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REDUCING CO_2 EMISSIONS WITH HEAT PUMP SYSTEMS

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Abstract—Many countries aim to reduce their primary energy demand and CO_2 emissions. In the northern hemisphere, domestic heating and the supply of hot water are the cause of a great part of these emissions. This paper presents a discussion of the potential of various compression and absorption heat pump systems for reducing the CO_2 emissions. A comparison with cogeneration systems or furnaces is presented. Compared to a standard oil fired furnace, the CO_2 emission is only slightly reduced by using a state of the art compression heat pump and electricity from a coal fired power plant. Yet there is a way to reduce emissions significantly even when coal is used as fuel. The combination of coal fired cogeneration plants with compression heat pumps is a very efficient way to decrease the emission level for heating systems. For gas fired absorption heat pumps or engine driven heat pumps the CO_2 emission is smaller still. In the future, compression heat pumps can make contribution to CO_2 reduction either by using CO_2 free or CO_2 low electricity, or by improving the COP to values better than 4.0. Some results for different combined heating and refrigeration systems are presented. In this case, advanced absorption cycles or compression-absorption cycles can reduce the CO_2 emission by up to 75%, compared to presently used standard systems.

NOMENCLATURE

CC	combined cycle
CHP	combined heat and power
COP	coefficient of performance
e_{Fuel}	specific CO_2-emission factor [kg/kWh heating value] natural gas: 0.19 kg/kWh; oil: 0.29 kg/kWh; coal 0.33 kg/kWh; lignite 0.4 kg/kWh
PE	primary energy [kWh]
PER	primary energy ratio
H	useful heat for heating purposes, supplied to the end user [kWh]
P	electricity, supplied to the end user [kWh]
Q_{waste}	waste heat, emitted by a cooling tower for example
η	efficiency [kWh heat/kWh PE input] or [kWh power/kWh PE input]

INTRODUCTION

The rational use of energy and the structure of the energy supply systems play a major part in the issue of environmental protection. In particular, domestic heating and the supply of hot water and electricity were responsible for about 50% of the total CO_2 emission of the FRG in 1987 [1, 2]. Cogeneration of heat and power, of heat and refrigeration, or of power and refrigeration are key technologies for the reduction of energy consumption and CO_2 emissions [3]. The large potential of this technology can be obtained by minimizing the final waste heat in the energy conversion processes.

Another technology is the utilization of ambient heat by the use of heat pumps; this will be especially discussed in this paper. It is very important for the evaluation of heat pump systems to take the driving energy into account. For example, the potential for the reduction of CO_2 emission by absorption heat pumps depends strongly on whether the heat pump is driven directly by primary energy or by heat from a combined heat and power (CHP) system. This is valid as well for systems with electrically driven compression heat pumps: is the power produced in coal fired or gas fired power stations, or in CHP-stations? The influence of these different driving energies will be discussed in detail in this paper.

Unfortunately, rather contradictory methods can be found in the literature to compare and evaluate energy supply systems. This statement applies especially to systems which produce two or more products, for example heat and power or heat and refrigeration. In these cases, the primary energy demand of the supply systems and, also, the emissions cannot be charged on one single product without arbitrary and subjective assumptions; this is the reason for most of the controversial results. For example, in one method of evaluating the energy efficiency, the power and heat output are added and then divided by the primary energy. The higher this number is, the better the energetic efficiency of the system seems to be. However, such a number is not particularly useful: a simple furnace may be rated higher than a CHP plant.

In a very general way, we want to state that the attempt to reduce the respective ratios of the different energy flows in a CHP plant to one number for comparison must fail, as will be shown in the following. We consider a general thermodynamic system with one input flow of primary energy PE and three outputs, namely power P, useful heat H and waste heat Q_{waste}. The first law of thermodynamics states:

$$PE = P + H + Q_{waste}. \tag{1}$$

The second law yields a further relation between PE, P, H and Q_{waste}, which leads for example to an equation for the power P as a function of PE, H and Q_{waste}:

$$P = P(PE, H, Q_{waste}). \tag{2}$$

Often, the second law is written as an exergy relation, which allows one to add power and heat in terms of exergy, so that different output streams can be treated as one single number. However, to get this simplification we have to assume an ambient temperature T_0, which is not part of the thermodynamic system itself, but a subjective assumption depending on the location in which we operate the system. Without these assumptions we can only eliminate one variable by combining equation (1) and (2), for example Q_{waste}, and obtain a relationship, for instance for the primary energy PE as a function of power P and heat H:

