13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

Heat pumps in existing residential buildings

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Abstract

Several reasons speak for using of heat pumps in residential buildings. They can provide heating, domestic hot water und cooling in an ecologically friendly and, in the majority of countries, an economical way. Particularly straightforward is the implementation in new residential buildings, typically equipped with a low temperature underfloor heating system. In a number of European countries heat pumps are the predominant heating technology in the new residential buildings.

However, the real challenge, as regards reaching the goals related to climate changes and higher energy efficiency, is to secure heating in existing residential buildings. Despite several technological solutions allowing for implementation of heat pumps in existing buildings, the number of end consumers choosing heat pumps when replacing an old heating system is still very low.

What is the minimal energetic standard of a building suitable for a heat pump? Are heat pumps able to deliver required temperature and expected thermal comfort? What is the efficiency achieved under real operation conditions? When are heat pumps better than fossil systems from energetical, ecological and economical point of view? Is technological development of heat pumps in recent years recognizable in the real field operation?

The author will attempt to answer these questions on the basis of the evaluation of the latest field monitoring program encompassing more than 60 single-family existing residential buildings in Germany.

Keywords: residential building; retrofitting; field efficiency; monitoring;heating systrem supply temperatures, CO_2 evaluation

1. Introduction

Heat pumps will play the major role providing the heat for space heating and domestic hot water in the residential sector of the future CO_2 reduced energy system. A wide range of studies [1-3] consider heat pumps as a crucial technology on the way to energy system transition and targeted CO_2 neutrality.

In a number of European countries, heat pumps are already now the dominating heating technology in new residential buildings. The real challenge for reaching the goals related to climate changes and higher energy efficiency, is to provide for heating in existing residential buildings. Despite several technological solutions allowing for implementation of heat pumps in existing buildings, the number of end consumers choosing heat pumps when replacing an old heating system is still very low.

In the discussion about the applicability of heat pumps in existing buildings, the main argument against this solution is the assumed high heating supply temperature, leading to poor performance of heat pumps and consequently to exclusion criteria. To verify this assumption, in the newest field test the Fraunhofer ISE examined sixty air-to-water and ground source heat pumps under real operation conditions in existing buildings. Extensive measurement setting and high frequency data acquisition system allowed for detailed analyses of the efficiency of the systems, including the temperatures of the heating system.

2. Heat pumps field tests

Since 2006, the Fraunhofer ISE from Freiburg, Germany has been investigating electric heat pumps in single-family dwellings. Nearly 250 air-to-water and brine-to-water heat pump 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).

The characteristic of the projects including the characteristic of the investigated buildings, measurement technology, main results and particular aspects, have already been presented during the 11th and 12th Heat pump Conference [4, 5].

The newest program "Smart Heat Pumps in Existing Buildings" includes heat pumps in older, usually un-retrofitted buildings. The measurement period was closed in June 2019. All investigated heat pumps units cover the heating demand, as well as the domestic hot water demand. In the majority of cases it concerns a mono-energetic systems - the heat pump is supported in emergency cases by a direct electrical back-up heater and is the only heat supplier in the building. One of the goals of the project was the investigation of hybrid heat pumps units; however the results of this investigation will not be consideration of the paper.

The heat pumps examined within the frame of the project "Smart HP in Existing Buildings", were installed in single-family houses built between 1850 and 2005. The range of their retrofitting covers from not retrofitted to retrofitted to the energy high efficient standard. This setting was necessary to investigate heat pumps in different operating conditions, including heating system supply temperature.

3. Overview of the efficiency results

3.1. System boundaries

Figure 1 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 [6].

