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Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock

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ABSTRACT

While many countries have set ambitious targets for reducing energy use and GHG (greenhouse gas) emissions, it remains highly uncertain whether the policies introduced will be suitable to reach these targets at the specified times. Models used to inform building policies often do not account for the different boundary conditions related to socio-economic development, climate, composition and age structure of the existing building stock, and lifetime expectancy, which hinders effective strategy development and realistic target setting. This study presents a dynamic Type-Cohort-Time (TCT) stock-driven modelling approach that considers demographic aspects, lifestyle-related issues, and building-specific characteristics. Case studies were conducted for the dwelling stocks in Germany and the Czech Republic, two countries with different boundary conditions, but that are sheltered under the same European energy-reduction policies and goals. The effects of the policies on nearly zero energy buildings and increased renovation rates were tested. The results showed that current regulations are sufficient to achieve the 20% energy efficiency goal by 2020, but not to reach the 2050 energy and GHG-emission goals. The scenarios further demonstrate that the same policies on renovation and construction in different countries lead to different energy reduction levels. Accordingly, country-specific policies and measures are suggested.

1. Introduction

The buildings sector is crucial for the reduction of overall energy use and climate change mitigation. According to the IPCC [1,2] the operation of the building stock is currently responsible for almost one third of the final energy demand and around one fifth of the greenhouse gas (GHG) emissions worldwide. Baseline scenarios project a doubling of the energy demand and a rise by 50–150% in CO_2 emissions by mid-century in the sector [1]. If already available cost-effective best practices and technologies are broadly diffused final energy use may stay constant or even decline in the same period [2]. Yet, the achievement of significant energy reductions requires a deep and fast transformation of the building stock [2,3] to a zero or even positive energy system.

In the European context, buildings are considered to have the largest energy-saving potential among all sectors [4]. Thus, the promotion of the aforementioned transformation has been led by the European Directives on the Energy Performance of Buildings (EPDB) and on Energy Efficiency (EED), and the Energy Efficiency Plan 2011 [3,5,6]. These policies have decreed (i) the need for increased renovation rates, (ii) minimum energy performance requirements during major buildings' renovation, and (iii) the implementation of all new buildings after 2020 as NZEB (nearly zero-energy buildings).

Through these policies the building sector is expected to significantly contribute to the achievement of the European goals of saving 20% of the Union's primary energy consumption by 2020 compared to projections [4], and of reducing GHG emissions in the residential sector by 88–91% by 2050 with respect to the emission level of 1990 [7].

Consequently, robust building stock models are essential for informing decision makers about the effectiveness of different policies or combinations of policies for (i) realizing current goals, (ii) defining realistic goals, (iii) prioritizing climate change mitigation strategies, and (iv) avoiding misinformation and fragmented actions and policies that lead to weaker results in the long run [8]. The IPCC's fifth assessment report already identified a lack of adequate models in this regard [2,9]. Currently, LCA (life cycle

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assessment), economic input-output LCA, and hybrid LCA are the most widely used approaches for supporting decisions for individual buildings [10]. Nonetheless, these are insufficient to address the gap between targets and expected outcome from policies on national or regional levels.

Models of the energy use of the building stock have to be able to handle the complex and heterogeneous nature of the stock [11,12]. This complexity can be dealt with by decomposing the stock into its essential dimensions. Consequently, models can be characterised by the different dimensions they incorporate along with their driving forces and modelling techniques. Three dimensions are emphasized: (i) building types, (ii) cohorts, and (iii) time. The types and cohorts correspond to the way the building stock is structured (typology). Combinations of these two are commonly described in the literature as archetypes. Both dimensions are important because they are representative of the buildings' construction technology/materials and energy performance. Time refers to the modelling time frame – one or several years – and whether this corresponds to historic, present, or future situation. Models addressing long time periods are of high importance to capture inertia and lock-in effects related to the long lifetime of buildings. Differentiated lifetime across building cohorts and types complements the archetypes.

