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Using a segmented dynamic dwelling stock model for scenario analysis of future energy demand: The dwelling stock of Norway 2016–2050

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ABSTRACT

The housing sector is important for future energy savings and greenhouse gas emission mitigation. A dynamic, stock-driven and segmented dwelling stock model is applied for dwelling stock energy analyses. Renovation activity is estimated as the need for renovation during the ageing process of the stock, in contrast to exogenously defined and often unrealistic renovation rates applied in other models. The case study of Norway 2016–2050 shows that despite stock growth, the total theoretical estimated delivered energy is expected to decrease from 2016 to 2050 by 23% (baseline) and 52% (most optimistic scenario). A large share of the energy-efficiency potential of the stock is already realized through standard renovation. The potential for further reductions through more advanced and/or more frequent renovation, compared to current practice, is surprisingly limited. However, extensive use of heat pumps and photovoltaics will give large additional future energy savings. Finally, user behaviour is highly important. A strong future rebound effect is expected as the dwelling stock becomes more energy efficient. The estimated total 'real' energy demand is expected to decrease by only 1% (baseline) and 36% (most optimistic scenario). Hence, reaching significant future energy and emission reductions in the Norwegian dwelling stock system will be challenging.

1. Introduction

1.1. Background and context

Residential buildings are responsible for 24% of the global final energy consumption and the building sector is important for future mitigation of greenhouse gas (GHG) emissions [1,2]. Energy analyses and scenario models are important tools for quantifying the energy saving potentials of the stock, and political road maps and action plans should be used to ensure that as much as possible of the potential savings will be obtained. Scenario analysis of future building energy demand can reveal discrepancies, uncertainties and priority areas of improvements, as well as highlight the need for improved data collection [3].

To facilitate the implementation of successful climate-change mitigation policies, it is crucial to better understand the dynamic and complex nature of the future building stock energy system. The energy demand of a dwelling stock depends on (i) the size and composition of the stock, (ii) the energy-efficiency state of the buildings, (iii) outdoor climate, (iv) the energy mix and efficiencies of the energy distribution and conversion technologies, (v) the use of local energy sources and (vi) the user behaviour. All these factors will change over time, and the temporal changes must be examined in scenario analyses. To understand the influences of the long-term transformation of a dwelling stock, there is also a need to quantify and analyse the robustness of key data, from retrofitting rates to total stock energy effects, as well as the associated assumptions [4].

1.2. Dwelling stock energy models applied in literature

Building stock energy models are commonly classified as either 'top-down' or 'bottom-up'. However, a more refined classification system is required to better understand the qualities and applicabil-

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ity of the models. A detailed review of existing models is presented in Vasquez et al. [5], and classified by modelling dimensions and approaches according to material flow analysis (MFA).

Accounting models mainly quantify stock size and composition, and associated material or energy flows (e.g. [6–8]). This type of models is based on accounting principles and does not intend to analyse the drivers of stock development and energy use. Quasi-stationary and dynamic modelling 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 (e.g. [9–11]). Dynamic building stock energy models analyse changes over multiple years. As in Vasquez et al. [5], we classify dynamic models as either (a) input- or activity-driven, or (b) stock-driven. Dwelling stock energy models using dynamic models are presented in Table 1, where they are classified by the modelling dimensions and approaches.

Activity-driven models generally use construction and demolition rates as drivers. The activity-driven dynamic models presented in Table 1 mostly apply construction and demolition rates that are based on recent trends, whereas the energy analysis is often conducted in high detail. However, the realism of the applied rates or the resulting simulated future evolution of the stock is not discussed in these papers. Furthermore, several studies show that the results of building stock energy scenario analyses are highly dependent on the applied renovation rate. This rate is often based on exogenously defined assumptions with little evaluation of the actual realism of the applied rate. These studies commonly conclude on large possible energy savings through energy efficient new construction and renovation. However, implied in this is renovation rates increasing rapidly to levels of e.g. 2.3–3% by 2030, and the likelihood of this really happening is rarely discussed.

