THE OUTCOMES AND LESSONS LEARNED FROM THE WIDE-SCALE MONITORING CAMPAIGN OF HEAT PUMPS IN FAMILY DWELLINGS IN GERMANY

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Abstract: Since 2006 Fraunhofer ISE in Freiburg, Germany, has been investigating electric heat pumps in single-family dwellings. Within three projects nearly 250 air-to-water and brine-to-water heat pumps system have been investigated under real operating conditions in houses with various energetic standards (from low-energy to un-retrofitted stock buildings with high energy demand).

Key Words: heat pumps, efficiency, SPF, monitoring, field test

1 INTRODUCTION

The share of heating and domestic hot water production in residential buildings in Germany (representable for most European countries with high heating demand) constitutes in average more than 75% of overall energy consumption in residential buildings (Galvin 2010), (Graichen et al. 2012). Covering this demand in a possibly environmentally friendly way is thus key to fulfilling the climatic goals on the national and international level. Heat pumps is a technology which can meet this challenge (Hepbasli et al. 2009). Furthermore, the higher its efficiency, the better can it be achieved. It is thus crucial to have reliable data assessing the efficiency of heat pumps units under real operating conditions and to draw conclusions how to ensure the best possible efficiency of the systems.

2 CHARACTERISTIC OF THE PROJECTS

Figure 1 shows the names of the performed projects with the number of investigated units in each project.

The project "Heat Pumps in Existing Buildings" includes heat pumps in older, un-retrofitted buildings. All other projects have been performed predominantly in newly built single-family dwellings. The average heated area of the buildings in all projects is similar and amounts to approximately 190 m^2 (2045 ft^2). The average heat demand for older buildings amounts to 120 $kWh/(m^2a)$, and for newly built dwellings - 70 $kWh/(m^2a)$.

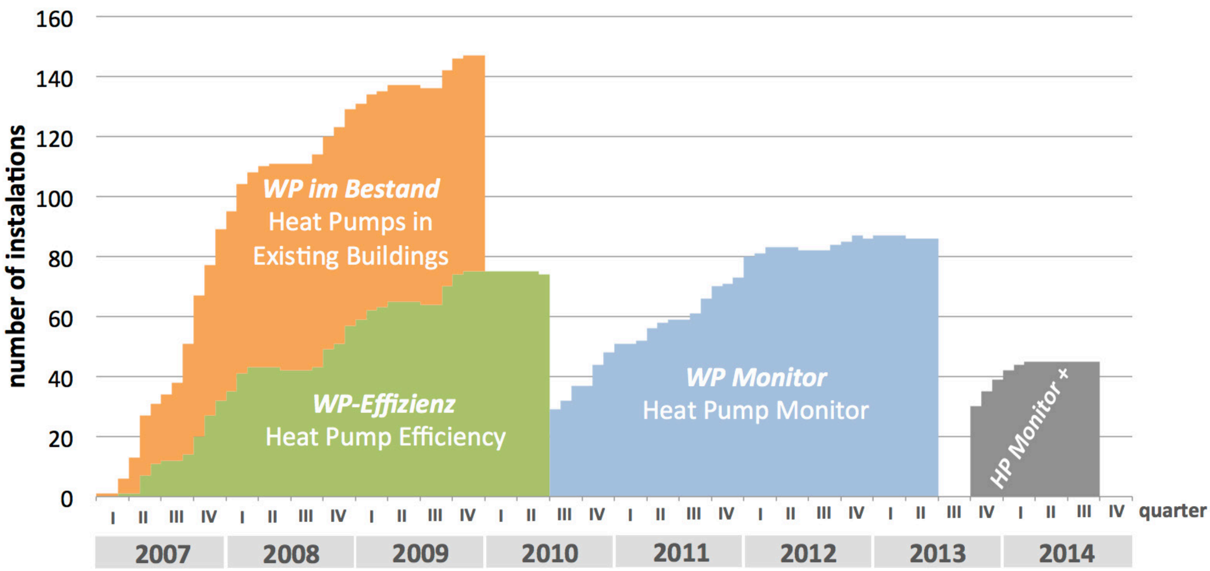

Figure 1: Performed projects with the number of investigated

Each project has been different financing and also the projects partner varied. At the same time, all projects have been performed in a very similar way as to the methodology and measurement equipment used. More information about each project could be find in (Miara et al. 2011).

