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Detailed efficiency analysis for heat pumps in existing single-family houses within a large-scale field test

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Abstract

The study presents the main results of the efficiency analysis from the field measurement "WP-QS im Bestand" in which 77 heat pumps in existing single-family houses (built between 1826 and 2015; for the efficiency analysis, buildings up to 2001 were considered) were examined in detail using appropriate measurement technology. For 49 air-source heat pumps, seasonal performance factors (SPF; generator efficiency, combined for space heating and domestic hot water) between 2.6 and 4.9 were determined, with an average of 3.4. The 13 ground-source heat pumps investigated achieved SPF values from 3.6 to 5.4, with an average of 4.3. The assignment of the measured objects to different building age periods showed no significant correlation between efficiency and building age. The determined annual efficiency factors in space heating mode range from 0.44 to 0.52 for nine ground-source and from 0.32 to 0.44 for 49 air-source heat pumps. The reduction in greenhouse gas emissions compared to a gas boiler as reference system - considering time-variable factors such GHG emissions of the electricity and the electrical loads of the heat pumps - amount to 58% in 2023 and 64% in 2024.

Keywords: Heat pumps; field measurement, existing buildings, seasonal performance factors, efficiency factors, GHG-emissions

1. Introduction

The significant role of heat pumps (HPs) in decarbonizing the building sector has been comprehensively described in recent years, among others in [1, 2]. To achieve this ambitious goal, it is essential to implement heat pump technology in the existing building stock as well. In this area of application, the stakeholders are faced with a more complex situation than in new buildings. This is primarily because the initial situation (e.g. the building's heating load, existing heat distribution systems, and hydraulics) must first be investigated before an ecologically and economically appropriate supply concept can be developed. At the same time, there are still prejudices against heat pump technology in existing buildings. At this point, the projekt "WP-QS im Bestand" ties in, which was completed at the end of 2024 and funded by the Federal Ministry for Economic Affairs and Energy (BMWE, funding reference number 03EN2029A). One of the main objectives of the project is to analyze the efficiency and operation of electrically driven compression HPs in existing single-family homes as part of a broad-based field study [3].

The focus of this study is the efficiency analysis regarding the determined Seasonal Performance Factors (SPF) and Carnot Efficiency Factors (CEF). Finally, a comparative assessment of greenhouse gas (GHG) emissions is carried out. The evaluation includes 49 air-source (ASHP) and 13 ground-source heat pumps (GSHP) with ground probes. Due to the higher number of systems, the deeper evaluation of the SPF values is limited to the group of ASHPs. Seasonal performance factors of HPs in existing buildings based on field measurements were also determined in [4], among others. In this field study, 36 GSHPs and 35 ASHPs were examined. The average SPF of the ASHPs was 2.6, with a range from 2.1 to 3.4. For the 26 GSHPs with ground probes, the SPF values ranged from 2.1 to 4.4, with an average of 3.3. The distinction from this study lies in the largely unrenovated buildings and the much earlier measurement period (2008 and 2009). In the field study

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[5], 29 ASHPs and 12 GSHPs with ground probes were measured in existing buildings from July 2018 to June 2019. Here, the ASHPs (GSHPs) achieved SPF values from 2.5 to 3.8 (3.3 to 4.7), with an average of 3.1 (4.1). The condition of the buildings is comparable to that in the present study. The distinction from [5] is the measurement of a newer generation of HPs, particularly regarding the devices' power control. In [6], sensor data from 1,023 HPs from one manufacturer in 10 European countries were analyzed. There, 883 ASHPs (124 GSHPs) achieved average SPF values in space heating mode of 4.03 (4.90) and in domestic hot water mode, 753 ASHPs (120 GSHPs) achieved average SPF values of 2.95 (3.13). Due to the simplified measurement, this study differs from the present one. However, the large number of objects measured leads to statistical relevance of the results. Furthermore, [6] does not distinguish between new and existing buildings.

CEF values in the present study were determined for nine GSHPs and 36 ASHPs. Comparative values based on field measurement results were also calculated in [4]. These ranged in heating mode for the GSHPs (ASHPs) from 0.38 to 0.46 (0.28 to 0.44), with an average of 0.30 (0.42).

Regarding the targeted sector coupling, the electricity demand of HPs should preferably be met from renewable sources such as wind power or photovoltaics (PV) to achieve the intended reductions in GHG-emissions in the building sector. To reflect this requirement the assessment of the GHG-emissions in this study considers time-variable factors: ¼-hour GHG-emissions of the electricity and the electrical loads of the HPs.

2. Methodology

2.1. Monitoring Concept

The project "WP-QS im Bestand" was carried out from December 2019 to the end of 2024 in collaboration with nine heat pump manufacturers and two energy suppliers. The measurement objectives aimed to determine the generator and system efficiency of the systems - both for the entire operation and separately according to operating mode space heating and domestic water heating. To be able to indicate different balance limits, the separate measurement of the electrical consumers compressor, control system, heat source drive, and heating element was targeted. To enable operational analysis, measurement data were recorded every 30 or 60 seconds. The measurement concept is based on the installation of heat meters (HM) directly after the heat pump, after the domestic hot water storage tank, and - if available - after the buffer storage tank for space heating. The HMs record energy, power, volume flow, as well as supply and return temperatures. Due to the design of the systems, individual wiring diagrams, or other special circumstances, the planned measurement concept could not be implemented uniformly for all systems. Deviations from the standard measurement concept occurred, for example, with direct condensation in the domestic hot water storage tank (no measurement of charging) and compact units (in some cases, no measurement of charging of the integrated thermal storage). The outdoor temperature was either measured on side or measurement data from the nearest German Weather Service weather station were used. More detail on the monitoring process is given in [3].

2.2. Balance Boundaries for SPF Evaluation

The efficiency of the HP in real operation is described by the Seasonal Performance Factor (SPF), which is the ratio of measured delivered thermal energy to measured consumed electrical energy. The system boundaries for determining the SPF must be defined according to the objectives of the respective efficiency analyses. For ease of understanding, the system boundaries used in this study are shown in Figure 1.

