Adaptation of a stochastic simulation model for long-term investigation of the development of the energy demand in larger building stocks

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Abstract. In order to design the energy transition process, strategies to gain high energy saving potentials are needed. To assess the primary energy demand of a building stock of about 3,5 million buildings a model originally used for calculating the heat demand of rural districts was adapted. To close the gaps in the statistical data many assumptions had to be made. The impact of the assumptions had to be summarized as well as several supplements which indicate the technical components had to be implemented.

1. Introduction

The urgent necessity to design and implement the energy transition requires a targeted action. In the public discussion the use of renewable energies is often named as a solution of the problem. Whereas it is often neglected that especially the increase of efficiency in the use of energy can make a key contribution to cope with the energy transition. An extensive increase in the rate of renewable energies can mainly be reached through the reduction of the energy demand. .

In Germany more than a quarter of the final energy demand (AGEB 2011) is required for heating residential buildings. Beside this more than two thirds of the buildings were built before the year 1978, when the first legal ordinance formulated requirements for thermal protection during the construction of buildings. The majority of these buildings still exist today, without any heat protection measures. Users as well as homeowners do not estimate the potential savings properly and the existing potential is often not utilized. Although the techniques to reduce the demand are explored as far as possible, the renovation of existing buildings takes place very slowly. To resolve the refurbishment congestion a targeted action is required in order to use the current high volume of cases and the high savings. The objectives of the Federal Government for the year 2050 purport a reduction of the primary energy demand by 80%, whereas the existing building stock acts almost carbon neutral covering the remaining demand by renewable energy. To show ways to reach these savings it is necessary to define strategies that emanate from the target and incorporate the various building structures.

Depending on the observed region the structure of the building stock in Germany is very different. While in rural areas the living space per capita is on a higher level than the average of whole Germany, in cities and urban areas it is well below the average. The growth of the human need for comfort together with social changes support on the long term a further increase in the living space per habitant. Unfortunately, this affects the energy demand in a negative way. The knowledge of these special factors is of crucial importance in order to assess the reachability of the formulated goals. The adjusting screws of the system have to be identified in order to develop the appropriate tools.

Along with the reduction of the demand a serious transformation of the energy supply structure is necessary. Due to the nuclear exit, and the necessary substitution of this energy source increased pressure on budgets is to be expected. The substitution of nuclear energy can be supported by the reduction of the demand for natural gas from the building sector. The substantial reduction in energy consumption for space conditioning has the consequence that the use of renewable energies is much easier because only a low temperature level heat demand has to be covered. Like the demand patterns vary depending on the observed region, the supply patterns also differ between rural regions with a high proportion of biomass and large cities with an often existing district heating supply.

The draft of strategies for achieving the saving targets thus requires the consideration of different ways which can be assessed and analyzed by using complex simulation models. Hence, the assessment of the effectiveness of the different influencing system-components is crucial for the development of effective strategies and requires a detailed picture of the overall system.

As a topic of several publications, different models were developed to calculate the energy performance of the building stock. Kohler. N & Hassler. U (2002) summarize an overview of models for the European building stock approach.

This paper describes the further development of a bottom-up model which is used to calculate the energy demand of larger building stocks. Therefore the goal is to make sensitivity studies for identifying the importance of the various development components. These are the rehabilitation of buildings, the energy supply and the activation in the long-term rehabilitation strategy. Building stock models like this are used in many scientific projects, for example (Kavgica et al 2010) and (Coffey et al 2010).

