sciendo

CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2019; 29 (4): 198-217
DOI: 10.2478/ceer-2019-0055
Original Research Article

DEVELOPMENT OF REFERENCE BUILDINGS TO ANALYZE THE POTENTIAL FOR ENERGY-EFFICIENT REFURBISHMENT OF BUILDINGS

Lukas SCHWAN, Jakob HAHN[1], Michael BARTON, Ronja ANDERS,
Christian SCHWEIGLER
Munich University of Applied Sciences, Munich, Germany

Abstract

The building sector offers the largest potential for a significant reduction of greenhouse gas emissions. Based on own preliminary investigations for the State of Bavaria, a complete renovation of the building envelope of the current residential building stock would result in a reduced demand for final thermal energy for space heating and domestic hot water by about 70 %. The present study analyzes different existing reference buildings and reference methods. Based on a general literature review, specific criteria will be developed for reference models to represent the thermal energy consumption of the residential building stock for the regional domain under investigation. The objective is to represent the building stock with a limited amount of reference buildings. The method for the development of a reference building will be shown exemplarily for one category.

Keywords: reference buildings, building modelling, energy transition, energy optimization, DesignBuilder, energy planning and policy

1. INTRODUCTION

The global greenhouse gas emissions have increased significantly in the last years. About one third of the CO_2 are emitted by the building sector; which is also

---

[1] Corresponding author: CENERGIE - Research Center Energy Efficient Buildings and Districts, Munich University of Applied Sciences, Department 05: Building Services Engineering, Lothstr. 34, Munich, D-80335, Germany, e-mail: jakob.hahn@hm.edu, tel.+4908912654368

responsible for 40 % of the global energy consumption. According to the Sustainable Buildings and Climate Initiative of the United Nations Environment Program, the worldwide energy consumption of both new and existing buildings can be reduced by 30 to 80 % using proven and commercially available technologies [1].

A complete renovation of the building envelope of the current residential building stock in the state of Bavaria would result in a reduction of final thermal energy demand for space heating and domestic hot water by about 70 % [2]. The resulting CO_2 emissions will be reduced in the same range and could be lowered even further by integrating renewable energy systems. The knowledge about the current building stock will be combined with own preliminary investigations on the thermal sector in Bavaria. The development of reference buildings for a specific age and location of buildings can help to determine potential energy savings for the specific building class. The utilization of the selected reference building models will allow a modelling of the overall heat demand followed by an optimization of the individual building envelope and of the technical building systems. The use of reference building types can help to decide on suitable, effective and favorable optimization measures. The developed class of reference buildings can be a basis for further investigations and optimization of the building stock.

2. METHODOLOGY

The aim of the present work is the development of a class of reference building types for a realistic representation of the building sector, supporting the energy transition in the thermal sector of Bavaria. For this purpose, the building stock should be modelled with as few reference buildings as possible. These reference buildings shall form the basis for identification of optimization potentials and renovation possibilities.

In a first step, a literature review will point out the existing reference buildings and methods, as well as the corresponding legal regulations regarding energy supply and related primary energy consumption. Then, the most important findings from the analysis of the thermal sector of Bavaria are presented. It will be described how the results can be used for the development of a class of reference buildings and quantitative data will be developed to represent the thermal energy consumption of the residential building stock of the state of Bavaria. The study considers the special local building structure of the building stock in Bavaria and the metropolitan region of Munich. An exemplary reference building is simulated with the software Design Builder based on the building simulation program EnergyPlus to show the procedure for an exemplary category. For the building age class of the years 1949 – 1978, the potential of final energy savings through an energetic refurbishment of the building envelope is studied in detail. Parts of this publication have been presented at the 32th ECOS Conference 2019 [3].

3. REFERENCE BUILDINGS FOR THE THERMAL SECTOR OF BAVARIA

The first step for the definition of reference buildings for the thermal sector in Bavaria is to analyze all building parameters and underlying conditions in detail. Therefore, a literature review and a study of relevant statistics from different sources are conducted in order to define reference buildings which are as representative as possible.

3.1. Existing reference buildings

In general, reference structures and objects are used in the whole life-cycle of buildings from early planning phases through construction and operation phase till demolition and recycling. Moreover, they are applied on various levels, from a single component (e.g. heating appliances) to units or buildings all the way up to districts and entire cities. Hence, the accuracy and attention to detail of the model must be adjusted to the specific application. However, in application it is often difficult to select the essential parameters and meet appropriate accuracy.

Typical applications for the use of reference buildings are the evaluation of optimization measures and energy and greenhouse gas saving potentials [4]. They can be used for studies of building envelopes (e.g. percentage of glazing, U-values of constructions). The renovation of buildings can be assessed regarding sustainability, energy- and cost-efficiency. Reference buildings can be used as a basis for the definition of the building structure or the choice of technical equipment. This can contribute to climate protection programs on national or regional level.

Furthermore, reference buildings are used for comparison and verification of different dynamic building simulation programs.

The VDI 6020, part 1 – “Requirements on methods of calculation to thermal and energy simulation of buildings and plants: Buildings” [5] – describes a reference room. Using a similar procedure, the International Energy Agency (IEA) building energy simulation test (“BESTEST”) for systematically testing of building energy simulation programs presents a whole building as reference [6].

An explicit definition of the term "reference building" (RB) in the context of the Energy Performance of Buildings Directive (EPBD)[2] [7] can be found in Article 2 (11) in the framework of the Annex "cost-optimal methodology" [8]: "reference building means a hypothetical or real reference building that represents the typical building geometry and systems, typical energy performance for both building envelope and systems, typical functionality and typical cost structure in the member state and is representative of climatic conditions and geographic location."

