EFFICIENCY OF HEAT PUMP SYSTEMS UNDER REAL OPERATING CONDITIONS

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Abstract: Under the direction of the Fraunhofer ISE, two large field tests of newly installed heat pumps have been investigated during last three years. Nearly 200 of air-water, brine-water and water-water heat pump systems were examined under real operating conditions in single and multi-family dwellings. Values of volume flows, temperatures, heat quantity and electricity consumption were collected and sent daily to the Fraunhofer ISE headquarter where they underwent an automatic plausibility check. The results show that the ground source heat pumps are especially promising when it comes to reaching high efficiencies under real conditions. However, there is still a need for optimization in the integration of the unit in the supply system for the house and for the control strategies of the heat pump. Thus, a poorly integrated heat source or an incorrectly designed heat sink can significantly worsen the SPF of the heat pump.

Key Words: heat pumps, monitoring, efficiency, seasonal performance factor, SPF

1 INTRODUCTION

Heat pumps have been taking in Germany a vastly increasing share within the range of the heating- and water heating systems for new constructed buildings. Furthermore, the heat pump installations applied in renovations and the exchange of systems with fossil fuels are an issue of rising importance. The investors seem to be increasingly convinced of the advantages of heat pumps. However, the knowledge on the efficiency of the systems is necessary, in order to evaluate them under ecological, energetic and economic criteria. Therefore the Fraunhofer Institute for Solar Energy Systems ISE in Freiburg accomplished two large field test campaigns and examined scientifically almost 200 heat pump systems. The article describes the methodology, elaborates the results from both projects and provides recommendations for higher efficiency of heat pump systems. In addition, it descrybes a new monitoring project “HP Monitor” and the possibility to analyze several heat pump systems on-line.

2 DESCRIPTION OF THE PROJECTS

In the years 2006-2010 a large number of heat pump systems has been investigated under the direction of the Fraunhofer Institute for Solar Energy Systems ISE. At the course of these monitoring projects, values of volume flows, temperatures, heat quantity and electricity consumption have been collected and sent daily to the Fraunhofer ISE headquarter where they underwent an automatic plausibility check.

2.1 „Heat Pump Efficiency“ Project

In the field test “HP-Efficiency” approx. 110 heat pumps in new single family houses were measured. The Institute examined, in co-operation with seven heat pump manufacturers and two power suppliers EnBW and E.ON Energy, how efficiently electrical heat pumps can cover the heat requirement of new family-houses. The project received a funding of 50% from the Federal Ministry for Economics and Technology (funding characteristic 0327401A). The power suppliers and the manufacturers support the project as to the content and financially. [1]

2.2 Replacement of Central Oil-Boilers with “Heat Pumps in Existing Buildings”-Project

In another project, funded by the E.ON Energy AG, approx. 70 heat pumps in non-retrofitted buildings were examined. The heat pump units were installed in buildings of the E.ON customers, who had been previously using oil-fired boilers. The aim of the project was to examine the coverage of the heat supply of buildings by heat pump systems with high temperature heat distribution systems, typical in older buildings. Furthermore an ecological and economic comparison in relation to the use of an oil heating system has been made.

3 CHARACTERISTICS OF THE EXAMINED HEAT PUMP SYSTEMS AND BUILDINGS

Both projects aimed to consider a representative number of different types of heat sources. The objective was successfully achieved with the heat source ground and outside air. Systems with groundwater (water/water heat pumps) played a subordinate role. The heat distribution and heat delivery systems correspond to the specific requirements of newly built or old (un-retrofitted) buildings. The dominance of heat pumps with low temperature heat distribution system is clear in the “HP-Efficiency” project: more than 90% of the houses are equipped with floor heating. In older buildings, the tendency is reversed – more than 95 % of the plants use the radiators as heat distribution system. This requires inevitably higher inlet temperatures compared to systems with floor heating. The heated floor space of the examined objects accounts for both projects marginally more than 190 m².

The evaluated objects from the new building project have a middle specific heating energy consumption of approximately 70 kWh/m² and year. Thereby the bandwidth ranges from 30 to 150 kWh/m² and year. For 28 objects, a comparison between the calculated need and the measured consumption were accomplished. Within this comparison, in approximately 60% of the houses the difference between both values is smaller than 12%. By six plants a clearly higher need (on average over 40%) and with five plants a higher consumption (on average around 20%) was proven. The determined space heating demand of the old buildings for both space heating and domestic hot water, on basis of the oil consumption of the last 5 years, amounted to average value of 177 kWh/m² and year.