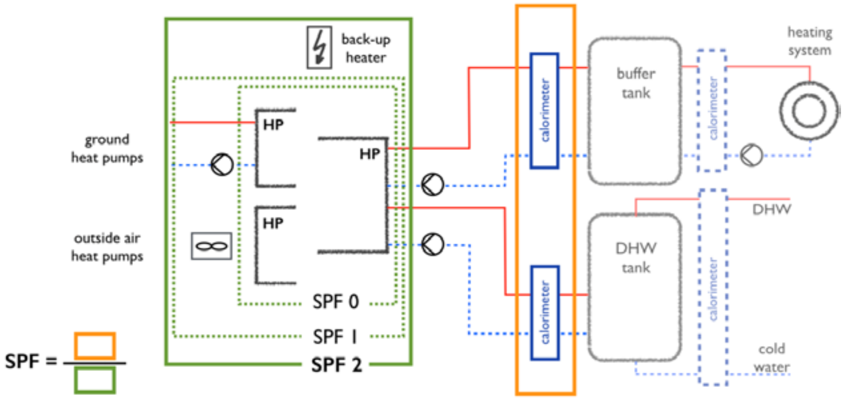

Fig. 1. Heat pump installation and the system boundaries for calculation of SPF values

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 electric 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.

3.2. SPF values

Figure 2 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-source heat pumps. Ground-water heat pumps were omitted due to a neglectable number of the examined installations. Calculation periods differ and are indicated for each project.

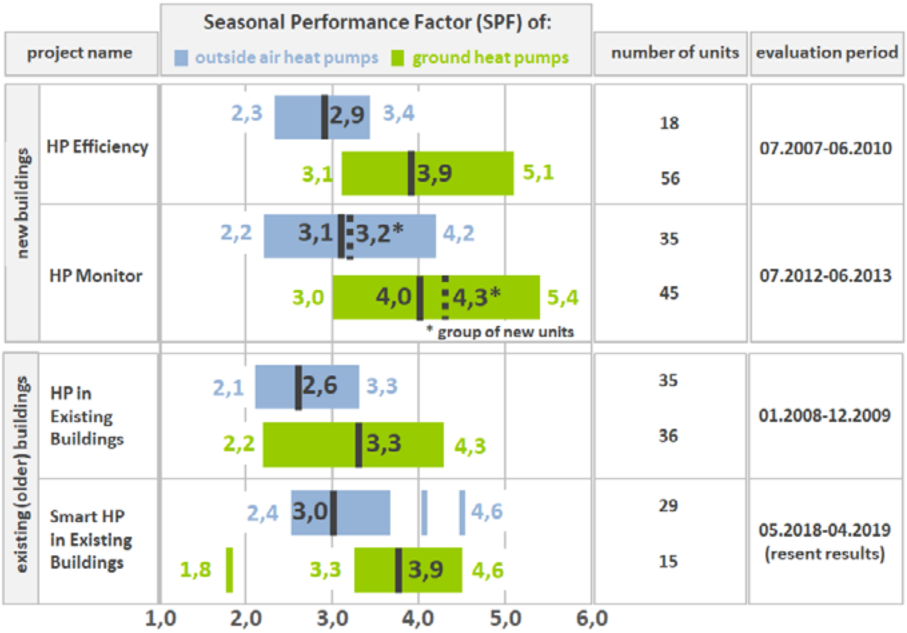

Fig. 2. Averages values and ranges of the SPF in existing residential houses in Germany

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 source heat pumps. The ground as a heat source is more beneficial from the point of view of its temperature in the 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. Underfloor 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 (as opposite to the units transferred from the older project “HP Efficiency”) 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 systems with air-water 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 would not automatically guarantee a high efficiency. Errors in designing, installation and/or running process, result in a decrease of potential efficiency and diminish economical and ecological benefits of theoretically more efficient, but at the same time more expensive, heat source.

The newest results originate from the project “Smart HP in Existing Buildings”. One year of evaluation shows following results:

- air-to-water heat pumps achieved the average SPF value of 3.0 with the range between 2.4 and 3.7. Two units with highest results reached the values of 4.1 and 4.6 and have not been reflected in the average value calculation.
- ground source heat pumps achieved average SPF value of 3.9 with the range between 3.3 and 4.6. The unit with the smallest value of 1.8 has not been reflected in the average value calculation.

