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

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ABSTRACT

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

1. Introduction

1.1. Background and context

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

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

1.2. Dwelling stock energy models applied in literature

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

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

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

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

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

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

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

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

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

1.3. Hypothesis and research questions

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

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

Main research questions are

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

Table 1
Dynamic models and studies for energy use in building stocks: classification by modelling dimensions and approaches.

Model approach	One type, one cohort	Multiple types, one cohort	Multiple types, multiple cohorts
Activity driven	Ozturk et al. [12] Lavenergiutvalget [15] The Climate and Pollution Agency [18] Buildings Performance Institute Europe [21]	Sartori et al. [13] Heeren et al. [16] Onat et al. [19]	Kohler et al. [14] Palmer et al. [17] Petersdorff et al. [20] U.S. Energy Information Administration [22] Siller et al. [23] Hens et al. [24] McKenna et al. [25] Reyna and Chester [26]
Stock driven	Sandberg et al. [27] Sandberg and Brattebø [29]		Global Buildings Performance Network [28] Boermans et al. [30] Pauliuk et al. [31] Bettgenhäuser [32] Vasquez et al. [5] Sandberg et al. [33]

ambitious and frequent renovation measures, b) increased use of local renewable energy sources, and c) likely rebound effects of future user behaviour?

2. Methodology

2.1. Analytical methods

The conceptual outline of the segmented dynamic dwelling stock model and its application for energy analyses is presented in Fig. 1. This shows how different variables are related to each other. The main principles of the model are explained below, and the mathematical framework is presented in Appendix A. Further description of the model and its algorithm is offered in previous publications [36,38].

The model consists of two parts, where the first part is the building stock model and the second is the building stock energy model. The core of the dwelling stock model is the population's demand for dwellings. Inputs to the model are time series for the historical and future development of the *population* and the lifestyle parameter *persons per dwelling*. From this, the size and composition of the dwelling stock is estimated for all years. Long time series are needed due to the long lifetime of buildings. The dwelling stock is distributed to segments according to the dwelling types and construction periods (cohorts).

Demolition activity is estimated by applying a demolition probability function to the construction activity from all previous years. Furthermore, mass-balance principles are used to estimate construction activity as what is needed to replace demolished dwellings and meet net change in demand.

Finally, the model aims at estimating the 'natural' renovation rate, resulting from the need for renovation during the ageing process of the dwellings. A cyclic renovation probability function is applied to construction activity from all previous years to estimate the renovation activity in the system. While demolition of a dwelling can happen only once, renovation can happen several times during a building's lifetime. The average time between renovations of a certain type is case specific and is defined according to the type of renovation under study. The renovation activity does not affect the stock's size or age composition.

The energy-efficiency state of a dwelling can be substantially improved when the dwelling is renovated. In the model, this is implemented by the use of archetypes. Each segment, defined by dwelling type and cohort, is divided into three archetypes according to three renovation periods that refer to if and when the dwelling was last renovated. Dwellings being in their original state are placed in archetype 1. If a dwelling was renovated so far back in time, during renovation period 1, that the renovation was assumed not to significantly affect the energy-efficiency state of the building envelope, the dwelling remained in archetype 1. From the start of renovation period 2, energy-efficiency measures are assumed to be commonly introduced during dwelling renovation. Hence, dwellings going through renovation in renovation period 2 are moved from archetype 1 to archetype 2. Future renovation, in renovation period 3, characterized by possible even more improved energy-efficiency measures, makes dwellings move to archetype 3.

In the building stock energy model, the stock composition in number of dwellings per archetype and year is combined with segment-specific average heated floor area per dwelling and bottom-up determined archetype-specific energy parameters: i.e. energy need intensities, contribution from local energy sources, weighted average efficiency of heating systems and energy mix. This is used to estimate the energy need, delivered energy and use of different energy carriers for all years, either for the total stock, per dwelling type, cohort, segment or archetype. The energy need depends on the technical standard of the building envelope and is the amount of energy needed for space heating or cooling, domestic hot water, ventilation and electrical appliances. The delivered energy is the amount of energy that has to be delivered to the dwelling to fulfil the energy need after accounting for onsite energy generation and losses in the heating system.

The technical estimated energy demand may differ from the real energy consumption. In buildings of poor energy quality, the real energy use is commonly lower than the technical estimate as smaller shares of the building is heated to the temperatures assumed in the technical estimate. This is called a 'prebound effect' [39,40]. On the other hand, a 'rebound effect' is observed when a highly energy-efficient dwelling is heated to higher temperatures than assumed in the technical estimate, due to the comfort factor and the low additional cost of increased temperatures [39–41]. The real energy saving after renovation might be significantly lower than the technical energy-saving potential [40]. In the present model, a thermal adaptation factor is applied to the technical estimated energy demand of the dwelling stock, to correct for possible prebound and rebound effects and to estimate the 'real' energy demand.

2.2. Data and assumptions for the Norwegian case

The presented model is generic and can be applied to any dwelling stock and to any time period. In the following, we present a scenario analysis for future development in energy demand in the Norwegian dwelling stock towards 2050. Data and assumptions are presented briefly below and in depth in Appendix B. A summary of the parameter values of the input data in the years 2016 and 2050 is given in Table 2, with data sources and underlying assumptions and followed by explanations of important definitions and assumptions applied in the study.

