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A component based bottom-up building stock model for comprehensive environmental impact assessment and target control

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ABSTRACT

The building stock is one of the most important energy consumers worldwide. Therefore, a number of energy reduction targets and regulations exist for the construction sector. Different building stock models have been developed in order to investigate the potentials of energy-efficiency and changes in energy source in the building stock. However, these models often have important shortcomings, since they are single-issued and do not include the life cycle of buildings. Thus, we propose an innovative assessment methodology in the form of a life cycle-based building stock model (LC-Build). The building stock is clustered in building cohorts of similar construction and equipment characteristics in terms of type, construction period and building technology systems. The most important building components are assigned specific thermal transmittance values. Figures for diffusion and retrofit rate describe the development of the building stock fabric. Additionally, environmental impact from the energy supply side is taken into account. This approach facilitates the evaluation of the effectiveness of measures and their dynamics on the building stock, such as newer and more efficient technologies and practices related to energy policies and prices. Furthermore, the model has a direct relationship to the construction activity (energy-efficiency measures, substitution of fossil energy based heating systems) and fosters the comprehension of material flows, related environmental impact, and costs. The practicality of this approach is demonstrated by means of a case study in the city of Zurich in Switzerland. The results suggest that Zurich has a remarkable potential to reduce its greenhouse gas emissions from the building sector: 85% by 2050. The case study highlights the advantages of the proposed modeling approach. The LC-Build is a valuable tool to identify and test sustainable energy targets for building stocks, such as the European 20–20–20 target.

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1. Introduction

Worldwide, different visions for the abatement of anthropogenic climate change exist. For instance, the European Union (EU) agreed in 2008 on the so-called 20–20–20 targets [1]. This intermediate-range vision has three target criteria for the year 2020 (20% reduction of greenhouse gas emissions below 1990 levels, 20% share of renewable energies, 20% higher energy efficiency/20% lower primary energy use compared with projected levels). In December 2011, a follow-up road map was published, in which the European Union commits to a reduction of greenhouse gas emissions of 80 to 95% until the year 2050.

The residential building stock is responsible for 36% of total EU27 greenhouse gas emissions and ca. 25% of final energy demand [2,3]. In order to harness the buildings reduction potential, the EU Parliament amended the energy performance of buildings directive (EBPD) in 2010 with regulations postulating 'nearly zero energy buildings' by 2020 [4]. Since the European building stock has a relatively elevated average age and retrofit rates are lengthy, buildings have a considerable average energy demand of approximately 200 kWh/m^2 a for all end-uses [5]. Recent refurbishment projects prove the effectiveness of newly developed technologies and materials in the building sector. A number of reference projects prove the feasibility of reducing space heating demand of old residential buildings by a factor of 10 [6–9]. That corresponds to a reduction in greenhouse gas emission of approximately 75 kg of CO_2-equivalent (CO_2-eq.) per square meter per year [10]. Such figures illustrate that both new and existing buildings hold significant reduction potential.

Governments, building owners and other stakeholders have an interest in knowing the impact of efficiency measures on the building stock. On the one hand for reasons of financial planning, but on the other hand also in order to control their performance in terms of climate change visions, such as the 20–20–20 target. For this purpose, a number of models were developed in recent years. This paper gives an overview and proposes an enhanced approach, called (LC-Build), including additional parameters, compared to existing models.

In this first section, the paper gives an overview of common building stock modeling techniques and their use as an environmental impact and target control tool. Section 2 proposes a new method for building stock modeling by incorporating the life cycle approach, building components and energy supply sector (LC-Build). In Section 3, feasibility is demonstrated by means of a case study. Potentials and limitations of the approach are discussed in Section 4. Finally, conclusions and an outlook on future enhancements are given in Section 5.

1.1. Overview of modeling techniques

Swan and Ugursal [11] and also Kavgic et al. [12] provide valuable reviews of current residential building stock models. Both differentiate between top-down and bottom-up models and discuss shortcomings of each type. Pure top-down models are an interesting option to describe building stocks, especially when data availability is limited. However, these models are practically unable to investigate the impact of specific measures or technologies since they do not explicitly consider a system's constituents [11–13].

Bottom-up models consider individual houses or aggregates of a building stock. Swan and Ugursal [11] differentiate bottom-up models by their use in statistical and engineering models with further subgroups defined for each (cf. Fig. 2 in [11]). The common advantage of engineering bottom-up models over top-down approaches is their ability to model the energy demand of end uses and (new) technologies in detail. The most important disadvantage of non-statistical bottom-up models is the lack of consideration they give to occupant behavior. Recent studies show that occupant behavior and socio-economic factors have an important influence on residential energy demand [14,15]. Statistical bottom-up models try to overcome this limitation by means of regression analysis from recorded data, such as energy bills [11]. However, these models are also less suitable to investigate technological change.

Furthermore, Swan and Ugursal [11] differentiate engineering bottom-up models into 'distribution', 'archetype', and 'sample' types. The archetype approach uses reference buildings clustered according to certain characteristics to describe the building stock. This is especially useful when only aggregated data on the building stock is available.

1.2. Shortcomings of existing stock models

So far, final or useful energy demand is considered as an output parameter in most building stock models, with some models including greenhouse gas emissions as well (cf. Table 2 in [12]). However, energy demand and greenhouse gas emissions for building operation do not provide comprehensive information about the total ecological impact of buildings. In recent years, the methods of life cycle assessment (LCA) and material flow analysis (MFA) have become increasingly popular in the consideration of not only impacts due to operation but also overall environmental impact during the entire life cycle of a product. This is important because considerable parts of environmental impact often take place upstream or downstream of a process. For instance, compared to incandescent light bulbs, energy saving bulbs may consume less electrical energy during their service life. However, their greatest environmental impact might actually take place in the production and especially disposal phase of the product since they contain toxic material such as mercury. Hence, multi-criteria analysis and LCA-based indicators are also increasingly applied in typical energy sciences [16–21]. That approach allows for a broader view on the environmental impact of systems or technologies and construction activity.

Consideration of the entire lifetime of an energy efficiency measure in buildings is necessary to evaluate its factual effectiveness and payback. The reduction in energy demand for building operation represents only part of the environmental and economic impact. Transport, fabrication, fitting, usage and disposal of building components or systems may involve substantial impacts directly or within their upstream or downstream processes. Ramesh et al. [22] show that 10–20% of a building's primary energy use is due to embodied energy. This relative share