



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



Nina Holck Sandberg<sup>a,\*</sup>, Igor Sartori<sup>b</sup>, Magnus I. Vestrum<sup>a</sup>, Helge Brattebø<sup>a</sup>

<sup>a</sup> Industrial Ecology Program and Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway

<sup>b</sup> SINTEF, Department of Building and Infrastructure, P.O. Box 124 Blindern, 0314 Oslo, Norway

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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<sup>2</sup> are offset by changes in user heating habits. A significant decrease in average delivered energy intensity per m<sup>2</sup> is only observed after the introduction of heat pumps.

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## 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

\* Corresponding author.

E-mail addresses: [nina.h.sandberg@ntnu.no](mailto:nina.h.sandberg@ntnu.no) (N.H. Sandberg), [igor.sartori@sintef.no](mailto:igor.sartori@sintef.no) (I. Sartori), [magnus.i.vestrum@ntnu.no](mailto:magnus.i.vestrum@ntnu.no) (M.I. Vestrum), [helge.brattebo@ntnu.no](mailto:helge.brattebo@ntnu.no) (H. Brattebø).

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  $\text{m}^2$  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

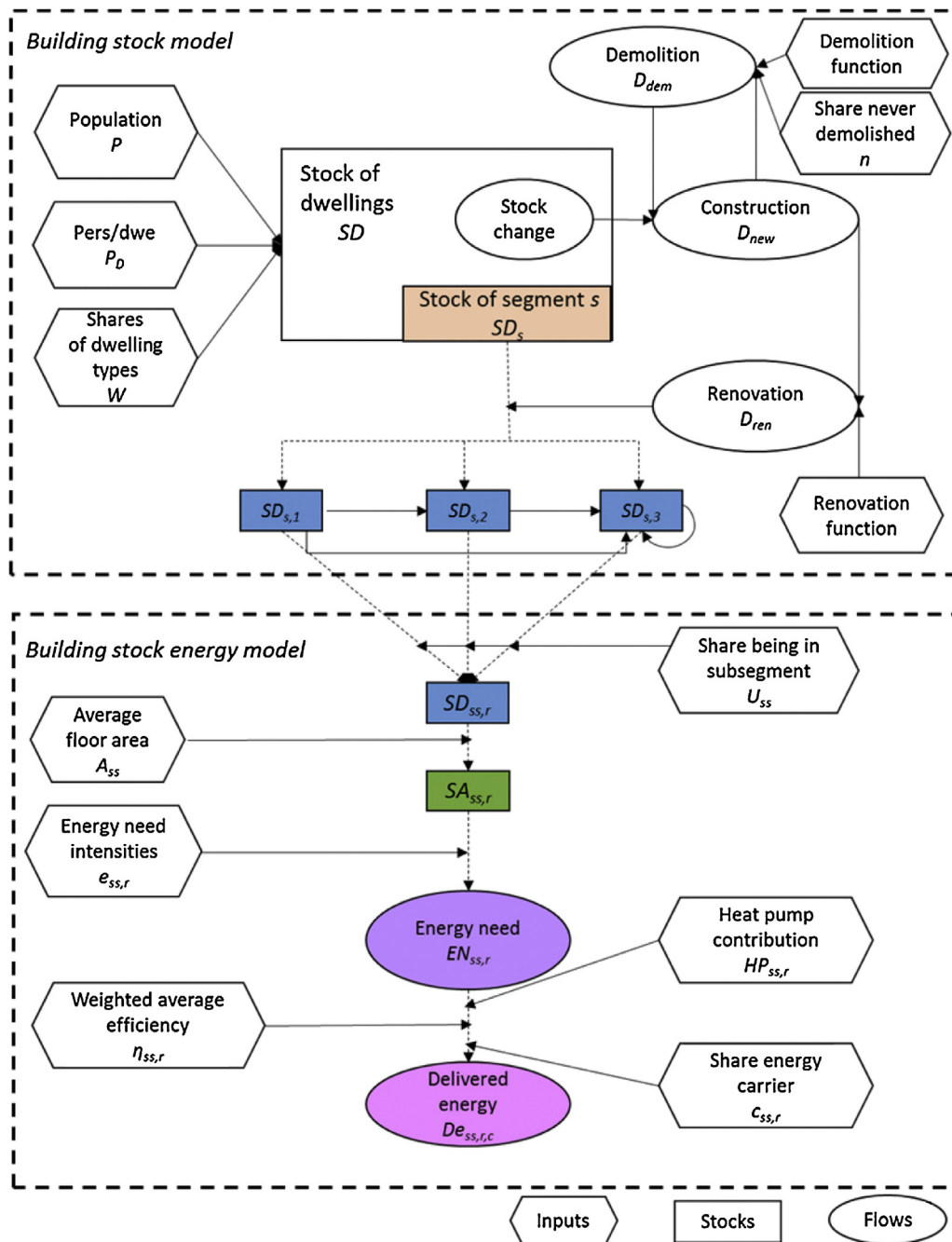


Fig. 1. Conceptual outline of the building stock model and the building stock energy model. Hexagons represent input variables, rectangles stocks and ovals flows. All inputs and outputs are time-dependent.

and use of various energy carriers are estimated per segment and for the total stock.

In this study the model results are calibrated against statistics on total delivered energy in the system, since 1960. The simulated delivered energy is expected to differ from the statistics, especially far back in time when the heating habits differed substantially from what is assumed in the technically estimated energy need intensity (calculated according to current standards and methods). The adaptation factor  $f_A$  is defined as the aggregated measured over calculated annual energy demand, hence annual delivered energy values from statistics over annual values calculated by the model. The adaptation factor therefore includes changing user behavior (heating habits) and uncertainty in model results.

## 2.2. Data and assumptions for the Norwegian case

The presented model is generic and can be applied to any dwelling or building stock and to any time period. In the following we present a case study of historical development in energy demand in the national aggregated Norwegian dwelling stock. The main inputs to the model are described in this section. More detailed information about the data and assumptions is presented in Appendix C (Supplementary material).