2. The base model

A main difficulty in the assessment of the current and future building stock is the lack of statistical data on its energetic development. Since the introduction of legal ordinance in 1977 the requirements to use measures for reducing energy loss placed on both the construction and the refurbishment of residential buildings have increased in several steps. The latest change happened in 2009 with the amendment of the so called *Energieeinsparverordnung*, the German law to minimize energy demand of new-built and refurbished buildings,. Since the requirements to implement technical improvements must be met only under certain conditions and at the same time no recording of the refurbishments was done the change of the energy levels of the building cannot be determined exactly. Partly because of this missing data a method for mapping the temporal changes in housing was developed in (Nemeth, 2011). The virtual life cycle of buildings is simulated by using technical lifetimes of components and results in a synthetic refurbishment sequence for individualized building. With the help of stochastic steps used in the model the failure time points of the components in the heat-transmitting envelope of a building are simulated. Thus an assessment of the improvements of the building envelope can be made together with the regulatory requirements in the case of an energetic renovation. The model developed originally for the estimation of regional building stocks calculates thermal heat demand of the building stock. Therefore the model is using district-specific residential areas as well as the physical properties of the various types and building classes of the building typology (IWU 2005 1). By modeling the refurbishment time-points starting with the year of construction both future and retrospective observations can be performed. Hence the heating energy demand of the building stock in the year 1990 which is defined as the reference year for the savings targets can be determined.

The described procedure is in principle also adequate for the simulation of much larger building stocks. Thus as part of a research and development work the model should be adapted for use on a housing stock of about 3.5 million buildings. An embracing adaptation and extension of the model was required to assess the reachability of the formulated savings targets and the sensitivity of the building stock.

3. Adaption of the model

3.1 Processing of the expanded data set

The described basic model in the original concept was designed for the simulation of the heating demand of regional building stocks, each comprising about 35,000 buildings. The new use for the simulation of a building stock of about 3.5 million buildings required adjustments so that both the processing of the much larger amount of data and also the automation and enhancement of needed calculation capabilities is possible. To obtain a better handling the first in Excel VBA implemented calculation procedure was therefore converted into the programming language MATLAB. Compared to Excel VBA a more structured programming and in particular an optimization in terms of computing speed is possible. Since a lot of data has to be processed independently for every building, the use of multi-core calculation is a must to speed up the program. The initialization routines which create the buildings in the simulation don't profit from that, but the heating demand calculation and the following calculations of primary energy, final energy, CO2-emissions were speed up by a factor of 10. In the future, more optimization of the parallelism will take place, especially for using this model together with simulation models for energy supply or agent-based models of refurbishment processes.

Now the building stock of 71 rural and 25 urban districts had to be analyzed. These districts have significant structural differences due to their large spatial distribution. These differences are a widely varying living space per capita and the different rates of each building type, which is presented in Figure 1.

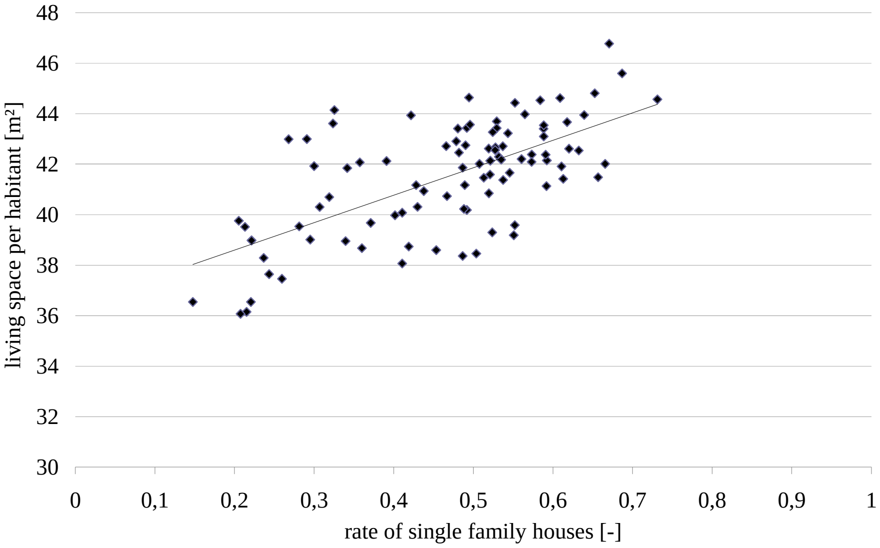

Figure 1: Dependency between rate if single family houses and living space per habitant in the simulated districts