According to Corgnati et al in 2013 [9], a standard methodology valid for different member states was not available at that time. They aim at characterizing the concept of reference buildings, the international state of the art and illustrate a general methodology for the creation of reference buildings. Concerning the definition of reference buildings, they refer to the Annex of the EPBD. They claim that "some experts believe RBs for the existing stock should be as accurate as possible to the present average building stock, but national experts reckon this kind of models would be very complex and unrealistic, even if built on statistical basis" [9]. Another important discussion in the field is the level of detail for the envelope and the technical building equipment of the RBs. According to the U.S. Department of Energy (DOE) four input categories should be considered for the definition of RBs [9]. Figure 1 shows the four input categories for building energy reference models according to the DOE methodology [10]. The present study mainly focuses on the categories form and fabric.

Dealing with this topic of research on reference buildings associated with the EPBD, lots of publications from different countries, for instance considering the Greek [11–13] or Portuguese [14, 15] residential building stock, have been published.

Features defined by DOE were developed for non-residential buildings. Several commercial building reference models have been developed by the DOE for use in the building simulation software EnergyPlus. These include office buildings, schools, malls, restaurants, hotels, hospitals, warehouses, etc. for 16 locations in different climate zones in the USA [10].

In the course of defining characteristic residential buildings two major cross-border research projects have been carried out in the "Intelligent Energy Europe (IEE)" program of the European Union (EU).

Within the project TABULA "Typology Approach for Building Stock Energy Assessment" [16–18] the typology of German residential buildings has been characterized by IWU [19]. Within the current investigation, this source is used

---

[2] The Energy Performance of Buildings Directive has been revised in 2018. However, the definition remains unchanged.

for the development of the reference buildings for Bavaria, which will be explained in more detail in the following sections.

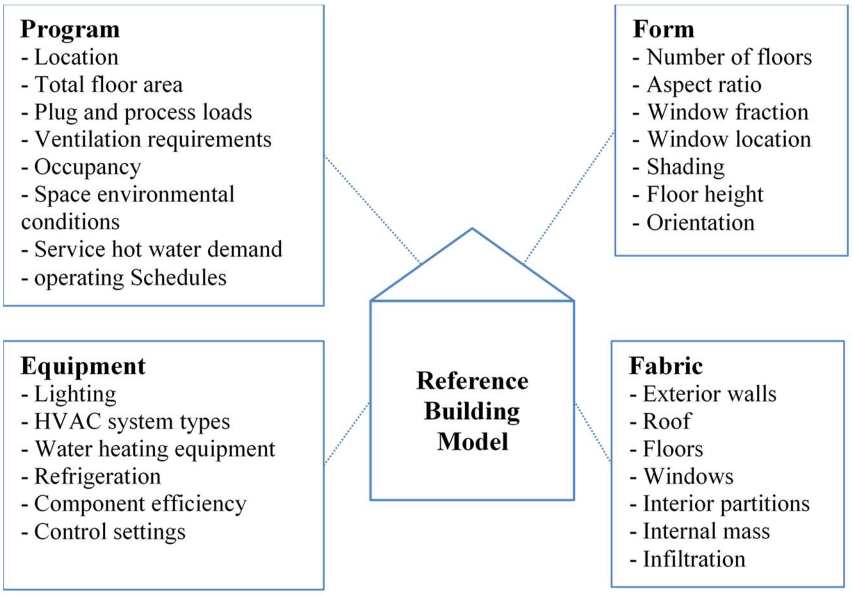

Fig. 1. Building Energy Model Input Categories according to DOE methodology [10]

The second project, ASIEPI – "Assessment and improvement of the EPBD Impact (for new buildings and building renovation), focuses particularly on the "comparison of the energy performance requirements among Member States - Reference buildings for energy performance calculation studies" [20].

However, in Germany a reference building was already introduced into standards and legal regulations within the Energy Saving Ordinance (EnEV) for non-residential buildings in 2007 [21]. According to EnEV §4 "requirements for non-residential buildings", characteristic criteria for the reference building are building geometry, net floor space, orientation and user profile of the planned building as well as the basic configuration of the technical building equipment. Updated in 2009, in the following version [22] the systematic approach of EnEV was adopted to residential buildings – "section 2, §3 requirements for residential buildings (1)". According to the EnEV methodology, the energetic quality of a building is benchmarked in comparison to a reference building with the same geometry, effective area and orientation. Besides these parameters a technical reference system is considered for all newly planned residential buildings. Prior to the EnEV, the Thermal Insulation Ordinance (WSchVO) prescribed the requirements for the primary energy consumption for the building sector. Figure 2 shows the requirements for primary energy consumption in residential buildings from 1978 to present according to the respective Energy Saving Ordinances in Germany.

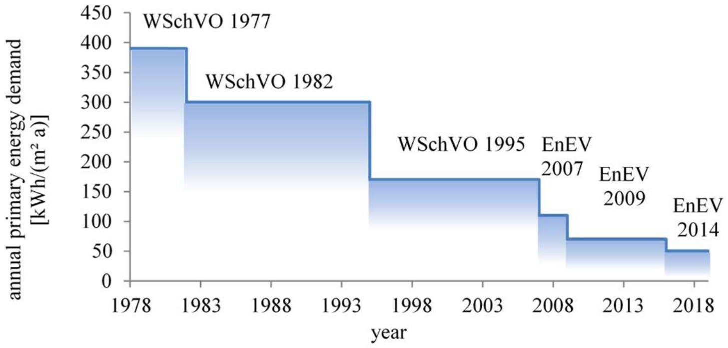

Fig. 2. Regulatory limits for primary energy consumption in residential buildings from 1978 to date [23]

Governed by the series of ordinances WSchVO and EnEV (see Figure 2) a substantial reduction of the energy demand of buildings has been accomplished. Thus, a differentiation of the building stock by age classes should closely follow these temporal steps of the regulatory limits.