The model's driving forces and modelling techniques are interrelated. We refer to these as modelling approaches or types of models. These can be classified into three: (i) accounting, (ii) quasi-stationary, and (iii) dynamic. Dynamic models are further divided into (a) input-driven or activity-driven, and (b) stock-driven. Accounting models mainly quantify the stock size and composition, and associated material or energy flows. This type of model is based on reckoning principles and does not intend to analyse the drivers of the stock development and energy use. In contrast, the other two model approaches make use of different drivers to explain the size, composition, and energy consumption of the stock. Quasi-stationary models commonly study the building stock for one single year, while dynamic models analyse multiple years. The activity-driven models generally use construction and demolition rates, mostly based on historic trends, as drivers. The stock-driven models use the service demand/provision concept [13], which relies on time-changing factors like population and preference in size and type of building. Stock-driven models use the buildings' lifetime for explaining and estimating construction and demolition activities. In turn, this type of model requires a longer modelling time-span due to the long lifetime of buildings. The impact of renovation is often captured by the use of renovation rates or renovation cycles.

Table 1 presents a review of existing models and studies for the energy use in the building stock using the discussed classification of dimensions and model approaches. The further to the right and to the bottom a model is positioned in Table 1, the greater its analytical capabilities and the larger the input data requirements. This is more characteristic of bottom-up models since top-down models are normally "accounting models" and commonly aggregate the stock into one type and one cohort. Studies addressing only one type and/or one cohort and/or one year are useful to identify key challenges of specific parts of the stock, but are unsuitable to address long-term challenges and to inform policies and targets of the sector. Most of the current studies concerned with multiple types and multiple cohorts lie within the accounting or activity-driven modelling approaches. The majority of these studies focus on the existing stock while disregarding the role of future buildings.

The presented references either mention the name of the author, the institution, the model, or the project. The "one type" classification refers either to studies addressing one specific type of building or the building stock as a whole (i.e. no type differentiation). One cohort refers to studies analysing buildings built in a specific year or range of years (because similarities in construction technology), or to studies on the total building stock without cohort differentiation. Some of the presented studies could be classified differently because they have components that may lie between two or more modelling approaches. Some studies use the type dimension for the differentiation of household, appliances/technologies, or energy-carriers types instead of building types.

There is a gap of studies that: (i) use stock-driven models; (ii) are multi-type, multi-cohort and multi-year in the approach; and, (iii) evaluate the energy demand of not only the existing but also the future buildings. Only one study, carried out by Pauliuk et al. [63], was found to be positioned at this methodological level. Although there are a growing number of studies of the building stock using multidimensional stock-driven models, these have focused on topics other than energy. Most of them are concerned with stock development (stock size, stock change, construction and demolition) and/or materials [13,64–70].

Here, we present a *dynamic stock-driven type-cohort-time* (TCT) approach based on MFA principles that aims to fill this research gap. Two case studies on the residential building stocks of Germany and the Czech Republic were developed. The effects of a successful implementation of the European policies on NZEB by 2020 and increased renovation rates were tested and compared with national and European energy targets. The TCT approach was also used to identify priority areas for mitigation actions in different specific parts of the stocks.

The choice of the countries was based on: (i) the past and expected future socio-economic differences between them; (ii) the data availability for the composition and energy performance of the existing stock; and, (iii) the relevance of the dwellings in the national buildings stock and energy consumption.

2. Method

2.1. System definition

The system describes floor-area development and energy use of the dwelling stock (see Fig. 1). The dwelling stock was differentiated using the types and cohort groups reported by the European projects TABULA and EPISCOPE [26], in accordance to the "European unified building typology". Single-Family Houses (SFH), Terraced Houses (TH), Multi-Family Houses (MFH), and Apartment Blocks (AB) were the four dwelling types studied.

Living area, according to national definitions, was the used reference floor-area. Energy use includes the theoretical delivered energy for space heating and hot water during the dwellings' use phase. The energy definition follows the EN ISO 13790 standard [71], and excludes energy for appliances. Issues related to primary and final energy, losses in transmission, energy carriers, user-related energy consumption behaviour, and GHG emissions are beyond the scope of the study.

2.2. Model description

A dynamic stock-driven model (see Fig. 1) was developed for tracking flows of floor area and energy through all type-cohort fractions of the stock. Floor-area stocks and flows were studied for the period 1800–2100. Energy was studied for the period 2010–2100. The 301-years modelling time frame allotted sufficient time-step calculations to account for the stock's slow change in composition due to the long lifetime of buildings. The last year, 2100, corresponds to the current last year in the climate change discourse [1].

The model builds on Müller's [13] dynamic MFA-model and following applications. Six different output variables are generated: