Target/actual comparison and benchmarking used to safeguard low energy consumption in refurbished housing stocks

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Abstract

A method of realistic energy performance calculation has been developed and applied for target/actual comparison on refurbished subsets of housing stocks. The aim is to continuously monitor the energy consumption for heating and hot water after renovation. The overall motivation of the involved housing companies is to limit the heating cost of tenants and the fossil fuel consumption to the level targeted by the retrofit investments.

The core of the concept is a structured "building data table" including specific monitoring indicators which reflect the main energy characteristics of the apartment blocks. The indicators are inputs to a simple but realistic energy performance calculation, used for tracking consumption on a year-by-year basis. The model includes data gap and uncertainty handling for all input quantities: If information is missing qualified typical or average values are used as input values and a larger uncertainty is assigned to the respective input quantity. Hence, an uncertainty range is assigned to the calculated energy use reflecting the typical variation and uncertainty of input parameters (user behaviour, weather conditions, shading, etc.). The actual energy consumption is supposed to lie within the uncertainty range of the realistically calculated energy demand – metered values deviating from this target range are indicated as "suspicious" and are subject to an in-depth analysis.

The target/actual comparison was applied to a group of mostly refurbished apartment blocks owned by three housing companies. From these 129 building entities a few suspiciously high consumption values were identified, which are subsequently being investigated. The focus is to detect defects of building or system insulation but also to check and improve operating conditions and give advice to occupants, if necessary.

After supplementing further datasets of unrefurbished buildings the total group of 155 building entities covers a large span of refurbishment states. A useful result of the database analyses is the mean measured consumption differentiated by the energy retrofit level. These benchmarks demonstrate that the model allows for an accurate prediction of the actual energy use of apartment blocks over the whole range of renovation states – from unrefurbished buildings to ambitious passive house or nZEB renovation levels.

Introduction

Half of the 40 million homes in Germany are in multi-family buildings. Thereof about one third is owned by housing companies. A large fraction of these buildings is equipped with central heating systems – the heating bills usually form part of the ancillary cost paid by the tenants. Although databases are used for heat billing by the housing companies or by commissioned metering services, energy benchmarking for the housing portfolio is rarely performed. Some large heat meter and billing service companies have been publishing statistical analyses of their databases – but none of these provide benchmarks for different refurbishment levels (Loga et al. 2019, p. 77ff.). As regards the refurbishment levels information is available at least at national level: Two energy-related housing surveys were performed in 2009 and 2016 for the residential building stock (owner query based on a random sample) which provide insight about the achieved level of energy upgrade and the annual upgrade rates, differentiated by single- and multi-family buildings and by age bands (Diefenbach et al. 2010) (Cischinsky/Diefenbach 2018).

Many housing companies put a lot of effort into energy refurbishment activities, driven by the challenges of the climate crisis. However, most of them do not systematically track the applied measures and the energy savings. Although energy performance certificates (EPCs) are usually available due to legal requirements, the input data are only used to produce the EPC and are rarely saved and maintained in a database. Several software solutions for EPCs are on the market – but none of them can store input and output data in a database. Therefore, a statistical evaluation of insulation states, window types, heating system types for a housing portfolio is not easy. The concept presented in the following provides a solution that housing companies could use to track their actual refurbishment process, to predict the energy consumption after refurbishments and to safeguard the achievable savings by detecting defects, improving operating conditions and giving advice to tenants.

Concept

The concept is to expand the existing process of heat billing to provide annual target/actual comparison and benchmarking. The core element is a specific "monitoring database" that includes information on the energy performance of the building envelope and heat supply system, the expected energy consumption and the actual energy consumption. For a recently refurbished building, the envisaged process (as in Figure 1) is to:

1. Plan and supervise the energy refurbishment (as to date).
2. Store the insulation and energy performance data in the monitoring database (new).
3. Calculate the expected range of energy consumption (new).
4. Collect the meter readings and prepare the heating bills as part of ancillary cost management (as to date).
5. Distribute the heating bills and claims for refund to tenants (as to date).
6. Assign metering information for the current year to the building entities in the monitoring database (new).
7. Compare target/actual performance and check if the consumption meets or exceeds/undercuts the expectation range (new).
8. In case of noticeable high consumption: Examine building insulation, operating conditions and user behaviour (e.g. window opening in winter). Employ improvement measures or give advice to tenants, if possible. In case of noticeable low consumption: Check for data faults, especially formerly applied insulation not yet registered. (new)

The process can be started by considering only recently refurbished buildings and should be extended to ultimately cover the entire building portfolio.

The expected immediate benefit of the concept is that a low energy consumption would be safeguarded in the refurbished houses. Long-term advantages can be achieved by a statistical analysis of the target/actual values of all buildings. The resulting energy benchmarks are supposed to enable a realistic prognosis of the actually attainable energy consumption level for different types of refurbishment measures. In the long run, the concept can provide a powerful basis for energy management and strategic development of housing portfolios.

Method

GATHERING AND INPUTTING ENERGY PROFILE INDICATORS

Core to the concept is a specific set of query variables, the "energy profile indicators". These include information about the physical characteristics of a building which have the biggest impact on its energy performance. These data can in principle be collected by on-site inspections or by asking building owners. They are (see Figure 2):

- Data on size and layout: living space, number of full storeys, whether attic and basements are heated, number of attached buildings, number of apartments, date of data acquisition, …
- The thermal quality of the building envelope: year of construction, type of construction, insulation thickness and insulated fraction of envelope elements (roof, wall, floor), year of insulation, type of windows, …
- The characteristics of the heat supply system: available types of heat generation, storage, distribution for heating and hot water; use of renewable energies, year of installation/renewal, …

The set of energy profile indicators is designed to meet two applications: to roughly calculate the expected energy use of single buildings (Loga et al. 2005) – and to determine statistical information about the state and the annual rate of refurbishment of the building stock by means of a survey (Cischinsky/Diefenbach 2018). The role of these indicators in national and local building stock monitoring is outlined in (Loga et al. 2019, p. 355).

