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Explaining the historical energy use in dwelling stocks with a segmented dynamic model: Case study of Norway 1960–2015

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ABSTRACT

A segmented dynamic dwelling stock model is proven useful for understanding the development and changes of ageing building stocks, which is highly relevant for renovation measures and estimates of energy use and emissions in aggregated building stocks. In this paper, such a model is developed further for detailed analyses of dwelling stock energy demand and exemplified for the Norwegian dwelling stock 1960–2015. The dwelling stock model simulates the development in stock size and composition and is combined with archetype-specific energy intensities to estimate the total energy demand. After calibrating the model results with statistics, the model is used to explore the phenomena and causes of historical changes. A large-scale improvement of the energy efficiency of the Norwegian dwelling stock has taken place through renovation and construction of new dwellings. A historical shift to more efficient energy carriers and heating systems has had an effect on energy savings in the system, of the same size as the effect of the improved energy efficiency of the stock. However, the total average energy savings per m^2 are offset by changes in user heating habits. A significant decrease in average delivered energy intensity per m^2 is only observed after the introduction of heat pumps.

1. Introduction

The building sector is important for future mitigation of greenhouse gas (GHG) emissions [1], as buildings are responsible for about 40% of the energy consumption in the EU [2]. To quantify the energy saving potential of the stock and to ensure that any potential savings will be obtained, energy analyses, scenario models, road maps and action plans are important policy tools.

A range of models investigate and analyse energy use in building stocks [3–6]. Such analyses are based on models for the development of the dwelling stock in terms of the number of dwellings, and their characteristics (type, age, size and technical standard). The modelled dwelling stock size is subsequently multiplied with the average energy intensity per square meter to find the total energy demand. This means that good estimates for the total energy demand depend on detailed and reliable models, for both the stock and the average energy demand.

A detailed overview of existing models is presented in Vásquez et al. [7]. The energy analyses used to model future energy consumption of specific building types are commonly very detailed and well grounded (e.g. [3–6,8]). However, traditional stock models applied for scenario modelling and forecasting of energy use of dwelling stocks often use linear or simplified assumptions regarding how construction, demolition and renovation activities change over time. By combining basic linear assumptions for the stock development with a detailed energy analysis, the reliability of the final results will be limited by the simplifications of the stock model. The uncertainty of the input parameters in dwelling stock models and their effect on the final results of the energy analysis are rarely discussed. To achieve reliable and valid results from a building stock energy model, a proper dwelling stock model should be combined with a detailed energy analysis.

In contrast to traditional dwelling stock models, which are often based on accounting (e.g. [9–12]), dynamic dwelling stock models aim at describing the development in dwelling stock size and composition by use of mass-balance time-consistent calculation principles. Construction, demolition and renovation activities are based on the underlying drivers and parameters in the system; the population's demand for dwellings and the aging of dwellings leading to need for renovation and finally demolition [13]. Vásquez

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et al. [7] found that the dynamics of a dwelling stock system is of large importance for the recommended future strategies for energy savings in the dwelling stocks.

Sandberg et al. [14,15] made a first attempt at making energy scenarios for dwelling stocks by using a dynamic dwelling stock model for Norway. Their results clearly showed that the simplifications in the linear models commonly used for dwelling stock development had large implications on the resulting energy demand in the dwelling stock and on potential energy reductions. However, these studies also revealed a need for combining more detailed energy analyses with dynamic dwelling stock modeling. The dynamic dwelling stock model that had been developed through a range of publications [13–18] had until then examined the development of a total dwelling stock, regardless of the stock composition of different dwelling types.

To improve the quality of the energy analysis, more detailed information about the dwelling stock composition was required. Based on the same principles, Sandberg et al. [19] developed a segmented dynamic model that allowed for segmentation of the dwelling stock in dwelling types and construction periods (cohorts). Renovation activity was modeled within the model, as in Sartori et al. [17], attempting to estimate the need for maintenance and upgrading of previous construction. The renovation rate was thus a result from the model rather than an input to it. One of the main findings in Sandberg et al. [19] was that the renovation rates (share of the stock to be renovated per year) commonly assumed in traditional scenario models and action plans are far above what can be expected based on the "natural" need for renovation of dwellings due to aging processes in the building stock. This finding was shown to be robust in a thorough scenario analysis [20].

