Acta Polytechnica CTU Proceedings **38**:470–477, 2022
https://doi.org/10.14311/APP.2022.38.0470

USE OF ENERGY PROFILE INDICATORS TO DETERMINE THE EXPECTED RANGE OF HEATING ENERGY CONSUMPTION

Tobias Loga*, Britta Stein, Guillaume Behem

IWU – Institut Wohnen und Umwelt, Institute for Housing and Environment, Rheinstraße 65, DE-64295 Darmstadt, Germany

* corresponding author: t.loga@iwu.de

Abstract. A small set of query variables designed to collect information about the energy-related features of residential buildings is presented. These "energy profile indicators" include information about those visible characteristics of a building which have a notable impact on its energy performance and are simple to assess. The queries are an interesting source for a rough energy performance calculation for single buildings as well as for housing portfolios or housing stocks.

A method has been developed to transform the energy profile indicators into input data for a physical calculation model. It consists of procedures to estimate the envelope area, U-values, and efficiency values of the heat supply system. To all model input variables an uncertainty is assigned. If information from a query is not available, the model input is set to a state representing the average building stock and the uncertainty of this quantity is adjusted to a value reflecting the variance in the stock. The resulting uncertainty of the calculated energy use is determined.

Examples of the application of the method are given to show the influence of different unknown quantities including occupant behaviour. Experiences on the coherence with metered consumption are reported.

Keywords: Monitoring indicators, building stock, surveys, statistical evaluation, realistic physical model, uncertainties, target/actual comparison.

1. Introduction

Various activities in the building sector aim at gathering building data, executing energy performance calculations and assessing the metered energy consumption, often in the context of Energy Performance Certificates (EPCs). However, huge challenges are faced when cross-section and longitudinal analyses are needed to get an overall view of the refurbishment progress and energy consumption of housing stocks. This is not only due to data gaps but also to the used calculation methods and software applications focussing on official proof of requirements and rating. The detailedness and complexity of input data, recurrent revisions of the regulatory framework, but also the lack of software applications to store, calculate and analyse multi-building data are barriers for aggregation and statistical evaluation.

The idea of the concept presented in this paper is to tackle these challenges by introducing an additional level of energy assessment addressing evaluation purposes. The overall objectives are:

- Facilitate the collection and maintenance of information about energy-related features of housing stocks, allowing for an assessment of the overall state of refurbishment, annual refurbishment rates and for a comparison with milestones on the refurbishment path.
- Provide reliable estimates of the energy consumption of single buildings and of housing stocks for different levels of insulation and various heat supply system types to be used for prognoses in the context of refurbishment scenarios.
- Enable a target/actual comparison of the consumption after implementation of refurbishment measures for single buildings and also for housing stocks.

In order to reach these aims, a methodical framework has been developed within the research project MOBASY, consisting of two parts [1]:

(1.) A set of monitoring indicators representing those visible characteristics of buildings that have the most important effect on its energy performance, suitable for use in questionnaires and quick on-site inspections.

(2.) An energy performance calculation using the mentioned monitoring indicators as input data and providing a realistic bandwidth of the expected energy consumption, reflecting the uncertainty of the data acquisition (uncertain or unavailable information) and of the model input data (thermal properties of materials and components, occupant behaviour, climate) depending on the specific field of application (assessment of past consumption or prognosis).

This paper gives an overview of the monitoring indicators ("energy profile indicators"), and of the principles of the uncertainty assessment attached to the realistic energy performance calculation ("simple combined physics-probability model"). The influence of

Characteristics of	Indicators (query variables)
Building size and form	Living space, number of attached buildings, number of full storeys, heating situation in attic and basement, number of dwellings
Thermal properties of the opaque envelope (categories: roof, ceiling, wall, floor)	Building: year of construction; Per envelope category: existent insulation upgrade, year of insulation upgrade, insulation thickness + covered fraction
Thermal properties of windows (two types)	Per window type: Number of panes, low-e coating existent, type of window frame, year of installation, fraction of the second window type, if applicable
Heat supply system (heating / DHW)	Heat generators (type, specification, year of installation), thermal solar system, heat storages (type, location inside or outside of thermal envelope), heat distribution (type, insulation level, location inside or outside of thermal envelope)
Further systems	Ventilation system (with / without heat recovery), PV system (with / without electrical storage)

Table 1. Overview of energy profile indicators for residential buildings.

the origin and detailedness of data on the uncertainty of the estimated energy consumption is illustrated for a single- and a multi-family house. Furthermore, results are presented from the application of the method to a housing stock sample, providing statistical information on the energy-related state, on the estimated and actual consumption.