REALITY-BASED PHYSICAL MODEL INCLUDING UNCERTAINTIES

The energy profile indicators, displayed in Figure 2, are used as input variables for the energy performance calculation model by:

- Estimating the thermal envelope area on the basis of the indicators on building size and layout (Loga et al. 2005)/(Loga et al. 2015).;
- Estimating U-values[1] on the basis of the building's construction period and the insulation level (see description below);
- Assigning precalculated efficiency values for heat generators, storage and distribution systems on the basis of the system configuration (availability and type of components) (Loga et al. 2015).

1. Measure of heat loss for a given part of the thermal envelope.

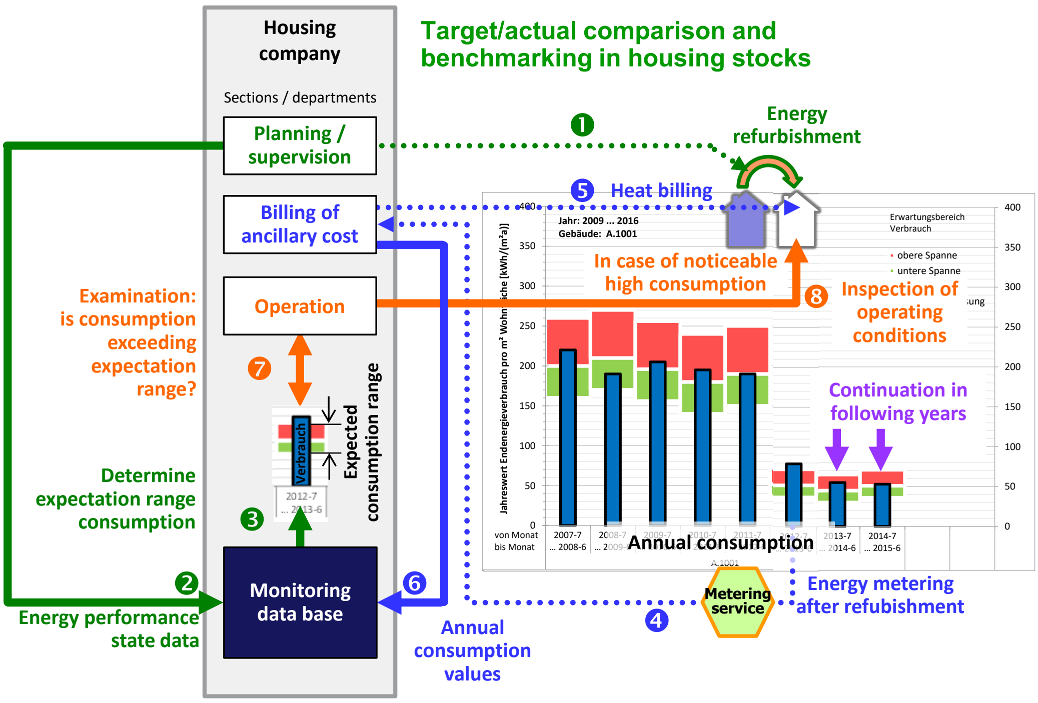

Figure 1. Scheme of the envisaged target/actual comparison and benchmarking in the building stock of housing companies.

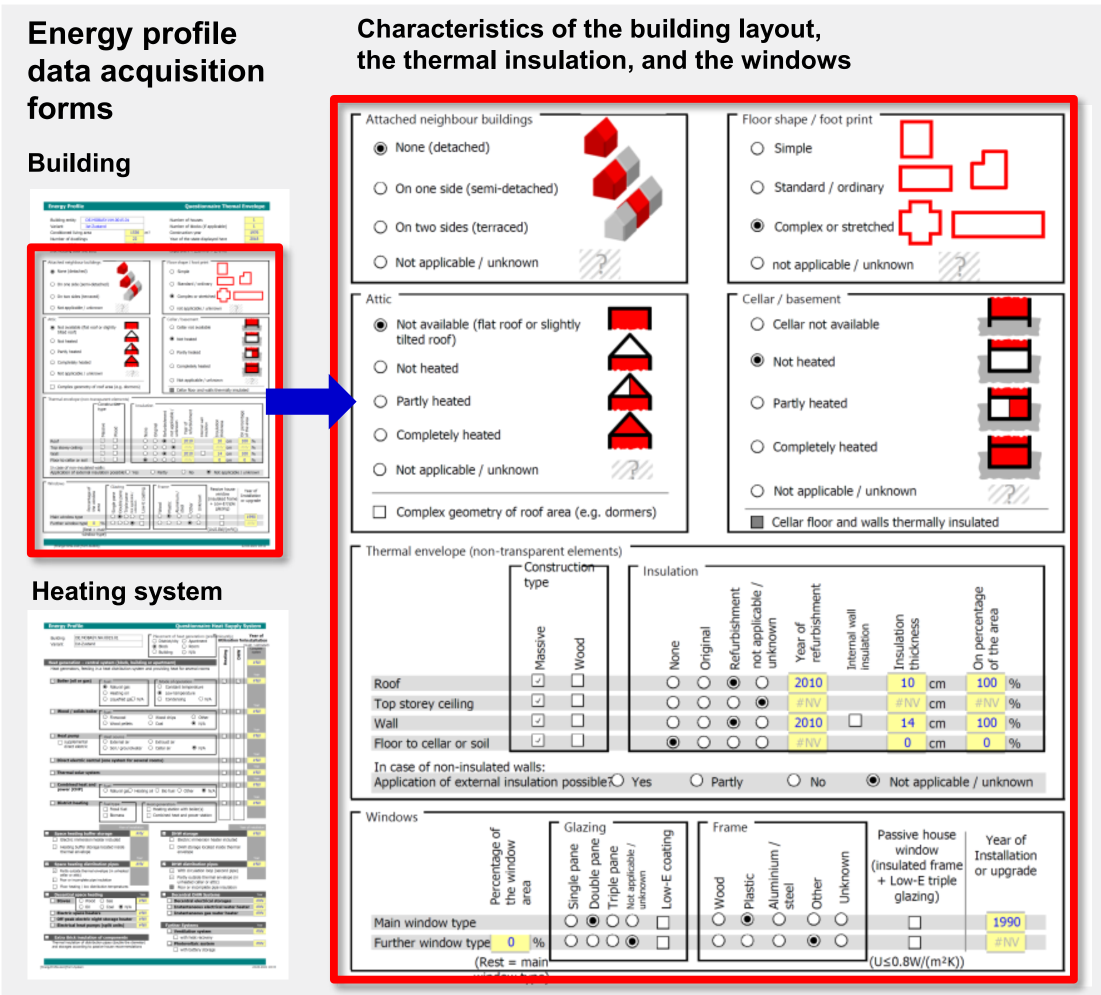

Figure 2. "Energy Profile Monitoring Indicators" – two forms used to enter basic data representing the energy performance state of buildings; zoom in on the building fabric aspects.