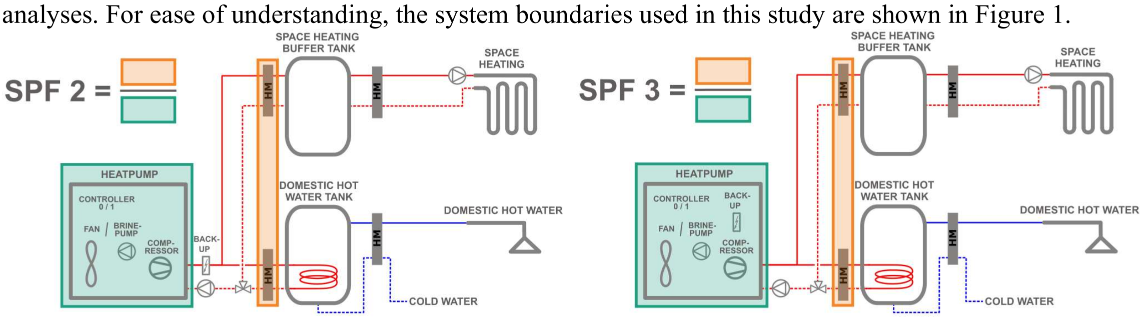

Figure 1: Illustration of the system boundaries for determining SPF 2 and SPF 3 using the example of a simplified schematic of an air-source heat pump system.

The CEF described in Section 4.2 are based on SPF according to system boundary 2. It includes the electrical energy consumption of the compressor, controller, and brine pump or fan. Only the energy provided by the heat pump before any storage tanks is considered as thermal output. System boundary 3 is used to calculate SPF 3, as presented in Section 4.1. Additionally, this considers the electrical energy consumption and the thermal energy provided by the electric heater. For both system boundaries, the thermal energy used for defrosting (reversal of the refrigeration cycle) is subtracted from the heat provided when calculating the SPF. These system boundaries are based on the definitions established in the EU project SEPEMO [7].

2.3. Weather conditions during the evaluation period

The evaluations for SPF 3 in Section 4.1 cover the year 2024, while those for the CEF in Section 4.2 cover the heating period from November 2023 to March 2024. Figure 2 illustrates the weather conditions during both evaluation periods. On the left of Figure 2 the climate factors indicate that heating demand would have been 27 % (07/23 – 06/24) and 20 % (2024) higher in a meteorologically average year [8]. This results in lower mean temperatures for space heating (heating curve control) and lower energy shares for space heating. The plots on the right of Figure 2 show the courses of the hourly values of outdoor air temperature - as an average across Germany [9] – over the evaluation periods. This figure is used to display cold periods for evaluating the operation of electric heaters. Temperatures below 0°C occurred for an extended period only at the beginning of December 2023 and in January 2024. Outdoor air temperatures below -5°C are marked in red and occurred only at the beginning of January 2024. It should be noted that the average values shown smooth out the extreme temperatures. Cold spells may also occur regionally or at different times. In addition, regarding general operating concepts for monoenergetic heat pump systems, it can be assumed that the use of electric heaters during the evaluation period is lower than in a long-term reference year.

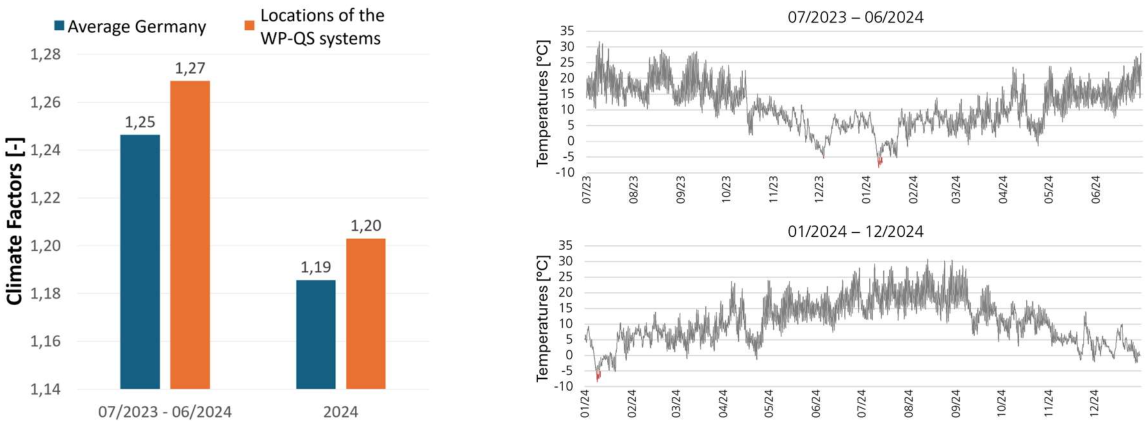

Figure 2: Climate factors [8] during the measurement period as an average for Germany and as an average for the regions of the system locations (left), as well as outdoor air temperatures as average hourly values for all of Germany [9], for the measurement periods 07/2023 to 06/2024 and 2024. Hourly values below -5 °C are shown in red.

2.4. Calculation of GHG-Emissions Considering Time-variable Factors

The hereafter considered time-variable factors are the electrical loads of the heat pumps (HP) and the GHG-emissions of the electricity production each with an ¼-hour time step. The analysis was conducted for the years 2017 to 2024. For the entire period, electricity data from the Fraunhofer ISE Energy Charts [15] were used. The measured load profiles of the HP-pool from 2023 and 2024 were applied. For the assessment of the years 2017 to 2022, a simple regression model considering the correlation between the electrical load and the outdoor air temperature was build based on 2023 and 2024 data. By using the outdoor air temperatures from 2017 to 2022, the electrical load profiles for the HP-pool could be determined according to the model.