3.2. Analysis of the thermal sector of Bavaria

Without far-reaching changes in the thermal sector, the ambitious objectives for saving greenhouse gas emissions and reducing the energy consumption for Germany and Bavaria cannot be accomplished. In order to achieve the long-term targets for 2050, there is an enormous need for action in the building sector. In 2016, 34 % of CO_2 emissions and 49 % of final energy consumption in Germany were accounted for heat supply. In Bavaria 45 % of the CO_2 emissions and 47 % of the final energy demand are related to the building sector. The significantly higher percentage of CO_2 in Bavaria compared to Germany as a whole can be explained inter alia by a larger share of heating oil used for heat generation. Within the current investigation, data for the heat supply of residential buildings have been developed for the years 2016 and 2050. As part of a research project about future energy systems for Bavaria [2], statistical data for the Bavarian residential building stock and the heat demand have been compiled for these two years, specifically. This data will serve as a basis for future investigations, research and measures.

For the heat demand analysis of the building sector, different data sources are available at different regional levels. According to the Building Performance Institute Europe (BPIE) the European building stock can be divided into non-residential buildings (25 %) and residential buildings (75 %) regarding their floor space. The residential sector on EU level consists of 64 % single-family homes and 36 % apartment blocks [24]. In 2016, 14 % of the German building stock consists of non-residential buildings and 86 % of residential buildings, excluding industrial buildings. 83 % of these residential buildings are one- and two-family houses [23]. In 2016 there is a total sum of 18.8 million residential buildings with 40.3 million apartments, with total floor space amounting to 3.7·billion m^2 [25]. The number of buildings with the corresponding share of final energy consumption is shown in Figure 3 [23].

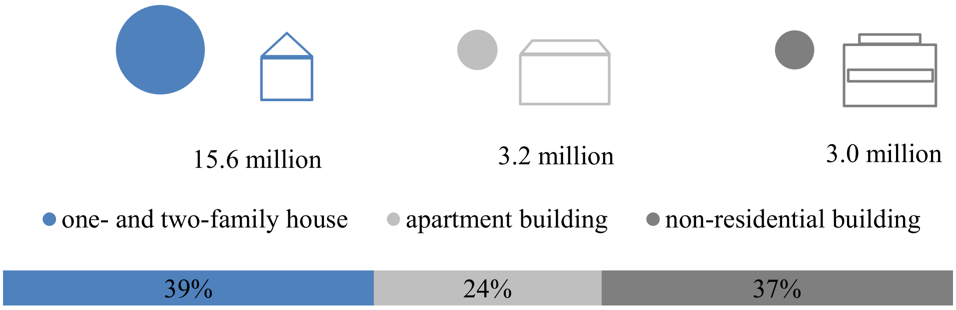

Fig. 3. Number of buildings in millions (top) and final energy consumption (bottom) by building type according to the dena building report for Germany [23]

The present study focuses on the representation of the residential building stock for the state of Bavaria, with slightly more than 3 million residential buildings [25]. The buildings contain 6.3 million flats with 0.61·billion m^2. Similar to the rest of Germany, 82 % of Bavarian residential buildings have one or two units and belong to one- and two-family houses [2].

In order to repartition the current heat demand to individual building types and age classes, different sources have been used. In particular data from the census [26], the IWU investigations [27] and the TABULA project [19] have been processed and integrated due to their quality and level of detail. As result, the distribution of buildings/apartments among age classes with average apartment sizes, refurbishment levels and energy-demand values for Bavaria 2016 has been obtained.

The information for the distribution by age classes with average housing sizes and the definition of the apartment size intervals, the calculation of the total area per building age class and the number of apartments is taken from the census 2011 [26] for all age classes until 2011. The building and apartment data have been linked in order to obtain the total and average area per age class for all permutations of building type and number of apartments. The data for all buildings until 2016 is derived from the data about new apartment buildings in Bavaria [28] and the data for Germany [25] with the assumption that the national data for this time period can be transferred to the Bavarian situation. Definitions of the refurbishment levels and the energy demand values are adopted from the dena building report and IWU building typology [19, 23]. Finally, the national data is connected to the census data for Bavaria [26].

The energy demand and size of the building stock of the year 2050 is estimated following an assessment of documentation and forecasts for the development of building stock and population. For this purpose, factors for demographic and building development are compiled. On the basis of past trends as well as current and future investments and refurbishment measures, the renovation rates and the distribution of renovations are estimated. In addition, a prediction for improvements in current and future energy demand values is conducted. [16, 23, 25, 27–29]

As a result, the structure of the Bavarian residential building stock is represented by 720 different categories for 2016 and by 840 categories for 2050. These categories are a result of the combination of the following classification criteria:

- **building type** detached house, semi-detached house, terraced house, other building type)
- **building age class** (until 1919, 1919–1948, 1949–1978, 1978–1986, 1987–1990, 1991–1995, 1996–2000, 2001–2004, 2005–2008, 2009–2011, 2012–2015, 2016)
- **number of apartments per building** (1, 2, 3–6, 7–12, >12)
- **level of refurbishment** (not renovated, partially renovated, fully renovated)

Each category is associated with a specific energy demand value from which the individual absolute demands are calculated. The categories can be summarized according to one of the classifications. Figure 4 shows the number of buildings of each building type and the corresponding share in final energy consumption.