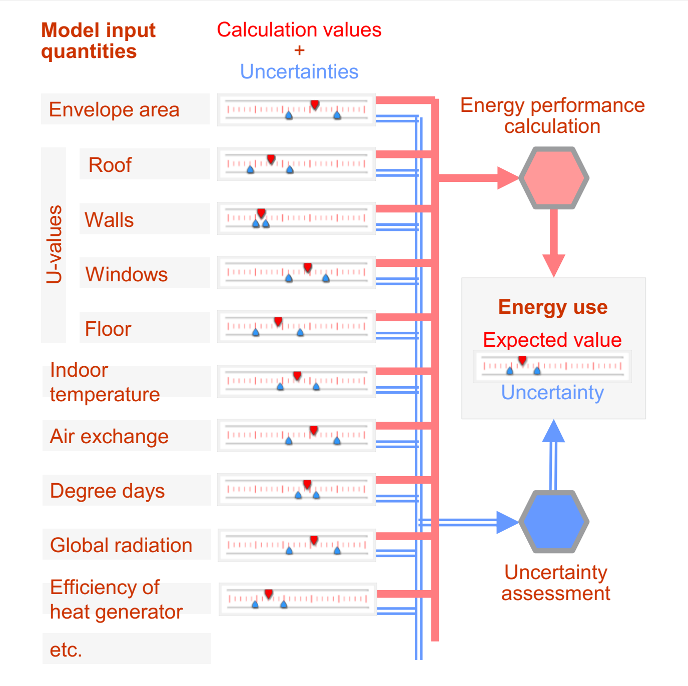

Figure 3. Energy performance calculation including quantified uncertainties (simplified model).

The physical model also includes realistic boundary conditions (calculation values and assigned uncertainties) as follows:

- Utilisation data were derived from measurements in model projects (Loga et al. 2019, p. 285ff.) supplemented by estimates where reliable measurements were not available.[2]
- Climate data used in the calculation are selected by postcode of the building address. This is built on a database created from climate data of the German Weather Service (DWD) with monthly values of the external air temperature for over 800 weather stations and monthly values of solar radiation (different orientations) for 3,000 measuring points in Germany. The method used to create the data tables can be found in (Loga et al. 2020b).

The approach for combining physical and statistical data is illustrated in Figure 3. The inputs are a set of “calculation values” and uncertainties. The calculation values are used by the physical model to estimate the energy use. The assigned input uncertainty values serve to determine the expected range of energy use. Gaussian error propagation law (square root of the added-up squares of the uncertainties caused by each single variable) is used. Since most of the probability density distributions of input variables are assumed to be symmetrical and the energy balance procedure is mainly linear the systematic deviations produced by this simplification are assumed to be small – but this still has to be verified (e.g. by applying a Monte Carlo simulation). The energy performance calculation is based on the TABULA method[3] (Loga/Diefenbach 2013). The details of the simple combined physics-probability-model are described in (Loga et al. 2021).[4]

CORE CHALLENGE: INSULATION STATE OF BUILDING STOCKS (MODEL + EXAMPLES FOR DIFFERENT SITUATIONS)

The insulation state of the building envelope is the most relevant factor for the energy consumption of existing buildings – and it is the primary starting point for energy retrofits. However, there are major challenges to assessing the existing state of a building and estimating the possible energy savings. These include:

- Rarely the materials used to build a house are reported from the past. Often, they also are not accessible to visual inspection.
- Even if information about the kinds of materials is available their actual thermal conductivity can only be guessed at. Testing of materials in a laboratory is far too expensive.
- The thermal transmittance of poorly insulated components is strongly dependent on included cavities/air layers, wooden beams and boards, but also on the external and internal heat transfer coefficients (bordering sheds, façade greenery, thick bushes, close buildings etc. at the outside; shelves, wardrobes, curtains, etc. on the inside). In practice there is a large range of variation of these effects which are very difficult to determine.

All difficulties only apply to non-refurbished elements. When thermal insulation is applied the effects mentioned above are reduced – for large insulation thicknesses they practically disappear. Then the dominant influence on the amount and the uncertainty of the heat transmission losses is the thickness and the thermal conductivity of the insulation.

Facing this situation, it seems to be hopeless trying to determine accurate U-values for existing buildings and thus to accurately predict their energy use. However, the combination of the uncertainty approach and the reality-based physical model makes the energy performance calculation possible (and reliable). The proposed assessment procedure is based on the following concept (for details see (Loga et al. 2021)):

- Original U-value: The variety of constructions as-built was analysed in the framework of (Renhof 2018) by use of regional building typologies (information material with showcase examples, usually developed by regional energy consultants). Average values and standard deviations were generated for all German building age bands (variable U_Original [W/(m²K]).
- Additional thermal resistance: In the case of a later insulation upgrade, additional thermal resistance is calculated based on the insulation thickness (d_Insulation [cm]) and its thermal

2. The main deviation to official German EPC calculations is the higher internal temperature in the heating season for well insulated buildings. The mean indoor temperature measured in several model projects was 22 °C. However, the German EPC procedure is using 19 °C (old standard DIN V 4108-6) or 20 °C (new standard DIN V 18599) for all buildings.