2. Energy profile indicators

A set of "energy profile indicators" has been developed in [2], then continuously further refined and applied in several projects for portfolio assessment and quality assurance (examples: [3, 4]). The indicators have also been used in house owner surveys in 2009 [5] and 2016 [6] on the basis of random sampling[1] to get an image of the refurbishment state and progress of the German residential building stock. Table 1 gives an overview of the query variables.

These indicators represent the physical characteristics of a building that have the biggest impact on its energy use for heating and domestic hot water (DHW). The variables are designed to gather information by asking (technically informed) building owners and by executing on-site inspections of residential buildings. For these purposes, a two-page questionnaire [7] and a structured data table [8] have been developed.

Energy profile indicators provide information that can be used to estimate the energy consumption of a building. For this purpose, a transformation to a physical model including an uncertainty assessment has been developed.

3. Simple combined physics-probability model

There are different approaches to quantify the uncertainties of the building energy assessment [9]. The concept presented here uses forward uncertainty, that tries to quantify the uncertainty in the calculation outputs propagated from uncertain input variables through mathematical models. Due to the stationary, quasi-linear energy calculation model, a very simple, non-sampling probabilistic method can be employed, assuming normal distributions and applying the Gaussian error propagation law.

3.1. Principle

The principle of the indicator-based energy performance calculation is shown in Figure 1. The first step is a transformation of energy profile indicators to input variables of the physical model. As a result, a "calculation value" is provided for each quantity, directly used by the energy performance calculation ("model input variables"), and an "uncertainty range" is attributed, which represents the span of values that might include the actual (unknown) real value.

Preferably, the parameters of the transformation should be derived from empirical data of large building stock samples. However, for certain quantities extended surveys or large measurement campaigns are not available. In these cases, the calculation value and uncertainty range can only be estimated. A pragmatic way to do this is to ask an expert: Which is the highest, which is the lowest value that might be present and still be seen as "not unusual"? The average of both is the calculation value, half the difference between both represents an indicator of the uncertainty. As an important means for transparency and inducement for continuous improvement of the method, the derivation of calculation values and uncertainties must be documented for each variable.

The calculation values are used as input for the physical model to determine the theoretical energy consumption. In a separate calculation, the uncertainty of the calculated energy consumption is determined by combining the effect of the uncertainties of all input

[1] The 2016 evaluation is based on about 17 000 evaluable questionnaires (18 % of ca. 92 000 queries sent to a random sample of German house owners) [6].

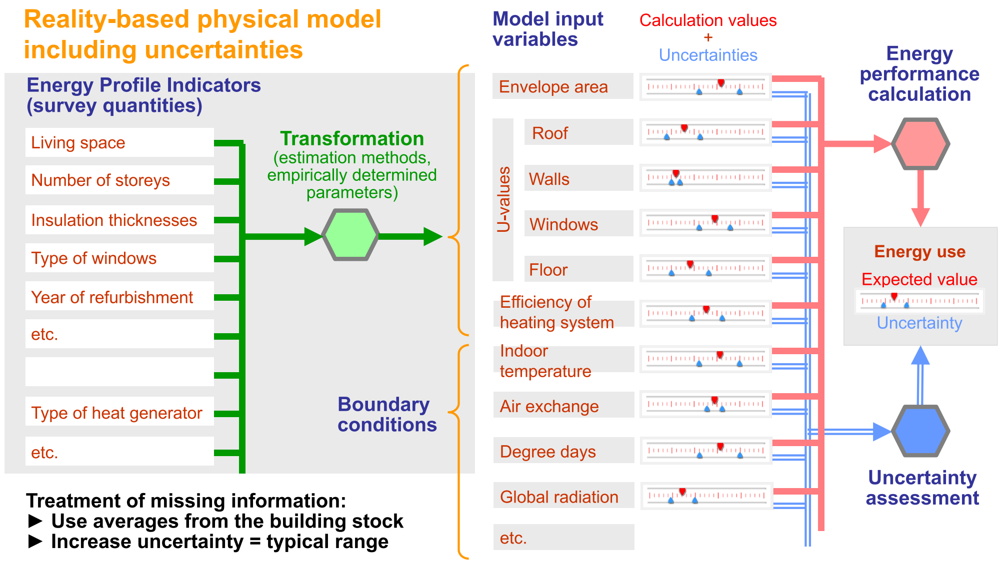


Figure 1. Principle of the combined physics-probability model based on energy profile indicators.