2 CHARACTERISTICS OF HEAT SOURCES OF INVESTIGATED HEAT PUMPS UNITS

Figure 2 shows the division of heat sources of the analysed heat pumps for the individual projects.

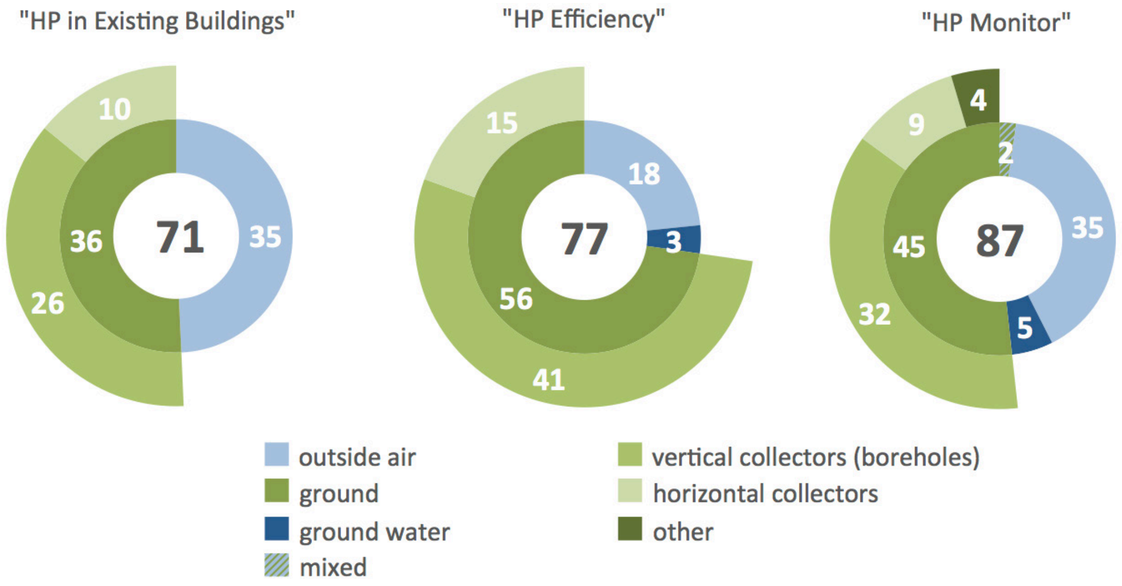

Figure 2: Heat sources of the heat pump systems

In the project "HP in Existing Buildings" 71 units have been analysed. The number of the ground and of the outside air heat pumps examined was similar. Among ground heat pumps the units with boreholes (26) outnumbered those with horizontal collectors (10). In the second project ("HP Efficiency"), 77 units were examined. Most of them were ground heat pumps (56); among them 41 units with boreholes and 15 with horizontal collectors. Air heat pumps constituted 23% (18 units). Additionally, a small number of ground water heat pumps was investigated. The project "HP Monitor" was characterized by the greatest variety of heat sources. In addition to air and ground heat pumps, a small number of mixed and combined heat sources has been included.

Information concerning the buildings and the heat distribution systems, as well as buffer tanks is available in (Miara 2009).

