Use of energy performance certificates for realistic prognoses – a method to calibrate the national calculation procedure by the average actual consumption

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Keywords

energy performance certificates, existing residential buildings, metering, energy efficiency gap, statistics, prognosis model, calibration

Abstract

The calculation models of Energy Performance Certificates (EPCs) are designed for energy rating and for proof of compliance with regulations. Their principles are comparability, replicability and verifiability. To ensure this, a national EPC procedure typically uses the same boundary conditions for all buildings, similar to a test bench in a laboratory: From the variety of indoor conditions found in practice a specific set is selected and applied. Particularly in unrefurbished old houses also the thermal characteristics of components are uncertain so that many assumptions are needed for the performance calculation. In consequence, larger differences between theoretical and actual energy consumption can be expected for single buildings, and also systematic deviations, when a large number of existing buildings is considered. The idea of this article is to quantify the deviations and use this information to calibrate the EPC output and thus provide realistic estimates of the actual consumption.

The empirical basis of the proposed method is a building sample of various energy performance levels. For all buildings the floor-related values of the calculated and of the measured energy use are combined to pairs. Since the absolute consumption variance of unrefurbished houses is much larger than that of refurbished, a precondition for linear regression is not fulfilled. In consequence, a logarithmic transformation of the variables is applied in the forefront of regression. The implementation of such analysis on a sample of about 2800 residential buildings in Germany is presented. The result is a function that assigns the average actual consumption and the typical spread to a given EPC calculation result. Examples show how the model can be used to interpret different actual consumption values resulting from different household sizes and utilisation intensities in similar unrefurbished buildings and to estimate the probable span of energy consumption after refurbishment for these different cases.

Introduction

Physical models of heat transfer and energy flow are largely used to understand the actual energy consumption of buildings and to make a prognosis of the consumption for different refurbishment scenarios. In many countries these are also employed for a proof of legal requirements and for standardised information about the energy performance of buildings in Energy Performance Certificates (EPCs). In contrast to the field of consultancy, the official national EPC method needs standardisations to ensure comparability, replicability and verifiability (Atanasiu / Constantinescu 2011; Pascuas et al. 2017; von Platten et al. 2019). In some countries, very extended and complex models are used to map the effects of different parameters on energy consumption (Volt et al. 2020; Semple / Jenkins 2020). This works well for issuing EPCs and legal proofs – however, the numbers provided do not usually seem to reflect the actual consumption, neither of individual buildings nor of the total stock (see overview from different countries in Sunikka-Blank / Galvin 2012, or, more recent e.g. Cozza et al. 2020, Anđelković et al. 2021; Bandurski 2021; Coyne / Denny 2021).

This finding is not surprising. Complex physical models with important input uncertainties are in need for adjustments to reality. Ideally, average boundary conditions and physical parameters for the total building stock and its different subsets would be determined to set up a realistic model: average indoor and outdoor temperatures, opening times for windows, solar shading, thermal conductivities and thicknesses of all materials, etc. In reality, the empirical determination of actual mean values for all input variables would require a gigantic effort. Nevertheless, building owners and occupants as well as policy makers depend on reliable information to be able to make meaningful and targeted decisions. To improve the information provided in EPCs, different strategies to increase the accuracy of the theoretical consumption assessment or optimise the actual consumption can be applied (an overview can be found in Cozza et al 2021). However, since statistically every expected value also has a variance, discrepancies are always to be expected when looking at individual buildings.

The idea of the concept presented in this paper therefore is to tackle these issues by introducing a calibration of the EPC calculation result by use of empirically derived factors or functions, also considering the probable range of consumption. The overall objectives are:

- Assign an average energy consumption and the associated standard deviation to the calculated energy demand (based on empirical data).
- Enable more realistic estimates of savings potentials for individual buildings on average or depending on the intensity of use.
- Provide more reliable information to building owners, occupants and policy-makers.

In the following, a methodology is presented to provide such a calibration procedure. Existing residential buildings before and after energy upgrades as well as new buildings are considered. Building samples from Germany have been used as data basis. However, the method is in principle applicable in other countries with EPC rating schemes based on standard energy performance calculation.

The contents presented here are part of a study carried out on behalf of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) (Loga et al. 2019).

Concept and methods

In this section, the overall concept of the study and the applied methods are presented in a generalised form. The details of the study carried out with German building datasets are presented after this section.

USED TERMS

In the following, the expression “actual consumption” (or “consumption”) refers to the metered energy consumption, the expression “energy demand” refers to the theoretical energy consumption calculated by use of an official national EPC rating method (“standard calculation”). If not mentioned otherwise, given numbers for both quantities refer to square meter living space and to one year, are representing the energy supply of boilers (gross calorific value) or heat transfer stations, and are associated to space heating and domestic hot water (DHW).

PRE-STUDY: EXAMINATION OF POSSIBLE SOURCES AND CREATION OF AN EVALUATION DATABASE

As an empirical basis for quantifying the relationship between actual consumption and EPC calculation, different sources can be considered which include the calculated energy demand and the measured annual energy consumption for the same buildings. An ideal approach would be to gather this information through building stock surveys based on random samples. If this is not possible, other sources can be considered: Databases used for EPC administration and quality assurance, databases for energy advice campaigns or for evaluation of funding programmes, or documentations of research projects focussed on the implementation and the effect of measures A further possibility is to merge datasets by address from an existing heat billing database and from an EPC database. These databases may have specific focus areas (consumption of unrefurbished, refurbished, new buildings, ambitious insulation, etc.) or specific restrictions. Whether they are qualified for investigating the relationship between consumption and demand should be screened in a pre-study. If it turns out that the existing data basis is poor for a country, or specific building groups are not covered, the implementation of a specific survey addressing these voids might be considered.

The pre-study also includes an examination of the datasets with respect to important preconditions for the analysis of the relationship between consumption and demand. Both quantities must be related to the same building entity, features and energy uses. It may be worthwhile to cross-check the year of metering with the date of refurbishment, the indication of living space, number of apartments, energy carrier(s) on both, heat bill and EPC. A further important point is to clarify if domestic hot water is fully included in the measured consumption or not. To be excluded are dwellings with supplemental heat systems (wood stoves, electric heaters) having no indication of the respective additional consumption. Furthermore, attention must be paid to the comparability of metering and calculation scope with respect to the meter positions (heat distribution losses or solar heat included or not) and to climate conditions (possibly applied weather corrections). If there are doubts as to whether building records or even a database meet these requirements, they should not be used in order to ensure high data quality.