Compering the results from the latest project with the older project “HP in Existing Buildings”, which has been performed 10 years ago also in existing buildings, the average efficiency increase is significant.

With all restrictions of the direct comparison of various projects (different houses, diverse average heating systems temperatures, unique weather condition for the year of evaluation), it may still be concluded that the efficiency of heat pumps increased in the recent years. Coincidently, the average efficiency results from the latest project with older existing buildings mirrored the results from the project in newly build residential houses conducted 10 years before.

4. Heating systems supply temperatures

The previous section discussed average data from all investigated heat pumps. The focus of this section will be analysis of a group of air-to-water heat pumps. The data are based on a one-year measurement period. The selection criteria for this group was the average heating system temperature. Only units with the temperature 36 °C [97 °F] and above were chosen for the evaluation, in total 16 units.

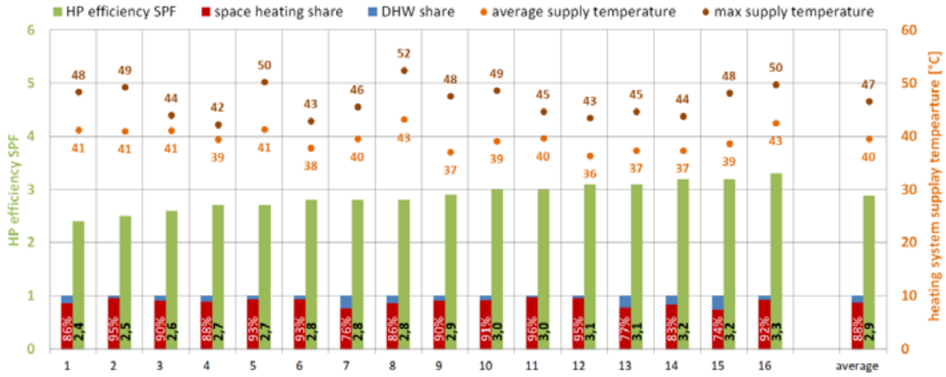

Fig. 3. Heat sink characteristic of 16 air-to-water heat pumps operating in existing residential houses in Germany evaluated over a one-year period

Fig. 3 shows the sink side (heat distribution side) characteristic of the 16 air-to-water heat pumps including their efficiency (green columns). The average SPF value for the whole group of installations amounts to 2.9 with the range from 2.4 to 3.3. The percentage share of the delivered heat in space heating mode (in red) and DHW (domestic hot water) mode (in blue) have been shown on the left side of each efficiency column. The extreme right columns symbolize the average values of all systems. In average, the share of the heat delivered for the space heating equals 88% and the share of DHW heat equals 12%.

Above the columns, two types of the heating system supply temperatures have been shown. The lower one (in orange) indicates the average heating system temperature (supply minus return temperature) over the whole period of evaluation. The higher values (in brown) indicate the maximal daily heating system supply temperatures (only in space heating mode) measured during the heating season.

For the further considerations, it is important to differentiate between three types of heating system temperatures. First one, and usually the highest one, the *design temperature*, is determined by the planning of the heating system and planned for the normative regional lowest outside air temperature. The second one, the lowest, is the *average temperature calculated (or measured) for the whole heating season*. This temperature, indicated on the fig. 3, is significant for the average efficiency of the heat pump and consequently for the ecological and economical results of the system. The third one is the *highest (daily) measured temperature*. This temperature indicates the best the real weather condition, respectively the real lowest outside temperatures.

The investigated group of heat pumps shows considerable low average heating system temperatures, in particular in the light of the fact that the heat distribution in rooms is based on radiators in the majority of the systems. The average value of all units equals to 40 °C (104 °F). The highest average temperature, in the units numbered 8 and 16 equals to 43 °C (109 °F).