3 OUTCOMES OF THE SEASONAL PERFORMANCE FACTORS (SPF)

3.1 System boundaries

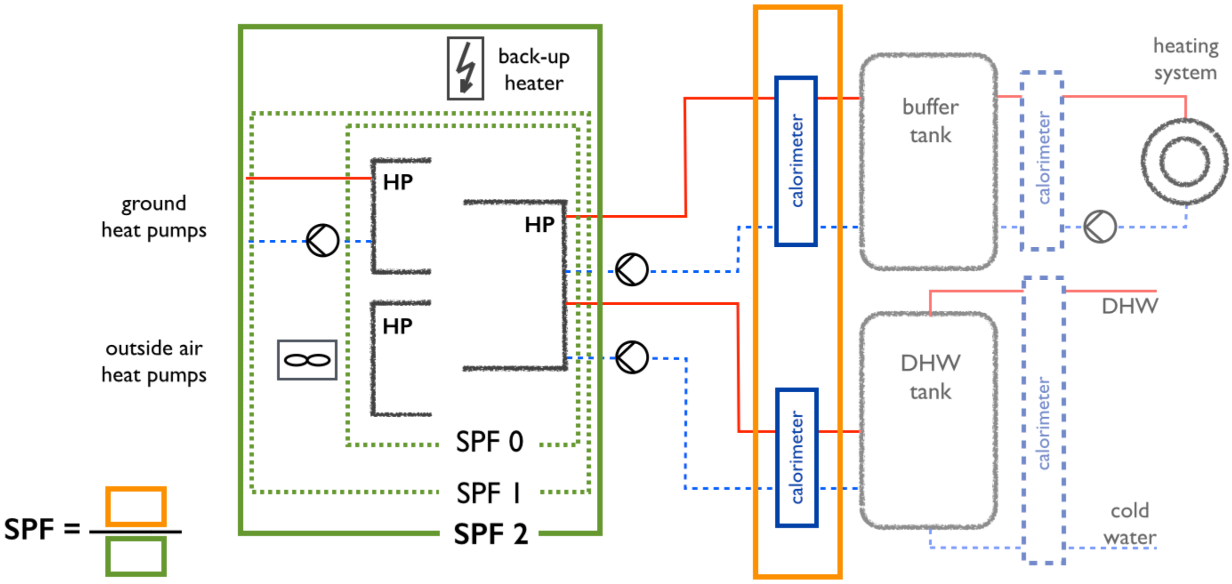

Figure 3: Heat pump installation and the system boundaries for calculation of SPF values

Figure 3 shows the scheme of a typical heat pump installation and illustrates the system boundaries. There are various possibilities to calculate the efficiency of a heat pump system. The outcomes of efficiency calculations presented in sections 3.3 and 3.4 were based on the boundary SPF 2, unless specified otherwise. The same calculation boundary was suggested as a main boundary for presenting the efficiency outcomes of heat pump systems in the European project SEPEMO-BUILD (Zottl and Nordman 2012).

The following equation was used for the computation of the seasonal performance factors SPF (SPF 2):

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

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]