For the usable sources identified in the pre-study, the datasets containing values of consumption and demand as well as additional information (type of heating system and energy carrier, energy usages, building size, …) are extracted and – if necessary – converted to a coherent data structure, and then merged in one evaluation database. Of course, the data protection rules for shielding personal information are to be respected when processing data and publishing results.

CALCULATION OF BENCHMARKS: AVERAGE CONSUMPTION PER ENERGY DEMAND CLASS

The first step of the statistical analysis is to create energy consumption benchmarks: The calculated energy demand is subdivided into classes (e.g. in intervals of 50 kWh/(m²a)) for which the average consumption is calculated. The evaluation also includes the standard deviation and the number of cases per class. Furthermore, appropriate conditions can be set to exclude cases which are likely to be defective ("outliers"). Separate benchmark tables are created for "Space heating + DHW" and for "Only space heating", if available. Next to that, a differentiation is necessary by heat generator and heat metering type: At least three types should be analysed separately, grouping buildings that are supposed to have similar consumption values for the same building insulation levels: (1) boilers / fuel or heat, (2) heat pumps / electricity, (3) direct electric systems. The benchmark tables and associated charts give a concise overview of the relationship between consumption and demand, of the scattering and the availability of cases per class.

DERIVATION OF A MODEL FOR ESTIMATING THE CONSUMPTION: REGRESSION ANALYSIS

In order to supplement the EPC calculation and rating for a single building with an estimated energy consumption, a function describing the relation between consumption and demand is empirically derived. An appropriate model is selected with view to the shape of distribution and benchmarks (averages, standard deviation) and fitted to the empirical data. The "least squares" method is considered for fitting: The coefficients of the model are chosen so as to minimise the sum of the squared residuals of model from data. Attention is paid to the preconditions of regression: Given that the variance of the consumption in kWh/(m²a) is likely to be very different for unrefurbished and refurbished or new buildings (the values are "heteroscedastic"), a transformation of variables (e.g. logarithmisation) is needed. Standard deviation and uncertainty of the estimation model are calculated.

TRANSFORMATION OF RESULTS TO OTHER EPC CALCULATION METHODS, IF NECESSARY

In some countries the national standard calculation method has changed or two separate methods are available at the same time. In order to use the benchmarks and the estimation model for both methods, a model is needed for the transformation from one to the other. An appropriate approach is a parameter study in which both methods are applied for a large number of different buildings or building variants, covering the relevant energy performance levels and heat supply systems. With view to the shape of the data point cloud, an appropriate function is identified and fitted to the results of the parameter study. Standard deviation and uncertainty of the estimation model are calculated.

Implementation, analyses and main results using a German sample

USED DATA BASIS

The above-described concept has been implemented for residential buildings in Germany (Loga et al. 2019). In a pre-study, a meta-analysis was carried out to review existing publications with regard to the actual energy consumption. The information given by 6 of the 22 studies were assessed as appropriate to the conditions mentioned above. They comprise data collected during implementation of pilot projects for energy efficient construction or refurbishment, energy consulting activities and field tests. Unrefurbished, refurbished and new buildings with conventional as well as ambitious insulation levels are included. The omitted studies lacked important information that would have been necessary for comparison and aggregation. In some cases, a transformation to a uniform reference area (living space) and to the gross calorific value was necessary. Mainly central heating systems with boilers and district heating systems were included in the data sources. These datasets were merged in one database. Systems with heat pumps and direct electric heating were considered separately. However, since the number of these cases was very small, a statistical analysis was not possible. The underlying EPC calculation method of the studies assessed (which has existed since 2002) is based on the German standard DIN V 4108-6 + 4701-10. All consumption values were climate corrected to German standard climate by use of heating degree days. A total of 2856 cases with value pairs demand/consumption and additional information could be extracted and merged in a data table. In 1 the data points are displayed, representing climate corrected actual consumption versus calculated demand (fuels or heat, used for heating and DHW, annual values related to square meter living space).

BENCHMARKS: AVERAGE ENERGY CONSUMPTION BY ENERGY DEMAND CLASS

For an initial analysis of the relationship between the two variables, benchmarks were determined. The theoretical energy demand was subdivided into classes of 50 kWh/(m²a). For each demand class, the average value of actual consumption and the respective standard deviation were then calculated (solid and dotted green lines in Figure 1). At the bottom of the chart, the respective frequencies are shown (number of data pairs, thin orange columns). Averages and standard deviations were only calculated for demand classes including 5 or more data pairs.

Table 1 shows the corresponding numerical values. In addition, the ratio of average metered to average calculated consumption as well as the relative spread of this factor for each demand class is given. These "calibration factors" are already representing a primitive model for estimating the energy consumption: If the energy use of a building is known from EPC calculation, it can be multiplied with the calibration factor belonging to the relevant energy demand class to obtain an estimate of the actual consumption. Multiplication of this value with the relative standard deviation provides the uncertainty of this estimation.

Values in the last column of the table indicate the model uncertainty, meaning the (absolute) uncertainty of the average consumption calculated per demand class (standard deviation divided by square root of number of cases). This can be interpreted as the uncertainty of the estimated total consumption of all buildings included in the respective demand class.

ESTIMATION MODEL: FUNCTIONAL RELATIONSHIP BETWEEN ACTUAL CONSUMPTION AND THEORETICAL DEMAND

Following the concept described above, functions were developed that can be used for estimating the actual energy consumption if a calculated demand is known for a building. Two models have been considered (see curves in Figure 2, the formulas are shown in the legend of the chart):

