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Large potentials for energy saving and greenhouse gas emission reductions from large-scale deployment of zero emission building technologies in a national building stock

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ABSTRACT

High energy and material demand in the building sector causes large greenhouse gas (GHG) emissions. This sector needs large-scale technological improvements in the transition to a future low-emission society. Extensive research is carried out on highly energy-efficient and zero emission buildings (ZEB), but the new technologies slowly penetrate the market. Until now, no bottom-up studies have applied a dynamic building stock energy model at the national level to quantify effects of a large-scale ZEB introduction. Using the RE-BUILDS 2.0 model, we explore and extensively discuss the aggregated potential for energy and GHG emission savings in the Norwegian building stock towards 2050. A Baseline scenario is compared with two ZEB scenarios assuming introduction of the ZEB definition and ZEB technologies applied in the future new built and renovated buildings, with an increased ambition level over time. The results reveal a large potential for energy and GHG emission savings of ZEB deployment towards 2050. Hence, stricter future regulations and practice will have important aggregated effects. Due to the long lifetime of buildings and potential lock-in effects, it is urgent that ZEB policies are implemented if the climate change mitigation potential of the Norwegian building stock is going to be reached.

1. Introduction

The building sector accounts for almost one third of the total global final energy use and more than half of the final electricity demand. About one fourth of global direct and indirect greenhouse gas (GHG) emissions originates from the building sector (International Energy Agency, 2017). The UN Agenda 2030 policy, with Sustainable Development Goal 13, calls global action to combat climate change (United Nations, 2018), and the Paris Agreement sets target to limit global warming to well below 2 °C in 2100 compared to preindustrial levels, which requires a rapid decline in global GHG emissions (Rogelj et al., 2018).

The building sector can contribute significantly to climate change mitigation targets through large-scale energy efficiency measures and decarbonizing its final energy mix (Lucon et al., 2014). Mitigation pathways consistent with a 2 °C future in integrated assessment models are reliant on a large-scale electrification of the global building sector and on energy savings from improvements of building envelopes and appliances (Rogelj et al., 2018). Especially, the need for pushing new and ambitious building standards becomes relatively more important in low energy demand scenarios meeting strict climate targets without using negative emission technologies (Grubler et al., 2018).

Aggregated GHG emissions from the building sector towards 2100 will highly depend on political decisions and large-scale implementation of promising climate change mitigation measures in the upcoming years. The long lifetime and renovation cycles of buildings can create significant lock-in effects, and the International Energy Agency (2017) emphasizes the need for a rapid large-scale introduction of high performance buildings to lock-in better buildings for the future: A ten-year delay of action will result in an aggregated global energy loss towards 2060 that corresponds to three years of additional energy consumption in the building sector. Transitioning to near-zero or

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net-zero emission technologies will be key to reaching the building sector's mitigation potential, and according to European goals, the national building stocks should be carbon neutral in 2050 (European Parliament and the Council, 2018).

The revised Energy Performance of Buildings Directive (EPBD) of the EU (European Parliament and the Council, 2018) requires efforts to renovate existing building stocks with priority to energy efficiency by clear guidelines and measurable targeted actions. Member states are required to establish a long-term renovation and roadmaps to secure a highly energy efficient and decarbonized building stock by 2050. Financial mechanisms, incentives and institutions for energy efficient renovations must have a central role in national long-term renovation strategies. The revised EPBD also highlights the important role of the building stock in providing charging solutions for electric vehicles, which is also important for the electrification and decarbonisation of the transport sector.

Recent advances in the building sector include the development of a variety of highly ambitious building standards such as passive houses and zero energy buildings, which have made it possible to lift the energy efficiency of modern buildings to new levels (Williams et al., 2016). One of the newest additions is the emergence of the Norwegian Zero Emission Building (ZEB) guideline, making use of new solutions of building envelops, highly efficient appliances and local energy generation (Fufa et al., 2016).