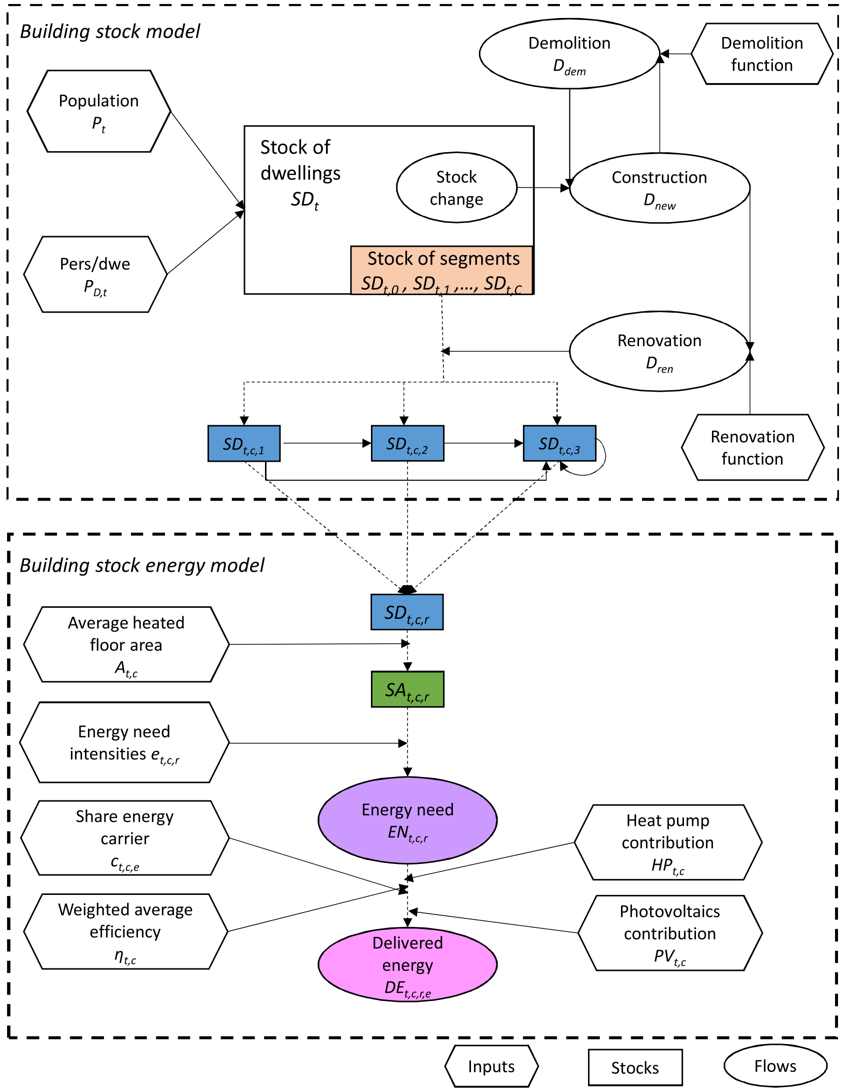

Fig. 1. Conceptual outline of the building stock model and the building stock energy model. Hexagons represent input variables, rectangles represent stocks and ovals represent flows. All inputs and outputs are time-dependent.

The combination of increasing population and decreasing number of persons per dwellings leads to a growing stock. The lifetime probability function is assumed to follow a Weibull distribution with an average lifetime of dwellings of 125 years.

The definition of the renovation activity is case-specific in the model. In this study, we explore the dynamics of renovations of building envelopes that have the potential for including energy-efficiency measures leading 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 for other reasons anyway. Hence, such measures could be implemented when the dwelling is renovated because of a 'natural' need for maintenance and upgrading due to its ageing process. In this study, we assume deep renovation of facades to occur in renovation cycles of 40 years, and we estimate the total renovation activity resulting from this ageing process of the dwelling stock in Norway. These changes in the building envelopes affect the energy need of the dwelling stock.

The dwelling types Single Family House (SFH), Terraced House (TH) and Multi Family House (MFH) and 9 cohorts are applied in the analysis. The cohorts are defined in Table 3 together with the heated floor area per dwelling in each segment. Energy need intensities per type/cohort/renovation variant are taken from the IEE research project EPISCOPE [54], where a set of buildings representing type/cohort combinations in the national dwelling stocks of a range of European countries has been described in detail. The technical standard including energy intensities has been described in detail for each building in their original state, for a standard renovation as well as an advanced renovation. In the Norwegian typology, the energy need intensities decrease from older cohorts to newer (up to 258 kWh/m^2 in original state for dwellings constructed before 1955 and 35 kWh/m^2 in future dwellings constructed after 2020) as well as from original state to standard or advanced renovation (decreasing by up to 50% and 75%, respectively) [37].

The archetypes are defined by the dwelling type, cohort and renovation period. The actual renovation variant (original state, standard renovation or advanced renovation) and its corresponding energy need intensity, chosen for each renovation period, is defined as part of scenario assumptions.

Technology changes in the building envelopes affect the energy need in the system. In parallel, we may have changes in energy mix and increased use of local energy sources, which affect the conversion from energy need to delivered energy. Archetype specific and time dependent assumptions on energy mix and use of local energy sources are made use of in the analysis.

Table 2
Overview of parameter values in 2016 and 2050, with data sources and short explanations.

	2016 value	Source/comment	2050 value	Source/comment
Population	5.2 million	Statistics Norway [42]	6.7 million	Statistics Norway [42]
Persons per dwelling	2.2	Statistics Norway [43]	2.1	Assumption
Average lifetime of dwellings	125 years	Estimation in line with Bohne et al. [44]	125 years	Assumed continuation of trends
Average heated floor area per dwelling	Segment specific	Statistics Norway [45]	Segment specific	Assumed continuation of trends
Renovation cycle (deep renovation of facades)	40 years	Estimation in line with Kristjansdottir et al. [46]	Scenario specific	Assumed continuation of trends
Energy need intensities for heating and domestic hot water	Archetype specific	EPISCOPE [37]	Archetype and scenario specific	EPISCOPE [37]
Energy mix	Segment specific	Statistics Norway [47]	Segment specific	Assumed continuation of trends and out phasing of fuel oil
System efficiencies	Energy carrier specific	Standards Norway [48]	Energy carrier specific	Assumed continuation of trends
Electric load	4500 kWh/dwelling	Standards Norway [48]	4500 kWh/dwelling	Assumed continuation of trends
Share having heat pump	Segment specific	Statistics Norway [49]	Scenario specific	Continuation of trends/assumptions
Average COP	Segment specific	Statistics Norway/Standards Norway [47,48]	Scenario specific	Assumptions
Share of heating demand covered by heat pump	40%	Prognosesenteret AS [50]	Scenario specific	Assumptions
Share having photovoltaics	0	Statistics Norway [49]	Cohort and scenario specific	Assumptions
Energy production from photovoltaics	Segment specific	EPISCOPE [37]	Segment specific	EPISCOPE [37]
Outdoor climate (HDD factor, relative difference in heating need from 1961–1990 average)	0.88	Norwegian Meteorological Institute [51–53]	0.76	Norwegian Meteorological Institute [51–53]
Average thermal adaptation factor (Real/theoretical energy demand)	1.37	Trendline presented in Fig. 2	0.91	Trendline presented in Fig. 2

Table 3
Cohort definition and average heated floor area per segment.