3.2 Averages values of the SPF

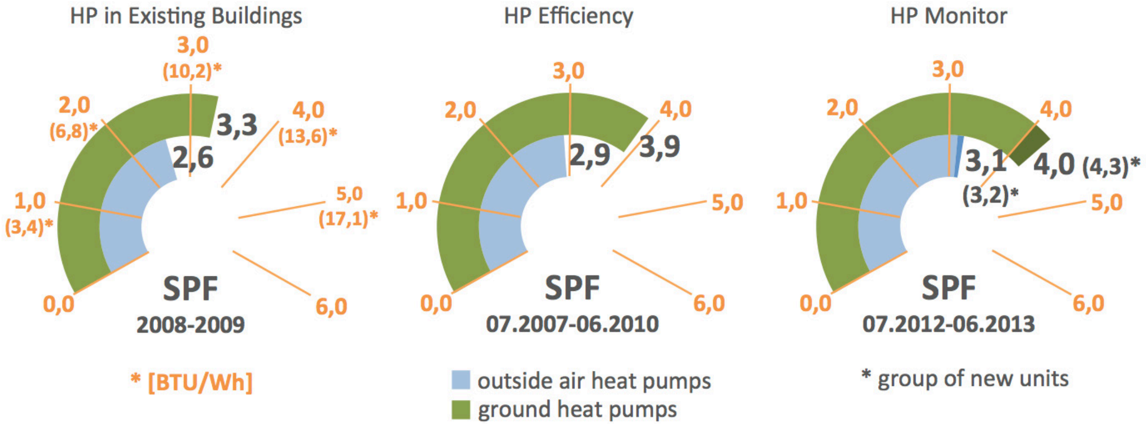

Figure 4: Averages values of SPF values

Figure 4 shows average values of SPF values among individual projects, as well as the individual heat sources. The comparison takes into account outside air heat pumps and ground coupled heat pumps. Ground water heat pumps were omitted due to a little number of the examined installations. Calculation periods differ and are indicated for each project.

The differences in the average SPF values depend on a type of a heat source, type of a building and the period of installation (indicating advancement of technology). The difference between outside air heat pumps and ground heat pumps is evident to the benefit of ground heat pumps. The ground as a heat source is more beneficial from the point of view of its temperature in coldest periods with the most demand for heating.

Another important difference was noted between older and newer buildings. It results mainly from a type of the used heat distribution system. Under-floor systems, mostly used in newer buildings, enable lower supply temperatures compared to systems based on radiators in older buildings. Lower supply temperatures contribute significantly to higher efficiency of heat pumps.

In the framework of the “HP Monitor” project, a group of newly installed units was investigated separately (on the graph shown with the symbol * in black). The outcomes from this group indicate the improvement in the heat pump efficiency resulting from technology development in the recent years.

3.3 Ranges of the SPF

Figure 5 shows the range of the SPF values for each project and heat source.

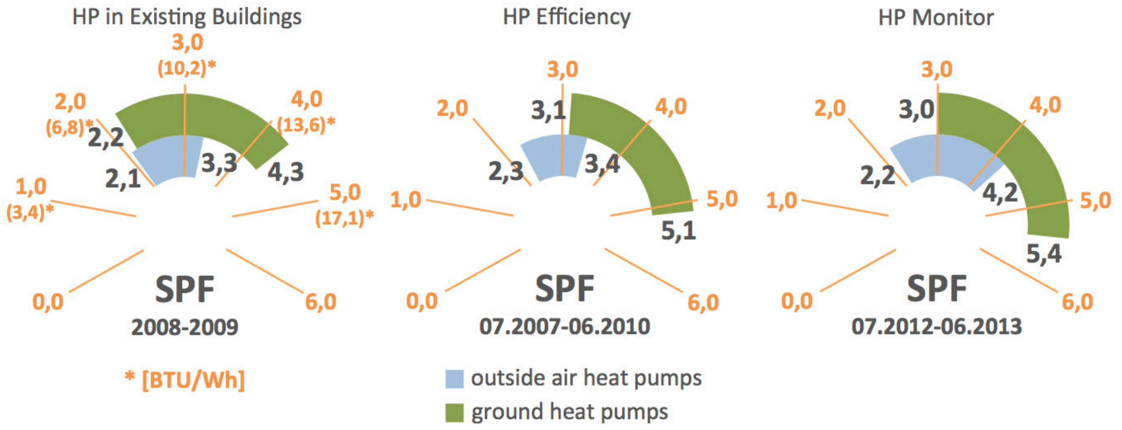

Figure 5: Range of SPF values of individual units

The results of all projects indicate smaller range of outcomes for individual units with outside air heat pumps, compared with ground heat pumps. The wide range of SPF achieved by ground heat pumps (at least 2,0 points) indicates a high potential of efficient functioning of ground heat pumps. On the other hand, it shows that the choice of a heat source seems not to automatically guarantee a high efficiency. Errors in designing, installation and/or running process, result in decrease of potential efficiency and diminish economical and ecological benefits of theoretically more efficient, but at the same time more expensive, heat source.

