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From the building level energy performance assessment to the national level: How are uncertainties handled in building stock models

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Abstract

A considerable share of greenhouse gas (GHG) emissions is caused by the energy consumption for space heating and cooling in residential buildings. In Germany for instance about one third of the end energy consumption is accounted to space heating and cooling of buildings. Consequently, efforts to increase energy efficiency and substitute non-renewable energy with renewables are high. To explore the technical, economic and social effects of environmental mitigation strategies in order to increase energy efficiency in the building stock various models are used. Many of these models have to deal with the challenges of how to estimate energy demand levels. Derived from the recent development in this field researchers, planners and politicians are increasingly relying on energy models with integrated energy performance rating for environmental policy and strategy evaluation. However, energy assessments suffer from the common barriers of data access and data granularity. Therefore the approaches of energy building stock models comprise a mixture and variety of methods and have limits, which will be addressed in this contribution. The goal is to show how uncertainty is considered in existing models. This contribution provides general overview and key takeaways from the insight into different models and methodologies on the different levels of detail of building stock models.

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Keywords: building stock models; energy modelling; uncertainty; uncertainty management; built environment

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1. Introduction

Many countries aim at pioneering in energy system transition and cutting greenhouse gases emission. In Germany the officially reported end-energy consumption reveals that the building stock is responsible for nearly 38 % of the heating related end-energy consumption [1].

Therefore, the German government strives for a nearly climate neutral residential building stock until 2050 [2]. A few milestones for the building stock development are set, such as increasing energy efficiency by 20% until 2020

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and cutting primary energy demand by 80% by 2050 [1] [2]. However, reaching these goals will not happen without effective plans of action.

In order to develop such plans, systematic and comprehensible approaches are much-needed to show the efficiency and reduction potentials, depict development paths and disclose low hanging performance fruits. Complying with this demand many models for assessing buildings energy demand evolved (see Sections 3 and 5). Furthermore, the private and commercial interest to be informed about buildings' energy demand and consumption is increasing steadily. This is especially observable in an increasing demand and integration of energy related consulting services such as the calculation of performance ratings for assisting tenants and owners of buildings in decision making. Consequently, understanding the energy consumption of buildings is a current field of interest and research. Additionally, this development indicates that the results of models in this field should be easily and quickly comprehensible.

A key element which the models, studies, strategies and services have in common is the energy performance assessment of buildings. Depending on their scope and aim, most of the models have to deal with the challenges of processing data from different sources and on different levels of detail in order to receive informative and valid results. Therefore and in order to minimize the effects of incomplete and uncertain data, combinations of different approaches and techniques are utilised.

An important issue is the quality and conclusiveness of the models' results in supporting and informing end-users[2] who typically are policy or decision makers. Since numerous reviews about the existence of models (see Section 3) have been written, this contribution does not aim at elaborating the current portfolio of building stock models. Instead, it focuses on how shortcomings in building stock models on different scales are dealt with. Particularly, the objective of this paper is to list the various methodologies of how building stock models assess the energy demand resulting from space heating in building stocks and especially on how results are ensured to be plausible. The results of this study are presented in condensed form.

2. Objective and method

The objective of this study is to provide an insight into how a multiplicity of building stock energy models deals with uncertainty in building stock models for energy related assessments. An extensive literature research on building stock models revealed that many models, reviews and much literature exist. The most relevant reviews of building stock models are presented in the next section and Table 1. In this work, an investigation of existing models was conducted and those which considered uncertainty explicitly were selected for further analysis (27 of 72). In this analysis, an uncertainty classification framework was applied on the 27 models. The main focus of this investigation are uncertainties which afflict the models' results and how the modellers deal with different shortcomings. On this account modelling techniques and basic model descriptions are presented only briefly. In the following sections the comparison and analysis framework is set.