Because of the relationship between living space and the heated volume, which is worst in the group of the one- and two-family-houses, this group requires high attention. Beside this the group represents a significant part of the residential building stock in many areas. The high number of counties and cities made an automated generation of 8-9 building types per building age class necessary. The basis for this automated process is statistical data on residential structures from the 1987 census as well as statistical data on the housing completions from 1988 to 2010. From this data the average living area per living unit for each building type in each building age class can be calculated for every county, resulting in different building types. By using the so called *Flächenschätzverfahren* described in (IWU 2005 2), a statistically verified area approximation algorithm based on the average living space per building type and building age class, typical component surfaces of the building envelope are generated automatically. The quality of the building is derived from the typical physical building characteristics of the German building typology (IWU 2005 1). while the window area is distributed to the cardinal directions according to the information contained in the German building typology.

If data on the area in the building stock, the building age distribution and some building topology for a district are given, this process can be easily applied to other districts. But here it has to be mentioned that the area approximation algorithm was developed in Germany, and therefore it has to be checked that it can be also applied to buildings in other regions.

3.2 Application and influence of the area approximation algorithm to the calculation

The area approximation algorithm used in the model forms one of the central components to model the heat-transferring enveloping surfaces of the building. In the calculation of the heating demand there is a linear correlation between the component areas and the calculation result, so that errors in the assumptions of these surface areas would be significant. While for one- and two-family houses the application of the surface estimation process gives adequate results due to the relatively small spread of residential space in these buildings, the application of the method on multi-family homes includes bigger uncertainties. Within the base model the component surfaces were related to individual housing units of apartment buildings, and those units were then grouped to form a building. In contrary to the now investigated regions the proportion of multi-family houses is quiet high, so the previous approach cannot be used. In order to identify the change of compactness and influence of the number of floors in dependency to the net dwelling area of the building and the influence to the contact area, these interconnections in the area approximation algorithm have been studied in detail.

Dependencies between number of floors and area of surface components

- The area of the outer wall surface is linearly correlated to the number of floors.
- The window area is independent of the number of floors, because it is defined as a function of the net dwelling area (see constant progress in Fig. 1)
- The roof surface and the area of the lower building statement are indirectly proportional to the number of floors

In Figure 2 the named dependencies for the example of a free standing building with 1,500 m² of heated living space, a compact footprint (i.e. the ratio of the floor plan perimeter to the perimeter of an area-equal-sized square is less than 1.2), unheated basement, attic fully heated, no dormer windows and 2.5 m room height are illustrated. As the figure shows, particular for large floor areas in conjunction with a small number of stories the approximation for the upper and lower surfaces of the building closure is too big. With increasing number of floor levels the height of the building increases, the width and thus the surfaces of the upper and lower building closure change only insignificantly.

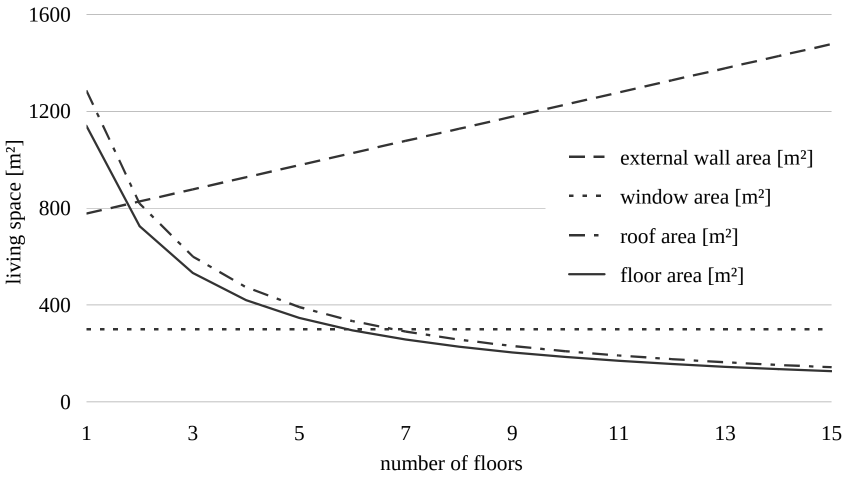

Figure 2: Dependency between envelope areas and number of floors in the used method