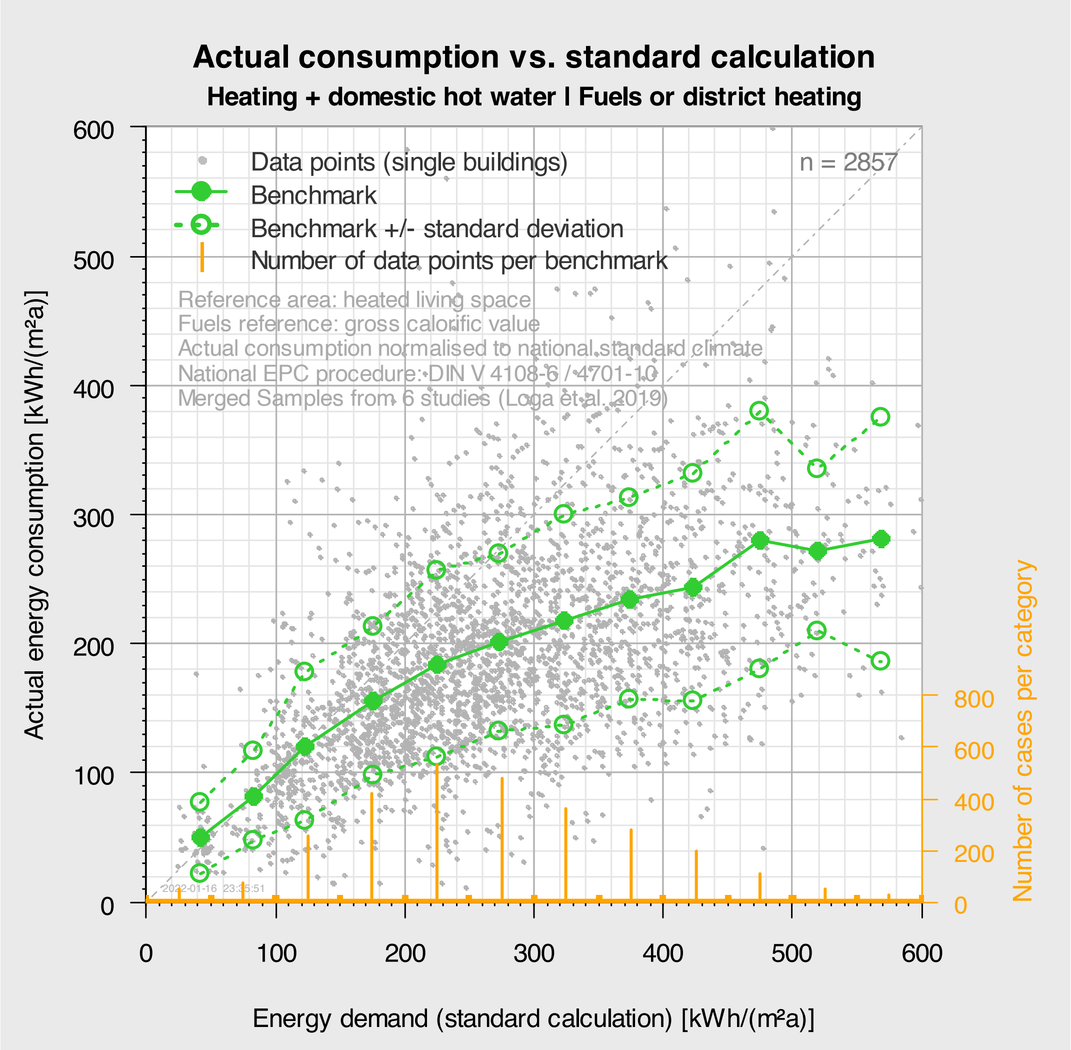

Figure 1. Consumption versus demand for the database merged from 6 building data samples; data points (single buildings) and statistical evaluation for intervals of 50 kWh/(m²a) (Loga et al. 2019).

Table 1. Benchmark table (demand-differentiated consumption benchmarks) for the analysed building sample.

Combined systems for heat supply: space heating + domestic hot water							
Natural gas / heating oil / district heating (for fuels related to gross calorific value H_s)							
Theoretical energy demand (standard calculation) * related to heated living space		Sample	**Actual energy consumption, related to heated living space**				
			Average	Calibration factor: Ratio actual consumption to theoretical demand		Standard deviation of the actual consumption	Model uncertainty (uncertainty of the determined average consumption)
Interval	Average	Number of buildings		Average	Relative standard deviation		
kWh/(m²a)	kWh/(m²a)		**kWh/(m²a)**			kWh/(m²a)	kWh/(m²a)
1 … 50	41	n=49	**50**	1,20	± 55 %	± 27	± 3,9
51 … 100	83	n=76	**82**	0,98	± 42 %	± 35	± 4,0
101 … 150	123	n=257	**121**	0,98	± 48 %	± 57	± 3,6
151 … 200	176	n=421	**156**	0,89	± 37 %	± 57	± 2,8
201 … 250	225	n=534	**184**	0,82	± 39 %	± 72	± 3,1
251 … 300	274	n=482	**201**	0,74	± 34 %	± 69	± 3,1
301 … 350	324	n=364	**218**	0,67	± 37 %	± 82	± 4,3
351 … 400	374	n=281	**235**	0,63	± 33 %	± 78	± 4,7
401 … 450	424	n=199	**244**	0,58	± 36 %	± 88	± 6,3
451 … 500	475	n=109	**280**	0,59	± 36 %	± 100	± 9,5
501 … 550	519	n=52	**272**	0,52	± 23 %	± 63	± 8,7
551 … 600	569	n=25	**281**	0,49	± 34 %	± 95	± 18,9
*) Theoretical demand calculated according to the German standards DIN V 4108-6 + DIN V 4701-10							

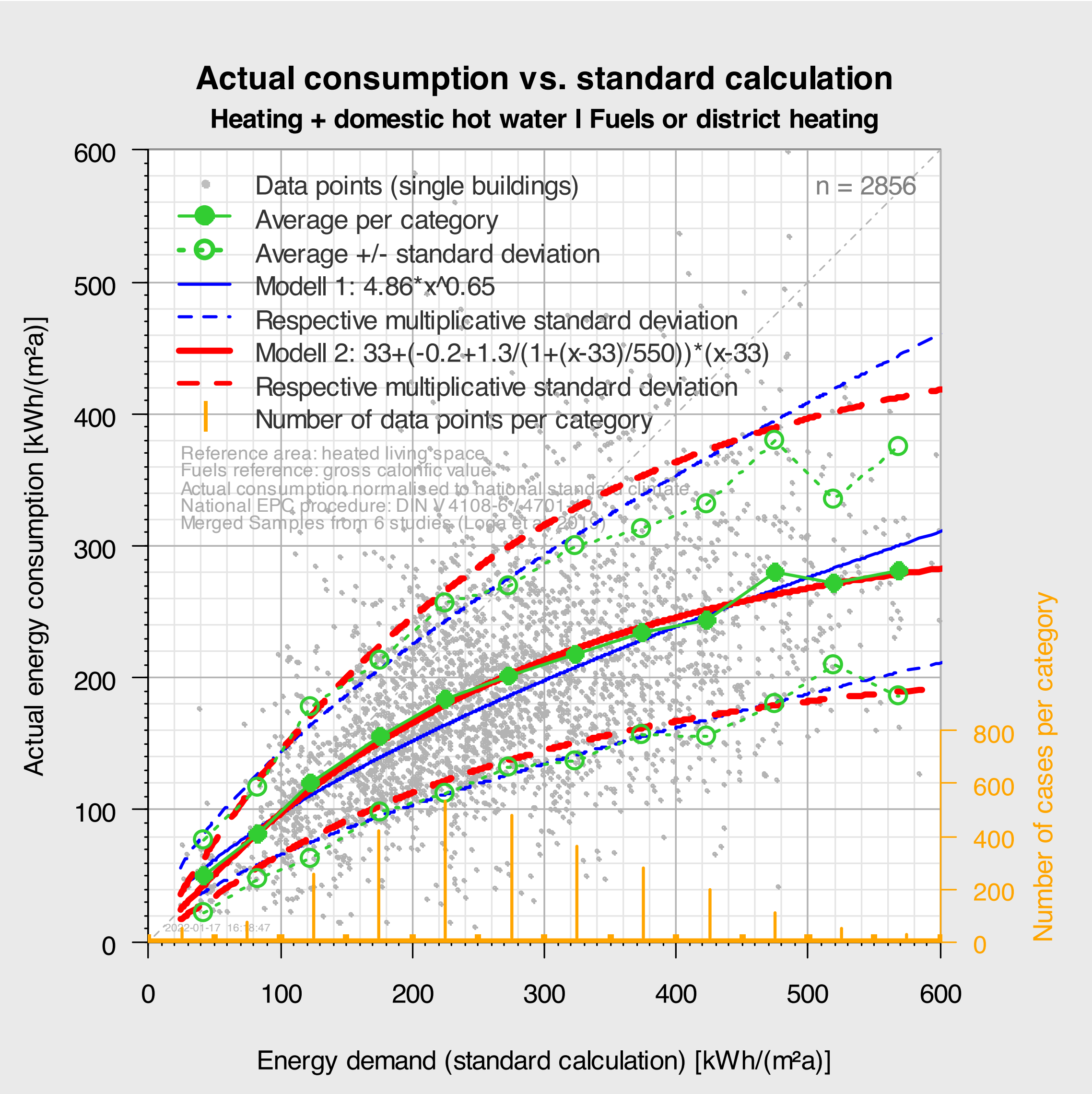

Figure 2. Comparison of benchmarks and continuous estimation functions (Models 1 and 2) (Loga et al. 2019).

- Model 1: a power function with real exponent (described in Hörner et al. 2016 and Hörner / Lichtmeß 2017);
- Model 2: a linear function with a multiplicative correction term (which had already been used in previous studies, see Sunikka-Blank / Galvin 2012, Loga et al. 2015, and Pehnt et al. 2015).

Model 1 is a commonly used straightforward model to achieve equality of variances across the independent variable ("homoscedasticity"). By logarithmising the variables, the function is transformed to a linear equation. The coefficients are found by linear regression (least square criterion). The estimation model is completed by entering the coefficients into the original power function (see function in the legend of Figure 2).[1]

Model 2 was originally selected with a view to the physics expecting a linear correlation of consumption and demand for buildings with well-defined, good insulation and average indoor temperatures close to set-point temperatures. For buildings with poor insulation, uncertain thermal properties, high energy costs per additional Kelvin indoor temperature, stronger effects of night-setback and partial heating, a correction factor is applied that becomes more and more dominant the higher the standard energy demand is calculated. The original formula is related to demand and consumption for heating only (without DHW), here it is applied to combined heating and DHW by a transformation of the independent variable (see formula in the Annex of the present article). Also, for this model, the values of the dependent variable (consumption) were logarithmised to find the coefficients (by least squares fitting) and assess the model.

As a result, the quality of both estimation functions is similar: About 40 % of the variance of the logarithmised consumption values can be explained by the models (coefficient of de-

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[1] A simple linear regression is no valid model due to the large differences of the absolute scattering intensity (random disturbance) across the calculated energy demand (the data are "heteroscedastic", see explanations in Hörner et al. 2016 and quantitative proof for these data in Loga et al. 2019).

