

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



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ABSTRACT

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.

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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 likelihood 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. Kavgić 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]. Meijer 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 policy 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

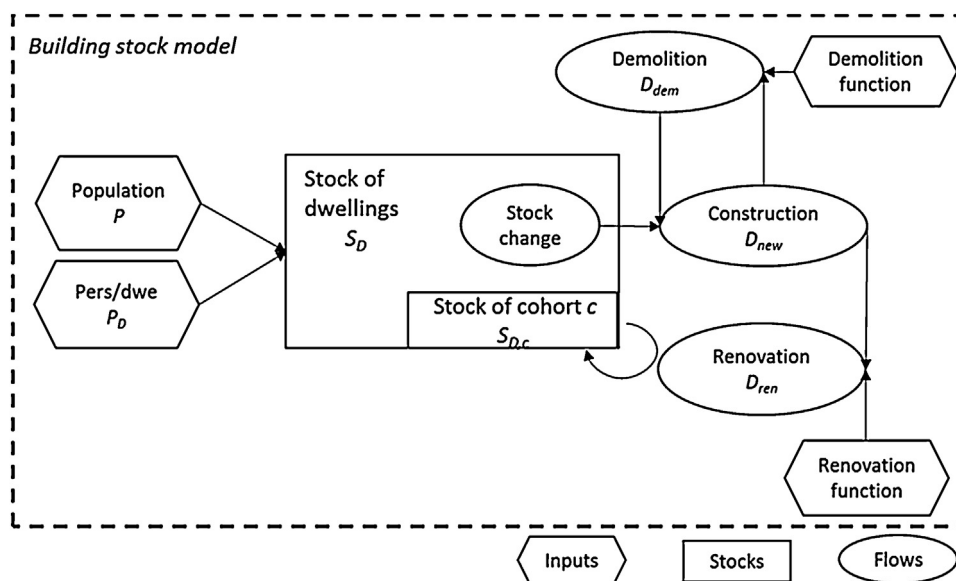


Fig. 1. Conceptual framework of the model.

to reside. Annual demand for dwellings S_D is estimated as the population P divided by the average number of persons per dwelling P_D . The total number of demolished dwellings D_{dem} is estimated each year by applying a demolition probability function on the construction from all previous years. A defined share of the construction from each year is assumed never to be demolished to preserve the national building heritage. Mass balance principles are used to estimate the construction activity D_{new} in year i , that is equal to the sum of new dwellings that are needed in order to replace the demolished ones and meet the change in demand from year $i-1$ to year i .

Finally, renovation activity D_{ren} in year i is estimated by applying a renovation probability function to the construction from all previous years. The model allows for cyclic repetitions of the renovation probability function, described by the average time between renovations of a certain dwelling, R_C . The cyclic renovation probability function is linked to the lifetime probability function, preventing a dwelling to be demolished shortly after being renovated. The definition of the renovation activity is case-specific and the related renovation cycle should describe the average time between renovations of the defined type.

The model results are the yearly demand for dwellings S_D , construction activity D_{new} , demolition activity D_{dem} and renovation activity D_{ren} , as shown in Fig. 1. Model results are segmented in cohorts (construction periods c) to visualize the stock composition of different cohorts as well as to understand the extent to which different cohorts are exposed to demolition or renovation activity.

2.2. Input data and assumptions

The input data used in this study are summarized in this section. Detailed information about the data sources, assumptions and data processing for each country is presented in Appendix B.

In some of the countries included in the study, the geographical area belonging to the country has changed over time. When this is the case, input data referring to the current territory of the country are collected or estimated by rescaling data from other time periods or from a geographical area not completely corresponding to the current territory of the country. Historical data on number of persons per dwelling is sometimes only available for parts of the territory or a larger area, and this is then assumed to be representative for the geographical area currently belonging to the

country. When relevant, this is explained in detail for each country in Appendix B.

Short-term variations in the input time series population P and persons per dwelling P_D result in fluctuations in the model results. This can give the impression that the model captures short-term processes. To avoid this noise in the results, non-linear regression is applied to the raw data to make smooth input curves for population P and persons per dwelling P_D .

2.2.1. Population

Population statistics, projections and some additional assumptions are used to create the smooth input curves for the population. The details of the data availability and data processing for each country are presented in Appendix B. The availability of population data is good in all countries, mainly sourced from census data and population projections from national statistics offices. In some countries, however, like the Czech Republic and Serbia, it is difficult to fit a smooth curve to the raw data due to periods of rapid changes in the population. In the Czech Republic the strong increase in the population in the early 1900s and the subsequent decrease during and after World War II are not well reflected in the smoothed curve. In the case of Serbia the smoothed curve differs notably from the raw data in the recent past and the future.

The smooth population curves are presented in Fig. 2. The non-linear regression function with the best fit was chosen for each country. In countries with a steadily increasing population, a Sigmoidal regression is used. A Gaussian regression is used in the countries where the population has increased followed by a period of (expected future) decrease. The R^2 value of the non-linear regression was larger than 0.95 for all countries. Model projections are most sensitive to the recent past rates of change. For all countries except Cyprus, Czech Republic and Serbia the smooth regression curve shows a very good fit with the raw data for this critical period. For these three exceptions, the poorer fit is considered when analyzing the results.

2.2.2. Persons per dwelling

Historical persons per dwelling data are available from censuses since about 1900 in most of the countries, in Great Britain and Norway since 1800 and in France, Germany and Serbia since about 1950. Future development in P_D is based on assumptions and continuation of trends for each country. When full time series are not

