Energy monitoring of residential buildings in the Passive House city district of Heidelberg-Bahnstadt

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October 2016

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On behalf of the City of Heidelberg

Heidelberg

Co-financed within the framework of the EU project PassREg

Co-funded by the Intelligent Ener
Programme of the European Uni

- In cooperation with the municipal utilities company of Heidelberg City -

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1 Introduction

The world's largest Passive House estate is presently being built on the 116 hectare area of the former rail freight station and shunting yard. This city district will be one of the biggest zero-emission housing developments worldwide due to 100 % coverage of its heating and electricity requirements through renewable energy.

The success of the Passive House development area "Heidelberg-Bahnstadt" was tested through monitoring of some of the residential buildings. Monthly meter readings for the total heat consumption (space heating, hot water, losses etc.) were available for entire building complexes with each having over a hundred apartments (only one has fewer apartments). Detailed measurements could not be carried out with the available budget; for this reason, evaluation of the data took place in the context of so-called minimal monitoring [Peper 2012a], in which the heating energy consumption was calculated to a good approximation from these monthly averages with the aid of research results from other projects as well.

The Passive House Standard was compulsory for the entire construction, therefore in the planning phase of the building, among other things, a maximal heating energy demand of 15 kWh/(m²a) was strived for. The study by the company Techem relating to heating energy consumption in existing buildings for different construction year categories for the year 2013 is mentioned here for the purpose of comparison. According to this, buildings with district heating supply had an energy consumption of 112 kWh/(m²a) on average for space heating [Techem 2014]).

Fig. 1: Aerial view of the part of the Bahnstadt in which the buildings studied here are located (Picture: Kay Sommer / Copyright: Heidelberg City)

The study presented here will analyse the energy consumption data for heating energy for the years 2014 and 2015 and for electricity for the year 2015 in residential buildings in the Bahnstadt district which has a total of 1,400 apartments and a total area of almost 90,000 m².

Fig. 2: Views of some buildings in the Bahnstadt district (Picture: PHI)

2 District heating

2.1 Energy consumption in the Bahnstadt district in Heidelberg

The Passive House development area Bahnstadt in Heidelberg consists of several large building sites, each of which is supplied by a central district heat connection. This means that only one central district heat connection for billing purposes exists for up to five large apartment blocks. The supplier has no access to any other sub-meters in individual buildings. The main heat meters at the transfer stations were previously read by the public utilities company "Stadtwerke Heidelberg" during on-site visits roughly every six months. In the future, these electronic heat meters will be read regularly via a data network connection. The monthly meter readings took place repeatedly and were provided for evaluation to the Passive House Institute for a review of the overall functioning of the housing estate.

This consumption data is available for the building sites listed in Table 1. The treated floor area here constitutes the useable areas defined in accordance with the Passive House Planning Package (in case of apartments: living areas); when classifying the results, account must be taken of the fact that for these buildings the areas A_N on average will be ca. 28 % (25 to 34 %) larger for characteristic values determined according to the German EnEV Standard; the specific consumption values will then be accordingly lower in relation to this. To illustrate this additionally with reference to the A_N area, these consumption values are shown in Fig. 8 further below.

Table 1: Overview of the type of buildings in the studied building sites

Type	Number	Treated floor area	Number of dwelling units
Residential development	5	74 218 m²	834
Student hostel	2	15 457 m²	564

For a meaningful evaluation, the buildings must have been fully occupied or utilised for at least one year, only then will it be possible to calculate a reliable annual consumption. Up till now, analysable data of this scale was available from the building sites with residential utilisation and the student hostels. These could be analysed for the complete years 2014 and 2015. However, for three building sites this applies only to a limited extent for the year 2014, because these were fully occupied only one to three months later (January till March 2014). Exact details regarding the time of full occupancy are not available. It is not known whether the state of full occupancy in these buildings led to over-consumption or under-consumption.[1]

Fig. 3: District heating transfer stations in two of the studied buildings (Pictures: PHI)

[1] If an apartment in a building is not in use yet, then the following two variants are possible:
(I) Increased consumption will result if heating at the home level is already taking place but internal heat sources (occupants, electricity use) are not present. The activity relating to occupancy itself (such as open doors and windows) can also lead to considerable additional losses.
(II) A reduction in the consumption is also conceivable if no or reduced heating takes place before occupation of the building.

2.2 Minimal monitoring method for heat consumption

With the provided monthly readings of the central heat meter the consumptions for all heat applications are available as total values for each building site. These total values include the following consumption variables:

- Heating energy consumption
- Energy consumption for hot water
- Heat dissipation of distribution pipes (useable and non-useable)
- Transfer losses of the district heating station
- Storage losses of the hot water storage tank
- Miscellaneous, e.g. ramp heating for the entrance of the underground car park

The individual consumption variables cannot be differentiated from the total amounts of the monthly consumptions, therefore an empirical method must be used which will at least enable a good estimate of this allocation. In doing so, it should be kept in mind that the examined buildings do not have any solar heating panels and hot water generation in the residential buildings takes place completely via district heating.

In the summer months the energy expenditure for all those applications which are not related to heating of the building can be determined from the monthly consumption values. It is assumed that unintentional and undesirable heating in summer does not take place in the process. In Passive House buildings there is no distinct summer heating demand – on account of their long time constants even during "cold snaps" lasting several weeks, such buildings will still exhibit comfortable indoor temperatures without any heating at all. The month with the lowest summer consumption must not be used because some apartments may not be used in the summer due to long holiday periods. Since these are large buildings with many apartments, a slight simultaneity can be assumed in the holiday periods.

The average consumption of the four summer months (June till September) is calculated and used as the consumption variable "**Expenditure without heating**" for each month; in a Passive House building in this climate, the heating demand in these months is definitively zero. If this average consumption value for the summer is now extrapolated to the whole year, this will result in the annual expenditure for "Expenditure without heating". Fig. 4 shows this consumption for the evaluation year inside the box with the green dotted line. For the sake of abbreviation, this will be referred to as the "**base consumption**". In this building site the average summer consumption value for Summer 2014 was 3.72 kWh/(m² month). All consumption values in the other months which are now <u>above</u> the green box are assessed as the "heat consumption".

With this simplest approach, the heat dissipated by the distribution pipes is assumed to be constant in the course of the year. The forward flow temperature of district heat is determined by the demand for year-round provision of hot water. Principally, the heat dissipated by the distribution pipes is influenced by the temperature difference between the surface of the pipework and the surrounding air (e.g. basement room, underground garage).

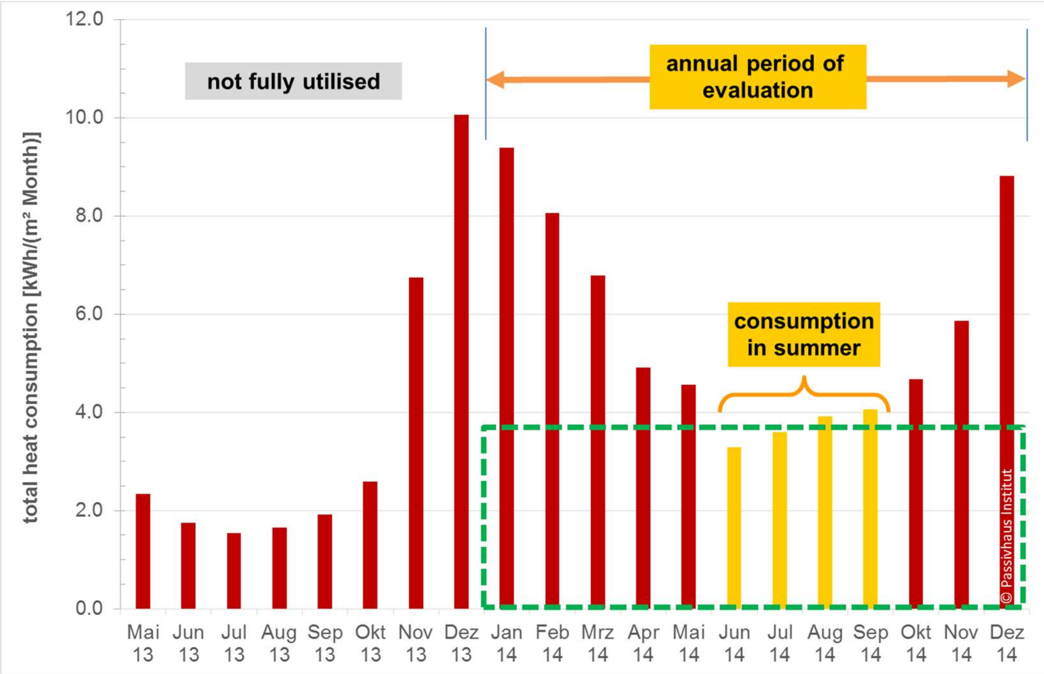


Fig. 4: Monthly consumption values for district heat in an example building site in the Bahnstadt district in Heidelberg. The method for determining the heating energy consumption is explained in the text.

According to this method, the district heat consumption for the entire building site in the example shown in Fig. 4 results as 23.3 kWh/(m²a) in a first approximation. The base consumption is 3.72 kWh/(m² month) x 12 months = 44.6 kWh/(m²a).

This type of calculation basically allows the heat consumption value to be calculated from the little measured data that is available. However, this first approximation leads to **overestimation of the heat consumption** for different reasons:

- Hot water consumption in residential buildings is lower in summer than it is in winter. The deduction for the winter is too low due to the calculation of the base consumption in summer. In a building in Ludwigshafen (Germany) with 12 apartments, an analysis of the measured data from a detailed examination that was carried out there [Peper 2012a] shows that hot water consumption in winter is ca. 10 % higher than the average summer consumption. In a first approximation, overestimation of the heat consumption would be about **1 to 2**

kWh/(m²a). In another project in Frankfurt with 19 apartments, the measured data showed an even stronger increase (by 29 %) from winter to summer. A more moderate approach with an excessive increase of 10 % from winter to summer is used in the analysis carried out here.

- Heating of the underground car park entrances for some building sites does not take place in summer and is therefore attributed to the heat consumption. An estimation of the consumption share for these building sites with central underground car parks results in values of between **0.1 and 0.3 kWh/(m²a) for heating of the underground car park entrance ramps**.
- Unwanted heating may possibly be encountered (e.g. in the month May) due to unintentional operation. These expenditures are included in the calculated "Heat consumption".[2] In the residential-use projects studied here, the heat consumptions in May which exceed the base consumption in summer are between 0.4 and 1.2 kWh/m²; **0.7 kWh/m²** on average.
- Heat dissipation from the distribution pipes in the ground and in the basement area - with largely constant forward flow temperature of the district heat - is determined by the type and quality of insulation and by the surrounding temperature of the pipes. In winter the surrounding temperatures are lower and therefore heat dissipation from heat distribution pipes increases. The increased dissipated heat in winter can be completely attributed to the heat consumption by calculating the "base heat" from the summer values. The extent of this was estimated for one of the building sites. In doing so, a distinction was made between pipe lengths in the ground and in the basement, and the linear thermal transmittances of the different pipes were taken into account. The result is a difference of 1800 kWh/a between the summer approach and taking into account of the lower temperatures in winter, corresponding with about **0.2 kWh/(m²a)**. For the sake of simplification, this value was also used for the other building sites.

Due to a first approximation ("base method"), the effects described here in total result in an overestimation of 1.4 to 2.5 kWh/(m²a) of the heat consumption **plus** the

[2] This heating energy share was consumed in May. It is known from other Passive House projects that heating in May is not necessary and is usually unintentional; often it may even lead to overheating. The heating period in an energy efficient building ends much earlier in the year, in March/April at the latest. The consumption values for May are deducted for the sake of comparability in the PHPP, but they are still included in the total district heat.

respective "unintentional" heat consumption for May. With the maximum value[3] of 2.5 kWh/(m²a) and the project-specific heat consumption for May, the overestimation results as **2.9 to 3.7 kWh/(m²a)**. In order to achieve a more realistic value for the district heat consumption for heating, this consumption must be deducted in the second approximation that has now taken place. The following heating energy consumption (second approximation) results for the building site in Fig. 4:

23.3 kWh/(m²a) – 3.3 kWh/(m²a) = **20.0 kWh/(m²a)**

The major influences that lead to overestimation of the heat consumption in this method are thus taken into account. The values of the second approximation that are thus determined again will subsequently be referred to as the "heat consumption" for the purpose of abbreviation.

