compressed to a higher pressure and temperature. The hot vapor then enters the condenser where it condenses and gives off useful heat. Finally, the high-pressure working fluid is expanded to the evaporator pressure and temperature in the expansion valve, returned to its original state and once again enters the evaporator. The compressor is usually driven by an electric motor supplied with electricity or sometimes by a combustion engine supplied with liquid or gaseous fuels. Absorption heat pumps are thermally driven, which means that heat rather than mechanical energy is supplied to drive the cycle. Absorption heat pumps for space conditioning are often gas-fired, while industrial installations are usually driven by high-pressure steam or waste heat. Absorption systems utilize the ability of liquids or salts to absorb the vapor of the working fluid. The most common working pairs for absorption are water (working fluid) / lithium bromide (absorbent) and ammonia (working fluid) / water (absorbent).

In absorption systems, as shown in Fig. 9.4, the compression of the working fluid is achieved thermally in a solution circuit which consists of an absorber, a solution pump, a generator and an expansion valve. Low pressure vapor from the evaporator is absorbed in the absorbent which generates heat. The solution is pumped to high pressure and then enters the generator, where the working fluid is boiled off with an external heat supply at a high temperature. The working fluid (vapor) is condensed in the condenser while the absorbent is returned to the absorber via the expansion valve. Heat is extracted from the heat source in the evaporator. Useful heat is given off at medium temperature in the condenser and in the absorber. In the generator high-temperature heat is supplied to run the process. A small amount of electricity may be needed to operate the solution pump.

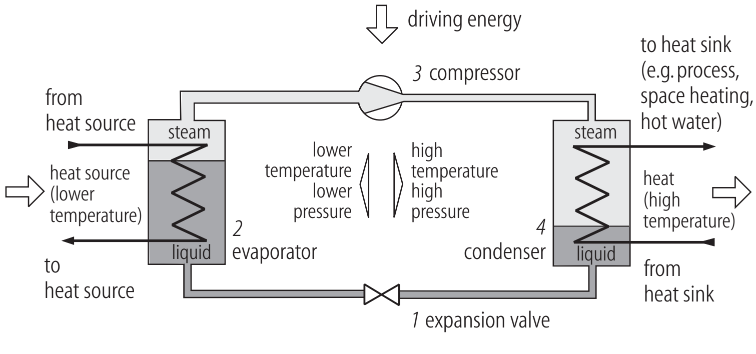

Fig. 9.3. Schematic of a vapor compression heat pump. *1* - Pressurized liquid working fluid is expanded in the expansion valve. *2* - Working fluid evaporates in the evaporator by taking up heat energy from the environment. *3* - Working fluid is compressed with driving energy, increasing its temperature. *4* - Working fluid releases heat and is again liquefied.

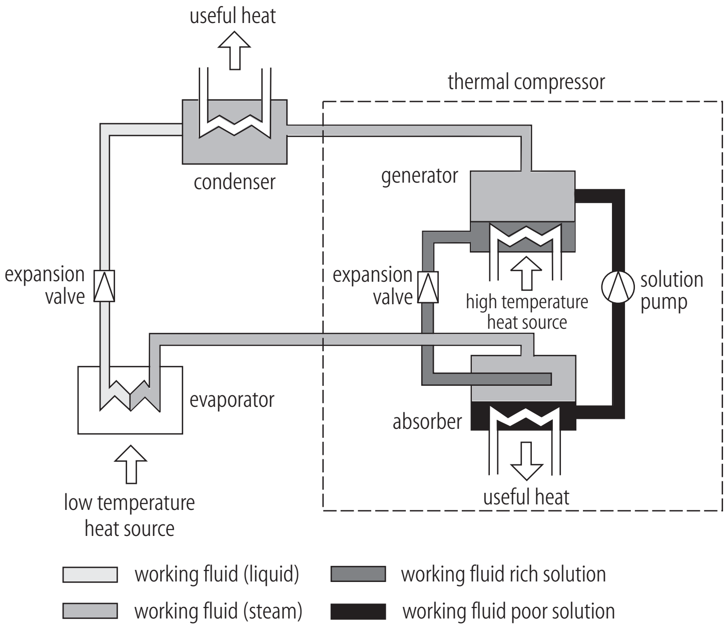

Fig. 9.4. Schematic of an absorption heat pump.

9.5 Heat sources

The specific advantage of heat pumps in comparison to conventional heating systems is the free-of-charge use of environmental heat. For a most convenient use of the environmental heat the heat sources soil, ground water and ambient air are favored. They all represent stored energy of the sun and therefore indirectly use solar energy, i.e. renewable energy.

In accordance with the above mentioned Carnot process, a high *COP* and excellent technical and economic performance of a heat pump is closely related to the temperature difference ΔT between heat source and useful heat (heat sink), as can be seen in Fig. 9.5. Consequently, the temperature of the heat source should be as high as possible and stable during the year, whereas the temperature of the heat sink should be at the lowest possible level appropriate to the intended application, e.g. floor heating systems with 35/28°C supply/return temperatures. Table 9.1 presents commonly used heat sources. Ambient and exhaust air, soil and ground water are practical heat sources for small heat pump systems, while sea-, lake-, and river-water as well as waste heat are used for large heat pump systems.

Ambient air is free and widely available and it has been the most common heat source for heat pumps. Compared to water-source heat pumps, however, air-source heat pumps achieve a lower SPF by 10-30% on average. This is mainly due to the rapid fall in capacity and performance with decreasing outdoor temperature, the relatively high temperature difference in the evaporator and the energy needed for defrosting the evaporator and operating the fans.

Exhaust air is a common heat source for heat pumps in residential and commercial buildings. The heat pump recovers heat from the ventilation air and provides water and/or space heating. Some units are also designed to utilize both exhaust and ambient air.

Earth-coupled (soil) systems are used for residential and commercial buildings. At present more than 65% of all new installed residential heat pumps in Germany use earth-coupled heat sources. Heat is extracted from pipes laid horizontally (earth collectors) or vertically (earth probes) in the soil. Both direct and indirect brine (mixture of anti-freeze and water) systems can be used. Due to the extraction of heat from the soil, the soil temperature will fall during the heating season. However, in summer the sun will raise the ground temperature and a complete temperature recovery may be possible.

Ground water is available with stable temperature (4-10°C) over the year in many regions. There are normally two wells required, one to extract the water from the ground, pump it through the heat pump evaporator and cool it to reinject it into the ground through a second well. Local regulations may impose severe constraints regarding interference with the water table and the possibility of soil pollution. More detailed information on the design, installation and operation of heat sources for residential application are found in [98RWE].