values. Gaussian error propagation law (square root of the added-up squares of the uncertainties caused by each single variable) is used for this purpose. Since most of the probability density distributions of input variables are assumed to be symmetrical and the energy balance procedure used (seasonal method) is mainly linear, the systematic deviations produced by this simplification are assumed to be small. The result of this combined probability-physics model is an expectation value and an expectation range of the energy use for heating and DHW.

3.2. Systematic uncertainty assessment

The uncertainty of the energy performance calculation is in principle depending on the type of data source and on the completeness of information (see Figure 2).

Type of data source: Information provided by building owners is a useful data source, however inspections can provide additional information and thus reduce the uncertainty. More trustworthy are design data from refurbishment planning (including issued EPCs), at best if the implementation is secured by quality assurance (QA).

Completeness of information: Information can be missing from all mentioned data sources (even in a quality assured planning process). When typical or average values from the building stock are used instead the uncertainty of the calculation increases.

This global principle has been translated into an algorithm: For each model input variable five uncertainty classes A to E are defined with rules for selection and uncertainty values to be used. As an example, Table 2 shows the uncertainty assessment of the insulation thickness, applied separately for all opaque envelope categories. Analogue definitions are available for the other input variables[2].

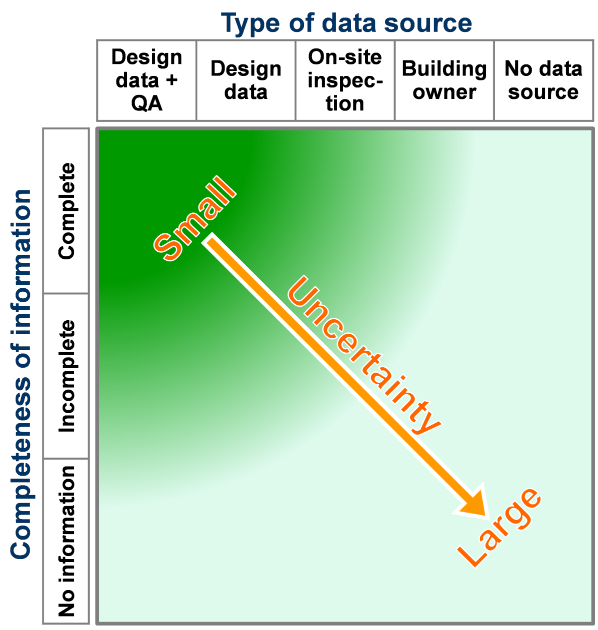


Figure 2. Influences on the uncertainty of an energy performance calculation.

The method presented in this paper is focussing on data from building owners and from on-site inspections, associated with uncertainty classes C and D. These data sources facilitate the energy assessment of a large number of buildings – as a start from files and records – updates can be provided in the course

[2]These are: envelope area, U-values of original constructions, insulated fractions by envelope type, thermal conductivities of insulation by envelope type, U-value of windows, thermal bridging surcharge, heating degree days, annual solar radiation, effective passive solar aperture, internal heat load, efficiency of ventilation heat recovery, DHW heat need, efficiency of heating system, efficiency of DHW system. Tabled values and explanations in English language are displayed at the end of the supplemental document [10]. A detailed description of the algorithms for a selection of variables is given in Annex D of [1] (German language).

Uncertainty Class	Description	Uncertainty of insulation thickness*	
		Relative	Absolute
A	Insulation thickness from design data, quality assured	5 %	0.5 cm
B	Insulation thickness from design data	10 %	1 cm
C	Insulation thickness determined by inspection on-site / record or statement of building owner	25 %	2 cm
D	Insulation available; insulation thickness unknown; use of average values from the building stock differentiated by implementation period	40 %	5 cm
E	Insulation thickness and year of implementation unknown; use of average values from the building stock (all buildings)	50 %	8 cm

* Relevant for the calculation is the minimum in cm, derived from the relative and absolute uncertainty.

