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10 years of heat pumps monitoring in Germany. Outcomes of several monitoring campaigns. From low-energy houses to un-retrofitted single-family dwellings.

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Abstract

Since 2006, Fraunhofer ISE from 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 systems 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). In 2016, another project focusing heat pumps in stock buildings was started.

The main focus of all projects was the examination of the efficiency (SPF - seasonal performance factors) of heat pumps under consideration of various operating conditions. Second goal was to investigate possible optimization of running heat pumps systems and of their installation process.

The collected data and achieved results, based on an extensive number of investigated units and a long-term data acquisition, provide a good picture of the operation of heat pumps in central Europe. For example, the last year's improvements of the components, in particular in air-to-water heat pumps, correspond with the increase of the average efficiency of newly installed units.

The main results confirm the high potential of heat pumps in term of reaching a high efficiency by correctly planed, installed and operated units. Still, a high spread of efficiency of similar heat pumps installation indicates potential of increasing the average values by avoiding failures.

Keywords: heat pumps; efficiency; SPF; monitoring; field test

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1. Intoduction

Increasing the efficiency of the technical appliances is a genuine task of producers and scientists. In case of the technology which is already far developed and mature, the product based efficiency improvements are usually rather small. The heat pumps are such products. The efficiency measured in the lab is already very high for a number of products, the further improvements relatively limited.

However, the real purpose of the heating device is not the work in the lab but to deliver the needed heat in real operation conditions in the field. The measured efficiency of the heat pump in the field depends on a number of factors, not only on the unit itself. The planning, the installation process, the operating of the whole system and all involved components and at last but not least the users behavior influence strongly the end results. The boundary conditions coming along with the case of application as well as the potential failures or adverse circumstances decide on the total efficiency losses. Unfortunately, not seldom, the negative impacts can be very significant and overrun the improvements done by the units itself.

This paper describes some results and lessons learned from a number of monitoring projects investigating heat pump units running in real operation conditions. Basic information about the projects and the chosen methodology has been described in the paper presented for the 11th HPC in Montreal [l].

2. Characteristic of the projects

Figure 1 shows the names of the performed projects with the number of investigated units in each project. Besides the financing model and the number of involved partner in each project (indicated in the graphic), all projects have been performed in a very similar way as to the methodology and measurement equipment used.

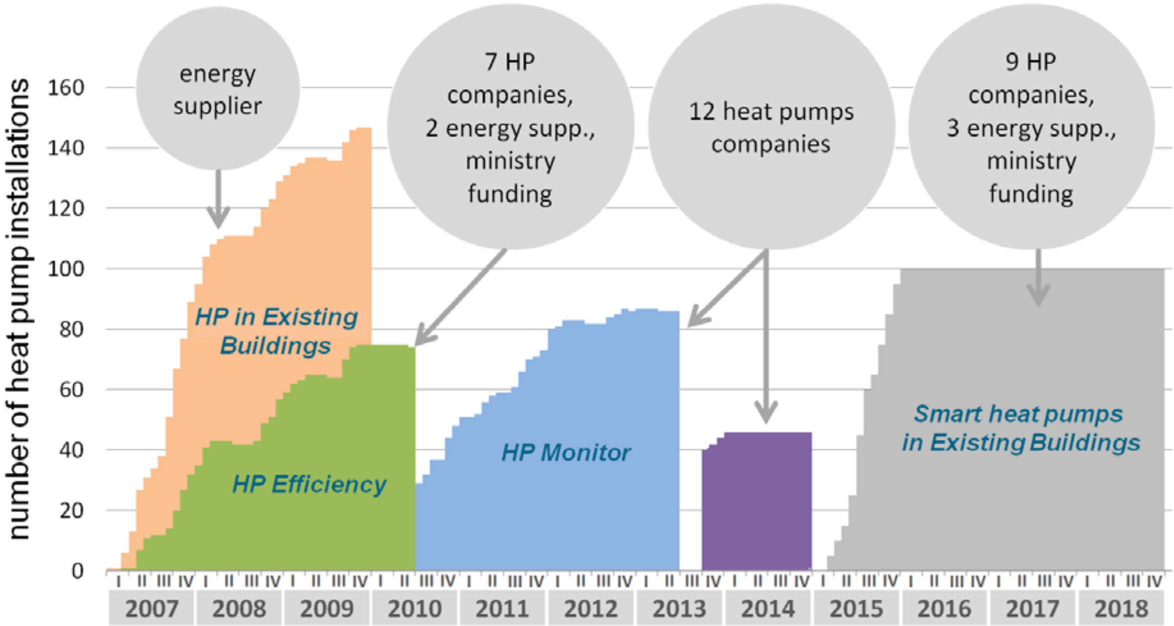

Fig. 1. Heat pump installation and the system boundaries for calculation of SPF values