In reality, the requirements for natural lighting of the rooms and the increasing costs due to building height regulate the emergence of large contact areas or buildings with slender footprint for apartment buildings with 4-10 units. Since the classification of statistical data on residential apartment buildings in groups with 3, 4-6, 7-12 and 13-19 residential units is relatively tight, the risk of modeling a 10-apartment building with one or two levels is small. To avoid extremely unrealistic contact areas, the number of residential units per floor is given in the model. Thus for older building age classes a smaller number of residential units per floor is possible, for newer years of construction and thus more generous floor plans with more residential units per floor are allowed.

As Figure 3 illustrates, several variants for the number of floors give a reasonably accurate mapping of the geometric boundary conditions. For this example a building with a heated living area of 600 m², 10 housing units and construction year 1983 were used to distribute the living area to different floor numbers.

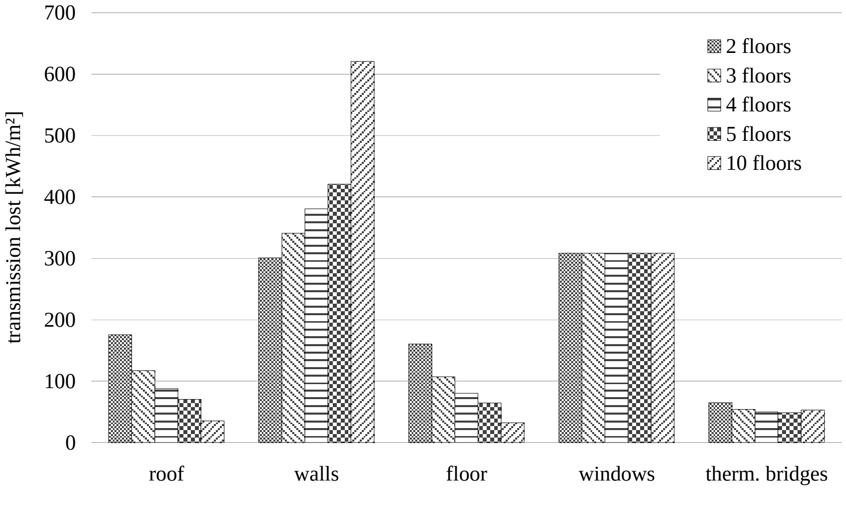

Figure 3: Transmission losses of different components in an example building

The heat transfer coefficients were taken from the German building typology for this building type. In the range of 2-5 floor levels occurs, as was shown above, an overestimation of the upper and lower building closure, while at the same time there is an undervaluation of the outer wall surface. Only with an increase up to an unrealistic number of floors (10 in the example) the resulting heating demand increases significantly because of the large overestimation of the outer wall surface. This effect is prevented by the given number of residential units per floor.

The compactness of the multi-family houses which have usually energetically favorable shapes is also indirectly influenced by the assumptions outlined above. Due to large contact surfaces the reduced compactness of the buildings causes higher values for the energy demand of the buildings. Due to the previously described limitation of the deviation this effect is small

Figure 4 shows the A/V-ratio in a freestanding building with three full floors, a compact footprint, an unheated cellar, a fully heated attic, 2.5 m room height and without dormer windows. Only for high values of compactness and thus energetically unfavorable configurations, such as in case of one-family-houses, major changes of the ratio are possible.