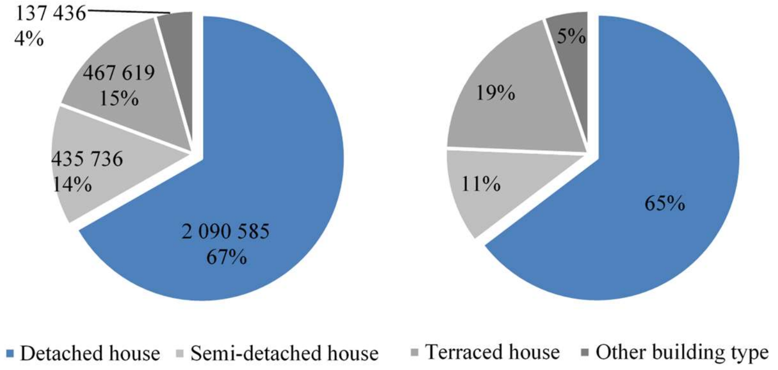

Fig. 4. Number of buildings (left) and corresponding percentage of final energy consumption (right) by building type for the building stock of Bavaria [2]

The detached houses cover the highest share of the final energy consumption. Taking into account the number of apartments per building, it is found that about 2/3 of the energy demand is to be attributed to single and two-family houses, as shown in Figure 5.

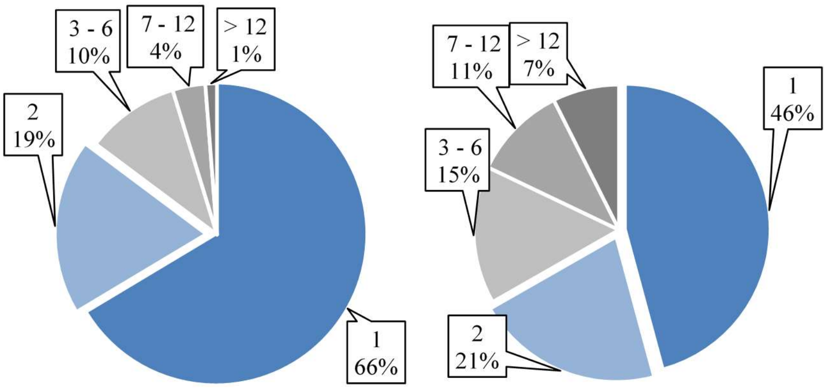

Fig. 5. Distribution of number of apartments per buildings (left) and corresponding percentage of final energy consumption (right) for the building stock of Bavaria [2]

Table 1 shows the ranking of building classes with the highest share of final energy for the state of Bavaria, summarized for building age classes from 1949 – 1978 and 1979 – 2016 and according to the defined categories. The highest final energy consumption is attributed to the group of not renovated detached houses with one apartment built in the years 1979 – 2016. 13.3 % of the final energy demand for space heating (SH) and domestic hot water (DHW) are consumed by this building class.

Table 1. Ranking of building classes in share of final energy for the state of Bavaria [2]

Ranking of the building classes / categories				Number of buildings		Energy SH+DHW	
				[ ]		[MWh/a]	
Total				3,131,377	100%	10,1314,761	100%
Detached house	1 apartment	Not renovated	1979 - 2016	561,555	17.9%	1,342,7051	13.3%
Detached house	1 apartment	Not renovated	1949 - 1978	255,679	8.2%	8,396,157	8.3%
Detached house	>3 apartments	Not renovated	1979 - 2016	92,165	2.9%	6,252,499	6.2%
Detached house	2 apartments	Not renovated	1949 - 1978	121,171	3.9%	6,072,647	6.0%

Detached house	2 apartments	Not renovated	1979 - 2016	152,271	4.9%	5,846,155	5.8%
Detached house	>3 apartments	Not renovated	1949 - 1978	55,471	1.8%	4,710,669	4.6%
Terraced house	>3 apartments	Not renovated	1949 - 1978	30,935	1.0%	4,146,345	4.1%
Detached house	1 apartment	partly renovated	1949 - 1978	194,644	6.2%	3,889,714	3.8%

Table 2 shows the relation between the number of building classes (categories), which have to be considered to represent a corresponding share of final energy demand. An illustration of this relation is displayed in Figure 6.

Table 2. Relation between number of building classes and share of energy

Share of total final energy	52%	63%	72%	80%	90%	95%	98%	99%	100%
Number of building classes	8	11	15	21	34	48	63	71	108
Share of total building stock	47%	57%	69%	75%	85%	91%	96%	97%	100%