3.4 SPF values for individual units

Figure 6 shows individual outcomes from 47 ground source heat pump installation from the project “HP Monitor”. The number of the months in which measure data have been analyzed is indicated in the lower part of the bars showing the SPF value.

Most of the installations (light green) were taken over from the project “HP Efficiency” and analyzed in the framework of “HP Monitor” in parallel with the new units (dark green).

Nine installations used horizontal collectors and the remaining units were equipped in boreholes (1 to 4 per heat pump installation). Among the boreholes units, one consists of a 300 m borehole filled with water instead of brine together with another filled with CO_2. Further two installations were based on the direct evaporation principle.

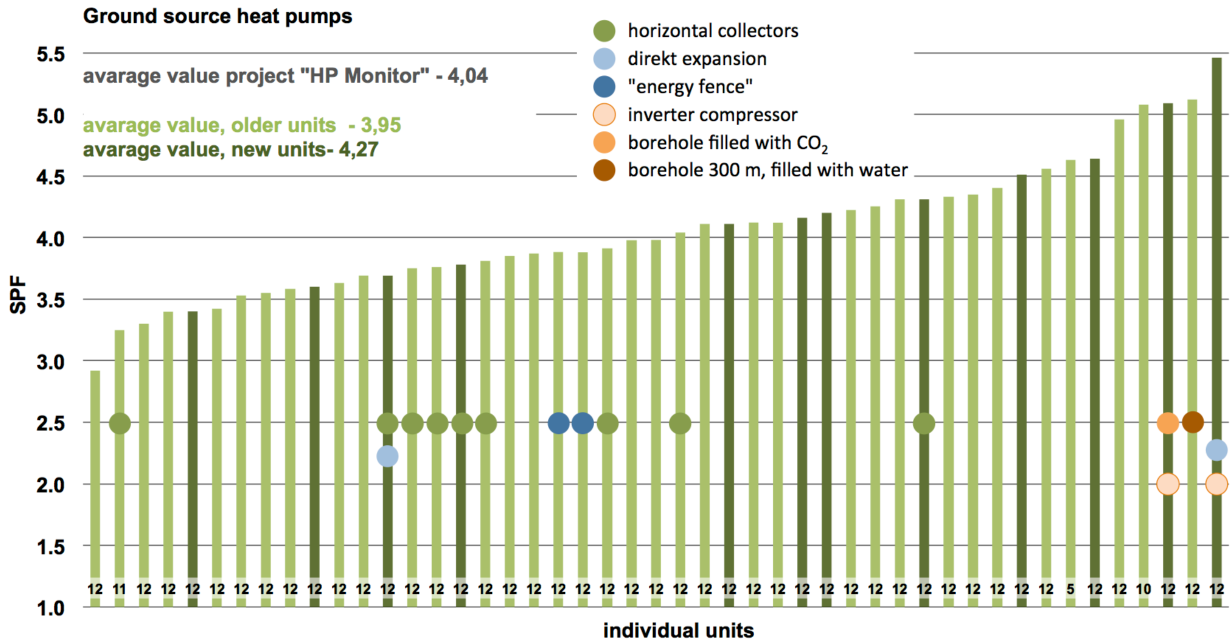

Figure 6: Individual SPF values of the ground HP with indication of the technology

Another form of a non-standard installation was a so-called “energy-fence”. The pipes filled with brine form a fence sank in 1/3 in the ground. This solution uses both outside air and ground as a heat source.

Two installations used relatively rare for ground source heat pumps inverter compressors.

3.5 SPF values for different calculation boundaries

Figure 7 shows outcomes from various calculation boundaries of the SPF values for ground source heat pumps.