In the analysis of the consumption data that was carried out here it must be considered that the achievable level of accuracy is limited. This method uses simplifications and assumptions which ensures that the level accuracy of about ± 3 kWh/(m²a) [Feist 2004] that is achievable with detailed measurements in this analysis cannot be any lower under any circumstances. The average measurement bias may be in the range of ca. ±4 kWh/(m²a). Even with this (relatively large, but in absolute terms very small) error margin, the heating energy demand of the almost 90,000 m² of useful area measured here is extremely small. It is already apparent that the Passive House project in the Bahnstadt district in Heidelberg was extremely successful.

2.3 Evaluation of the energy consumption with district heat

As already described, the meter readings of the supply meters are the starting point for the evaluation of the district heat consumptions for heating, hot water and the distribution system. Based on the treated floor area, the average value was **54.6 kWh/(m²a)** in the first annual period (2014) and **53.2 kWh/(m²a)** in the second year (2015). The average value in the second year is slightly lower because another building site (BS-05) could be evaluated which had the lowest measured value in total. When looking at the measured values of the individual building sites (Fig. 5), it becomes clear that in the second measurement year there is a moderately higher consumption for all building sites. The increase in the total consumption values ranges between 0.5 and 3.6 kWh/(m²a). In the section with the comparison of the planned values using the

[3] Bei den beschriebenen unterschiedlichen Effekten, welche zur Überschätzung des Heizwärmeverbrauchs führen, wurden tendenziell eher niedrige Werte angesetzt („sichere Seite“). Daher wird in der folgenden Auswertung die obere Grenze dieser vorsichtigen Abschätzung angesetzt.

PHPP further below, it is shown that this increase is caused by the different weather conditions during these two annual periods.

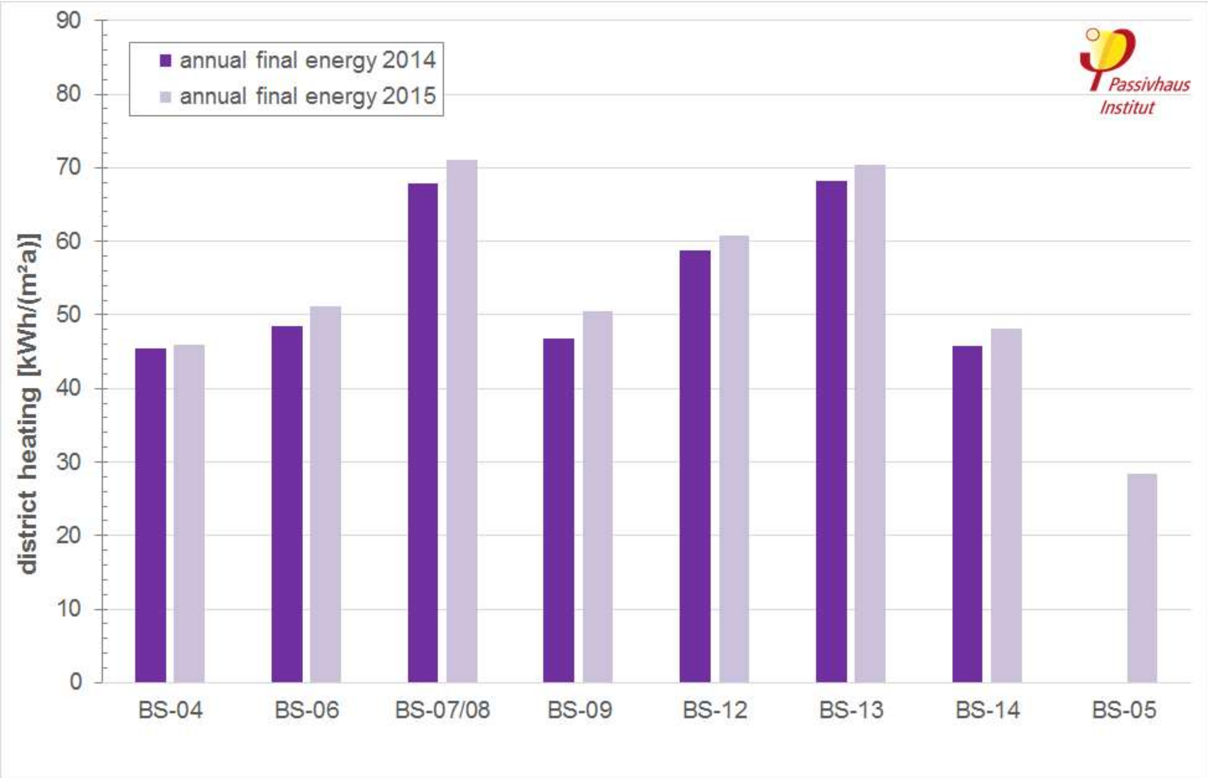


Fig. 5: Annual measured consumption values for "total district heating" for residential use (including student hostels) according to building sites for the calendar years 2014 and 2015.

Evaluation of the available data from residential use building sites took place in accordance with the method described above. The average values of the same summer months (June to September – separately for each of the building sites) were always used to calculate the base consumption values (first approximation). For adjustment of the district heat consumption for heating for the second approximation, the respective calculated values between 2.8 and 3.7 kWh/(m²a) were deducted and added to the "base consumption". This shifts the allocation of the consumption values but not their total amount.

The specific total consumption values for "district heat" of the building sites with residential utilisation and their allocation to both measurement years can be taken from the following table and the two graphs below (Fig. 6 and Fig. 7).

Table 2: Overview of the district heat consumption values and allocation to the sub-divisions of the buildings with residential utilisation in both measurement years

[kWh/(m²a)]	**2014**	**2015**
Supplied district heat	45.5 to 68.2	28.4 to 71.1
Hot water and distribution	33.0 to 48.0	19.1 to 47.9
Space heating	9.3 to 24.2	9.3 to 26.6
Weighted average value of heating energy	**14.9**	**16.4**

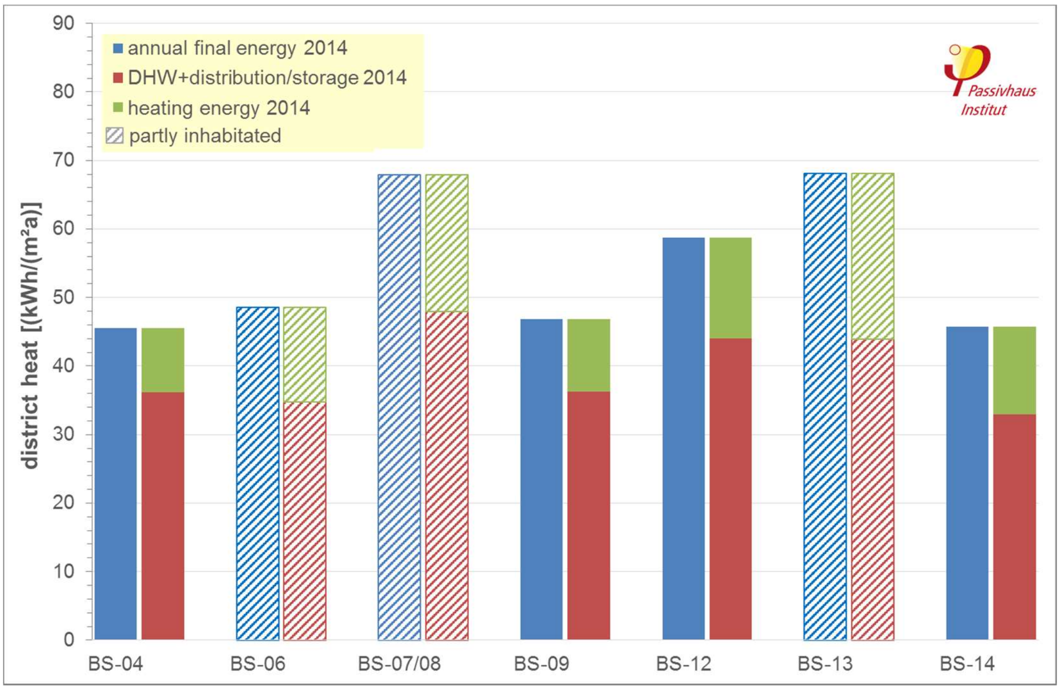


Fig. 6: Annual consumption values for district heat in 2014 for residential use buildings (including student hostels) according to building sites. The total consumption (blue) is divided into space heating (green) and the remaining consumption (red) according to the method described in Section 2.2. The building sites indicated with shading were only fully inhabited after one to three months in the year 2014 ("partly inhabited ").

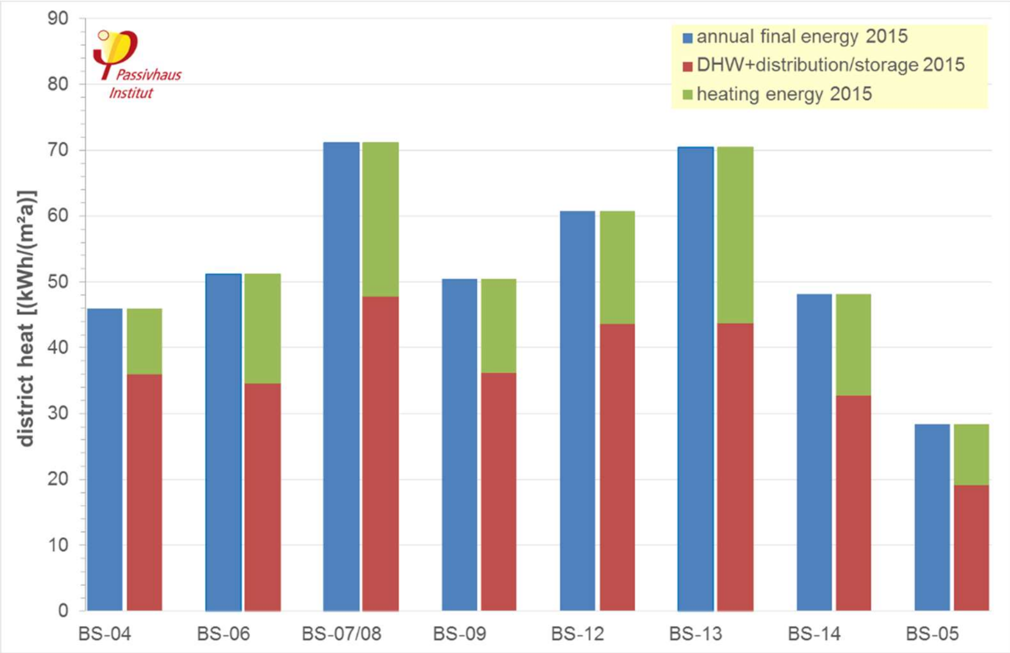


Fig. 7: Depiction of the annual consumption values for district heat for the year 2015 (see text for Fig. 6 for explanation). Evaluation of an additional building site was possible for the year 2015.

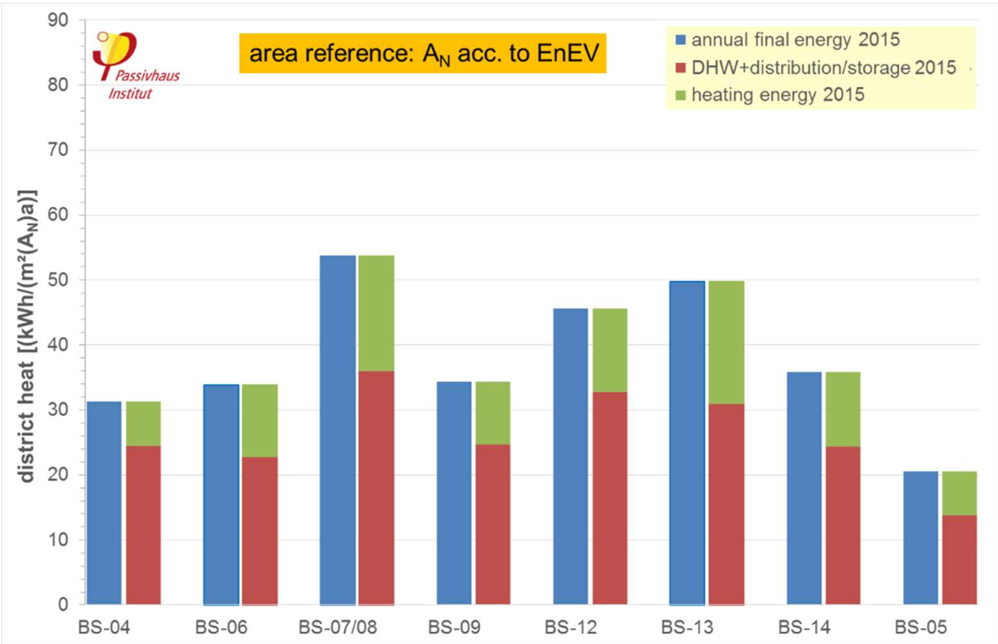


Fig. 8: For comparison, Fig. 7 is shown again, but this time with the area reference BASED ON THE AREA A_N according to the German energy saving standard EnEV instead of the heated area (treated floor area) as was done in the rest of the study. The specific consumption values are significantly lower on account of the considerably larger reference areas, but they are well-suited for a comparison with values from other buildings that are based on A_N; these will no longer be used in the rest of this report.

