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Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU

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A B S T R A C T

A dynamic building stock model is applied to simulate the development of dwelling stocks in 11 European countries, over half of all European dwellings, between 1900 and 2050. The model uses time series of population and number of persons per dwelling, as well as demolition and renovation probability functions that have been derived for each country. The model performs well at simulating the long-term changes in dwelling stock composition and expected annual renovation activities. Despite differences in data collection and reporting, the modelled future trends for construction, demolition and renovation activities lead to similar patterns emerging in all countries. The model estimates future renovation activity due to the stock's need for maintenance as a result of ageing. The simulations show only minor future increases in the renovation rates across all 11 countries to between 0.6–1.6%, falling short of the 2.5–3.0% renovation rates that are assumed in many decarbonisation scenarios. Despite this, 78% of all dwellings could benefit from energy efficiency measures by 2050, either as they are constructed (31%) or undergo deep renovation (47%). However, as no more than one deep renovation cycle is likely on this timeframe, it is crucial to install the most energy efficient measures available at these opportunities.

1. Introduction

Delivering energy efficiency improvements in the building stock is central to published city and national plans to achieve carbon reduction targets across Europe [1,2]. According to a recent EU-JRC report [3], energy renovation is instrumental for reaching the EU2020 goals i.e. reduce GHG by 20%, have 20% of energy from renewables and increase in energy efficiency by 20%. This calls for a common EU renovation plan with a regional approach prioritizing less developed regions. In the EU, feasibility studies, national roadmaps and action plans for energy savings in building stocks commonly assume a significant increase in the renovation rates in order to obtain future energy savings, but the likeliness of reaching these increased rates is rarely evaluated or discussed [4–9].

Understanding and influencing the existing and future dwelling stock is of vital importance as there are significant lock-in risks associated with the long lifespans of buildings and infrastructures

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[10,11]. Consequently, the majority of today's dwellings will still exist in 2050 and beyond [12]. If stringent regulations are not introduced universally and high-standard energy retrofits are assured when buildings are renovated, energy use and corresponding GHG emissions could be 'locked-in' for many decades to come. This lock-in is estimated to lead to a 33% increase in global energy use for buildings by 2050 instead of a decrease of 46% if changes are made [13].

Dwelling stocks were constructed over various periods (cohorts) and segments of the stock to be prioritized for renovation should be identified [14]. Housing stocks are exposed to refurbishment activities during the ageing process, and renovation in the coming decades to a large extent depends on the age composition of the stock and the previous renovation activity.

Throughout Europe, national approaches for the monitoring of the building stock have evolved separately [15]. Information about the progress of the energy performance renovation is required to track the progress of policy implementation. Better information and data are needed to help develop roadmaps in order to achieve more energy efficient buildings [4]. To address the shortcomings and challenges identified there is a need for a new methodology that can be used for consistent and scalable analysis of building stock across multiple countries.

Energy analyses of dwelling stocks are defined by a stock model and an energy model. The stock model describes the development of the stock in terms of size, composition and renovation state, whereas the energy model includes average energy intensities of the various segments of the stock, and assumed savings obtained when dwellings are renovated. Standard linear dwelling stock models commonly assume fixed rates for construction, demolition and renovation activities [16–18] whereas in reality these rates are dynamic, both in the short and long term, and depend upon external drivers as well as the type and age composition of the building stock. The nature of housing supply and the impacts of demands and housing supply is elastic, but an increase in demand in the long term is expected as a result when population increases [19].

In the literature, there are various models and tools to assess energy consumption in dwelling stocks. Kavgic et al. [20] differentiated between top-down and bottom-up approach in stock-level energy consumption modelling. They highlighted the importance of transparency and quantification of inherent uncertainties within any stock model. A range of bottom-up models are used for material, energy or carbon analyses of dwelling stocks, e.g. [21–25]. Meijier et al. [24] also identified serious gaps in the monitoring of the physical residential stock, noting that none of the countries monitored the renovation effects on the housing stock. In material, energy or carbon analyses of building stocks there is often a lack of data on the models' inputs and outputs, as well as the algorithms used that make the reproduction of the results difficult [20,24]. Developing scenarios of future dwelling stock energy demands can unearth such discrepancies, uncertainties, and areas of improvements as well as highlighting the need of more robust data collection [26]. There is a need to quantify and analyze the robustness of key data from retrofitting rates to total stock and its associated assumptions in order to understand the influences of the long-term transformation of the dwelling stock [27].

There is a lack of dwelling stock models that describe the development of the stocks in a good way, and it becomes clear that there is an urgent need to get a more detailed understanding of the long-term dynamic of the dwelling stocks to be able to evaluate the future energy reduction potential. This will lead to a deeper understanding of the dynamics that drive the activities in the system and should be a precondition for a more consistent way to address evolutions of the existing and future building stock and its energy demand. This should also support the previous request for the definition on future practice for the dwelling stock [28].

A dynamic dwelling stock model has been developed through a range of publications and is used to study the long-term development in dwelling stock size and composition with various applications [29–41]. The core of the model is the population's need to reside and the main input parameters are the drivers in the system, the population and the number of persons per dwelling. The construction, demolition and renovation activity in the system are outputs from the model, aiming at describing the dynamics of the stock resulting from the changing demand and ageing of the stock.

A separate paper explored the sensitivity in model results and conclusions to changes in input parameters. For the case of Norway, they concluded that the most sensitive input parameters population and lifetime of dwellings are also the input parameters of highest uncertainty. However, even when changing these input parameters to extreme and unrealistic values, the main conclusions regarding future renovation rates remained unchanged. The model results and conclusions for the case study of Norway were robust to changes in the input parameters. Renovation rates at levels necessary to achieve polity targets in energy and emission savings seemed unrealistic to be achieved when modelling the "natural" need for renovation [38].

The dynamic dwelling stock model is general, though the version focussing on renovation so far has been applied only to Norway [31,37,40]. In the present paper, we apply the same method to analyze the construction, demolition and renovations activities in the dwelling stocks of 11 European countries using consistent definitions and data for all countries, to evaluate how the model fits to other countries and if general conclusions can be made across a range of European countries. The model and algorithm presented in Sartori et al. [40] are applied to Cyprus, Czech Republic, France, Germany, Great Britain, Greece, Hungary, the Netherlands, Norway, Serbia and Slovenia. For each country the housing stock is modelled with respect to its past evolution and with projections towards 2050.

The key research questions to be addressed are:

- How well does the model represent the long-term historical development in the dwelling stocks of the given European countries?
- What are the differences between the countries in data availability, feasibility of the model, quality of the results and national conclusions to be drawn from the results?
- What general trends are observed and what general conclusions can be made from the comparative analysis of the results from the different countries?
- What is the potential for future development in energy-related renovation of the dwelling stocks in the given European countries and to what extent are these findings in line with the recommendations from Saheb et al. [3] or the assumed renovation rates in traditional scenario models, national roadmaps and action plans [4,6]?

2. Methods

2.1. Overview of the dynamic dwelling stock model

A full description of the model, including the underlying equations and justification, is provided by Sartori et al. [40]. The key principles and model steps are now summarized to enable understanding of the analysis presented in this paper, while the model equations are presented in Appendix A.

The dynamic dwelling stock model describes the long-term development of the size and age composition of the dwelling stock in a country or region. The conceptual framework of the model is presented in Fig. 1. The core model driver is the population's need