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Comparison of natural gas driven heat pumps and electrically driven heat pumps with conventional systems for building heating purposes

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ABSTRACT

Electrically driven heat pumps achieve good efficiencies for space heating. If heat pumps are driven directly by a combustion engine instead of an electric motor, losses attributed to the production and transport of electricity are eliminated. Additionally, the use of the combustion engine's heat leads to a reduced temperature difference across the heat pump. This article presents annual efficiencies of these systems and compares internal combustion engine and electrically driven heat pumps in terms of primary energy consumption and CO_2 emissions. Because heat pump performance depends strongly on the heating circuit's flow temperature level, the comparison is performed for air-to-water and geothermal heat pump systems in two cases of maximum flow temperatures (40 °C and 60 °C). These temperature levels represent typical modern buildings with large heating surfaces and older buildings with high-temperature radiators, respectively. In addition to the different heat pump setups, conventional space heating systems are included in the comparison. The calculations show that natural gas-driven heat pumps achieve about the same efficiency and CO_2 emissions as electrically driven heat pumps powered with electricity from the most modern natural gas-fired combined cycle power plants. The efficiency of such systems is about twice that of conventional boiler technologies.

1. Introduction

For a fair energy comparison of different space heating solutions, a proper consideration of their annual efficiencies is essential. The annual efficiency includes all relevant influences, such as the building's heat and flow temperature demand over a year, the influence of the ambient temperature on the heating system's performance, its part load efficiency, and its standstill losses. A method to determine annual efficiencies for internal combustion engine driven heat pumps, which is based on available experimental data from electrically driven heat pumps has been proposed [1]. Using the same approach as that for standardized use for a moderate central European climate, annual efficiencies for electrically driven heat pumps can be calculated as well. As a result, a direct comparison with identical methods and boundary conditions of these two heat pump systems can be performed. Additionally, conventional boilers can be included in a comparison, whereas their standardized use [2] has to be considered to achieve direct comparability with heat pump systems. As an extreme solution, pure electrical heating can also be taken into account. For a comparison of the energetic efficiencies from primary- to end-energy, the energy rating of fuels using their net calorific value is a common practice and will be used across this article. For a fair comparison of CO_2 emissions, CO_2 intensities of upstream processes (especially for electricity production) have to be considered carefully.

Because heat pump performance is much more sensitive to the building's flow temperature demand and ambient conditions than conventional heating systems, these boundary conditions have to be integrated carefully.

2. Comparison of natural gas engine and electrically driven heat pumps

2.1. Efficiencies

Table 1 lists the annual efficiencies of natural gas engine and electrically driven heat pumps for standardized use in Zurich, Switzerland, as an example for a moderate central European climate. The values were determined using the methods described elsewhere [1] using measured data [3,4]. In addition to average system data, cases with best-in-class efficiencies were used to evaluate the sensitivity of the technical level on the results. The key parameters of these cases have been listed [1]. Two cases of building heating circuit dimensioning are included: one with a flow/backflow temperature of 40/30 °C and another with 60/50 °C in the heating system's design point. System dimensioning was assumed to be such that the heating systems are able to cover the

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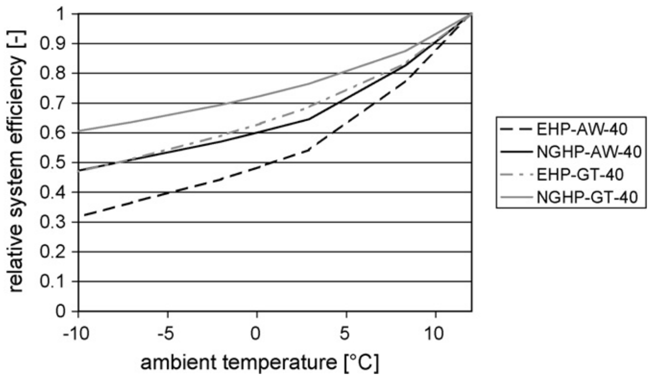

Fig. 1. Influence of the different system's efficiencies on the ambient temperature relative to their best efficiencies for the average quality cases operated with a 40/30 °C heating circuit.