Given the above, the building sector is likely to undergo major changes in the next decades, and in principle, there are three main mitigation pathways: i) large-scale energy efficiency measures through improved technology and user behaviour, ii) electrification of the building sector, and iii) decarbonizing the energy supply system, including large-scale adoption of renewable energy (Lucon et al., 2014) (Rogelj et al., 2018). The zero emission building (ZEB) concept involves solutions across all these mitigation pathways, and there is a rapidly growing literature and empirical evidence on the achievements of ZEB projects (Andresen et al., 2019; Sørensen et al., 2017; Wiik et al., 2017, 2018). However, the market penetration rates of new building standards depend on building stock characteristics due to lock-in effects. Accelerating the ZEB transition will require a push through legislative or regulatory instruments (Toleikyte et al., 2016). No study has yet estimated the potential aggregated impact on energy use and GHG emissions, or explored the implications of a policy where the ZEB concept is systematically built into forthcoming building codes. The essence of this is that technical requirements in building codes can set ambitious minimum standards for all future new built, and give directions for energy upgrading in future building stock renovation activities.

There is a knowledge gap related to how quickly ZEB technology can be implemented in established building stocks and how different policies and regulations might affect accumulated energy and GHG emission savings in the long-term perspective. This study aims to explore the aggregated impact and the policy implications of incorporating the ZEB concept in building codes and common renovation practice. To do this, we need to filter out the impact of electrification of the building sector and focus on the two other mitigation pathways that are more at the core of the ZEB concept. Therefore, we use the Norwegian building stock as an example, which is a rather unique system as it is already to a large extent (>85%) electrified.

Here, we try to answer two questions. What energy and GHG emission savings are possible by pushing the ZEB technology compared to a continuation of recent trends? To what extent can a large-scale deployment of ZEB buildings and ZEB technology make electricity available for use in other sectors?

2. Background and literature review

2.1. Literature review

During the last decades there have been extensive research and development on low energy buildings, passive houses, (nearly) zero energy buildings and (nearly) zero emission buildings (D'Agostino et al., 2016; Sartori and Hestnes, 2007; Voss and Musall, 2013).

Zero energy and zero emission buildings as well as energy upgrading of existing stock are considered highly important to progress towards the EPBD targets in Europe. Extensive research has been done on the design and technical solutions of Zero energy or emission buildings. Belussi et al. (2019) provides a review of the performance of zero energy buildings and energy efficiency solutions. Furthermore, literature offers studies on the cost aspects of these buildings compared to traditional buildings (Hu, 2019), and of selected technical solutions (Li et al., 2019).

Within the Norwegian Research Centre on Zero Emission Buildings (ZEB Research Centre) a net zero emission building (ZEB) definition (Fufa et al., 2016) was developed. According to this definition, a zero emission building produces enough renewable energy to compensate for the building's greenhouse gas emissions over its life span. The ZEB Research Centre defined different levels of zero emission buildings depending on how many phases of a building's lifespan that are counted in. The ambition levels are increasing from the one where emissions related to energy use for operation, except energy use for equipment and appliances (ZEB - O ÷ EQ), adding additional elements in the consecutive ambition levels, to the most ambitious one where emissions from all operational energy, embodied emissions from materials as well as the construction and end of life phases are to be compensated (ZEB – COMPLETE).

The importance of improved energy efficiency of the existing building stock is acknowledged in literature, with studies on how to renovate existing buildings to zero-energy buildings (Rose et al., 2019) and the related economically feasibility (Asaee et al., 2019; Ekström et al., 2018; La Fleur et al., 2019; Luddeni et al., 2018; Semprini et al., 2017). A large energy-efficiency potential is commonly found, but some studies conclude that the cost-optimal solution will not allow large-scale upgrading of the existing stock to (nearly) zero energy or emission levels.

Most of these analyses study only individual or a small number of buildings. A few case studies evaluate the effects of possible future policies, using scenario analysis to estimate the aggregated impacts of large-scale implementation of strict building codes: e.g. Yang et al. (2019) for the introduction of zero energy buildings in the Chinese building stock, and Sheng et al. (2020) for the overall thermal transfer value (OTTV) legislations on electricity consumption in Hong Kong. Yang et al. (2019) use scenario analysis to evaluate how the Chinese building stock should be upgraded and developed to reach specific energy or emission reduction targets by 2050. Their most optimistic scenario assumes that all existing buildings are renovated to the ZEB standard. This is however not linked to the stock dynamics and need for renovation in the stock. Sheng et al. (2020) use an econometric model to estimate how much stricter OTTV regulations can contribute to the Hong Kong energy saving targets for 2030.