3. Overview of reviews of building stock models

Several authors have developed models (Tables 2,3,4) and others have written comprehensive reviews of building stock models for energy system modelling (Table 1). Since these reviews provide extensive insight into different aspects of numerous models, only the most important findings are summarised. Swan & Ugursal [3] and Kavgic et al. [4] addressed fundamental characteristics of building stock models in their reviews. They identified two distinct modelling techniques: bottom-up and top-down modelling. In few words, bottom-up models represent models which are based on building physics (of subsets or individual buildings of a building stock) and top-down models build on economic theory, aggregated and statistical data. Top-down models can be further differentiated into technological or econometric models and bottom-up models into statistical or engineering-based models. Mundaca et al. [5] sub-classify bottom-up models into optimising, simulating, accounting and hybrid models. Several complementing frameworks and classifications can be found in the contributions in Table 1. Despite the body of acquired knowledge

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[1] compared to base year: 2008

[2] Frequently, end-users were not involved in the development of these models.

in the subject area of modelling technique selection for modelling energy systems, there are still many challenges which primarily emerge from data quality and interpretability of the results. Consequently, verification and validation of the models are essential requirements to ensure their functionality. These challenges are addressed here. The remainder of this paper applies a typology framework for uncertainty to the selected models and lists the methods by which the models deal with this challenge.

Table 1. Publications with reviews of building stock models.

Authors and reference	Coverage	Main focus
Bourdic & Salat [6]	11 models	City and district scale models; Classifies models on the basis of a calculation tool typology; Discrimination between agent based, economic, energy environment and morphological
Crawley et al. [7]	20 programs	Building energy performance simulation programs/software
Firth et al. [8]	5 models	English housing stock models; Detailed description of the Community Domestic Energy Model (CDEM)
Huntington & Weyant [9]	16 models	Energy models (Multi-sector)
Kavgic et al. [4]	15 models	Review of bottom-up building stock models; Comparison of five models of the United Kingdom
Keirstead et al. [10]	56 studies	Review of urban energy system models
Kialashaki & Reisel [11]	309 references	Regression models and artificial neural networks for the United States
Mata et al. [12]	17 models	Overview of bottom-up studies which assess energy use in building stocks
Nakata [13]	269 references	Energy-economic models (Multi-sector)
Pfenninger et al. [14]	13 models	Energy systems models

4. Uncertainty

Definitions and classifications of uncertainty are context dependent. Modelling of complex systems lacks unified or shared definitions of uncertainties and respective management methodologies to determine, investigate and handle these. Booth et al. [15] state that uncertainty analysis in building energy modelling has mainly been restricted to the level of individual buildings. Hence, they have to be synthesised for energy related building stock models. In dictionaries[3] uncertainty is defined as ”the state of being uncertain; Not able to be relied on; Not known or definite”. Elsewhere, uncertainty is associated with absence of knowledge, imperfection, accuracy, precision, ambiguity, faultiness, inconsistency, ignorance and other analogical terms. However, tackling and handling of the named does not lend itself to decrease uncertainty [16]. Due to the focus of this study on buildings stock models and energy performance assessment which are commonly utilized for decision support this study uses the analysis framework according to the investigations and frameworks of Walkers et al. [17] and Booth et al. [15]. Both of them provide an overview of definitions of uncertainty for model-based decision support [17] and housing stock models [15].

Walker et al. [17] developed a conceptual uncertainty matrix framework as a tool to classify and report the different dimensions of uncertainty. Their general definition of uncertainty is ” [...]any departure from the unachievable ideal of complete determinism”. Furthermore, they suggest to discriminate between three dimensions of uncertainty:

- The *dimension of location*: Where does uncertainty manifests itself in the model complex?
  According to Walker et al. [17] there are five generic *locations*:
  1. *Context uncertainty* which describes the uncertainty related to model systems’ boundaries. Consequently leading to faultily problem definition or framing.
  2. *Model uncertainty* which comprises two sorts of uncertainty: *model structure uncertainty* (”wrong or incomplete representation”) and *model technical uncertainty*. Model technical uncertainties are associated with the technical implementation of the model in a development/programming environment.
  3. *Inputs uncertainty* which can be caused by the basic input. On the one hand, the so called external *driving forces*, as in scenario variable definition, and on the other *system data*, such as the lack of knowledge of the basic properties.
  4. *Parameters uncertainty* which describes uncertainties in constants like in universal constants, fixed values or

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[3] Example of a reference: Oxford dictionaries

values determined via calibration.
5. *Model outcomes uncertainty* is sometimes called prediction error and evolves from the accumulation of all the uncertainties in the mentioned locations.

