Heat Pump Efficiency in Existing Buildings

– Results from a Field Measurement Campaign

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In newly built single-family houses in Germany, heat pump systems have become the most popular heating system. However, heat pump systems also operate reliably in existing buildings. This is a conclusion of a field test of heat pumps in existing residential buildings conducted by Fraunhofer ISE. This article gives an overview of the operation conditions of the application area, the energy-related performance of the systems as well as their impact on greenhouse gas savings.

Keywords: heat pumps, existing buildings, renovation, single family houses, field trial, monitoring

The Project

Several studies pointed out the significant role of heat pumps in the future heat supply of buildings [IWES/IBP 2017; BCG/PROGNOS 2018; DENA 2017, ISE 2020a]. The results of these investigations underline that the use of heat pumps in existing buildings must increase significantly in order to reach sustainability targets. The research project "HPsmart in existing buildings" (12/2014 – 07/2019) addressed this area of application with heat pumps in existing residential buildings. The project focused on two central research topics: load management with heat pumps and the analysis of the efficiency of heat pumps in existing single-family houses (SFH). This article addresses the latter topic and gives an overview of the measured heating temperatures and the seasonal performance figures (SPF), as well as an ecological classification of the results. More detailed explanations and further analyses are described in the project report [ISE 2020b].

The project consortium consists of eight heat pump manufacturers and three energy suppliers and is led by Fraunhofer ISE. A scientific monitoring of 56 heat pumps installed in 42 single-family homes and 14 two- to four-family houses was conducted. This includes 32 systems with ambient air as the heat source. Mostly one heat pump combines space heating (SH) and domestic hot water (DHW) in a single component whereas nine systems applied two heat pumps dedicated to these services – one heat pump with ambient air as heat source (for SH) and the other one with room air as heat source (for DHW)). Furthermore, 13 heat pumps using the ground as heat source (exclusively geothermal probes) and two heat pumps with ice storage on the source side were examined. All systems provide SH as well as DHW. Ten of the systems are designed as bivalent systems, comprising a natural gas or fuel oil boiler in addition to the heat pump unit. Solar thermal systems are installed in four systems. In many of the buildings, a stove is installed, for example in the living room. According to the information provided by the residents, these stoves are very rarely operated in most of the houses and contribute substantially to space heating in four monitoring objects only.

Building and Heating Temperature

The oldest building in the field test was built in 1850, the newest one in 2005. The buildings are classified according to their year of construction. The classification is oriented towards the implementation of the first Thermal Insulation Regulation in Germany (WSchV´77). 57% of the buildings were built before 1979 and have been renovated energetically to varying degrees. In 89% of the cases the windows were replaced, 86% have renovated roofs and 57% renovated outer walls significantly. The buildings constructed after 1979 were – from an energy point of view – only slightly renovated.

In order to characterize the original and the current energetic state of the building envelope in a semi-quantitative way, the "building coefficient" was introduced within this project. **Figure 1** represents an area-weighted average heat transition coefficient (U-value) of the exterior wall, window and roof. The calculation bases on the information provided by the house owners, such as the structure of the original building envelope and the renovation measures that were carried out. According to these data, around 60% of the buildings constructed up to 1979 currently have a "building coefficient" between the thresholds of the Thermal Insulation Regulation 1977 and those of the version revised in 1995. One quarter of the buildings have a significantly better energy condition.

In consequence of differently realized renovation measures – and the variation in user habits – there is no correlation between the specific heating consumption and the age of the building. The specific, weather-adjusted heat consumption of the buildings range from 50 kWh/(m²·a) to 250 kWh/(m²·a), with a median of 110 kWh/(m²·a). The space heating load is one of the factors influencing the required heating circuit temperature. This is influenced by the selection of the heat transfer system (e.g. radiator vs. floor heating), its dimensioning (e.g. width, height and type of a panel radiator) and commissioning (e.g. with/without hydraulic adjustment and optimization of the heating curve).