Waste heat and effluent are characterized by a relatively high and constant temperature throughout the year. Examples of possible heat sources in this category are effluent from sewers (treated and untreated water), industrial effluent, cooling water from industrial processes or electricity generation and condenser heat from refrigeration plants. The major constraints for use in residential and commercial buildings are the distance to the user and the variable availability of the waste heat flow. However, waste heat and effluent serve as an ideal heat source for industrial heat pumps to achieve energy savings in industry.

Table 9.1. Commonly used heat sources.

Heat source		Temperature range [°C]	Heat output
Ambient air		–15 - 15	0.69 - 1.4 $W/m^3/h$ [1])
Exhaust air		10 - 22	0.69 - 1.4 $W/m^3/h$ [1])
Ground coupled	- Collector	0 - 10	20 - 50 W/m^2
	- Earth probe	0 - 10	50 - 120 W/m
Ground water		6 - 10	2300 - 4600 $W/m^3/h$ [2]) (Ground water, Lake water, Sea water)
Lake water		0 - 10	
Sea water		–2 - 10	
Waste heat and effluent		more than +10	–

[1]) Heat limit (by experience): 15°C; cooling: 2-4 K ≈ 1.25 kJ/m^3K.
[2]) Cooling: 2-4 K ≈ 4200 $kJm^{-3}K^{-1}$.

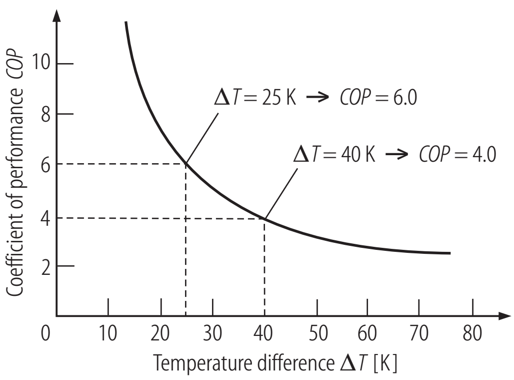

Fig. 9.5. Coefficient of Performance *COP* as a function of the temperature difference ΔT; $\varepsilon = 0.5\varepsilon_C$ related to $T_0 = 273$ K.

9.6 Heat pump working fluids

Since around 1930, closed-cycle compression type heat pumps have used the so called "safety refrigerants" chlorofluorocarbons (CFCs) and hydrochloro-fluorocarbons (HCFCs) as working fluids. In the middle of the seventies, it was theoretically ascertained that CFCs are not harmless to the global environment due to their chlorine content and chemical stability [74Mol]. Today it is known that CFCs have both a high ozone depletion potential (ODP) and a global warming potential (GWP). HCFCs have a lower ODP (typically 2-5% of CFCs) and GWP (typically 20% of CFCs). The replacement of CFCs/HCFCs was therefore internationally regulated by the Montreal Protocol and its follow-up conferences 1990 in London and 1992 in Copenhagen. In Germany the CFC-Halon Interdiction Decree goes beyond the Montreal Protocol, banning CFCs since 1995 and HCFCs since 2000 as working fluids in new equipments.

As a result, a number of alternative working fluids have been developed. Table 9.2 shows the present known alternatives for heat pumps. Possible alternatives for R22, the major fluid for residential heat pumps before the Montreal Protocol, are HFC-mixtures, e.g. R407C and R410A, as well as natural refrigerants, e.g. hydrocarbons, ammonia, carbon dioxide and water.

Table 9.2. Comparison of specific properties of typical working fluids (ODP-value related to R11, GWP-value related to CO_2 in a timeframe of 100 years) [05Bit].

Name	Formula	ODP	GWP	Alternate for	Flammable	Toxicity	NBP [°C]
R134a	$C_2H_2F_4$	0	1300	R22 $CHClF_2$	no	small	-26.3
R407C R32/R125/ R134a	$CH_2F_2/CF_3CHF_2/$ $C_2H_2F_4$ 23/25/52 wt-%	0	1530	R22 $CHClF_2$	no	small	-44.3/ -37.1
R410A R32/R125	$CH_2F_2/$ CF_3CHF_2 50/50 wt-%	0	1730	R22 $CHClF_2$	no	small	-50.5/ -50.3
R404A R125/ R134a/ R143a	$CF_3CHF_2/C_2H_2F_4/$ CF_3CH_3 44/4/52 wt-%	0	3260	R502 R115/R22 $C_2F_5Cl/CHClF_2$ 51.2/48.8 wt-%	no	small	-46.5/ -46.0
R290 Propane	C_3H_8	0	3	R22 R502	yes	small	-42.1
R1270 Propylen	C_3H_6	0	3	R22	yes	small	-48.0
R717 Ammonia	NH_3	0	0	R22 R502	yes	yes	-33.3
R744 Carbon- dioxide	CO_2	0	0	several	no	no	-78.4
R718 Water	H_2O	0	0		no	no	100.0

9.6.1 HFC-mixtures

HFC-mixtures or -blends represent an important possibility for replacement of CFCs and HCFCs for both retrofit and new applications. A blend consists of two or more pure working fluids and can be zeotropic or azeotropic. Azeotropic mixtures evaporate and condense at a constant temperature, zeotropic ones over a certain temperature range (temperature glide). The temperature glide can be utilized to enhance the performance, but this requires equipment modification. The advantage of blends is that they can be custom-made to fit particular needs.

Two of the most promising alternative working fluids which have already replaced R22 in heat pumping applications are the mixtures R407C and R410A:

- *R407C* is the only refrigerant available for immediate use in existing R22-plants as its thermal properties and operating conditions are close to those of R22. However, because of its temperature glide it is only suitable for certain systems. The use of this refrigerant is increasing, although there are still some engineering difficulties for service companies and manufacturers.
- R&D has shown that the use of *R410A* can result in an improved *COP* compared to R22. Using R410A means that overall cost reductions can be achieved as the system components, particularly the compressor, can be significantly downsized due to a higher volumetric capacity. The main advantage is the higher operating pressure compared to R22. R410A is already very popular mainly in the USA and Japan for packaged heat pumps and air-conditioning units.

However, fluorinated gases (F-gases) including HFCs as well as FCs and SF_6 have a relatively high GWP. (HFC-heat pump fluids see Table 9.2). The Commission of the European Union has therefore initiated regulations for F-Gases as part of the EU commitment to the Kyoto Protocol, and in Germany the Federal Ministry of the Environment has already started preparatory activities which may negatively influence the use of HFCs in heat pumps in future as no economically and environmentally acceptable alternatives are presently available. In order to determine the very small overall contribution of HFCs to global warming, the so called Total Equivalent Warming Impact (TEWI) should identify the negligible role of the working fluid to the total environmental effect of heat pumps. TEWI is the sum of the direct contribution of greenhouse gases used to manufacture or operate the systems and the indirect contribution of carbon dioxide emissions resulting from the energy required to run the systems over their normal lifetime [97San].