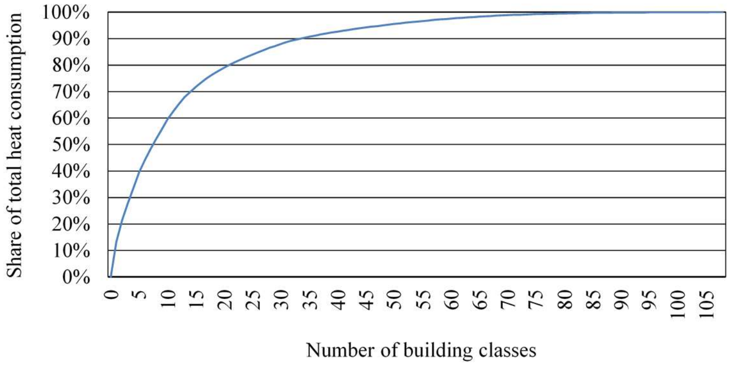

Fig. 6. Relation between number of building classes and share of energy

The division of the building stock into a range of longer age classes still results in 108 different building classes. Figure 6 indicates, that the required number of building classes increases exponentially when an increasing share of total heat consumption shall be covered. Nevertheless, only 8 building classes (7 % of reference buildings) have to be modeled to cover over 50 % of the heat demand of the Bavarian domestic building stock. To avoid high variance of the data within the classes, the building age classes must be divided into sub-classes, which increases the number of reference buildings. The procedure and methodology as well as all results for each building category and combination are described in more detail in a previous publication [2].

3.3. Definition and selection of a reference building

Besides the different characteristics of reference buildings named in literature, the following assumptions are made within the framework of this paper in order to represent the building stock of Bavaria. They can be used to quantify the energy saving potential of building refurbishment measures. The aim is to map the building stock with a limited number of reference buildings. Since the reference buildings serve as statistical models, initially the focus is on average values for form and fabric (see right-hand side of Figure 1). After analyzing potential savings, concrete refurbishment measures can be applied. In a second step, for example, the plant technology and occupancy are investigated, and different variants can be compared.

From the presented results, the shares of the energy demand of the different building categories can be deduced. Therefore, it can be conclude how many buildings have to be considered in order to cover a desired share of the total energy demand. The analysis of the data indicates the possibility to group detached single-family houses of the years 1949 to 1978 in a single class without major deviations in terms of their heat demand, because there were no regulations on thermal insulation until 1977 in Germany. This group of buildings represents 8.3 % of the heat demand and 8.2 % of the building stock and therefore offers the highest renovation potential. For this reason, it is used as the first exemplary reference building for investigating the impact of thermal simulation. The building energy demand is simulated taking into account three levels of refurbishment to show the potential for energy savings, enabling to quantify costs, benefits and expenses. Analogously, any reference building can be created from the collected and processed data. The level of detail should be adjusted according to the focus of investigation. In the following, the procedure for modeling the energy demand of the reference building using an established software tool is described. This methodology can be applied to any number of further reference buildings.

4. SIMULATION PROCEDURE OF A REFERENCE BUILDING

4.1. Software for building simulation

First of all, thermal building energy simulation of reference buildings requires the selection of suitable building performance simulation software. In the last 50 years, multiple programs have been developed in the field of application. Hereby, the focus is laid on modeling the entire building in order to generate statements and forecasts about physical parameters like temperatures or humidity as well as the total energy consumption and costs. Crawley et al. [30, 31] give an overview of publications dealing with the comparison of different programs and compare the twenty most important programs for building simulations.

The simulation also allows a better understanding of the interaction between design and operating parameters and facilitates a more efficient design of the building. Typical input values of a building model are building geometry, material properties of the building envelope and components, internal heat sources, specifications for ventilation, heating and cooling, and schedules for operation and control of facilities. The systems used and their interactions are described by mathematical models in order to calculate and evaluate the resulting loads, energy consumption and indoor climate for a given location and time-resolved local weather data.

The described reference building does not represent an existing building, but a typical average configuration. For the simulation, it is necessary to simplify the construction of the building to make it verifiable and easy to adapt. Implementation of a new reference building for individual circumstances should be feasible with limited computational effort. Software with a large database and a comprehensive selection of templates is suitable for this application. The simulation modules should be adjustable regarding their complexity. For the current investigation, the reference building is simulated exemplarily in EnergyPlus using the DesignBuilder software.

4.2. Mathematical model for dimensioning the building geometry

In order to be able to model the selected reference building, the building data are averaged regarding characteristics of the envelope and energy consumption values. The challenge in defining the geometry is to select the input data so that they represent an average building of the respective reference category.

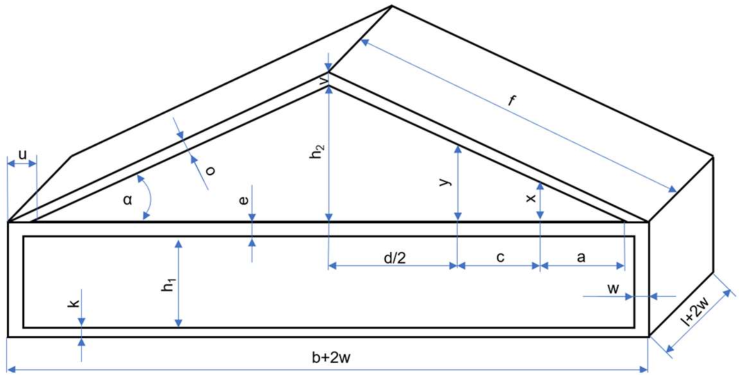

Fig. 7. Simplified geometry of the reference building

The geometry is adapted so that the surface area to volume (S/V) ratio complies with characteristic data of the IWU database [19] to the Bavarian building data. The values for the geometry are adapted and scaled based on the floor area. The building simulation software requires the definition of several geometry parameters. Figure 7 shows the most important input values of the considered reference building. Additionally, further input data are collected in Tables 3-5. With appropriate assumptions a set of equations can be set up, from which the building length, building width, roof pitch, as well as the attic height can be calculated. In addition, the floor height is deduced from the room height and the thickness of the ceiling. The scaled values are converted to detailed data to define the form of the reference building by means of the set of equations. The resulting calculated geometry data is listed in tables 3 – 5, together with further boundary conditions and specifications.