Cohort number	0	1	2	3	4	5	6	7
Start year	–	1801	1956	1971	1981	1991	2001	2011
End year	1800	1955	1970	1980	1990	2000	2010	2020
HFA SFH (m^2)	133	133	139	144	161	139	142	152
HFA TH (m^2)	88	88	101	100	96	85	88	96
HFA MFH (m^2)	56	56	53	61	64	58	60	68

Norway is a unique case internationally, as the energy mix for dwellings is by far dominated by electricity [21]. The current overall energy mix for heating and domestic hot water is 77% electricity, 19% bio-fuels and wood, 3% fuel oil and 2% district heating. Fuel oil is phased out by 2020 [55]. Only heat pumps and photovoltaics (PV) are considered relevant for utilization of local energy sources in the Norwegian dwelling stock system.

The energy demand for space heating is corrected for expected future development in outdoor climate. The official Norwegian projections for the temperature change according to IPCC's RCP4.5 scenario is applied [52,53].

A thermal adaptation factor is developed and applied to correct for all factors that make the real energy demand for heating and hot water differ from the theoretical estimate. User behaviour will dominate the factor, and the adaptation factor corrects for heating habits varying between dwellings of different energy state. Empirical data from various sources [47,56,57] are used to estimate the average divergence of real energy demand from the theoretical estimate in dwellings of different type and energy state. In Fig. 2, the 45° line indicates the situation where there is no adaptation, as the real energy demand is equal to the theoretical estimate. The linear trendline resulting from the empirical data, however, is less steep than the 45° line. This implies that in very energy efficient buildings, the average real energy use is higher than the technical estimate, and in very inefficient buildings, the average real energy use is lower. According to the available observations, the turning point is in dwellings with technical estimated energy demand of about 100 kWh/m^2, where the average measured real demand is the same.

The dwelling stock energy model is calibrated against real historical development in our previous publications [33,36,38]. The model results are compared with statistics on real dwelling stock development [36,38], construction, demolition and renovation activity [38] and calibrated against energy statistics [33]. The model was found suitable for this type of analyses. Naturally, it is not possible to calibrate the future development as the real development is not yet known.

2.3. Scenario analysis

A scenario analysis is carried out to evaluate the effects of different possible strategies for energy savings in the dwelling stock system. The conceptual outline of the scenario analysis is presented in Fig. 3 and the detailed specifications of all scenarios are listed in Table 4. The *Baseline scenario* is constituted by the assumptions on future development in the system that are considered most likely, according to the present common practice, recent trends and known policies, regulations for the near future and qualified assumptions. Three alternative development paths differ from the baseline: 1) Advanced rather than standard renovation, 2) rapid introduction of local energy sources and 3) more frequent renovation. The effect of each strategy as well as combinations of them are evaluated in Scenario 1–6. The combination of advanced and frequent renovation constitutes the 'Minimizing energy need scenario', whereas the combination of all three constitutes the 'Minimizing delivered energy scenario'. The estimated total delivered energy will be the final model outcome of all scenarios, in GWh/year.

2.4. Uncertainty of input parameters

In a perturbation analysis, various inputs are changed marginally, one at a time, and the effects on the final results are studied [58]. This effect is measured through the sensitivity ratio

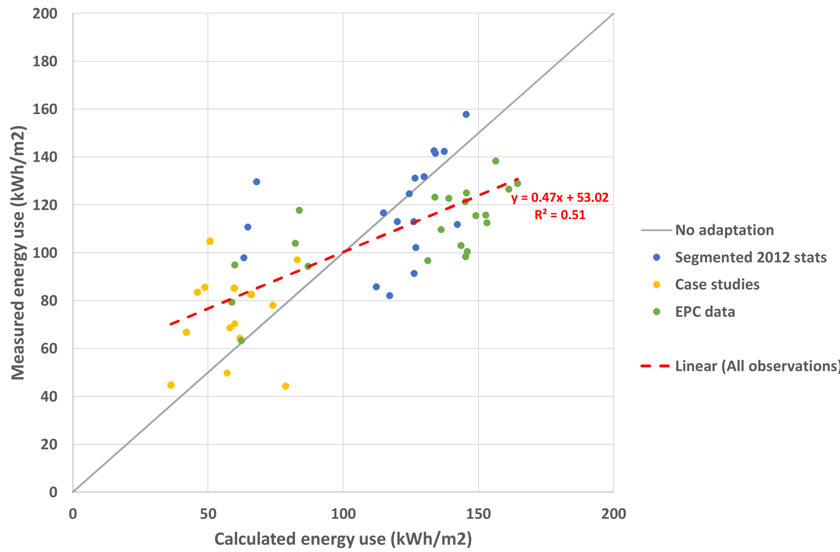

Fig. 2. Thermal adaptation factor trendline. Linear trendline from empirical observations for measured versus calculated energy use (current trends).

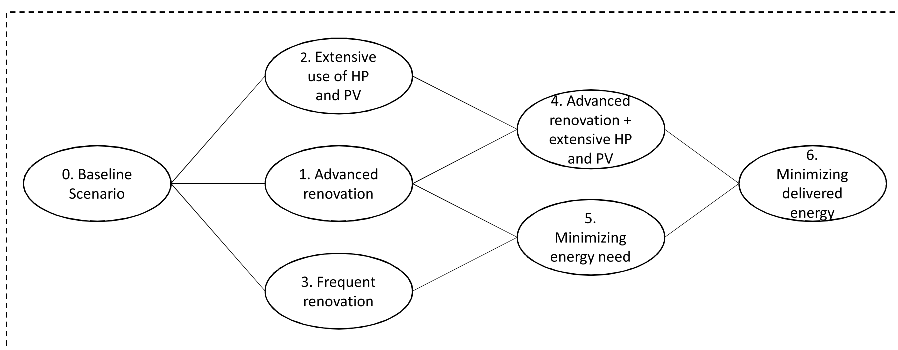

Fig. 3. Conceptual outline of the scenario analysis. The lines between the scenarios indicate how the scenarios build on each other, as they either include a change from the Baseline scenario (Scenario 1–3), or combinations of changes (4–6).