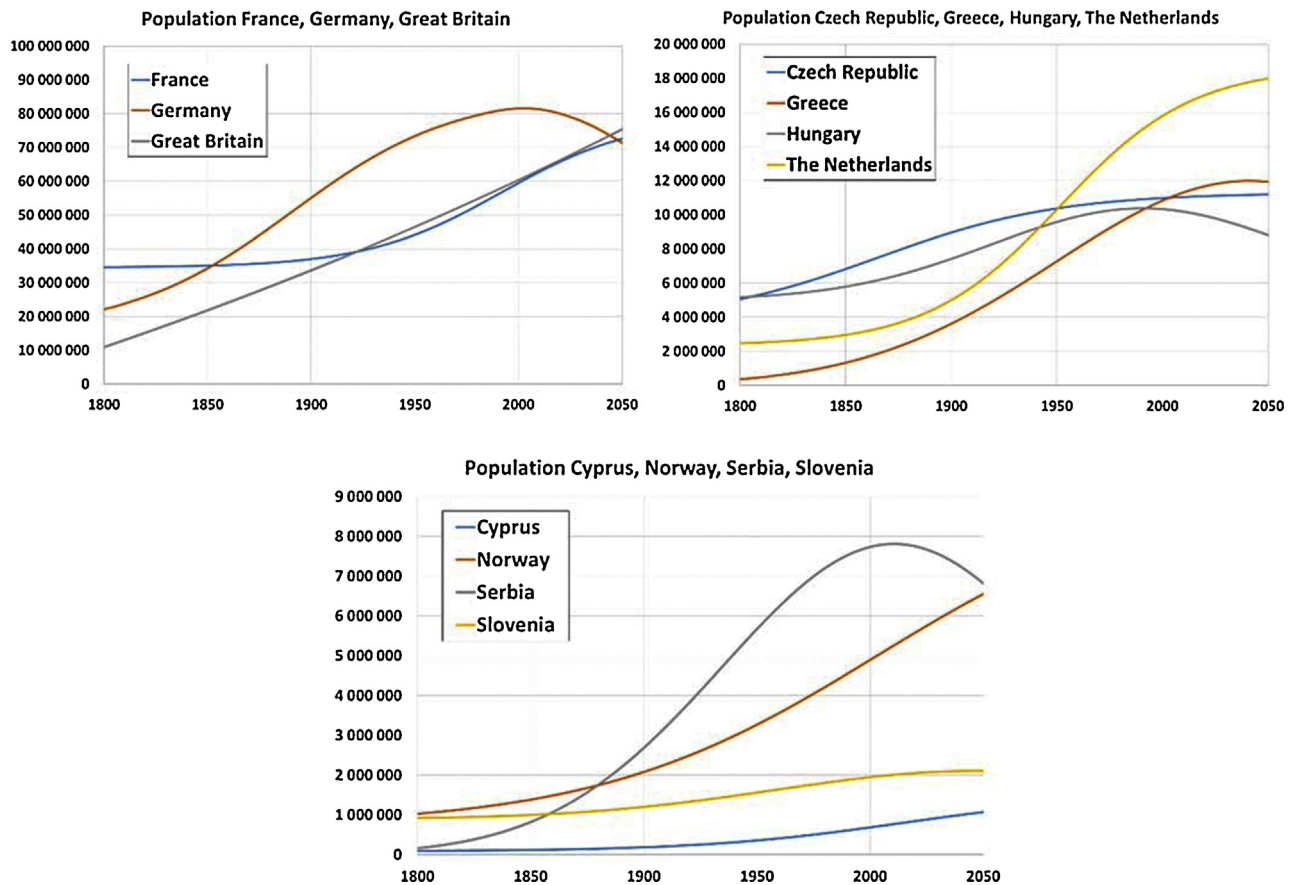


Fig. 2. Development in population (P) in all countries, countries are grouped into three graphs according to population size.

available, additional assumptions are included in the regression to obtain a smooth input curve for the whole period 1800–2050. This is explained in detail for each country in Appendix B.

The smooth P_D curves have the same shape for all countries, although with different starting values. Sigmoidal non-linear regression is used. The shape of the typical curve is exemplified for the case of Great Britain in Fig. 3 together with the raw data used to make the smooth curve. Further, the extreme cases of Serbia and Cyprus are also presented in Fig. 3. Serbia has a high starting value of 6.7 persons per dwelling in 1800. Cyprus is the country with the lowest starting value of 4.1 and the atypical development with a constant level of persons per dwellings from 1800 to 1965 followed by a rapid decrease to a level of 1.9 in 2011. All other countries have a smooth curve with a shape more similar to the curves presented for Great Britain and Serbia, starting at a value of 4.6–5.5 and ending at approximately 2 persons per dwelling in 2050, as shown in Appendix B.

2.2.3. Dwelling lifetime and renovation parameters

The lifetime probability function is assumed to follow a Weibull distribution defined by the parameters average lifetime per dwelling and the initial period after construction where the probability of demolition is zero. This is explained in detail in Sandberg et al. [37] and Sartori et al. [40], and is consistent with recommendations by Sereda [42]. The country-specific probability function parameters are described in Appendix B.

The definition of the renovation activity in the model is case-specific. An “energy saving modernization” such as changing the heating system or installing a photovoltaic can be thought as having a 20-year cycle or even shorter. In this study though, we explore the dynamics of deeper renovations that have the potential for includ-

ing energy-efficiency measures that lead to much larger reductions in energy demand. These measures are costly and unlikely to be implemented if a dwelling is not going through a major renovation in any case, perhaps due to its “natural” ageing process, a change of ownership, or the need for maintenance and upgrading. We estimate the total renovation activity resulting from the ageing process of the dwelling stock in each country involved. For most countries, this relates to deep renovation of facades, commonly estimated to occur in cycles of 40 or 50 years. Only in the case of Greece are single measures with a renovation cycle of 30 years are assumed to have a larger contribution to the energy savings than deep renovation of facades. The renovation probability function is assumed to follow a Normal distribution for all countries, as explained in detail in Sandberg et al. [37] and Sartori et al. [40].

The lifetime and renovation parameter values for all countries are listed in Table 1. The column “Construction period” refers to which segments of the stock the assumptions are applied to. In principle, the parameter values can differ between dwellings constructed in different years. However, due to limited empirical data, the same values are assumed for all dwellings regardless of construction year for all countries except Hungary. In the case of Hungary, the initial period without demolition is assumed to decrease for future construction. Further descriptions, references and explanations of the parameter values chosen for each country are given in Appendix B.

2.2.4. Cohort definition

Some of the model results will be segmented into cohorts. For easier comparison of the results, the cohorts are defined equally for all countries, as listed in Table 2. Cohort 0 represents the initial stock at the start of the modelling in year 1800, Cohort 1 is