- The dimension of the *level of uncertainty* describes the states between determinism and total ignorance.
  Walker et al. [17] suggest five levels of uncertainty with a progressive transition between them. First of all, there is determinism the state of being all knowing. Then, statistical uncertainties are uncertainties which are statistically describable or related to probabilities in the model. Thereafter, scenarios cause scenario uncertainty via setting not verifiable assumptions. Next to last is the recognised ignorance that describes the lack of understanding of fundamental mechanism and functional relationships (can be further divided into reducible and irreducible ignorance). Lastly, total ignorance is the state of not knowing what is unknown.
- The dimension of the *nature of uncertainty* is the distinction between the imperfection of knowledge or *epistemic uncertainty* and *variability uncertainty* due to the inherent variability or randomness.

Booth et al. [15] recognise analogies between conditions in a medical field approach for identifying sources of uncertainty and the building stock, they transfer the approach to building stock models. Based on these analogies, Booth et al. [15] discuss uncertainties in building stock models and suggest a similar typology of uncertainty as Walker et al. [17]. They conclude four sources of uncertainty:

I. *Chance variability* is a source of uncertainty which is analogue to variability uncertainty according to Walker et al. [17].
II. *Heterogeneity* as source of uncertainty describes the uncertainties originating from grouping of characteristics into subsets.
III. *Parameters uncertainty* is described by Booth et al. [15] as analogue to the nature of uncertainty according to Walker et al. [17]. However, they subdivide parameters into theoretically measurable parameters and assumptions, which can be assigned to the dimension of location and level of uncertainty according to Walker et al. [17].
IV. *Ignorance* is the lack of knowledge to model the process and hence in accordance with Walker et al. [17] epistemic and context uncertainty.

Booth et al. [15] are partially in accordance with the concept of Walker et al. [17]. As noticeable, the sources of uncertainty fit into the three dimensions of uncertainty. Hence, both concepts complement one another. Consequently, the frameworks are combinable and transferable to the subject matter of this paper. For the investigation, each of the inspected models are classified according to the dimensions named above. The classifications of the 27 models are summarised in the next sections and in Tables 2, 3, 4.

5. Results

The investigation of how different models account for uncertainty comprises 27 accessible building stock models. Each publication was scanned for how the modellers dealt with uncertainties (see Tables 2, 3, 4). The accessibility of the building stock models is limited and detailed information about the implementation are in many cases lacking or not transparent. This situation made a detailed investigation of the models infeasible. Therefore, the models were not challenged or analysed to disclose uncertainties. Only uncertainties which are acknowledged by the authors/modellers themselves are considered. Accordingly, uncertainties not addressed by the authors/modellers are not considered. The approaches acknowledged for handling uncertainty were then classified according to Walker et al. [17] and Booth et al. [15]. However, it is not always possible to assign them unambiguously to a certain dimension or class due to smooth or blurred transition and interpretation. The results are structured in the following order: At first the results for the single building energy models are presented (Section 5.1 and Table 2), followed by the results of the regional district and city scale models (Section 5.2 and Table 3) and lastly the results for the national level are presented (Section 5.3 and Table 4).

5.1. Individual building energy performance assessment

In this subsection, approaches and models which aid decision makers and users in assessing individual buildings are presented (Table 2). For calculating the energy demand for space heating and cooling standardised energy calculation formulas are commonly used on this individual building level (e.g. in Germany DIN V 4701-10/DIN V4108-6, DIN V 18599, DIN EN ISO 13790, DIN EN 15625). These standardised methods have specific data requirements. Hence, on-site inspection of the respective building are prevalent in order to ensure data availability for these models. Several of the considered models combine optimisation and simulation which encompasses model structure uncertainty. Therefore and despite being based on standards, some of the scanned contributions acknowledge uncertainty at the location of model outcomes uncertainty (by testing model outcomes). This uncertainty forms the accumulated uncertainty and indicates a general error. As summarised in Table 2, the prevalent methodology to deal with this uncertainty is comparative and analytical testing (e.g. [18]) and to conduct empirical studies. For easing data requirements, some models assist assessment through presets, building or building elements archetypes and typologies, which cause uncertainties in the locations of inputs and parameters uncertainties, at the level of statistical uncertainty and at the level of the nature of variability uncertainty.

Table 2. Models for individual building assessment.

Name/Author and reference	Model type	Audience/Scope of application	Country	Acknowledged uncertainty (according to [17])	Uncertainty handling
EnergyPlus [18]	Simulation model	Building energy simulation tool	United States	Model outcomes and model structure	Comparative analysis
Hasan et al. [19]	Optimisation and simulation model	Tool for building designers	Finland	Model outcomes	Comparative analysis
Jin & Overend [20]	Optimisation and simulation model	Whole-life value based facade design and optimisation tool	United Kingdom	Model outcomes	Empirical studies
Kunze [21]	Optimisation and simulation model	Decision support model for owners regarding building retrofit	Germany	Inputs	Sensitivity analysis
Nielsen [22]	Optimisation and simulation model	Early design stage support tool for building design	Denmark	Model outcomes	Comparative analysis
TELKA [23]	Simulation model	Methodology for interactive investigations of the building energy performance	Sweden	Model outcomes	Empirical studies; comparative analysis
Peippo et al. [24]	Optimisation and simulation model	Integration of a non-linear optimisation scheme in building modelling	Finland	Inputs, model outcomes, context	Comparative analysis (outlook: definition of distributions for input parameters and sensitivity analysis)
TRNSYS [25]	Simulation model	Building energy simulation tool	Germany	Model structure and technical model	Comparative analysis

5.2. *District or municipality level building stock energy performance assessment*

District, municipal or city building stock models form the intermediate/local level between individual buildings and the national building stock. These models can comprise individual building blocks with few buildings or entire cites with thousands of buildings. Therefore, the audience of these models are typically urban planners, developers, local policy makers and similar. Most of the models in this field work with simplified thermal simulation engines or are archetype-based. Most of the models considered here are bottom-up simulation models. In the next paragraph one hybrid model [26] is outlined. In Table 3 the classification results of district building stock models with a focus on energy are summarised.

Due to the different models' scopes, system boundaries are set more heterogeneously than in models of individual building models, so that in some cases multi-sector considerations are included and user behaviour is considered (e.g. [27,28]). This handicaps comparative analysis with reference systems and with other models. The prevalent methodology to handle uncertainty is comparative and analytical testing and to conduct empirical studies (cf. Table

3). A current development in district level building stock modelling is the utilisation of geographic information systems and 3-dimensional city models in order to improve system data. This can substantially decrease uncertainty of building stock data and improve model quality. For example, the CityGML development promises individual building level energy performance assessment for entire building stocks (e.g. Nouvel et al. use CityGML models in an hybrid approach [26]). Additionally it promotes developing common standards.

Table 3. Models for district or municipality building stock assessment.

Name/Author and reference	Model type	Audience/Scope of application	Country	Acknowledged uncertainty (according to [17])	Uncertainty handling
CitySim [27,28]	Bottom-up engineering model	Decision support tool for urban energy planners	Switzerland	Inputs (driving force and system data)	Probability modelling (Markov); Empirical studies (outlook)
District-ECA [29]	Bottom-up engineering model	Early planning stages decision support for urban planners, housing companies, developers and local political decision makers	Germany	Model outcomes	Empirical studies; comparative analysis
Heeren et al. [30]	Bottom-up engineering model	Assessment methodology in form of a life cycle-based building stock model	Switzerland	Model outcomes	Comparative analysis and calibration
Mattinen [31]	Bottom-up model	Calculation and visualization approach for energy use and greenhouse gas emissions from residential stock in a case district	Finland	System data	Sensitivity and Monte Carlo analysis
EQ-Tool [32]	Bottom-up model	Excel based tool for calculation of efficiency potentials in the residential building stock and the transportation sector	Germany	System data	Empirical studies (outlook)
Mastrucci et al. [33]	Bottom-up statistical model	A GIS-based statistical downscaling approach for assessing the residential building stock	Netherlands	Model outcomes	Bootstrapping (statistics)

5.3. *National level building stock energy performance assessment*

National level building stock models are the least granular and primarily utilised for environmental policy assessment and greenhouse gas emissions prediction. Additionally, they have simulation time horizons of 30 and more years (e.g. [34,35]). The audience are mainly policy makers. The field of national level building stock modelling is the most heterogeneous regarding modelling approaches and handling uncertainties. Furthermore, the construction of many scenarios in these models is very common. Similar to district and city models they utilise simplified thermal simulation but have extra modules for considering socio-demographic dynamics. In this field a change from rather static models to agent-based models is noticeable and an increase in endogenous computation of many parameters and driving forces can be seen (e.g. [34–36]). Firth et al. [8] state that most UK models ignore the issue of uncertainty. This can also be observed for other models. A justification can be found in the scope of models which simulate very large building stocks (e.g. about 20 million dwellings [34]) where statistical uncertainty and system data is assumed to level out on the national level. In general, modellers focus on scenario and inputs uncertainty such as related to exogenous parameter setting and driving forces. In Table 4 findings from the considered national level models are summarised.

Table 4. Models for national building stock assessment.

Name/Author and reference	Model type	Audience/Scope of application	Country	Acknowledged uncertainty (according to [17])	Uncertainty handling
AWOHM [34]	Bottom-up simulation model	Approach for national level environmental policy design for the residential sector	Germany	Inputs (System data and driving forces), parameters, model outcomes, scenario	Comparative analysis, Monte Carlo simulation, parameter calibration and sensitivity analysis
Aydinalp et al. [37–40]	Bottom-up simulation model	Neural network based energy consumption model for the residential sector	Canada	Model outcomes	Comparative analysis
Bauermann [41,42]	Bottom-up simulation model	Approach for national level environmental policy design for the residential sector	Germany	Inputs (driving forces); model outcomes	Comparative analysis
BEAM^2 [43]	Bottom-up accounting model	Approach for national level environmental policy design for the residential sector	Germany	Model outcomes	Comparative analysis and calibration
CDEM [8]	Bottom-up model	Exploration of potential routes to reduce carbon dioxide (CO2) of the existing English housing stock	Great Britain	Inputs (System data)	Local sensitivity analysis (uncertainty quantification approach)
Charlier & Risch [44]	Bottom-up model	Approach for national level environmental policy design for the residential sector	France	Model outcomes, inputs	Sensitivity analysis
Mata et al. [12]	Bottom-up model	Energy, carbon, and cost assessments of building stocks	Sweden	Model structure and outcomes	Comparative validation and empirical studies
Fung [45]	Bottom-up simulation model	Framework to develop an end-use energy consumption and greenhouse gas emissions model for the Canadian housing stock	Canada	Model outcomes	Sensitivity and comparative analysis
Zhou et al. [46]	Hybrid model	buildings energy model with U.S. state-level representation, nested in an integrated assessment framework of the Global Change Assessment Model (GCAM)	United States	Inputs (System data; driving forces) and model outcomes	Calibration
Henkel [47]	Bottom-up model	Simulation model of the stock development of heating appliances in Germany and the household decision making concerning the heating system	Germany	Model structure, inputs (Driving forces)	Monte carlo simulation
Invert [35,36]	Bottom-up simulation model	Approach for national level environmental policy design for the building sector	Austria and Germany	Inputs, parameters, model outcomes	Calibration, sensitivity, comparative analysis
Kialashaki & Reisel [11]	Bottom-up model	Neutral/artificial networks; Energy-demand models to predict the future energy demand in the residential sector	United States	Model structure	Empirical studies (outlook)
Kost [48]	Bottom-up model	Simulates the development of the building stock including renovation, demolition and construction. Quantifies energy demand for space and water heating and associated CO2 emissions	Switzerland	Model outcomes	Comparative analysis

For validating model outcomes, the prevalent methodologies are comparative analyses. The modellers mostly rely on national energy consumption data for this type of analysis. In order to minimise parameters uncertainties, calibration is the preferred method. In the case of scenario uncertainty, a few studies conduct sensitivity analyses and in AWOHM [34] a Monte Carlo simulation is integrated in the model structure. Furthermore, uncertainty is subject of the discussions of the screened contributions, for example system boundaries are discussed as they particularly frame and weight many interrelations and dependencies (which cause context uncertainties).

6. Conclusion and outlook

In this contribution handling uncertainty in building stock modelling is presented. It is shown that the commonly applied methods are sensitivity analysis, comparative analysis and empirical studies. In some of the reviewed works, models' uncertainty and sensitivity are handled together. Also, the process of model validation is combined with handling uncertainty. Most of these approaches handle uncertainty with aiming at improving model outcomes stability and quality. Sensitivity analyses are typically used to provide an understanding of model behaviour and indicate uncertainties. Based on this analysis, model testing and calibration can be conducted. However, this does solely provides insight in the model outcomes' confidence level and does not decrease uncertainties directly. Empirical studies are often conducted to ensure better understanding and to reduce epistemic uncertainty. Most of the individual models provide a validated core simulation engine (often ensured by standardised testing). Nevertheless, the uncertainty handling while operating the models are commonly allocated to the models' users. District and national models focus more on inputs and outcomes uncertainty. Besides conducting empirical studies, only a few modellers try to reduce uncertainty itself, as e.g. done by Stengel [34]. In the national level model AWOHM by Stengel [34], a Monte Carlo simulation is integrated in order to reduce uncertainty in the compilation of the initial building stock inventory. In AWOHM the initial building stock is derived from detailed micro census data for Germany (2006). By integrating the Monte Carlo simulation the system data uncertainty propagation in the model itself is reduced. Many of the listed models belong to the type of bottom-up engineering models which do not consider the behaviour of building users. Occupants' or users' behaviour has high influence on energy consumption and forms a substantial uncertainty which is not considered comprehensively yet.

Regardless of the various techniques which can be applied for uncertainty handling, empirical studies are the most accentuated one. Almost all screened models stress the importance of access to more detailed and specific data. All models need a great amount of data such as comprehensive and detailed building stock and census data. Generally speaking, most of the bottom-up models (in particular the national models) combine different sources of data which introduces additional uncertainties into the models. The respective effort in aggregating and pre-processing data is high and complex. The same applies to post-processing or validation of the simulation or scenario results. Additionally, many of the datasets are collected for multiple purposes and not for the sole purpose of energy modelling which increases the urge to include a strategy to handle uncertainty when processing these data sets, making assumptions and setting system boundaries and parameters. The huge interest in the field of energy efficiency leads to a more targeted data aggregation and shared databases, as valuable data is increasingly administered and made accessible. This provides additional options to handle uncertainty.

This study gives a condensed overview of uncertainty handling in building stock models. But the assessment is restricted to the modellers contribution due to the limited transparency. In future works, the models could be assessed by evaluating the different uncertainty handling approaches in detail and include additional building stock models.

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