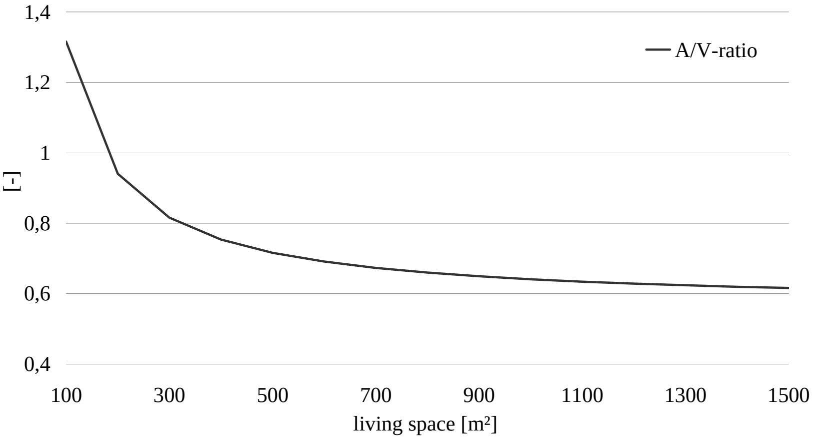

Figure 4: A/V-ratio depending on the net dwelling area

Particularly in the area of small multi-family dwellings there must be a fine subdivision into size categories.

3.3 Automating the development of future building construction

Similar to the basic model the future construction of residential buildings between 2012 and 2040 is determined by three influencing variables. On the one hand the development of the model includes the automation of this process, so it is possible toprocess a large number of regions. On the other hand sensitivity studies on the model and the results can thus be carried out on a larger scale. The three components of the development of new residential buildings are:

1. determination of net dwelling area growth / decrease due to changes in population
2. determination of net dwelling area growth by the increase in living space per inhabitant
3. structuring the area change in the different building sizes

The regionalized population projections (LfStaD 2012) issued by the Bavarian Statistical Office is used for the future development of the net dwelling area which depends on the quantitative changes of the population. These projections use the coordinated population projections of the state government and the commonly agreed assumptions on the future development of birth rates, death rates and migration processes to predict the population change until 2030. The internal migration which is not taken into account on the state level of Bavaria is the most important component of the changes in (LfStaD 2012). Missing data in the period 2031 to 2040 is continued by the average of the development in the years 2021 to 2030.

Different to the base model, in which the increase in living space per inhabitant was continued by extrapolation of the development in the years 1990-2008, now the details of the projections for the housing market until 2025 (BBSR 2011) are used. This study projects for so-called planning regions (which include rural districts and cities) considers how the average living space per inhabitant in these regions will change until 2025. In the development of the living space per inhabitant the increased comfort needs of the residents play a significant role. These needs cause a steady increase in the average living space per capita. As in the planning regions both urban and rural districts are considered together, the difference in living space per capita per year is calculated for each planning region for the period 2011 to 2025. Based on the net dwelling area per capita and district in 2010 the future living space per capita is calculated using the development in the corresponding planning region. As this forecast is always an increase of average living space it is assumed that this development will not continue indefinitely. Starting from the year 2026 only half of the expected growth rate due to comfort needs is used.

The sum of areas from the above-mentioned shares is calculated for each district by multiplying the existing population with the comfort change given by the projection of the housing Market until 2025 and adding or subtracting the change of population in the district multiplied by the average living space. If the total quantitative change of living space is positive the appropriate number of buildings will be built based on the building type distribution. If the total quantitative change of the living space change is negative, nothing happens because the building demolition is incorporated by fixed odds. This sum of areas is then for each district allotted to the different newly constructed building types (single-family house, two-family house, apartment building) in the period 2012 until 2040. This is done on the basis of the distribution of the building types erected between 2000 and 2010.

3.4 Final and primary energy demand of buildings

Within the base model the heating energy demand is the target size of the calculation. In order to conduct a validation of the results and to incorporate the increasing proportion of the use of renewable energies in buildings, an extension of the model towards the used heating systems was done. This is a substantial part of the current development for calculating the final and primary energy demand. Unfortunately, the used energy sources for existing buildings are not recorded. The data base for modeling the heating systems of the buildings are therefore the census surveys in 1987 and from then on the annual statistics on housing completions. In this data for each building the kind of energy source and the type of heating is independently collected.