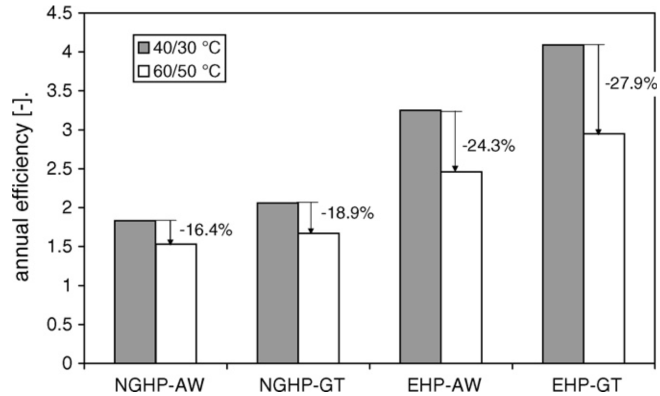

Fig. 2. Annual efficiencies of the average quality heat pumps studied for different nominal flow/return temperatures.

building's heating needs down to an ambient temperature of −10 °C when they are operated at full load, i.e., the system's design point is set at an ambient temperature of −10 °C. The 40/30 °C cases represent typical setups for buildings with large heating surfaces (floor heating, wall heating, or large-area radiators), whereas the 60/50 °C setups represent typical setups for older heating system layouts with conventional high-temperature radiators. Considering these two heating circuit setups, the influence of the building's heating surface layout on the building's energetic efficiency can be quantified for the different cases.

The efficiency values of the natural gas engine and the electrically driven heat pumps cannot be directly compared because natural gas engines use primary energy (natural gas), whereas the electric motors use electricity as an energy carrier that first has to be produced from primary energy elsewhere. Therefore, the inclusion of primary energy conversion efficiencies and CO_2 emissions produced will be discussed later in this article.

Geothermal systems offer better annual efficiencies than air-to-water systems. Because heat pumps operate using a thermodynamic cycle, this high sensitivity to the temperature levels of the heat source (ambient air or geothermal heat) and the heat sink (building's heating circuit) is evident from a physical point of view. Fig. 1 depicts this behaviour quantitatively. It shows the system efficiencies relative to their best-case efficiencies, which appear at the highest ambient temperatures considered (i.e., the assumed building's heating limit of 12 °C [1]). The relative representation was chosen in order to omit the inclusion of different input energy qualities.

Fig. 1 shows that natural gas engine-driven heat pumps (NGHP) feature lower efficiency decay compared with electrically driven systems (EHP) toward lower heat source temperatures. This is because the NGHP systems use the internal combustion engine's heat to reduce the temperature difference across the system. It was shown in Figure 8 of reference [1], that the engine heat accounts for 36% (NGHP-GT-40) or 46% (NGHP-AW-40) at an ambient temperature of −10 °C.

Not only do different temperature levels of the ambient heat influence the efficiencies of heat pumps but the temperature level demanded by the building's heating circuit is also influential, as Table 1 shows. Fig. 2 gives a more detailed view of the annual efficiency's sensitivity on the flow temperature. Although all system's annual efficiencies clearly depend on the flow temperature level, natural gas engine-driven systems show less efficiency degradation with increased flow temperature than electrically driven systems. However, it is always wise from an energetic point of view to lay out the heating circuits of buildings heated by heat pumps such that the flow temperature is as low as possible.

2.2. Comparison of component sizing

The energy fluxes at the system's design point determine the sizing of the components, such as the motor(s), compressor, and evaporator, because the heating circuit's heat demand is largest at the system's design point and the heat pump's efficiencies are lowest. For internal combustion engine-driven systems, the engine's heat, which is coupled to the heating circuit, also increases the heat pump's efficiency. Both effects lead to smaller heat pump components. Fig. 3 depicts the energy fluxes inside the systems at the design point of the studied natural gas engine-driven heat pumps compared to an electrically driven heat pump (EHP-GT-60). The values are depicted relative to the electrically driven heat pump's condenser power, which is equal to the total heating power in the electrical heat pump case. For the internal combustion engine-driven cases, engine heat from the exhaust gases and from engine cooling is added to the condenser's power.

Table 1
Annual efficiencies of natural gas engine and electrically driven heat pumps for average and maximum quality systems, standardized use in Zurich.

Heating system	Heating system's input energy	Ambient heat source	Abbreviation	Annual efficiency at flow/return temperature		System quality
				40/30 °C	60/50 °C	
Natural gas engine driven heat pump	Natural gas	Ambient air	NGHP-AW-40	1.83	–	Average
Natural gas engine driven heat pump	Natural gas	Ambient air	NGHP-AW-60	–	1.53	Average
Natural gas engine driven heat pump	Natural gas	Geothermal	NGHP-GT-40	2.06	–	Average
Natural gas engine driven heat pump	Natural gas	Geothermal	NGHP-GT-60	–	1.67	Average
Natural gas engine driven heat pump	Natural gas	Geothermal	NGHP-GTmax-40	2.69	–	Maximum
Electrically driven heat pump	Electricity	Ambient air	EHP-AW-40	3.25	–	Average
Electrically driven heat pump	Electricity	Ambient air	EHP-AW-60	–	2.46	Average
Electrically driven heat pump	Electricity	Geothermal	EHP-GT-40	4.09	–	Average
Electrically driven heat pump	Electricity	Geothermal	EHP-GT-60	–	2.95	Average
Electrically driven heat pump	Electricity	Geothermal	EHP-GTmax-40	5.2	–	Maximum