Due to the long lifetime of dwellings, the dwelling stock system changes slowly and the composition of the stock depends on activities far back in time. A long time horizon is therefore needed when working with dwelling stock models. This case study covers the period 1800–2050 in order to capture long-term changes in the

**Table 1**  
Cohort definition and average heated floor area per dwelling in each segment.

		SFH 00–01	SFH 02	SFH 03–04	SFH 05–07	TH 00–01	TH 02–07	MFH
1960	Share of dwelling stock	51%	5%	0%	0%	21%	2%	22%
	Share of floor area stock	64%	6%	0%	0%	17%	2%	11%
	Share of delivered energy (heating + dhw)	68%	5%	0%	0%	17%	1%	9%
1990	Share of dwelling stock	25%	12%	20%	0%	10%	11%	20%
	Share of floor area stock	29%	11%	0%	0%	16%	3%	11%
	Share of delivered energy (heating + dhw)	37%	14%	22%	0%	9%	9%	9%
2015	Share of dwelling stock	14%	8%	15%	12%	6%	17%	28%
	Share of floor area stock	18%	11%	22%	16%	5%	15%	15%
	Share of delivered energy (heating + dhw)	23%	11%	22%	12%	6%	13%	13%

Norwegian dwelling stock. The energy analysis, however, can start at any point in time, as the energy demand in a certain year depends on the current stock size and composition, but does not depend directly on the energy demand in previous years. In this paper, the analysis of the historical development in delivered energy in the Norwegian dwelling stock is simulated for the period 1960–2015. Detailed statistics on energy use in households is available for this period and is used for model calibration and reference.

A set of buildings represented in the national dwelling stocks of a range of European countries has been described in detail in the Intelligent Energy Europe research projects TABLE and EPISCOPE [30]. For the Norwegian case, three dwelling types Single Family Houses (SFH), Terraced Houses (TH) and Multi Family Houses (MFH) and 7 cohorts (cohort 1–7) result in 21 type/cohort combinations for which both a real example building as well as a synthetic average building has been described. This segmentation of the dwelling stock is also used in the present study, however, due to the way the model works, the initial 1800 stock needs to be a separate cohort, defined as cohort 0. The cohort definition and the average heated floor area per dwelling for each segment (taken from statistics [31]) are listed in Table 1.

The segments defined by dwelling type and cohort are further distributed to archetypes according to their renovation period,  $r$ . The renovation period defines if and when a dwelling has gone through its most recent renovation. Dwellings in their original state and dwellings exposed to renovation prior to 1980 are placed in renovation period 1, since the common renovation measures until 1980 to little degree included energy-efficiency measures. Further, it is assumed that since 1980 technology has been available so that inclusion of energy-efficiency measures was possible whenever a dwelling was renovated. Dwellings renovated since 1980 are therefore placed in renovation period 2. The baseline assumption, used in model calibration and in some of the scenarios, is that renovations in renovation period 2 correspond to standard renovation as defined in the TABLE project [30].

Fig. 2 shows the time series for the input parameters Population,  $P$ , (left figure, left axis), share living in SFH or TH,  $W$ , (left figure, right axis) and persons per dwelling,  $P_D$ , (right figure). Further details about these inputs, data processing and assumptions in the segmented dwelling stock model in the case of Norway are described in Sandberg et al. [19] and Appendix C (Supplementary material).

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, as explained in detail in Sandberg et al. [19] and Sartori et al. [21] (this issue). This is in line with the recommendations in Sereda [32]. The average lifetime of dwellings is estimated to 125 years, in line with the findings in Bohne et al. [33] and the initial period after construction with no demolition is assumed to be equal to one renovation cycle,  $R_c$ .

Based on data from the Directorate of Cultural Heritage [34] the share of buildings from each construction year that is assumed

never to be demolished is estimated to 5% for SFH and TH and 9% for MFH.

The definition of the renovation activity in the model is case-specific. In this study, we explore the dynamics of renovations that have the potential for including energy-efficiency measures that lead to a large decrease in the energy demand. The implementation of these measures are costly and not likely to take place if a dwelling is not going through a renovation in any case. Hence, such measures could be implemented when the dwelling is renovated due to its “natural” ageing process and need for maintenance and upgrading. In this study, we estimate the total renovation activity resulting from this ageing process of the dwelling stock in Norway; deep renovation of facades which are assumed to occur in renovation cycles,  $R_c$ , of 40 years. This is in line with findings in Kristjansdottir et al. [35].

In TABLE [30], the technical standard of each example building and synthetic average building has been described in detail for typical buildings in their original state, after a standard renovation is carried out, and after an advanced renovation is carried out. The energy need intensity per dwelling type, cohort and renovation variant in TABLE is shown in Fig. 3. These values include energy need for space heating and domestic hot water (dhw), excluding electrical appliances.

In this study, archetypes are defined by the dwelling type, cohort and renovation period. The actual renovation variant, and its corresponding energy standard, chosen for each renovation period, is decided to be scenario specific. This adds flexibility to the model, since energy intensities are a consequence of building codes, energy saving measures and other factors that may change over time. In this study, energy need intensity values (in kWh/m<sup>2</sup>/year) for each archetype are taken from TABULA, and reflect energy-related changes in the Norwegian dwelling stock since 1960.

The historical development in the energy mix in Norwegian households is known from statistics [36–38]. Estimations on share of the energy being used for heating and dhw and system efficiencies per energy carrier as a function of time are used to estimate the overall weighted average system energy efficiencies, as presented in Table 2.

Finally, the energy need per archetype,  $EN_{ss,r}$ , is corrected for energy contribution from heat pumps and converted to delivered energy per archetype,  $DE_{ss,r}$ , using the weighted average system efficiency. The model is calibrated for changing outdoor climate and changing electric load, as described in Appendix B (Supplementary material).

A summary of the definition of key terms that are used in the model and analysis is given Appendix A, at the end of this paper.

### 2.3. Scenario description

A Baseline scenario and six additional scenarios will be explored. The dwelling stock model is the core of all the scenarios, and the model is run using the inputs described in Appendix C (Sup-

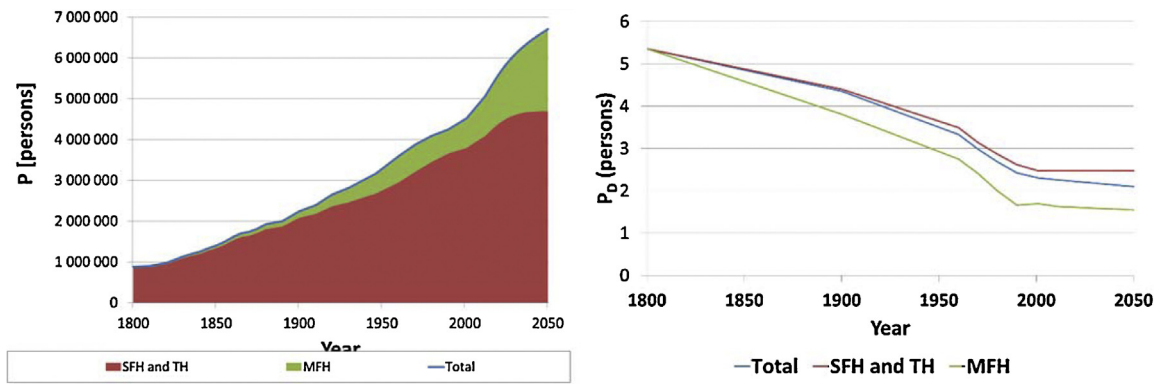


Fig. 2. Left: development in total population, and in persons living in each of the two dwelling types. Right: development in persons per dwelling for the total stock as well as for each dwelling type.