As the technical lifetime of heating systems is short compared with the components of the building envelope, the majority of the plants is assumed to have central heating systems. Corresponding to the available data the single room heating concerns basically the use of firewood, which is already recognized in the recent statistics as an own section. For mapping the heating system each building was appointed with an energy carrier. Buildings built after 1994 can be allocated a heating system using the DIN 4701-10, which gives additional parameters such as solar heating support, heat transfer system and domestic hot water support. With the tables of DIN 4701-10 implemented into the model to determine the plant expenditure figures, it is possible to calculate the primary energy demand of each building using the specific heating demand and the heated living space. For the future development a refinement of the heating systems regarding the technical figures and an increased integration of renewable energy sources is represented.

Regarding the heating systems in existing buildings and the renewal of those plants a significant uncertainty remains. According to the VDI guideline 2067 the average technical lifetime of a heating system is assumed to be 20 years. This can be easily implemented into the model using the stochastic life cycle simulation for individual components. The change of the energy source caused by the renewal of the heating system is currently modeled by uniformly distributed random variables. This is based on own assumptions, because so far there are no sufficiently reliable figures for the mapping of this structural change.

3.5 Mapping of apartment buildings

Another gap in the statistical data is the lack of distinction between small and large multi-family homes built until 1987. Here the census in 1987 made no division into size classes. It is only known how much living space and how many housing units are available in buildings with three or more dwelling units. In building completion statistics used for the construction of buildings between 1988 and 2010 the size of the apartment buildings is, however, stated more precisely. There are size classes with 3, 4-6, 7-12, 13-19 and 20 or more dwelling units. A division of multi-family homes that were built before 1987 on those size classes was made to simplify the algorithm for generating the buildings and the data structure in the program. As in the base model, the distribution according to the project IKARUS (Gülec et al. 1994) was used to determine a percentage distribution of the different building sizes depending on the building age class. To adapt the proportions of different types of multi-family house constructions to different densities, the dependence between the proportion of living space in apartment buildings and the population density is determined and applied in figures 5 and 6.