The project “Heat Pumps in Existing Buildings” and the newest program “Smart heat pumps in Existing Buildings” include heat pumps in older, usually un-retrofitted buildings. Other projects have been performed predominantly in newly built single-family dwellings. All investigated heat pumps units cover the heating demand of the buildings as well as domestic hot water demand. In the majority of cases its matter of mono-energetic systems - the heat pump supported in emergency cases by the direct electrical back-up heater is the only heat supplier in the building. Systems with solar thermal units have been evaluated separately. One of the goals of the currently running project is the investigation of hybrid heat pumps units; however the results of this investigation are not yet available.

3. Outcomes of the Seasonal Performance Factor (SPF)

3.1. System boundaries

Figure 2 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 3.2 were based on the boundary SPF 2. 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 [2].

The SPF is the ratio of the heat energy produced by the heat pump (not including the losses of the heat distribution system and the buffer tanks) 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.

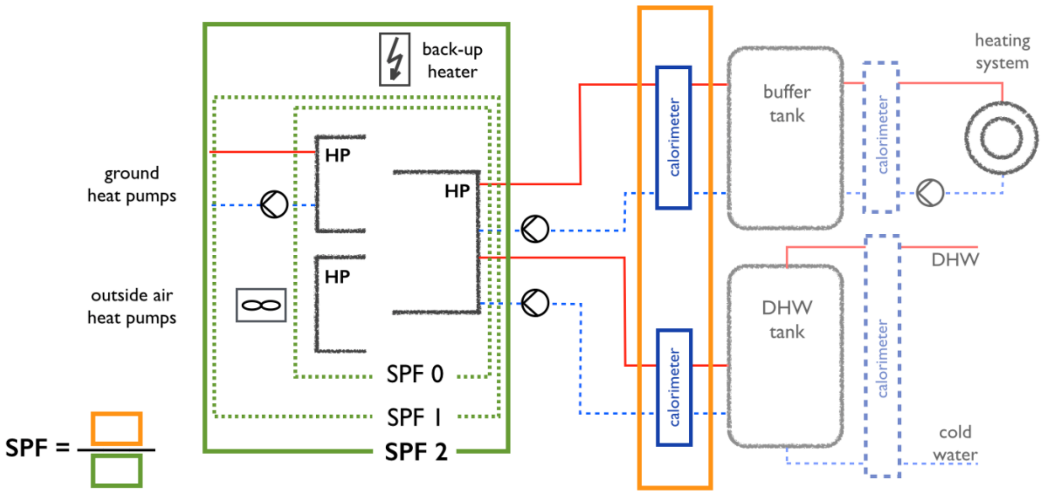

Fig. 2. Heat pump installation and the system boundaries for calculation of SPF values

3.2. Averages values and ranges of the SPF

Figure 3 shows average values of SPF values among individual projects, as well as the ranges of individual results for all heat pumps units grouped for different heat sources and projects. 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.