TABLE 2. Example of uncertainty classification for an input variable (insulation thickness).

of on-site investigations. Even if input is missing for some indicators (class E), the estimation of the actual energy use of the sample or portfolio can be commenced – with corresponding larger expectation ranges. If available, design data with or without quality assurance (classes A or B) can also be integrated. The improvement achieved by gradually adding reliable data from inspections and from quality assured refurbishments will result in narrowed ranges of the expected energy use.

3.3. Mechanisms of the energy performance calculation based on energy profile indicators

Following the above-described principles, a coherent method for an energy performance calculation by use of energy profile indicators has been developed and implemented in form of an Excel-Workbook and an R script (description of the method in [1]). Core aspects are the estimation of the thermal envelope area [11] and of the U-values [12]. The energy performance calculation is based on the TABULA seasonal method [13], using climate data differentiated by postcode: In the first instance, the physical model is calculated by use of the local long-term average climate (of the past 20 years). For performing target/actual comparisons for specific years, calculated heat losses and gains are calibrated by the actual temperatures and solar radiation of the metering period.

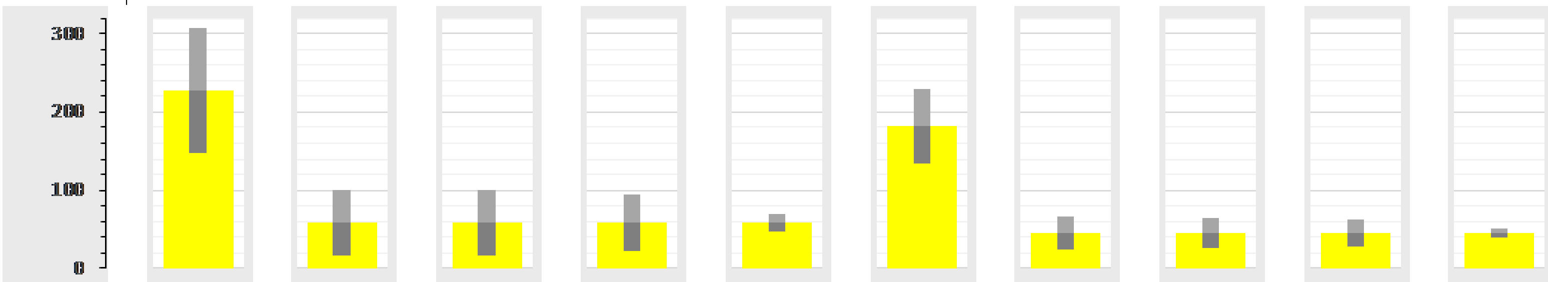
4. Showcase: Influence of different parameters on the uncertainty of the estimated consumption

For a single building, the described method allows a prognosis of the energy consumption, providing an estimation value (result of the physical model) and an estimation range (result of the uncertainty assessment). The actual consumption is expected to be found within the estimation range, however in rarer cases it can also go beyond that.

Table 3 shows examples of expectation ranges for a single-family and a multi-family house (SFH, MFH), depending on the state of refurbishment, on the data acquisition type and on the utilisation of the buildings. These are results from the combined physics-probability model with uncertainty assessment as described above. The examples are intended to illustrate the uncertainty of the consumption estimate based on energy profile indicators (house owner statement) as opposed to those based on design data, considering particularly the influence of unknown occupant behaviour.

For the variants 1.1 to 1.3 the calculation is assumed to be based on energy profile indicators, with input from house owners. For the single-family house, the relative uncertainty of the calculated energy use for heating and DHW is ±35 % before (var. 1.1) and ±72 % after a deep refurbishment with passive house components (var. 1.2). The relative increase is mainly caused by the influence of occupant behaviour. However, the state of the building is much better defined after refurbishment, so the absolute uncertainty caused by the envelope is only $\pm 25\,\mathrm{kWh/(m^2a)}$ compared to $\pm 52\,\mathrm{kWh/(m^2a)}$ before refurbishment. If the real climate conditions of the climate zone are used, the uncertainty of the energy demand caused by the climate is reduced from ±26 % (var. 1.2) to ±19 %, (var. 1.3), having only a small effect on the total uncertainty.