In approximately 25% of the buildings, only radiators are installed and in less than 20% of the buildings only underfloor heating is installed. Around 50% of the buildings combine both radiators and panel heating systems. In the following, these systems will be referred to as combined heating systems and are classified in three groups: "radiator guided" (21 systems), "surface heating guided" (2 systems) and not clearly assignable (6 systems).

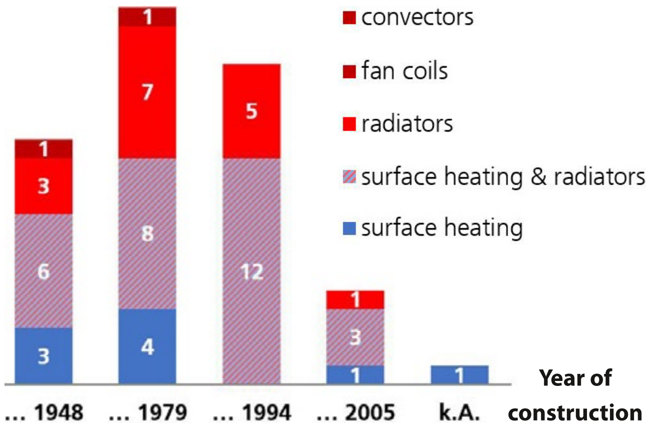

Figure 2. Distribution of building ages and heat transfer systems (year of construction of one building is unknown) [ISE 2020b].

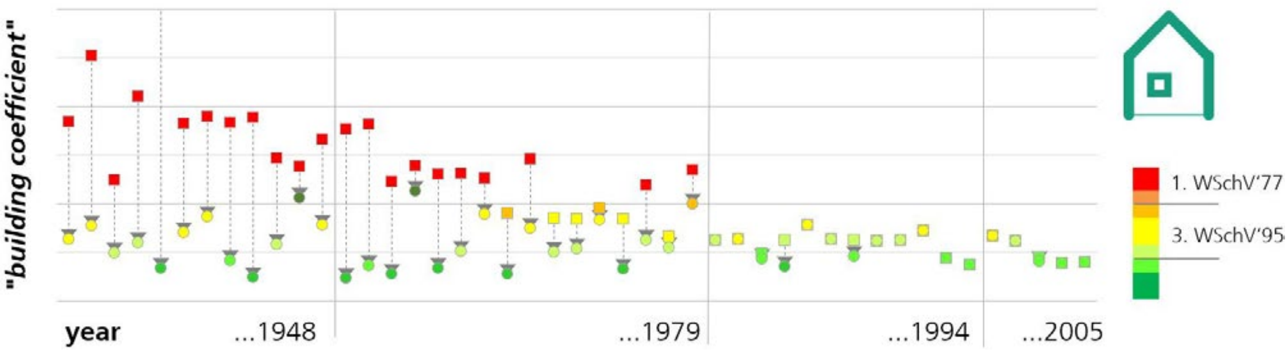

Figure 1. "Building coefficient" in the state of construction (rectangular icon) and in the present state (round Marker) for 45 buildings sorted by the age of building [ISE 2020b].

Figure 3 shows the average heating circuit temperature (energy weighted average values of flow and return) for the individual monitoring objects. The type of heat transfer system is color-coded in the figure. On the one hand the expected tendency of the distribution of the different heat transfer systems is shown: Panel heating systems are often operated at lower temperatures than radiator systems. Seven of the systems, which are exclusively equipped with surface heating or a "surface heating guided" combined system, are operated at an average heating circuit temperature in the range of 31°C to 33°C. One system in this category has a significantly lower average heating circuit temperature (27°C), three systems have significantly higher average heating circuit temperatures (36°C to 39°C).

On the other hand, the evaluation shows that even panel radiators can be operated at temperatures that are in the range of the temperature level of panel heating systems. This presupposes appropriate dimensioning (and good commissioning). The majority of the systems (84%), which are exclusively equipped with radiators or are "radiator-guided" combined system, use – fairly evenly distributed – average heating circuit temperatures between 34°C and 43°C. Two systems in this category are operated at even lower temperatures and four at higher temperatures. One system with an average heating circuit temperature of 53°C has by far the highest average heating circuit temperature.