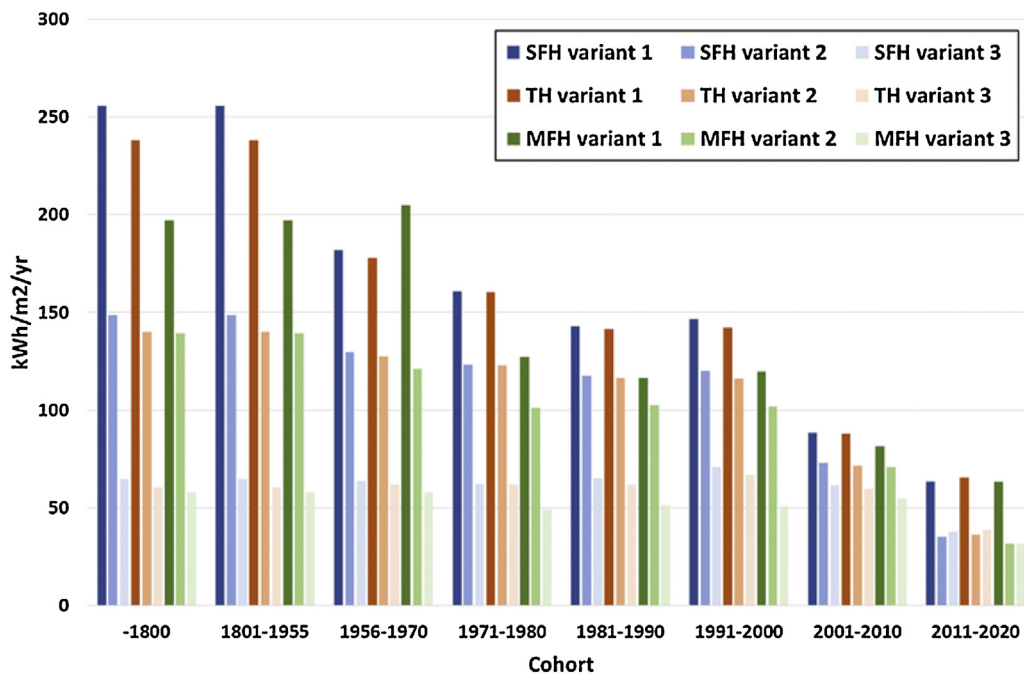


Fig. 3. Energy need intensities per dwelling type, cohort and renovation variant.

Table 2

Energy mix (space heating and dhw) and weighted average system efficiency specified for different segments and years.

	Year	1960	1982	1990	2012								
	Dwelling type	All	All	All	SFH			TH			MFH		
	Cohort	All	All	All	00–03	04–05	06–07	00–03	04–05	06–07	00–03	04–05	06–07
Share energy carrier (%)	Total	100	100	100	100	100	100	100	100	100	100	100	100
	El	27	62	67	72	73	81	82	86	87	67	82	72
	Bio	31	15	17	21	23	18	14	12	11	9	5	5
	Oil	42	23	15	6	4	0	4	1	0	12	5	2
	District heating	0	0	1	0	0	1	0	2	2	12	8	21
Weighted average system efficiency		0.64	0.83	0.84	0.87	0.87	0.91	0.92	0.94	0.94	0.92	0.96	0.96

plementary material) for all scenarios. The number of dwellings constructed, demolished and renovated each year do not change between the scenarios. Further, the conversion factor used to convert from Oslo climate to national average across different Norwegian climate zones is applied in all scenarios.

The Baseline scenario aims at reproducing the real historical development trends in the best possible way. The energy need intensities per segment and variant are as defined in Fig. 3, reno-

vation activity since 1980 is assumed to shift the energy efficiency from variant 1 to variant 2. The energy need is converted to delivered energy before the national climate conversion factor and the heating day degrees (HDD) trendline are applied to the simulated delivered energy for heating and before the adaptation factor are applied to the resulting delivered energy for space heating and dhw. The electric load is also included and assumed to follow the estimated trendline.



**Table 3**  
Scenario definition.

Scenario number	Scenario name	Renovation after 1980	New construction	Energy mix and efficiencies	HDD correction	Thermal adaptation factor	Electric load
0	Baseline	Shift to variant 2	Segment specific variant 1	Changing over time	Trendline	Trendline	Trendline
1	No energy efficiency through renovation	<b>Still variant 1</b>	Segment specific variant 1	Changing over time	Trendline	Trendline	Trendline
2	No energy efficiency in new built	Shift to variant 2	<b>No improvement after 1970</b>	Changing over time	Trendline	Trendline	Trendline
3	Fixed 1960 energy mix	Shift to variant 2	Segment specific variant 1	<b>1960 energy mix and efficiencies</b>	Trendline	Trendline	Trendline
4	Fixed 1960 climate	Shift to variant 2	Segment specific variant 1	Changing over time	<b>1960 value</b>	Trendline	Trendline
5	Fixed 1960 thermal adaptation factor	Shift to variant 2	Segment specific variant 1	Changing over time	Trendline	<b>1960 value</b>	Trendline
6	Fixed 1960 electric load	Shift to variant 2	Segment specific variant 1	Changing over time	Trendline	Trendline	<b>1960 value</b>

To explore the importance of the various energy-related parameters, these are varied between the scenarios, one at a time. The scenarios are defined in Table 3. In addition, some of the scenarios will be combined to explore the combined effect of changing more parameters simultaneously.

### 2.3.1. Uncertainty of input parameters

For this historical analysis, many of the input parameters are taken from official statistics, and their uncertainty is therefore low. This is the case for the parameters population, persons per dwelling, share of dwellings being in different types, average floor area per segment, share having heat pump and the energy mix.

The dwelling stock model is calibrated against statistics for the historical period under study. However, although the number of dwellings in the stock is well calibrated, there is some uncertainty in the dynamics of the system, in the parameters related to demolition and renovation, due to lack of empirical data. Further, although the average utility floor area per dwelling in each segment is based on statistics and of low uncertainty, there is uncertainty related to the conversion from utility floor area to heated floor area.

Finally, the energy need intensity of each archetype is estimated through the TABLE methodology, which uses a detailed description of the technical standard of each synthetic average building and renovation variant to estimate the energy intensities. There is a fairly high uncertainty related to how well the given segment and renovation variants represents the real average values in the stock.