3. A stationary seasonal energy balance calculation, resulting in the energy need for heating and the energy use by energy carrier for heating and DHW, developed in the framework of the Intelligent Energy Europe projects TABULA and EPISCOPE (www.episcope.eu).The calculation procedure is showcased by the TABULA Web-Tool: www.webtool.building-typology.eu.

4. An Excel workbook “EnergyProfile.xlsm” has been developed and applied for the calculations presented here – it will later be available at: www.iwu.de/forschung/energie/2017/mobasy/.

conductivity (Lambda_Insulation [W/(m·K)]). The additional thermal resistance only applies to the fraction of the surface area covered by the insulation (f_Insulation). The uncertainty of these input values depends on the data source type (files of building owner, on-site inspection, refurbishment planning, planning including quality assurance).

- The resulting U-value is calculated as follows:
  U_Effective = (1–f_Insulation)*U_Original+f_Insulation *(1/(1/U_Original+0,01*d_Insulation/Lambda_Insulation))
- If information is lacking for one or more of these variables, default values are used that represent the average of the German residential building stock. Here the information from the two random sample surveys of the German housing stock was used (Diefenbach et al. 2009) (Cischinsky/Diefenbach 2018). The use of average or typical values as a substitute for missing entries always leads to an increase in the uncertainty of this input data. As a consequence, the expected range of energy consumption increases.

In Figure 4[5] the simplified estimation of the U-value and of its uncertainty is demonstrated for several scenarios of a construction element (top ceiling) of several example buildings:

- The first three examples show the situation when the construction is as-built (no insulation upgrade) for three different years of construction (1960, 1980, 2000). According to the table of default U-values derived from typology analyses (see above), the typical U-values 1.10, 0.60, and 0.25 are selected and used in the energy performance calculation – the respective relative uncertainties are ±30 % for the two older buildings (reflecting the large variety and small undetectable changes from former times) and ±20 % (reflecting the variations allowed by the building code from 2000).
- Examples 4 and 5 show the effect of insulation upgrades of different insulation thicknesses (4 and 16 cm, data source: records of the building owner).
- Examples 6 and 7 illustrate the effect of the information source. The input values (completely insulated, insulation thickness 16 cm) and the resulting U-values are the same as those of example 5 – however, the uncertainties are different. The effective U-value 0.182 W/(m²K) has an uncertainty of ±0.031 when the data is from the building owner's records (example 5), ±0.020 when based on design data (example 6) and ±0.013 for design data with quality assurance (example 7).
- Examples 8 and 9 show the difference between 30 cm insulation on 50 % and on 100 % of the construction surface area (data from ex-post evaluation). Not only does the resulting U-value differ by nearly a factor of six, the relative uncertainty differs strongly: The uncertainty is ±40 % for the partly insulated and only ±15 % for the completely insulated area. This demonstrates that for large insulation thicknesses an important uncertainty source is the fraction of the area covered by insulation.
- Example 10 is a case where information on adding insulation on the ceiling has not been recorded in the company (this seems to be quite common in Germany, in contrast to external wall insulation implemented usually during major refurbishments that were and are registered, see example in (Loga et al. 2020a)). In this case the average state of buildings of this age band is applied for insulation thickness and fraction (see above) and the uncertainties for both quantities are set to the maximum. The resulting U-value of 0.58 W/(m²K) is nearly the same as for the insulation upgrade with 4 cm on 100 % of the area (example 4) but the uncertainty is about ±60 % compared to ±20 % for the case when information is available.
- The last two examples, 11 and 12, show the situation when information about the year of an upgrade was recorded but information about insulation thickness and fraction is not available. In this case the average insulation thickness applied in the building stock during this period and its variation range is used: For the upgrade reported from 1990 the value of 9 cm ±3.6 cm is assigned, for the upgrade reported from 2017 the value of 15 cm ±5.0 cm is assigned. The default values used for thickness and fraction were derived from the residential building survey 2016 (Cischinsky/Diefenbach 2018), see explanation above.

Implementation

HOUSING STOCK SAMPLE: METERED VS. CALCULATED CONSUMPTION

The reality-based physical model was used to implement the target/actual comparison and benchmarking concept (Figure 1) for samples of apartment buildings in collaboration with three housing companies. The housing companies identified subsets of their building stocks which were upgraded in the last ten years and for which metered consumption is available for at least two years (see Table 1). Apart from these building groups A, B, and C (129 building entities) a further group of unrefurbished buildings D was added (26 building entities) to expand the range of consumption benchmarks. Mostly the building entities are representing apartment blocks, in some cases several blocks are included.

For each building entity the energy profile indicators were used to calculate the expected energy demand of the building and the uncertainty of this value. The metered consumption was compared with the values from the model. Depending on the inclusion of domestic hot water (DHW) the comparison scope is either <H+W> (heating plus DHW) or <H> (only heating). Figure 5 shows on the left a bar chart with the calculated and metered consumption and the relation between them. The consumption values with the highest values of metered compared to modelled are at the bottom of the chart, those with the lowest at the top. The top and bottom of the bar chart is enlarged on the right. The criterion used for sorting the datasets is the "relative exceedance of the expectation range" (negative and positive bars). A relative exceedance of +1.0 would result from a situation where the metered consumption is equal to the calculated energy use plus uncertainty, a relative exceedance of -1.0 would mean that the metered consumption is equal to the calculated energy use minus uncertainty.

5. Download Excel workbook including these calculations: https://www.iwu.de/fileadmin/tools/uvalest-calcpad/UValEst-CalcPad.xlsx.