9.6.2 Natural working fluids

With the present knowledge, environmentally sound solutions consist of substances that naturally exist in the biosphere – so called natural working fluids – like ammonia, hydrocarbons, carbon dioxide, air and water, which all have negligible global environmental drawback (zero or near zero ODP and GWP), but some are flammable or toxic.

Hydrocarbons (HCs) are well known flammable working fluids with favorable thermodynamic properties and material compatibility. Presently propane and propylene are the most promising hydrocarbon working fluids in heat pumping systems. However, due to the high flammability hydrocarbons should only be retrofitted and applied in systems with low working fluid charge (>150 g). To ensure the necessary safety during operation and service, precautions should be taken such as proper placing and/or enclosure of the heat pump, fail-safe ventilation systems, use of gas detectors etc. At present, however, the leading compressor manufacturers do not accept hydro-carbons as working fluid in heat pumps due to the safety implications and related problems of product liability.

Ammonia (NH_3) is the leading working fluid in medium and large refrigeration and cold storage as well as absorption plants in many countries. Codes, regulations and legislation have been developed mainly to deal with the toxic and flammable characteristic of ammonia. Thermodynamically ammonia would be an excellent alternative to R22 in new heat pump equipments, but ammonia with the normal water content can not economically be considered in small heat pump systems as copper components have to be replaced by expensive stainless steel.

Carbon dioxide (CO_2) is a potentially strong refrigerant that is attracting growing attention all over the world. CO_2 is non-toxic, non-flammable, environmentally sound and compatible to normal lubricants and common construction material. The volumetric refrigeration capacity is high and the pressure ratio is greatly reduced. However, the theoretical *COP* of a conventional heat pumping cycle with CO_2 is rather poor and effective applications of this fluid depends on the development of suitable methods to achieve a competitively low power consumption during operation near and above the boiling point. As an unfavorable side effect of the application of CO_2 high pressure is necessary which exacts the technical components like compressors and heat exchangers.

Due to the thermodynamic properties, CO_2-heat pumps are able to generate high heating temperatures and are therefore of particular interest for the retrofitting of heating systems in existing buildings and hot-water generation, the most interesting residential heat pump applications in the future. CO_2 products are still under development, and research continues to improve systems and components. A major joint R&D project [02Cor], funded within the JOULE-program of the European Commission – Energy-efficient and environmentally friendly heat pumping systems using CO_2 as working fluid (COHEPS) –, has developed, constructed and tested first prototypes of

- hot water heat pumps for residential applications (Austria),
- commercial heat pumps for water heating and heat recovery (Norway),
- heat pumps for retrofitting high-temperature space heating systems in existing buildings (Germany),
- heat pumps for dehumidification and drying processes in residential and commercial applications (Germany),

but additional development of the components and systems is required for commercial applications.

Water (H_2O) is an excellent fluid for high temperature industrial heat pumps due to its favorable thermodynamic properties and the fact that it is neither flammable nor toxic. Water has mainly been used as a working fluid in open and semi open MVR systems (see Sect. 9.8.2), but there are also a few closed-cycle compression heat pumps with water as working fluid. Typical operating temperatures are in the range of 80-150°C. There is a growing interest in utilizing water as a working fluid, especially for high temperature application. The major disadvantage with water as a working fluid is the low volumetric capacity of water which requires large and expensive compressors, especially at low temperatures.

9.7 Heat pumps in residential and commercial buildings

Heat pumps for heating and cooling can be divided into three main categories:

- Heating-only heat pumps, providing space heating with or without water heating;
- Heating and cooling heat pumps, providing both space heating and cooling;
- Heat pump water heater only.

9.7.1 Heating-only heat pumps

Heating-only heat pumps with water distribution systems (hydronic systems) are predominantly used in Central and Northern Europe, Canada and the northern part of the USA. Electric driven vapor compression systems are dominating the market, and ambient air, soil and ground water are the mainly used heat sources [98RWE]. Heating-only heat pumps are classified by their method of operation:

- *Monovalent* heat pumps are heating systems which meet the annual heating demand alone. Ground-coupled or ground-water heat pump systems are operated in the monovalent mode due to the constant temperature of the heat sources during the heating season
- *Bivalent* heat pumps are systems in which the heat pump is supplemented by an auxiliary heating system in order to assist the plant on unusually cold days or when the heat pump is out of operation. Bivalent heat pumps are sized for 20-60% of the maximum heat load only, but normally meet around 50-95% of the annual heating demand, e.g. in a European residence. The term *bivalent* is employed for an auxiliary heating system based on a different supply of energy, e.g. oil, gas or coal boiler, used to operate the heat pump.
- In a *monoenergetic* system the auxiliary heating is based on the same supply of energy used for the heat pump, e.g. an electric resistance heater for low outdoor temperatures.

Ambient air heat pump systems have been operated in a bivalent or monoenergetic mode due to the low outside temperature during the heating season. In new buildings only monoenergetic systems are used for air-water heat pump systems due to the uneconomic operation with two independent heating systems. Today's modern low temperature systems, e.g. floor or wall heating, are designed for 35/28°C supply/return temperatures, whereas conventional radiator systems require high distribution temperatures, typically 60-90°C.

Present development in Central Europe is concentrated on economically competitive and energy-efficient heat pumps for the retrofit of heating systems in existing buildings. The aim is mainly directed to economic air-to-water systems with around 60°C heating temperature, operated in monovalent mode with high *COP*. Possible solutions are CO_2 as working fluid (see Sect. 9.6.2), multi-cycle systems or speed regulated compressors. Table 9.3 shows measured average SPFs of German residential heat pumps installed between 1990 and 1998.

The heat capacities of heat pumps for the different types of buildings or application are as follows, depending on the age, status of construction, insulation and heat distribution temperature:

- Single-family-houses: mainly electric driven compression heat pumps, 3.5-20 kW;
- Multi-families-houses: mainly electric driven compression heat pumps, 15-100 kW;
- Large apartment-houses: electric and gas motor driven compression heat pumps, 100-1000 kW;
- Public buildings (schools, kindergarten etc.): mainly compression and some absorption heat pumps: 50-100 kW;
- Commercial buildings; compression and absorption heat pumps, 50-500 kW;
- District heating: compression and absorption heat pumps, up to 5 MW;

Table 9.3. Measured seasonal performance factors (SPF) of installed residential heat pumps in Germany between 1990 and 1998 [99Hei1].