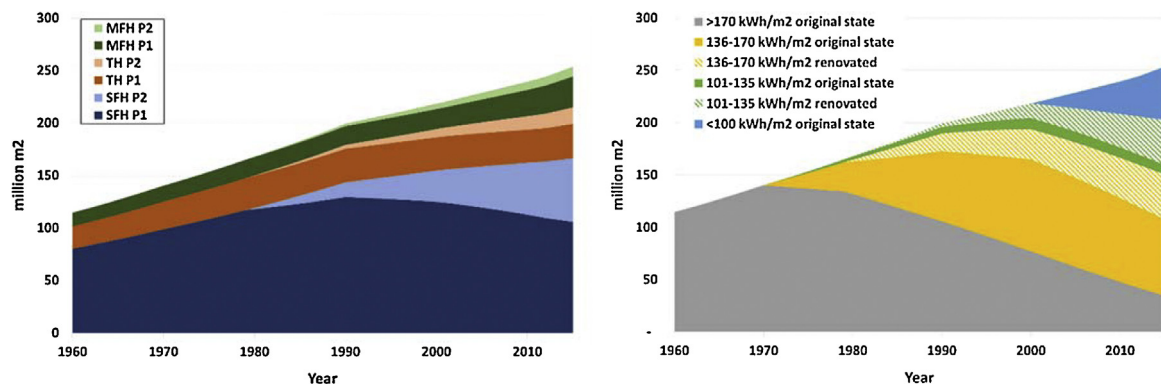
Finally, there is high uncertainty in the assumed contribution from heat pumps and in the heating system efficiencies.

The uncertainty of the various input parameters is evaluated in Table 4. The parameters are grouped according to the part of the model that they influence: i) the dwelling stock size and composition measured in number of dwellings, ii) the floor area stock measured in square meters of heated floor area, and iii) the delivered energy demand measured in GWh. The source of the input data and the evaluation of the related uncertainty is listed. When the uncertainty is regarded as high, the input parameter will be included in a sensitivity analysis, where input parameters are varied to their low and high variants, one at a time. The low and high variants will be  $\pm 10\%$  for all parameters except the start year of renovation, where  $\pm 10$  years will be used. Finally, the resulting effects on the model results are evaluated.

## 3. Results and discussion

### 3.1. Evolvement of dwelling stock size and composition

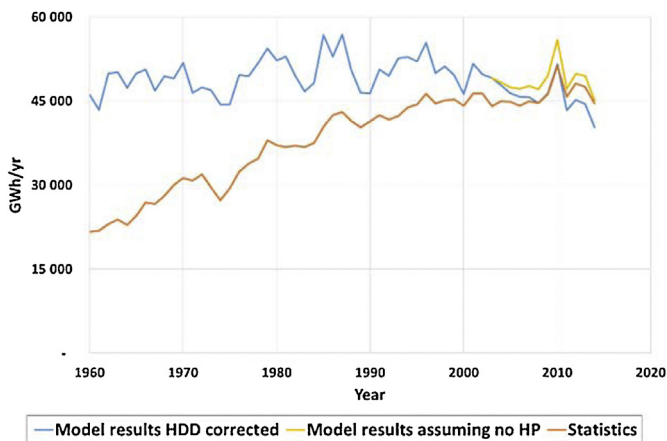
Fig. 4 shows the simulated historical evolvement the Norwegian dwelling stock size and composition, measured in square meters of heated floor area. The simulated dwelling stock evolvement is applied to all the historical scenarios. The stock has grown by 121% from 115 million  $m^2$  in 1960 to 254 million  $m^2$  in 2015, in terms of heated floor area. The left part of the figure shows the development in stock composition of dwelling types and renovation periods. Ren-



**Fig. 4.** Dwelling stock development in million  $m^2$ . Stock distributed to types and renovation periods (left) and to energy need levels (right).

**Table 4**  
Uncertainty of input parameters.

	Parameter	Source	Uncertainty	Variant low	Variant high
Dwelling stock dynamics (#dwellings)	Population	Censuses	Low		
	Persons per dwelling	Censuses	Low		
	Share of dwelling types	Censuses	Low		
	<b>Average lifetime</b>	<b>Estimation</b>	<b>High</b>		
	<b>Share never demolished</b>	<b>Data on heritage buildings</b>	<b>High</b>	-10%	+10%
	<b>Renovation cycle</b>	<b>Literature</b>	<b>High</b>	-10%	+10%
	<b>Start year renovation period 2</b>	<b>Calibration</b>	<b>High</b>	1970	1990
Floor area stock (#m <sup>2</sup> )	Average utility floor area	Statistics	Low		
	<b>Share heated floor area</b>	<b>Estimation</b>	<b>High</b>	-10%	+10%
Delivered energy demand (#GWh)	<b>Energy need intensities</b>	<b>TABULA</b>	<b>High</b>	-10%	+10%
	Share having heat pump	Statistics	Low		
	<b>Contribution from heat pump</b>	<b>NS3031</b>	<b>High</b>	-10%	+10%
	Energy mix	Statistics	Low		
	<b>Efficiencies</b>	<b>NS3031</b>	<b>High</b>	-10%	+10%
	<b>Electric load</b>	<b>Statistics (Norway and Sweden)</b>	<b>High</b>	-10%	+10%



**Fig. 5.** Simulated total delivered energy with and without introduction of heat pumps compared with statistics.

ovation period 1 consists of all dwellings in their original state and dwellings renovated before 1980. Regardless of their energy standard when constructed, new construction in all years is added to the renovation period 1 band. Renovation period 2 consists of dwellings renovated after 1980. Fig. 4 demonstrates how the Norwegian dwelling stock has been and still is dominated by single family houses (SFH), but the share of the floor area stock being in multi family houses (MFH) has increased over time.

The development of the stock composition in terms of the energy standard is presented in the right part of Fig. 4, where segments with similar energy need intensities are grouped together. Each color represents a certain range of energy intensities. The shaded yellow and green areas represent the estimated total floor area that has reached this energy intensity level after renovation. There has been a strong trend of an improving aggregated energy standard of the stock, both through energy-efficient new construction and renovation. Until 1970, all dwellings had a calculated energy need intensity above 170 kWh/m<sup>2</sup> (according to current calculation method). According to the model results, this share is reduced to 14% of the floor area stock in 2015.

### 3.2. Evolution of dwelling stock energy demand and the adaptation factor

The simulated development in total delivered energy corrected for temperature variations is compared with energy statistics in Fig. 5. Despite the yearly fluctuations, the simulated total delivered energy was rather stable at a long-term yearly level of about 50

GWh from 1960 to 2000. Given the strong growth in population and floor area during this period, these results confirm the aggregated improvement in calculated (technical) specific energy need intensities (kWh/m<sup>2</sup>/year).