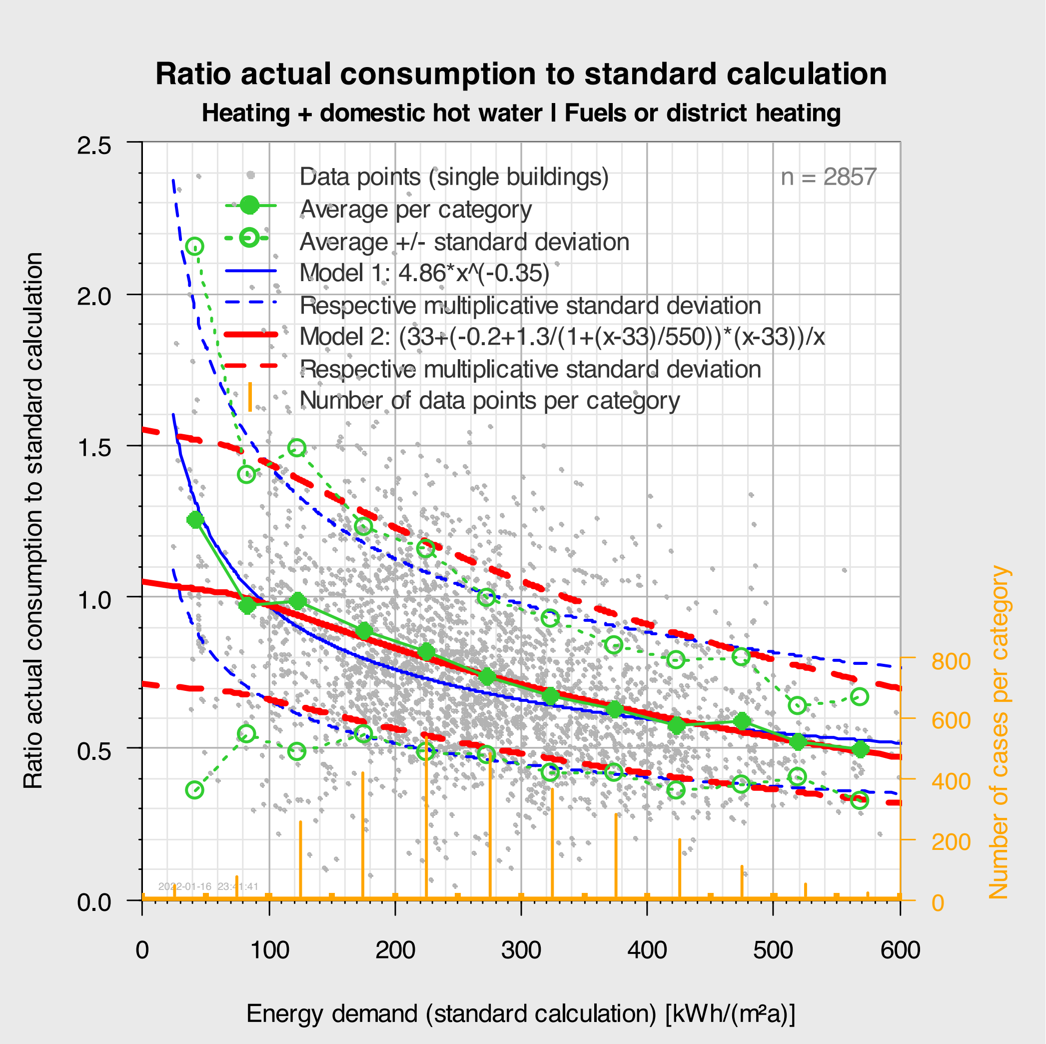

Figure 3. Ratio actual consumption to standard calculation, estimation model 2 (thick lines) proposed as calibration function for German EPCs (Loga et al. 2019, the complete formula with corrections for extreme values can be found in the Annex of this paper).

termination R^2 of the logarithmised values of Model 1 is 0.398, that of Model 2 is 0.390). The standard deviation of the logarithmised dependent variable is 0.39 for both models, resulting in factors 1.48 and 0.68 (see "multiplicative standard deviation" in Figure 2).

Figure 3 displays the ratio of consumption to demand versus demand for the two functional estimation models described above in comparison to the averages from the benchmarks. These are the factors to be applied to the energy demand for calibrating it to the typical level of consumption.

DISCUSSION OF RESULTS

The course of the estimation curves is in principle close to the previously presented benchmarks in most demand classes (Figure 2). A minor discrepancy can be detected for Model 1 in the area between 150 and 350 kWh/(m²a), where the estimated values are about 20 kWh/(m²a) lower than the benchmarks.

Comparatively, there are fewer buildings in the best demand class so that the relative uncertainties of the models are larger in this area. However, this accuracy seems good enough for practical use. For this demand class the calibration factor of Model 2 is lower than that of the benchmarks (Figure 3). On the other side, the calibration factor of Model 1 has a large gradient in this area, a particularity of this type of function which may not be in line with actual physical effects. Here, more cases are needed to improve the estimates (for example by introducing a correction term).

However, it should be noted that due to the different concepts of calculating averages (minimised linear variances) to calculating functional estimates as used in this study (minimised squared variances of logarithmised values), an exact match of the estimates of both approaches cannot be expected.

A further systematic difference occurs with respect to the spread: For benchmarks equal distances are used on both sides (average plus and minus standard deviation), for the estimation functions the factors 1.48 and 0.68 (=1/1.48) ("multiplicative standard deviation") are applied, reflecting the standard deviation based on logarithmised values. Which model of scattering is more adequate in which application case could be explored in future investigations. Also, more differentiated data are necessary to distinguish between single- and multi-family houses and to determine separate benchmarks, calibration functions and models of the spread.

In summary, the estimation functions are simple mathematical representations for a continuous calibration of the results, which could e.g. be useful in displaying the expected consumption in EPCs[2]. Benchmarks however consist of discrete consumption values, presentable in tables and diagrams and usable e.g. for visual comparison of the metered consumption of a given building. Also, benchmarks can highlight particularities of specific building categories (demand classes), including the lack of data. A combination of both, benchmarks and estimation functions, seems an adequate means to represent reality and address the different application cases.

Since the functional models do not differ greatly and Model 2 is already in use in energy consulting (dena / ifeu / PHI 2017), it was favoured in the study reported here (Loga et al. 2019) and proposed as a model to be used to calibrate the official German EPC calculation to the typical level of metered consumption. In addition, a systematics for the application in the context of energy consulting for the prognosis of the actual consumption was developed, which also comprises the case where DHW is not included in the metered consumption. Furthermore, a rule was formulated how to make prognosis if the actual consumption in the initial state is known for a building: The ratio of consumption to expectation value is considered as constant, provided that no change in use is foreseen (see examples below, the formulas are documented in Loga et al. 2019, chapter 4.3.9).

A fundamental discussion point is if the EPC calculation models could not be more realistic so that a calibration would not be necessary in the first place. That seems to be difficult due to the standardisations needed to achieve comparability, reproducibility, and verifiability. Detached from official proofs and ratings, realistic physical models of existing buildings can of course be designed and used (e.g. in the context of energy consultations). This needs a quantification of the uncertainties of input variables and a supplemental assessment of the calculation uncertainty (Loga / Behem 2021). Such methods might be used in parallel to official EPC procedures for purposes like energy consultancy, target-actual comparison or evaluations of policy instruments.