Various models exist for studying the future energy demand in building stocks. Li et al. (2017), Reinhart and Cerezo Davila (2016) and Brøgger and Wittchen (2018), provide reviews of methods used in models estimating the energy-saving potential in urban and national building stocks. It is important that the building stock energy models provide reliable results in a transparent way, since they are often used for guiding political decision-makers (Brøgger and Wittchen, 2018). Scenario models for future energy use in a building stock need to simulate how the building stock will develop in terms of demand for floor area, as well as construction, demolition and renovation activities, and the future development in the energy demand per unit of floor area. Energy-upgrading of existing buildings is strongly related to renovation activity, as many energy-efficiency measures are only cost-effective if the building is anyway going through renovation. For instance, the upgrading to highly energy-efficient windows might be cost-effective if the windows need to be replaced anyway, due to ageing, but most likely not if the original windows are otherwise not to be replaced. To provide realistic results on the future aggregated energy demand in the stock, it is crucial that it builds on a well-grounded model for the stock development, in addition to good estimations for the energy use individual buildings or of archetypes.

There is a lack of studies that use well-grounded building stock energy models to study the aggregated impacts of future policies for large-scale introduction of zero energy or emission building technologies in building stocks.

A dynamic dwelling stock model has previously been developed for studying the long-term development of a national residential building stock (Sartori et al., 2016). Sandberg et al. (2016a) applied the dynamic dwelling stock model to the residential building stock in 11 European countries. The study showed that the model was well-suited to simulate the long-term historical development of the residential building stock and reproduce the current stock size and composition in all the countries. A key model output is the renovation rate, which expresses the dwelling stock's need for maintenance due to ageing. The simulations show that the resulting renovation rates are remarkable stable across countries and time, with renovation rates always within the range from 0.6 to 1.6 towards 2050. This reinforces the finding in Sandberg et al. (2014 a,b) that renovation rates at levels of 2.5–3% are unlikely to be achieved through the stock's natural renovation requirements.

Sandberg et al. (2016b, 2017) applied the model for scenario analyses of the dwelling stock energy use in the Norwegian residential building stock 1960–2015 and 2016–2050, respectively. The present study builds on these and extends the model to include also non-residential buildings.

2.2. The Norwegian context

The Norwegian building-energy system is different from that in many other countries, due to the 85% share of electricity in final energy carriers and the dominating role of 95% hydropower in domestic power generation. Historically, the electricity price has been low, and therefore a large share of the Norwegian building stock is heated by direct electricity. In addition to electricity, district heating and bio (firewood) are also used for heating Norwegian buildings, with about equal shares. Historically, fuel oil has also been used, but this has been phased out to reduce carbon emissions, and since 2020 it is prohibited by law. Furthermore, Norway has also already a large number of electric vehicles. Therefore, Norway to some degree is already a step ahead of many other countries, in the way that the buildings are heated by renewable energy and operate in a common system with charging of electric vehicles.

The large-scale use of direct electricity for heating in the Norwegian building stock makes energy savings important for society in order to make hydropower electricity available to other sectors. The Norwegian Water Resources and Energy Directorate (NVE) estimates the future demand for electricity in mainland Norway to increase by 23 TWh from 2018 to 2040 (Spilde et al., 2019). This is mainly due to electrification of the transport and petroleum sectors, increased activity in the metal industry and new data centres. Spilde et al. (2019) does not include any analysis of the electricity saving potential in the building stock, but assumes that "a small reduction in the electricity use is expected in the household and service sectors". Onshore wind power production is often mentioned as a possible way to meet the future increased demand for electricity. NVE has also suggested possible locations for this increased wind power production (Jakobsen et al., 2019), which is under large debate due to conflicting interests like e.g. new renewable energy production vs. local environmental consequences.

The GHG emissions from energy use in the Norwegian building stock is dominated by the indirect emissions from electricity generation and district heating production. In addition, there is a small amount of direct emissions from bio. What emission intensity to use when calculating the greenhouse gas emission from electricity use in the Norwegian building stock is, however, heavily debated, and with rather different alternatives suggested for use in scenario analysis by the Norwegian standard NS3720:2018 (Standards Norway, 2018). Norway is part of the European electricity market, and the emission factor could either be assumed as the average Norwegian consumption mix, the average European consumption mix or the marginal production in Europe. The chosen emission intensity factor will strongly influence the resulting estimated emissions and possible savings.