Table 4
Scenario specification.

Scenario description	Ambition level of renovation after 2020	Use of local energy sources	Renovation cycle after 2020
0. Baseline	Standard renovation	Following trends/expected future development	40 years
1. Advanced renovation	Advanced renovation	Following trends/expected future development	40 years
2. Extensive use of local energy sources (heat pumps and photovoltaics)	Standard renovation	Extensive use of HP and PV	40 years
3. More frequent renovation	Standard renovation	Following trends/expected future development	30 years
4. Advanced renovation and extensive use of local energy sources	Advanced renovation	Extensive use of HP and PV	40 years
5. Minimizing energy need: Advanced and frequent renovation	Advanced renovation	Following trends/expected future development	30 years
6. Minimizing delivered energy: Advanced and frequent renovation and extensive use of local energy sources	Advanced renovation	Extensive use of HP and PV	30 years

(SR) which is the fraction of the relative change in the result ($\Delta R/R_0$) over the relative change in the input parameter ($\Delta P/P_0$), as shown in Eq. (1) [59], where P_0 is the initial parameter value and R_0 is the initial result

$$SR == \frac{\Delta R/R_0}{\Delta P/P_0} \quad (1)$$

In this study, the sensitivity ratio is used to quantify the effect of a change in selected input parameters, on the final results, for delivered energy in the end year of the analysis, 2050.

There is uncertainty related to all model input parameters. However, the uncertainty of stock-related inputs is studied in detail in previous publications [33,60] and will not be repeated here, as their findings are valid also for the present application of the model. The uncertainty of the energy-related input parameters will however be explored, as this is not covered in earlier publications. Table 5 gives an overview of these variables, their sources, an evaluation of their uncertainty and how they are varied in the perturbation analysis (low and high variants). For most variables, a ± 10% change of the 2050 value is used in the perturbation analysis. For the average system efficiency, a +10% change would result in an efficiency larger than 1, which is impossible. Therefore, ± 2% is used for this variable. For the outdoor climate ± 5% is used, as a larger decrease would lead to temperatures lower than the current ones, which is not realistic.

3. Results and discussion

3.1. Evolution of the dwelling stock

The evolution of the Norwegian dwelling stock from 1960 to 2050 is presented in Figs. 4 and 5. Both figures show how the total stock of heated floor area has more than doubled from 115 million m^2 in 1960 to the current level of 255 million m^2, and that the stock is expected to increase further to 324 million m^2 by 2050. The historical stock growth is due to increase in the population combined with a decrease in the number of persons per dwelling. The future stock growth is mainly driven by the expected further increase in the population, as the number of persons per dwelling is expected to stabilize. The total stock size and composition of segments is the same in all scenarios, but the future energy state of dwellings in the various segments varies between the scenarios.

The dynamics of the stock (dwelling stock model outputs) are presented in Fig. 4 as the changing stock composition of heated floor area in dwellings of various renovation states and construction periods, according to the *Baseline scenario*. The area marked A in Fig. 4 represents dwellings constructed prior to 2020 and remaining in their original state or renovated before 1980 (without a significant energy-saving effect). Area B represents past constructions that has been subject to historical renovation in the period 1980–2020 (with an energy-saving effect corresponding to a segment-specific standard renovation). Area C represents constructions subject to future renovation after 2020, and area D represents future new construction after 2020 (according to passive house energy standards). Hence, A and B represent the share of the stock that is not expected to be changed with respect to energy state in the period 2020–2050, if following the 'natural' renovation cycle. The actual potential for improved energy efficiency in the stock is hence limited to C and D. Therefore, 50% of the 2020 stock is expected to be unchanged until 2050, either still remaining in the original state or in the state of a historical renovation. To improve the energy efficiency of the stock, it is therefore highly important that the opportunity is taken to introduce energy-efficiency measures when dwellings are renovated after 2020 (C), and that new construction (D) are as energy-efficient as possible. If reducing the renovation cycle to 30 years from 2020 onwards, as in Scenario 3, a larger share of the stock will be renovated, but 36% of the 2020 stock will still be unchanged by 2050.

Fig. 5 shows how the energy efficiency of the stock evolves over time, according to the *Baseline scenario*. An important improvement in the energy efficiency of the stock has already taken place and is expected to continue towards 2050. The grey wedge band represents old buildings of poor energy efficiency, with energy need intensities higher than 150 kWh/m^2. After 1980, they are decreasing in number as they are either upgraded through renovation or phased out through demolition. The solid yellow wedge band is the share of the stock being in its original state with an energy need intensity in the range 101–150 kWh/m^2, whereas the patterned yellow is the share that has reached this level through renovation. The corresponding green and blue wedge bands represent the higher energy standard ranges of 51–100 kWh/m^2 and larger than 51 kWh/m^2, respectively.

Fig. 5 is an effective way of visualizing the shares of the dwelling stock that represent various energy-efficiency levels, for any year between 1960 and 2050. As an example, in 1960 all dwellings performed worse than 150 kWh/m^2, and in 2000 roughly half of the dwellings performed in the range 101–150 kWh/m^2. The figure shows that, according to the *Baseline scenario*, after 2020 only a very small share of the dwelling stock will have an energy need intensity larger than 150 kWh/m^2. Further, a large share of the future stock will be in the range of 101–150 kWh/m^2, the share of the stock being in the range 51–100 kWh/m^2 will be rather stable, and the share having an energy need intensity less than 51 kWh/m^2 is increasing steadily.