The highest maximal daily temperatures are in average 7 K higher. The highest maximal temperature is observed in the unit 8 and equals to 53° C (127 °F). The highest delta between average and maximal temperature is observed in unit 9 and equals to 11 K. In general, the maximum temperatures measured during the heating season are lower than the design temperatures of the systems. The one reason for this situation is the lower real outside temperature than the normative one used during the planning. The second reason is link to the features of radiators in older buildings. Very often their size is over dimensioned and the actual temperatures required to deliver the necessary amount of heat to the rooms, can be lower than those designed.

Detail analysis of the heating system temperature for exceptional heat pump system is conducted in the next section.

5. Maximal heating supply temperatures

In the discussion about the applicability of heat pumps in existing buildings, the main argument against this solution is the assumed high heating supply temperature, leading to poor performance of heat pumps and consequently to exclusion criteria.

The previous section presented and discussed the average and the maximal heating supply temperatures for a group of heat pumps installations. Bellow, one exemplary installation will be analyzed. It concerns the air-to-water variable speed heat pump installed in a partly retrofitted building. The space heat distribution system bases on radiators (water based system). The investigated time period is the heating season 2018/19.

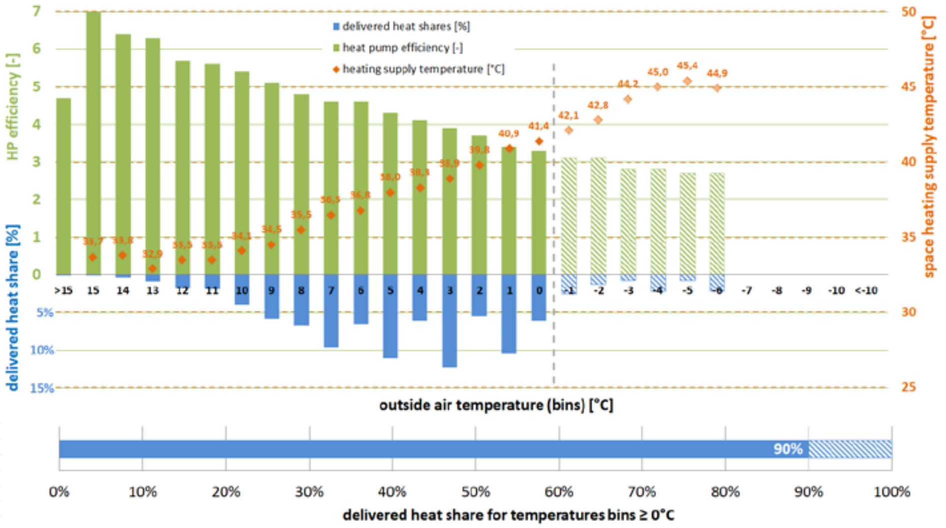

Fig. 4. Delivered heat share for temperature bins in dependency of the efficiency of the heat pump and space heating supply temperature (heating season 2018/2019 in Germany)

Fig. 4 shows the share of delivered heat (blue bars), for space heating, for each temperature bin. The distribution shows a typical bell-shape with the largest share of heating energy delivered by the outside air temperature of 3 °C (37 °F). The shares for the temperature bins below 0 °C and higher than 9 °C, are in the range of 1% to 4% of the total delivered heat and thereby play only a secondary role. The heating energy delivered for the outside air temperatures below 0 °C (32 °F) amounts only to 10% of the total delivered heating energy, which is shown in the lower part of the graph.