	Heat Distribution System	SPF		
		minimum	average	maximum
Air/Water	35°C/28°C	3.0	3.2	3.4
	55°C/45°C	2.5	2.7	3.0
Ground/ Water	35°C/28°C	3.1	3.7	4.5
	55°C/45°C	2.9	3.1	3.5
Water/Water	35°C/28°C	3.8	4.1	4.5
	55°C/45°C	-	-	-

9.7.2 Heating and cooling heat pumps

The most common types in residential applications in the mature heat pump markets of Japan and the USA, but also in southern Europe, are reversible air-to-air heat pumps which either operate in heating or cooling mode. The air is either passed directly into a room by the space-conditioning unit or distributed through a forced-air ducted system. The output temperature of an air distribution system is usually in the range of 30-50°C. The heating/cooling capacity of residential systems is normally between 1 and 10 kW. Large heat pumps in commercial/institutional buildings use water loops (hydronic) for heat and cold distribution, providing heating and cooling simultaneously.

9.7.3 Heat pump water heater

Heat pump water heater often use air from the immediate surroundings as heat source, e.g. in the storeroom in the basement, but can also be exhaust-air heat pumps or desuperheaters on air-to-air and water-to-air heat pumps. The nominal capacity of water heaters is between 0.4 and 1.4 kW.

9.8 Heat pumps in industry

Industrial heat pumps, in general using waste process heat as heat source, deliver this heat at higher temperatures for use in industrial process heating and preheating or for space heating in industry. They represent a worthwhile method of improving the energy efficiency of industrial processes and/or reducing primary energy consumption. Relatively few heat pumps are currently installed in industry. The principal reason seems to be the demand in industry for very short payback periods to justify capital expenditure. Other reasons for their neglect are a lack of experiences from demonstration projects in many types of industry. However, as environmental regulations become stricter, industrial heat pumps should become an important technology to reduce emissions, improve efficiency and limit the use of ground water for cooling.

To ensure the sound application of heat pumps in industry, processes should be optimized and integrated. Through process integration, improved energy efficiency is achieved by optimizing entire industrial processes thermodynamically. An important instrument for process integration is the pinch analysis, a technology to characterize process heat streams and identify possibilities for heat recovery [82Lin]. Such possibilities may include heat exchanger networks, cogeneration and heat pumps.

Industrial applications show a great variation in type of drive energy, heat pump size, operating conditions and type of application. The heat pump units are generally designed for a specific application and are therefore unique [94Lau], [97Ber]. The major types of industrial heat pumps are

- closed-cycle compression heat pumps,
- mechanical vapor recompression systems (MVR),
- thermal vapor recompression systems (TVR),
- absorption heat pumps and
- heat transformers.

Figure 9.6 shows the industrial heat pump installations in the major IEA countries divided into the above mentioned heat pump types, dominated by the closed cycle compression and mechanical vapor recompression types. The installed heat capacity of the vapor recompression types in industry is between 1 and 10 MW per plant, the one of compression and absorption types between 0.5 and 5 MW.

Industrial heat pumps are mainly used for

- space and district heating,
- heating and cooling of process streams,
- water heating for washing, sanitation and cleaning,
- steam production,
- drying/dehumidification,
- evaporation,
- distillation or
- concentration.

In Europe heat pumps are presently mainly used in the food industry, principle applications are in sugar refining, abattoirs and meat processing, vegetable canning and starch production. In the dairy industry major applications are pasteurization, hot water production, evaporation, drying of milk powder and casein production. Further applications are in malting, brewing and distilling, where MVR systems are widely employed. Other sectors are pulp and paper, oil refining and petrochemical as well as textile industry.

When heat pumps are used in drying, evaporation and distillation processes, heat is recycled within the process. For space heating, heating of process streams and stream production, heat pumps utilize (waste) heat sources between 20 and 100°C. The most common waste heat streams in industry are cooling water, effluent, condensate, moisture and condenser heat from refrigeration plants. Because of fluctuation in waste heat supply, it can be necessary to use large storage tanks for accumulation to ensure stable operation of the heat pump.

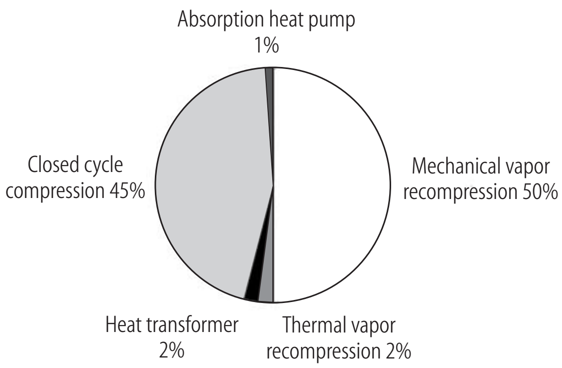

Fig. 9.6. Industrial heat pump installations in major IEA countries divided into heat pump types [97Ber].

9.8.1 Closed cycle compression heat pumps

Closed cycle compression heat pumps are mostly used to recover waste heat at relatively low temperature and to upgrade it for process preheating to temperatures between 50 and 100°C. Currently applied working fluids limit the maximum output temperature to 120°C (see also Sect. 9.4 and Sect. 9.7).

9.8.2 Mechanical vapor recompression systems

Mechanical vapor recompression systems (MVR) are the most common types of industrial heat pumps, classified as open or semi-open systems. Instead of employing a separate refrigerant, as in the closed cycle systems, the vapor itself is compressed and its temperature is raised by a mechanical compressor. The process vapor acts as both a waste heat stream and a working fluid. The high pressure vapor can either be re-used directly or condensed in an exchanger to supply heat to another process stream. The different types of open and semi-open cycles are shown in Fig. 9.7. Type (a) is the conventional open cycle consisting of a compressor operating directly on waste vapor and delivering high pressure vapor in the process. Type (b) shows the most common variant where waste vapor is compressed and then condensed in a heat exchanger. Type (c) shows an alternative semi-open cycle where the heat source is used to boil a liquid in a heat exchanger. This vapor is then compressed and supplies heat to the user either directly or indirectly. This latter variant is useful when the heat source is contaminated.