In the same period, however, there was a doubling of the actual energy demand, recorded in the statistics, from 22 GWh in 1960 to 44 GWh in 2000. Various factors affected the development in total energy demand during this period. The growth in number of dwellings in the stock and the increased use of household appliances would lead to an increase in the total energy demand. However, this increase was decelerated by improved energy standard in the stock, increase in the share of energy carriers and heating technologies with a higher system efficiency and a larger share of the stock being apartments with smaller floor area and lower energy intensities. All these factors are included in the model results. The changing adaptation factor  $f_A$ , shown in Fig. 6, i.e. measured over calculated energy, can explain the remaining difference between the model results and the statistics, including the changes in heating habits.

From 2000 onwards, there has been a decrease in the simulated total delivered energy, whereas the actual energy demand in dwellings, according to the statistics, was rather stable. Heat pumps were introduced to dwellings in 2004 [39]. In the period 2004–2015 this has led to a stronger decrease in the simulated total delivered energy (blue curve in Fig. 5). The yellow curve in Fig. 5 shows the estimated delivered energy if no heat pumps were used and direct electricity was used instead to meet the same heating energy need. The tendency would then have been a continuation of the long-term trend observed earlier, which indicates a discontinuity in the user behavior after heat pumps are installed. When the additional cost of increasing the indoor temperature is very low due to use of local energy sources (e.g. heat pump) or due to very high energy efficiency of the building, the indoor temperature is often increased. This is commonly referred to as the comfort factor [40].

Fig. 6 shows the estimated historical adaptation factor for heating and dhw,  $f_A$ , obtained by dividing the yearly statistics by the model results, representing the ratio of measured over calculated delivered energy demand. The electric load is kept outside this adaptation factor as its evolution is already estimated directly. A split trendline is used to cover the changing user behavior after the introduction of heat pumps from 2004.

The  $f_A$  trendline starts at a level of 0.4 in 1960 and ends at a level of 1.1 in 2015. The main reason for the lower adaptation factors backwards in time is different heating habits. Backwards in time, areas such as kitchen and living rooms were heated like today, others were heated much less (bedrooms and bathrooms) and some were not heated at all (basement and loft, that only later were con-

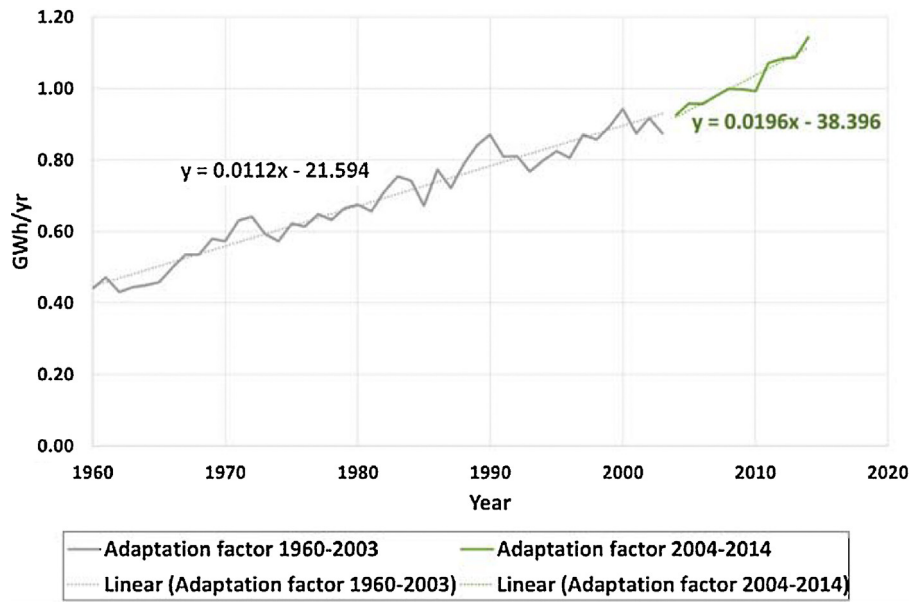


Fig. 6. Historical adaptation factor development.

verted to useful and heated floor area). Further, there might be some uncertainty in how well the energy need intensities in TABLE reflect the real averages of each segment. This uncertainty is also accounted for in the adaptation factors.

3.3. Scenario results

The scenario results for the development of total delivered energy are presented in Fig. 7. By definition, all scenarios have the same starting point in 1960 and thereafter the development differs between them. The discontinuity observed between 2003 and 2004 is due to the use of the split  $f_A$  trendline.

The red curve in Fig. 7 shows the results of the baseline scenario that represents the model results where we are aiming at reproducing the real development trend, as explained in Section 2.3. The baseline results corresponds well with the statistics presented in Fig. 5.

The blue dotted lines in Fig. 7 represent the scenarios 1–4, where 1) the energy efficiency standard of renovated buildings, 2) the energy efficiency of new construction, 3) the energy mix and 4) the outdoor climate are kept at the 1960 level, one at a time. These scenarios show that if these parameters had not changed since 1960, the energy demand in the dwelling stock would have increased to a higher level. The effect of combining all scenarios 1)–4) is shown in the solid blue line. If all these parameters were still at the 1960 level, the 2015 delivered energy would have been 94 TWh, which is more than a doubling of the baseline result. Consequently, significant energy intensity reductions the dwelling stock, represented by the shaded blue area in Fig. 7, has certainly already taken place since 1960.

The dotted green lines in Fig. 7 represent the scenarios 5 and 6, where 5) the thermal adaptation factor and 6) the average electric load are kept at the 1960 level, one at a time. The effect of combining the scenarios 5 and 6 is shown in the solid green line. If the thermal

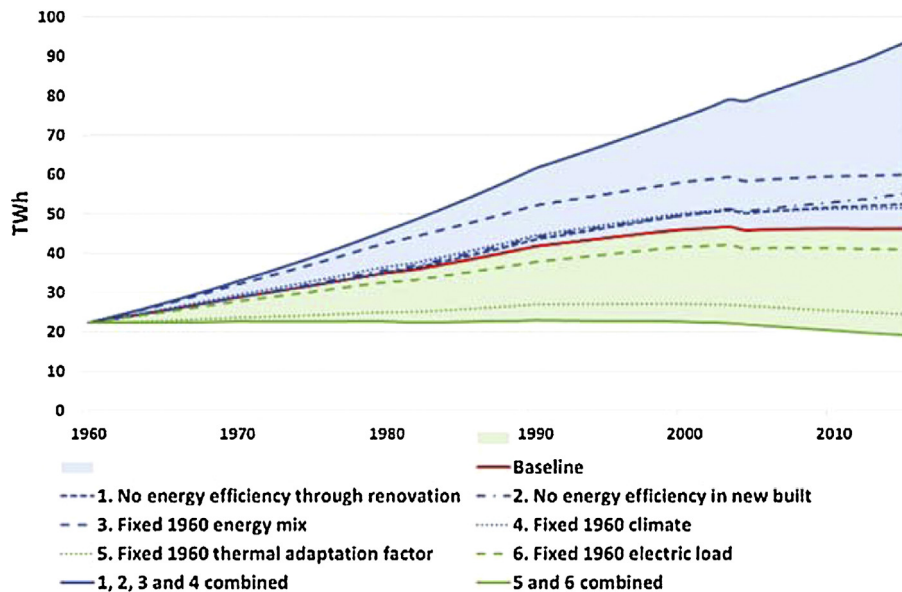


Fig. 7. Scenario results.