If the energy efficiency after renovation or the frequency of the renovation differs from the assumptions in the *Baseline scenario*, the wedge bands in Fig. 5 would evolve differently. In Table 6, snapshots of the stock composition in 2016, 2030 and 2050 are presented for the scenarios that involve different renovation regimes (Scenarios 1, 3 and 5). Graphs showing the full time series for these scenarios are given in Appendix D.

Table 6 demonstrates that the share of very inefficient dwellings with energy need intensities higher than 150 kWh/m^2 is decreasing to the same level regardless of the choice of renovation regime. Even without advanced or more frequent renovation, standard renovation of 'normal' cycles is expected to reduce this share to the level of the dwellings that remain in the original state for heritage reasons. Furthermore, the future share of very energy efficient dwellings does not differ much between the scenarios. This is because only cohort 7 and 8 can reach an energy need intensity below 51 kWh/m^2. In cohort 7, this is an effect from either standard or advanced renovation, and in cohort 8 even in original state. Hence, only a more frequent renovation of cohort 7 (Scenario 3 and 5) will increase the share of very energy efficient dwellings.

However, there are significant differences between the scenarios regarding future shares of the stock in the range of 51–100 kWh/m^2 rather than 101–150 kWh/m^2. Advanced renovation (Scenario 1 and 5) will strongly increase this share, while the share being in the range of 101–150 kWh/m^2 will remain unchanged if more frequent standard renovation is applied (Scenario 3).

When modelling developments in dwelling stock energy use, underlying models and assumptions are used to describe how the dwelling stock and energy intensities are changing over time. Realistic models are needed to avoid that a simplified underlying stock model and/or renovation rates leads to unrealistic results for the estimated future energy demand. The presented segmented and dynamic dwelling stock model gives a detailed description and thorough understanding of the changing size and composition of dwelling stocks, in terms of dwelling types, cohorts and renovation state. The model therefore forms a necessary basis and is well suited to be applied for energy analyses.

3.2. Scenario results on total delivered energy

The scenario results on total delivered energy are given in Figs. 6 and 7. Fig. 6 shows the total delivered energy for all scenarios in years 2016, 2030 and 2050, both as the theoretical technical estimate and the estimated 'real' delivered energy after applying the thermal adaptation factor and accounting for occupant behaviour. The technical estimated delivered energy is decreasing in all scenarios. The *Baseline scenario* shows a reduction of 23% from 2016 to 2050, which is a significant improvement given the 27% stock growth during the same period. Only minor further reductions are expected in Scenario 1, 3 and 5, which assume more use of advanced and/or frequent renovation than the *Baseline scenario*. This is in stark contrast to the significant reductions shown for Scenario 2, 4 and 6, which involve more extensive use of local energy sources by use of heat pumps and PV than in the *Baseline scenario*. This is a very interesting finding; extensive use of local energy sources has

Table 5
Variables to be studied in the sensitivity analysis.

Parameter	Source	Evaluation of the data uncertainty	Variations applied in the perturbation analysis
Energy need intensities	TABULA	High	±10% in 2050
Contribution from heat pump	NS3031 and assumptions	High	±10% in 2050
Contribution from photovoltaics	TABULA	Medium	±10% in 2050
Average system efficiency	Assumed continuation of trends	Low	±2% in 2050
Future outdoor climate (HDD)	Official projections	High	±5% in 2050
Electric load	Assumed continuation of trends	High	±10% in 2050
Adaptation factor	Statistics and case studies	High	±10% in 2050

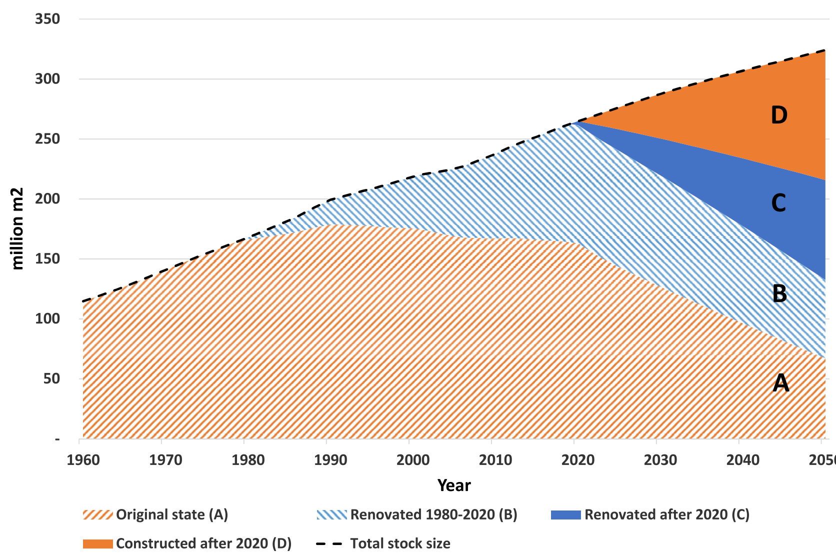

Fig. 4. Dwelling stock (heated floor area) evolution 1960–2050. Shares of the stock being in original state, renovated 1980–2020, renovated after 2020 and constructed after 2020. Baseline scenario.

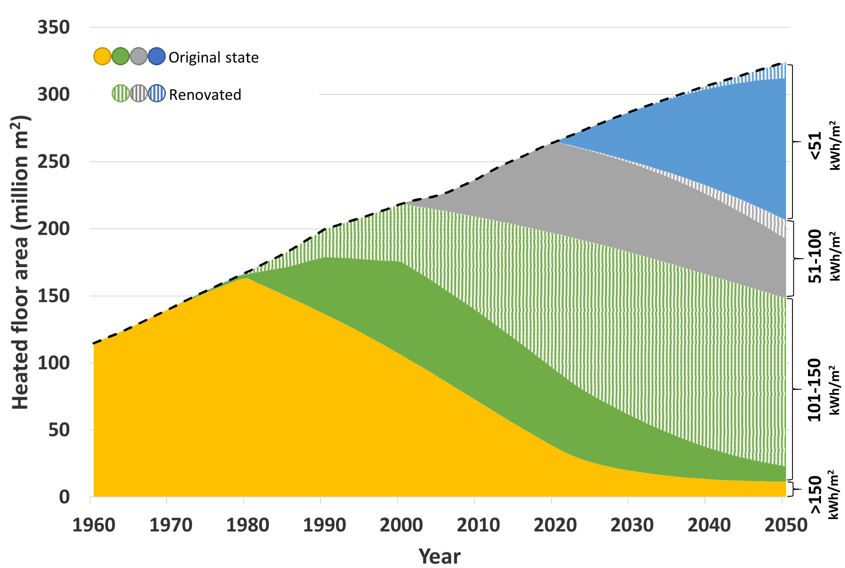

Fig. 5. Shares of the stock being of different states and energy need intensities. Evolution 1960–2050. Baseline scenario.

the potential for much larger reductions in total delivered energy than implementation of advanced and more frequent renovation. Scenario 6, which is the most optimistic scenario, shows a 52% reduction in theoretical estimated total delivered energy from 2016 to 2050.