In variant 1.4, design data from the planning of the refurbishment (detailed calculation of envelope area, of U-values, and of supply system performance) and long-term climate data are used. This is the typical pattern of energy performance certificates, issued in the context of modernisation. It reduces the total uncertainty from about ±70 to ±60 %. The effect is rather small due to the predominating large uncertainties of utilisation and climate. Variant 1.5 shows a situation where the design data are quality-assured (update of information about actual implementation

Exemplary building	SFH (single-family house) [1958–1968]					MFH (multi-family house) [1958–1968]				
State of refurbishment	Unrefurbished	Refurbished (passive house components)				Unrefurbished	Refurbished (passive house components)			
Type of data source	Ex post (house owner statement)			Design data	Design data + QA	Ex post (house owner statement)			Design data	Design data + QA
Climate	long-term average		specific year	long-term average	specific year	long-term average		specific year	long-term average	specific year
Occupant behaviour	unknown				detailed measurements*	unknown				detailed measurements*
Variant	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	2.4	2.5
Calculated energy use (natural gas) [kWh/(m²a)]										
Energy use**										
• **Heating**	203	50	50	50	50	156	31	31	31	31
• **DHW**	25	9	9	9	9	26	15	15	15	15
Sum	**228**	**59**	**59**	**59**	**59**	**183**	**45**	**45**	**45**	**45**
Uncertainty***										
• **Envelope**	±23 %	±42 %	±42 %	±15 %	±7 %	±17 %	±29 %	±29 %	±12 %	±5 %
• **System**	±9 %	±10 %	±10 %	±7 %	±5 %	±9 %	±12 %	±12 %	±10 %	±6 %
• **Utilisation**	±19 %	±52 %	±52 %	±52 %	±13 %	±4 %	±14 %	±14 %	±14 %	±4 %
• **Climate******	±16 %	±26 %	±19 %	±26 %	±13 %	±16 %	±33 %	±24 %	±30 %	±10 %
Total	**±35 %**	**±72 %**	**±70 %**	**±60 %**	**±20 %**	**±26 %**	**±47 %**	**±42 %**	**±37 %**	**±14 %**

* Indoor temperatures and windows opening have been measured, e.g. in a research project (assumption for the shown case: building has utilisation close to the average of all buildings); however, internal heat sources and external shading have not been measured or modelled in detail.
** Natural gas, in kWh/(m^2a); calculation with simple probability-physics model.
*** Relative uncertainty, related to energy use for heating and DHW.
**** Including uncertainty of external shading (assumption for all variants: No detailed assessment of the reduction of passive solar gains caused by surrounding trees and buildings or by use of shutters etc.).

TABLE 3. Estimation of the actual energy consumption before and after deep refurbishment for two example buildings and assigned uncertainty, depending on the type of data source and measurements (A PDF demonstrating the calculation flow for the 10 building variants can be viewed in the supplemental document mentioned above [10]).

during refurbishment) and where the utilisation and the climate are measured in detail, for example in the framework of a research project. In this case, the uncertainty of the consumption estimate can be reduced to ±20 %[3].

For the multi-family house with 24 flats (var. 2.1 to 2.5), the effect of the utilisation uncertainty is significantly smaller because of stochastic effects (compensation between flats with high and low intensity of usage).

It may be noted that a very deep refurbishment has been assumed here, resulting in very low energy consumption and causing large relative uncertainties. However, the absolute uncertainty of about ±40 kWh/(m^{2}a) for SFH (var. 1.3) and of ±20 kWh/(m^{2}a) for MFH (var. 2.3) is not changing much for less ambitious refurbishments, resulting in smaller relative uncertainties (see results for the building sample presented in the following chapter). If design data are not available for such a deep refurbishment, the thermal envelope's uncertainty is predominated by the unknown effects of thermal bridging. If a characterisation is possible (for example as a result of on-site inspection: no relevant constructive weaknesses), the uncertainty of the energy use caused by the envelope can be reduced from ±29 % to ±16 % (MFH, var. 2.3), the total uncertainty reduced from ±42 % to ±34 %.

These uncertainties of consumption estimates are valid with view at a single building. However, if large building samples or stocks are considered, the uncertainty of the predicted total consumption (and thus the uncertainty of the average) is reduced to 1/10 of the shown values for 100 buildings and to 1/100 for 10 000 buildings.

In summary, the expectation ranges of the energy consumption determined by quantifying input uncertainties seem rather large, especially for single-family houses. This is not only true for the calculation based on energy profile indicators but also for the EPC calculation based on design data. For both, the predominating factors determining the uncertainty of the prognosis of an annual consumption are unknown occupant behaviour and climate conditions.