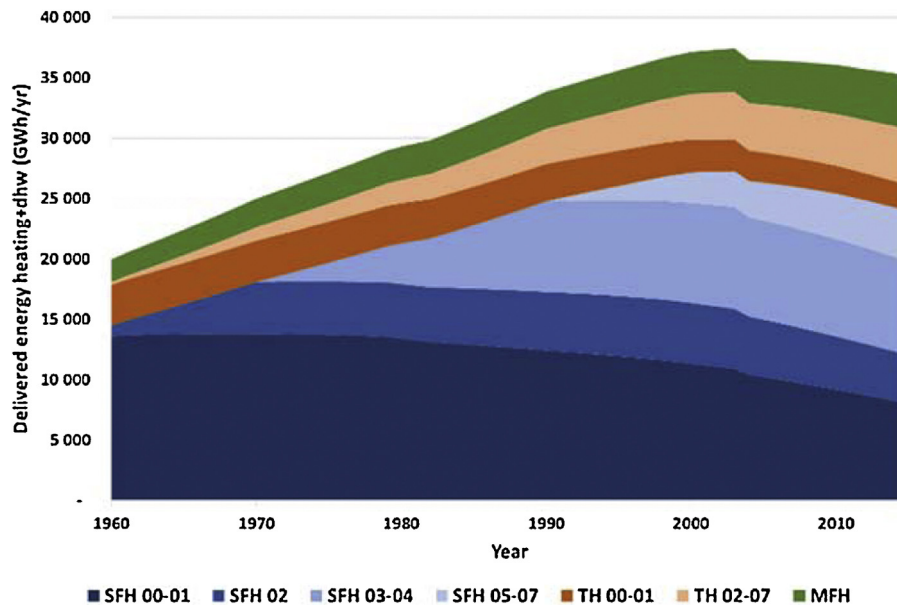


Fig. 8. Segmented results for the baseline scenario.

adaptation factor and the electric load were still at the 1960 level, the 2015 delivered energy would have been 19 TWh, 59% less than the baseline result. These scenarios show that energy savings in the stock have been offset by the changes in the adaptation factor and the electric load.

A “1960 Frozen scenario” where all parameters 1)–6) are kept at the 1960 level (not shown in Fig. 7) would lead to delivered energy of 38 TWh in 2015, 18% less than the baseline results. This means that in total, the factors leading to an increase in energy demand has had a larger effect than the energy savings that have been achieved in the system in the period 1960–2015.

Segmented results for the baseline scenario are presented in Fig. 8, illustrating the distribution of the total energy demand to different parts of the dwelling stock. For better readability of the figure, some segments are grouped together. Fig. 8 demonstrates that the major share of the energy demand has been in single family houses, and the single family houses constructed before 1955 play the most important role.

### 3.4. Importance of segments

The importance of different segments of the stock is further explored in Table 5 where the shares of the number of dwellings, total floor area and delivered energy for space heating and dhw for the same groups of segments are listed for the three observation years 1960, 1990 and 2015. In 1960, single-family houses constructed before 1955 dominated both the dwelling stock, the floor area stock and the energy demand, with shares of 54%, 66% and

69%, respectively. In 2015, this group of segments still accounts for 26% of the energy demand even though the share of the dwellings and floor area is reduced to 16% and 20%, respectively. In total, 49% of the current dwellings are single-family houses and they account for 64% of the floor area and 67% of the energy demand. The total share of terraced houses of the dwelling stock, floor area stock and the energy demand has been rather stable at about 23%, 19% and 18%, respectively, although terraced houses constructed before 1955 naturally played a much more important role in 1960 than in 2015. The share of multi-family houses of the dwelling stock and floor area stock has increased from 17% and 8% in 1960 to 29% and 16% in 2015, respectively and the share of the energy demand has increased from 7% in 1960 to 14% in 2015.

From the information in Table 5 we conclude that the largest future energy-saving potential in the Norwegian dwelling stock is still in the segment of single-family houses constructed before 1955. However, the total delivered energy demand in 2015 is well distributed over many dwelling segment groups. This indicates that future ambitious energy-saving policies will have to target renovation measures in a variety of dwelling types and age cohorts, and the choice of strategies and technologies should reflect this.

Finally, the development in average energy intensity per m<sup>2</sup> and the average energy demand per person are illustrated in Fig. 9. The yearly results of the baseline scenario are divided by the corresponding simulated total number of square meters in the stock and population, respectively. Improved energy efficiency of the stock, the changing energy mix and the higher average outdoor temperature lead to a decrease while the changing user behavior lead to

Table 5  
Shares of different segments in the dwelling stock, floor area stock and delivered energy (space heating and dhw) in 1960, 1990 and 2015.

		SFH 00-01	SFH 02	SFH 03-04	SFH 05-07	TH 00-01	TH 02-07	MFH
1960	Share of dwelling stock	51%	5%	0%	0%	21%	2%	22%
	Share of floor area stock	64%	6%	0%	0%	17%	2%	11%
	Share of delivered energy (heating + dhw)	68%	5%	0%	0%	17%	1%	9%
1990	Share of dwelling stock	25%	12%	20%	0%	10%	11%	20%
	Share of floor area stock	29%	11%	0%	0%	16%	3%	11%
	Share of delivered energy (heating + dhw)	37%	14%	22%	0%	9%	9%	9%
2015	Share of dwelling stock	14%	8%	15%	12%	6%	17%	28%
	Share of floor area stock	18%	11%	22%	16%	5%	15%	15%
	Share of delivered energy (heating + dhw)	23%	11%	22%	12%	6%	13%	13%