The limited effect of ambitious and more frequent renovation is explained by the applied archetype-specific energy need intensities (presented in Appendix B). Even standard renovation of old dwellings constructed before 1955 gives an energy saving of up to 100 kWh/m^2. In dwellings constructed in the period 1956–2000, savings up to 80 kWh/m^2 are possible, and the potential for savings through standard renovation of dwellings constructed after 2000 is up to 30 kWh/m^2. Large savings are possible through standard renovation of existing dwellings in their original state, but a major share of this potential has already been realized in the past. The remaining potential for energy efficiency through renovation is

Table 6
Shares of the stock having various energy need intensities in 2016, 2040 and 2050, according to the Baseline scenario and Scenario 1,3 and 5.

		<51 kWh/m²		51–100 kWh/m²		101–150 kWh/m²		>150 kWh/m²		Total	
		million m²	Shares	million m²	Shares	million m²	Shares	million m²	Shares	million m²	Shares
2016	All scenarios	0	0%	53	21%	151	59%	50	20%	255	100%
2030	Baseline	38	13%	68	24%	162	56%	19	7%	288	100%
	Scenario 1	38	13%	97	34%	133	46%	19	7%	288	100%
	Scenario 3	38	13%	67	23%	165	57%	17	6%	288	100%
	Scenario 5	38	13%	105	36%	127	44%	17	6%	288	100%
2050	Baseline	118	36%	58	18%	136	42%	12	4%	324	100%
	Scenario 1	118	36%	118	36%	76	24%	12	4%	324	100%
	Scenario 3	133	41%	43	13%	136	42%	12	4%	324	100%
	Scenario 5	133	41%	119	37%	60	18%	12	4%	324	100%

therefore limited to standard renovation of the small share of older existing dwellings that are still in the original state, standard renovation of newer existing dwellings where the savings are lower, and further upgrades of the existing stock through advanced renovation. Advanced renovation can give additional savings of up to 84 kWh/m², compared to a standard renovation, and the potential savings are largest in older dwellings.

In total, it is obvious that important work has already been carried out to improve the energy efficiency of the dwelling stock. It is still possible to achieve further savings through renovation, but a large share of the potential has already been used. New construction from after 2020 is assumed to always be of passive house standard, where additional reductions in the energy need intensity is likely not possible through renovation. Savings in the delivered energy to these are only possible through increased use of local energy sources.

Fig. 6 shows that when assuming extensive use of local energy sources, there is a substantial further decrease in the technical estimated total delivered energy in 2050. In Scenario 6 (the *Minimizing delivered energy scenario*) where extensive use of heat pump and PV is combined with frequent and advanced renovation, the technical estimated delivered energy is 52% lower in 2050 than in 2016, despite the 27% growth in total dwelling stock.

In 2016, the estimated 'real' delivered energy, after applying the thermal adaptation factor, is 7% lower than the technical estimated delivered energy. Hence, there is an aggregated prebound effect in the dwelling stock in 2016, where the user behaviour including heating habits on average leads to lower estimated 'real' energy use than the technical estimate. This can be explained by Fig. 5 that shows how the 2016 stock is still dominated by dwellings with average energy need intensities larger than 100 kWh/m². However, by 2030, the number of very inefficient dwellings has decreased and a substantial number of dwellings with energy need intensity below 100 kWh have entered the stock. By then, an aggregated rebound effect occurs in all scenarios, as the comfort factor is expected to make the real energy use higher than the technical estimate, according to what is observed in highly energy-efficient buildings today (see Fig. 2). By 2050, this rebound effect is surprisingly large, as the estimated total 'real' delivered energy is 20–28% larger than the technical estimate in all scenarios. In the *Baseline scenario*, the estimated total 'real' delivered energy only decreases only by 1% from 2016 to 2050. Hence, user heating habits in dwellings with high energy standard may counteract a significant improvement in real total delivered energy in future. This is a highly policy-relevant and important finding. The expected future rebound effect should be addressed further in aggregated studies to obtain deeper insight on this phenomenon.

Furthermore, the historical and expected near-future elimination of the prebound effect is desired from a user perspective, as this is obtained by raising the average indoor temperature to a comfortable level. However, further increase in the indoor temperature, recognized as the comfort effect in very energy-efficient buildings, is unnecessary and should be avoided. Policy should therefore aim at counteracting this future likely large rebound effect by influencing user behaviour through information, smart steering of the energy use and smart house design principles, as well as the introduction of differentiated energy price structures (such as the use of two-step tariffs).

Regardless of the effects of applying the adaptation factor, the simulations show that use of local energy sources has a much larger potential for future reductions in total delivered energy than ambitious or more frequent renovation. This is another interesting finding, as use of local energy sources is also considered more cost-efficient.

Fig. 7 shows the energy mix, as well as the energy from heat pump and PV, in 2016 and in the various scenarios in 2050. The delivered energy for heating and hot water is expected to decrease in all scenarios, by 15–65%. Again, the largest reductions are found in the scenarios with extensive use of local energy sources.