4 COMPUTATION OF SESONAL PERFORMANCE FACTOR (SPF)

The evaluation of the measuring data by the new building project (“HP-Efficiency”) covers three years, from July 2007 to June 2010 and two years by the old buildings project (“Heat Pumps in Existing Buildings”), from January 2008 until December 2009. The great majority of the examined heat pump units in both projects covered jointly space heating and domestic hot water. The efficiency characteristic values – seasonal performance factors SPF - were determined in both projects with the identical systematic.

4.1 System Boundaries and Characteristic Numbers

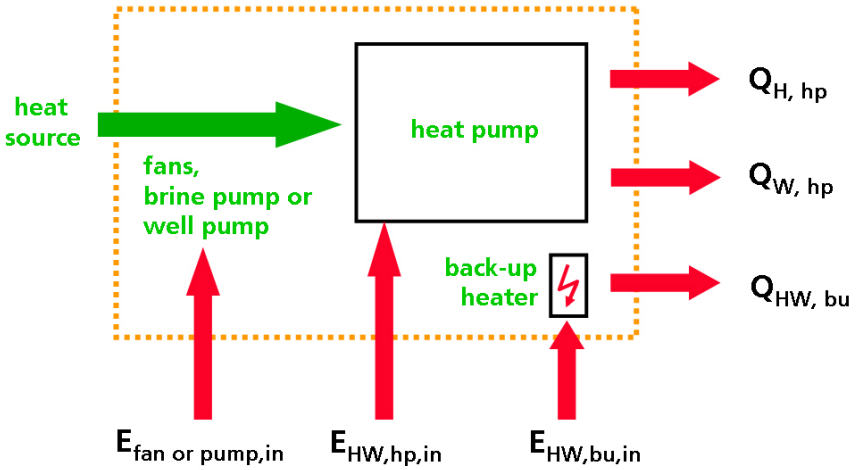


Figure 1: System boundary and characteristic numbers

Figure 1 shows the system boundary and characteristic numbers used for the assessment of the air-to-water, brine-to-water and water-to-water heat pump systems [2].
The following equation was used for the computation of the seasonal performance factors SPF, shown in the section 4.2:

$$SPF = \frac{Q_{H,hp} + Q_{W,hp} + Q_{HW,bu}}{E_{fan\ or\ pump,in} + E_{HW,hp,in} + E_{HW,bu,in}} \quad (1)$$

The SPF is the ratio of the heat energy produced by the heat pump and the back-up heater and the corresponding energy need of the heat pump, back-up heater and source fans in case of the A/W heat pump, brine pump in case of the B/W heat pump and well pump in case of W/W heat pump.

Nomenclature:

SPF	seasonal performance factor of the heat pump system (including electrical back-up heater)	[-]
SH	space heating	
DHW	domestic hot water	
$Q_{H,hp}$	produced heat energy of the heat pump in space heating operation	[kWh]
$Q_{W,hp}$	produced heat energy of the heat pump in domestic hot water operation	[kWh]
$Q_{HW,bu}$	produced heat energy of the electrical back-up heater for SH and DHW	[kWh]
$E_{fan\ or\ pump,in}$	electrical energy use of the HP source: fan (air-to-water HP), brine pump (ground source HP) or well pump (water-to-water HP) for SH and DHW	[kWh]
$E_{HW,hp,in}$	electrical energy use of the heat pump for SH and DHW	[kWh]
$E_{HW,bu,in}$	electrical energy use of the electrical back-up heater for SH and DHW	[kWh]