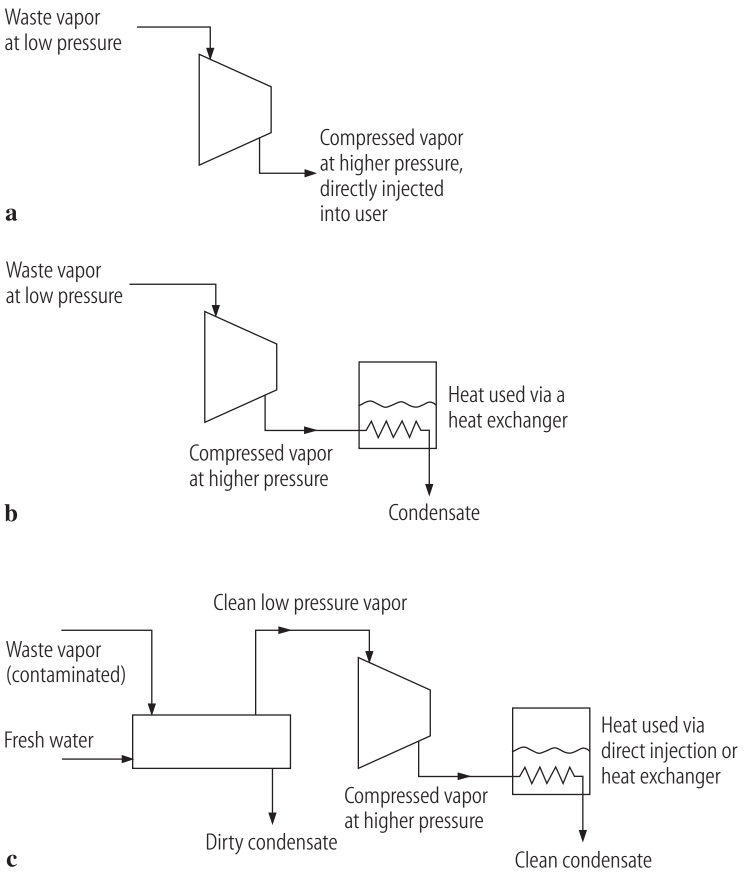

Fig. 9.7. **(a)** Open cycle heat pump. **(b)** Semi-open cycle heat pump. **(c)** Alternative semi-open cycle heat pump.

These systems have a typical *COP* between 10 and 30, much higher than closed cycle systems. Also, the investment costs are low compared to closed cycles. As many industrial heat distribution systems are low-pressure (2-6 bar) steam grids, the direct compression of steam has certain advantages, particularly in evaporation and distillation plants. Current MVR systems work with heat source temperatures from 70 to 80°C and deliver heat between 110 and 150°C, in some cases up to 200°C. Water is the most common working fluid (i.e. recompressed process vapor), although other process vapors are used, notably in the chemical industry.

9.8.3 Thermal vapor recompression (TVR) systems

Heat pumping is achieved with the aid of an ejector and high pressure vapor. It is therefore often simply called an ejector. A TVR heat pump is driven by heat, not mechanical energy, so there are no moving parts, which leads to low maintenance costs. A common area of application is given by evaporation units. The theoretical *COP* is modest, but not comparable with mechanically-driven compression heat pumps.

9.8.4 Absorption heat pumps

Absorption heat pumps are not widely used in industrial applications. Some have been realized to recover heat from refuse incineration plants, notably in Sweden and Denmark. Current systems with water/lithium bromide as working pair achieve an output temperature of 100°C and a temperature lift of 65°C. The *COP* typically ranges from 1.2 to 1.4. The new generation of advanced absorption heat pump systems will have higher output temperatures (up to 260°C) and higher temperature lifts.

9.8.5 Heat transformers

Heat transformers have the same main components and working principle as absorption heat pumps. With a heat transformer waste heat can be upgraded virtually without the use of external drive energy. Waste heat of a medium temperature is supplied to the evaporator and generator. Useful heat of a higher temperature is given off in the absorber. All current systems use water and lithium bromide as working pair. These heat transformers can achieve a delivery temperature up to 150°C, typically with a lift of 50°C. *COP*s under these conditions range from 0.45 to 0.48.

9.9 Energy-efficiency and environmental aspects

There is a worldwide growing understanding that energy production and use must be carried out in an environmentally acceptable manner and that the greenhouse effect accentuates the importance of the environmental dimension in energy policy and can, in the long term, be the main constraint of energy use. In Germany the space and process heat sector presently requires around 60% of the total annual final energy consumption, covered by nearly 80% with imported fossil fuel and is responsible for more than 50% of the total, energy-related CO_2-emissions. The cornerstones of integration of the environmental dimension into energy policy are the improvement of energy efficiency as well as the introduction of more efficient energy technologies, which will substantially contribute to a more rational use of energy, thereby reducing emissions, in particular CO_2 and other greenhouse gases. The heat pump, which can be used for heating and cooling buildings as well as in a variety of industrial heat-intensive processes, is believed to offer the best prospects for attaining these goals in a wide variety of appropriate applications.

As the vast majority of heat pumps in Europe operates on the electric driven vapor compression cycle for heating of residential and commercial buildings, two German studies have given a general indication of the potential of heat pumps for improved energy-efficiency and the reduction of emissions, in particular greenhouse gases, in the residential sector.

The first study [99Hei1] carried out a comprehensive collection of measured data of installed heat pumps between 1990 and 1998 (see Table 9.3). For their calculation in the second study, [99Hei2] took into account the whole chain from primary energy exploitation to useful energy. The calculation was based on the latest version of the computer model GEMIS [00OEK] as well as a modification of the model by Fichtner Development Engineering [98FIC] and the Information Centre on Heat Pumps and Refrigeration (IZW) [00Hei]. Figure 9.8 presents the atmospheric pollution of a monovalent operated heat pump driven by the German electricity mix opposed to oil- and gas-fired plants with regard to the whole chain from primary energy exploitation to useful heat. The comparison shows the advantage of the heat pump as opposed to an oil-fired plant.

The possible primary energy savings and reduction of greenhouse gas emissions are directly related to the type of electricity generation, the environmental characteristics of the energy sources and the performance of the complete heat pump plant. Table 9.4 presents the final energy characteristics of the primary energy consumption and CO_2-emissions of the three types of electricity used in the study,

- German public mix 1998 [99VDE],
- gas combined cycle plant (58% efficiency) and
- renewable energy (80% hydro- and 20% wind-energy),

as well as the data for natural gas and fuel oil including combustion with 100% efficiency.

Table 9.4. Final energy characteristics for heat pump plants (GEMIS 4.05 [00OEK]).