Stock-driven models use the service demand/provision concept introduced to dwelling stock modelling by Müller [34]. This concept relies on time-changing factors like population and lifestyle. Mass-balance principles are used to model construction activity, so that new construction satisfies changes in demand and accounts for demolished buildings. Demolition activity is modelled either by use of a fixed demolition rate [28,30,32], a leaching model [31], or a demolition probability function [5,27,29,33].

The stock-driven energy models presented in Table 1 are stock driven as the turnover of the stock is estimated based on the changing dwelling stock demand. However, the renovation activity is mostly modelled by use of exogenously defined renovation rates. In fact, the models are therefore hybrid models as the construction and demolition activity are estimated using the stock-driven model, while the renovation activity is activity based. The only exception is our previous study [33] where renovation activity is estimated by use of a renovation probability function.

In their stock-driven model describing the long-term dynamics of the Norwegian dwelling stock, Sartori et al. [35] make the first use of renovation probability functions. The renovation activity is then also estimated internally in the model, according to the stock-driven modelling principles. This makes it possible to estimate the 'natural' need for renovation, resulting from the ageing process of the stock.

The model from Sartori et al. [35] was further developed in Sandberg et al. [36], where the dwelling stock is segmented in dwelling types and construction periods (cohorts). The distribution of the stock to segments makes it possible to keep track of how the stock's composition is changing over time. Modelling the renovation activity by use of a probability function allows using realistic estimates for the renovation activity, according to the best available information. The simulated energy refurbishment frequency therefore follows the 'natural' renovation activity in the system, based on the best available information. This segmented and entirely dynamic dwelling stock model can be applied for detailed analyses of how a dwelling stock's energy demand is changing over time. The segmentation of the stock and the internal modelling of renovation activity together makes it possible to apply energy intensities defined for each dwelling type, cohort and renovation state combination. This can be used to describe in detail, inside the model, how the energy demand of the stock is changing over time. This is an important difference from our first and simplified energy analyses carried out in Sandberg et al. [27] and Sandberg and Brattebø [29].

The segmented dynamic dwelling stock model was first applied for energy analyses in our study of the historical development (1960–2015) of the energy demand in the Norwegian dwelling stock in Sandberg et al. [33]. There, the dwelling stock model is combined with segment-specific energy intensities from a Norwegian residential building typology database developed in the IEE-EPISCOPE project [37]. Five important factors are found to have influenced the aggregated historical energy demand in the stock. Energy-efficiency improvements in the building envelopes, through new construction and renovation activity are – as expected – found to significantly slow down the growth in total energy use over the period. More surprisingly, the effects of changing energy mix and improved heating system efficiencies are in the same order of magnitude as the effects of improvements in the building envelopes. Further, increasing outdoor temperatures over the period has reduced the energy demand significantly compared to a hypothetic situation with constant climate. Changes in user behaviour have, however, led to much higher energy demand than the unchanged 1960 behaviour would suggest. This includes both changing heating habits as larger shares of the houses are heated to higher temperatures, and a doubling in the electric load per dwelling during the period under study.

1.3. Hypothesis and research questions

The main lessons learned from the historical analysis are that the Norwegian dwelling stock energy use system went through significant and important changes over the past decades, as described above, and that a dynamic segmented bottom-up model is necessary to examine the cause-effect relationships in this development. The model should therefore also be used for scenario analysis of future likely development. The novelty of this dwelling stock energy model is the use of a dynamic, multi-type and multi-cohort stock-driven model, where annual renovation activity, in addition to annual construction and demolition activity, is estimated within the model as a function of the changing stock size and composition. To our knowledge, no existing forecasting models have applied such a stock-driven and mass-balance based dynamic methodology for energy analyses of dwelling stocks.

The present study is a follow-up to our historical analysis [33] and uses the same methodology for energy analyses for the future Norwegian dwelling stock towards 2050. Our hypothesis is that by introducing currently available technology in refurbished and new buildings, it will be possible to reduce the energy demand in the Norwegian dwelling stock by some 50% by 2050, despite strong stock growth.

Main research questions are

i) How is the Norwegian dwelling stock expected to evolve in terms of size, composition of building type-age segments and energy efficiency standard as a result of future renovation, new built and demolition activities?
ii) What are the potentials for energy savings in the system?
iii) What is the relative and combined importance of different phenomena: a) improved energy efficiency of the stock due to more