Fig. 7 also demonstrates how the electric load will increase in importance, both in absolute and relative terms. The total el-specific energy use is expected to increase by 34% from 2016 to 2050. Further, the share of the total delivered energy being electric load is expected to increase from 28% in 2016 to 37–59% by 2050 in the various scenarios. Finally, from 2016 to 2050, the local energy utilized by heat pumps and PV is expected to increase by 90–130% in the scenarios assuming the baseline use of local energy sources and by 325–385% in the scenarios assuming extensive use of these. However, the contribution from PV will not be able to cover the electric load in 2050, not even when assuming extensive use of PV.

Furthermore, the model can be used to study the importance of various stock segments on the results for the total stock. Although the increase of the dwelling stock will mainly be in terraced houses and multifamily houses (THs and MFHs), the energy use in the system will still be dominated by old single-family houses (SFHs) in 2050. SFHs also have the largest potential for production of electricity from PV. Segmented results are given in Appendix D.

Finally, the presented future scenario results should not be regarded as predictions that aim at projecting precisely the future development in energy demand. The exact value of the simulated energy demand in each of the scenarios in e.g. 2050 is of less importance than insights to help understanding the expected differences between potential future development paths, and identifying the main causes of these differences. The various factors in the segmented dynamic dwelling stock model are defined precisely and vary between the scenarios, and hence the model can be used to evaluate the importance of each factor.

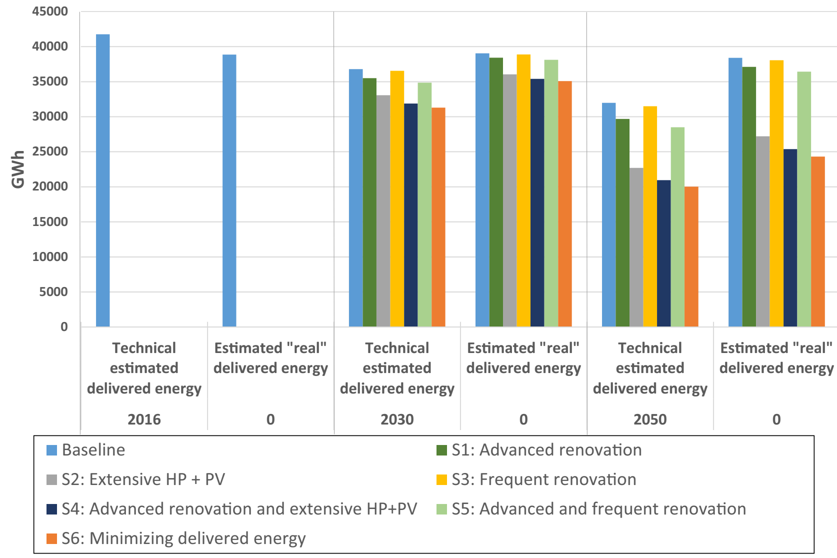

Fig. 6. Scenario results total delivered energy in 2016, 2030 and 2050. 'Technical estimated delivered energy' refers to the energy demand calculated according to the technical standard of the dwellings while 'Estimated "real" delivered energy' is the estimated energy demand after correcting for prebound/rebound effect.

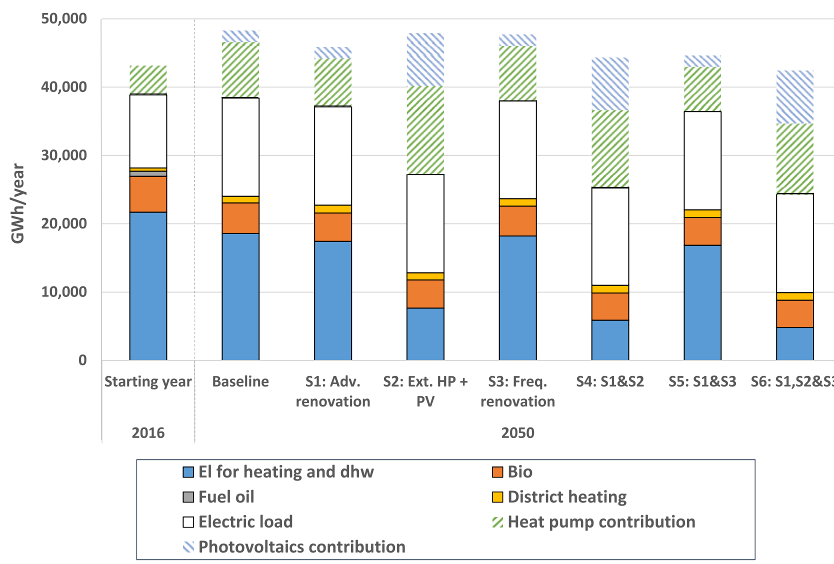

Fig. 7. Energy mix in 2016 and in all scenarios in 2050. Estimated 'real' total delivered energy. The net thermal delivered energy equals the sum of electricity for heating and dhw, bio, fuel oil and district heating. The total net delivered energy also includes electric load. The local energy used in each scenario is the sum of 'Heat pump contribution' and 'Photovoltaics contribution'.

3.3. Sensitivity analysis

The perturbation analysis is used to evaluate the effect of an arbitrary change in the energy-related input parameters on the model results for total delivered energy in 2050. The input parameters are changed one at a time, as described in Table 5.

The absolute value of the sensitivity ratio *SR* in year 2050 is shown in Fig. 8 for both the *Baseline scenario* and Scenario 6 *Minimizing delivered energy*. For some of the input parameters, the corresponding sensitivity ratio is negative, which tells that an increase in the input leads to a decrease in the results and vice versa. This is the case for the contribution from heat pump, contribution from PV and average system efficiencies. The absolute values of the corresponding SRs are presented in Fig. 8 for better readability.

The effect of changing the input parameters is different in the *Baseline scenario* and the *Minimizing delivered energy scenario*. The highest *SR* value is 0.63, and is found for the adaptation factor in the *Baseline scenario*. In Scenario 6, the corresponding *SR* is 0.41. This is because the energy for heating and dhw, which the adaptation factor is applied to, has a larger share of the total energy demand in the *Baseline scenario*. Changes in the future outdoor climate also have a higher related *SR* in the *Baseline scenario* where there is a higher energy need for heating. However, this parameter shows low *SR* values that indicate a much lower effect on the result.