4.2 Analysis of The Measured Data

4.2.1 SPF of the ground source heat pumps

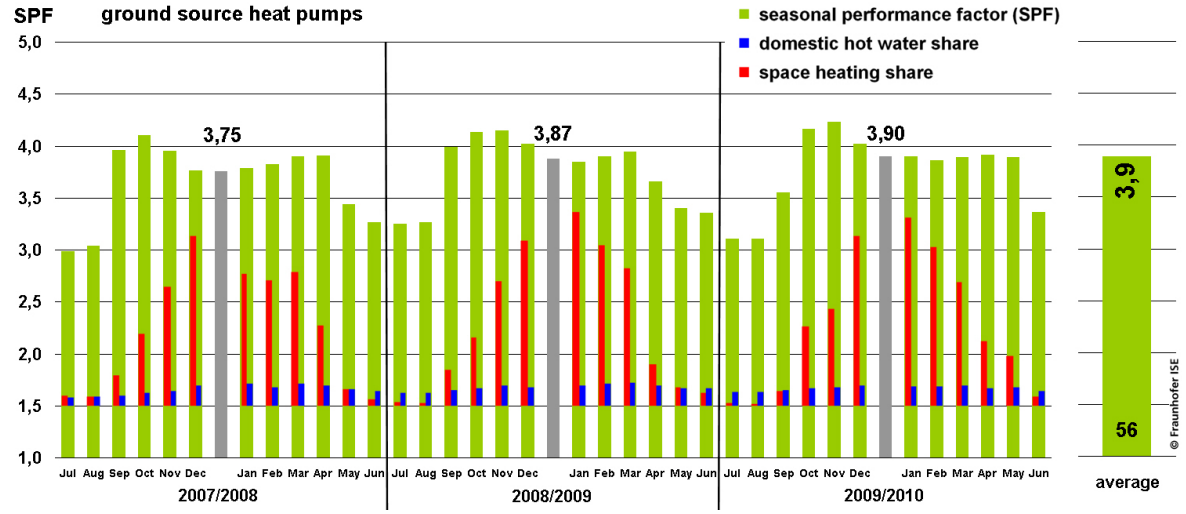


Figure 2: Monthly, annual and total seasonal performance factors of the ground coupled heat pump systems of the project "HP-Efficiency" (new buildings)

Figure 2 shows the monthly, annual as well as the average value of seasonal performance factors for the entire evaluation period of the ground heat pumps of the project "HP-Efficiency". In the period between July 2007 and June 2010, the average value of the SPF amounted to 3.9 [3]. The number of evaluated plants rose from ten units at the beginning of the evaluation period (July 2007) to 56 units in October 2010. The blue and red bars on the green bars represented monthly performance factors show the space heating (red) and domestic hot water (blue) energy in absolute values for orientation. The share of the domestic hot water energy amounted to 18% of entire energy produced by average heat pump unit. Figure 3 shows the range of the achieved efficiency from 3.0 to 5.2. The best unit differs from other units because the borehole is much deeper (300 m) than others and filled with water instead of brine [3].

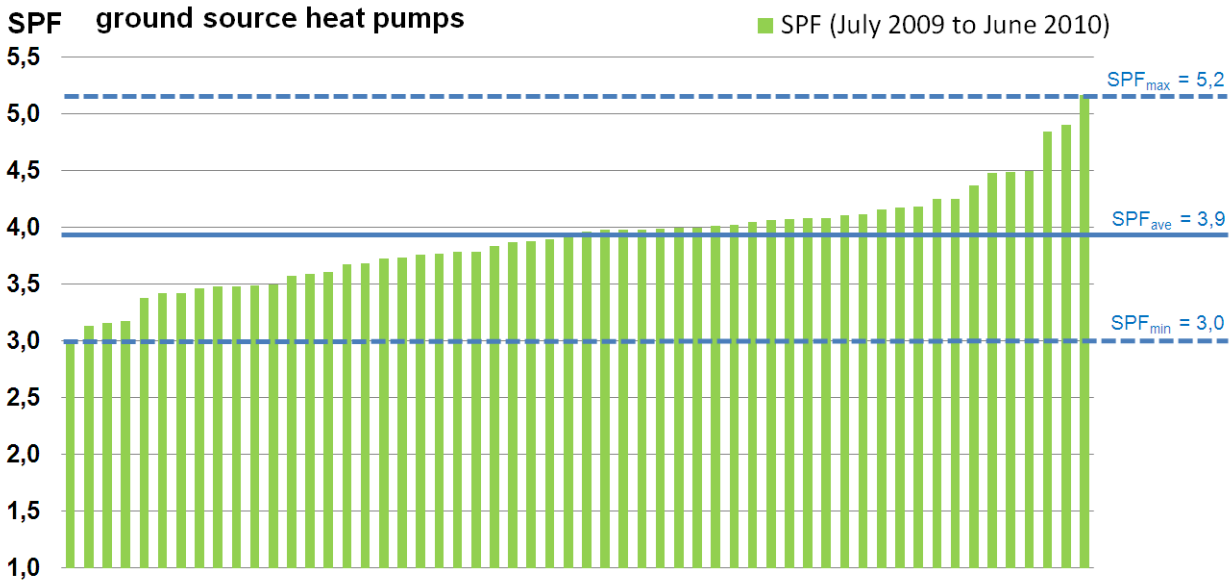


Figure 3: Range of the achieved efficiency of the ground coupled heat pump systems of the project "HP-Efficiency" (new buildings)