It is clear that there is a relatively large spread between the consumption values of the building sites. It is evident that there have not been any major changes in both these years in the case of the three building sites that were partly inhabited in 2014 (BS-6, BS-07/08 and BS-13) compared to those that were continuously inhabited. Varying consumptions would have been conceivable here due to the occupants moving in later (see Section 2.2). The differences in the district heat consumptions can thus only be explained by the following:

- Type of usage (residential apartment or student hostel) or size of the apartment,
- Different user behaviours (indoor temperature, hot water consumption),
- Differences in the building systems or type of heat distribution (line lengths, transfer stations) and
- Differences in the building envelope (thermal insulation, airtightness,…)

With more than 100 dwelling units, the user groups per building site are so large that the influence of individual occupants with significantly lower or higher consumption only has an extremely small effect on the average consumption value of the entire building site. A cumulative effect of occupants with user behaviour that leads to considerably higher or lower consumption on average in a building site is also unlikely. The differences between the building sites are therefore determined mainly by the performance of the building technology and the building envelope.

The scale of distribution between space heating and the remaining consumptions with "base heat" for hot water provision, distribution and storage in the Bahnstadt district is within the typical range compared with Passive House projects studied previously. In order to illustrate this, the data from a building with 19 apartments that was centrally supplied with heat and investigated in detail is provided (Fig. 9). The space heating, hot water consumption, distribution heat and other detailed variables were analysed in more detail in the related study [Peper/Grove-Smith/Feist 2009]. In this project, it was exemplarily demonstrated that the heating energy had a 33 % share of the total supplied energy. The Bahnstadt objects presented here with shares between 20 and 36 % (2014) and between 22 and 38 % (2015) were thus within a realistic scale.

The potential for further technical optimisation certainly also exists in this project, particularly in respect of the storage and distribution losses. In this regard the two outliers with values of 70 kWh/(m²a) should be further examined in detail and optimised if necessary.

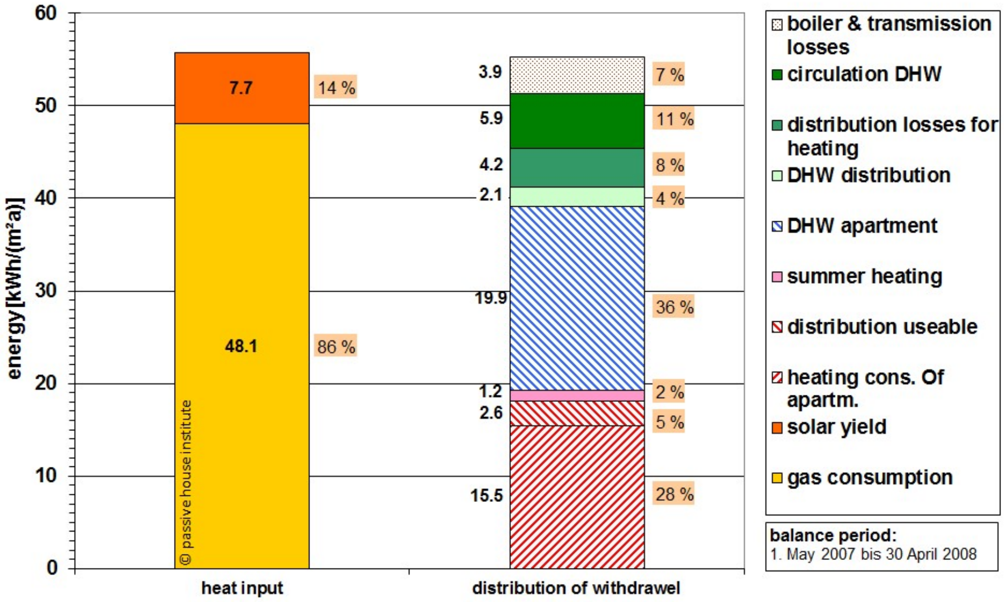


Fig. 9: Energy balance of a Passive House building with 19 apartments with centrally supplied heat from the study by [Peper/Grove-Smith/Feist 2009]. The heat supply and heat applications could be broken down in detail in metrological terms. Interestingly, the annual total for this object is of the same scale as that of the Passive House building sites of the Bahnstadt district in Heidelberg studied in this article.

2.3.1 Hot water provision, distribution and storage

As described in the previous section, the scale of the "base consumption" for hot water provision, distribution and storage is within the typical range. Fig. 11 shows only these values without the space heat consumption. These consumption values are between 19 and 48 kWh/(m²a), the area-weighted average value is 36.7 kWh/(m²a).

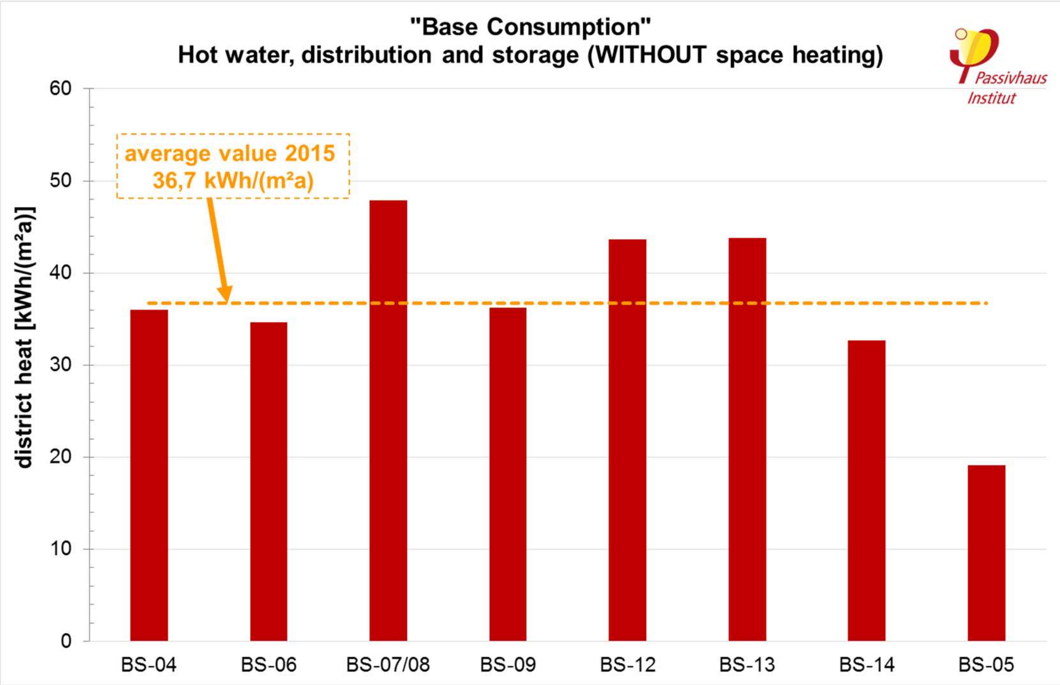


Fig. 10: Annual district heat consumption for the so-called "base consumption" (hot water, distribution and storage without space heating) of the residential-use buildings (including the student hostels) separately according to building sites for the year 2015 (taken from Fig. 7).

The reason for the different base consumption values has already been focussed on above, that this may principally be due to the performance of the building services systems and building envelope. Even without more information relating to the details it is therefore clear that the different technical solutions in the building sites have a significant impact on these consumption values. Besides the hot water consumption, in particular the kind of building technology that is implemented is decisive in the case of base heat. A number of parameters have a significant influence in this regard, particularly the following:

- Length, routing and insulation quality of the distribution lines
- Forward flow and return flow temperatures for internal distribution
- Number and quality of the transfer stations
- Size and quality of buffer and hot water storage tanks
- Choice of system and insulation of the hot water circulation system
- Setting of the control parameters and runtimes

For heat consumptions that are already largely optimised to a minimum level, the determining savings potential presumably lies in the reduction of the distribution losses and standby losses through optimisation of the building services systems and adjustment.

2.4 Evaluation of the heat consumption

The influencing factors *weather condition* and the individually selected *indoor temperature* during the studied period which affect the heat consumption cannot be known at the planning stage (see also [Peper 2012b]), therefore the planning team must use standardised design values. Like the characteristic values of the buildings, these "boundary conditions" also determine the consumption values.

When evaluating the heat consumption values, it must be considered that - in the case of a completed building - the consumption data significantly depends on the influencing factors of weather and indoor temperature. Hence, it cannot be expected at all that a building which was designed for e.g. 15.0 kWh/(m²a) during the planning will have exactly this consumption. As a general rule, Passive House buildings are planned to have an indoor temperature of 20 °C. A change in temperature to e.g. 21 °C during usage will lead to an increase in the heat consumption by about 15 % typically. This relatively large value in terms of percentage equates to about 2 kWh/(m²a) per Kelvin of temperature difference as an absolute change in consumption.

In the case of a large number of apartments in a complex, it is always the average consumption value that matters as only this is meaningful for the quality of the building. Consumption values of individual apartments in a building do not provide any reliable information. Precisely these average values were available for the present study.

The evaluation of the consumption data convincingly shows that the extensive efforts of the city of Heidelberg to design an entire city district to a high standard of energy efficiency through specifications and quality assurance have paid off. With heat consumption values of **14.9 kWh/(m²a) (±4; 2014)** or **16.4 kWh/(m²a) (±4; 2015)** on average**,** an excellent result has been achieved here. Particularly impressive is the fact that this concerns a very large number of dwelling units (1400) with a studied living area of almost 90,000 m² in total. With these comprehensive statistics, it can be demonstrated significantly that the implementation of highly energy efficient buildings on a broad scale can be achieved with many different stakeholders successfully and with good results.

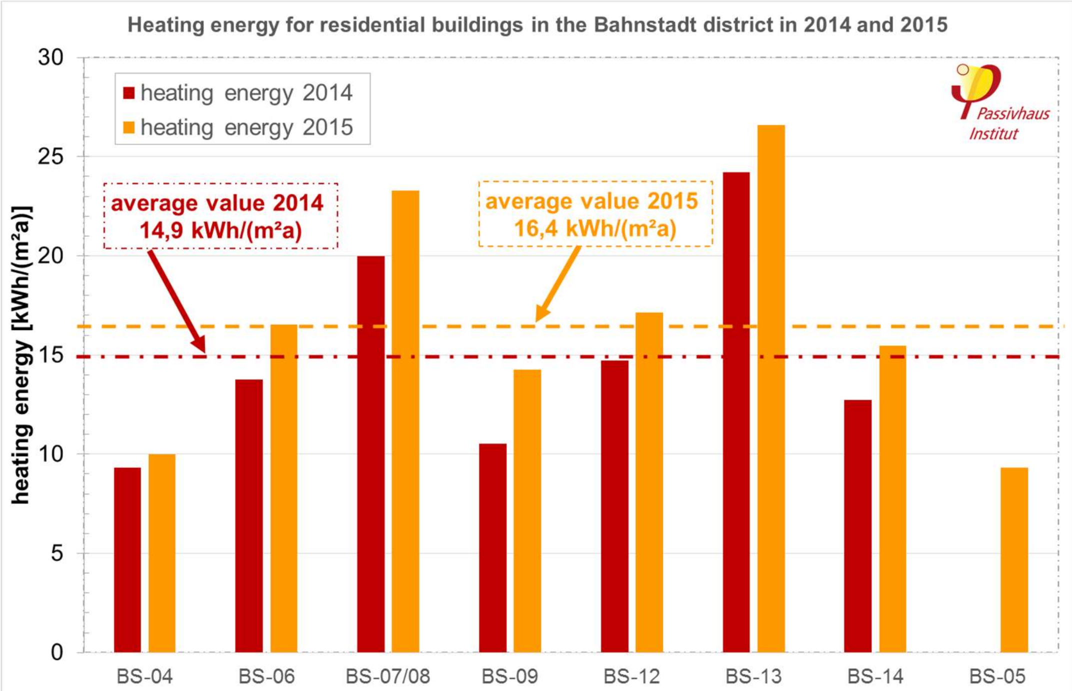


Fig. 11: Annual heat consumption values in the Bahnstadt district for residential-use buildings (including student hostels) separately according to building sites (taken from Fig. 6 and Fig. 7) for both studied years (error analysis: ±4 kWh/(m²a).