$$PE = PE(P, H). \tag{3}$$

Therefore, the laws of thermodynamics can only provide a relationship for the total amount of primary energy, which is consumed to simultaneously produce a certain amount of heat and power. They do not give an individual relationship for PE(P) or PE(H). We can associate a certain amount of primary energy to the production of power and the rest to the production of heat only, if we make additional assumptions, like the ambient temperature in the exergy method. These assumptions are subjective and quite often guided by economic considerations [4].

For a strictly thermodynamic comparison we have to use a method which is based only on the relationship PE = PE(P, H).

In most cases this relationship can be linearized:

$$PE = aP + bH. \tag{4}$$

The factors a and b are efficiencies or combinations of efficiencies.

The simplest energy system for the supply with power and heat is a power station and a furnace. In this case, the factor a is the reciprocal efficiency of the power plant multiplied by the distribution efficiency. The factor b is the reciprocal boiler efficiency. In the case of an energy conversion chain, including an electrically driven heat pump, a is the same factor as above and b is the reciprocal coefficient of performance (COP) of the heat pump multiplied by the power plant and distribution efficiency. Many examples for the relation (4), particularly for CHP, can be found in the literature [5, 6, 7].

Starting from the equation (4) we get the CO_2 emission E_{CO_2}, simply by multiplying the primary energy demand with a specific CO_2 emission factor e_{Fuel}, which is defined as kg CO_2 per kWh of primary energy and depends on the used fuel (oil, coal, lignite, natural gas and so on):

$$E_{CO_2} = e_{Fuel} \cdot PE. \tag{5}$$

In this paper we will present results of such evaluations of the CO_2 emission. The relationship of equation (5) is shown in various plots, in order to be able to compare different energy supply systems, especially heat pump systems.

CO_2 EMISSION OF HEAT AND POWER SUPPLY SYSTEMS: STATE OF THE ART

In Fig. 1 different systems for the supply with electricity and heat are compared with regard to their CO_2 emission. The different lines in Fig. 1 represent standard systems which are already installed, or at least obtainable in the FRG. The plot shows the CO_2 emission in kg for the supply with one kWh power plus H kWh heat.

For the points on the ordinate no heat is produced. So, the intersect of the lines with the ordinate represents the amount of CO_2 emitted by pure power production. If additional heat is needed, the power station must be combined with heat supply systems.

In the case of a conventional coal fired power plant with an electrical efficiency of 0.38 and a distribution efficiency of 0.95, 0.9 kg CO_2 are emitted for each kWh of power delivered to the user. All systems in Fig. 1 use this power plant, so all curves intersect at the same point on the ordinate. The steepest line represents a system combining this coal power plant with an oil furnace for heating ($\eta_{boiler} = 0.7$). For example, for the supply with one kWh power from the power plant and two kWh heat from the furnace we get a CO_2 emission of 1.7 kg. When we change the fuel for the furnace from oil to natural gas, we get a 12%-reduction in CO_2 from 1.7 to 1.5 kg for this example. If we further improve the boiler efficiency up to 1.0, which is the value for modern condensing furnaces, we obtain a reduction of the CO_2 emissions of 24%.

The compression heat pump with a COP of 2.5, operated with electric power from the coal power station, shows only slightly less emission than the oil furnace and is even worse than standard gas furnaces and especially condensing gas furnaces.

Yet, all these systems do not reach the low emission of coal fired cogeneration plants with steam extraction at 90°C [8], see line "district heating" in Fig. 1; this line ends at the back pressure point. For a larger heating demand, only gas engine driven compression heat pumps, with a primary energy rate (PER) of 1.5, or direct gas fired absorption heat pumps (PER = 1.3) show a similarly high reduction in CO_2 emission.