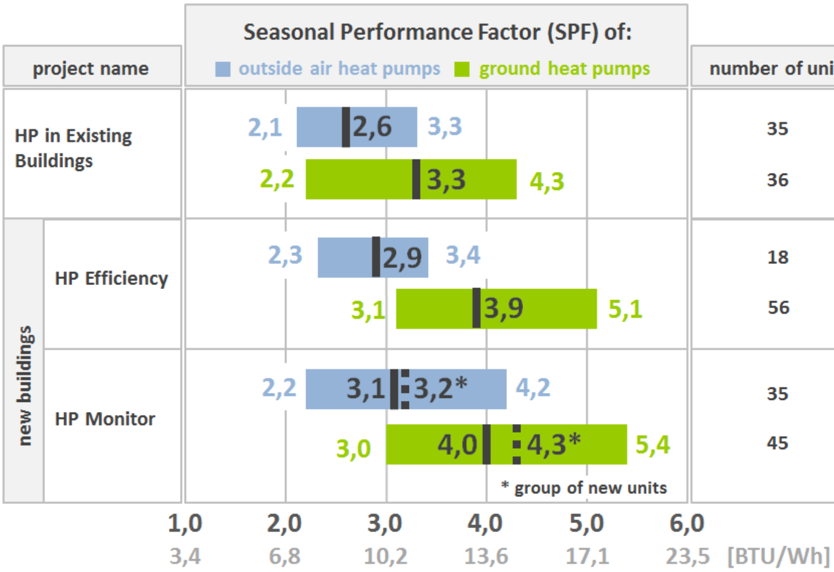

Fig. 3. Averages values and ranges of the SPF

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 improvement 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 *). The outcomes from this group indicate the improvement in the heat pump efficiency resulting from technology development in the recent years.

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.

3.3. Influence of the system design on the efficiency

Figure 4 shows two examples of heat pump units with different hydronic system design. The first system, schematic shown on the left side, includes two buffer tanks – one for space heating and one for domestic hot water. The second system (on the right) includes only one, so called combined tank, for domestic hot water and heating. In both systems the heat pump unit itself has the same efficiency expressed in the COP values. Also the heat source type, the boreholes, is the same. The average temperature of the heat source is more beneficial for the left system, but the difference of 0.9K is not crucial for the end result of the efficiency. Also the supply temperature of the heating system, in both houses with under-floor heating, is almost the same – 36°C respectively 35°C.

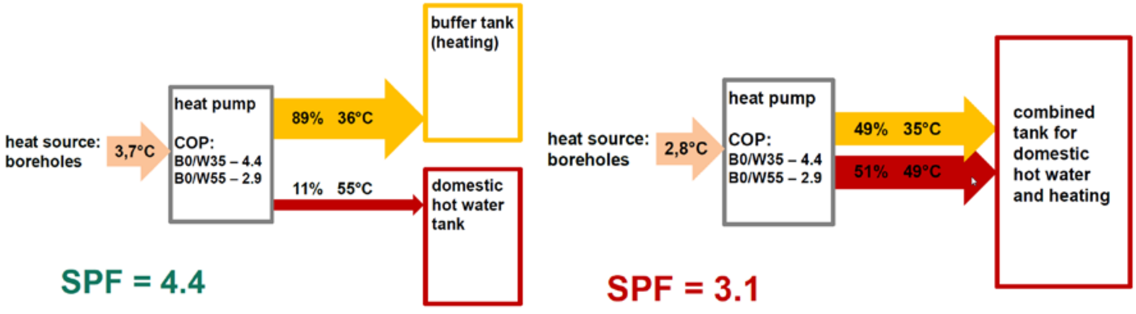

Fig. 4. Two examples of the hydronic system design and the archived efficiency

The most significant difference, which caused a considerable drop of the efficiency in case of the system on the right (SPF = 3.1 versus SPF = 4.4), is the share of the heat delivered for the space heating and domestic hot water (DHW). In case of the system with the combined tank, a large share of the DHW was not caused by the actual hot water demand of the inhabitants. Accordingly, it is justified to conclude that the control system of the heat pump unit was not able to work properly with the hydronic system or, specifically speaking, with the combined buffer tank. The incorrect operation resulted in an unnecessary high share of the DHW, followed by a high average supply temperature and, as a consequence, much lower SPF value compering with a properly working system with two buffer storages.

This example shows the importance of the observation of the whole heating system and its proper design for reaching the high overall seasonal efficiency. It also shows the significant drop of efficiency by systems with suboptimal design even if the heat pump itself is able to reach high theoretical efficiency.

4. Lessons Learned, Improvement Suggestions for Design, Installation and Operation

The heat pump’s efficiency basically depends on the difference between the temperatures of heat sink and heat source. Concerning the heat sink (heating circle, DHW), it should be strived for the lowest temperatures possible. The greatest effect has the enlargement of heat-transmitting surfaces such as the utilization of underfloor or wall heating. In existing buildings with a low potential of thermal refurbishment, special low temperature radiators might be used.

The heat source should provide as high temperatures as possible, in particular during the heating period. These temperatures are primarily influenced by the type of the heat source or the design of the heat exchanger used. The highest temperatures during the heating period and the most constant temperatures in the course of a year can be reached by water source heat pumps. Slightly lower and more fluctuating temperatures are achieved by ground source heat pumps using boreholes. The applications with horizontal ground collectors supply even lower and more fluctuating temperatures in the course of a year than those with boreholes. The heat source temperatures of air source heat pumps provide the least suitable preconditions with regard to the heat pump’s efficiency. In this context, the divergence between the outside air temperature and the space heating demand is essential.