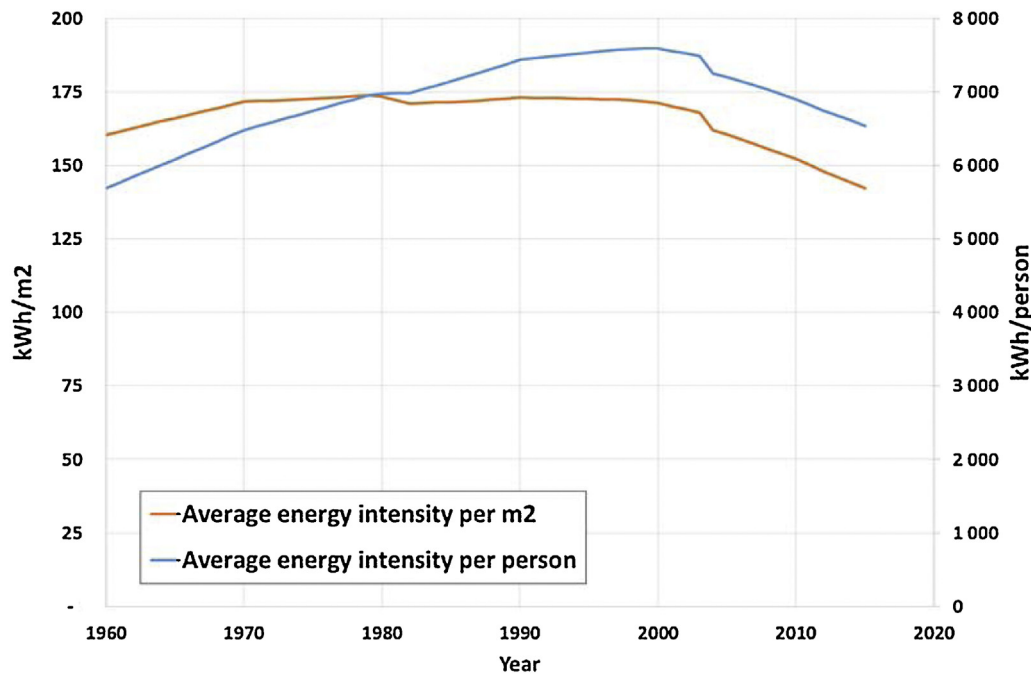


Fig. 9. Average energy intensity per m<sup>2</sup> and per person.

an increase in the energy intensities. In sum, the long-term trend from 1960 to 2003 shows that these factors have more or less neutralized each other in the case of average energy intensity per m<sup>2</sup>, which was at a rather stable level of 160–175 kWh/m<sup>2</sup>/yr. However, as the average floor area per person increased in the period, the average energy intensity per person increased correspondingly from 5700 kWh/person/yr in 1960 to 7500 kWh/person/yr in 2003. After the introduction of heat pumps, there has been a decrease in both intensities from 2003 to 2015. The simulated average 2015 energy intensities per m<sup>2</sup> and per person are 142 kWh/m<sup>2</sup>/yr and 6500 kWh/person/yr, respectively.

The total savings due to changing energy mix, energy efficiency of the stock and warmer climate are however cancelled out by the changing user behavior and the increased floor area demand per person. This is in line with findings in other studies where the theoretical effect of energy efficiency measures (or measures for other environmental issues) is higher than the real observed effect [41–45].

### 3.5. Sensitivity analysis

The sensitivity analysis investigates the impact on final results when changing the input parameters with high uncertainty. The parameters with high uncertainty identified in Table 4 are changed one at a time, by  $\pm 10\%$  or  $\pm 10$  years, while all other parameters are kept as in the baseline scenario. The sensitivity results for 2015, relative to the baseline results, are presented in Fig. 10. More detailed results from the sensitivity analysis, including a corresponding graph for 1960 as well as the full time series, are presented and discussed in Appendix D (Supplementary material).

The sensitivity analysis reveals large differences in the impacts of variations in different input parameters. Some parameters are a direct factor in the equation used to calculate the energy need for heating and dhw. A 10% change in these parameters will lead to a corresponding close to 8% change in the model results, or 10% change in the energy for heating and dhw excluding el-specific load. In the sensitivity analysis, this is the case for the parameters *share heated area* and *energy need intensities*. This demonstrates the importance of having both a good dwelling stock model and realis-

tic energy intensities to get reliable results in dwelling stock energy models.

Further, variations in the efficiencies of heating systems have corresponding large impacts on the resulting delivered energy. There is high uncertainty in the system efficiency for wood and fuel oil, whereas the uncertainty in the system efficiencies for electricity and district heating is low. Back in 1960, wood and fuel oil covered a large share of the household energy use. The real efficiencies of the heating systems used back then are also of higher uncertainty than the current equipment that is better documented. Consequently, there is some uncertainty in the model results in the beginning of the period under study, but as the model results are calibrated against statistics and the adaptation factor applied to the various scenarios, this will not influence the conclusions from the historical scenario analysis. From 1960 to 2015 the use of electricity for heating has increased and is currently dominating the energy mix. The share of district heating has also increased. The current uncertainty of average heating system efficiencies is therefore low.

Variations in *renovation cycle Rc* and *start year of renovation* also result in variations in the estimated delivered energy. A  $\pm 10\%$  in Rc and  $\pm 10$  years in the start year of renovation lead to a  $\pm 3$ –5% change in the simulated delivered energy for heating and dhw.  $\pm 10\%$  variation in the *share of energy need covered by heat pump* lead to a minor change of  $\pm 1\%$  in the simulated delivered energy for heating and dhw. When varying the *electric load* by  $\pm 10\%$ , the total delivered energy change by  $\pm 2\%$ .

Finally, variations of 10% in the lifetime parameters *average lifetime* and *share of never demolished buildings* do not lead to any significant change in the model results. This is an interesting finding as these parameters are considered to be highly uncertain. However, a difference larger than  $\pm 10\%$  is well possible for these parameters.

There are some significant uncertainties in the model, but the presented sensitivity analysis demonstrates that the model results are not very sensitive to changes in the most uncertain input parameters. Further, we claim that it is better to use a detailed model, where all important parameters are specified directly based on the best available information, rather than to make more superficial and linear assumptions that cannot be re-examined in the same