The loading of the domestic hot water storage takes place with an average temperature of 52 °C, the loading of the heating circle takes place in average at 36 °C. Accordingly clear differences show up by the SPF values between summer and winter months. The temperature delta between heat source and heat sink contributes to higher performance factors in the winter- and to lower performance factors in the summer months. Particularly high monthly SPF values appear in the autumn months. At the beginning of the heating season, the heat source ground exhibits relatively high temperatures with at the same time moderate space heating inlet temperatures. This is particularly observed for the units with ground collectors. The ground coupled heat pumps divide themselves in 27% ground collectors and in 73% boreholes.

In the second phase of the project in September 2008, installation of heat pump units was initiated. The consideration of the insights from the first phase positively affected the results (Figure 4). In particular, the installations of the heat pump systems were realized very carefully and the individual elements of the whole system were fitted more accurately. Furthermore, in some cases new generations of heat pumps were installed.

The heat pumps in the “Heat Pumps in Existing Buildings” project possess in total higher inlet temperatures in the heating circle. Inlet temperatures between 45°C and 55 °C were reached during winter months for most plants, for individual plants up to 65 °C. Domestic hot water temperature was provided throughout the year between 50 °C and 51 °C. The share of a domestic hot water energy amounted to 14% of entire energy produced by an average heat pump unit.

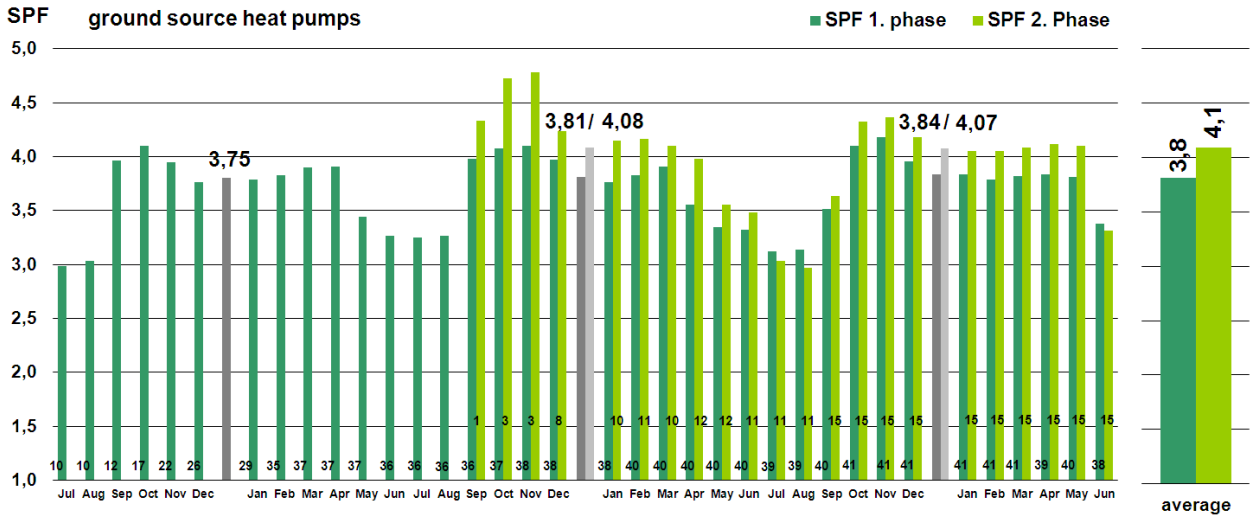


Figure 4: Monthly, annual and total seasonal performance factors of the ground coupled heat pump systems of the first and second phase of the project “HP-Efficiency” (new buildings)

Due to the higher temperature delta between the heat source and the heat sink and the higher absolute inlet temperatures in the heating circle in relation to the plants in the HP-Efficiency-project, average seasonal performance factor of whole investigation period reached the value of 3.3 (Figure 5) for the ground coupled water heat pumps. The trend of monthly seasonal performance factors is comparable with the pathway of the heat pumps in “HP-Efficiency“, although on a lower level. The differences between the summer and winter months in existing buildings are smaller then in new buildings.