The electrical heat loads of the HPs correlates to the SPF3 boundary condition as shown in Figure 1 and considers the compressor, the heat source drive (brine pump or fan), and any electric heating rods. To minimize the error in the intra-annual weighting of the emission factors (EF) while taking as many systems as possible into account, 40 HPs were selected for the pool considered here, considering data gaps. On average, the data gaps across both years are 0.63%, and a maximum of 3.77% per system and year. All building age classes from "up to 1859" to "2002 to 2009" are represented by at least two and up to seven HPs. No restrictions were made regarding the characteristics of the systems. Regarding properties that influence the HP load profile, the HP pool is characterized as follows: 28 HPs use outdoor air as a heat source and 12 HPs use the ground. Eight HPs are bivalent and equipped with a boiler, 34 are monoenergetic and have an electric heating rod. Six HPs are optimized for self-consumption of PV electricity. Regarding power modulation, 29 HPs are inverter-controlled, four are multi-stage, and seven have no power control.

To calculate the ¼-hour GHG-emission factors for electricity production in Germany, corrections for export and import, the specific GHG-emissions resulting from load coverage by pumped storage power plants, and losses incurred up to the delivery of electricity at the consumer low-voltage level were all considered. The GHG-emissions (EM) caused by the HP-pool are calculated according to Eq. 1 by weighting the ¼-hour emission factors of the electricity production (EF_{EL}) with the corresponding load of the HPs (P_{HP}). Finally, taking into account the thermal energy provided by the HPs ($Q_{th,HP,year}$) the emission factors on the thermal energy level ($EF_{HP,Th,Dyn}$) were calculated according Eq. 2.

$$EM_{GHG,HP,Dyn,Year} = \sum_{t=0}^{35040} EF_{El}(t) \cdot P_{HP}(t) \quad (1)$$

$$EF_{HP,Th,Dyn} = \frac{EM_{GHG,HP,Dyn,Year}}{Q_{th,HP,Year}} \quad (2)$$

The procedure for calculating the dynamic GHG-emissions is detailed explained within [14].

3. Characterization of the Data Basis

3.1. Heat Pumps and Heat Sources

Throughout the “WP-QS im Bestand” project, the following systems were measured: 55 outdoor-air heat pumps; five systems with both outdoor- and indoor-air heat pumps; 16 ground-source heat pumps with ground probes; and one groundwater heat pump. Of these, the results from 49 air-source and 13 ground-source heat pumps are included in this study. Factors reducing the data basis include e.g. missing measurement data during the evaluation period or measurement positions deviating from the system boundary (c.f. section 2.1).

The heat pump units examined differ in various characteristics. Of air-source heat pumps (ASHP), 80% are inverter-controlled, 12% are two-stage, and 8% are fixed-speed units. Ten of the ground-source heat pumps (GSHP) have inverter control, while the remaining six (38%) are fixed-speed. The installation years for ASHPs are between 2012 and 2023, with one outlier installed in 2006. The nominal performance coefficients according to DIN EN 14511 under standard conditions A2/W35 range from 3.2 to 4.6. The performance coefficients of the newer units are on average higher than those of the older heat pumps. The GSHP were installed between 2011 and 2021. The nominal performance coefficients (B0/W35) of the GSHPs range from 4.3 to 5.0, clearly exceeding those of the ASHPs on average. For the entire sample of 77 heat pumps, 46 units use R410A, four units use R404A, and eight units use R407C. Refrigerants with a GWP below 1000 were used in about a quarter of the systems. Of these, nine units contain R32, four units contain R454C, and six units contain the natural refrigerant propane (R290).

3.2. Additional Heat Generators

For the heat generators used in addition to the heat pump, a distinction is made between those integrated into the heating system and autonomous heat generators. In the systems examined here, integrated heat generators include electric heaters, solar thermal systems, gas, oil, and pellet boilers, as well as tiled stoves with water pockets. The following information also refers to all 77 measured objects studied.

In 61 (84%) of the systems, the electric heaters are used as auxiliary systems for both domestic hot water (DHW) and space heating (SH). In five systems, the electric heater is used only for DHW, and in one system only to support SH. Ten systems do not have an electric heater installed. However, only four of these ten systems are designed as monovalent, meaning they have no additional heat generator. These are two air-source and two ground-source heat pumps. Six of the ten systems without electric heaters have a boiler as an additional heat generator. Nine systems have a solar thermal system in addition to a heat pump, which primarily supports DHW.

The following are autonomous heat generators that are not integrated into the central control and hydraulic systems. In four buildings, an instantaneous water heater is additionally installed for DHW (e.g., in a converted attic). The electric energy consumption of these water heaters was not measured. In 38 buildings, wood-burning stoves or similar are present in a living room. Most of these stoves are not used very often, if at all.

3.3. Buildings and Heat Transfer Systems

Of all 77 buildings, 58% were built up to 1978, 25% between 1979 and 1995, 16% between 1996 and 2009, and one building dates from 2015. The newer buildings were included in the project with a focus on PV-optimized systems. The analysis for SPF 3 includes only heat pumps installed in buildings constructed up to 2001. According to the information in [3], the age structure of the buildings studied here is similar to the German stock of single- and two-family homes. To classify the renovation measures carried out on the buildings studied, the following compares these with the statistical data from the 2016 residential building stock survey [10]. Although these statistical data are not currently up to date, they are considered sufficiently meaningful for comparison due to the longevity of the building stock and the low annual renovation rates. The list gives the share of building components with subsequently installed thermal insulation or replaced windows for buildings constructed before 1979:

- Component: “WP-QS im Bestand” | building stock (SFH, 2FH) in Germany [10]
- Roof: 82 % | 59 %
- Wall: 56 % | 35 %
- Cellar: 28 % | 16 %
- Window: 95 % | N/A

The comparison shows that the buildings constructed before 1979 examined in the “WP-QS im Bestand” project have higher renovation rates for all components than the national average. Buildings constructed after 1979 have hardly undergone any significant energy-related renovations.