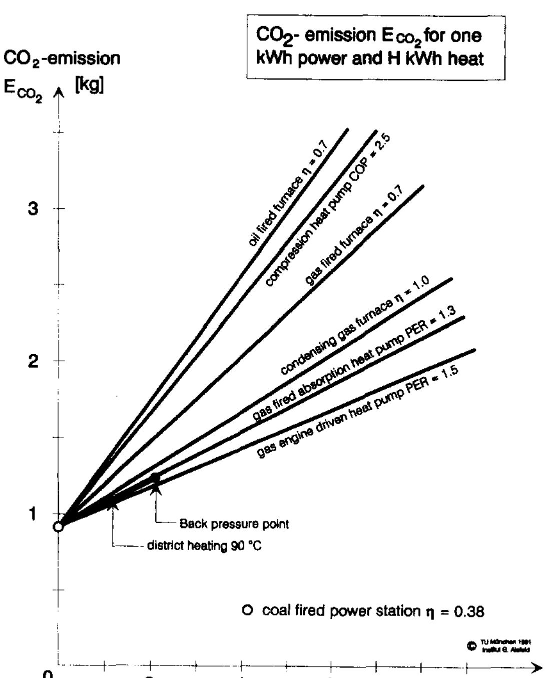

Fig. 1. CO_2 emission for systems with a coal fired power plant.

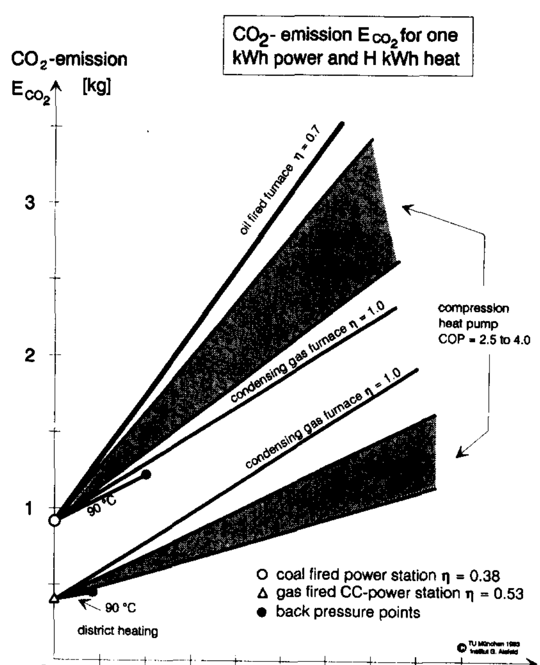

Fig. 2. CO_2 emission for systems with advanced compression heat pumps.

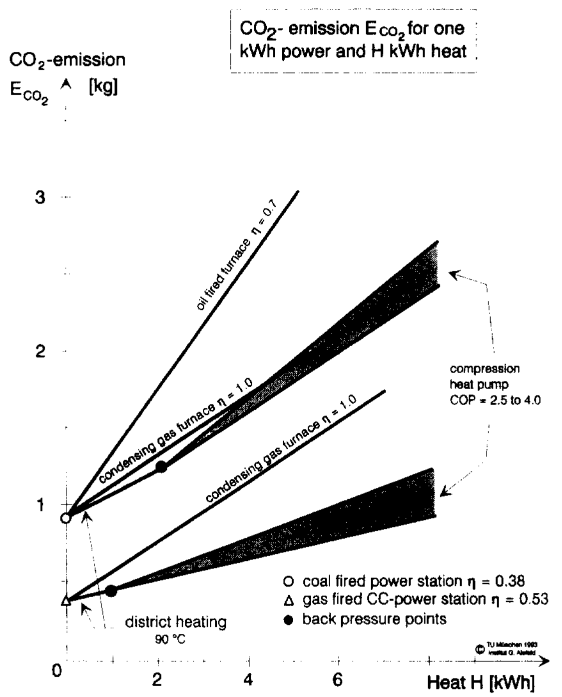

Fig. 3. CO_2 emission for advanced compression heat pumps combined with CHP-power plants.