Efficiency Analysis and Green House Gas Emissions

For the comparative analysis of the seasonal performance factor (SPF) a common system boundary for its calculation is shown in **Figure 4**. The SPF considers the provided thermal energy for space heating (SH) and domestic hot water (DHW) which are both measured close to the heat pump and not include possible storages. As input the electrical energy consumption of the compressor, the control, the brine pump respectively the ventilator and the electrical back-up heater are included in the calculation. To ensure a comparative data base, the results of 29 ambient air source heat pumps (ASHP) and 12 ground source heat pumps (GSHP) are considered.

Out of the 41 considered heat pumps around 75% were installed from 2013 to 2016. The remaining heat pumps were installed before, apart from one heat pump. For efficiency analysis the coefficient of performance (COP) – which represents the basic quality of the devices in terms of efficiency – is important to mention. Thus, the COP values of the ASHP reach from 3.2 to 4.2 (A2/W35) and from 4.5 to 5.0 (B0/W35) for the GSHP. Most ASHP are operated in monoenergetic mode whereby six systems are designed as bivalent systems. According to the different operation strategies for the bivalent systems only 4 boilers cover the heat demand significantly from 20% to 40%. The GSHP

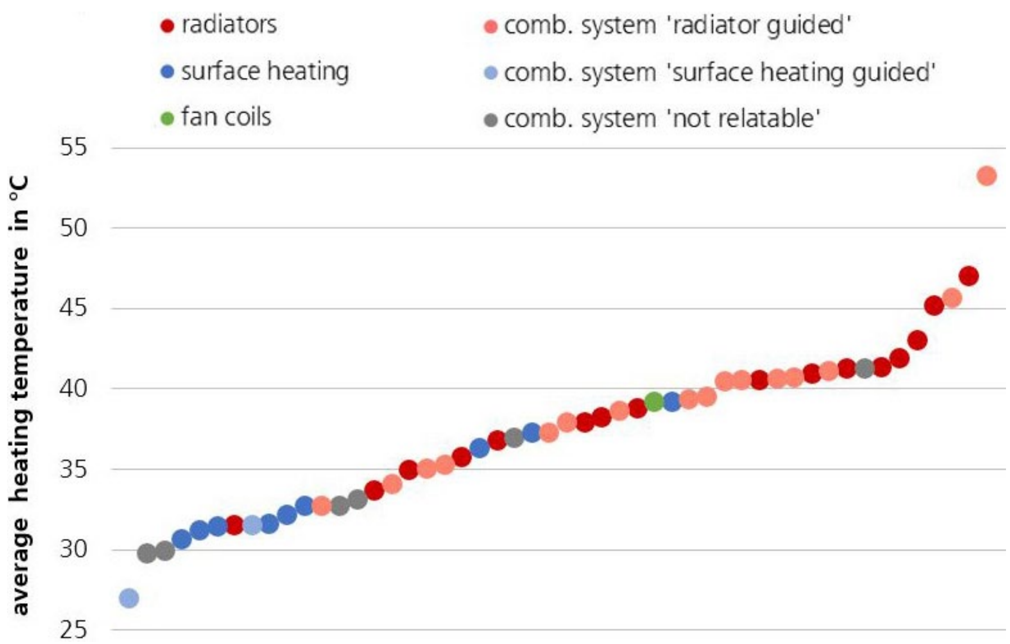

Figure 3. Average operating temperature of the heat pump in space heating mode of 50 systems (data base: bivalent heat pump systems with a coverage fraction of the boiler > 10% are not shown; evaluation period 2018/2019 with the exception of 2 systems that were evaluated for the period 2017/2018).

are solely monovalent or monoenergetic driven. Solar thermal systems support DHW production with three GSHP but none of the ASHP. The characteristic of the buildings and heat transfer systems of the 41 monitoring objects show a similar bandwidth and distribution as shown for the 56 monitoring objects before (overall data base of the project).