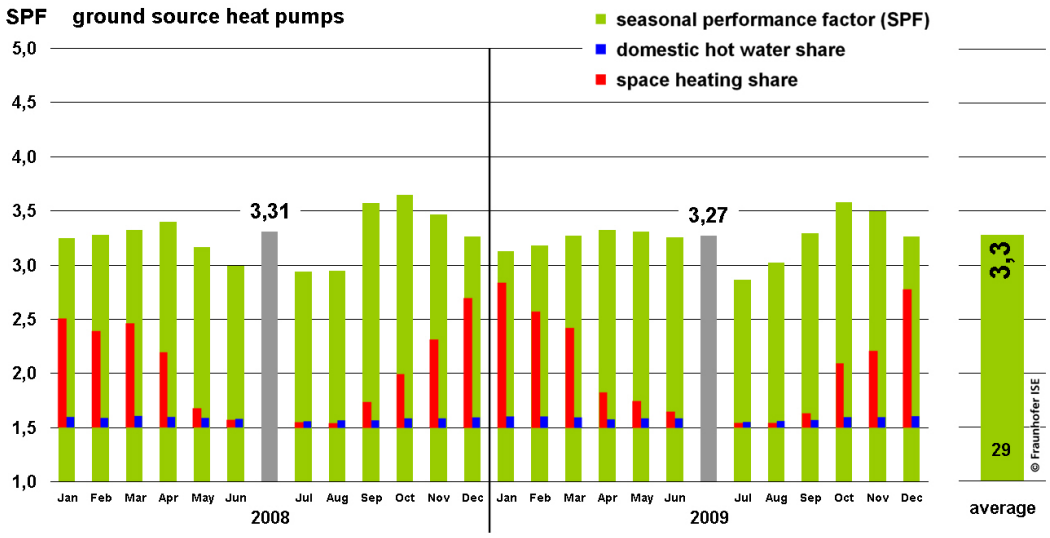


Figure 5: Monthly, annual and total seasonal performance factors of the ground coupled heat pump systems of the old buildings project

4.2.2 SPF of the air-to-water heat pumps

In case of outside air heat pump systems the trend of the monthly performance factors differs from the trend of ground coupled heat pumps. While for the last mentioned higher performance factors appear during the autumn/spring and winter months, air units show their weakness in winter due to the low air temperature. Similarly to the ground units, the high share of the domestic hot water in the summer months results in higher inlet temperatures on the sink side and reduces the positive influence of the higher heat source temperature. This fact negatively affects the performance factors.

Since the heat requirement of buildings is independent from the heat source, the trend of energy use in the course of the year, relatively as well as absolutely, behaves like those of the ground coupled heat pumps. Thus, the substantial weighting by the calculation of the performance factors for air heat pumps takes place also in winter months (negative for the heat pump), which is reflected in a average seasonal performance factor of 2,9 (Figure 6) for new buildings and 2,6 (Figure 7) for old buildings. The lowest monthly performance factors are to be observed in January 2009 and 2010. This correlates strongly with the lowest outside temperatures for these two months.

Altogether 18 air-to-water heat pumps were evaluated within the new buildings project and 35 within the existing buildings project. It must be taken into account that only as of the second heating season (2008/09) in the project “HP-Efficiency” the amount of heat pump units enabled statistically reliable evaluation.