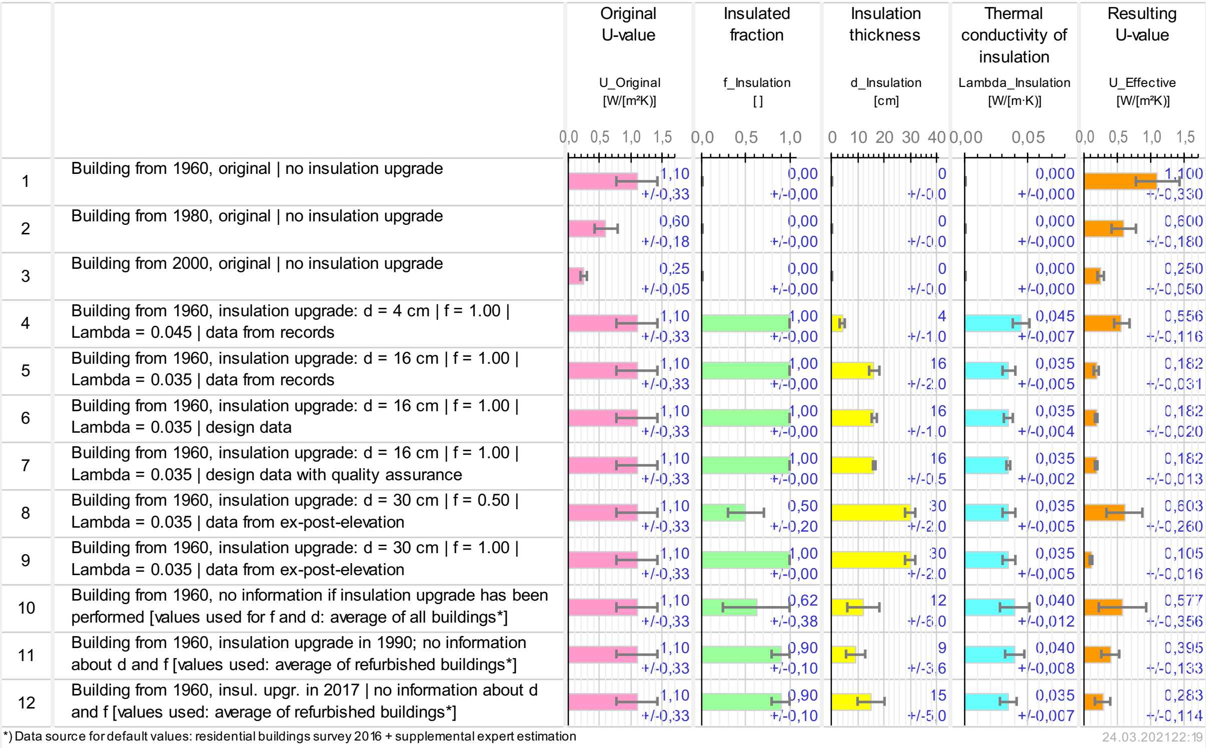

Figure 4. Examples demonstrating the U-value estimation model including uncertainty assessment for different situations (here: ceiling).

Table 1. Statistics of the housing stock subsets investigated.

Group	Shortcut	Housing company	Datasets/ building entities	Apartment blocks	Houses*	Dwellings	Living space
A	"BV upgraded"	Bauverein AG	53	63	156	1,376	91,308 m²
B	"WBG upgraded"	Wohnbau Gießen	35	35	58	718	47,041 m²
C	"NHW upgraded"	Nassauische Heimstätte	41	41	85	822	53,735 m²
D	"NHW original"	Wohnstadt	26	26	42	413	27,023 m²
Total			**155**	**165**	**341**	**3,329**	**219,106 m²**
Thereof datasets with meter readings		**Metering scope****					
		<H+W>	**85**	**94**	**196**	**2,080**	**132,667 m²**
		<H>	**82**	**90**	**176**	**1,958**	**128,348 m²**

) "House" = a building unit with a separate entrance, staircase and/or address (street + house number).

***) Explanation of shortcuts for metering scope: <H+W> = heating and domestic hot water (DHW); <H> = only heating.*

The highest value of exceedance found is +2.45 (bottom of the chart), meaning that the relative deviation of metered to calculated energy use exceeds the upper uncertainty range by a factor of 2.45. The highest value of negative exceedance is -1.25 meaning that the relative deviation of metered to calculated energy use exceeds the lower uncertainty range of the calculation by a factor of 1.25. The identified apartment blocks with suspiciously high deviation between calculation model and metering are now to be the subject of further investigation.

"CHECK AND FIX" – NEXT STEPS OF THE INVESTIGATION

As a next step in the project the identified buildings with suspicious high and low consumption values will be investigated in detail. The tasks are:

Step 1. Search for more detailed information from files in the housing company (modernisation planning files, invoices of crafts enterprises, input data for energy performance certificates, …); in-depth examination and correction of energy profile indicators, if necessary;

Step 2. Retrieval of more detailed information about the heating bill: plausibility check of fuel, heat and hot water consumption, as far as available; check of allocation to building block if a heating plant is used for supplying several blocks; in-depth examination of the supplemental information and correction of energy profile indicators, if necessary;

If errors are detected and the specific input data is corrected the target/actual comparison is renewed. When the consumption values then lie within the expectation range of the calculation the building block's metered consumption is regarded "as expected" and no further action is necessary. If no data faults are detected or the found ones are not relevant for the target/actual comparison the next steps are:

Step 3. On-site inspection of the state of the building block: examination of geometric data, insulation of roof, wall and floor, window type, insulation of heat pipes and storages, location of meters, …; if differences are found compared to those on record the energy profile indicators will be corrected appropriately;

Step 4. On-site examination of the operating conditions of the building: settings of the controllers of the heating system, actual temperatures of storages and heating/DHW pipes, state of pumps, …; if anomalies are found improvements will be applied. Furthermore: Visual examination of window opening by users (several times in winter if possible) and check of the performance of the ventilation system (if available); if necessary, information about energy saving behaviour will be given to the tenants by the housing company.

Comprehensive Analyses

COHERENCE OF PHYSICAL MODEL AND ACTUAL CONSUMPTION

The two charts of Figure 6 show the metered energy consumption of the buildings plotted by the calculated energy use (reality-based physical model), on the left for meter readings with scope <H+W> (heating + DHW), on the right with scope <H> (only heating). Each single datapoint represents a building entity with its calculated energy use on the horizontal axis and the metered consumption on the vertical axis.