Figure 5 shows the SPF values of the 41 assessed heat pump systems for the measurement period from July 2018 to June 2019, divided into the heat sources ambient air and ground. For the ASHP SPF values from 2.5 to 3.8 were determined, the average SPF amounts to 3.1. Two SPF outliers (4.1 and 4.6) are not considered in the averaging. As expected, the SPF values of the GSHP reach a higher level with values from 3.3 to 4.7. The average was calculated to 4.1. The SPF bandwidths reflect the various efficiency influences such as the individual COP values, the operating temperatures on the sink and source sides or the relation between the produced energy for DHW and SH. The average share of the thermal energy production for SH amounts to 85% which underlines the significance of the heating circuit temperature in terms of efficiency.

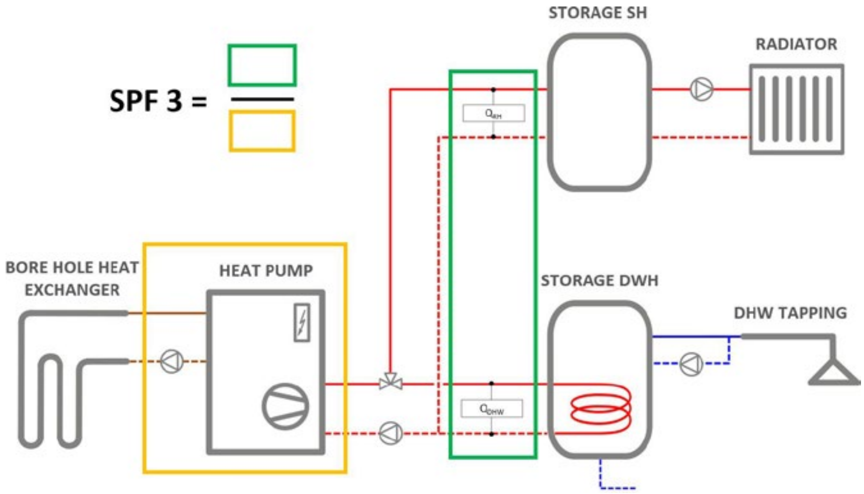

Figure 4. System boundary 3 for the seasonal performance factor calculation illustrated with an exemplary hydraulic scheme [ISE 2020b].