Fig. 11 shows the heat consumptions of the residential buildings (from Fig. 6 and Fig. 7) as well as the area-related average value for both studied years separately. The two higher consumption values are still very low as well and should by no means be assessed as problematic.

The heat consumption values consistently show a slight increase in the average consumptions in the second measurement year. In percentage terms, the increases in consumption range between 7 and 35 %. As already indicated above, the main cause of this is the difference in the weather conditions during the periods under consideration. This will be analysed in the following section with the aid of the PHPP.

For clarification, the difference between the individual heat consumption of an apartment and the average values for all apartments in a building is explained here. For this, typical results from another detailed monitoring project are presented in Fig. 12. These are the measured results of a residential building in Frankfurt am Main which was modernised using Passive House components [Peper/Schnieders/Feist 2011]. There are very large variations in the consumption between the individual apartments which are identical in design with regard to energy efficiency. This a typical result with such measurements. This kind of scattering around the average value occurs regardless of the energy standard of a building, so this is also found in the case of low energy buildings or existing buildings.

As already described above, only the average value of the apartments that are identical in design in terms of energy efficiency provides reliable information about the quality of the building as a whole. These average values were used in this study relating to the Bahnstadt district. However, it is evident from the chart that the individual consumption value of an apartment can differ greatly from this average value. Deviations of between +100 and -50% from the average value are not unusual. This also makes it clear that it is not meaningful or possible to draw any conclusions about the quality of a building using measured values from just one apartment.

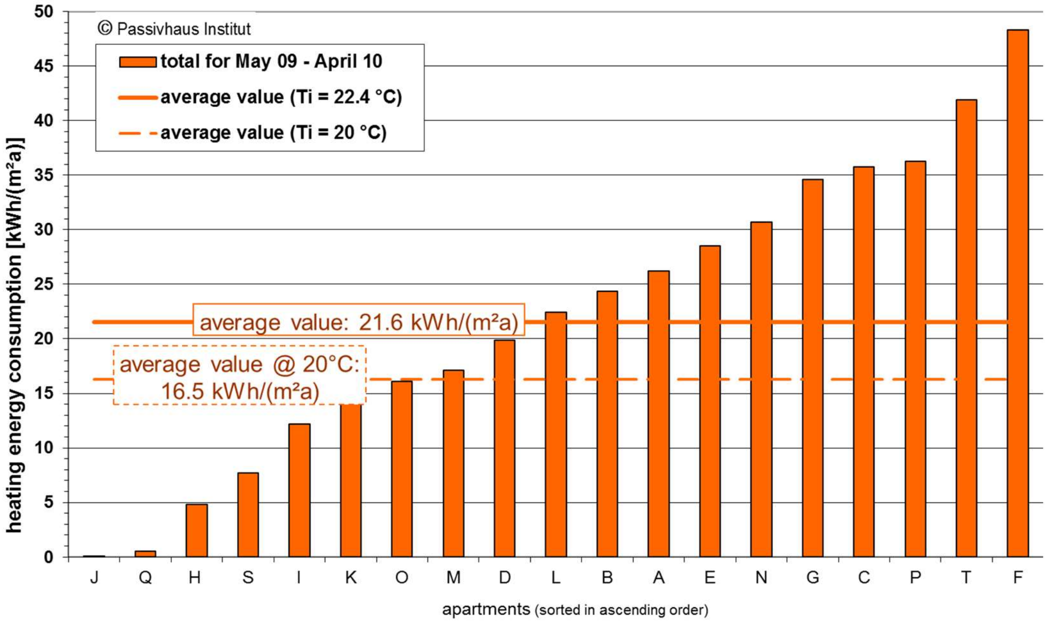


Fig. 12: Annual heat consumption values of 19 centrally supplied apartments as single values for apartments of an apartment block in Frankfurt am Main which was modernised using Passive House components (heating period 2009/2010). The range of the consumption values shows the large differences between the apartments. These show the typical dispersion with apartments that are identical in design due to the user needs regardless of the building standard. Besides the area-weighted average value, the average value at an indoor temperature translating to 20 °C is also entered here [Peper, Schnieders, Feist 2011].

2.5 Comparison of heat consumption with PHPP planning data

The PHPP (Passive House Planning Package) was used as a planning tool for all buildings in the Bahnstadt district. This allows for energy-relevant optimisation of the building during the planning process. The PHPP was also used by the city of Heidelberg for the purpose of quality assurance. Certification of the buildings by the Passive House Institute or an accredited certifier only took place in a few cases; of the buildings on the building sites investigated here, only one was certified.

Accurate and complete tracking of all the changes made during the planning and particularly during the construction process are crucial for a realistic calculation. This is not a trivial requirement, and a reliable comparison between the calculated data and the measurement data will only be possible and meaningful if this is successfully carried out.

Experience has shown that if this is done with the necessary care, the PHPP will deliver a realistic heating demand in accordance with the applied boundary conditions, such as climate data, occupancy density, internal heat gains, indoor temperature etc. In the case of projects that were studied in more detail, the comparison of the consumption data and the PHPP calculation of the demand often shows quite good correlations (see Fig. 13). As explained above, as the most important parameters for the comparison with the measurement, the climate data and the indoor temperature must be determined for this purpose in accordance with the actually existing boundary conditions and used in the PHPP.

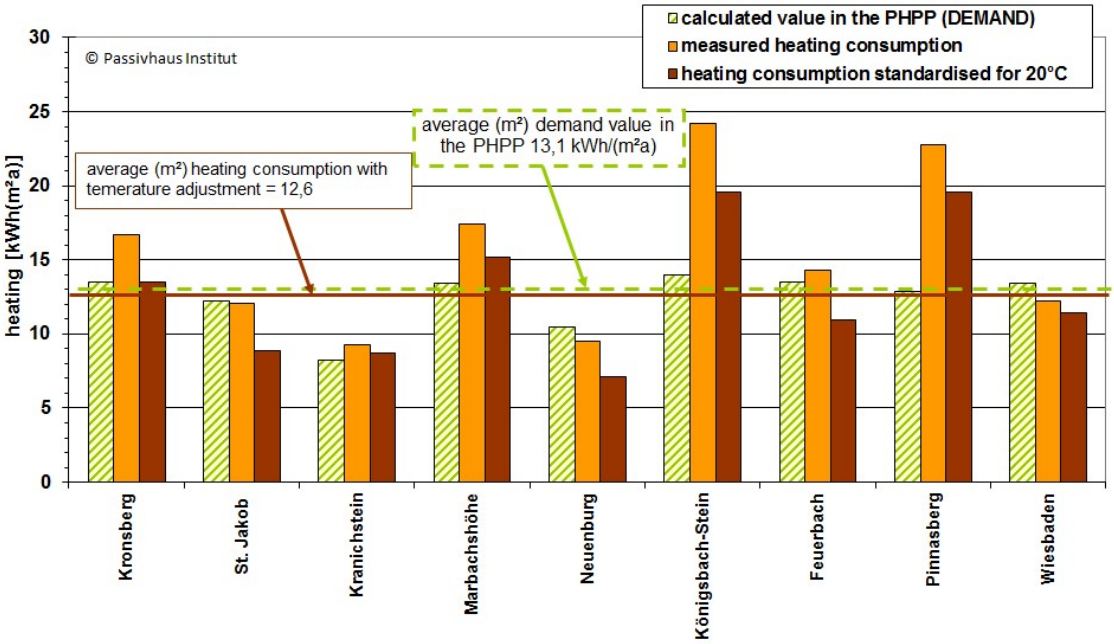
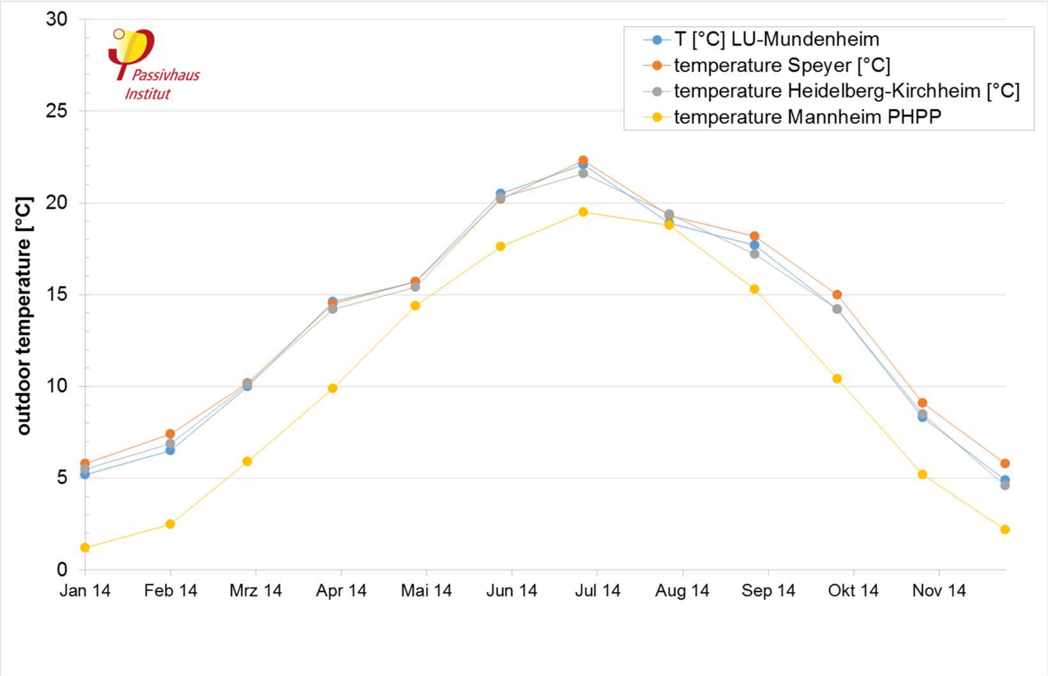


Fig. 13: Measured heat consumption in comparison with the projected value of terrace, semi-detached and multiple-family houses built to the Passive House Standard. The value determined in the PHPP was calculated for an indoor temperature of 20°C (from [Peper 2008])

2.5.1 Weather data

As a next step, the consumption data of the studied residential buildings in the Bahnstadt district should be compared with the planning data in the PHPP. In this way it will be possible to check the data for plausibility and to identify any outliers. For the study in the Bahnstadt district, the actual weather data for Heidelberg during the observation period in 2014 and 2015 was necessary. At least the monthly outdoor temperature and the monthly total global radiation (horizontal) were required for this. Data from a measuring station in Heidelberg-Kirchheim was used for the outdoor temperature (http://heidelberg-kirchheim-wetter.de). This was at a distance of ca. 2.5 km. Comparison with measurements from Ludwigshafen and Speyer (both in Germany) only showed slight variances.

A source for obtaining the global radiation data for Heidelberg could not be found, therefore the radiation data for the location Ludwigshafen-Mundenheim was obtained from ZIMEN, the monitoring network of the German State of Rheinland-Pfalz (www.luft-rlp.de). The outdoor air temperatures for Heidelberg exhibited minimal deviations from the location in Ludwigshafen-Mundenheim compared with the other alternative (Speyer). For this reason Ludwigshafen was also taken as the measurement location for the global radiation data. The weather data set that was thus prepared will subsequently be referred to as "Wetter LU/HD".