The use of heat transfer systems in the examined buildings is heterogeneous. In each of around a quarter of the buildings, either radiators (e.g. sectional or panel) or surface heating systems are installed. Around half of the buildings use both radiators and surface heating systems. Fan coil units are used in three buildings. While this distribution is not representative of existing buildings in Germany, it can be assumed that heating existing single-family homes with different heat transfer systems is quite common.

4. Results

4.1. Evaluation of Seasonal Performance Factors

4.1.1. Overall Assessment

Due to current market relevance and the number of systems examined, the efficiency analysis focuses on heat pumps with outside air as the heat source. Nevertheless, it should be noted at this point that the 13 ground source heat pumps achieved SPF values of 3.6 to 5.4, with an average of 4.3 (further information in [3]). Anyway, this section focuses on the seasonal performance factors (SPF) according to system boundary 3 (cf. Section 2.2) of 49 ASHP that could be evaluated for the year 2024, in relation to building age, the energetic quality of the buildings, and the heat transfer systems.

Figure 3 clusters the results of these objects by construction period and sorts them in ascending order according to SPF 3 within each group. Each measured object is assigned an ID number. Characteristic properties – such as additional boiler, type of heat transfer systems, level of renovation - are indicated in the figure using different markers. A building indicator is used to simply represent the energetic quality of the building envelope in its original state and current state. The color coding is based on the threshold values of the thermal insulation regulations from 1977 and 1995. The exact methodology for determining the building indicator can be found in [3].

The SPF 3 values (gray columns) of these ASHP systems span a wide range: across all systems from 2.6 (ID 579, 529, 556) to 4.9 (ID 555); the average is 3.4. The average share of electricity consumed by the electric heater is less than 2% of the total consumption in a heat pump system (orange-black stacked columns) which accordingly means a minor impact on the efficiency. Anyway, considering individual systems this influence can be considerably higher. For six systems, a still moderate electric share of 2% to 4% was determined. Significant shares of electric heater operation were found for systems ID 600 at 15% and ID 540 at 17%. These high shares are mainly due to DHW production in PV-optimized operation (ID 600) and electric heater use during a several-week heat pump failure (ID 540). For eight of the ten bivalent systems, the boiler's share in heat supply could be determined (gray-green columns). The contribution of the boiler varies widely, from 6% (ID 545) to 46% (IDs 575 and 577), indicating markedly different remaining operating conditions for the heat pumps (HPs). These variations subsequently affect the individual SPF values.

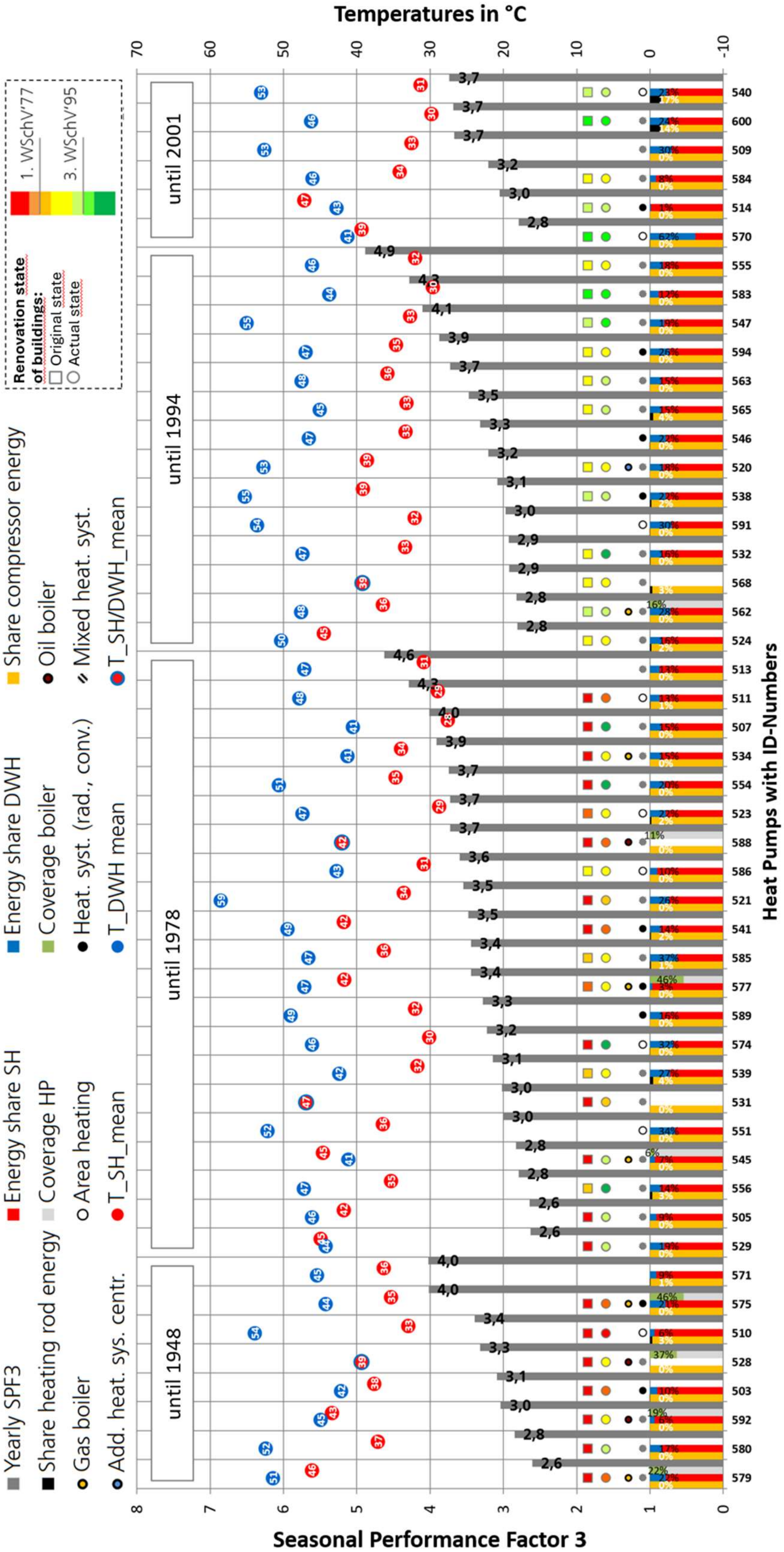

Figure 3: SPF 3 in the context of building characteristics in the original and current state for 49 air-source heat pumps, grouped by construction periods and sorted by efficiency values.