When selecting the appropriate heat source, one has to take more effects into account than efficiency and resulting ecological and economic effects only. These include local conditions such as the space available, approval procedures (especially in case of water source heat pumps) or the economic conditions with regard to investment costs.

Designing the whole heating system, setting up the heat distribution system is very important for the future efficiency. Besides directly supplying the heating circuit, there is the possibility to install buffer storage in a serial or parallel manner. These storages are mainly installed in order to bridge blocking times (energy supplier) as well as to enable longer compressor running times. The last-mentioned point, in particular, could be confirmed, especially during the transitional period in which low heating demand faces a heat pump which is designed for intensive heating phases. Air source heat pumps using reverse cycle defrosting are usually equipped with buffer storage. Furthermore, buffer storage ensures the minimum flow rate which the heat pump requires. Different types of storage also enable the integration of additional heat sources such as solar thermal systems. Although the buffer tanks have certainly a number of advantages, there are two significant disadvantages. The first one is the additional heat losses unavoidable by any heat storage, and the second – each additional element in the system make the system more complicated and usually more difficult to control. Concluding, it is advisable to check the possibility of avoiding the buffer tank. In general the units without the buffer tanks have reached the higher efficiency.

A further problem when it comes to the design of heat pump systems is the use of primary pumps whose capacity is too high. This especially applies to well pumps installed with ground water source heat pumps. The use of high-efficiency pumps is strongly recommended.

Heat pump systems require an integral and object-specific planning which should also include the building. A thorough design of the whole system which takes into account individual components too (heat source, heat pump, heat sink) has to be ensured.

Besides a well thought-out design, the careful installation of the heat pump system is important too. Special attention should be paid to the function of the hydraulic components as well as the correct installation of components which are connected to the control unit.

The division between heating and DHW circuit is either achieved with the help of a three-way valve and a pump or without the valve and one pump in each circuit. As far as the three-way valves are concerned, it could be observed that they did not close completely. This led to a slow but constant discharging of the DHW storage. This effect was even increased by the unnecessarily operating charge pump. Thus, during the installation it should be ensured that the valve closes completely.

The use of storage requires the correct installation of temperature sensors as well as an appropriate parametrization of the heat pump control unit. Some storage provides variable positioning of the temperature sensors. These measures aim at providing ideal conditions for the storage charge, especially for combined storage.

During the monitoring process, by all types of buildings and heat sources, the activity of the electrical beck-up heater was neglected small. In the predominant number of cases the electrical back-up heater can be deactivated entirely. Correctly designed ground source heat pumps do not require an electrical back-up heater. It is only necessary in case of malfunction or if the building needs to be dried out.

Furthermore, a hydraulic balancing as well as the complete insulation of pipes and other hydraulic components should be done as standard.

The heat pump should not be seen as a heating system which can be neglected once it is installed. Even in operation the efficiency can be influenced positively.

Efficiency can be influenced positively by adjusting heating and the DHW temperatures. Although both values are determined in the design phase, the real consumption as well as the actual demand may vary. Ideally, both values should be as low as possible. Normally the heating temperatures can easily be adapted by gradually reducing the heating curve.

Another option is to adjust the pump's capacity in the primary and secondary circuit. One should be aiming at ideal temperature differences in the heat exchanger by adjusting the flow rate appropriately.

5. Responsibility for Efficiency

There are basically three groups that can help to make full use of the theoretically high potential of heat pumps and thus contributing to a real efficiency as well as to the effectiveness of the whole system: the heat pump manufacturers, the planners and installers as well as the users (residents) of the heat pump system.

The manufacturers have the responsibility to offer efficient and reliable heat pumps. As far as the last point is concerned, the field test could show that heat pump systems operate very reliably. Further potential for optimization, however, lies in the field of heat pump efficiency. This can be realized with a constant increase of the COP values, e.g. by improving individual components as well as the further development of appropriate control algorithm. Moreover, it is important to train and further educate staff and inform the users about how to use their heat pump efficiently. Finally, the manufacturers have to consider future challenges such as the integration of heat pumps in the Smart Grid, the increasing energy demand for cooling in summer and the combination with other heat sources.