	Electricity			Natural gas	Fuel oil
	Public mix	Combined cycle	Renewable sources	incl. combustion (η = 100%)	
Primary Energy [kWh/kWh]	2.98	2.01	1.09	1.14	1.15
CO_2 [g/kWh]	646.8	393.2	38.5	220.5	314.2
CO_2-Equiv. [g/kWh]	687.8	421.2	40.1	243.9	306.6

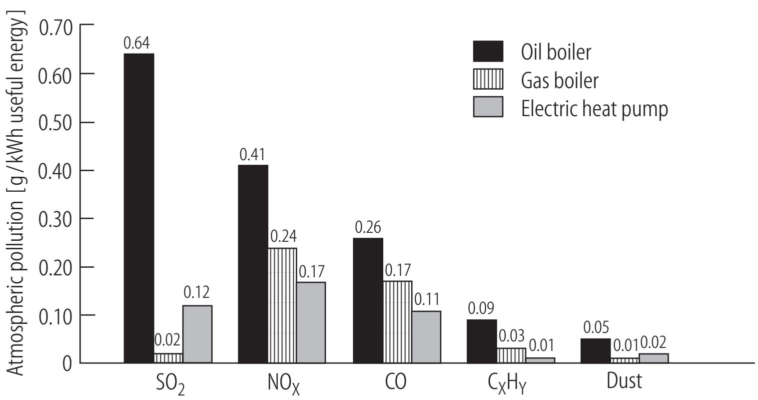

Fig. 9.8. Atmospheric pollution of heat pumps compared with oil- and gas-boilers [99Hei2].

Table 9.5. Seasonal performance factors of heat pumps used for GEMIS calculations [99Hei2].

	Heat distribution system	SPF
Installed heat pumps between 1990 and 1998		
Air/Water	35°C/28°C	3.3
	55°C/45°C	2.8
Ground/Water	35°C/28°C	3.8
	55°C/45°C	3.3
Water/Water	35°C/28°C	4.3
	55°C/45°C	3.8
Heat pumps Type 2000		
Air/Water	35°C/28°C	3.8
Ground/Water	35°C/28°C	4.3
Water/Water	35°C/28°C	5.0

Table 9.5 presents the seasonal performance factors of the different types and operation modes of the heat pumps analyzed in the study. Besides the series of heat pumps with measured SPFs, the SPFs of modern, future oriented heat pump systems – Type 2000 – were estimated and evaluated. For the corresponding condensing boiler plant a 100% efficiency was assumed, while for the conventional oil- and gas-boiler 85% efficiency was considered. For the gas-absorption heat pump a calculated annual *COP* of 1.35 was used, and a *COP* of 1.6 for the gas-motor driven compression heat pump.

The Figures 9.9-14 present the primary energy demand, CO_2-emissions and CO_2-equivalent (emissions of CO_2 and other greenhouse gases converted to the corresponding CO_2-emissions) of heat pumps driven with different types of electricity, with low and medium heating temperature and measured SPFs compared with conventional oil- and gas-boilers. Analyzing the results, only the worst case

- monovalent air/water heat pump system with
- medium 55/45°C supply/return temperature
- driven by electricity of the present public mix

has nearly identical results as the most environmentally sound conventional heating system, the gas-condensing boiler. All other heat pumps have much lower primary energy demand and higher reduction of greenhouse gas emissions. Whereas condensing boilers are not able to go beyond the theoretical limit of 111% efficiency, additional R&D will further improve the seasonal performance factor and therefore energy-efficiency and reduction of greenhouse gas emissions of heat pumps and the performance of electricity generation, e.g. gas combined cycle plants, cogeneration plants and fuel cells.

In accordance with the new German energy saving order (Energieeinsparverordnung) for buildings, Fig. 9.15-17 present the primary energy demand and CO_2-emissions of modern low temperature heating systems and the use of high performance heat pumps – Type 2000 – compared with modern conventional heating systems and gas-driven heat pumps. The latter have so far not significantly entered the market despite interesting R&D results, with the exception of the large market of gas-driven heating and cooling air-to-air heat pumps in Japan. The comparison again indicates the central role of electric driven heat pumps for the reduction of primary energy consumption and greenhouse gas emissions as an important contribution to the Kyoto protocol. It also shows the further possible reductions of the CO_2-emissions as a function of the heat pump performance – increasing SPF – and the type of electricity generation, e.g. high efficient gas combined cycle and renewable energy plants.

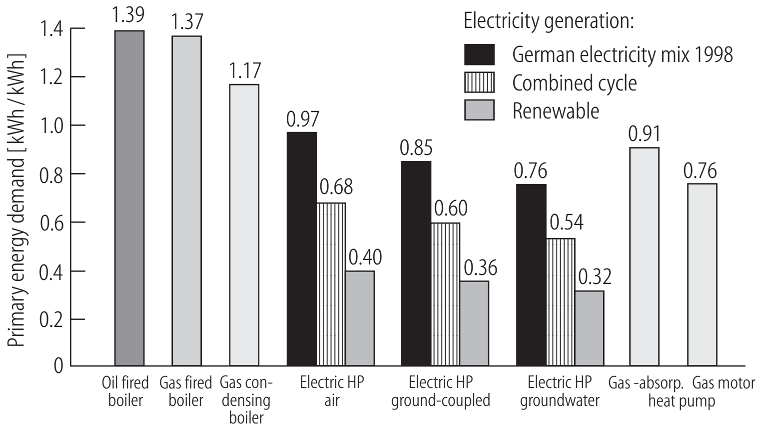

Fig. 9.9. Primary energy demand of installed heating systems with 35/28°C supply/return temperature.

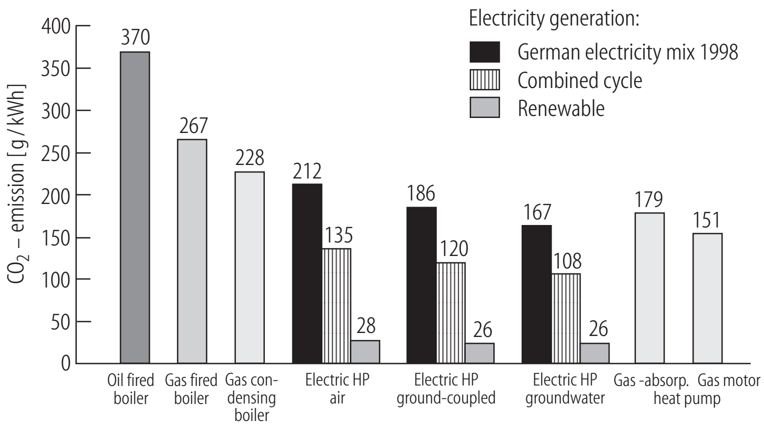

Fig. 9.10. CO_2-emissions of installed heating systems with 35/28°C supply/return temperature.