The operating temperatures of the heat pumps are given as the mean of energy-weighted supply and return temperatures. Where possible, the operating modes space heating (SH, red) and domestic water heating (DHW, blue) are distinguished. If the operating modes SH and DHW could not be distinguished by measurement (as in ID 528), the red circle with a blue border represents the energy-weighted average sink temperature across both modes. Averaged over all systems that can be evaluated separately, the mean temperature for SH is 36 °C, ranging from 28 °C (ID 507) to 47 °C (ID 514). These values, which at first glance may seem low, are due to the very different renovation states of the buildings, a high variance in the sizing of the heat transfer systems, the bivalent-alternative operation of some boilers at low outdoor temperatures, and the comparatively high outdoor temperatures in 2024. In addition, the maximum SH supply temperatures of the HPs measured in 2024 has been evaluated, based on one-minute values. Only heat pump operation was considered, without the influence of the boiler or heating rod. The maximum supply temperatures (not shown in the figure) range from 33 °C (ID 511) to 68 °C (ID 505), with an average of 49 °C. The temperature at which the heat pumps supply energy for DHW is - except for three systems - higher than for SH. The average temperature for DHW across the systems is 48 °C, ranging from 41 °C (ID 545, 534, 507, 570) to 59 °C (ID 521). The explicit influence of these very different operating temperatures on efficiency is discussed in more detail in Section 4.1.3.

The energy provided by the heat pump is assigned to the operating modes SH and DHW. In Figure 3 their shares are shown in a stacked column in red (SH) and blue (DHW). The energy share of the operating modes describes how strongly each mode influences the overall efficiency. On average, the DHW share across all systems is 19%, ranging from 1% (ID 514) to 62% (ID 570). Except for the systems ID 514, 545, and 529, where the average temperature for SH is higher than for DHW, an increasing DHW energy share reduces the average SPF. Two aspects must be considered when interpreting the values. Eight systems use a combination storage tank; charging in the upper storage area is assigned to DHW, and charging in the lower area to SH. In several combination tanks, the storage zones and their heat use are clearly separated; in others, DHW is mainly supplied via charging of the lower zone (ID 514, DHW share 1%), or heat for the heating circuit is also partly supplied via charging of the upper zone (especially ID 570, DHW share 62%), cf. [3]. Additionally, it should be noted that in bivalent systems, the boilers might not cover the same share of SH and DHW, cf. [3]. In systems with a solar thermal system, the DHW share supplied by the heat pump is lower. Furthermore, the different specific heating loads and the individual DHW system designs (storage concept and parameterization (setpoint, hysteresis)), influences the DHW share.

The values presented the key factors influencing efficiency as measured during HP´s operation. Other values in this category would include, for example, the electrical energy consumption of the control system or the heat source drives, which were only determined separately for a few plants in the study and are therefore not listed here. Another significant factor influencing efficiency is the nominal performance coefficients (COP values), which vary greatly in the sample, as discussed in more detail in section 3.1. This illustrates that there are many efficiency factors within the scope of heat pump use in existing SFH alone, which also vary greatly, and this must be taken into account in the planning, installation, commissioning, and operating phases.

4.1.2. Focus on Building Characteristics and Individual Aspects

Regarding construction periods, it becomes clear that, in the sample studied, no dependencies exist between heat pump efficiency and building age. The average SPF 3 values per construction period range between 3.3 and 3.5 and are thus close together. The range of SPF 3 values per construction period also shows comparable variance in all periods.

In the period up to 1949 (eight systems), all buildings for which information was available were energetically renovated, and the building indicators in the current state range from the threshold values of the 1977 thermal insulation regulation to a range between the 1977 and 1995 regulations. The average temperature for SH is 38 °C, slightly above the overall average of 36 °C. Only systems ID 579 and ID 592, which are equipped with surface heating and radiators, provide significantly higher SH temperatures of 46 °C and 43 °C, respectively. The two systems (ID 503 and ID 575), using only radiators, operate at an average SH temperature of just 38 °C and 35 °C, respectively. In system ID 510, renovation included a complete conversion to underfloor heating, reflected in the low average SH temperatures of 33 °C. The high share of bivalent systems in this period - four out of eight systems also equipped with a boiler - is advantageous regarding the average SH temperatures.

All 18 (out of 21) buildings from the construction period 1949 to 1978 that could be evaluated in this respect were also energetically renovated, with the range of building indicators in the current state extending from the 1977 thermal insulation regulation up to and beyond the threshold of the 1995 regulation. The average temperatures for space heating (SH) are 35 °C, slightly below the overall mean of 36 °C, with a range from 28 °C to 45 °C. The five systems with surface heating, except for ID 551 (36 °C), operate at very low average temperatures from 29 °C to 31 °C and, with regard to SPF 3 values, are distributed almost across the entire range. In contrast, the SPF 3 values of the systems with radiators as heat emitters fall into the middle range, with the lowest SPF 3 of 3.3 achieved by a system operated at an average of only 32 °C in SH mode. The highest average SH temperatures of 45 °C were determined for two systems using radiators as well as surface heating. The SPF values of both heat pumps are correspondingly below average - at 2.6 (ID 529) and 2.8 (ID 545). Only four of the 21 systems additionally used a boiler.