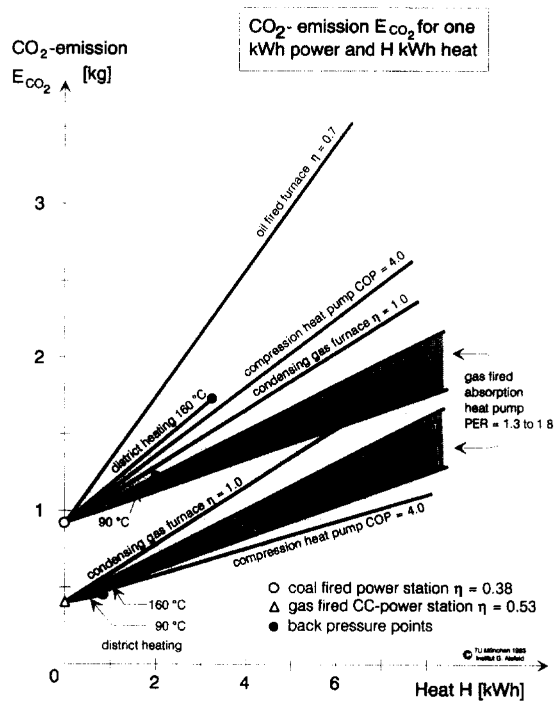

Fig. 4. CO_2 emission for systems with absorption heat pumps.

REDUCTION OF CO_2 EMISSIONS BY THE USE OF COMPRESSION HEAT PUMPS

The efficiencies assumed in Fig. 1 are not the best values for available compression heat pumps. Modern systems reach a COP of 3.0 and sometimes 4.0. Modern power stations with a combined gas- and steam turbine cycle (CC) reach electrical efficiencies up to 0.53. In Fig. 2 the CO_2 emissions are plotted for these systems. The shaded areas indicate the range of COPs of the advanced heat pumps.

As can be clearly seen, heat pumps driven by electricity from conventional coal power stations cannot reduce the CO_2 emission in comparison to condensing gas furnaces, in spite of the COP-improvement from 2.5 to 4.0. The situation changes appreciably with modern CC-power stations with an efficiency of 0.53. In such a system, even heat pumps with a rather poor COP of 2.5 have lower emission ratios than the best furnaces. Of course, much better results are achieved with COPs up to 4.0, which are also shown in Fig. 2.

There is another way to reduce the CO_2 emission by the use of compression heat pumps; namely, we get almost the same emission ratio for heat pump systems as for condensing gas furnaces, if the electricity for the heat pumps is produced by a CHP-plant, see Fig. 3.

The following operation mode has to be applied: the district heat is used from the CHP-plant, as long as the back pressure point of the plant is not yet reached. Only for a larger heating demand is a back up system needed for the heat supply. This is normally a peak load boiler, but in the case depicted in Fig. 3 an electrically driven compression heat pump powered by a CHP-plant is used. So, the total heat is supplied partly by the district heating system and partly by the heat pump. The shaded area again represents, like in Fig. 2, a range of the COP of the heat pumps between 2.5 and 4.0. It is no surprise that the lowest emission level is again reached by the use of power from gas fired CC-CHP-plants.

A first conclusion is as follows: electrically driven heat pumps contribute significantly to the reduction of CO_2 emissions only, if they are powered by modern high efficiency gas power stations or by CHP-plants, even if these are fired with coal.

THE REDUCTION OF CO_2 EMISSIONS BY THE USE OF ABSORPTION HEAT PUMPS

In Fig. 4 the potential of absorption heat pumps for a CO_2 reduction is shown, in comparison to furnaces, cogeneration and compression heat pumps. Advanced absorption heat pumps with a PER of 1.8, which are presently under development [5], are nearly as effective as the best CHP-systems. The following numbers refer to a ratio of 2:1 for heat to power demand. The system, consisting of a gas fired absorption heat pump with a PER of 1.3 in combination with a conventional coal power station, emits only 1.2 kg CO_2. This value is 30% below the value for the combination of a standard oil furnace and the same coal power station and still 6% lower than with a condensing gas furnace. With an improvement of the PER up to 1.8 we can raise this reduction to 35%.

Since we get almost the same results for gas engine driven heat pumps, these systems are not shown here. Their PER also ranges from 1.3 up to 1.8 or even 2.0 with a good heat source such as ground water.

As shown before in Fig. 2, compression heat pump systems, even with a COP of 4.0, have higher emission values as condensing gas furnaces, as long as they are driven by electricity from a coal fired power station. Only with CC-power stations and a COP greater than 3.6 they emit less CO_2 than advanced gas fired absorption systems.

Another way of integrating absorption heat pumps in heating and power supply systems is to use heat from cogeneration for the operation of the absorption systems. This results in lower CO_2 emissions, but due to the already low emission level of cogeneration systems without heat pumps, the further improvement is not very high.