The planners and installers have the best opportunity to influence a heat pump's efficiency. Correct planning as well as a careful and professional installation of the heat pump system is essential for their reliable and efficient operation. Only under these conditions, heat pumps can meet the expectations in terms of economic and ecological advantages. Above all, the wide range of determined SPF values shows the significant potential for optimization in this field. Planners and installers have the obligation to inform the users about how to operate a heat pump efficiently.

Residents are able to influence the heat pump's efficiency and the energy consumption basically on two levels. First of all, it is the user who decides about investing in such a system in the end. This involves their willingness to construct a building with either a low demand of heating energy that is equipped with underfloor heating or to refurbish a building in order to increase its energy efficiency and thereby choosing the most suitable heat pump's heat source. As far as the heat system's configuration in existing buildings is concerned, residents can primarily influence the heat sink's temperature. Easy menu navigation on the heat pump's display allows a convenient adjustment of the heating curve. Furthermore, the residents could deactivate the electrical back-up heater and reactivate it if necessary. Hereby, unwanted back-up activity can be prevented in advance. As already mentioned, residents should be informed about the system before they actively use it. Necessary information should be provided by manufacturers, planners and installers. During the field test, one could divide the residents into two groups. One group did not show any interest in the heat pump and therefore had hardly any knowledge about it. The other group of residents was very interested in the system and thus tried to improve the heat pump's efficiency actively.

6. Comparison of Laboratory COP Values through In-depth Analyses of Field Monitoring Data

One of the specific outcomes of the monitoring projects was the development of a method allowing for comparison of COP values (Coefficient of Performance) measured in the laboratory conditions with coefficients defined as COP_{QS}, determined on the basis of measurement data during so-called quasi-stationary operating conditions. The methodology attempts to verify the reproducibility of laboratory results in accordance with EN 14511 in real conditions.

6.1. Description of the method

During a laboratory COP measurement according to EN 14511 (EN 255 respectively) the heat pump faces constant boundary conditions for a time period of at least 35 minutes of measurement and one hour (inertia phase) in advance. In case of field operating heat pumps the boundary conditions usually fluctuate. A quasi-stationary condition "QS" was defined to handle this problem. It describes time periods inside heat pump operation cycles where all COP related measurements are within an allowed deviation comparing to EN 14511. The standard defines the allowed deviation from a fix set point. Since there is no such set point in field operation, the conditions at the end of each operation cycle were used as a reference for deviation. The method approach is that a heat pump is closest to "stationary" conditions at the end of its operation cycle.

The heat source temperature and heat sink temperature as well as the temperature spread from the achieved COPQS usually do not match with those of the laboratory COP values. Therefore a method from [3,4] was used to transfer the standard COP to field conditions. The method´s first approach is to describe the COP as a function of the (thermodynamic) quality grade η. The second approach approximates the change in quality grade with a variation of either heat sink or heat source temperature as a linear function. Following these approaches a quality grade (and respectively a COP) can be inter- and extrapolated over one temperature while the other temperature is left constant.

6.2. Exemplary results

The selected heat pump uses a horizontal ground collector as a heat source and has the thermal power of 8 kW. The investigated house has a heated area of 173 m² and heating energy consumption of approximately 90 kWh/(m²a). In the hydronic system there is a domestic hot water tank and no buffer tank in the heating circuit. The heat distribution system based upon under-floor heating.

The analyses of the quasi-stationary conditions have been done for the measurement data from the period of January 2010 to June 2013.