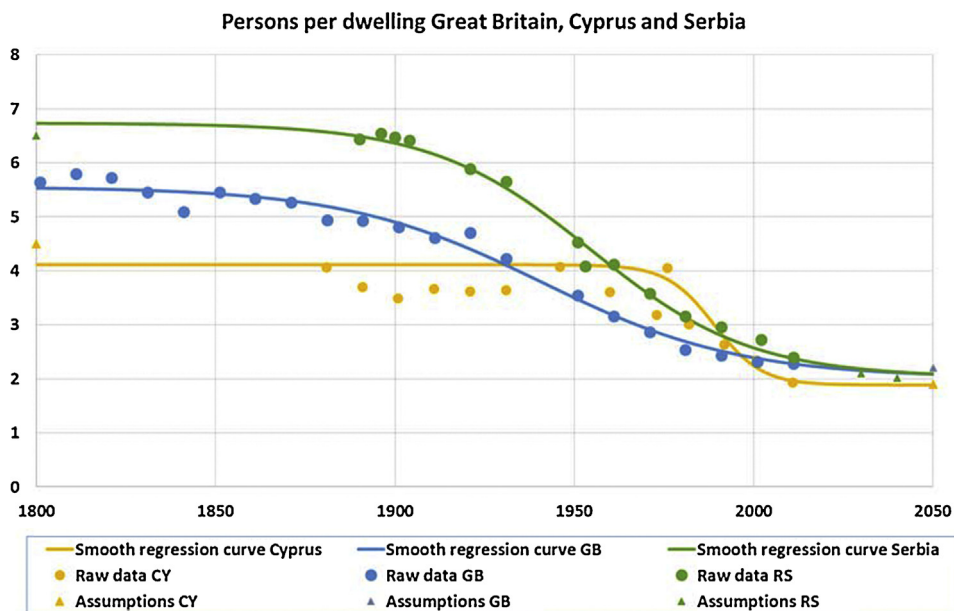


Fig. 3. Evolution in the number of persons per dwelling (P_D) in Great Britain, Cyprus and Serbia.

Table 1
Lifetime and renovation parameter values for all countries.

Country	Construction period	Average Lifetime (years)	Initial period without demolition (years)	Share never demolished	Renovation cycle (years)
Cyprus	All	125	40	5%	40
Czech Republic	All	120	60	5%	40
France	All	125	40	5%	40
Germany	All	125	40	5%	40
Great Britain	All	175	40	10%	40
Greece	All	70	40	5%	30
Hungary	–2015	125	50	5%	40
	2016–	125	40	5%	40
The Netherlands	All	120	40	3%	38
Norway	All	125	40	5%	40
Serbia	All	100	50	5%	50
Slovenia	All	120	40	8%	40

Table 2
Cohort definition.

Cohort number	Start year	End year
0	–	1800
1	1801	1945
2	1946	1980
3	1981	2015
4	2016	2050

the construction from 1801 to the end of World War II. Although there are large differences between the dwellings constructed in the early 1800s and in the 1930s, it is assumed that future renovation technologies, including those for energy-saving purposes, will be similar. The share of the current stock constructed before 1945 is also limited (less than 25% in most of the countries considered here). Cohort 2, 3 and 4 represent periods of 35 years where Cohort 2 is the post-war construction from 1946 to 1980, Cohort 3 is the most recent construction from 1980 to 2015 and Cohort 4 is future construction from 2016 to 2050.

3. Results and discussion

Country-specific detailed results are described in Appendix B. In the following, the results are presented for all countries, or making reference to one or a subset of countries.

3.1. Dwelling stock size and composition

The observed historical development of dwelling stock size, measured in terms of the number of dwellings, is used as an input to the model through the parameter persons per dwelling P_D . Nevertheless, the model results are compared with the statistics to ensure that the smoothening of the input curves has not resulted in significant differences between the model results and the statistics. For all 11 countries in this study, there is a good fit, as shown in Table 3 and the related discussion.

In Fig. 4 the modelled dwelling stock size, and composition of cohorts, is presented for all countries for the years 1980, 2015 and 2050. The current stock size varies significantly, from 0.4 million dwellings in Cyprus to 39 million dwellings in Germany. Therefore, all results are normalized against the size of the stock in the respective country in 2015. The total number of million inhabited dwellings in each country in 2015 is shown next to the 2015 bar.

Fig. 4 shows that the size of the dwelling stock has increased in all countries from 1980 to 2015, although at different rates. In all countries except in Cyprus, the number of dwellings in 1980 was 62–84% of the current stock size. Cyprus has experienced a large recent growth in the dwelling stock and the simulated 1980 stock was only 35% of the current stock size. According to the country-specific comparisons with statistics presented in Appendix B, there was a large increase in the construction activity in the Repub-

Table 3
Stock composition compared with statistics.

	Year of comparison		Cohort 0–1 (–1945) % share	Cohort 2 (1946–1980) % share	Cohort 3 (1981–) % share	Unknown cohort % share	Total % share
Cyprus	2011	Statistical	2.0	23.1	74.8	–	100
		Modelled	11.6	19.8	68.6	–	100
Czech Republic	2011	Statistical	22.0	43.0	32.6	2.3	100
		Modelled	35.2	32.7	32.1	–	100
France	1999	Statistical	32.9	45.7	21.3	–	100
		Modelled	32.7	38.6	28.7	–	100
Germany	2009	Statistical	24.5	43.5	32.0	–	100
		Modelled	31.5	35.5	32.9	–	100
Great Britain	2013	Statistical	36.9	39.8	23.3	–	100
		Modelled	30.0	32.1	37.9	–	100
Greece	2011	Statistical	5.7	49.3	45.0	–	100
		Modelled	8.3	34.3	57.4	–	100
Hungary	2011	Statistical	29.2	40.0	30.8	–	100
		Modelled	30.6	34.6	34.7	–	100
The Netherlands	2012	Statistical	19.5	40.9	39.7	–	100
		Modelled	18.2	37.2	44.6	–	100
Norway	2011	Statistical	16.6	42.7	36.4	4.4	100
		Modelled	22.4	33.5	44.1	–	100
Serbia	2011	Statistical	11.9	52.6	35.5	–	100
		Modelled	15.7	40.9	43.4	–	100
Slovenia	2013	Statistical	21.3	45.0	33.7	–	100
		Modelled	27.6	31.3	41.1	–	100

lic of Cyprus after the Turkish invasion in 1974. This increase is delayed by about 10 years in the simulation, and the real number of dwellings in 1980 was therefore somewhat higher than in the value shown in Fig. 4.

The dwelling stocks are expected to keep growing in all countries except those with decreasing future population projections: Germany, Hungary and Serbia. The expected increase in the stock size in the other countries is 12–25%, except in Cyprus and Norway where the expected increase is about 35%.

A decrease in the length of a certain color in the bars shown in Fig. 4 from one observation year to the next, indicates the simulated demolition of dwellings from the corresponding cohort between the two observation years. A new color shows the new construction in the given period, represented as a new cohort.

In Table 3, the simulated dwelling stock size and composition is compared with the most recent official national statistics on the dwelling stock composition for each country. A common pattern is observed in many of the countries: the stock is composed of a small share of dwellings constructed before 1945 and the model results compare well with these statistics. For most countries, this share is 6–25% of the stock. Exceptions are Great Britain, Hungary and France with shares of the stock being constructed before 1945 of 30–37%. From the larger shares of the stock constructed after 1946, the post-war construction boom in cohort 2 is commonly not fully explained by the model, and the construction from the most recent decades is commonly somewhat overestimated. These discrepancies are expected to lead to corresponding distortions in the model results on renovation activity in the relevant cohorts, but the resulting total renovation activity of the stock is not expected to be significantly affected by this.