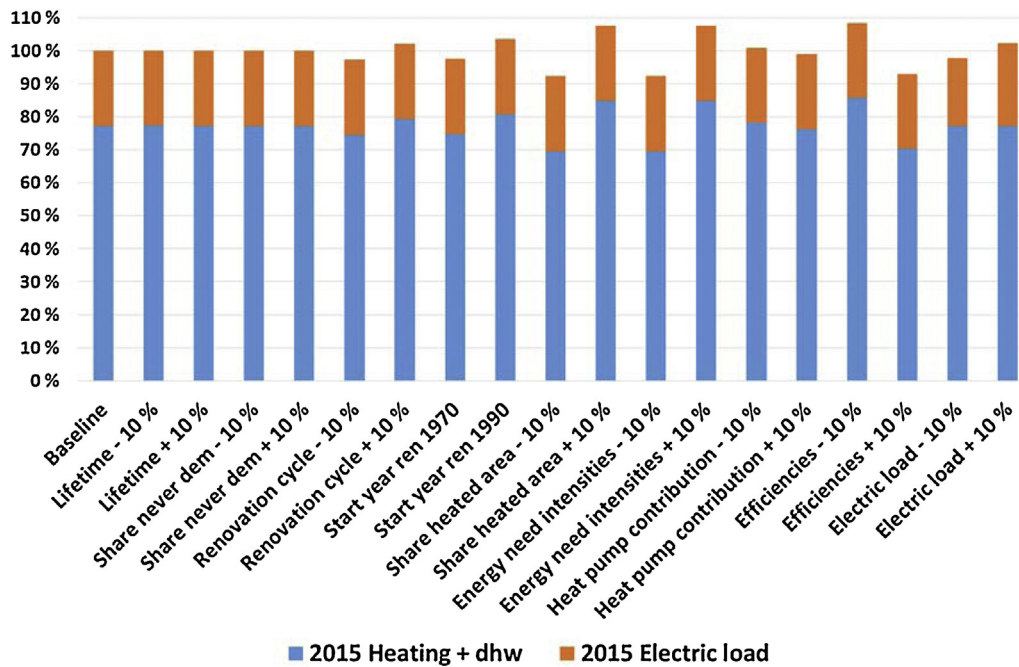


Fig. 10. Sensitivity analysis: Total delivered energy, relative to the baseline scenario in 2015.

way and are less likely to represent reality. When using the detailed model, all uncertainties can be identified and their relative effect on the final results and conclusions can be studied, and the reader can evaluate the reliability of the model results more easily. Actually, these aspects are some of the obvious strengths of modelling, also in situations where one has to accept uncertainty in input values and assumptions.

#### 4. Conclusions

The development of the Norwegian dwelling stock system is highly dynamic and strongly depends on the history of the system. There is in general a need for models describing the development in dwelling stocks in a realistic and detailed way. The dynamic building stock model outlined in this study is found useful for this purpose, and the model results correspond very well with the actual dwelling stock development in the statistics. The model is generic and can also be applied for other countries, or for different kinds of building stocks. Similar energy-related input data are e.g. readily available for the countries involved in the EPISCOPE project [30].

The scenario analysis shows that important energy savings have already taken place through the shift to more efficient energy carriers and heating systems, and this has improved a lot the overall technical energy efficiency of the Norwegian dwelling stock. The effect of the changing energy mix is at the same level as the combined effect of energy efficiency through renovation and new construction. Higher outdoor temperatures have also already lead to reductions in the energy demand. The total savings due to changing energy mix, energy efficiency of the stock and warmer climate are, however, cancelled out by the changing user behavior and a growing stock, i.e. increased floor area demand per person.

The average estimated energy demand per  $m^2$  was rather stable from 1960 to 2000 whereas the energy demand per person increased. In the same period, there was also a large increase in the population and heated floor area, leading to a strong increase in the total energy demand.

This historical analysis has shown that single-family houses have dominated the system in the past, both in terms of number of dwellings, number of square meters heated floor area, and

energy demand. The largest potential for further energy savings in the existing stock is found in old single-family houses. However, future ambitious energy-saving policies will have to target a variety of dwelling types and age cohorts.

The sensitivity analysis showed that the model results are directly related to the input parameters that determine the dwelling stock size and the average energy need intensity. This confirms our hypothesis that detailed and reliable models are needed both for the dwelling stock development and for the energy demand. Further, the sensitivity analysis showed that the model results were less sensitive to the input parameters that were of highest uncertainty, at least within the range of variation that was used in the sensitivity analysis. Therefore, we conclude that the model results are robust to changes in these input parameters and that the overall results of this model are of relatively low uncertainty when applied to the historical analysis.

The dynamic building stock energy model has proven to be suitable for explaining various important issues related to the past evolving energy demand in the Norwegian dwelling stock. Important changes in the system are also expected during the coming decades, and when analyzing future development pathways these can better be understood and implemented in a dynamic model compared to in a linear model. After now having successfully applied and calibrated our dynamic segmented building energy model to the historical energy demand from 1960 to 2015, we also believe the same way of modeling may serve as an excellent tool for analyzing possible effects of future energy-related policies. This would be relevant for both strategies and solutions in existing and in new buildings, and how these may help reach ambitious and needed greenhouse gas emission targets towards 2050.

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## Appendix A. Definitions

### • Definitions

- **Dwelling stock:** The total stock of dwellings in a system, defined for each year by its size and composition and measured in either number of dwellings or number of square meters
- **Dwelling type:** A classification of dwellings according to their characteristics. Three dwelling types are used: Single Family Houses (SFH), Terraced Houses (TH) and Multi Family Houses (MFH) [30]
- **Cohort:** A grouping of dwellings according to the period of construction. The cohorts used in this study are defined in Table 1.
- **Segment:** A share of the stock defined by dwelling type and cohort. Dwellings within the same segment are assumed to have similar characteristics in terms of size, energy need intensity at different renovation states etc.
- **Renovation period:** The renovation period defines if and when a dwelling has gone through its most recent renovation. Dwellings in their original state and dwellings exposed to renovation prior to 1980 are in renovation period 1, since the common renovation measures until then only to a little degree included energy-efficiency measures. Further, it is assumed that since 1980 technology has been available so that inclusion of energy-efficiency measures was possible whenever a dwelling was renovated. Dwellings renovated since 1980 are therefore placed in renovation period 2. The baseline assumption – used in model calibration and in some of the scenarios – is that renovations in renovation period 2 correspond to standard renovation.
- **Archetype:** A share of the stock defined by segment and renovation period
- **Energy need for heating and domestic hot water (dhw):** The amount of energy needed to heat the dwelling to a defined indoor temperature and to meet the demand for domestic hot water (dhw), resulting from the technical specifications of each archetype.
- **Electric load:** Electricity demand for appliances. (In the Norwegian case, this is only a small share of the total electricity demand, as electricity also covers a large share of the energy demand for heating and dhw.)
- **Delivered energy:** The amount of energy supplied to a dwelling in order to provide the estimated energy need. The conversion from energy need to delivered energy depends on 1) the share of the energy need that is covered by local energy (heat pump) 2) the shares covered by various energy sources and 3) the system efficiencies of the heating systems.
- **Total delivered energy:** The archetype-specific delivered energy per dwelling is multiplied with the number of dwellings in each archetype to obtain the total delivered energy in the system.
- **Simulated delivered energy:** The total delivered energy in the system, resulting from the model.
- **Measured delivered energy:** Total delivered energy in the system reported in statistics.
- **Energy efficiency of a dwelling:** The total mix of measures to improve the energy performance of a dwelling.
- **Adaptation factor:** The adaptation factor  $f_A$  is defined as the fraction measured over calculated energy demand, hence statistics over model results. The adaptation factor includes changing user behavior (heating habits) and uncertainty in model results.

## Appendix B-D Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.enbuild.2016.05.099>.

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