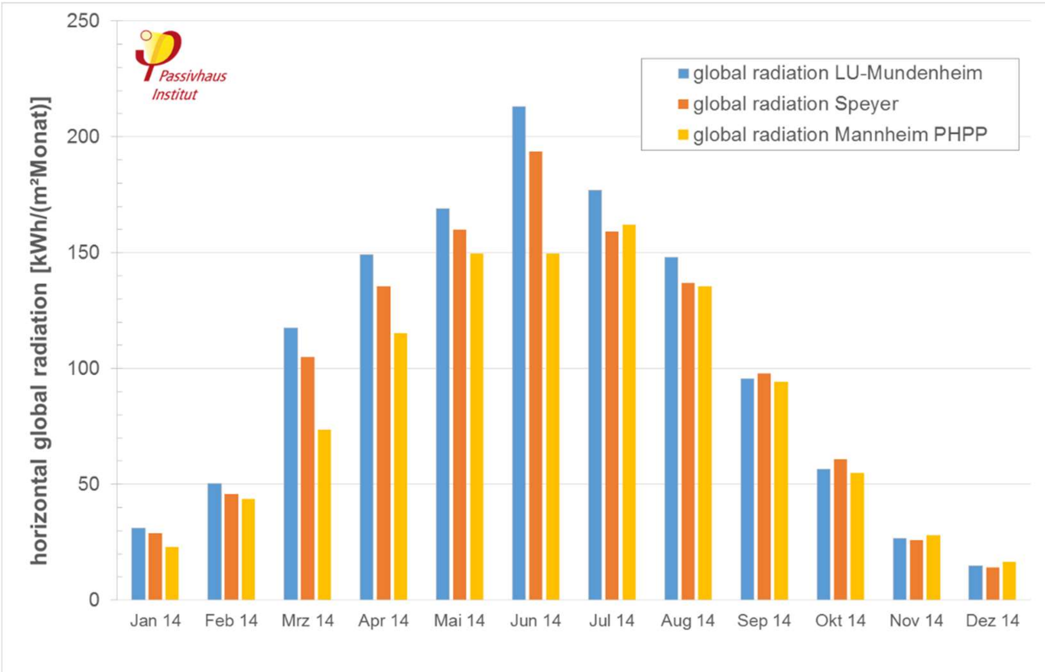
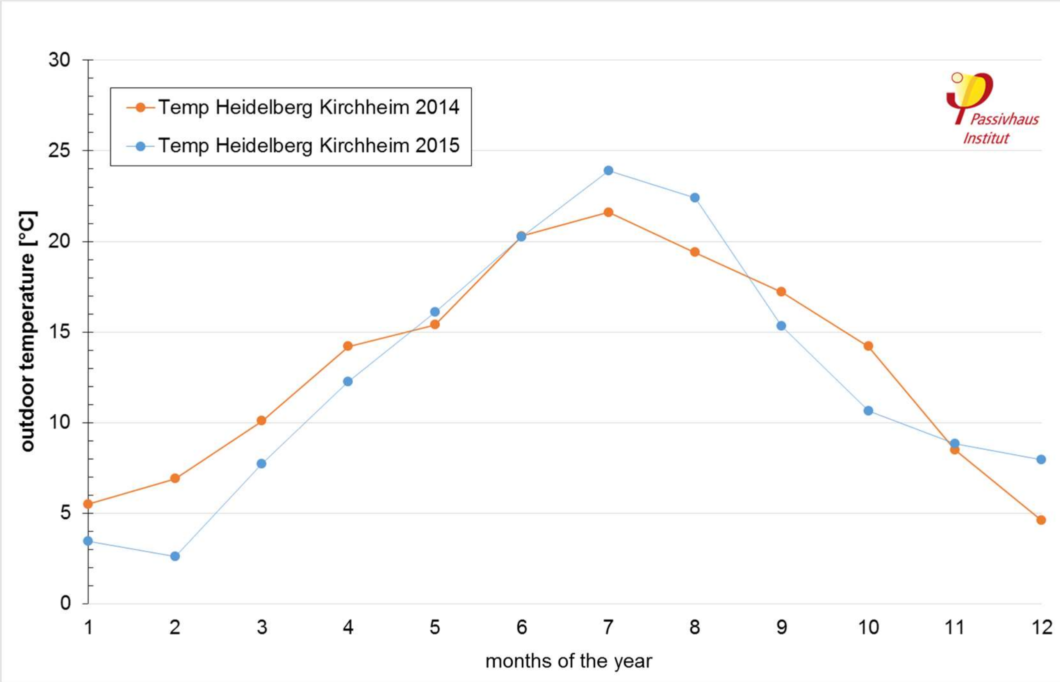


Fig. 14: Comparison of the weather data sets for outdoor temperature and horizontal global radiation for the year 2014.

The comparison of the weather data for Heidelberg that was available for 2014 and the standard climate data set "Mannheim" used during the planning in the PHPP clearly shows that in the 2014 period the winter months were significantly warmer than in the climate data set "Mannheim". Global radiation showed differences particularly during the summer months, which were not relevant here (see Fig. 14).

The comparison of the weather data for both annual periods of this study is shown in the two charts below (Fig. 15). The average value for the temperature was 13.2°C in 2014 and 12.6°C in the following year 2015:



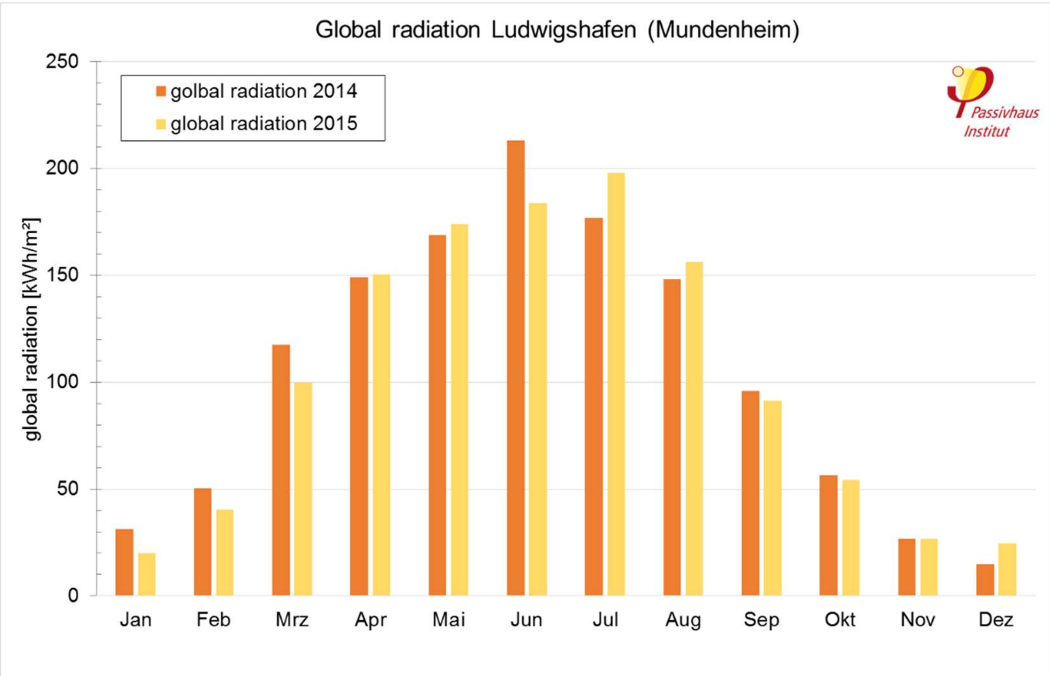


Fig. 15: Comparison of the weather data used in the PHPP for the outdoor temperature (Heidelberg-Kirchheim) and horizontal global radiation (Ludwigshafen-Mundenheim) for the measurement years 2014 and 2015.

It is apparent that the outdoor temperature is significantly lower in the first few winter months of 2015 (January to April) than in the previous year. It was also considerably cooler in October 2015, while December 2015 was significantly more temperate. The outdoor temperature in winter is decisive for the heat consumption. The average value for the months January to March as well as for November and December was 7.1°C in the year 2014, while the average value for winter in 2015 with 6.1°C was lower by 1 K. This leads to higher heat consumption values.

The global radiation values in Fig. 15 (below) are also similar: in 2015 overall and particularly also in the winter months these are lower than in the previous year. The total for the winter months (again: January to March as well as November and December) with 211 kWh/m² gives a 12 % lower value for the global radiation. This situation leads to an increase in the heat consumption. Only the measured horizontal global radiation has been used and depicted here. In the PHPP, radiation is taken into account according to the cardinal points and solar incidence is determined on the basis of window areas taking shading into account. Solar incidence accounts for one third of the heating energy balance in a Passive House.

2.5.2 Indoor temperatures

In the minimal monitoring carried out here, measured indoor temperatures were not available for the 1,400 dwelling units. This essential parameter for adjusting the PHPP planning calculation can thus only be taken from other monitored projects. In other measurements in residential-use Passive Houses, indoor temperatures of about 21.5 °C on average were measured in winter [Peper 2012b]. For this reason, this higher indoor temperature has also been applied here for both measurement years and was used as a boundary condition in the PHPP. For comparison, a set point temperature of 20 °C will also be considered additionally.

2.5.3 Conflation of the PHPP calculation

The residential buildings and student hostels studied here using minimal monitoring were balanced in a total of 35 PHPP calculations. Since only one heat meter exists for each building site, the demand values for heating energy from the individual PHPP calculations of the building site must be conflated into a comparative value in an area-weighted manner. The data for the student hostels is provided in a separate PHPP calculation. For the building sites with residential buildings there are between three and five PHPP calculations, and in one case ten PHPP calculations. These PHPP data sets are all calculated using the weather data set for "HD/LU" and "HD/LU 2015" as a boundary condition, and in a second step, the indoor temperature was increased from 20 to 21.5 °C. The balance value of a building site that is calculated in this way can now be compared with the consumption value from the previous section.

The PHPP calculations made available to the PHI could not be checked within the framework of this study. Even so, some points did stand out during the processing of the PHPP calculations, such as the addition of the weather data sets. Some of these have a noticeable influence on the heating demand and were therefore adapted:

- Some PHPP calculations were set to the annual method instead of the **monthly method**. At the time of planning, both methods were permissible verification methods for the Passive House Standard. For better comparability, only the more accurate monthly method has been used here. This results in an increase in the heating demand by up to 2.4 kWh/(m²a) in the studied buildings.
- During random tests of the PHPP calculations, questions came up regarding individual points of the **thermal building envelope** in the area of the basement as well as in relation to individual thermal bridges. Detailed clarification could not be achieved in the context of an analysis within the framework of this study.
- In random tests, individual buildings at three building sites were tested with reference to their **shading situations**. It turned out that shading had not been taken into account completely at one site, and to some extent, between sites. For this reason, shading was updated for a sample building site. This led to an increase of between 0.2 and 0.4 kWh/(m²a) in the heating demand (depending on the weather data set and indoor temperature). Since this is only a slight deviation, this adjustment was not further taken into consideration.
- For the comparison with the consumption data, the two student hostels studied here were calculated uniformly using the internal heat gains (IHG) of 2.1 W/m². The IHG in one of the PHPP calculations were varied for this. More detailed examination in a separate research project is necessary in order to determine which values are more suitable for modern student hostels. On account of the room sizes typically used nowadays and the additional common areas, approximation to the commonly used values of 2.1 W/m² for residential use seems realistic.
- In two buildings at a building site the IHG were established in project-specific calculations. The standard values of 2.1 W/m² were also adopted here.

There were no further tests or changes to the PHPP calculations. The adjustments that were made were taken into account in the values presented below.

In order to illustrate the influence of the different indoor temperatures and the climate/weather data sets, the results of the PHPP calculations for heating energy are shown in Fig. 16 using the changed boundary conditions. The results for the calculations using the climate data set for Mannheim (PHPP-Standard) show how mild the first measurement year of 2014 was. Higher demand values are indicated in the cooler and less sunny year of 2015. However, in total both measurement years indicate considerably milder conditions than the standard climate data set for Mannheim (long-term average of previous years). But comparatively low demand values of just 16 to 18.5 kWh/(m²a) result even if the climate data set for Mannheim is used.

The influence of the respective higher indoor temperatures can also be easily recognised for the three climate or weather data sets: the demand values for heating energy increase to **15.5 % on average for each Kelvin** of increased temperature of the indoor air. The range is between 9.6 and 18 % depending on the climate/weather data set and building site. This shows the significant influence of the temperature increase of the indoor air on the heating energy demand as a percentage, which however is not decisive in absolute terms.

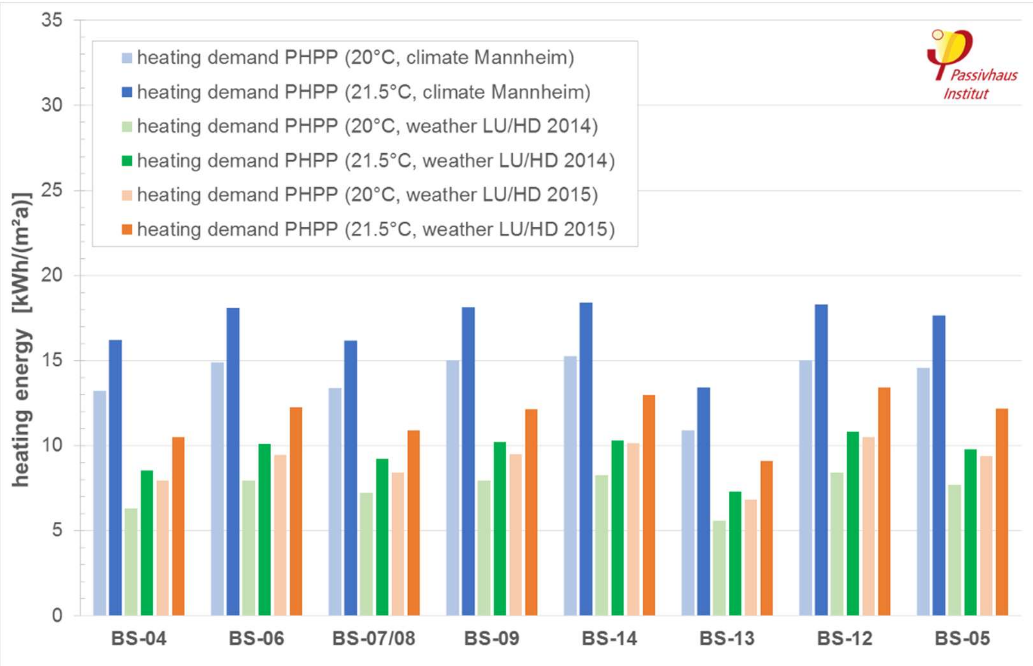


Fig. 16: Comparison of the demand values for heating energy in the PHPP calculations for the different climate/weather data sets and indoor temperatures in the studied building sites of the Bahnstadt district in both studied periods.