The buildings from the construction periods 1979 to 1994 and 1995 to 2001 were already required to comply with the respective requirements of the Thermal Insulation Regulation, as reflected in their original building indicators. Only ID 532 underwent significant energy renovations. In the construction period 1979 to 1994, the average SH temperature was 35 °C, slightly below the previously mentioned overall average of 36 °C. The range extends from 30 °C to 45 °C. The objects in this period are also dominated by buildings using different types of transfer systems. These HP systems were operated at average SH temperatures between 30 °C and 45 °C, while the three systems usind only radiators are supplied at only 33 °C, 35 °C, and 39 °C. Only two of the 14 systems also have a boiler. The six systems, which are installed in houses build between 1995 to 2001 are operated at an average SH temperature of 36 °C, corresponding to the average for all systems. The ranges are similar to those in the other construction periods, from 30 °C to 47 °C. Thus, the highest SH temperature is found in the most recent period, with system ID 514 at 47 °C. This value even exceeds the average DHW temperatures, while the energy share for DHW mode is only 1%. The low share of DHW mode is due to the integration of a combination storage tank. Since the SH temperature is higher than the required DHW temperature for much of the year, the upper storage zone is also heated by the lower zone due to thermal lift. Despite these conditions, the heat pump with radiators achieves an SPF 3 of 3.0. The range of SPF 3 values would be similar to those in the other periods if the two systems with significant use of electric heaters (ID 600 and ID 540) did not fall into this category.

The results show that it is not the year of construction but rather the individual requirements, coupled with integrated planning that takes into account the building, heat transfer system and heat generator in equal measure, that determine the final efficiency.

4.1.3. Focus on Operating Modes: Space Heating and Domestic Hot Water

In Figure 4, the efficiency values are plotted against the respective sink temperatures. In the plot on the left, all 49 ASHPs are considered throughout their entire operation, while the plot on the right distinguishes between the operating modes space heating (red) and domestic hot water (blue) for a reduced number of 25 (SH) and 18 (DWH) systems, respectivly. In the overall operation, the SPF 3 values range from 2.6 to 4.9 over average sink temperatures from 30 °C to 47 °C. A dependency between the two parameters is apparent, but only to a very limited extent. This is illustrated by examining the SPF 3 values within each 5 K bin. In the temperature clusters of “30 °C - 35 °C” (“35 °C - 40 °C”; “40 °C - 45 °C”), the SPF 3 values range from 3.1 to 4.9 (2.8 to 4.1; 2.6 to 3.7).

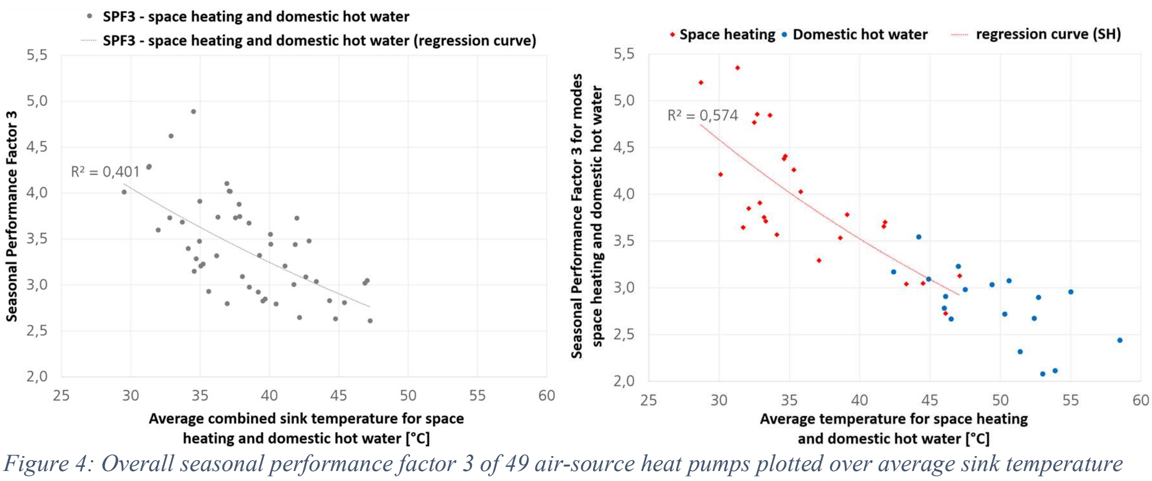

Figure 4: Overall seasonal performance factor 3 of 49 air-source heat pumps plotted over average sink temperature (left); seasonal performance factor 3 in space heating mode (red) of 25 ASHPs and domestic hot water mode (blue) of 18 ASHPs plotted over the respective average sink temperature (right).

For the subset of 25 ASHPs for which a separate SPF value could be determined, at least for SH mode, the overall SPF 3 is 3.4 on average. The average SPF 3 in SH mode is 3.9, with a range from 2.7 to 5.4. These values are distributed over average SH temperatures from 29 °C to 47 °C. The separate analysis of the SH mode results in an increase in the statistical relationship between efficiency and sink temperature, as confirmed by a higher coefficient of determination of 0.57. In [6], this correlation is determined to be 0.49 for a much larger number of systems. Nevertheless, in the temperature cluster " 30 °C - 35 °C", there is a very wide SPF 3 range, with values from 3.6 to 5.4.The average SPF 3 in DWH mode is 2.8, with a range from 2.1 to 3.5. The low SPF3 values compared to SH mode are mainly due to the generally higher average sink temperatures in most cases.

The results confirm the advisability of operating heat pumps at the lowest possible temperatures, although there are still other significant efficiency factors to consider with regard to the shown SPF bandwidths.