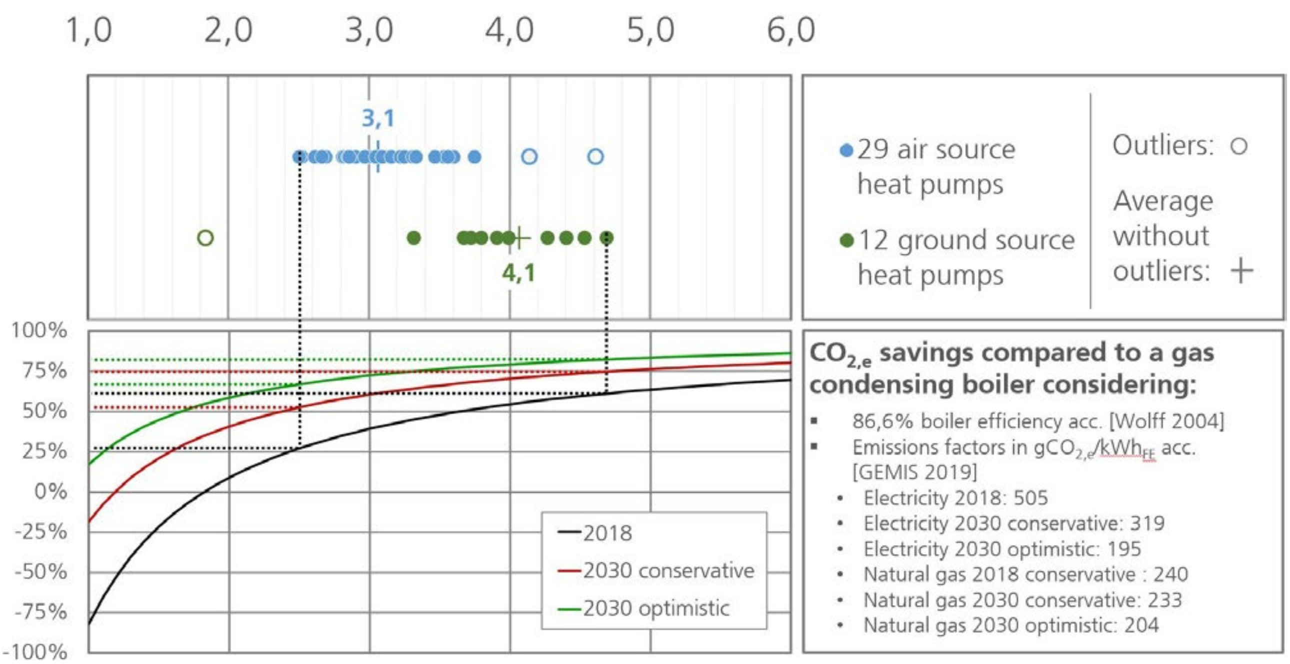

Figure 5. SPF of the investigated ambient air and brine heat pumps and their mean value as well as an estimation of the reduction in emissions (CO_2 equivalents) compared with a gas condensing boiler, taking into account the lowest and highest SPF (without outliers) for electricity/natural gas parameters for the years 2018 and 2030 in Germany [ISE 2020b].

The maximum temperatures provided by the heat pumps (daily average) for SH reach from 35/30°C to 65/57°C (average 45/39°C) and were measured at an average ambient temperature of merely −3,4°C. Subsequently, the required heating temperatures at design ambient temperatures (e.g. −12 to −16°C) would have been higher. However, significant in terms of SPF values are the average heating circuit temperatures during the operation. Those values are indicated as energy weighed average values of supply and return temperatures and reach from 30°C to 43°C (average 36°C) for the ASHP and 31°C to 52°C (average 39°C) for the GSHP. This shows that the estimation of SPF values for space heating in the project planning phase does not rely solely on the heating temperature according the design ambient temperature but on the necessary average space heating temperature based on the heating curve and the expected average ambient temperature. Those ambient temperatures were measured with 4°C in average.

The final energy consumption of the electrical back-up heater plays a minor role in terms of efficiency influence. For 11 of the 29 ASHP the back-up heater was set in operation for SH or DHW production. For five of these systems the relative electrical work of the back-up heater – related to the compressor work – was higher than 2%. For GSHP only 2 systems used the back-up heater. Significant back-up heater operation was only detected with activated legionella mode, with wrong parametrization or defect of heat pumps (once).

The lower part of **Figure 5** shows an estimation of greenhouse gas savings compared to a gas condensing boiler system. This is based on a simplified balance approach based on annual data [ISE 2020b]. As SPF bandwidth the efficiency values of the heat pumps with the lowest and the highest SPF values 2.5 and 4.7 (without outliers) are considered. The boiler´s efficiency is assumed with 86.6% based on the higher calorific value and is also determined within a field measurement project [Wolff 2004]. Considering the emission factors for 2018 in Germany the savings are between 27% und 61%. According to the presumed future emission factors the positive contribution of the increasing share of renewables in the electricity sector can be seen. With a conservative expansion scenario, the savings would reach 53% to 75%. The optimistic scenario, based on national climate protections plans with the ambitious goal of greenhouse gas reduction of 95% until 2050, savings would reach values from 67% to 82%.

Summary and Further Research

Compared to previous measurement campaigns [ISE 2011, ISE 2014] obvious malfunctions and faults – recognizable during the measurement – appeared rather seldom. The results from the measurements in context of the buildings showed, that renovation of the buildings to a standard for new building is not necessary to operate heat pumps ecological reasonable. The construction year of the building should not be an exclusion criterion for heat pump applications. The significant parameter is the necessary temperature level for space heating and thus the individual conditions according to the specific heat load and the type and dimensioning of the heat transfer systems. In this regard the efficiency prognosis – and thereby the ecological and economical values – should base on medium heating circuit temperatures and not on design temperatures. ■

Acknowledgement

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