3. Methods

3.1. Analytical methods

Here, we present a methodology to assess how ZEB standards can break through the market based on building stock characteristics, natural renovation needs and regulations. Applying the RE-BUILDS 2.0 dynamic building stock model to the Norwegian context, we simulate the development of the national building stock towards 2050. We explore the possible aggregated effects of large-scale implementation of ZEB technology in future building stocks, through strict regulations for new construction and advanced renovation of the existing stock.

The RE-BUILDS 2.0 model is a further development of the dynamic dwelling stock model from Sandberg et al. (2017). RE-BUILDS 2.0 covers the dynamic development of the complete building stock, including both residential and non-residential buildings. The model is generic and can in principle be applied to any building stock.

According to the classification developed in the IEA-EBC Annex 70 and described in Langevin et al. (2020), the RE-BUILDS 2.0 model is a hybrid model as it is *technological* in how it estimates the total dwelling stock size, *system dynamics* are applied to simulate stock dynamics and *physics simulation* is applied to estimate the energy demand per building archetype across the simulated stock. A detailed description of the model is presented in Appendix A, where the model is described according to the forthcoming *Best practice reporting guideline for building stock models* (Nägeli et al., 2021), which is directly linked to the classification system presented in Langevin et al. (2020).

A schematic outline of RE-BUILDS 2.0 is presented in Fig. 1. The core of the model is the long-term development of the building stock. The demand for floor area in buildings of various types is estimated by specifying assumptions for the drivers in the system, shown in the yellow hexagons in Fig. 1. A changing population size is combined with the corresponding average number of persons per dwelling and floor area per dwelling (for residential building types) or with the average floor area per person (for non-residential building types). This gives the total demand for building floor area and hence the building stock size and its distribution to various building types for each year.

Demolition functions are applied to simulate the annual demolition activity in the system. Furthermore, for every year, the annual construction activity is estimated as the sum of what is needed to replace demolished buildings and to meet the net change in demand.

The model uses renovation functions to simulate the annual 'natural' need for in-depth renovation as a response to the ageing process of the buildings. This also gives opportunities for energy upgrading. The building stock is distributed to a set of building archetypes, defined by the building type and the energy performance level of the building. The model allows buildings to move to a different archetype if it is energy-upgraded when renovated. The energy performance level of the various archetypes is given e.g. by building codes from various periods or segment-specific renovation packages.

Archetype-specific energy intensities and energy mix are applied to simulate the energy demand per energy carrier, per type, segment or archetype, or aggregated for the total stock. Finally, GHG emission intensities for each energy carrier are combined with the net delivered energy of the corresponding energy carrier to estimate the yearly total direct and indirect carbon emissions resulting from the direct energy use in the building stock. The energy emission intensities per energy carrier may vary over time, e.g. due to changes in the electricity mix.