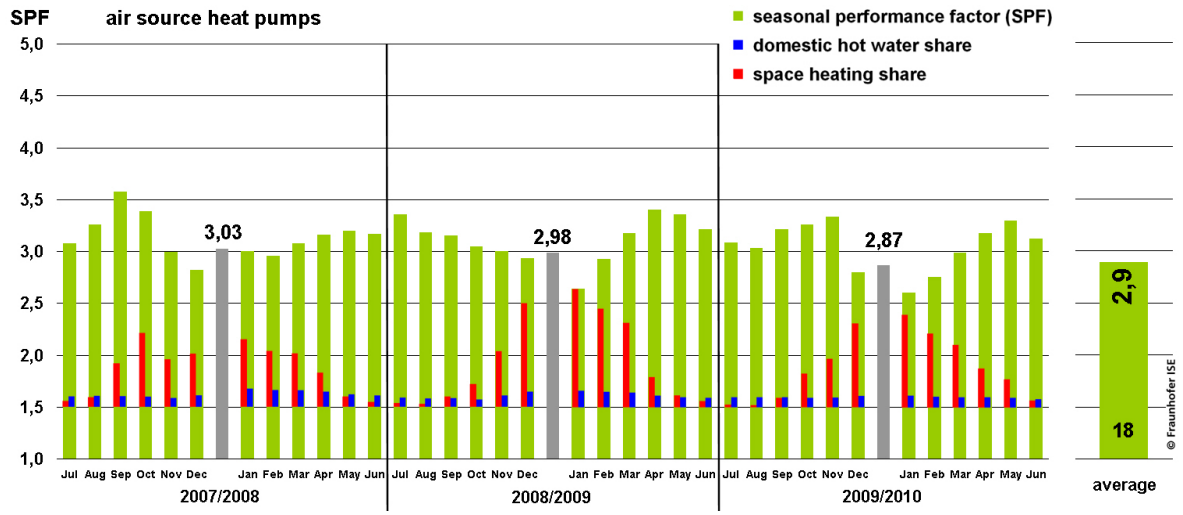


Figure 6: Monthly, annual and total seasonal performance factors of the air to water heat pump systems of the project "HP-Efficiency" (new buildings)

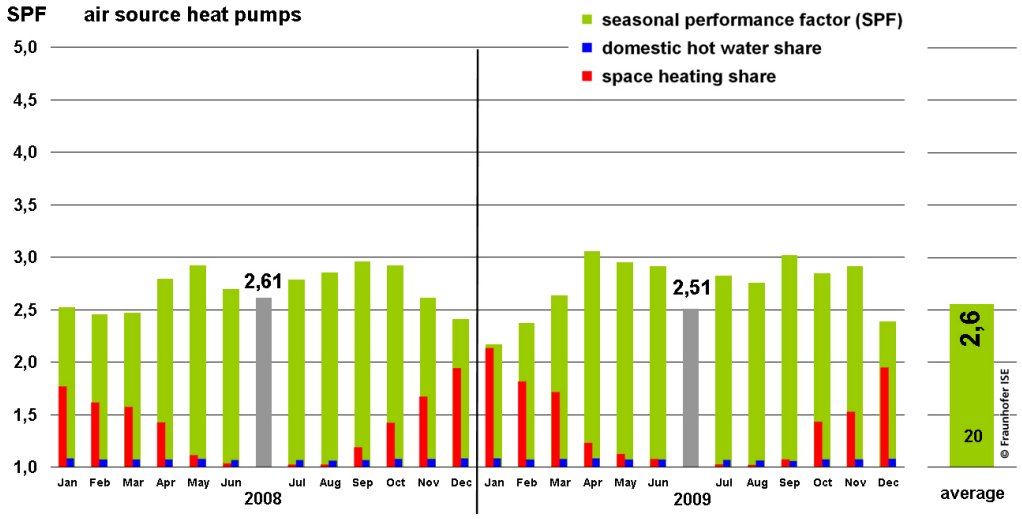


Figure 7: Monthly, annual and total seasonal performance factors of the air to water heat pump systems of the old buildings project

Figure 8 shows an overview of all calculated seasonal performance values for both projects.

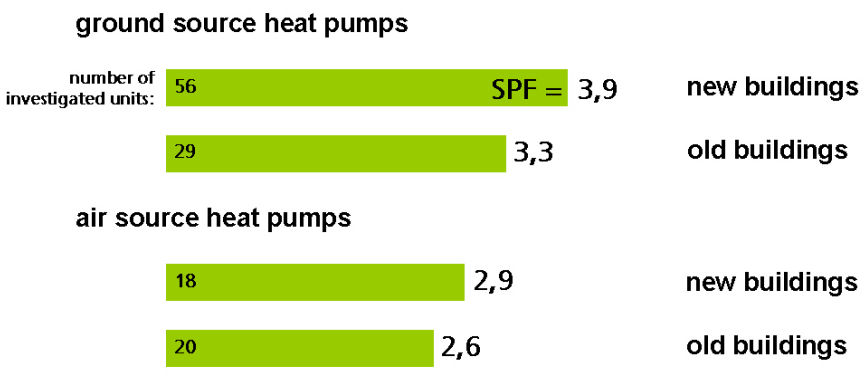


Figure 8: Overview of all calculated seasonal performance values for ground and air source heat pump units

5 ACTIVITY OF THE BACK-UP HEATER

The table 1 shows the share of the electrical energy use of the individual components for brine and air-to-water heat pump systems (project “HP-Efficiency”).