The methodology and algorithm of the dynamic dwelling stock model is explained in detail in Sartori et al. [21] and later applied in a comparative study for 11 European countries in Sandberg et al. [22] (both in this issue). The simulated future renovation rates towards 2050 in the 11 countries are in the range 0.6-1.6%, and thus never as high as the levels 2.5-3% that other studies commonly assume to be possible and necessary for reaching mitigation goals [3,6,23].

Models for assessing the energy demand in dwelling stocks commonly cover a specific year or potential future development [3,11,24–28]. However, to evaluate the reliability and applicability of the model, it should also be calibrated against historical development. Further, historical models can be used to understand what has been the important factors for the historical development, which is interesting in itself and important for describing possible future development paths. To the knowledge of the authors, this is rarely done in literature. One exception is Nässen and Holmberg's study on the historical improvement of the Swedish dwelling stock resulting from renovation and new construction [29]. They found that the calculated energy demand per m^2 in buildings with one or two dwellings was reduced by 11% between 1975 and 2000. 41% of this reduction could be attributed to new construction, and 59% to improvements of the existing stock. Changes in user behaviour was not taken into consideration.

Substantial changes have taken place in the Norwegian dwelling stock system during the period since 1960: strong population growth, changing energy standard of the dwellings through renovation and construction, changing energy mix, heating systems and outdoor climate, as well as changes in lifestyle and user behavior.

In this paper, the segmented dynamic stock model from Sandberg et al. [19] is developed further for detailed analyses of dwelling stock energy demand. The model is exemplified for a case study on the historical development in Norway since 1960. The applicability of the dwelling stock model for energy analyses is explored through calibration of the model results against recorded historical data. Through a scenario analysis, the importance of different causes of the historical changes on energy demand is examined. Finally, we explore what the situation would have been, if some of the important changes in the system had not taken place. These phenomena are rarely reported and documented in literature; therefore this study provides new insight both methodologically and empirically.

2. Methods

2.1. Analytical methods

The model is conceptually outlined in Fig. 1, which shows how different variables are related to each other. Further details of these relationships are not included, as this would make the figure too complex. The main principles of the model are explained below, and a more detailed description of the model and its mathematical frameworks is presented in Appendix B (Supplementary material).

The model consists of two parts; the first part is the building stock model and the second is the building stock energy model. The core of the building stock model is the population's demand for dwellings, *SD*, and the distribution of the stock over various dwelling stock segments, SD_s. A segment is defined by the dwelling type and construction period (cohort), e.g. Single Family Houses from the 1970s. The demand for dwellings is estimated for each year, based on the development in the underlying drivers in the system: population size, *P*, number of persons per dwelling, P_D, and share of dwellings being of each dwelling type, *W*.

Demolition activity in a certain year is estimated by applying a demolition probability function on construction activity from all previous years. Construction activity is estimated using mass-balance consistent calculation principles; i.e. what needs to be constructed to replace demolished buildings and to meet stock changes according to changing demand. No other additions or subtractions to the building stock than new construction and demolition (e.g. change of function) are included in the model.

While demolition of a dwelling can happen only once, renovation can happen several times during a building's lifetime. The renovation activity in a certain year, D_{ren}, is estimated by applying a renovation probability function to the construction from all previous years. The model allows for cyclic repetitions of this function, described by the renovation cycle, R_C, which represents the average time span between renovations of a certain dwelling. The cyclic renovation probability function is linked to the lifetime probability function, preventing a dwelling from being demolished shortly after going through renovation. The definition of the renovation activity is case-specific and the related renovation cycle describes the average time span between renovations of the defined type. The renovation activity is independent of the mass balance and does not affect the dwelling stock size or its distribution to segments.

The number of dwellings demolished, D_{dem}, constructed, D_{new}, and renovated, D_{ren}, each year are outputs from the model, and hence also the demolition, construction and renovation rates.

This model differs from previous versions by distributing the segments to archetypes according to their renovation state, e.g. Single Family Houses from the 1970s being in their original state without significant energy-renovation improvements. $SD_{s,r}$ is the archetype defined by segment, *s*, and renovation period, *r*. The actual energy performance of each archetype – of new construction and of dwellings that go through renovation during different time periods – is scenario specific. This means that the distribution to renovation periods does not determine the energy standard of the dwellings.

In the building stock energy model, average floor area per segment and archetype specific energy need intensities are applied to the number of dwellings per segment to obtain the energy need per segment. Finally, the heat pump contribution, delivered energy