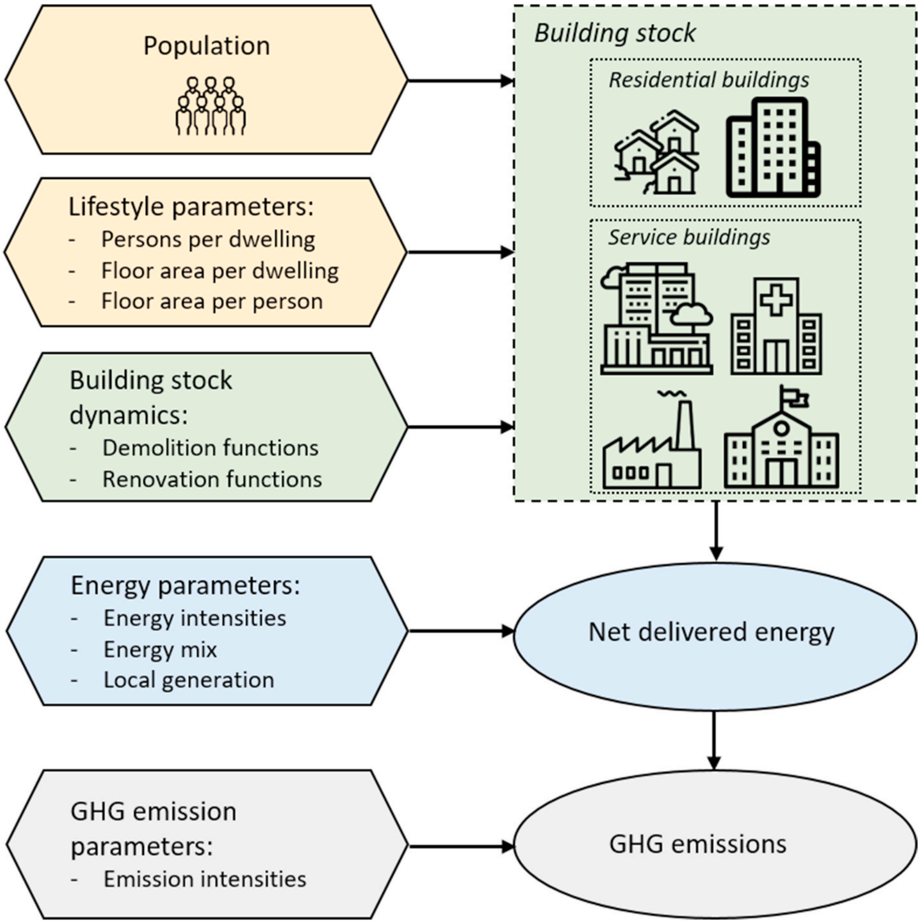

Fig. 1. Conceptual model outline RE-BUILDS 2.0.

Further details about the model, including the mathematical framework, is presented in Appendix A.2.

3.2. Case study: the Norwegian building stock 2020–2050

RE-BUILDS 2.0 is applied to the Norwegian building stock to investigate the possible long-term effects of a ZEB transition in the Norwegian building stock, by large-scale introduction of new zero emission buildings (ZEB) and ZEB technologies. The period studied in the scenario analysis is 2020–2050. The underlying drivers, other input data and assumptions used in the building stock model are described in detail in Appendix A.3.1.

The residential building stock is segmented in archetypes defined by dwelling type, construction period (cohort) and renovation state. The dwelling types are single family houses (SFH), terraced houses (TH) and multi-family houses (MFH). The types of non-residential buildings included in the study are office buildings, shops (including malls and retail buildings), education buildings and other buildings (excluding industry buildings). The stock of non-residential buildings is segmented in archetypes defined by the building type and energy performance level.

The energy performance level of a building is defined by the technical specifications of the building envelope, as well as the local renewable energy generation that is applied. It is therefore a main parameter for determining the net delivered energy intensities of the archetypes. Scenario-specific assumptions determine the energy performance level of buildings to be constructed in future and what archetype a given building type move to after undergoing renovation. The energy intensities for all archetypes in the model and the assumptions on future deployment of local renewable energy generation are

Table 1
Emission intensities for electricity. Variant a)-e).

Emission intensity variant	Description	Value(s)
a)	Norwegian consumption mix with a constant emission intensity factor	18 gCO_2-eq/kWh in all years
b)	Norwegian consumption mix with a dynamic emission intensity factor	Decreasing from 26 gCO_2-eq/kWh in 2020 to 13 gCO_2-eq/kWh in 2050
c)	European (EU28+NO) consumption mix with a constant emission intensity factor	136 gCO_2-eq/kWh in all years
d)	European (EU28+NO) consumption mix with a dynamic emission intensity factor	Decreasing from 309 gCO_2-eq/kWh in 2020 to 45 gCO_2-eq/kWh in 2050
e)	Marginal electricity is natural gas, with a constant emission intensity factor	530 gCO_2-eq/kWh in all years

presented in Appendix A.3.1.

The calculated GHG emissions from the Norwegian building stock will be strongly influenced by the chosen emission intensity for electricity. The Norwegian electricity production is dominated by hydropower, but Norway is also part of the European electricity market. What GHG emission intensity to apply for electricity consumption in Norway is therefore debatable, depending upon the analysis context and the preference towards using average, marginal or dynamic assumptions. In Table 1, we summarize the five alternative emission intensities that are applied in the scenario analysis. The reasoning behind the various emission intensity factors is presented in Appendix A.3.1.3. Scenario results for future GHG emissions from energy use in the Norwegian building stock are presented with all five calculation methods.