3.2. Construction, demolition and renovation activity by country

The simulated construction and demolition activity is compared with statistics for each country in Appendix B. Construction statistics are available in most countries since about 1950–1980. For most countries, the long-term level of construction activity is broadly comparable with reported statistics. A common pattern is however observed in many countries where construction statistics are available: the model tends to underestimate the post-war construction boom between 1950/60–1980/90, and thereafter overestimates the construction activity in the most recent decades.

This is also in line with the comparison of the simulated current stock composition with statistics from Table 3. The short- and medium-term variations in construction activity are explained by factors not included in the model, e.g. wider drivers such as economic, climate and unemployment.

Demolition statistics are hardly available, except for in the Czech Republic since 1955 and in some few other countries since about year 2000. The long-term demolition activity seems to be at the right level for the Czech Republic. However, the model results are generally slightly higher than the reported values for 1956–1990, which can be explained by the large number of dwellings destroyed during World War II and therefore not demolished at a later date, when they would have reached their end of life. The consequences of World War II are not captured in the model.

Results for expected annual renovation activity (R_i) in year 2015, 2030 and 2050 are presented for all countries in Fig. 5. The results are normalized against the 2015 total for each country. Fig. 5 shows the development in total renovation activity and its distribution to dwellings constructed in the different cohorts. In all countries except Cyprus, the model forecasts the yearly number of dwellings renovated to increase by 4–18% by 2030 and by 4–41% by 2050, compared with the 2015 rate. Future renovation activity will, to a larger extent, take place in dwellings constructed after 1980, as these dwellings reach an age with increased need for maintenance. The need for renovation of older dwellings will decrease due to the demolition of dwellings in these cohorts.

Cyprus is in a special situation due to the rapid recent and expected future growth in the dwelling stock size. This will lead to an increase in the required future renovation activity to maintain the new building stock. By 2030, the estimated annual number of dwellings needing renovation ($D_{ren,2030}$) is expected to be 70% higher than the current number of dwellings renovated ($D_{ren,2015}$). The increase in renovation will mainly take place in dwellings constructed in the period 1980–2015. By 2050 there will also be some need for renovation of dwellings constructed after 2016, and the total renovation activity is expected to be 85% larger than in 2015.

3.3. Interplay of construction, demolition and renovation

The simulated development in annual rates of construction, demolition and renovation for France, Hungary, Great Britain and Germany is presented in Fig. 6. France and Great Britain

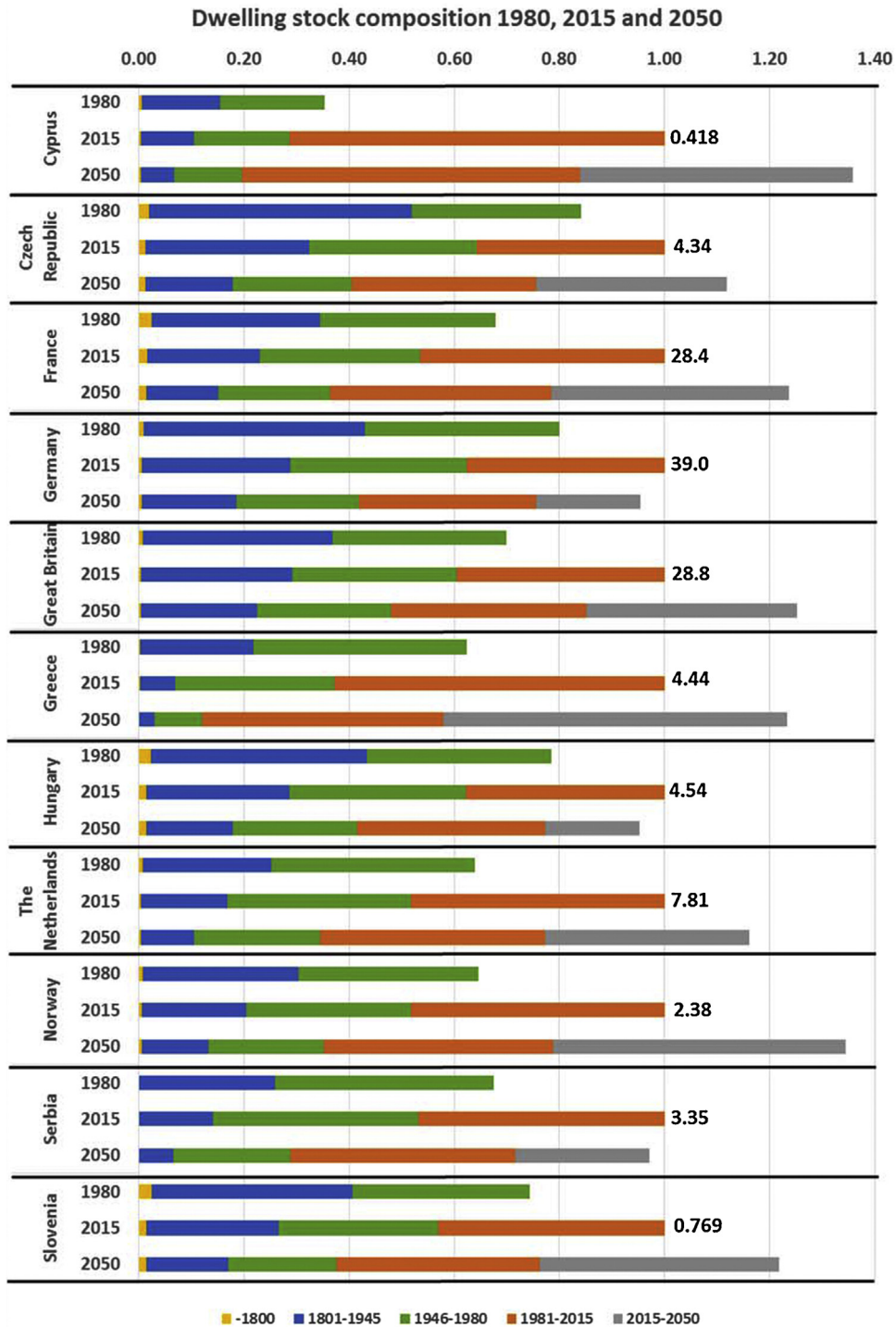


Fig. 4. Normalized dwelling stock composition in all countries in 1980, 2015 and 2050, relative to the 2015 total stock size. The numbers next to the 2015 bars are the number of million dwellings in total in the 2015 stock.

demonstrate a development pattern that is typical of most of the countries with increasing future population, whereas Hungary and Germany demonstrate typical development pattern in countries with expected decreasing population. All rates are defined as the number of dwellings exposed to the activity divided by the total number of dwellings in the stock in the same year.