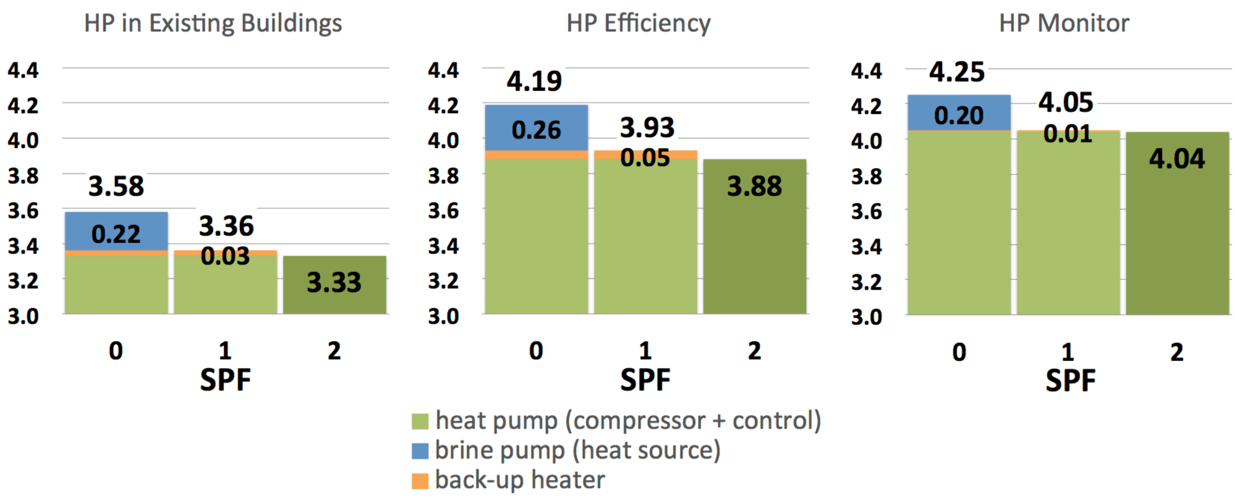

Figure 7: SPF values for various calculation boundaries

Calculation of SPF 0 takes into account only the electricity consumption of a compressor and of a control system. Calculation of SPF 1 includes the consumption of a brine pump and the calculation of SPF 2 – of a back-up heater. On the graph the blue and orange colours indicate the efficiency savings achieved by the absence of the mentioned components. The average share of brine pumps is equal to 0.22, 0.26 and 0.20, respectively. The difference in the share between projects “HP Efficiency” and “HP Monitor” results from the increased use of high efficiency brine circulation pumps in recent years. For example, in the project “HP Monitor” brine pumps’ share in the overall electricity consumption equals 4%. However, the range of the share for individual units amounted from 2% to 11%. It indicates the importance of use of energy-saving circulation pumps.

The values of SPF 1 and SPF 2 differ only insignificantly, showing that the electric back-up heaters do not cause a considerable consumption of electric energy, irrespectively of the type of a building. The same tendency was observed for outside air heat pumps with electric back-up heaters operating only during in the periods of extremely low temperatures, and even then not in all units.

4 Changes of the ground temperatures in borehole installations

Figure 8 shows the curves of the average daily brine inlet and outlet temperatures of 21 heat pump systems with boreholes. The number of boreholes per installation varied from 1 to 3. Furthermore, the average daily outside air temperature has been indicated. The average brine temperatures could be calculated solely in the operation periods of a heat pump.