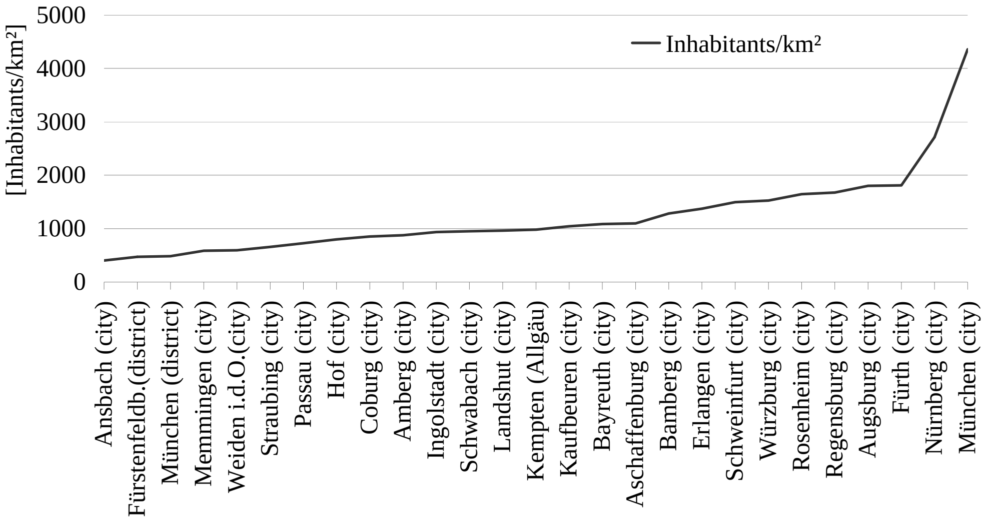

Figure 5: Inhabitants per km² in cities and districts with high density

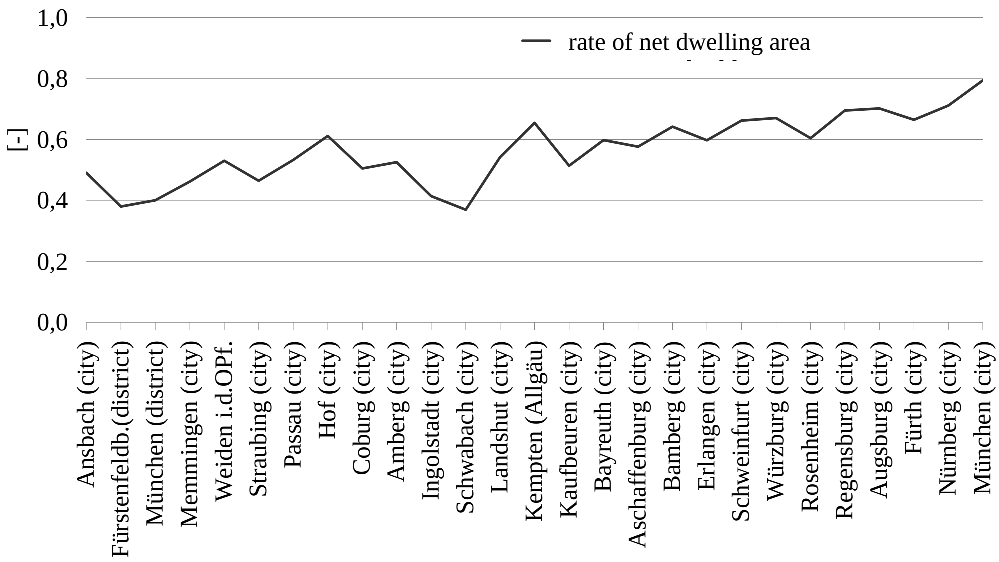

Figure 6: Rate of net dwelling area in apartment buildings in cities and districts with high density

From the illustrations it is evident that for cities up to a population density of about 2000/km² the proportion of the residential living space in apartment buildings increases in the same way as the population density. Large Cities such as Munich and Nuremberg represent a special feature which is indicated by the steep slope of the curve. Depending on the existing population density and the rate of living space in apartment buildings the distribution from (Gülec et al. 1994) will be moved toward an increased rate of large apartment buildings. In cities with population densities above 2000 inhabitants/km² additionally high-rise buildings with up to 250 housing units will be modeled.

4. Conclusion and Preview

For the adaptation of the basic model to an about 100 times larger building stock and the goal of being able to use the simulation to estimate future primary energy demand numerous adjustments were integrated to the model. Significant changes were made to gain the automation of many components. Due to the very heterogeneous existing building stock and the partial existing statistical classification of buildings characteristics the influence of the assumptions on the calculation was reviewed. Although for the modeling of the region-specific building geometries a statistically verified procedure was used, gaps in the typology of buildings were closed by additionally inserted building sizes and different distributions. Regarding the proportion of each type of apartment building constructed before 1987, in the urban areas many changes had to be made to avoid high energy demands due to the underestimation of the rate of low-energy buildings. With the help of the performed analyzes reasonable assumptions and an estimation of expected error sizes can be made for every building type.

The mapping the heating systems was an important part in the extension of the model. For most of the plants the assessment of the losses was made by implementing the standards prescribed in the underlying assets of the heating systems which exist since 1994. Based on life-cycle simulation systems can be changed at defined time-points and the transition to new techniques are observed. With this extension, the calculation of primary energy demand and assessing the reachability of the goals of the federal government is possible.

By simulating several scenarios under varying parameters, the extensive influences of many parameters are identified. Not only one way can be defined to reach the targeted goals, however energy efficiency has to be implemented in every part of the system. By using only the demand side or the supply side to reach the goals, an oversize oft the necessary actions must be expected. The exploding costs for heat insulation as well as the required amount of the solar heat supply can be given as an example. Actually, the required solar heat supply to cover the demand cannot be described. Hence a useful extension of the model is to consider hourly the demand as well as the supply.

Another useful extension of the model which is actually being edited contains the mapping of the implementation of energy policy through the involvement of stakeholders. By varying the incentives, different groups can be activated to increase the refurbishment quota. In order to select appropriate scenarios the integration of an optimization algorithm would be a way of supplementing the deterministic working model which at present is dependent on the chosen presettings.

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