2.5.4 Heating energy demand (PHPP) versus consumption

In order to be able to assess the heating energy consumption values determined from the measured data, these should be compared with the adjusted PHPP calculations (see previous section). This comparison took place separately for both annual periods. Fig. 17 shows the heating energy consumption values (see Section 2.4) conflated with the PHPP calculations for each building site. The results with the weather data set HD/LU 2014 are shown for the PHPP demand values. The heating energy demand value is depicted for 20 °C as well as for 21.5 °C.

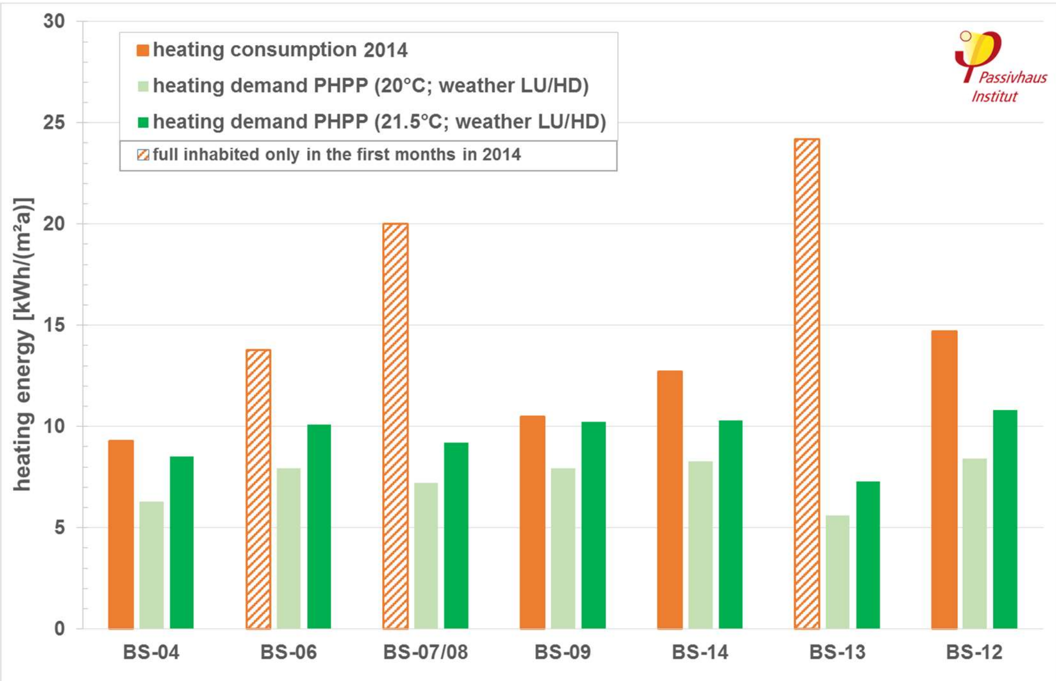


Fig. 17: Comparison of the consumption data for heating energy (orange) with the PHPP demand values for the weather data set HD/LU 2014 and different indoor temperatures for the seven investigated building sites in the Bahnstadt district (measurement error in the range of ±4 kWh/(m²a)).

The consumption data can be most effectively compared (orange bar with the dark green bar) using the above-mentioned current boundary conditions (the usual indoor temperature of 21.5 °C and weather data "HD/LU 2014") during the studied period. In doing so, five of the seven building sites show excellent correlation with variations between 0.3 and 3.9 kWh/(m²a). For comparisons of consumption measurements this is assessed as excellent particularly as this relaters to minimal monitoring with the expected measurement errors of the same order. Thus it can be assumed that reliable PHPP calculations are available.

However, two of the investigated projects (BS-07/08 and BS-13) with 10.8 and 16.9 kWh/(m²a) respectively show significantly larger differences between the measured consumption data and the PHPP calculations. These are also the building sites with the highest measured consumption values.

For further analysis, the same investigation was carried out for the measured values from the year 2015. A picture similar to that of the previous year results in Fig. 18. The building site BS-05 has been added for the year 2015.

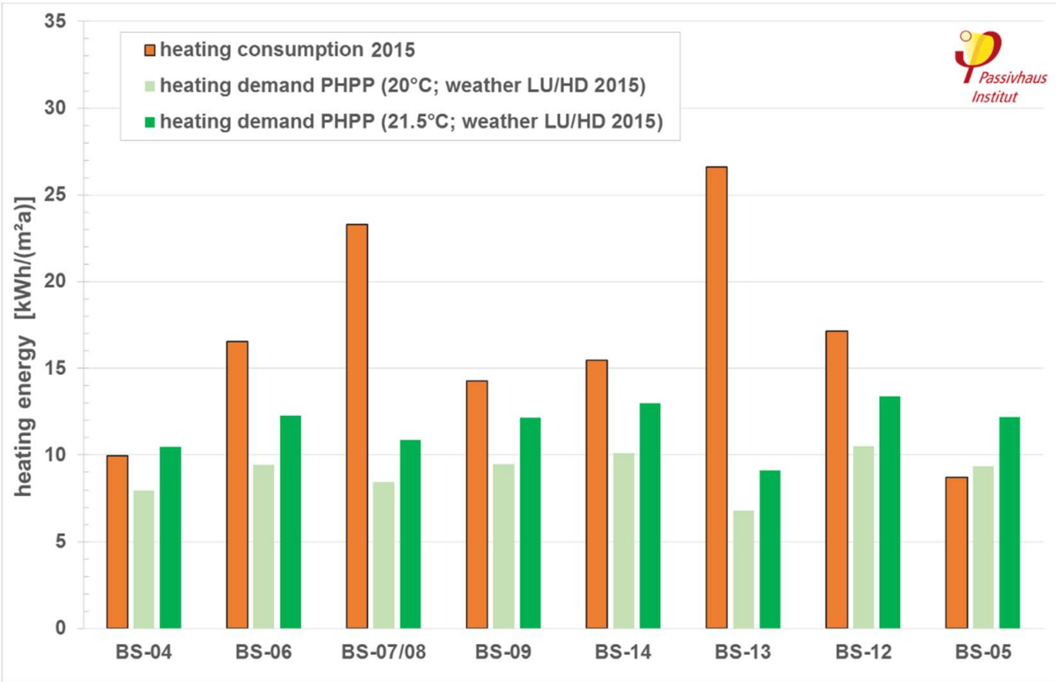


Fig. 18: Comparison of the consumption data for heating energy (orange) with the PHPP demand values for the weather data set HD/LU 2015 and different indoor temperatures for the now eight investigated building sites in the Bahnstadt district. All buildings were fully inhabited in the year 2015.

Here too, there is excellent correlation in six of the now eight building sites. The difference in the measured values for "heating energy" and the PHPP demand values at a temperature of 21.5 °C ranges between a lower consumption of 3.5 kWh/(m²a) and an additional consumption of 4.3 kWh/(m²a). These values confirm the assumption made for the year 2014 that the available PHPP calculations are reliable.

The same two building sites BS-07/08 and BS-13 stand out with significantly increased differences of 12.4 and 17.5 kWh/(m²a). Because the buildings in these building sites were fully inhabited in the year 2015, the influence of later occupancy in some dwelling units cannot be the reason for the significant variations. The main cause of these variations in consumption that are conceivable are:

- Possibly, individual changes to buildings during the course of construction were not fully incorporated into the final PHPP calculations for these building sites.
- The average user behaviour of the occupants of these buildings – despite the large number of dwelling units – differs greatly from the assumed usage (in itself this is not likely but can be tested by measuring the level of comfort).
- Suboptimal control settings or technical errors e.g. in the building services or ventilation technology, leading to an increase in the consumption (e.g. transferred air in the internal heat distribution network of the building, malfunctioning of the thermostats, runtimes or standard parameters are not optimal).

There may be a combination of different reasons – with the information accessible to the authors, any decision regarding this would be pure speculation. One of the objectives of this study was to identify precisely such projects so that more accurate investigations may follow here. This possibility exists with the present results.

In spite of the significant difference from the PHPP balance for both these projects, it can be said that even the consumption values of 23 und 27 kWh/(m²a) that were achieved here are still extremely low compared to other new constructions.

2.5.5 Reasons for the higher consumption in 2015

To answer the question regarding the reason for the slightly higher heating energy consumption in 2015 compared to 2014, the data for both years was compared once again. For this, the PHPP data for the heating demand for both years that was calculated for the respective year with the weather data sets LU/HD with an indoor temperature of 21.5 °C were placed next to the measured data (Fig. 19). No measured value can be given for 2014 for the building site BS-05 which was only assessable in 2015.

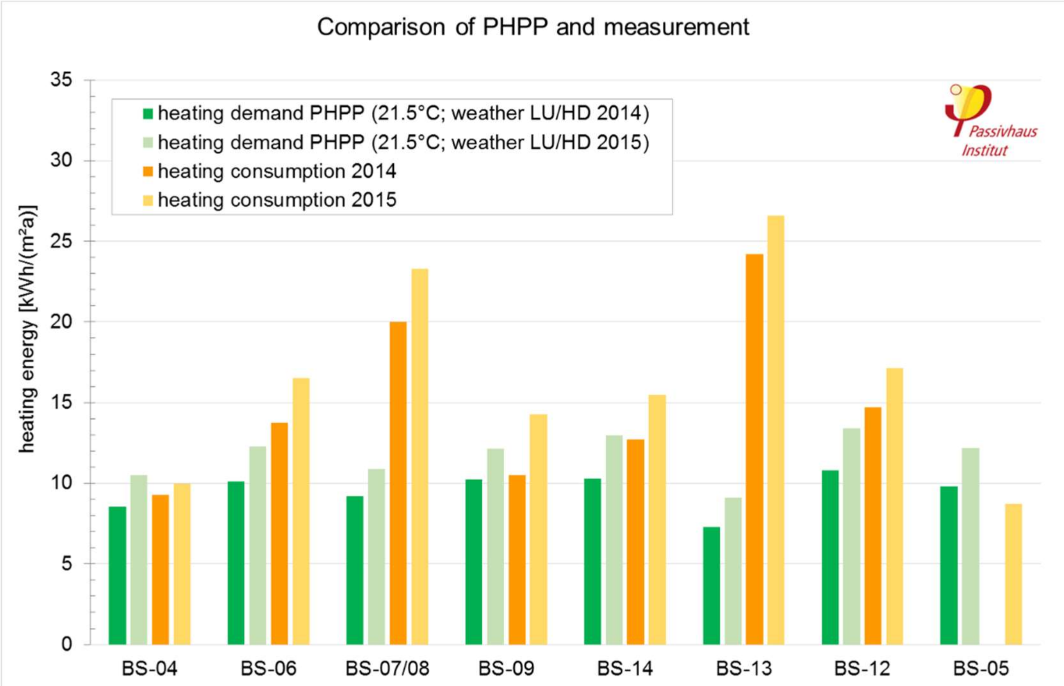


Fig. 19: Comparison of the PHPP demand values for heating energy at a temperature of 21.5 °C with the measured consumption data for both investigated years. The increases from 2014 to 2015 can be explained by the change in the weather conditions.

The comparison of the PHPP demand values (for 21.5 °C) in both measurement years shows differences between 1.7 and 2.7 kWh/(m²a) for each building site. In the case of the measured values the variations between the two measurement years fluctuate between 0.7 and 3.8 kWh/(m²a) depending on the building site. The individual values for each building site can be taken from Table 3. The increase in the heating energy in the case of the PHPP calculation thus is of the same scale as that of the measured consumption values. It can therefore be assumed that most of the changed heating consumptions identified for the year 2015 are caused solely by the change in the weather conditions.