CO_2 EMISSION OF COMBINED REFRIGERATION AND HEAT

As shown in the previous paragraphs, cogeneration is a very effective method for reducing the CO_2 emission. Another field for the use of cogeneration is the production of combined heat and refrigeration. In many commercial enterprises there exists a simultaneous demand for refrigeration/air conditioning and hot water. In Fig. 5 the CO_2 emission is compared for several systems producing air conditioning and hot water simultaneously.

Present technology is represented by the two solid lines: a compression refrigeration system

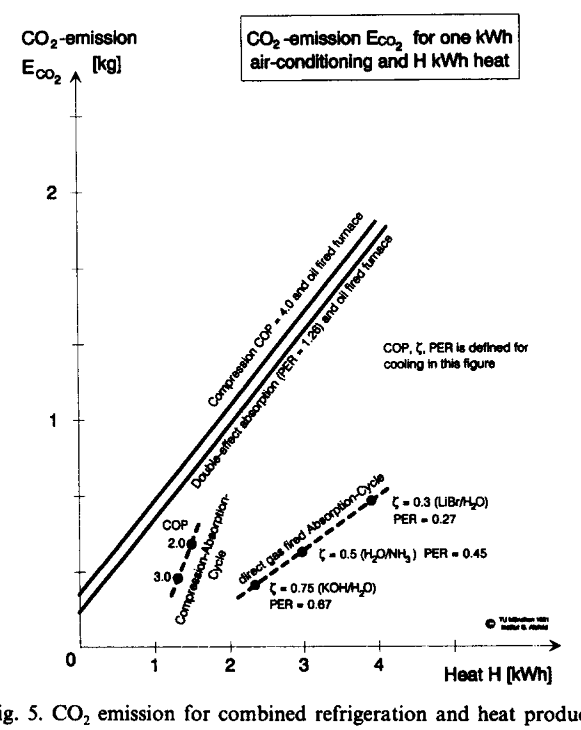

Fig. 5. CO_2 emission for combined refrigeration and heat production.

operated by coal generated electricity combined with a gas furnace, or a gas-fired double-effect absorption chiller combined with the same furnace. For comparison, the CO_2 emission of two advanced systems [5], presently under development, are shown as dashed lines. The first type of systems are compression–absorption cycles operated by electricity from coal. The second type of systems are gas fired absorption cycles with different working pairs and configurations.

There are some differences between these cycles in respect to the temperature of heat and cold produced. The absorption systems shown here can only be used for air conditioning and chilling with temperature levels above 0°C. The system with the working pair $LiBr/H_2O$ is a double lift cycle with a heat output at 80°C. The two other absorption heat pumps are single effect cycles with a heat output of about 50°C maximum. In contrast to these systems, the compression–absorption system can, however, be used for freezing down to −20°C with a simultaneous heat production at a temperature level of 80°C.

In particular, the absorption cycles yield very large reductions in the CO_2 emission. A drawback for a general application may be the intrinsic large ratios for heat to refrigeration, but this problem can be lessened by the installation of heat storage facilities.

CONCLUSIONS

- Compared to the standard heating system in the FRG, namely an oil-fired furnace with an overall efficiency of 0.7, one can reduce the primary energy demand and the CO_2 emission only slightly by using a compression heat pump (COP = 2.5) driven by electricity from a coal fired power plant.
- A condensing furnace, fired by natural gas, reaches a much lower CO_2 emission level.
- The only way to reduce the emissions to this low level, or even less, by still using coal as fuel for the power stations is the combination of CHP plants with compression heat pumps.
- With gas-fired absorption heat pumps or engine driven heat pumps one can get even less CO_2, compared to the above system.
- To obtain such a CO_2 emission level with a combination of coal fired power plants and compression heat pump systems, COPs of up to 6 have to be reached by new developments. Only with CO_2-free, or at least CO_2-poor, electricity from modern gas-fired combined cycle power plants, compression heat pumps are powerful CO_2 savers, even with presently available COPs from 2.5 to 3.0.
- Another promising sector for reducing the CO_2 emission is the wide field of air-conditioning and refrigeration. Here again the combination of heat production and refrigeration is the key. Advanced absorption cycles or compression-absorption cycles can reduce the CO_2 emission by up to 75% compared to systems which use compression chillers for the cooling and an oil-fired furnace for the heating demand.

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