Fig. 4 shows additionally the heating system supply temperature (in orange) for each temperature bin and corresponding heat pump efficiency (in green). The supply temperature is clearly depending on the outside temperature and rises from approximately 33 °C (91 °F) to 45 °C (113 °F), which means a temperature rise of 12 K. Obviously, the highest supply temperatures of more than 42 °C (108 °F) are needed for the lowest outside air temperatures (below 0 °C). Also the efficiency of the heat pump clearly depends on the outside air temperature and, consequently, on the supply temperature (delta between evaporating and condensing is getting higher). The overall average efficiency of the heat pump equals to 4.2. The efficiency calculated for the temperature bins 0 °C and higher (without the coldest outside temperatures and highest heating system supply temperatures) equals to 4,0.

As expected, the highest supply temperatures of the heating system meet the lowest outside temperatures, causing the lowest efficiency of the heat pump. However the amount of delivered heat under these conditions (in the presented example 10%) is rather small and affects the total efficiency of the heat pump only in a minor way.

It has to be noticed, that similar behavior has been noted in several further examples, even if the absolute values of the supply temperature differed.

6. Ecological assessment of the heat pumps efficiency results

The comparison of various heating technologies may be performed by using several indicators. The three most used ones are: economy, ecology and primary energy. The results of such comparison are strongly linked with the local situation and vary considerably from country to country and sometimes from region to region. To illustrate how differently the some technology may be evaluated, following section will show the CO_2 emissions saving potential of heat pumps when compared to a natural gas boiler, in different geographical boundaries.

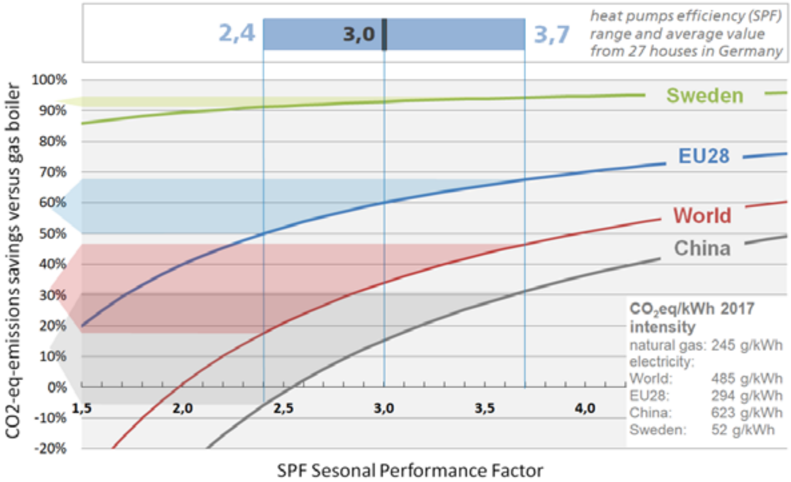

Fig. 5. CO2 emissions saving with heat pumps in dependency of CO2 electricity production intensity

Fig. 5 shows the dependency between the efficiency of a heat pump (impressed in SPF – Seasonal Performance Factor) and CO_2 emissions savings versus natural gas boiler. Crucial for that comparison is the CO_2 intensity of the electricity production in a particular region. The source for the values used for the calculation is the "IEA CO_2 emissions from fuel combustion statistics 2019" and the aggregated data from www.ElectricityMap.org, who track real-time carbon-intensity.

Following geographical regions have been taken in to account: global (the world), 28 European Union countries (EU28), China and Sweden. The CO_2 electricity intensity values are indicated on the lower right corner of the graph. The CO_2 values for the heat generation with natural gas have been taken equal for all regions. To simplify the calculation, the efficiency of the gas boiler has been assumed as 100%. Each colored line on the graph indicates one region (from the top: green – Sweden, blue – EU28, red – the world and grey – China).

The crossing point between virtual vertical line symbolizing the efficiency of the heat pump and the "region" line indicates the CO_2 savings. For example the efficiency of 3.0 means for the EU28 boundary CO_2 savings of 60% compared to natural gas boiler. Second example – the efficiency of 2.0 means for "the world" an even situation (no savings).

The efficiency results from the field measurement of air-to-water heat pumps systems in existing buildings (described in detail in the previous sections), have been indicated in the upper part of the graph.