5. Application on a sample of apartment blocks from housing companies

In the following, the application of the combined probability-physics model on a housing sample from three housing companies is reported. The energy profile indicators and the metered energy consumption values were collected for 155 building entities (mostly large building blocks) with 3329 apartments[4]. The energy characteristics of the building sample comprise a wide span from unrefurbished to deep renovations [12], which also includes the use of passive house components and installation of ventilation systems with heat recovery.

In two of the three companies, a large effort was required to collect the information from individual building-related files. In the third company, however, energy profile indicators were already introduced in 2008 for the complete portfolio and since then maintained and updated [3]. These data could therefore be used directly. For some of the buildings, the indicators were collected during a quick on-site inspection – the typical effort was half an hour per building.

Table 4 shows the results for a subset where metered consumption is available for both, heating and DHW. As a parameter for the theoretical heat loss the "thermal conductance" is defined, which is the heat loss of the building per Kelvin temperature difference, related to the reference floor area.

It can be stated that the average actual consumption by conductance class is very close to the calculation model averages (the ratio average actual to average theoretical energy use varies from 95 % to 115 % per class). The standard deviations of the actual energy consumption and the average uncertainty of calculation are in similar ranges.

In summary, the method seems quite suitable for modelling the consumption of housing stocks and for evaluating measures of different depths with respect to their actual effect. One conclusion that can be drawn from this is, for example, that the average energy consumption for heating and DHW of the class with best insulation level is about one third of that with the worst.

6. Conclusions

A method has been developed that is based on a set of monitoring indicators collectable by a questionnaire or a quick on-site examination. These "energy profile indicators" are used as input for an energy performance calculation to determine an expected range of actual energy consumption. Examples show how the uncertainty of consumption prognosis depends on information about data source and data completeness. Moreover, the methodology was applied to a sample of multi-family buildings involving statistical evaluations. For different levels of insulation, the estimated as well as the actually measured consumption were determined, with the actual consumption by conductance class being very close to the calculation model averages.

Future work should focus on the expansion of the database to include also single-family houses and different heat supply systems, especially heat pumps and solar systems.

[3]The type of energy calculation procedure has only a very small effect (for example the seasonal method has only an uncertainty of ±2 % compared to the monthly method [14]). Thus, nearly the same uncertainties would result if a high-resolution simulation programme was used.

[4]The datasets of the sample can be viewed at the Excel workbook mentioned above [8].

Thermal conductance class*	Range	W/(m²K)	0.01–0.80	0.81–1.00	1.01–1.20	1.21–1.50	1.51–2.00	2.01–
Equivalent insulation thickness of opaque elements**	Average	cm	31.6	21.5	12.1	13.0	2.4	2.7
U-value of windows	Average	W/(m²K)	0.80	1.29	1.52	2.62	2.68	2.68
Availability of mechanical ventilation with heat recovery	Percentage		100 %	0 %	0 %	0 %	0 %	0 %
Calculated energy use for heating and DHW (comparison value)***	Average	kWh/(m²a)	50	73	96	103	143	163
	Std. dev.	kWh/(m²a)	±7	±5	±10	±11	±14	±20
	Av. uncert.	kWh/(m²a)	±16	±20	±22	±27	±39	±43
Actual energy use for heating and DHW (metering)	Average	kWh/(m²a)	50	78	110	110	135	148
	Std. dev.	kWh/(m²a)	±9	±21	±15	±21	±16	±23
Ratio actual / calculated energy use			0.99	1.07	1.15	1.07	0.95	0.91
Frequency	Number of building datasets		n = 15	n = 10	n = 8	n = 23	n = 5	n = 11
	Number of annual consumption values		n = 28	n = 25	n = 21	n = 46	n = 10	n = 22

* The "thermal conductance" is the heat transfer coefficient by transmission and ventilation, related to the reference floor area of the building.
** Thermal resistance of opaque envelope, expressed in cm insulation with 0.035 W/(m · K) thermal conductivity.
*** Energy use, calculated by the combined probability-physics model, balance scope and climate consistent with metering (example: if heat is metered in the apartments the heat losses of the central heat distribution system are disregarded in this comparison).