For the calculated energy use classes are created with intervals of 25 kWh/(m²a) up to 150 kWh/(m²a) and intervals of 50 kWh/(m²a) above. The number of datasets of the classes are represented by the columns at the bottom of the chart, assigned to the secondary vertical axis on the right side. For each interval with three or more datasets an average of the metered consumption (full dots connected by straight lines) and the standard deviation were determined (values connected by dashed lines). For example in the energy demand class 101 to 125 kWh/(m²a) the average consumption is 112 kWh/(m²a) with a standard deviation of 21 kWh/(m²a) (Figure 6a).

We observe that the averages of the metered consumption per class of calculated energy use lie in the region of the bisecting line deviating about 10 % in case of scope <H+W> (heating + DHW) and 20 % in case of scope <H> (only heating). The reality-based physical model seems to be a good means for estimating the actual energy consumption. The slight random deviation between calculation and metering may disappear when more datasets have been entered in the database and thus more cases are included in each class.

One important observation is that there is no relevant systematic deviation of the reality-based physical model from the metered energy consumption. – This is in contrast to other findings concerning official EPC procedures (Sunikka-Blank/Galvin 2012) (Hörner/Lichtmeß 2017) (Loga et al. 2019) (Loga et al. 2020a), where calibration factors of 0.6 to 0.8 were necessary to achieve coherence of calculation and meter readings for unrefurbished buildings. Apart from the realistic utilisation conditions the most important reason for the match may be the different treatment of uncertainties: The default U-values for officially assessing existing buildings reflect conservative assumptions – at least in Germany. In addition, an EPC issuer facing an uncertain insulation state during data acquisition would set the input value on the safe side, not willing to risk that he might be accused of a too optimistic classification of the building (the EPC result must be displayed in rent and sale advertisements).

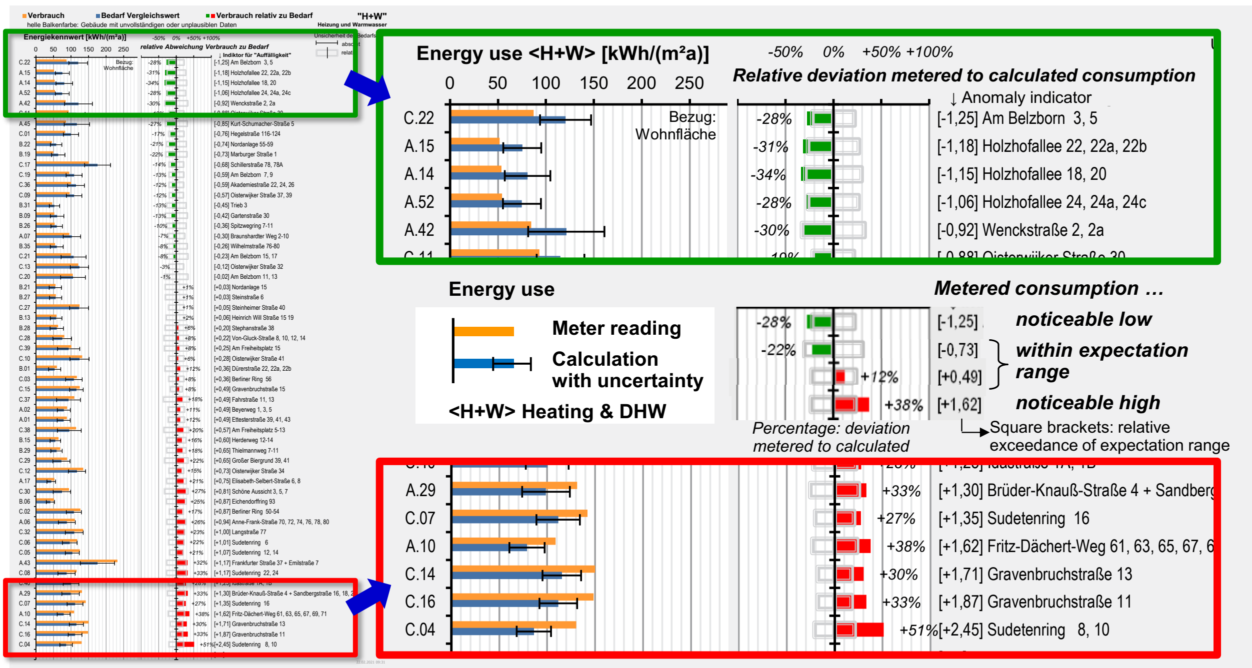

Figure 5. Identification of "noticeable high" and "noticeable low" values of measured consumption for the analysed building blocks – Left side: all datasets; right side: cutouts of the top and bottom of the sorted chart with most noticeable values; energy scale: light bars (orange) = metered consumption / dark bars (blue) = calculated energy use; relative scale: positive (red) and negative (green) bars = relative difference of metered to calculated values; light grey frames: relative uncertainty of the calculated energy use; numbers in square brackets [-1,25]: relative exceedance of uncertainty.