TRANSFER OF RESULTS TO THE NEWER VERSION OF EPC CALCULATION IN GERMANY

In Germany, a second EPC calculation procedure has been introduced in 2009 for residential buildings, the old method used for the analysis described above will expire at the end of 2023.[3] Until now the old method is predominant for residential buildings, therefore empirical data is so far only available for this method. To be able to transform the consumption benchmarks and calibration functions derived from the old method to the new one, a parameter study was carried out as described in the section “Concept and methods”. Starting from 9 example buildings, 85 building variants were defined, representing different levels of insulation, heat supply systems and additional systems like mechanical ventilation with heat recovery or thermal solar systems. Both EPC calculation procedures were applied to all variants and the demand values of the old procedure analysed with respect to the new one. Since the variance is rather constant for the total range of the independent variable, a linear regression is admissible in this case. For heating systems with boilers, a calibration factor of 0.86, for electric heat pumps a factor of 0.71 was derived. The factors are applied to estimate the demand of the old method if the demand of the new method is known. The coherence is rather high, the linear model can explain 99 % of the variance. The standard deviation of the sample is +/- 11 kWh/(m²a), the uncertainty of the estimation model based on all variants is +/- 1.6 kWh/(m²a). Figure 4 shows the data points and estimation function for heating systems with boilers. The actual consumption can now be estimated starting from the demand calculated by the new method: First, the estimated demand of the old method is assigned to the calculation result, then the typical consumption is estimated with the help of this value.

Illustration by examples

In the following, the application and benefits of the concept will be explained by use of (fictious) examples from energy consulting.

SAVINGS PROGNOSIS WITHOUT INFORMATION ON ACTUAL CONSUMPTION

First, the case of an existing building is considered for which a package of energy refurbishment measures is envisaged and the actual consumption in the current state is unknown. For this old single-family house, a final energy demand of 364 kWh per m² living space for heating and hot water is calculated by the standard EPC procedure (Figure 5). The curve “Typical consumption (estimate)” now provides the information that the consumption of buildings of this energy performance level is likely to be 235 kWh/(m²a) – the values scatter between 160 and 348 kWh/(m²a), indicated by the curves “Bandwidth of consumption (expectation range)”. The large scattering range around the estimated value can be partly explained by user behaviour, which in practice can deviate significantly from the standard values of the EPC calculation. But there are also major uncertainties with regard to the physical building features (e.g. materials, construction types, thermal bridging, leakages) of old buildings.

The energy consultant could explain this to the house owner in the following way:

> The actual energy consumption of the building is not available. On the basis of a standardised energy performance calculation and statistical data of actual consumption the annual energy consumption for heating and hot water is estimated to 235 kWh per sqm living space – values between 160 and 348 kWh per sqm living space are common for this energy performance level – depending on the intensity of use and variations of materials.

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[2] Such an indicator showing the estimation value and the estimation range is already included in the official EPC of Luxembourg, calculated by use of Model 1 with regression coefficients from a statistical analysis of the Luxembourg EPC database (Hörner / Lichtmeß 2017). A brochure of the Luxembourg energy agency displays the respective EPC form: https://media.enovosgroup.eu/energieagence/brochures/energiepass/de/10/.

[3] In order to implement the EPBD 2002, it was necessary to develop a new calculation method, as there were no coordinated approaches in Germany for air conditioning and built-in lighting installations. The new method (DIN V 18599) was introduced for non-residential buildings in 2007 and for residential buildings in 2009. Alternatively, the old calculation method (DIN V 4108-6 + 4701-10) can still be used for residential buildings.

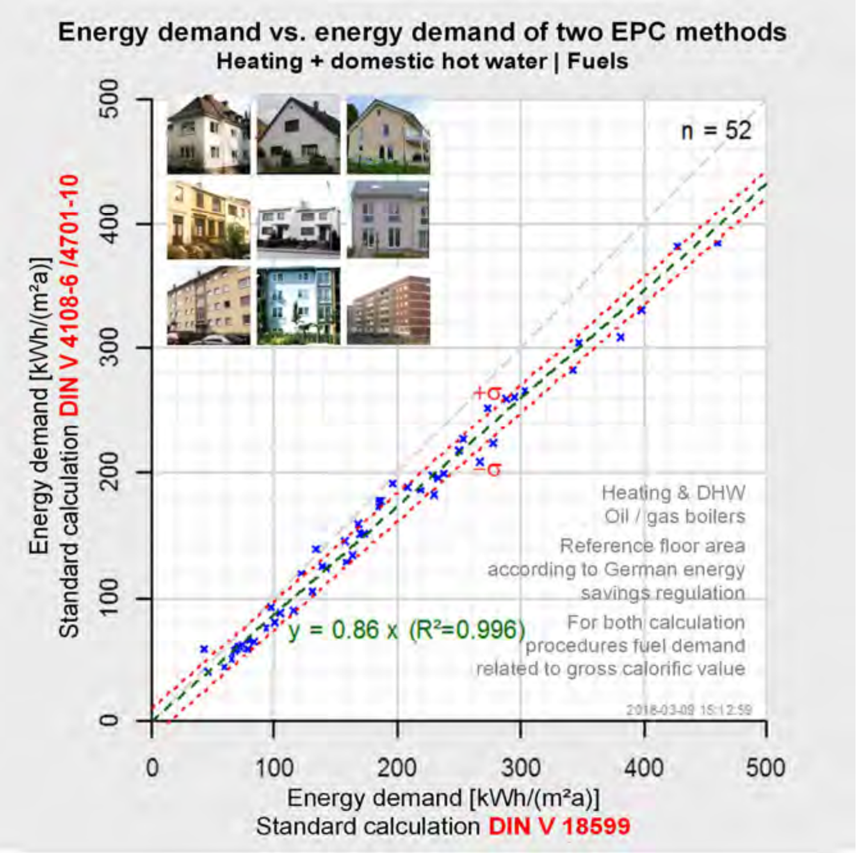

Figure 4. Relationship between the energy demand values (fuels) of two EPC calculation procedures (DIN V 4108-6 + 4701-10 versus DIN V 18599), result of the regression analysis for variants with heat generator boiler (Loga et al. 2019).