Most countries in the study follow the same pattern as France and Great Britain: The simulated construction rate was high from 1900 to about 1950–1980. Thereafter there has been a decrease in the construction rate, and the decrease is expected to continue in

the future. This is due to slower population growth and saturation of the number of persons per dwelling. Further, the simulated annual demolition rate in most countries has been rather stable at 0.3–0.7% in the past and is expected to remain at the same level or increase slightly to about 1.0% by 2050.

Similarly, in most countries the simulated annual renovation rate has been stable at 1–1.5% and is expected to remain at the same levels or increase slightly towards 2050. Our simulations suggest that renovation will, in most countries, be the dominant activity in

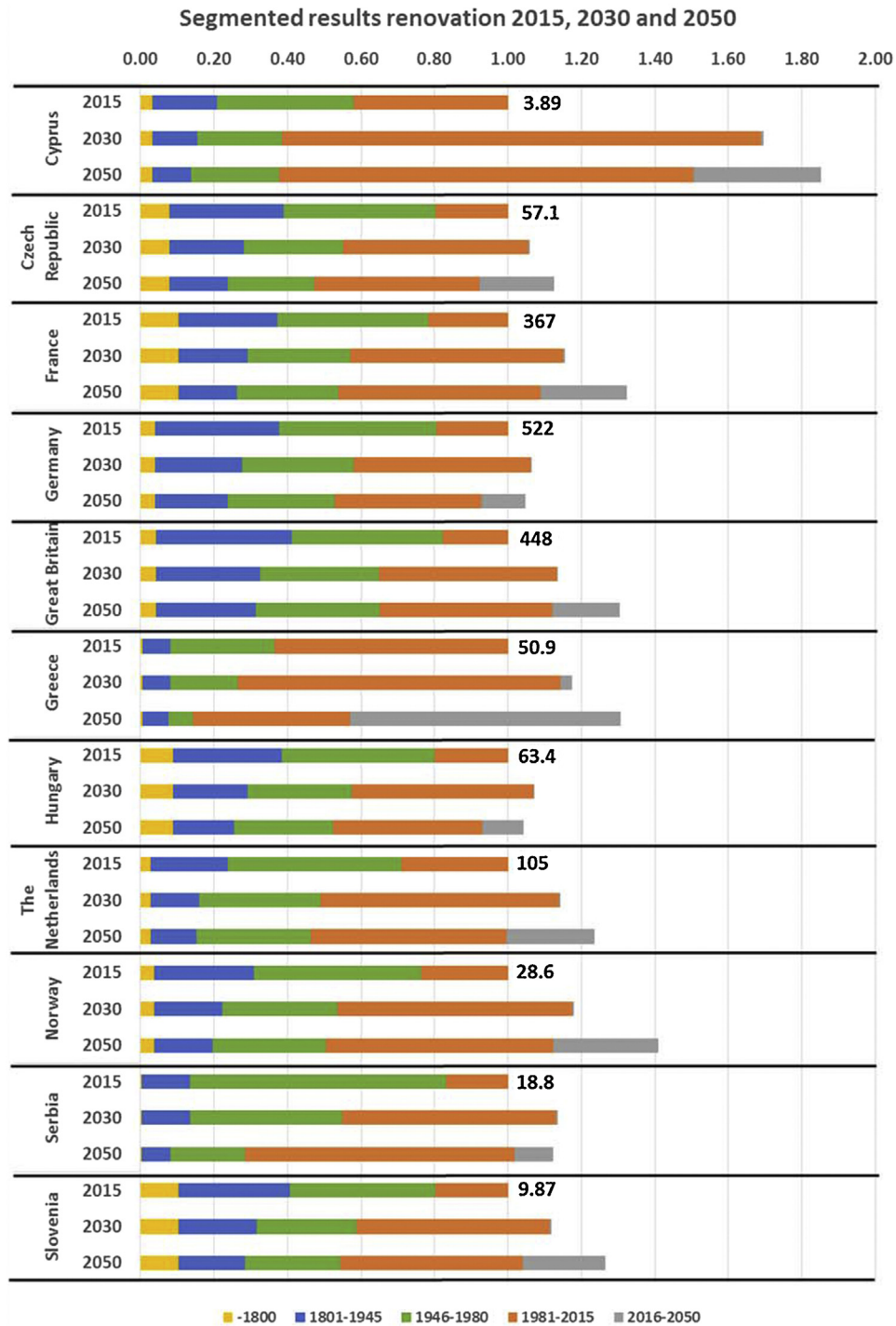


Fig. 5. Segmented results for expected annual renovation activity ($D_{ren,i}$) for all countries in 2015, 2030 and 2050, relative to the number of dwellings renovated in 2015 ($D_{ren,2015}$). The numbers next to the 2015 bars are the total number of thousand dwellings renovated in 2015.

the system in the future, in terms of number of dwellings exposed to the activity.

In some of the countries, the size of the population has leveled off and is expected to decrease in the future. The construction, demolition and renovation rates follow the pattern shown for Hungary and Germany in Fig. 6, where the annual construction rate has strongly decreased and is expected to fall to about 0.4% by 2050. The simulated annual demolition and renovation rates increase in these countries in the future, as the stock size is decreasing, and the con-

struction rate is expected to be lower than both the demolition and the renovation rates towards 2050.

The simulated construction, demolition and renovation rates for all countries in the years 2015, 2030 and 2050 are listed in Table 4. Minor variations over time are observed in the construction and the demolition rates. The simulated renovation rates, also presented in Fig. 7, are stable through time in all the countries and never exceeds 1.6% in any country. These describe the future expected renovation activity needed for maintenance of the existing stock and may be used to estimate the opportunities to readily introduce