Table 1: The share of electrical energy use of the components by air to water and ground source heat pumps (project “HP-Efficiency”)

Components:	fans	brine pump	compressor	back-up heater
air to water HP	7%		89%	**4%**
brine to water HP		6%	92%	**2%**

The share of the heat source-lateral components (fans or brine pumps) is very similar in the case of both heat sources. The same is valid for the compressor and back-up heater. Fortunately, the share of the back-up heater is in each case on a very low level. In case of the ground coupled heat pumps, the back-up heater should only be used during malfunction of the heat pump or to support the drying process in the first period of operation of a house. The measuring data confirmed this strategy. Only for approx. 30% of the examined units, a significant activity of the back-up heater was determined. In most cases it concerned short term malfunctions of the heat pump.

The activity of the back-up heaters correlates only slightly with the outside temperatures by ground heat pumps. However by air heat pump this correlation is clearly apparent. For almost all examined air units the activity of the back-up heaters was determined during the coldest months. This confirms the consciously selected strategy for the heat source air and refers to an accurate dimensioning and a correct work of these heat pump units.

6 RECOMMENDATIONS FOR THE HIGH EFFICIENCY

Within the scope of both projects it was possible to investigate operation of heat pump systems under real conditions in new and older residential buildings. By the evaluation of the collected data, theoretical correlations were confirmed and new insight gained.

The plants in newly built houses show a higher efficiency - the floor heating requires lower temperatures than radiators. Therefore, it is important to aim for low temperatures also for older buildings. The installation of the floor heating is seldom an option, however the existing radiators can often be exchanged by better suitable models or their size can be increased.

During the investigations many errors considering the installation of the plants were determined. Following shortcomings are to be named - undersized heat sources for ground heat pumps, missing hydraulic alignment, incorrect loading strategy of the buffer storage (particularly by buffers for domestic hot water and space heating in one unit), wrong temperature spreading both for heat source and for the heat sink, not insulated piping, not cleaned air filters of air heat pumps, wrongly ceased control parameters. All of them can be corrected relatively simple, however unfortunately come up again and again. A careful and accurate installation is the best precondition for a good efficiency of the heat pump systems.

It is often aimed at reaching a high efficiency through particularly sophisticated and complicated systems; however studies do not confirm this approach. Simple and robust units usually work with the highest efficiency. Whenever choosing a combination of several components and for example combining two or more heat generator, one should particularly

pay attention to the correct installation and fluent co-operation of all components. Even the best components cannot work efficiently, if the whole system is not configured properly.

7 PROJECT “HP MONITOR” AND ON-LINE VISUALISATION OF THE HEAT PUMP SYSTEMS

In the context of the new project "HP Monitor" a further independent and high-quality measurement of approximately 100 heat pumps is being accomplished. With a systematic similar to the “HP-Efficiency“ project, the substantial values are measured and save in one minute interval. The main aim of the project is to determine the seasonal performance factors of heat pump systems and to illustrate their operational behavior. Heat pumps coming from twelve German and Austrian manufacturers are investigated within this project. It is supported by energy supplier EnBW Energie Baden Württemberg AG. Each unit is measured and analyzed during at least 30 months, whereby the consideration of at least two heating and summer periods is guaranteed.

On the project web page (http://wp-monitor.ise.fraunhofer.de, under „evaluation and measuring data“) the graphical, anonymous evaluation of several heat pump systems in various configuration are available for anyone interested. Apart from information about buildings and heat pump system, measuring data and results are visualized. The real and current measured values provide the opportunity to see the function mode of heat pumps under real conditions.

8 SUMMARY

The heat pump systems are capable to work with an efficiency which ensures ecological and economical advantages compared to systems based on fossil fuels. However, the high efficiency cannot be guaranteed automatically. During the accomplished field tests, both weak and very good installations had been noted.
There are clear aspects, which play an important role for the future efficiency already by the selection of the heat pump system. For example the heat source and the heat distribution system determine to a certain extent the efficiency which can be expected. The mentioned aspects are however not exclusively crucial. Whether the inhabitants are satisfied with their heat pump systems depends not just on the heat pump manufacturer, but primarily on the planning, the installer and finally on the inhabitants themselves. The formula for high seasonal performance factors seems to be quite simple - the best results has to be expected by simple and robust units which are correctly planed, installed and well suited to the building and to the heat source.

9 REFERENCES

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