Table 3: Comparison of the differences in the heating energy demand of the adjusted PHPP calculations between the two measurement years 2014 and 2015 (weather data of the year and T_i = 21.5°C) and the measured values for the heating energy consumption between the two measurement years

Building site	Difference PHPP[1]) heating energy 2015 minus 2014	Difference measured value heating energy consumption 2015 minus 2014	Difference
	[kWh/(m²a)]	[kWh/(m²a)]	[kWh/(m²a)]
BS-04	1.9	0.7	-1.2
BS-06	2.2	2.8	0.6
BS-07/08	1.7	3.3	1.6
BS-09	1.9	3.8	1.9
BS-14	2.7	2.8	0.1
BS-13	1.8	2.4	0.6
BS-12	2.6	2.4	-0.2
BS-05	2.4	---	---

[1]) PHPP calculation with the weather data sets LU/HD 2014 and 2015 at indoor temperature of 21.5 °C.

If all the results of all building sites are averaged in an area-weighted manner, this will result in the following values:

Table 4: Average values for heating energy in all building sites for the PHPP calculation, with the corresponding weather data LU/HD at an indoor temperature of 21.5 °C, and the measured values for heating energy for both investigated years.

Heating energy [kWh/(m²a)]	**2014**	**2015**	**Difference**
Demand Average value PHPP weather LU/HD at 21.5 °C (area-weighted)	**9.6**	**11.8**	2.2
Consumption Average measured value (area-weighted)	**14.9**	**16.4**	1.5
Difference	5.3	4.6	----

The weather conditions in the following years will again lead to changes – in either direction – of the determined scale. This also means that there is no reason to suppose a further increase in the consumption values due to other causes.

3 Electricity

In order to obtain a complete picture of the energy consumption values of the building, the electricity consumption is of particular interest in addition to the heat consumption. The electricity consumption data from almost 1200 individual meters (meters for apartments, common-use areas and underground car parks) from six of the eight investigated building sites were provided to the PHI by the Stadtwerke Heidelberg in an anonymised form according to buildings only with their house numbers. The individual apartments are therefore not identifiable for data protection reasons.

3.1 Specific electricity consumption of the apartments (without common-use electricity)

The 12 monthly values of the whole year 2015 are available for the evaluation. The square metres of an entire building or a house entrance and not the individual apartments are always used as a reference area. The meter readings of the electricity meters in the apartments are accordingly added up and based on the area of the building or the building section.

Fig. 20: 10 examples of the ca. 1200 smart meters in one of the investigated buildings (utility room).

When evaluating the electricity consumptions for 33 buildings and building sections, specific electricity consumption values can be calculated for the year 2015 in this way. These electricity consumption values are shown in Fig. 21 with dispersion between 11.5 and 24.0 kWh/(m²a). A comparatively low value results as an area-weighted average with **17.9 kWh/(m²a)**. The buildings consist mostly of apartments and student rooms; some shops such as cafés, bakeries, banks, kiosks, hairdressers etc. exist sporadically only on the ground floors. This therefore relates to predominantly, but not exclusively, residential use.

3.2 Common-use electricity

The general consumption values are not measured by the individual meters in apartments. Additional **meters for general-use electricity** cover areas such as the stairwells, exterior and basement lighting, heating pumps, central ventilation systems, elevators etc. in all objects. The electrical loads which exist in the buildings vary; the small number of terraced houses can be mentioned as an example: only minimal common-use electricity consumption values occur here because the ventilation systems and exterior lighting are presumably measured via the apartment meters[4]; there are no elevators here. The situation that exists here is therefore completely different from that of the multi-family buildings with central heating, stairwell lighting and elevator operation.

A distinction could be made between the common-use meters in all buildings and the meters in the apartments. A different number of meters for common electricity consumption were used in the objects. For each building/building section, these were added up to the value "general use electricity" and also based on the area of the building/building section.

This resulted in very different common electricity consumptions with values between **0.7 and 15.4 kWh/(m²a)**. As already described, the individual reasons for the large differences and the exact allocation of the distribution of the consumption values to common electricity or apartment meters could not be determined.

Fig. 22 gives an average value of **26.3 kWh/(m²a)** as the total consumption for the apartments and common electricity. The average value compared to the consumptions within the apartments alone is thus increased by **8.4 kWh/(m²a)** (average value for common electricity).

[4] As an exception compared to all other apartment meter values, for the terraced houses this means that the electricity consumption of the home ventilation systems and the outdoor lighting is included in the domestic electricity consumption where necessary. For data protection reasons, detailed information regarding this is not available.

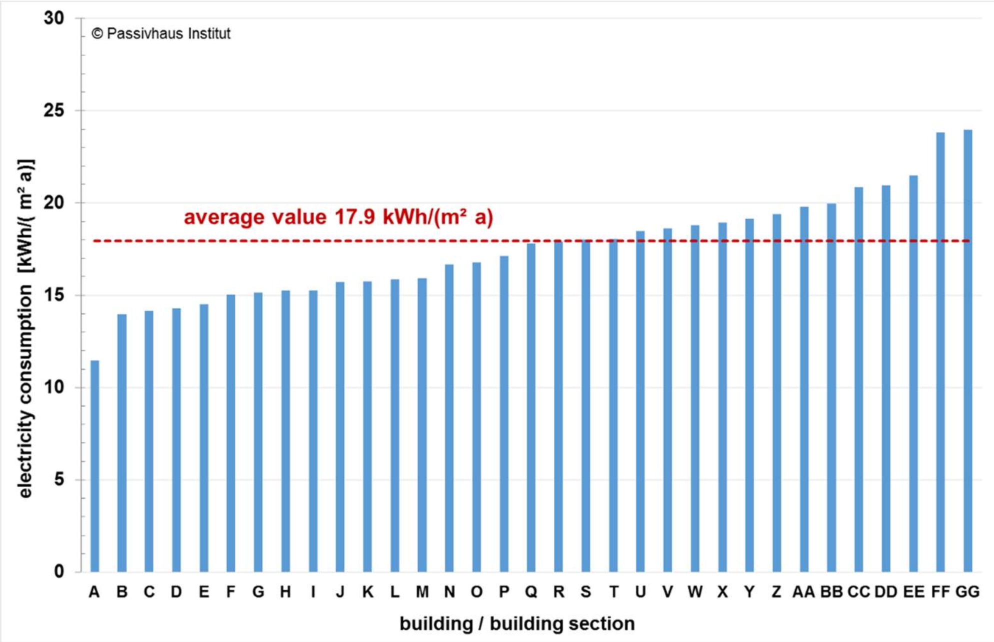


Fig. 21: Specific electricity consumption of the 33 buildings or building sections (house entrances) in the Bahnstadt district of Heidelberg with primarily residential use in the year 2015, sorted in ascending order. The consumptions of the apartment meters are shown <u>WITHOUT the common electricity</u>. (The electricity for the ventilation systems is included only for the small number of terraced houses). The area-weighted average value is 17.9 kWh/(m²a).

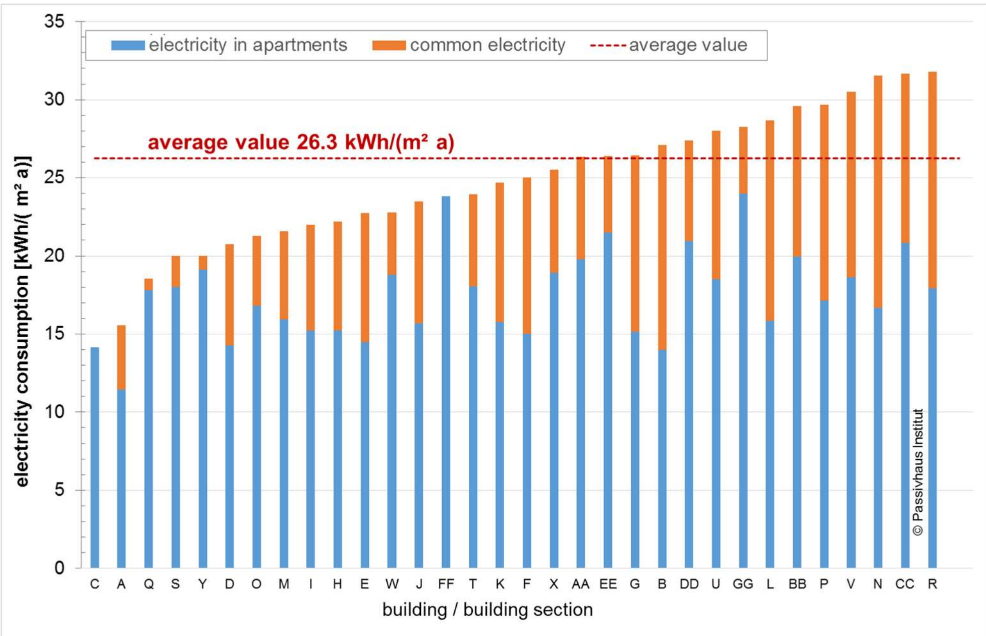


Fig. 22: Specific electricity consumption of the 33 buildings in Fig. 21 in the Bahnstadt district of Heidelberg in the year 2015 with the common electricity consumptions added (without the electricity consumption of the underground car parks). The area-weighted average value is 26.3 kWh/ (m²a).

3.3 Electricity consumption of the underground car parks

The electricity consumptions of the communal underground car parks e.g. for lighting, barrier systems, sliding gates, ventilation systems where necessary etc. are not included in all the values shown up till now. In five of the six building sites examined here with regard to electricity consumption, there are underground car parks where the consumption is recorded using separate electricity meters. For that building site there is no separate measured value for the underground car park; neither is the electricity consumption included in the common electricity consumption of this building site as evaluated above. To be able to directly compare the consumption data with the specific values of the apartments and the common electricity consumptions, the living area (treated floor area) was also chosen as a reference parameter here. For this purpose, the treated floor areas of all buildings at a building site are added together for each building site. There is a fluctuation between 1.6 and 4.7 kWh/(m²a). The area-weighted average value results as 3.3 kWh/(m²a).

Fig. 23: Specific electricity consumption for operation of the communal underground car parks for each building site. The living area (treated floor area) of the entire building site (total buildings) is used as the area reference. In this way, these values can be directly compared with the other consumption data.

3.4 Analysis of the electricity consumption values

Data from reference literature was used to analyse the measured consumption data.

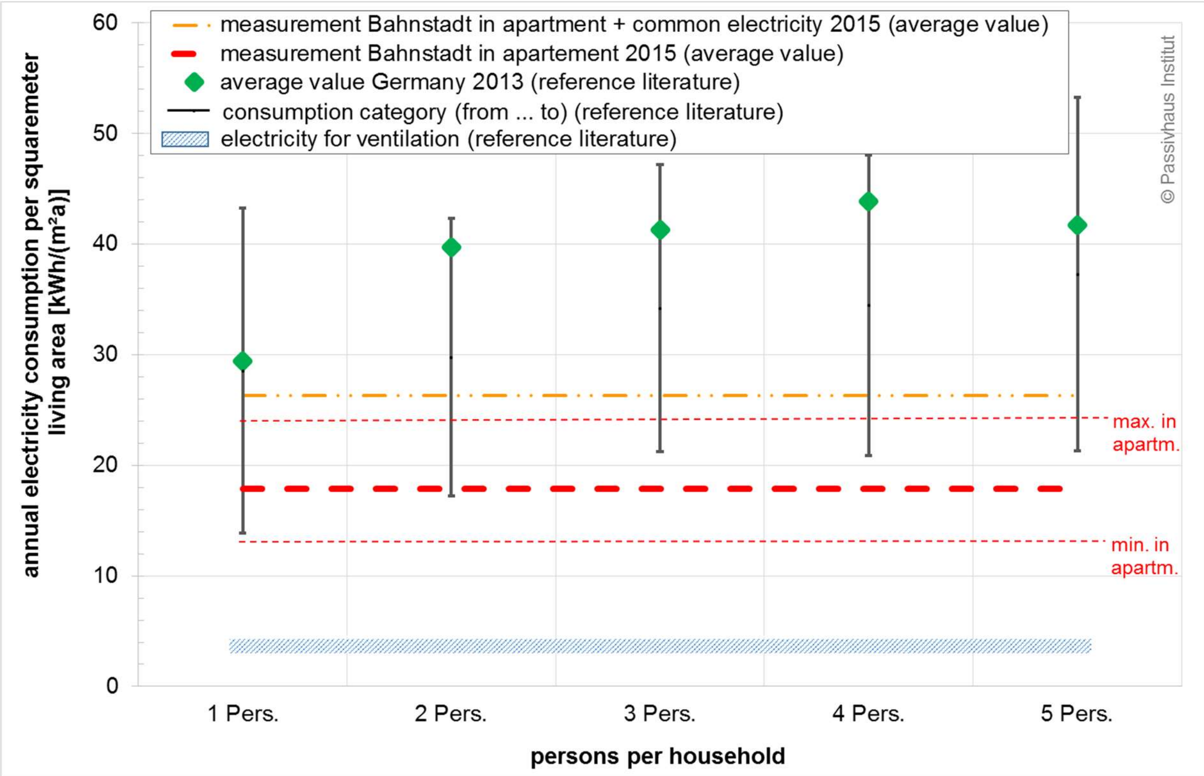


Fig. 24: Comparison of the measured electricity consumptions in the Bahnstadt district (2015) with average values taken from reference literature (see text for explanation). The electricity for underground car parks has not been plotted here.