4.2. Assessment of Carnot Efficiency Factors

In this study, the Carnot Efficiency Factors (CEFs) are determined based on annual values. The Carnot COP is used as the reference value for the CEF with the inlet temperature on the source side and the average of the inlet and outlet temperature on the sink side. The evaluation considers SPF 2, cf. section 2.2. On the thermal side, the heat supply from the HP (before storage), and on the electrical side, the energy consumption for the compressor, control system, and source drive is considered. There are many factors that influence the CEF defined here. With regard to the design of the HP, these include in particular: the heat source (outside air vs. brine), the heat exchanger layout, the compressor specification, other refrigeration circuit components, type of refrigerant (e.g., with/without glide), oil (viscosity), type of power control (inverter, fixed speed, etc.) and auxiliary energy (source drive, etc.). During operation, the temperatures of the heat source and heat sink, the temperature spread, the mass flow, the speed of the compressor and the thermal power all influence the CEF value. When considering the results, it must be taken into account that the CEF value is not determined for (quasi)stationary conditions but is based on annual values - an average of different operating conditions. The blurring of the results increases with rapid temperature changes and short operating cycles, among other things.

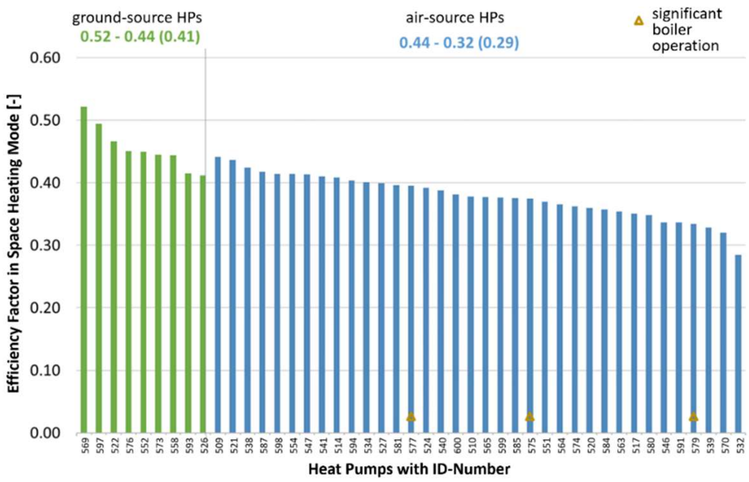

Figure 5: Carnot Efficiency Factors of ground source and outdoor air heat pumps in space heating mode (Evaluation period: November 2023 to March 2024)

Figure 5 shows the annual CEF values in space heating mode for nine GSHP pumps and 36 ASHP. The annual CEF for space heating of the GSHPs ranges from 0.44 to 0.52, with an average value of 0.46. For the ASHPs, the values range from 0.32 to 0.44, with an average value of 0.39.

In Figure 6, the nominal coefficient of performance (COP, EN 14511) of the HPs is included in the analysis of the CEF. In this figure, CEF in SH mode of the ASHPs is plotted against the average temperature difference between sink and source side. The color of the points corresponds to the COP of the HPs at operating point A2/W35. No correlation between the temperature difference and CEF can be identified in this sample. The expected correlation between the COP and CEF is slightly visible. Without considering the fixed-speed and two-stage heat pumps, which are in the lower CEF range here, the following ranges for CEF can be seen. In the system groups with high COPs (4.2 to 4.4 [dark green] and 4.0 to 4.2 [light green]), the CEF values range from 0.35 to 0.44 and 0.37 to 0.43, respectively. In the system group with the lowest COPs (< 3.8 [red]), the CEF values range from 0.33 to 0.38. The CEF values of heat pump units in the middle COP range (3.8 to 4.0 [yellow]) cover almost the entire range of CEF from 0.28 to 0.42.

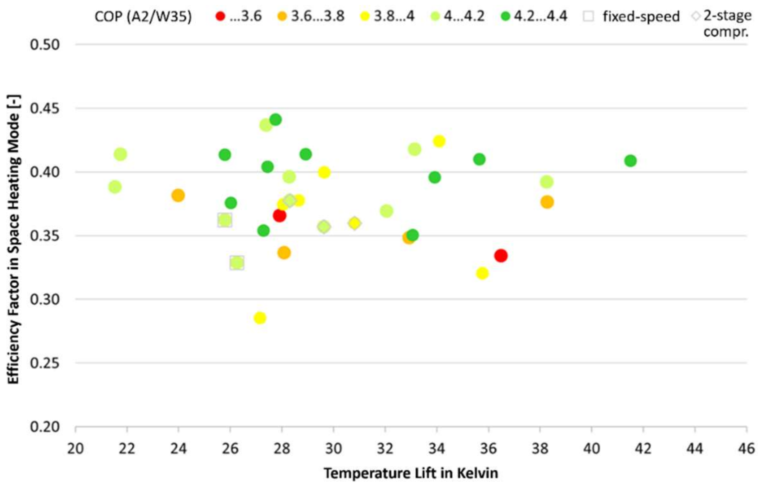

Figure 6: Annual CEF values from ASHPs applied over the average temperature difference between sink and source side during space heating mode. Different compressor designs and power control are highlighted in colour, as is COP(A2/W35). (Evaluation period: November 2023 to March 2024)

Compared to [4] with a measuring period from 2008 to 2009 the average CEF improved by 10% for GSHPs and 30% for ASHPs, which points to technological developments, particularly for ASHPs.

4.3. Evaluation of GHG-Emissions

The approach for determining GHG emissions considering time-varying factors, as explained in chapter 2.4, is hereinafter referred to as the dynamic method, while the classical annual balancing method is referred to as the static method.