On the contrary, the contribution from heat pump, contribution from PV and the electric load have higher shares in Scenario 6 and the related *SRs* are higher than in the *Baseline scenario*. The effect of changes in the energy need intensities and the average system efficiencies is also higher in Scenario 6 than in the *Baseline scenario*. This is because the parameter change leads to a corresponding change in the sum of energy delivered from carriers and PV. However, the energy from the PV is not affected by the changes in the parameters. Hence, the relative change in the energy supplied by carriers is larger in Scenario 6 where the PV has a larger share of the total energy demand.

In total, the absolute value of *SR* is never higher than 0.63 and in most cases smaller than 0.50, meaning that a given change in input parameters, say 15% increase, gives less than 7.5% change in total delivered energy. According to this, we regard the overall model and scenario analysis to represent an acceptable low uncertainty in how scenario results are estimated. The results in scenario 6 are more sensitive to changes in input parameters except for changes in adaptation factor and outdoor climate. In the *Baseline scenario*, the adaptation factor is the input parameter of highest sensitivity on the final results, and the importance of user behaviour should again be stressed.

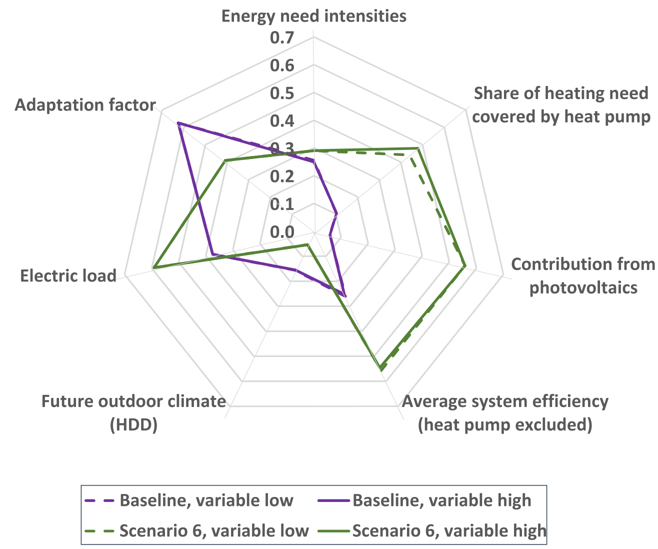

Fig. 8. The absolute values of the sensitivity ratios in 2050 for the Baseline scenario and Scenario 6.

4. Conclusions

The presented segmented dynamic dwelling stock model provides a new approach for dwelling stock energy analyses. It is the first mass-balance consistent stock-driven model that is applied for energy analyses of dwelling stocks, with model internal estimation of renovation activity. It provides a detailed understanding of the long-term evolution of dwelling stocks and the system dynamics. Such a model approach is necessary to understand this highly dynamic system and to give the level of detail that is required to give realistic results for the analysis of future dwelling stock energy demand.

When applied for energy analyses of the future Norwegian dwelling stock, the model has uncovered several important cause-effect relationships. It has proven to be a powerful tool as it gives informative results in the scenario analysis. The simulations show that the total heated floor area in the dwelling stock is expected to keep growing by 27% towards 2050, mainly due to population growth. However, only a share of the stock is a target for energy-efficiency improvements of the building envelopes in the period 2020-50. This share represent new construction or dwellings that are likely to be renovated in this period. As much as 50% of the 2020 stock will be unchanged towards 2050, as these dwellings will not have a 'natural' need for renovation or demolition during this period.

Still, an important further improvement of the overall energy-efficiency state of the stock is expected, through renovation or demolition of old inefficient dwellings and new construction of passive-house standard. This expected improvement of the stock will lead to overall energy savings in the stock even in our *Baseline scenario*, which includes the least ambitious assumptions in our study.

The scenario analysis shows that further energy savings, beyond the *Baseline scenario*, are possible if including additional measures. More ambitious or more frequent renovation, commonly mentioned as important ways to obtain energy savings, were found to have only a limited effect on the overall energy savings towards 2050. Extensive use of local energy sources can give much higher energy savings in the system. If assuming extensive use of heat pump and photovoltaics, the technical estimated delivered energy for heating and hot water in 2050 will be about 50% lower than in the *Baseline scenario*. If assuming extensive use of heat pump and photovoltaics, in addition to more frequent and advanced renovation, the technical estimated delivered energy for heating and hot water in 2050 is 65% lower than in the *Baseline scenario* and 80% lower than the corresponding estimate for 2016.

The electric load will be of larger importance in the system in future. The total electric load will increase by 34% from 2016 to 2050. Furthermore, the share of the total delivered energy being electric load is expected to increase from 28% in 2016 to 37–57% in the various scenarios in 2050.

The estimated 'real' reductions in energy demand, after applying the adaptation factor and correcting for user behaviour, are significantly lower than the technical estimate. In 2016, there is a situation with an aggregated prebound effect. The overall energy efficiency of the stock is still so low that the real use – on average – is lower than the technical estimate. This is expected to change in near future. By 2030, and even more evident by 2050, there will be a significant aggregated rebound effect if current observations for real energy use in highly energy-efficient buildings still hold. Hence, user behaviour might prevent the technical estimated energy saving potential in the systems from being realized.

There is high uncertainty related to many of the input parameters in the model. A perturbation analysis is carried out to analyse the sensitivity of the energy-related inputs on the final results. No input parameters with high uncertainty were found to have a strong influence on the model output result, and therefore we conclude that the overall model and scenario analysis represent an acceptable low uncertainty in how scenario results are estimated.

Our hypothesis presented in the introduction of this paper was that by introducing currently available technology in refurbished and new buildings, it will be possible to reduce the energy demand in the Norwegian dwelling stock by some 50% by 2050, despite strong stock growth. The results show that the hypothesis may be confirmed for the theoretical estimated total delivered energy in our most optimistic scenario. However, in this scenario, user behaviour is expected to reduce the saving potential from 51% for the theoretical estimate to 36% for the estimated 'real' energy demand from 2016 to 2050. The policy implications of this is that efforts should be made to counteract this rebound effect. Unless such measures are taken, the hypothesis will not hold and policy targets might not be met.

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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.2017.04.016.

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