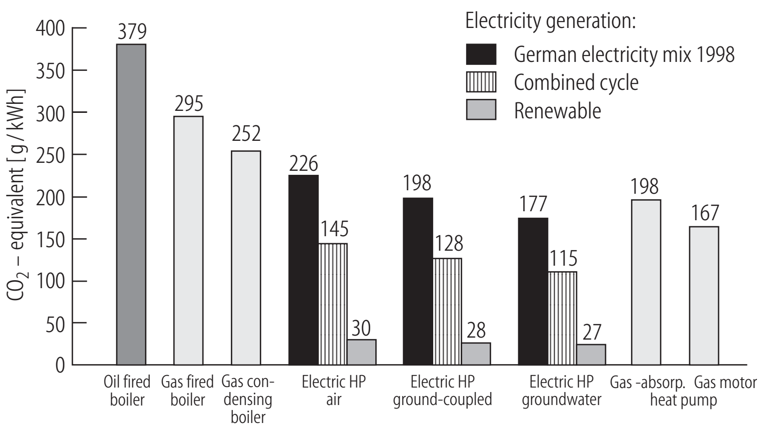

Fig. 9.11. CO_2-equivalent of installed heating systems with 35/28°C supply/return temperature.

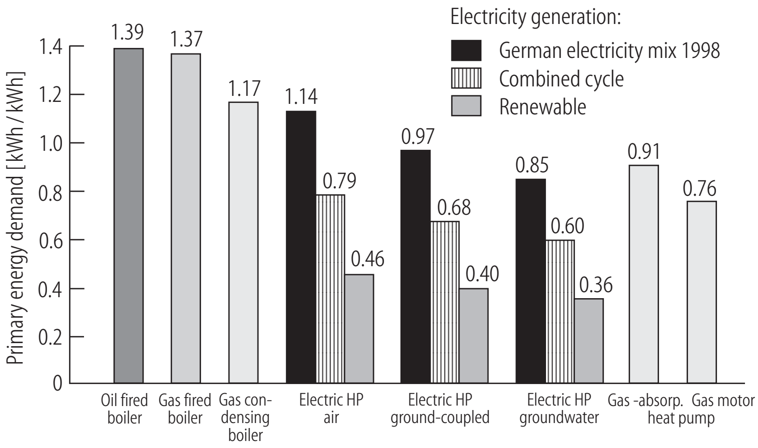

Fig. 9.12. Primary energy demand of installed heating systems with 55/45°C supply/return temperature.

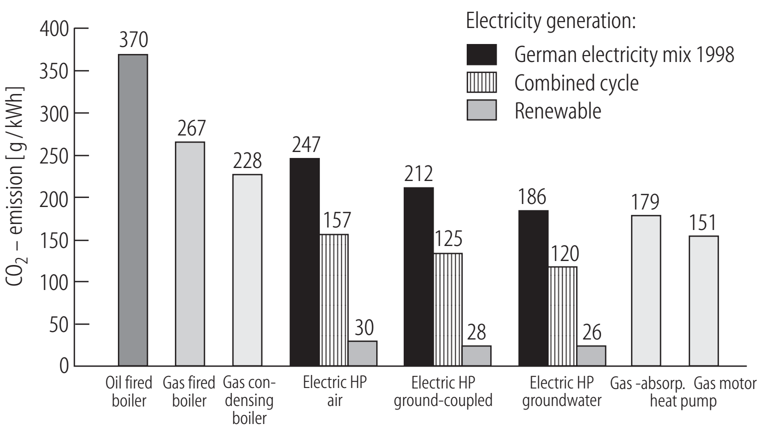

Fig. 9.13. CO_2-emissions of installed heating systems with 55/45°C supply/return temperature.

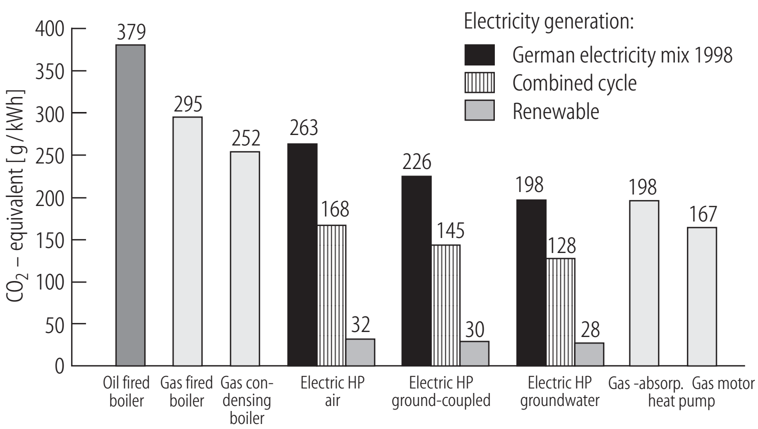

Fig. 9.14. CO_2-equivalent of installed heating systems with 55/45°C supply/return temperature.

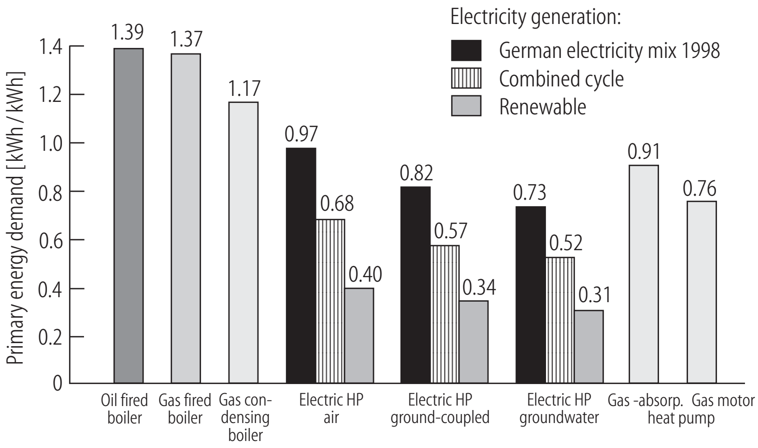

Fig. 9.15. Primary energy demand of "Type 2000" heating systems with 35/28°C supply/return temperature.

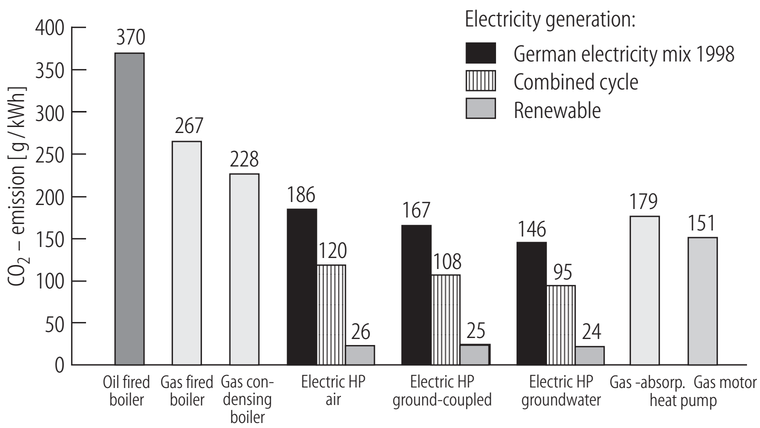

Fig. 9.16. CO_2-emissions of "Type 2000" heating systems with 35/28°C supply /return temperature.