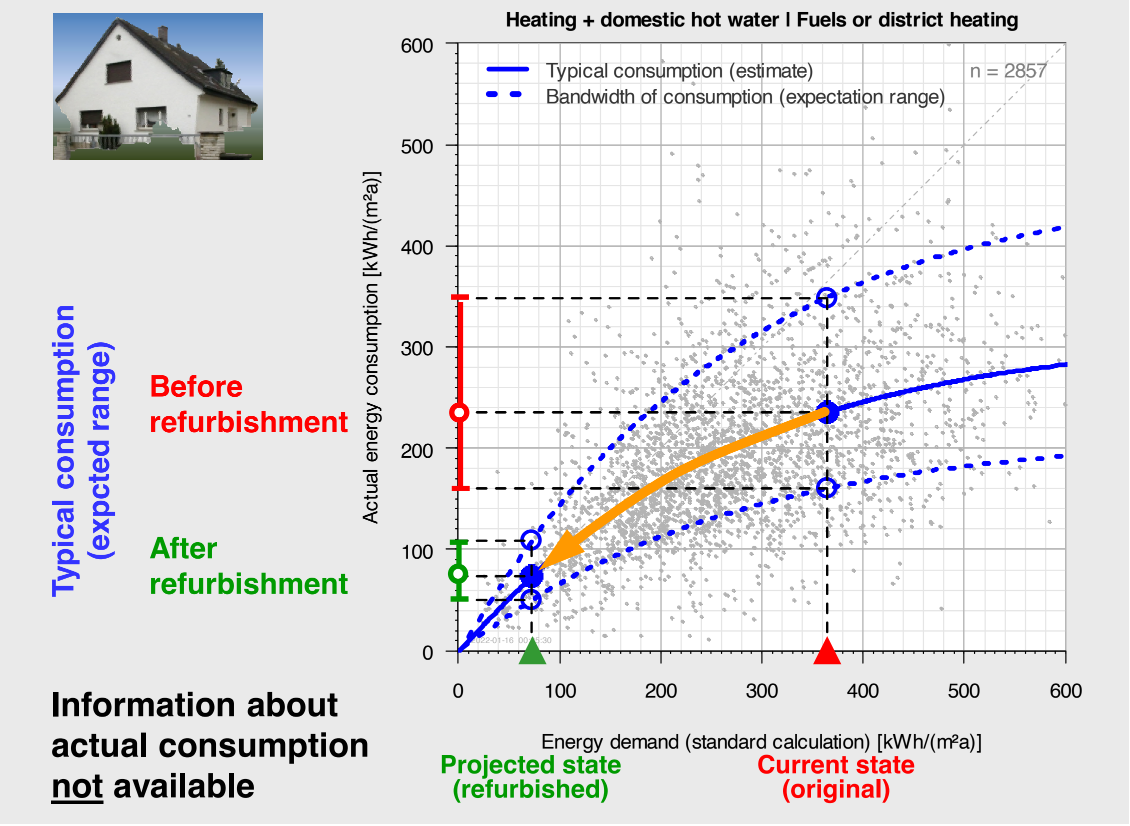

Figure 5. Exemplary single-family house: Calibration of the energy-saving calculation before and after measures if no individual consumption value is available (Loga et al. 2019).

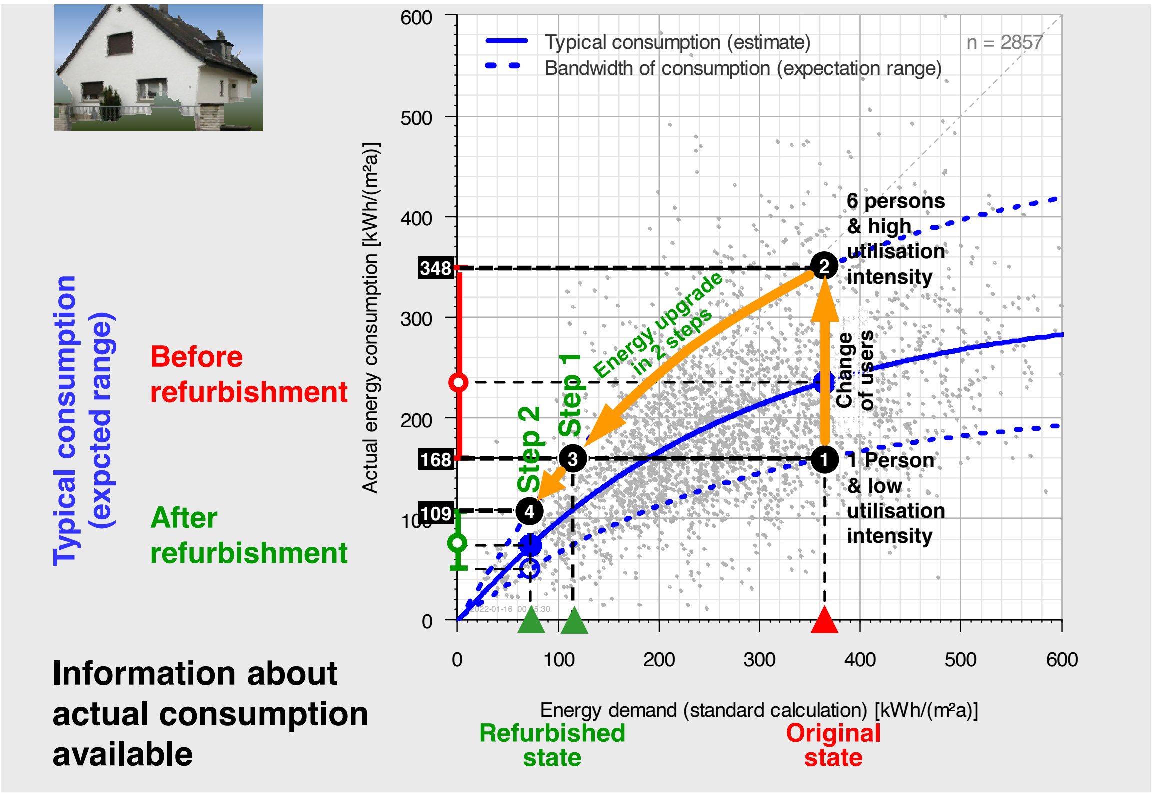

Figure 6. Example for an assessment and explanation of diverse actual consumption values in a single-family house; change of users and two-stage refurbishment (Loga et al. 2019).

As part of the energy consultation, thermal insulation measures are now proposed and a standard energy demand of 73 kWh per m² of living space is calculated for the recommended building state. According to the model shown in the diagram, the estimated consumption of houses of this energy performance state is 74 kWh/(m²a) – the typical bandwidth is 50 to 109 kWh/(m²a). The uncertainty in the refurbished state can mainly be attributed to user behaviour, because the thermal qualities of the insulation and the new windows are very well defined.

This means that the following prognosis is now possible in energy consulting:

> The annual energy consumption for heating and hot water expected after the implementation of the proposed measures is 74 kWh per sqm living space – values between 50 and 109 kWh per sqm living space are common for this energy performance level – depending largely on the intensity of use.