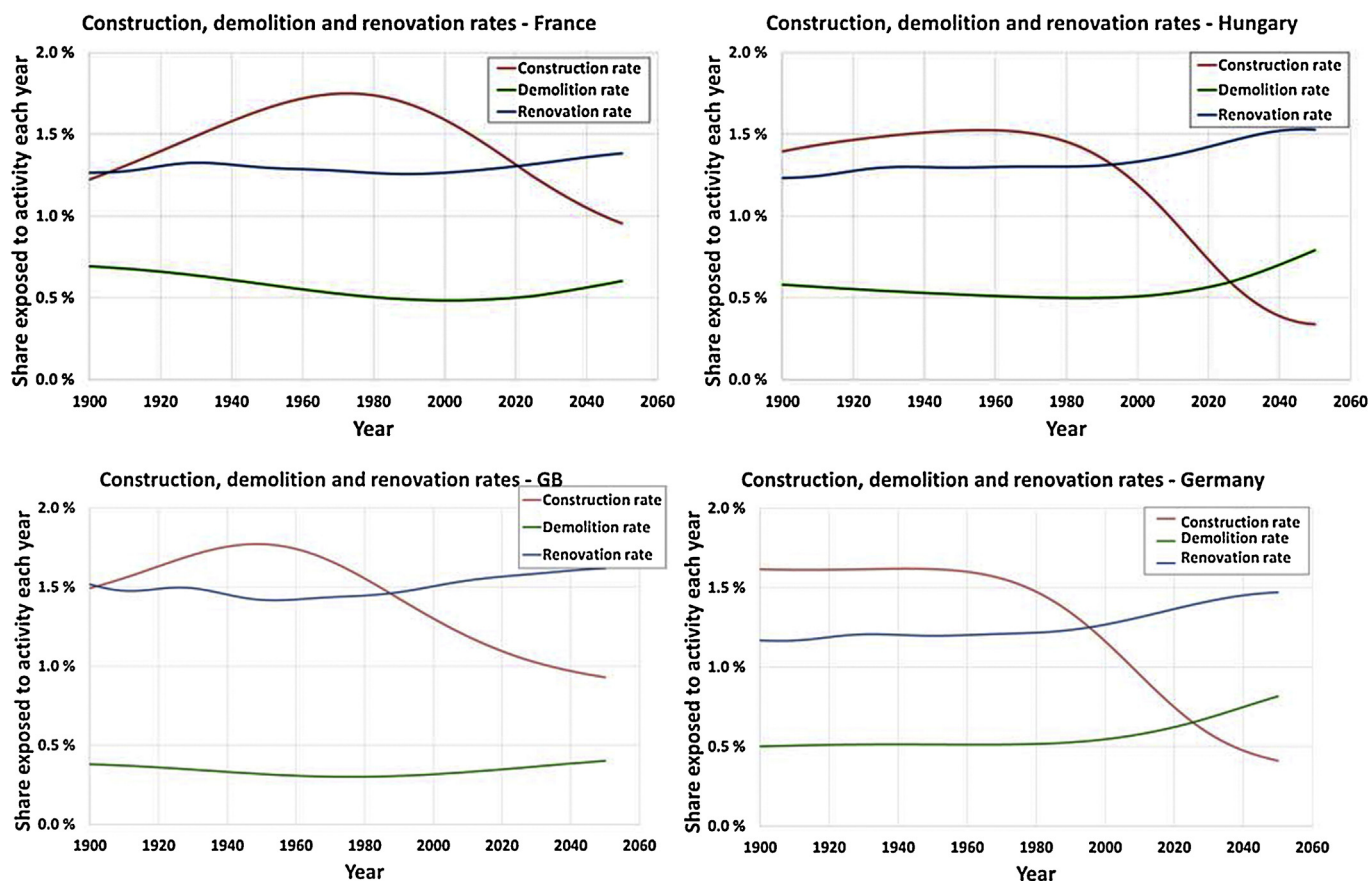


Fig. 6. Development in annual rates of construction, demolition and renovation in France, Hungary and Serbia.

Table 4

Construction, demolition and renovation rates in all countries in 2015, 2030 and 2050. All rates related to the stock size in the same year.

	Construction rate			Demolition rate			Renovation rate		
	2015	2030	2050	2015	2030	2050	2015	2030	2050
Cyprus	1.6%	1.2%	1.2%	0.2%	0.3%	0.5%	0.9%	1.3%	1.3%
Czech Republic	1.0%	1.0%	0.9%	0.6%	0.6%	0.7%	1.3%	1.3%	1.3%
France	1.4%	1.2%	1.0%	0.5%	0.5%	0.6%	1.3%	1.3%	1.4%
Germany	0.8%	0.6%	0.4%	0.6%	0.7%	0.8%	1.3%	1.4%	1.5%
Great Britain	1.1%	0.9%	1.0%	0.3%	0.4%	0.4%	1.6%	1.6%	1.6%
Greece	2.0%	1.7%	1.4%	0.9%	1.0%	1.2%	1.1%	1.2%	1.2%
Hungary	0.9%	0.5%	0.3%	0.5%	0.6%	0.8%	1.4%	1.5%	1.5%
The Netherlands	1.2%	1.0%	0.9%	0.5%	0.6%	0.7%	1.3%	1.4%	1.4%
Norway	1.5%	1.4%	1.2%	0.5%	0.5%	0.6%	1.2%	1.2%	1.3%
Serbia	1.1%	0.7%	0.5%	0.6%	0.8%	1.0%	0.6%	0.6%	0.6%
Slovenia	1.3%	1.2%	1.0%	0.6%	0.6%	0.6%	1.3%	1.3%	1.3%

energy-efficiency measures when dwellings are going through a deep renovation. This is an interesting finding regarding the energy saving potential of the dwelling stock. Scenario analyses and road maps for energy savings commonly assume rapid increases of the renovation rate to levels of 2.5–3% [4–9]. Our analysis shows that the renovation rates resulting from the dwelling stocks' ownership turnover, or need for maintenance, will be far below these levels in all the countries included in this study. Although the renovation process could probably be accelerated by appropriate incentive or investment schemes [43], to achieve a doubling of the renovation rate to meet national targets for reduction of energy consumption and CO₂ emissions will be difficult. Funding schemes should be used to ensure that when dwellings are renovated, high-level energy-efficiency measures are introduced to avoid lock-in effects.

Short- and medium term variations in the rates are not reflected in the model. In the case of Greece, this is clear in the case of the cur-

rent construction rate. Due to the ongoing turbulence in the Greek economy, the construction industry has come to a halt, and according to the latest statistics available [44,45] the construction rate in 2014 was 0.15%. Such short and medium term variations cannot be explained by this model.