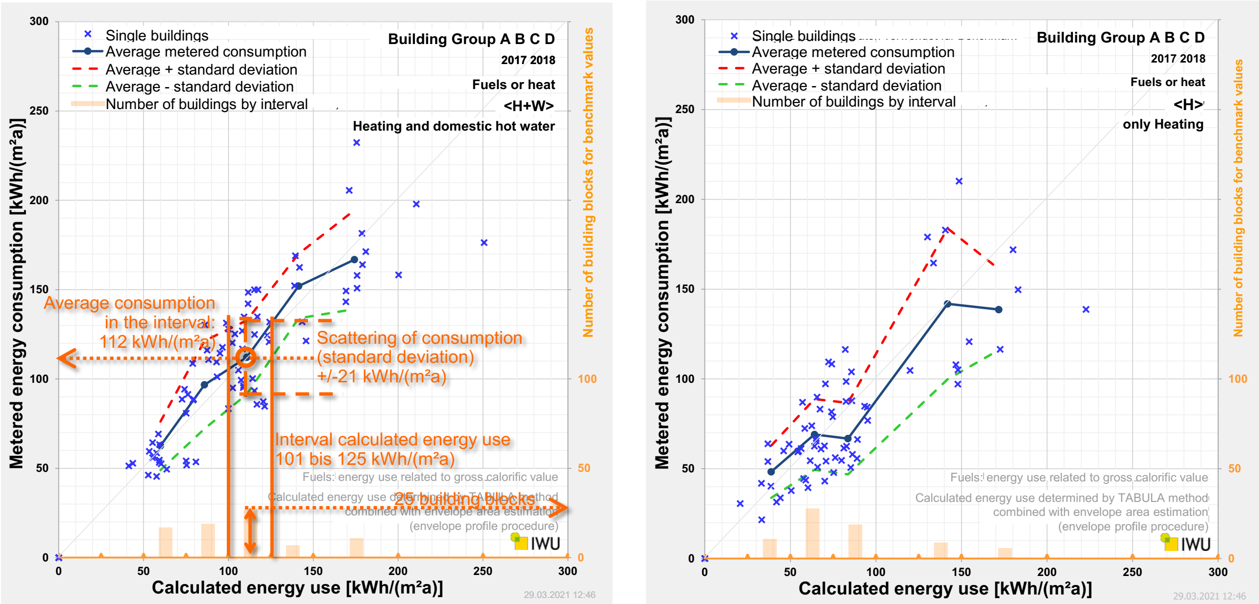

Figure 6 (a) and (b). Metered consumption (fuels or heat) vs. calculated energy use (reality-based physical model) for scope <H+W> = heating and DHW combined (left chart) and <H> = only heating (right chart): x = single values, —•— = average metered consumption per interval; – – – = average metered consumption ± standard deviation; columns at the bottom (secondary y-axis): number of buildings per interval.

CONSUMPTION BENCHMARKS

In the discussion with key actors and decision makers of housing companies, of associations and at political level, some doubts are expressed as to the energy savings achieved by insulation measures. There seems to be a lack of reliable information how much energy is actually consumed in houses of different refurbishment levels. To address this information need, the relationship of the metered energy consumption with the buildings' features is presented in Figure 7. The four displayed charts use the same quantity on the horizontal axis: the "thermal conductance"[6] of the building in W/K per m² living space, which is the theoretical heat loss and includes the heat transmission and the ventilation losses.

The top chart "Metered consumption" displays the single values of metered energy consumption, the averages determined for specific classes of the thermal conductance indicator, and the standard deviation of the measured data within that class (similar to Figure 6). The diagrams below the top chart show how the (rather abstract) thermal conductance indicator correlates with specific building characteristics. The second chart displays the interrelation of each building's thermal conductance with its "equivalent insulation thickness", which is a descriptive representation of the average U-value of opaque elements.[7] In case of the windows (third chart) the U-values are analysed in a similar way, showing the correlation of window type and thermal conductance indicator of the building. The chart at the bottom shows the installation of ventilation systems with heat recovery. The crosses reflect the single occurrences (1=Yes | 0=No) and the dots the frequencies of the systems for each thermal conductance class. It may be noted that solar systems, heat pumps or direct electrical heating were not installed in any of the buildings. When expanding the database these cases should be treated in separate benchmark charts.

The following observations can be made on the average metered energy consumption for heating and DHW (scope <H+W>):

- **Unrefurbished buildings** (mean floor-related thermal conductance 2.3 W/(m²K)): The average metered consumption is 177 kWh/(m²a). The average equivalent insulation thickness of these buildings is 3 cm and the average window U-value is 2.8 W/(m²K).
- Buildings with a **moderate refurbishment level** (mean floor-related thermal conductance of 1.1 W/(m²K): The average metered consumption is 103 kWh/(m²a). The average equivalent insulation thickness of these buildings is 18 cm and the average window U-value is 1.4 W/(m²K). Ventilation systems with heat recovery are not available in this group.
- Buildings with an **ambitious refurbishment level** (mean floor-related thermal conductance of 0.77 W/(m²K)): The average metered consumption is 63 kWh/(m²a). The average equivalent insulation thickness of these buildings is 31 cm and the average window U-value is 0.85 W/(m²K). In all buildings of this group ventilation systems with heat recovery are installed.

6. The thermal conductance represents the heat loss in Watt resulting from a temperature difference of 1 Kelvin (°C). Apart from transmission also ventilation heat losses are included here to represent the effect of heat recovery. The thermal conductance devided by the living space is an adequate quantity for classifying the heating characteristic of buildings.

7. Simplified determination of the "equivalent insulation thickness" in cm used for visualisation: d_Insulation_Equivalent = 100 * (1/U_Opaque_Average - 1/U_0) * Lambda_Insulation with U_Opaque_Average: average U-value of the opaque elements of a building; U_0: U-value of unrefurbished constructions, standard value 1.5 W/(m²K); Lambda_Insulation: thermal conductivity of the insulation, standard value 0.035 W/(m*K); the mentioned simplified standard values are only used for creating this chart. The idea of this simplification is to showcase a very simple version of benchmark analysis, which needs metered consumption, insulation thickness and percentage covered, windows type and ventilation type as an input.