In [BDEW 2013] the electricity consumption per household is given according to the size of the household (without electrical hot water generation and without electricity for heating) as a suitable comparison value for the year 2013. The living areas of the households based on the number of persons have been taken from [DESATIS 2013] from the section "Residential buildings with 3 or more apartments". If the specific electricity consumption values are calculated from these, the smallest value for the one-person household results as 29.4 kWh/(m²a) and the largest value for the four-person household results as 43.9 kWh/(m²a). The values for all household sizes are indicated as green squares in the above illustration (Fig. 24). The measured values of the apartment meters in the Bahnstadt district are given as average values as well as with the minimum and maximum values of the 33 buildings/building sections (red dotted line). The household sizes (number of persons) for these measured values are not known. The yellow dot-dash line shows the average value of the measurement including the common electricity consumption (see previous pages). The range of all categories (A "low" to G "high") in the 2016 electricity table for Germany is plotted as a comparative value for each household size [BMUB 2016]. The data for apartment buildings without electrical hot water generation was used.

For analysing the electricity expenditures for a central **ventilation system**, which were not separately measured in the buildings but are included in the measured value "Common Electricity", a comparative value taken from the reference literature was used. In [Lodenareal 2012], the annual electricity consumption in a large apartment block with a central ventilation system was measured as 4.1 or 4.2 kWh/(m²a). In the case of measurements with decentral (apartment basis) ventilation systems, the measured values were 3.8 kWh/(m²a) [Peper/Feist 2008] and 3.1 kWh/(m²a) [Peper/Schnieders/Feist 2011]. The range of these electricity consumption values for the ventilation systems is depicted in the illustration as a blue-shaded area.

The measured data of the households in the Bahnstadt district show appreciably low consumption values of the households compared with the average consumption in Germany. Even when the common electricity consumptions are taken into account the results are significantly lower than the average values; even though the measured values include the consumptions for the home ventilation systems which exist in all the Passive House buildings in the Bahnstadt district. There are probably several reasons for this:

- Impact of information and energy saving advice provided by Heidelberg City to the residents of the Bahnstadt district
- The very modern facilities of the newly constructed apartments on average, with new electrical appliances, lighting technology etc.
- Relatively large apartment sizes, particularly of owner-occupied apartments

It can also be concluded from these results that the electricity consumption for the comfort ventilation system is so low that the measured values on the whole are still below the average in Germany. The home ventilation systems therefore save considerably more primary energy than is required for their operation.

3.5 Winter/Summer electricity consumption

On account of the time-resolved electricity consumption measurements using smart meters (monthly values) and the statistically reliable number of household electricity meters, it is possible to determine the difference between the summer and winter electricity consumption. For this, the monthly consumption values of all individual apartment meters are added together, based on the living area and divided by the number of days in the month. The different lengths of months are thus taken into account.

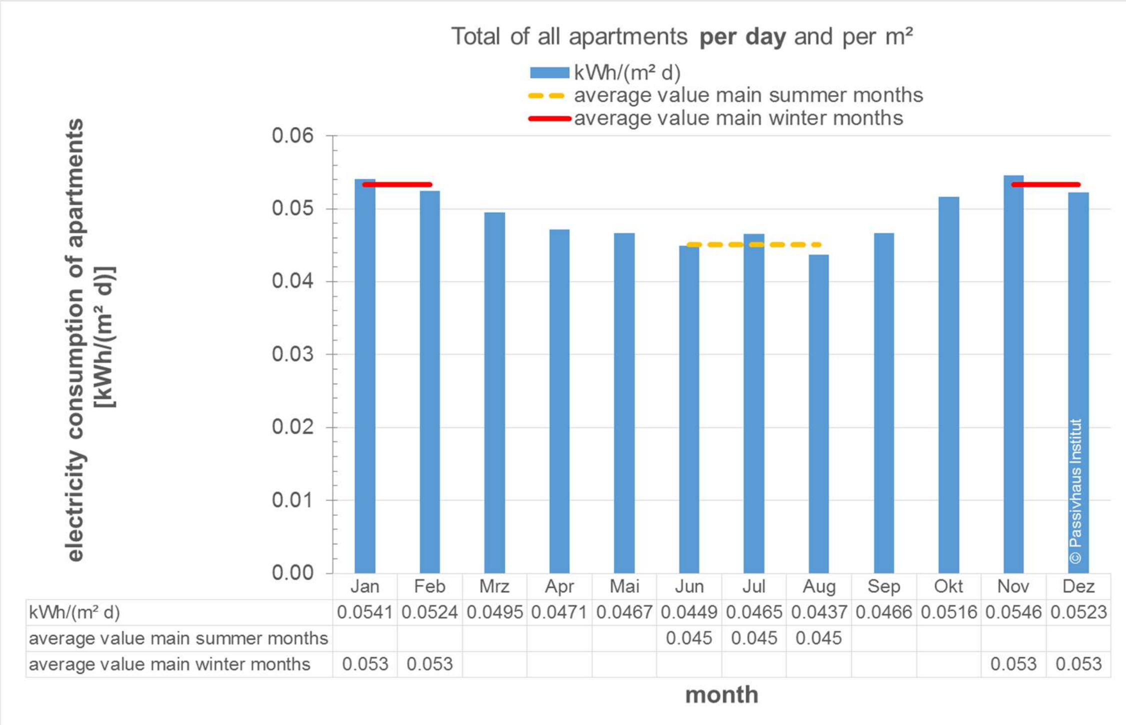


Fig. 25: Average monthly electricity consumption values for the household electricity for <u>all</u> studied buildings translated to specific daily average consumption values. The average values of the three main summer months and the four main winter months have been indicated in the graph.

The thus prepared consumption data in Fig. 25 show the expected low overall consumption in summer. The slightly higher value for July as well as the lower value for December show up as a negligible and unexpected outlier. The reasons for this cannot be determined from the data, but it was verified that these were not single outliers due to individual buildings.

In order to be able to assess the summer/winter fluctuation in the electricity consumption of households also in other studies, the average consumption values were determined and compared for the three main summer months (July to August) and the four main winter months (November to February). For the summer there was a reduction of **15.6 %** on average compared to the winter months. If the whole year is divided into the two parts "Summer" (April to September) and "Winter"(October to March) with 6 months each, this results in a difference of **12.4 %**. With these differences it is possible, for example, to more reliably extrapolate measured values of short-term measurements to annual values.

The consumption of specific electricity applications (none of the apartments has electrical heating or noteworthy contributions for electrical hot water generation) is thus significantly higher in winter than it is in summer. The reasons for this are the higher demand for electricity for lighting (shorter daylight hours) as well as the longer occupancy periods in the apartments with the corresponding use of IT and multimedia. Further analyses relating to this can be found in the appendix.

4 Conclusion regarding monitoring of the Bahnstadt district in Heidelberg

With the Bahnstadt district in Heidelberg, the efforts to create an exemplary city district can be assessed as extremely successful with regard to the residential buildings examined here. In summary, the present analysis shows that as an overall average, the studied building sites consumed just 55 kWh/(m²a) (2014) or 53 kWh/(m²a) (2015) final energy for all heat-related applications. That is only about one-third of the district heat consumption of comparable existing buildings for space heating, hot water, distribution losses and storage losses all together. This is a statistically significant survey of 1,400 apartments with a total of just under 90,000 m² useful area. The results are comparable with those of Passive House buildings with district heating connections that were examined in detail previously.

The district heat consumption for space heating is 15 or 16 kWh/(m²a) (±4) on average, which is an excellent result.

The comparison with values in the project planning using the PHPP (recalculated using the latest weather data) showed excellent correlation, with maximum measurement/ calculation deviations of ±4.3 kWh/(m²a), which is almost within the measurement accuracy of this study – only two building sites were beyond this mark. Basically, continuous checking of technical systems and setting parameters is recommended particularly in the case of "outliers".

Examination of the electricity consumptions of the individual apartments revealed very low values: the average value of the household meters was just 17.9 kWh/(m²a), and that for the additional common electricity consumption was 8.6 kWh/(m²a). The reason for this probably lies in the advice on electricity saving provided by the city, the modern facilities in the apartments and the size of the apartments.

With the decision to stipulate the Passive House Standard for the entire Heidelberg-Bahnstadt development area, the heating demand was specified as 15 kWh/(m²a). In other apartment buildings that were supplied with district heating (existing buildings), average values of 112 kWh/(m²a) were measured for the heating supply [Techem 2014]. A saving of 87 % in heating energy was thus strived for with the Passive House Standard compared to this consumption in existing building stock. The present evaluation of the consumptions shows that despite the two outliers, savings of the envisaged scale were actually realised very successfully. Implementation of the residential buildings in the Bahnstadt district on a large scale by different planning teams and with completely different users proves the robustness of the Passive House Standard. If the necessary quality assurance is carried out in a reliable manner, then nothing stands in the way of implementation of this low energy consumption standard for sustainable development on a broad scale.

5 Sources

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6 Appendix

Additional Fourier analysis of the household electricity consumption in Section 3.5:

In actual fact, the electricity consumption over the course of the year can be depicted very well by a harmonic approximation (see Fig. 26). The following coefficients result with the Fourier analysis:

The time constant basic consumption (absolute term) is 49.2 Wh/(m²d), the annual amplitude of the annually dependent cosine term is 4.7 Wh/(m²d) and thus 9.5 % of the average consumption; with this resolution, the spread between winter and summer is 9.4 Wh/(m²d) or 19.1% of the average.

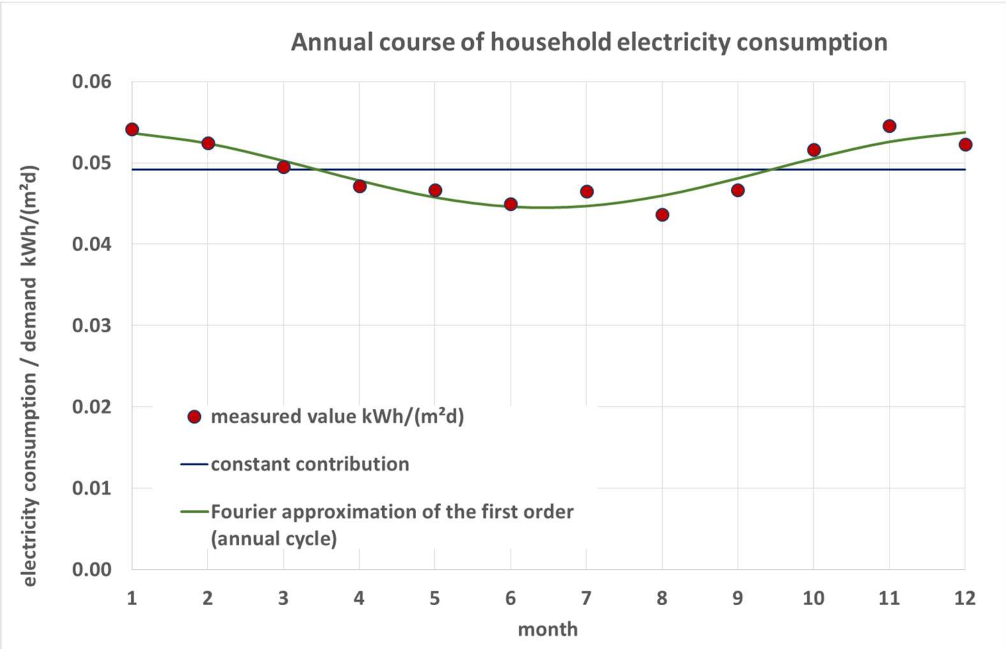

Fig. 26: Harmonic approximation of the annual period for the measured specific household electricity consumptions. The consumption shows a cosinusoidal annual cycle in good approximation (phase shift 14 days before the end of the year) with an amplitude which amounts to 9.5% of the average consumption.