Some studies define the construction, demolition and renovation rates as the number of dwellings exposed to the activity compared to the stock composition in a fixed year [4,37]. A fixed rate then means a constant number of dwellings exposed to the activity each year. In countries with a growing stock, future rates related to the stock size in a fixed year will be higher than if the rates are related to the changing stock size. In countries with a decreasing stock, the corresponding rates are lower. If relating the presented renovation activity to the 2015 dwelling stock size, the resulting 2050 renovation rate will be in the range 1.4–2.0% for all countries except Serbia with 0.7%. So even with this definition, the

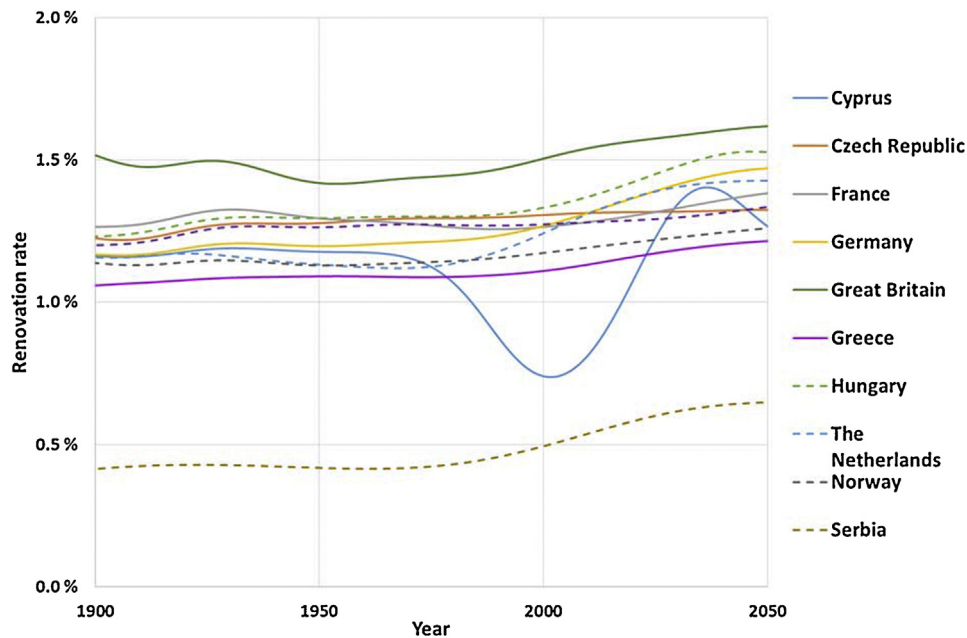


Fig. 7. Simulated renovation rate in all countries 1900–2050.

renovation rate is not likely to reach the level of 2.5–3% by 2050 and in any case not in the near future.

3.4. Applicability and reliability of the model and its results

In this study, a range of input data and assumptions are applied for the analysis of the long-term dynamics of the dwelling stocks in 11 European countries. The presentation of the data and assumptions in Section 2.2 and in Appendix B revealed large differences between the countries. This is mainly due to the large differences in historical development, current situation and expected future development in the countries' population, and probably also due to variations in the factors included in the population projections and estimation of lifetime of dwellings.

Data availability varies between the countries. Some countries do not have data available before 1900, requiring additional estimation steps. This is particularly the case for countries where the national territory changed over time prior to 1900. Later changes in border, e.g. after WWII are better documented and easier to address. The uncertainty caused by the estimation of input data this far back in time has little impact on the model results in the period of highest interest; the recent past and the future development.

The future development of dwelling stocks is strongly related to the expected change in the population in each country. The population projections are taken from the statistical offices, but are still uncertain. Moreover, expected lifetime, fertility rates and migration can be derived using different approaches and assumptions in the different countries. However, these projections provide the best available information on future population growth in the countries studied here. Migration is treated differently in the population projections for the different countries, and this may have significant effects since the future development in the population of European countries will substantially depend on migration policies. The future dwelling stock size and construction rate is highly sensitive to the future size of the population [38]. Further, the demolition rate and hence the construction needed to replace demolished dwellings are sensitive to the assumed lifetime of dwellings. Further, social factors, policies and changing user behavior might also influence the turnover rates of the dwelling stock.

The future renovation towards 2050 will mainly take place in dwellings in the current existing stock. The future renovation rate is therefore less sensitive to future development of the most uncertain input parameters than the future construction and demolition rates.

The most policy-relevant outcome of the presented analysis is the resulting renovation rates. Future construction is expected to be highly energy-efficient, and therefore the future energy savings in the system mainly depend on the improvements of the existing stock. The future energy saving potential in the existing stock should be identified through simulation of likely renovation rates and models showing possible average energy-intensity reductions when a dwelling is renovated. The future renovation rates are little dependent on the highly uncertain inputs, and the resulting renovation rates for all 11 countries turned out to be remarkably similar and stable over time, at levels of 1–1.6% for most countries, as shown in Fig. 7. This, together with the robustness of such results as emerged from the sensitivity analysis in Sandberg et al. [38], indicate that rapid increases of renovation rates to levels of 2.5–3% will be very difficult to obtain.

3.5. Implications for energy efficiency

The dynamic dwellings stock model can be used as a basis for detailed energy analyses of dwelling stocks [41]. Although no full energy analysis is carried out in the present study, the model results indicate the importance of new construction versus renovation of existing dwellings in the dwelling stocks of the various countries towards 2050.

The segmented results presented in Fig. 4 indicate that there are large differences in the importance of the different cohorts and that there is a large difference in the potential for, and necessary strategy to deliver, future energy-demand reductions. Countries with a growing stock have to improve the average energy efficiency of the stock even to keep the future total energy use in the stock at a constant level. In contrast, countries with a decreasing stock will achieve energy savings even if the average energy efficiency does not improve.

Eurostat [46] report 214 million households (dwellings) in 2013 for the EU 28 countries. This study of 124 million dwellings in 10

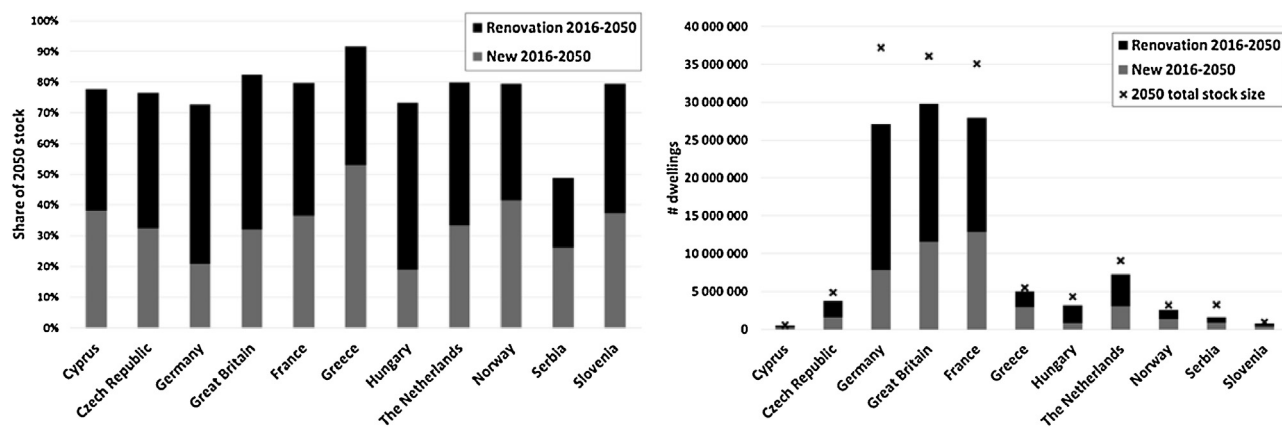


Fig. 8. Number of dwellings constructed or renovated in the period 2016–2050. Left: as percentage of 2050 stock size in each country. Right: absolute number of dwellings.