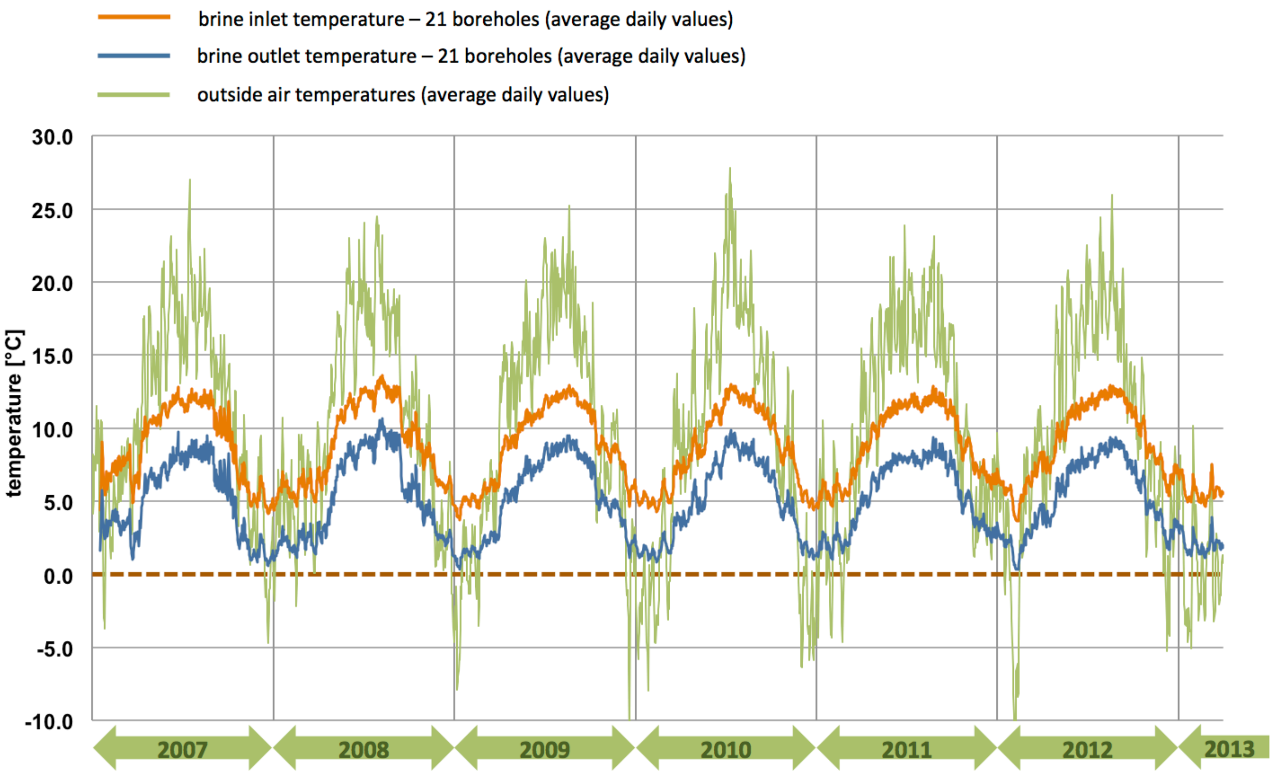

Figure 8: Brine temperatures of 21 heat pump units with borehole

The average brine temperature of all 21 installations has never reached 0 °C in the period of more than six years. The average brine inlet temperature was below 5 °C for a few days only during this period. It shows that the ground around the boreholes never froze, although it cannot be categorically excluded for individual installations.

During the investigated period no dropping of the ground temperature has been noted. It was observed that the full regeneration of the ground occurred both after short periods with extreme cold (February 2012), as well as after prolonged periods of relatively low temperatures (Winter 2010/2011). The phenomenon of dropping of the ground temperature caused by a borehole installation, widely quoted in the literature, could thus not be confirmed. Such observations were initially made in a computer simulation (Rybach et al. 1993), (Desideri et al. 2011) and in the case of a long-term monitoring of a single borehole (Bayer et al. 2013). The findings of the Fraunhofer ISE projects were on the other hand mirrored in (Montagud et al. 2011), which describes a similarly stabile ground temperature after five years of operation of a heat pump.

It must be taken into account that the temperatures were measured not directly in the ground but in the brine circuit.