Table 4. Comparison of theoretical and actual consumption for a building sample (heating + DHW). Averages, uncertainties and standard deviations differentiated by thermal conductance class. (Status of database analysis: 2022-02-17).

In practice, the simplification of data input, the ability to adequately consider data gaps and uncertainties and the output of estimation ranges may provide benefits for different purposes:

- Individual houses (occupants, owners, energy consultants, . . .):
  - ▷ The small effort to provide the indicators for an existing house makes it a useful method in energy advice campaigns. The current energy consumption can be interpreted and assessed. Achievable consumption bandwidths after refurbishment can be provided for the investigated house.
  - ▷ For refurbished buildings as well as for new build, the method provides a target range of the energy consumption. The occupant or owner can compare the actual consumption against this individual benchmark. If the consumption is above the expectation range, the implemented measures, the operating conditions, and the occupant behaviour can be checked and improved, if necessary. Besides, measurements of the actual utilisation conditions and of the local climate during the consumption period can help to significantly narrow down the expectation range.
  - ▷ Energy profile indicators can be attached to EPC issuing (e.g. "statistic forms", XML-files). This enables a plausibility control of the energy performance calculated for the EPC, for issuers as well as for inspectors on quality assurance.
  - ▷ The fact that visually provable indicators are used is also a benefit for application cases in the context of pricing rules, dependent on energy performance (building value, financing, sales, rents, . . .) and for grant applications.
- Housing portfolios (housing companies, energy service and billing companies, . . .):
  - ▷ The collection and regular update of energy performance indicators provides a basis to determine the current level of insulation and the current fraction of efficient/renewable systems for the entire stock as well as the respective annual improvement rates. These achievements can e.g. be compared with the climate protection targets for the portfolio or for the national stock.
  - ▷ The average estimated and, if available, actual consumption values and ranges per conductance class are benchmarks that can be useful in the preparation of refurbishments, especially in the communication with tenants, to strengthen the confidence in the actual effect of the measures.
  - ▷ By matching consumption values of single buildings against the benchmarks, cases with suspiciously high consumption can be identified. An uptake of low-cost measures can improve the situation, similar to the target/actual comparison described for individual buildings.
  - ▷ The calculation for all buildings of a portfolio may also be used as building stock model for developing refurbishment strategies.
- National housing stock (energy experts, authorities, energy agencies, . . .):
  - ▷ By using the energy profile indicators for a random-sample-based house owner survey, the achievements regarding levels of insulation and fractions of efficient/renewable systems can be determined for the national housing stock, similar to the evaluation of the energy profile database of a housing portfolio.

- ▷ In addition, the random sample can be used in national building stock models in form of a microsimulation model or by aggregation to average buildings to forecast the development of energy use by energy carrier and calculate different alternative scenarios.
- ▷ In the context of national information campaigns, the publication of benchmarks consisting of average consumption values and typical spreads for different insulation categories can provide useful information for occupants and owners that inspires confidence in different types of measures.

Acknowledgements

The work described in this paper is part of the research project MOBASY, supported by the German government (Federal Ministry for Economic Affairs and Climate Action (reg. N°: 03SBE0004A); project duration: 11/2017–10/2022; more information at: https://www.iwu.de/forschung/energie/2017/mobasy/). The analysis of the housing sample has been implemented in collaboration with three German housing companies: bauverein AG Darmstadt, Wohnbau Gießen and Nassauische Heimstätte Wohnstadt Frankfurt/Main. We very much appreciate the support and cooperation.

References

[1] T. Loga, M. Großklos, A. Müller, et al. Realbilanzierung für den Verbrauch-Bedarf-Vergleich (MOBASY Teilbericht). Tech. rep., Darmstadt, 2021. ISBN 978-3-941140-67-7. https://doi.org/10.13140/RG.2.2.22472.24328/1

[2] T. Loga, N. Diefenbach, J. Knissel, R. Born. Entwicklung eines vereinfachten, statistisch abgesicherten Verfahrens zur Erhebung von Gebäudedaten für die Erstellung des Energieprofils von Gebäuden („Kurzverfahren Energieprofil“). Tech. rep., Darmstadt, 2005. ISBN 3-932074-76-9. https://doi.org/10.13140/RG.2.2.20794.52160