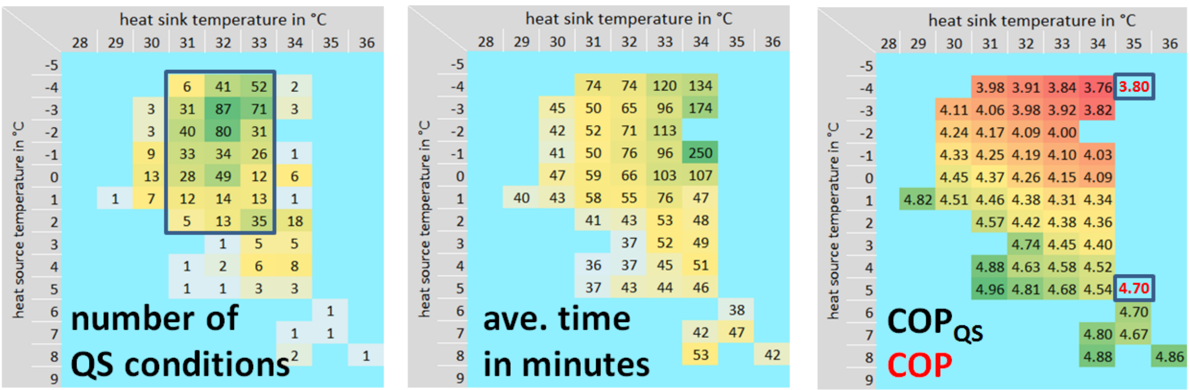

Fig. 5. The number of quasi-stationary conditions (left), the average duration of each condition (middle) and the average COPQS as well COP values (right) for certain combinations of heat source and heat sink temperatures for a single ground source heat pump system

Figure 5 shows the results of filtering the measurement data in the purpose to find the quasi-stationary conditions. The left graph illustrates the number of QS conditions which have been found for certain operating conditions. For example, for the temperature pair (operating point) B-2/W32 in total 80 QS conditions with an operating time of at least 35 minutes each have been identified The graph shows a very concentrated field of operating points with stationery operation of the heat pump (indicated with the blue square). On the heat sink side between 31°C and 33°C and on the heat source side between -4°C and 2°C.

The graph in the middle shows the average time of QS conditions found for each operation point. In the most representative field the heat pump runs in average approximately 60 minutes stationery. The longest average QS operation was found for the working point B-1/W34 and takes 250 minutes. The longest single stationary operation took 313 min for B-4/W33 (not shown in the graph).

The graph on the right illustrates the average COP_{QS} values measured in the field for each working point as well as two laboratory COP values for the operation points B-5/W35 and B5/W35 (indicated with the blue squares). The trend of the measured COP_{QS} values confirm the theory – the higher the heat source temperature and the lower the heat sink temperature the higher the efficiency. Vice versa - the lower the heat source temperature and the higher the heat sink temperature the lower is the efficiency. The red indicated COP values 3.80 respectively 4.70 are not directly comparable with the COP_{QS} values because the heat pump doesn't work in this working points stationary. However the COP_{QS} values for the points next to it are very close to the COP values.

heat source temperature in °C	heat sink temperature in °C								
	28	29	30	31	32	33	34	35	36
-5									
-4				-3.5%	-3.1%	-2.9%	-3.1%		
-3			-3.1%	-2.6%	-2.7%	-2.5%	-2.6%		
-2			-3.7%	-2.6%	-2.4%	-2.2%			
-1			-3.3%	-2.7%	-2.2%	-1.8%	-1.9%		
0			-3.7%	-2.3%	-2.4%	-2.2%	-1.1%		
1		-2.3%	-4.0%	-2.2%	-2.0%	-2.0%	+0.5%		
2				-2.9%	-2.8%	-1.3%	-0.5%		
3					-0.4%	-2.3%	-1.9%		
4				-4.7%	-4.7%	-2.5%	-1.3%		
5				-3.4%	-3.4%	-2.4%	-2.8%		
6								+0.3%	
7							-2.5%	-1.2%	
8							-3.4%		+0.1%
9									

Fig. 6. Deviation of the COPQS vales and intra- respectively extrapolated COP values.

Figure 6 shows the relative deviation of the COP_{QS} values and the intra- respectively extrapolated laboratory COP values. General speaking the deviations are very small for all operating points and amount to no more than 5 %. The average deviation for all working points sums up to -2.4%. The minus indicates that the investigated heat pump in the field operates with slightly lower efficiency then measured in the laboratory (if only QS conditions have been taken into account).

The graph below (figure 7) shows the relationship between the length of the single QS condition and the relative deviation from the intra- respectively extrapolated laboratory COP values. Their relation is quite clear – the longer the QS condition the smaller the deviation from the average value. The explicit symmetry of the deviation indicates the validity for both: the positive as well as negative deviations between COP_{QS} and COP values. The shape of the graph is not only caused by the real deviation of the field and laboratory operation of the heat pump but also by the limitation of the measurement instruments and methods. The longer the measurement period of single QS condition the smaller is the impact of measurement inaccuracy (e.g. reacting time of the temperature sensors, etc.).