EU countries and Norway, therefore analyses over half of European housing stock. If the results are representative of the remaining dwelling stock within Europe, the expected low rates of future renovation activity pose a far greater challenge for policy makers seeking to rapidly meet decarbonisation objectives than assumed in current strategies.

The simulated accumulated number of dwellings constructed or renovated in the period 2016–2050 is shown for all countries in Fig. 8 (left) as a portion of the 2050 stock size in the respective country and Fig. 8 (right) as absolute number of dwellings. As each deep renovation and each new construction is an opportunity to implement energy-efficiency measures, this indicates the potential for energy savings in each country. “Renovation 2016–2050” is the sum of the number of dwellings renovated each year in the same period. This does not correspond completely with the numbers of dwellings going through renovation in this period, as a few dwellings will be renovated twice. Within a 40-year cycle, however, only a small proportion will be renovated twice in a 35-year period.

Fig. 8 (left) indicates the shares of the 2050 dwelling stocks that are targetable for energy efficiency measures in the period 2016–2050, either as they are constructed or exposed to deep renovation. In total, this will be 70–80% of the 2050 stock in all countries except Serbia. This means that even though the simulated renovation rates are not expected to increase, there is a large potential for energy efficiency of the dwelling stocks towards 2050. However, as most dwellings are renovated only once in this period, it will be necessary to ensure that the best available energy measures are included when a dwelling undergoes renovation, and to stimulate large-scale introduction of technologies such as heat pumps and photovoltaics.

Fig. 8 (left) further demonstrates how the countries with an expected decreasing population (Germany, Hungary and Serbia) will have a correspondingly low share of new dwellings in 2050. Hence, the largest potential for total energy savings in these countries is through renovation and upgrading of the existing stock. In contrast, countries with a large expected growth in the dwelling stock, like Cyprus, Greece and Norway, will have a high energy-saving potential in the dwellings constructed in the future.

Fig. 8 (right) shows the absolute values of new construction and renovation in the 11 countries, indicating also the total 2050 stock size. As France, Germany and Great Britain contain 77% of the dwellings considered here, accelerated stimulus in these countries would contribute more to achieving a Europe-wide decarbonisation target.

More detailed studies on the energy standard of the dwelling stocks in each of the countries, and their potentials for cost-efficient

reductions through introduction of energy-efficiency measures, could be combined with the results from the dynamic dwelling stock model to identify the most cost-effective energy efficiency scheme for housing stocks throughout Europe.

4. Conclusions

A dynamic dwelling stock model is applied to 11 European countries (in alphabetical order): Cyprus, the Czech Republic, France, Germany, Great Britain, Greece, Hungary, the Netherlands, Norway, Serbia and Slovenia. The simulated long-term development in dwelling stock size fits well with the reported statistics for all countries. Despite the differences in data collection and reporting by the different countries, the modelled future trends for the construction, demolition and renovation activities lead to similar patterns emerging in all countries.

The countries included in the study have different expected future development in the size of the population. In some countries, a strong increase is expected, whereas in other countries the population is expected to level off or even decrease. This has large impacts on the simulated future development of the dwelling stock. Countries with large population growth will need high construction activity, and for energy saving matters it is important that the new construction is energy efficient. In countries expecting a lower population growth or decreasing population, the existing stock is of higher importance and energy efficiency achievements are more influenced through renovation of the existing stock.

Overall, the presented analysis shows that despite the differences between the countries included in this study, the model is applicable for all the 11 countries. The model is able to reproduce the current stock size and composition and the long-term dynamics in the system in an acceptable way. Short- and medium-term variations in construction and demolition activities may be explained by factors not included in the model, e.g. wider drivers such as economic, climate and unemployment. Unfortunately, demolition and renovation statistics are rarely available. Better data availability would be useful for model calibration.

The future development in construction and demolition is sensitive to the population input and the lifetime of dwellings parameter, which are highly uncertain. Still, we claim that it is better to include the best available estimates of these important parameters in the study and identify the implications of their uncertainty, rather than using traditional models with fixed construction, demolition and renovation rates that are based on recent trends without discussing their realism and applicability for future analyses.

We conclude that the model seems to perform reasonably well at simulating the long-term development of changes in dwelling stock composition and expected annual renovation activities. Short- and medium term variations in construction activity are not well captured by the model, as these depend on drivers not represented in the model. However, short- and medium term estimations are not the intended purpose of the model. The general trend observed in most of the countries studied, is that the modelled share of the stock constructed before 1945 shows a good fit with the reported statistics, whereas the post-war construction activity is often underestimated and the construction activity from the most recent decades is consequently overestimated. Although the overall accuracy appears satisfying, caution should be applied when interpreting the segmented results for different cohorts. Additional, or more accurate data, could improve the quality of the segmented results for some of the countries.

A key model output is the renovation rate, which expresses the dwelling stock's need for maintenance due to ageing. The simulations show that only minor increases are expected in the future renovation rate, always within the range from 0.6% to 1.6% towards 2050. Although there are uncertainties in the results, this trend of small incremental changes is consistent across all 11 countries and the results reinforce findings in Sandberg et al. [37,38] that renovation rates at levels of 2.5–3% are unlikely to be achieved through the stock's natural renovation requirements. Furthermore, it shall be noted that the simulated future renovation rate towards 2050 mainly depends on the current stock size and composition and is not significantly sensitive to future development in the input parameters of the model (such as projections on the population development), as shown in the sensitivity analysis [38]. We therefore conclude that the model results on future need for renovation are robust despite the uncertainties in the input parameters.

As future renovation rates are expected to remain close to the current level, it is highly important to make sure that the best available energy-efficiency measures are included when a dwelling is renovated. If European countries are going to follow the recommendations given in the EU-JRC report [3] calling for a common EU renovation plan with a regional approach prioritizing less developed regions, funding and other incentives must be allocated so that energy-efficiency measures are included when dwellings in the less developed regions are renovated, or even to accelerate the renovation process in these countries.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.enbuild.2016.05.100>.

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