[3] T. Loga, M. Repp, S. Swiderek. Verbrauchsbenchmarks – ein Soll-Ist-Vergleich für Wohnungsunternehmen. In *12. EffizienzTagung Bauen + Modernisieren 2020*. 2020. [2022-03-02]. https://www.researchgate.net/publication/350710240_Verbrauchsbenchmarks_-_ein_Soll-Ist-Vergleich_fur_Wohnungsunternehmen

[4] T. Loga, K. Müller. Evaluation of the TABULA database – Comparison of typical buildings and heat supply systems from 12 European countries, IWU, Darmstadt, 2012. TABULA Work Report, [2022-03-02]. http://www.building-typology.eu/downloads/public/docs/report/TABULA_WorkReport_EvaluationDatabase.pdf

[5] N. Diefenbach, H. Cischinsky, M. Rodenfels, K.-D. Clausnitzer. Datenbasis Gebäudebestand. Datenerhebung zur energetischen Qualität und zu den Modernisierungstrends im deutschen Wohngebäudebestand, IWU, Darmstadt, 2010. [2022-10-06]. https://www.iwu.de/fileadmin/publikationen/gebaeudebestand/datenbasis/Endbericht_Datenbasis.pdf

[6] H. Cischinsky, N. Diefenbach. Datenerhebung Wohngebäudebestand 2016, IWU, Darmstadt, 2018. [2022-10-06]. https://www.iwu.de/fileadmin/publikationen/gebaeudebestand/2018_IWU_CischinskyEtDiefenbach_Datenerhebung-Wohngeb%C3%A4udebestand-2016.pdf

[7] T. Loga. Energy profile. questionnaires thermal envelope and heat supply system, IWU, Darmstadt, 2021. [2022-03-02]. Completed with example data: https://www.iwu.de/fileadmin/tools/energyprofile/EnergyProfile_Forms_BuildingSystem_ENG.pdf Template with active form fields: https://www.iwu.de/fileadmin/tools/energyprofile/EnergyProfile_FormBuildingSystem_DataCapture.pdf

[8] T. Loga. Energy profile indicators. data table, showcase, IWU, Darmstadt, 2021. [2022-03-02]. https://www.iwu.de/fileadmin/tools/energyprofile/EnergyProfileIndicators_DataTable_Showcase_ENG.xlsx

[9] W. Tian, Y. Heo, P. de Wilde, et al. A review of uncertainty analysis in building energy assessment. *Renewable and Sustainable Energy Reviews* **93**:285–301, 2018. https://doi.org/10.1016/j.rser.2018.05.029

[10] T. Loga, B. Stein, G. Behem. CESB22 – Annex of the paper: Use of energy profile indicators to determine the expected range of heating energy consumption, CESB22 Prague, Documentation of the example building calculations, 2022. [2022-03-02]. https://www.iwu.de/fileadmin/publikationen/energie/mobasy/CESB22_EnergyProfileIndicators_Annex_ShowcaseExamples_CalculationFlow.pdf

[11] T. Loga, N. Diefenbach, J. Knissel. Entwicklung eines Flächenschätzverfahrens zur Abschätzung von Bauteilflächen als Grundlage für die energetische Bewertung von Wohngebäuden. *Bauphysik* **27**(2):102–116, 2005. https://doi.org/10.1002/bapi.200590017

[12] T. Loga, G. Behem. Target/actual comparison and benchmarking used to safeguard low energy consumption in refurbished housing stocks. In *Proceedings of the eceee Summer Study 2021*, pp. 461–471. 2021. [2022-03-02]. https://www.researchgate.net/publication/355124720_Targetactual_comparison_and_benchmarking_used_to_safeguard_low_energy_consumption_in_refurbished_housing_stocks

[13] T. Loga, N. Diefenbach. TABULA calculation method – Energy use for heating and domestic hot water. Reference calculation and adaptation to the typical level of measured consumption, IWU, Darmstadt, 2013. TABULA documentation, [2022-03-02]. https://episcope.eu/fileadmin/tabula/public/docs/report/TABULA_CommonCalculationMethod.pdf

[14] T. Loga. Heizgrenztemperaturen für Gebäude unterschiedlicher energetischer Standards. Abschätzung der Heizgrenztemperaturen und Bilanzzeiten für das Heizperiodenbilanzverfahren nach EN 832/DIN V 4108-6. *Bauphysik* **25**(1):2–14, 2003. https://doi.org/10.1002/bapi.200300020