It is clearly visible, that the same efficiency value leads to varied CO_2 comparison findings. Considering the average efficiency value of 3,0; the saving in China equals to 15%, in "the world" to 34%, in the EU28 – 60% and in Sweden, with the cleanest electricity production, even to 93%.

Also consideration of the efficiency range from 2,4 to 3,7 leads to fully different savings ranges. The largest range from -6% to 31% can be noted in China. The next one – 18% to 47% globally, 50% to 68% in the EU28 and finally 91% to 95% in Sweden.

Concluding, heat pumps or their efficiency may be judged in a diverse way depending on the CO_2 electricity intensity in a particular country or region. The same rule equally applies to the economical evaluation.

Second conclusion is that the "greener" the electricity, the lesser impact has the heat pump efficiency on the CO_2 savings. The countries or regions with less clean electricity have much larger potential for a considerable increase of the savings through increasing the heat pumps efficiency, even if in absolute terms it would be on a lower level (i.e. the increase of CO_2 savings in Sweden may be achieved solely in single percentage, reaching already more than 90%),

7. Case studies

On the website of the project "Smart Heat Pumps in Existing Buildings" in the section "Live Data" (https://wp-monitoring.ise.fraunhofer.de/wp-smart-im-bestand/german/index/live_visu.html) a number of heat pump installations has been visualized. The "live" data are updated daily. The user of the website has the possibility to read description of the house and the heat pump and analyze the hydraulic schema of the installation (including measured values from the sensors). It is also possible to see the efficiency results for different periods of evaluation, and "play" (changing the calculation boundary, for example with or without domestic hot water or back-up heater) with the efficiency results diagram. In addition, the real costs, as well as the ecological and energetical comparison with other heating technologies are shown.

8. Conclusions

Heat pumps are able to provide the required heat for space heating and domestic hot water not only in new but also in partly-retrofitted or even not-retrofitted residential buildings. It has been proven in the field test with sixty heat pump systems in existing buildings in Germany, which investigated both ground source and air-to-water heat pumps.

As evidenced by the field test, the average efficiency for the air-to-water heat pumps amounts to 3.0 with the range from 2.4 to 3.7. Ground source heat pumps reach the average efficiency of 3.9 with the range from 3.3 to 4.6. The efficiency results are very close to the results reached in previous field test project performed six years earlier in new buildings. This indicates the positive development of the technology and of the installations processes. Due to the variety of investigated units and of other influencing aspects, it is not possible to accurately quantify the mentioned developments.

Both measured average heating system temperatures and maximal supply temperatures for space heating in investigated houses are lower than generally expected in existing (oft not-retrofitted houses). The majority of heat for space heating is delivered not in the days with the lowest outside air temperatures. This explains the relatively low average heating systems temperatures. The delta between the real maximal temperature and the design heating system temperature may be explained by milder than assumed weather during the year of investigation, general oversizing of the radiators in older buildings and lower energy demand through renovation measures applied to the house envelope.

Heat pumps or their efficiency may be judged in various ways depending on the CO_2 electricity intensity in a particular country or region. The same rule equally applies to the economical evaluation. Taking as a basis for the evaluation the efficiency reached during the field test performed by the Fraunhofer ISE in the last 15 years in Germany, heat pumps perform well under real operation conditions ensuring in most cases significant CO_2 savings compared to natural gas boilers. It applies to the vast majority of the countries and world´s regions.

Acknowledgements

The implementation of a monitoring project is a challenging and complex task. The execution of the projects and the evaluation of the test results required participation of more than a hundred persons assisting for several years. Thus, special thanks are directed to all employees and former employees who assisted in this task, as well as to all industrial and institutional partners who made the whole implementation possible. This work was supported by the German Ministry of Economics and Technology (BMWi), under the Grant 03ET1272A upon decision of the German Bundestag and supervised by the Project Manager Jülich (PTJ).

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