4.3. Building simulation model - boundary conditions and specifications

The room area for the Bavarian buildings has been determined from previous studies [2] with the use of the data from the census 2011 [26] and the microcensus 2016 [28] for Bavaria. The number of floors, attic type, U- and g-values, ventilation and infiltration, as well as window proportion per compass direction and door areas were taken from an IWU study for German building classes [19]. The geometry is calculated as previously descried. For the investigated application, interior divisions are neglected. However, the inner walls are considered with a share of 10 % of the floor area and simulated with their associated thermal mass. According to IWU [26] and the TABULA project [18], the house is assumed to have one full floor and an occupied attic. From DIN 18599-10 [32] contribution of internal heat gains and sinks as wells as hot water demand are determined. Average indoor temperature is assumed to be 19 – 20 °C [33]. For the modelling of the reference building further specifications are used from different literature sources, as summarized in the following tables.

Table 3. Input data for the simulation of the reference building from literature sources

Input data	*Value*	*Source*
Number of floors and attic type	One floor + occupied attic	[19]
Building orientation	North-South orientated roof	[32]
Living space	126 m²	[2]
Room height	2.5 m	[19]
Person/m²	0.0227 p/m²	[26]
Roof inclination	35°	[34]
Domestic hot water (DHW)	12.5 kWh/(m²·a)	[32]
Internal heat gains	2.08 W/m²	

Indoor air temperature	19 – 20 °C	[33]
Surface area to volume (S/V) ratio	0.834 m²/m³ (± 10 % deviation)	[19]
Window surface per total wall area	East: 3.8 % (5.5 m²) South: 3.8 % (5.5 m²) West: 5.3 % (7.6 m²) North: 2.3 % (3.3 m²)	[19] [19] [19] [19]

Some input data and specifications for the reference building depend on the level of refurbishment. This includes the ceiling and wall thickness, g-value of the windows, as well as the air change rate per hour (ACH) by manual ventilation and infiltration. Furthermore, the U values of the roof, windows and the ground floor vary depending on the level of refurbishment. The corresponding values can be found in table 4.

Table 4. Input data depending on level of refurbishment [19]

Input data	*Not renovated*	*Partly renovated*	*Fully renovated*
Ceiling thickness	0.25 m	0.37 m	0.55 m
Wall thickness	0.25 m	0.33 m	0.49 m
G-value	0.75	0.60	0.50
ACH by user	0.4 /h	0.4 /h	0.4 /h
ACH by infiltration	0.2 /h	0.2 /h	0.1 /h
U-value of roofs	0.9 W/(m²·K)	0.9 W/(m²·K)	0.1 W/(m²·K)
U-value of windows	2.8 W/(m²·K)	1.3 W/(m²·K)	0.8 W/(m²·K)
U-value of ground floor	0.89 W/(m²·K)	0.29 W/(m²·K)	0.22 W/(m²·K)
U-value of walls	1.2 W/(m²·K)	0.3 W/(m²·K)	0.1 W/(m²·K)

Table 5. Calculated input values

Input data	*Value*
Building length	12.2 m
Building width	8.0 m
Ground area	97.6 m²
Attic height	2.7 m
Surface area S	382 m²
Volume V	458 m³

Figure 8 visualizes the reference building created in DesignBuilder for a detached single-family house for the building age class 1949 – 1978. Input data and values are presented in the tables above.

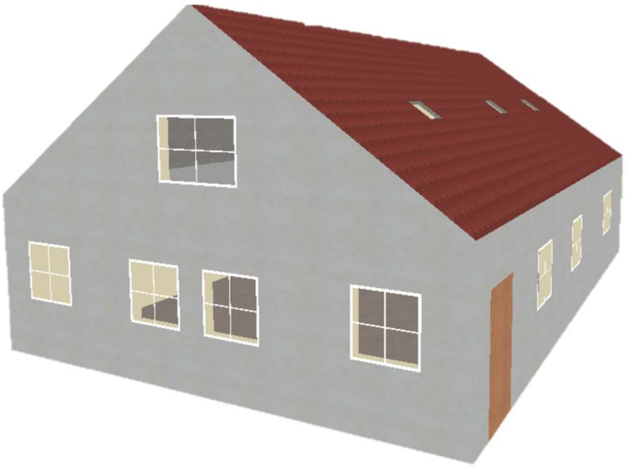

Fig. 8. Visualization of the reference building model simulated in DesignBuilder

4.4. Results

The average values for the three considered refurbishment levels are derived directly from the values for the state of Bavaria [19], without detailed calculation by complex building simulation tools. All further average reference values for the annual heat demand for space heating and domestic hot water can be found in table 6. With the defined reference building a time-resolved calculation of the heat demand can be carried out for the course of a year. Figure 9 shows the annual profile of the heat demand for three different levels of refurbishment.

Table 6. Reference values for annual heat demand and domestic hot water (DHW) for three levels of refurbishment based on [2]

Reference data	*Not renovated*	*Partly renovated*	*Fully renovated*
Heat demand + DHW	27,300 kWh/a	17,311 kWh/a	6,987 kWh/a

The graphs in Figure 9 clearly show the potential for savings in heat demand (room heating and domestic hot water) by renovation of a building in the age group from 1949 – 1978. Correlated with the values from the used database, the simulated results' maximum uncertainty is less than 5 %. Based on a parametric analysis, predictions for future years can be derived. In addition, individual optimization measures can be evaluated for particular weather conditions. In this way, the large data sets can be used for potential analyses and the selection of optimization measures. By means of dynamic simulation, the impact of the respective measures can be characterized and assessed in more detail, compared to the use of common-sense data of the specific annual demand.