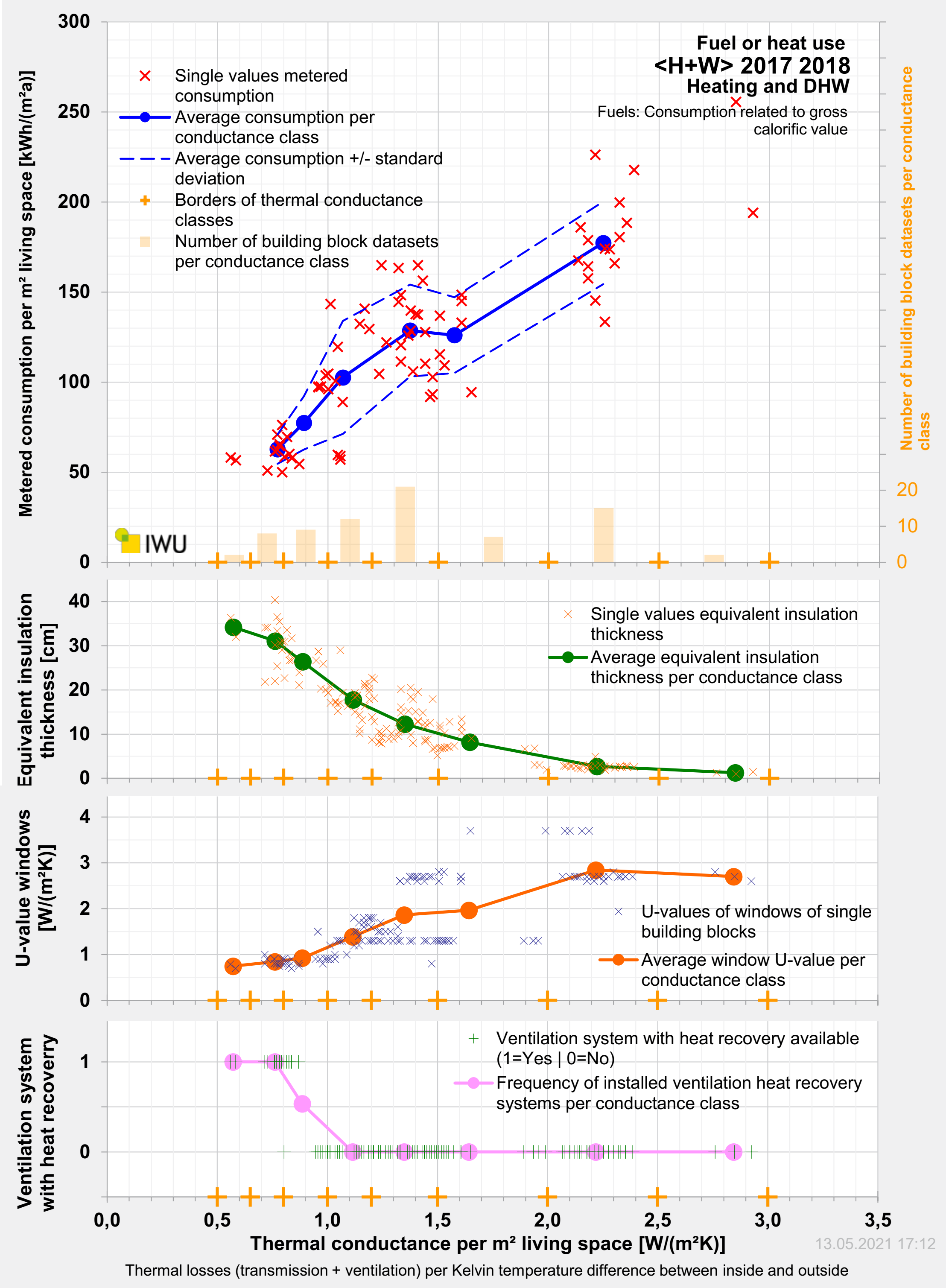

Figure 7. Relationship between average metered consumption and average building features: "Consumption Benchmarks" (top chart): Average metered consumption for different levels of the buildings' thermal conductance; building characteristics assigned to thermal conductance (further charts): equivalent insulation thickness, window U-values, ventilation systems with heat recovery.

Summarised, the combined benchmark chart of the buildings sample shows evidence that buildings with calculated conductance value corresponding to a "moderate" renovation level typically consume 42 % less energy than non-renovated buildings, and buildings with calculated conductance value corresponding to an "ambitious" renovation level typically consume 64 % less energy than non-renovated buildings – related to the energy consumption for heating and DHW.

The standard deviation of the consumption for the conductance classes of unrefurbished and moderately refurbished buildings is about 30 kWh/(m²a), for the ambitious renovation level it is much smaller. When more buildings are included the scattering of the consumption and a comparison with the uncertainties of the calculation model will be investigated more closely.

Summary/perspectives

In response to the climate crisis and the need to dramatically reduce the fossil energy consumption German housing companies are putting large effort into the renovation of their stock. To meet the climate protection targets more ambitious renovation with levels of passive houses and nearly Zero-Energy Buildings (nZEB) is required (Loga et al. 2018), however moderate refurbishments are still common (Cischinsky/Diefenbach 2018). Some key actors and decision makers are sceptical of the achievable energy savings of installing large insulation thicknesses. Hence, there is a need for reliable information about the effect of insulation on the energy consumption of buildings.

One of the objectives of this research project is to enable a reliable prognosis of the energy consumption for different refurbishment levels. For a sample of 155 building entities with 3,329 apartments the metered energy consumption was collected in combination with energy profile indicators, which provide standardised information on building size and layout, the level of insulation, and the type of windows and heat supply system. Based on these indicators a physical model calculates the expected energy use and its uncertainty. The result is that the average metered energy consumption and the average effect of the measures is in line with the predictions of the physical model for the whole range of energy performance levels. This is in contrast to the findings in the context of standard procedures for producing official energy performance certificates and their comparison with meter readings. An explanation for the more reliable prognosis of the presented method is the consideration of uncertainties: For all input values a typical range is determined within which the actual value most probably lies. As an input value of the physical model the mean value of this range is used. The overall uncertainty of the calculated energy use is determined from all input uncertainties. In consequence, the method results in an expected range of energy consumption.

The first stage of testing has been completed – the expected and actual consumption were compared for the sample buildings owned by three housing companies. For most of the buildings the energy consumption lies within the expectation range. Several single buildings were identified with noticeable deviations in both directions which will subsequently be checked. Measures for improving the operating conditions will be applied, if necessary. Once this is done it will become clearer if applying the target/actual comparison helps housing companies safeguard savings from refurbishments. Building on these experiences the intention is to expand the monitoring database to more buildings and implement an annual process of target/actual comparison.

In addition, some aspects of the method could be improved and refined. Areas of interest are: the default values and uncertainties of heat losses by thermal bridging, of air exchange due to the opening of windows, and of heat supply system efficiencies.

In summary, the reported experiences are encouraging. An expansion of the collection of monitoring indicators on national level to all fields related to the energy performance of buildings (issuing of energy performance certificates, representative surveys, grant applications, …) could make a significant contribution to more transparency regarding the actual energy performance and the effect of climate protection measures in the German housing stock.

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