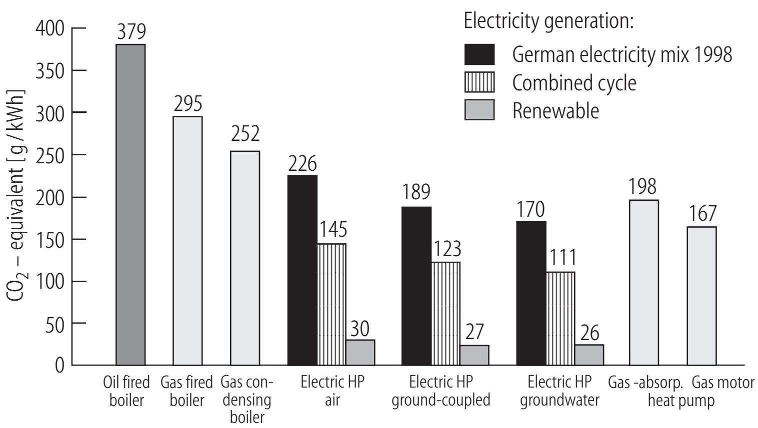

Fig. 9.17. CO_2-equivalent of "Type 2000" heating systems with 35/28°C supply /return temperature.

9.10 Economical aspects

The economy of a heat pump is a function of a number of different parameters like the *COP*, the annual plant utilization period, investment cost, fuel cost or electricity price, plant life time and others. For a given structure of electricity-, gas- and oil-prices a long annual operating time is important for the economy of a heat pump. In particular the coefficient of performance is directly related to the economy of a heat pump plant as modern high *COP* plants already compete with conventional plants. Due to the high technical standard of modern heat pumps, further economic viability can only be achieved by a reduction of the production and installation costs, e.g. increased production output, standardization of the plant components and the heat source or by suitable price relations of the energy sources. General statements of the economy are, however, not possible in the present stage and with the low market share. A realistic economic analysis can only compare heating costs of different systems under identical conditions. The VDI-direction 2067 presents a method for calculating the heating costs, divided in the cost categories

- energy costs, e.g. fuel, electricity, auxiliary systems,
- capital costs, e.g. investment and repair,
- operating costs, e.g. for maintenance, service and cleaning, and
- other costs, e.g. insurance, general costs.

Table 9.6. Cost comparison of residential heating plants [02Kru] (costs in €, number in brackets denotes the life time in [a]).

	Heat pump plant	Gas condensing plant	Oil fired plant
Investment cost	**18150**	**11710**	**14270**
Heat generator (20)	5420	3170	2556
Burner (12)	0	0	1500
Heat source (40)	4345	0	0
Oil tank (20)	0	0	970
Chimney (50)	0	511	1280
Gas supply (50)	0	1430	0
Planning, electro-installation (20)	1530	410	410
Annuity, interest rate [€/a]	1420	920	1132
Investment costs per installed heat power [€/kW]	2593	1673	2038
Annual operation cost [€/a]	**179**	**210**	**404**
Chimney sweep	0	12	45
Service and cleaning	0	51	148
Repair work	179	147	150
Insurance	0	0	61
Energy costs			
Final energy cost [€/kWh] (incl. tax)	0.094 [1])	0.051	0.043
Energy cost [€/a] [2])	263	567	566
Electricity cost for auxiliary plants	26	46	46
Energy cost (incl. auxiliary plants) [€/(kWh heat energy)]	0.026	0.056	0.056
Total cost [€/a]	**1888**	**1743**	**2148**
Total cost heat energy [€/kWh]	**0.17**	**0.16**	**0.19**

[1]) Renewable electricity (e.g. wind, hydro).
[2]) Annual heat demand: 11200 kWh. Electricity demand heat pump: 2800 kWh.
Gas demand gas condensing boiler: 22200 kWh. Oil demand oil fired boiler: 13175 kWh.

Table 9.6 presents as an example a cost comparison of a single-family house with a heat pump plant and alternatively a gas-condensing or oil-fired plant with the following conditions:

- Housing space: 150 m^2;
- Maximal heating power: 7 kW;
- Annual heat demand: 11200 kWh;
- Floor-heating system with 35°C supply temperature;
- Heat pump with measured SPF 4 (i.e. 3 parts ambient heat and 1 part electricity yield 4 parts of useful heat);
- Heat source: earth probe;
- Electricity of the heat pump from a renewable power plant (wind, hydro), i.e. environmentally sound but more expensive than conventional electricity;
- Gas-condensing plant: 100% efficiency;
- Oil-fired plant: 85% efficiency;

In general the higher investment costs of the heat pump plant are compensated by the lower operating and energy costs. As a result of the specific case of Table 9.6 the monovalent, earth-coupled heat pump plant is economically nearly equivalent to the gas condensing plant and better as the oil-fired plant. However, the still existing economic impediments are mainly related to the small market share of heat pumps and the related lack of standard solutions as well as the uncertain price development.

9.11 Conclusion

It has been shown that heat pumps offer the most efficient way to provide heating and cooling in many residential, commercial and industrial applications as they use ambient (= renewable) and waste heat. Through this unique ability heat pumps can radically improve the energy efficiency and environmental impact compared to any heating system that is driven by primary energy sources such as fuel or power. The following facts summarize the advantages of heat pumps presented above:

- Direct combustion to generate heat is never the most efficient use of fuel;
- Heat pumps are more efficient because they use renewable energy in the form of low-temperature heat;
- If the fuel used by conventional boilers were redirected to supply power for electric heat pumps, about 30-50% less primary fossil energy would be needed resulting in 35-60% less greenhouse gas emissions.

As heat pumps can meet space heating, hot water heating and cooling needs in all types of buildings as well as many industrial heating requirements, heat pumps have a large and worldwide potential.

Heating in buildings caused 30% and industrial activities caused 35% of the global CO_2-emissions of 23.5 billion metric tons in 2000. The potential CO_2-emissions reduction with heat pumps is calculated as follows:

- 7 billion tons of CO_2 come from heating buildings (30% of total);
- More than 1 billion tons can be saved by residential and commercial heat pumps, assuming that they can provide 30% of the heating of buildings with an emission reduction of 50%.

This is one of the largest reductions a single technology already available in the marketplace can offer. And with higher efficiency in power plants as well as for the heat pump itself, the future global emissions saving potential could even be higher by a factor two or three. In some regions of the world, heat pumps already play an important role in energy systems. But if this technology is to achieve more widespread use, a decisive effort is needed to stimulate heat pump markets and to further optimize the technology.

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