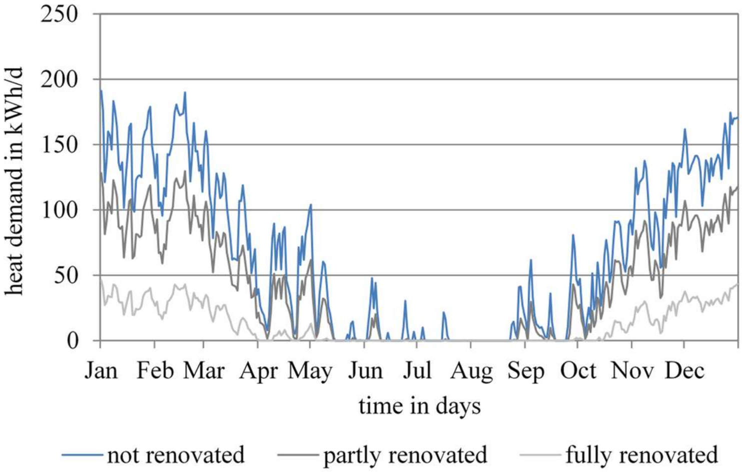

Fig. 9. Annual profile of the heat demand and domestic hot water for three levels of refurbishment (daily values)

5. CONCLUSION AND OUTLOOK

A process for the definition and modeling of reference buildings is described in detail, based on a statistical analysis of the heat demand of the Bavarian building stock. By combining different classifications, the potential of renovation measures can be estimated and evaluated. The largest potential for energy saving is found for the refurbishment of existing detached houses built before 1979. Taking into account a limited amount of reference buildings, the heat demand for the residential building stock of Bavaria can be modeled with reasonable effort and sufficient accuracy. The overall results of the building simulation confirm the predicted saving potential of about 70 % through full renovation of the present building stock.

Based on this study, further analytical research can be conducted. The selection of building reference models will constitute the starting point of future investigations aiming at a reduction of energy consumption and associated emission of greenhouse gases. For this purpose, optimization scenarios of the insulation quality of the building stock will be developed and analyzed. Joint application and simulation of the selected models for buildings and supply systems allows the definition and evaluation of integrated solutions, with potential interaction of different sectors. The reference structure can accelerate the design process of future buildings and building energy systems and could be adapted to non-residential buildings.

REFERENCES

1. UNEP SBCI. *Buildings and Climate Change: Summary for Decision-Makers*, **2009.** <https://europa.eu/capacity4dev/unep/document/buildings-and-climate-change-summary-decision-makers> (Accessed January 3, 2018).
2. Barton, M and Schweigler, C 2019. *Scenarios for the development of building heat demand in Bavaria - project report: Tools and solutions for the energy transition in the thermal sector (Szenarien für die Entwicklung des Gebäudewärmebedarfs in Bayern - Projektbericht: Werkzeuge und Lösungen für die Wärmewende)*; (in preparation): München.
3. Schwan, L, Hahn, J, Barton, M, Anders, R and Schweigler, C 2019. In: *32th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. Conference Proceedings*, Wroclaw, Poland; ECOS 2019, Ed.: Wroclaw, Poland.
4. Schaefer, A and Ghisi, E 2016. Method for obtaining reference buildings. *Energy and Buildings*, *128,* 660–672.
5. VDI. *Requirements on methods of calculation to thermal and energy simulation of buildings and plants - Buildings (Anforderungen an Rechenverfahren zur Gebäude- und Anlagensimulation - Gebäudesimulation)*, May 2001 (Accessed February 4, 2019).
6. Ron Judkoff and Joel Neymark. The BESTEST Method for Evaluating and Diagnosing Building Energy Software.
7. European Union. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. *Official Journal of the European Union*, 2010.
8. *Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elementsText with EEA relevance*, 2012.
9. Corgnati, SP, Fabrizio, E, Filippi, M and Monetti, V 2013. Reference buildings for cost optimal analysis: Method of definition and application. *Applied Energy*, *102,* 983–993.
10. Deru, M, Field, K, Studer, D, Benne, K, Griffith, B and Torcellini, P 2011. NREL, M, Liu, B, Halverson, M, Winiarski, D and M. Rosenberg: PNNL; Yazdanian: LBNL. U.S. Department of Energy Commercial Reference Building Models of the National Building Stock.
11. Dascalaki, EG, Droutsa, KG, Balaras, CA and Kontoyiannidis, S 2011. Building typologies as a tool for assessing the energy performance of

residential buildings – A case study for the Hellenic building stock. *Energy and Buildings*, *43,* 3400–3409.