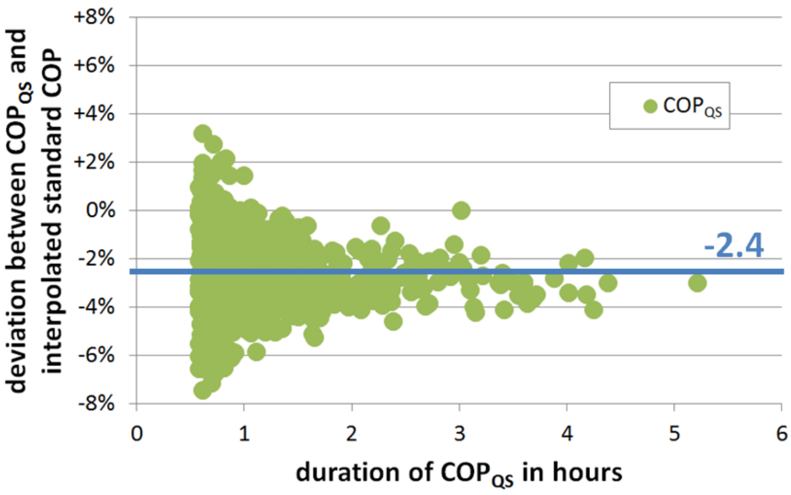

Fig. 6. Comparison of field and standard COP

6.3. Group evaluation and limitations of the method

The single heat pump unit described in chapter 6.2 shows an example of the whole group which has been investigated in the same way. So far the evaluation of more than 20 units is available and a further enlargement of the investigated group is planned. The next goal is to implement the QS conditions method into the running evaluation of all heat pump units in the ongoing and future field measurements.

In both types of the heat source, air and ground, the average deviation between laboratory COP values and field measured COP_{QS} values is rather small and amounts to less than 10%. The first evaluation shows in general the negative deviation in case of ground to water heat pumps and positive deviation in case of the air to water heat pumps. It means that the air to water units run in the field with higher efficiency than in the laboratory, and the ground coupled heat pumps in opposite way. In the majority of examined units also the single unit's deviation is usually less than 10 %. It allows the conclusion that the efficiency measured in the laboratory under stationery conditions can be confirmed in the field in the majority of cases.

Nevertheless it is necessary to mention the limitations of the quasi-stationery conditions method. Although it have been done as much as possible to make the field measurement and laboratory measurement comparable, it is not possible to repeat (and identify faultless) the stationary laboratory conditions in the field. The field conditions are only "quasi-stationery". Next aspect is the uncertainty of the measurement and the saving interval of the measured data by the data acquisition system. The uncertainty of the field measurement is unavoidable bigger than the lab measurement. The saving interval of the data in the lab amounts usually to one second, in the field to one minute. Following aspect is the uncertainty of the interpolation method of the COP values [3,4]. By the method a linear function has been used which is only a simplification of the real changes in the COP values along the operating points field.

7. Conclusions

Large amount of measurement data collected during performing several field monitoring projects allows for a thorough and comprehensive analysis of behavior of heat pumps installations under real operating conditions. The paper addresses briefly only two aspects – the efficiency of a unit, as well as so-called "quasi-stationery" operating conditions. Furthermore, general findings and lessons learned are provided, together with improvement suggestions for design, installation and operation. A more holistic analysis of the results can be found in the final reports of the projects [5-7]

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. The outcomes for individual installations disclosed much smaller range of extreme values for air heat pumps. A wide range of SPF values for ground source heat pumps indicated that the choice of the heat source is not a guarantee of a high efficiency.

During the monitoring process, for all types of buildings and heat sources, the activity of the electrical back-up heater was neglected small.

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.

Both the average values for groups of air- and ground heat pumps, as well as individual values for the majority of installations, indicate a broad convergence of the coefficients COP with the coefficients of COP_{QS}.

Acknowledgements

The implementation of the monitoring projects is a challenging and complex task. The execution of the projects and the evaluation of the test results required a participation of more than a hundred persons assisting for several years. Thus, special thanks are directed to all employees and ex-employees that assisted in this task as well as to all industrial and institutional partners who make the whole implementation possible. This work was supported by the German Ministry of Economics and Technology (BMWi), under Grant FKZ0327401A upon decision of the German Bundestag and supervised by Project Manager Jülich (PTJ).

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