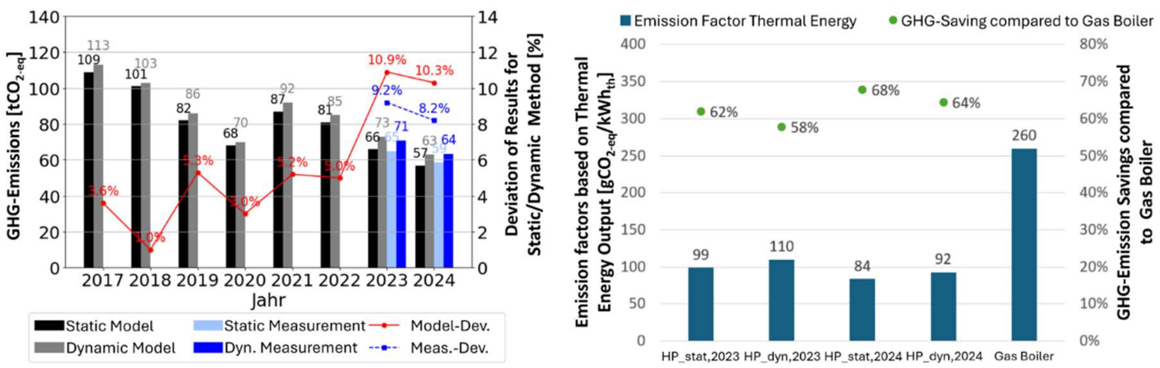

*Figure 7: **Left**: Results of the static and dynamic analysis of GHG emissions, including absolute values in tonnes and relative differences between both approaches. The model-based method is applied for 2017 to 2024, while the measurement-based method is used for 2023 to 2024; **Right**: Thermal-energy-based emission factors of the heat pump pool based on measurement data from 2023 and 2024 in comparison to the gas boiler*

Figure 7 on the left shows the absolute GHG-emissions of the heat pumps for the years 2017 to 2024, differentiated by static and dynamic methods as well as model-based (shades of grey) and measurement-based (shades of blue) data. Regardless of the accounting method, the GHG-emissions of the HP pool are developing positively. While in 2017 emissions were still 109 and 113 $t_{CO_2\text{-eq}}$, in 2024 they were only 57 and 63 $t_{CO_2\text{-eq}}$, which represents a reduction of 48% and 44%, respectively. This significant decrease is mainly due to two factors. First, the emission factor of electricity decreased by 40% over the same period. Second, the electricity consumption of the heat pump pool was 13% lower due to reduced heating demand.

To assess the static and dynamic methods, the left plot in Figure 7 also shows the percentage differences. In all years considered, emissions calculated using the dynamic method are higher than with the static method. Between 2017 and 2022, moderate differences of 1.0% to 5.3% are observed. However, these differences increase significantly to 10.9% and 10.3% in 2023 and 2024, respectively. This means that, on average, heat pumps tend to operate when power plants with higher emission factors are supplying electricity. This trend appears to be increasing, as seen in the years 2023 and 2024, based on the developments in German electricity production.

The plot on the right-hand side of Figure 7 shows the GHG-emission savings compared to a gas boiler considering the 2023/24 results for the dynamic and static approach based on measurement data. Considering the static method the saving amount to 62% in 2023 and 68% in 2024. Although the dynamic assessment method results in 9.2% (2023) and 8.2% (2024) higher absolute emissions, the savings compared to a gas boiler are only slightly affected. These amount to 58% in 2023 and 64% in 2024.

Also due to the increasing deviations between static and dynamic methods the contributions of heat pumps to achieving climate protection targets should be determined using a dynamic method. This will also make it easier to address the existing potential for additional GHG savings as a result of active load shifting.

5. Conclusion

This study presents a section of the investigations carried out as part of the field measurements of heat pumps ("WP-QS im Bestand") and summarizes key findings regarding the determined Seasonal Performance Factors (SPF), Carnot Efficiency Factors (CEF), and an assessment of the results in terms of GHG-emissions considering time-variable factors. The efficiency analysis, focusing on the generator seasonal performance factor (SPF 3), which includes both operating modes (space heating and domestic hot water), is presented for the 49 air-source heat pumps (ASHPs) that could be evaluated accordingly. These achieved SPF 3 values ranging from 2.6 to 4.9, with an average of 3.4. Regarding construction period, no significant dependencies were found between the efficiency of the HPs and the building's age. The evaluation of greenhouse gas emissions clearly demonstrates the advantages of using heat pumps instead of gas boilers. Using the static method, GHG emission savings are 62% in 2023 and 68% in 2024. The savings decrease only slightly when using emissions calculated by the dynamic assessment method, amounting to 58% in 2023 and 64% in 2024. In view of the targets set for the expansion of renewable energies in the electricity sector, this advantage will continue to increase in the future. Looking at the sample studied, it can be concluded that heat pumps in buildings constructed according to the WSchV'77 or later regulations can be operated efficiently from an ecological perspective. For older buildings, this is at least also the case when they have been retrofitted close to WSchV'77 standards. For the determination of CEF values, nine GSHPs and 36 ASHPs were considered. The annual CEF values in space heating mode for the GSHPs range from 0.44 to 0.52, with an average of 0.46. For the ASHPs, the efficiency factor ranges from 0.32 to 0.44, with an average of 0.39. Compared to the study presented in chapter 1 from 2008 to 2009 [4], the average efficiency factor improved by 10% for GSHPs and 30% for ASHPs.

Based on the results, it can be concluded that heat pumps can fulfil their assigned role [1, 2] as one of the key technologies for decarbonizing the building sector. Nevertheless, it should be mentioned at this point that significant potential for optimization was identified in the research project [3]. It should therefore be emphasized that, with a view to minimizing greenhouse gas emissions and grid load, all stakeholders along the process steps of planning, installation, commissioning, as well as operation and maintenance, should exercise appropriate care to fully realize efficiency potentials.

6. Nomenclature

ASHP	Air-source heat pump(s)	HP	Heat Pumps(s)
CEF	Carnot Efficiency Factors	P	Electrical power
COP	Coefficient of Performance	PV	Photovoltaics
DHW	Domestic hot water	SFH	Single family house(s)
DWH	Domestic water heating	SH	Space heating
Dyn	Dynamic (approach)	SPF	seasonal performance factor(s)
EM	(Absolute) Emissions	Stat	Static (approach)
GHG	greenhouse gas	Th	Thermal (energy)
GSHP	Ground-source heat pumps(s)	2FH	Two family house(s)
HM	heat meters		

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