12. Theodoridou, I, Papadopoulos, AM and Hegger, M 2011. A typological classification of the Greek residential building stock. *Energy and Buildings*, *43,* 2779–2787.
13. Dascalaki, EG, Kontoyiannidis, S, Balaras, CA and Droutsa, KG 2013. Energy certification of Hellenic buildings: First findings. *Energy and Buildings*, *65,* 429–437.
14. Serra, C, Simões, N, Tadeu, S and Tadeu, A 2013. Definition of reference buldings for energy performance calculation - Portuguese case. *Energy for Sustainability*, *2013*.
15. Brandão de Vasconcelos, A, Duarte Pinheiro, M, Cabaço, A and Costa Manso, A 2016. Energy Cost-Efficient Rehabilitation Measures for the Portuguese Residential Buildings Constructed in the 1960–1990 Period. In: *Sustainable construction*: *Building performance simulation and asset and maintenance management*. Delgado, J.M.P.Q., Ed.; Springer: Singapore, vol. 8, pp. 23–42.
16. Loga, T, Stein, B and Diefenbach, N 2016. TABULA building typologies in 20 European countries—Making energy-related features of residential building stocks comparable. *Energy and Buildings*, *132,* 4–12.
17. Balaras, C, Dascalaki, E, Sijanec Zavrl, M, Rakuscek, A, Corrado, V, Corgnati, S, Despretz, H, Roarty, C, Hanratty, M, Sheldrick, B, Cyx, W, Popiolek, M, Kwiatkowski, J, Groß, M, Spitzbart, C, Georgiev, Z, Iakimova, S, Vimmr, T, Wittchen, KB, Kragh, J and Diefenbach, N 2010. *Use of building typologies for energy performance assessment of national building stocks: Existent experiences in European countries and common approach;* IWU: Darmstadt.
18. Ballarini, I, Corgnati, S.P and Corrado, V 2014. Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project. *Energy Policy*, *68,* 273–284.
19. IWU 2015. *German residential building typology - exemplary measures to improve the energy efficiency of typical residential buildings (Deutsche Wohngebäudetypologie - Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden);* institute for housing and environment (Institut Wohnen und Umwelt): Darmstadt.
20. ASIEPI 2009, 1. Comparison of the EP requirements among Member States: Reference buildings for EP calculation studies.
21. *Ordinance on energy-saving thermal insulation and energy-saving system technology for buildings (Energy Saving Ordinance) (Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden (Energieeinsparverordnung)): EnEV*, July 26, 2007.

22. *Ordinance amending the Energy Saving Ordinance (Verordnung zur Änderung der Energieeinsparverordnung): EnEV 2009*, 2009.
23. Bigalke, U, Armbruster, A, Lukas, F, Krieger, O, Schuch, C and Kunde, J 2016. *Statistics and analyses on energy efficiency in existing buildings (Statistiken und Analysen zur Energieeffizienz im Gebäudebestand)*.
24. Economidou, M, Atanasiu, B, Despret, C, Maio, J, Ingeborg, N, Rapf, O, Laustsen, J, Ruyssevelt, P, Staniaszek, D, Strong, D and Zinetti, S 2011. *Europe's buildings under the mircoscope: A country-by-country review of the energy performance of buildings*.
25. Federal Statistical Office (Statistisches Bundesamt) 2018. *Existing housing stock - Construction of flats and residential buildings - Long series from 1969 - 2017 (Bestand an Wohnungen und Wohngebäuden - Bauabgang von Wohnungen und Wohngebäuden - Lange Reihen ab 1969 - 2017)*.
26. Bavarian State Office for Statistics and Data Processing (Bayerisches Landesamt für Statistik und Datenverarbeitung) 2012. *Stock of residential buildings and flats in Bavaria - basis: final results of the building and flat count 2011 (Bestand an Wohngebäuden und Wohnungen in Bayern - Basis: Endgültige Ergebnisse der Gebäude- und Wohnungszählung 2011)*.
27. Cischinsky, H and Diefenbach, N 2018. *Data collection residential building stock 2016 - Data collection on energy characteristics and modernisation rates in the German and Hessian residential building stock (Datenerhebung Wohngebäudebestand 2016 - Datenerhebung zu den energetischen Merkmalen und Modernisierungsraten im deutschen und hessischen Wohngebäudebestand):* Darmstadt.
28. Bavarian State Office for Statistics and Data Processing (Bayerisches Landesamt für Statistik und Datenverarbeitung). GENISIS-Online Database - Projection: Districts, Population, Deadlines (GENISIS-Online Datenbank - Vorausberechnung: Kreise, Bevölkerung, Stichtage). Results - 12421-001. <https://www.statistik.bayern.de/statistik/demwa/>.
29. Statista. Development of the population in Bavaria from 1960 to 2017 (Entwicklung der Einwohnerzahl in Bayern von 1960 bis 2017). <https://de.statista.com/statistik/daten/studie/154879/umfrage/entwicklung-der-bevoelkerung-von-bayern-seit-1961> (Accessed February 12, 2019).
30. Crawley, DB and Hand, JW 2008. Kummert, M.; Griffith, B.T. Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, *43,* 661–673.
31. Crawley, D, Hand, J, Kummert, M and Griffith, BT 2005. *Contrasting the Capabilities of Building Energy Performance Simulation Programs*.
32. DIN 2007. *Energy assessment of buildings - Calculation of useful, final and primary energy requirements for heating, cooling, ventilation, domestic hot water and lighting (Energetische Bewertung von Gebäuden - Berechnung des*

Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung).

33 DIN. *DIN V 4108-6:2003-06, Thermal insulation and energy saving in buildings - Part 6: Calculation of annual heating energy demand and annual heating energy demand (Wärmeschutz und Energie-Einsparung in Gebäuden - Teil 6: Berechnung des Jahresheizwärme- und des Jahresheizenergiebedarfs);* Beuth Verlag GmbH: Berlin.

34 Corradini, R 2013. Regionally differentiated solar thermal potential for buildings with one residential unit (Regional differenzierte Solarthermie-Potenziale für Gebäude mit einer Wohneinheit). dissertation, Ruhr-Universität Bochum: Bochum.

Editor received the manuscript: 04.12.2019