5 CONCLUSIONS

Measurements of heat pumps in real operating conditions determined the average seasonal efficiency for different types of heat pumps. The results indicate a clear difference of efficiency between heat pumps operating in older buildings (un-retrofitted) and heat pumps in newly constructed buildings with heating systems based on surface heat distribution. The average SPF values for outside air and ground source heat pumps clearly reveal higher efficiency of ground heat pumps. However, SPF values achieved by individual installations of ground source heat pumps had a much wider range then the one noted for the outside air heat pumps, leading to a partial overlapping of both ranges. It enables a conclusion that the choice of the heat source is not an automatic guarantee of a higher efficiency. Errors during the design, installation and operation process markedly decrease the achievable efficiency of heat pumps. Simple and robust units usually work with the highest efficiency.

The analysis of the measurement of electric energy consumption of individual components of the heating system based on a heat pump exposed a large range of energy consumption by fans and brine pumps among individual units. It has been shown that the optimization of heat pumps in terms of efficiency should not be limited to heat pump components (compressor, evaporator, etc.). It is advisable to apply possibly energy-saving fans and circulation pumps.

The results of long-term monitoring of both types of buildings (new and old) and all types of heat pumps (outside air and ground) revealed a very small share of electricity consumption by electric back-up heaters, thus not confirming the often formulated concerns about its high share.

The most recent test results obtained from measurements within the project “HP Monitor” confirmed the increase in efficiency of heat pumps resulting from developments of the technology.

Analysis of long-term data on temperature of heat source in systems with boreholes showed no decrease in soil temperature during the first six years (the period of data acquisition). The average values indicate a total regeneration of the ground during the summer months and its return to the baseline before the start of the heating season.

6 REFERENCES

Bayer, Peter, L. Rybach, P. Blum, and R. Brauchler. 2013. “Review on Life Cycle Environmental Effects of Geothermal Power Generation.” *Renewable and Sustainable Energy Reviews* 26 (October): 446–463.

Desideri, U., N. Sorbi, L. Arcioni, and D. Leonardi. 2011. “Feasibility Study and Numerical Simulation of a Ground Source Heat Pump Plant, Applied to a Residential Building.” *Applied Thermal Engineering* 31 (16) (November): 3500–3511.

Galvin, R. 2010. “Thermal Upgrades of Existing Homes in Germany: The Building Code, Subsidies, and Economic Efficiency.” *Energy and Buildings* 42 (6) (June): 834–844.

Graichen, Verena, V. Bürger, S. Gores, G. Penninger, W. Zimmer, W. Eichhammer, T. Fleiter, B. Schlomann, and A. Strigel. 2012. “Energieeffizienzdaten Für Den Klimaschutz”. Dessau-Roßlau.

Hepbasli, Arif, Z. Erbay, F. Icier, N. Colak, and E. Hancioglu. 2009. “A Review of Gas Engine Driven Heat Pumps (GEHPs) for Residential and Industrial Applications.” *Renewable and Sustainable Energy Reviews* 13 (1) (January): 85–99.

Miara, Marek. 2009. “Heat Pumps in Action.” *Renewable Energy World Magazine*.

Miara, Marek, D. Günther, T. Kramer, and H.-M. Henning. 2011. “Efficiency of Heat Pump Systems under Real Operating Conditions.” In *10th IEA Heat Pump Conference*. Tokyo: Heat Pump Centre.

Montagud, C., J.M. Corberán, Á. Montero, and J.F. Urchueguía. 2011. “Analysis of the Energy Performance of a Ground Source Heat Pump System after Five Years of Operation.” *Energy and Buildings* 43 (12) (December): 3618–3626.

Rybach, L, W. Eugster, R. Hopkirk, and B. Kaelin. 1993. “Borehole Heat Exchangers: Longterm Operational Characteristics of a Decrntral Geothermal Heating System.” *Geothermics* 21 (5): 861–867.

Zottl, Andreas, and R. Nordman. 2012. “Project SEPEMO, D4.2./D2.4. Concept for Evaluation of SPF.” www.sepemo.eu.