SAVINGS PROGNOSIS IF ACTUAL CONSUMPTION IS KNOWN (TWO DIFFERENT UTILISATIONS)

Figure 6 illustrates how the scheme can be used for the interpretation of measured consumption values (example: single-family house of 155 m² living space). The four points shown in the diagram are representing the following steps:

1. In the completely unrefurbished building lives a single person, who only heats two rooms in winter. The measured gas consumption for heating and hot water of this frugal person is 160 kWh/(m²a) and thus 30 % below the average[4].
2. There is a change of users. A family of six moves in. In comparison with other 6-person households, there is a rather high usage intensity. The measured consumption of 348 kWh/(m²a) is about 50 % higher than the average of houses with the same energy performance state.
3. The first stage of an energy refurbishment is implemented. The consumption is halved to about 160 kWh/(m²a). It is now back at the value of the previous occupant before energy refurbishment.
4. The second stage of modernisation to an ambitious energy performance level is implemented. The consumption is now reduced to 109 kWh/(m²a) and thus to a third of the initial value of the six-member family. However, it is still 50 % higher than the average of similar buildings, but within the usual span of consumption (at the border of the expectation range).

The presented scheme may help owners and residents to classify the measured consumption. For climate protection policy, however, the exceeding of the expected energy consumption value found in individual cases is not relevant since it is com-

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[4] The term "average" is mathematically not correct, but used here since it is helpful to explain this scheme in everyday speech.

pensated by others below the average. The primary aim there is to ensure that, on average, the pursued consumption target is attained across all refurbishments.

The example also illustrates that square-meter-related statements are not sufficient for an assessment of the climate protection effect. In the initial state, the per capita emissions for heating and hot water for the one-person household are 6.0 tons of carbon dioxide (equivalent) per year, despite economical behaviour, and 2.2 tons of carbon dioxide for the 6-person household.[5] Thanks to the refurbishment measures, the family's emissions were reduced to 0.7 tons per capita. If the frugal individual had not moved out and instead carried out the same energy upgrade, the person would have reduced the consumption for heating and hot water to around 50 kWh/(m²a) – a value that is about half of the value reached by the family after refurbishment. However, even after refurbishment, the per capita emissions for heating and hot water would still amount to 1.9 tonnes of carbon dioxide per year for the one-person household (and would therefore still be higher than the German average).

Summary / perspectives

A meta-analysis of the data of several German studies has provided insight in the relationship between the theoretical energy demand displayed by Energy Performance Certificates (EPC) and the actual energy consumption of residential buildings in Germany. The proposed concept and applied methods are, however, not bound to German specifics and thus applicable in other countries.

The statistical analysis carried out supplies a benchmark table with average consumption values and typical bandwidths for 12 categories of the energy demand. In addition, functions were identified which enable a calibration of the standard energy demand from the EPC calculation to the typical level of measured consumption, delivering expectation values and ranges.

The calibration functions can be used in EPC-related energy advice activities to assess the actual consumption of buildings and interpret it with view to user behaviour and uncertain assumptions. Furthermore, empirically based prognoses of the consumption after refurbishment can be made for scenarios calculated with the EPC software.

The authors propose that the German government enriches the EPC-related regulations by specifying a supplement to the certificate that displays estimates and expectation ranges of the actual energy consumption in addition to the standard calculation result. By such an addendum, the calculated EPC rating could attain more practical relevance for house owners and tenants – also with respect to the expected heating costs. The variation ranges of benchmarks and calibration functions make it clear that different consumption values for similar buildings are to be expected due to the influence of user behaviour and other uncertainties. However, the benchmarks and functions show how – despite the influence of different users – the average consumption depends on the physical properties, such as insulation level and supply system type. For key actors in governments, this is the most relevant aspect with view to climate protection instruments: Which average consumption of fossil fuels and other energy carriers is related to specific (theoretical) energy performance levels? More reliable statements about the effectiveness of specific measures are possible, with regard to typical cases and – at the same time – for the entire residential building stock.

The authors recommend that the benchmarks are made available for the general public to strengthen the confidence in the energy savings achievable by refurbishments. This requires also a scheme for data update and expansion of the data basis in the long run. Since there are many buildings without a calculated EPC, supplemental benchmarks are needed providing average measured consumption values by building characteristics to provide owners and tenants of these buildings with the relevant information.

From a scientific point of view, the method requires further development, optimisation and validation. Particular attention must be paid to improving and enlarging the data basis so that more differentiated evaluations are possible:

- Extension of the database to further heat supply systems (especially buildings with heat pumps) and to more buildings with ambitious energy performance (nZEBs, passive houses, …);
- Differentiation of analyses by single- and multi-family houses, since the uncertainty ranges are expected to be quite different;
- Refined estimation models to include available knowledge about user behaviour and local climate.

A further focus is needed on practical application of benchmarks and estimation functions and on how to communicate these results comprehensibly to owners and residents.

Acknowledgments

The work described in this paper is part of the study "Berücksichtigung des Nutzerverhaltens bei energetischen Verbesserungen" ("Consideration of user behaviour in energy improvements") carried out on behalf of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) (Loga et al. 2019). We very much appreciate the support and cooperation.

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[5] Assuming a greenhouse gas emission factor of 240 g carbon dioxide equivalent per kWh

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Formula annex

The calibration functions proposed in Loga et al. (2019) for calibration of the German EPC procedure are (expressed in the syntax of the programming language R):

Calibration function for heating only:

fapply (cbind (0.4, (-0.2 + 1.3 / (1 + (q_calc_h) / 550))), 1, max)

Calibration function for heating + DHW:

fifelse (q_calc_hw <= 66, 0.5 * (-0.2 + 1.3 / (1 + (0.5 * q_calc_hw) / 550) + 1) * q_calc_hw, 33 + apply (cbind (0.4, (-0.2 + 1.3 / (1 + (q_calc_hw - 33) / 550))), 1, max) * (q_calc_hw - 33))

with q_calc_h and q_calc_hw being the energy demand determined by the EPC standard calculation method (old method DIN V 4108-6 + 4701-10), related to the heated living space and for fuels to the gross calorific value

(Note: The R syntax “apply (cbind (x, y), 1, max)” is representing the mathematical function max (x, y) with a row-by-row application resulting in a vector of the same length.)