The emission intensities for other energy carriers are based on the principles described in Fufa et al. (2016). GHG emissions from waste combustion in district heating production is allocated to the waste treatment system and the five variants a)-e) described above are applied for the electricity part in district heating production.

3.3. Scenario description

The scenario analysis compares three scenarios to evaluate the possibilities for saving energy and reducing GHG emissions from the Norwegian building stock towards 2050. The study includes the delivered energy to the building stock, and the carbon emissions from generating this energy. The system boundaries are therefore the same in all scenarios, even though different system boundaries are applied when simulating what local renewable energy needs to be generated to compensate for the emissions according to the various ZEB ambition levels (Fufa et al., 2016).

The Baseline scenario assumes a development that would have been likely if zero emission technologies as part of the ZEB concept are not introduced. Here, new construction is according to the TEK17 standard in the period 2020–2024. TEK17 is the current conventional building code for new built in Norway, and it is already very energy efficient and roughly about the same energy efficiency as low energy buildings. From 2025 onwards, new construction is assumed to be according to the Norwegian passive-house standards (Standards Norway, 2012, 2013). Furthermore, the Baseline scenario assumes that buildings that are renovated are energy upgraded corresponding to current practice until 2035. From 2035 onwards, advanced renovation with higher energy savings is assumed.

Two ZEB scenarios are compared with the Baseline scenario. Zero emission buildings are introduced for new construction. Renovated buildings are assumed to have a building envelope according to either a standard or advanced renovation. In addition, the local renewable energy generation and implementation of energy efficient electrical equipment is in some cases assumed to be the same as in the corresponding building constructed according to the ZEB definition. The ambitious ZEB scenario (ZEB 2) assumes a more rapid introduction of ZEB buildings and ZEB technology than the moderate ZEB scenario (ZEB 1).

The assumptions used in the three scenarios are summarized in Table 2. For residential buildings, standard and advanced renovation for each segment is according to Brattebø et al. (2016). For the non-residential buildings, standard and advanced renovation correspond to upgrading to higher energy performance levels, as detailed in Table A.6 in Appendix A.3.4.

4. Results

4.1. Building stock development 2020–2050

Fig. 2 (left) shows the RE-BUILDS 2.0 model results on simulated development in building stock size and composition in the period 2020–2050. The total floor area increases from 370 million m^2 in 2020 to 448 million m^2 in 2050, due to the expected population growth. Throughout the period, about 70% of the total floor area is in residential buildings.

This study examines the possible effects of large-scale implementation of the ZEB definition and advanced renovation in the Norwegian building stock. The resulting potential for improving the energy efficiency of the building stock is therefore limited to the floor area that is either constructed or renovated in future. Fig. 2 (right) shows the estimated shares of the stock that are constructed, renovated and unchanged after 2020. In 2050, each of the three shares are roughly one third of the stock. Hence, the composition of the future stock is very different from the present one. The share of the stock that is unchanged over the period, is assumed to have the same energy intensity in 2050 as in 2020. The energy performance level of new and renovated floor area is scenario specific and follows the principles described in Table 2.

The overall average energy intensity in the building stock is the weighted average of intensities across all building types, cohorts, and renovation states. This value changes over time, as old buildings are demolished or renovated, and more energy-efficient new construction is added to the stock. Fig. 3 demonstrates a significant decrease in the estimated development in average energy intensity per square meter in the stock and per person in the Baseline scenario, and that the ZEB scenarios give large additional savings in the system. The average energy intensities are about 27% lower in 2050 than in 2020 in the Baseline scenario, and as much as 48% and 65% lower in the two ZEB scenarios, respectively.

Table 2
Scenario definition.

Period	Baseline		ZEB 1: Moderate ZEB scenario		ZEB 2: Ambitious ZEB scenario	
	New construction	Renovation	New construction	Renovation	New construction	Renovation
2020–2024	TEK17	Standard renovation	TEK17	Standard renovation	ZEB–O ÷ EQ[a]	Standard renovation of building envelope. Local renewable and energy efficient equipment as in ZEB – O ÷ EQ
2025–2034	Passive house	Standard renovation	ZEB–O ÷ EQ[a]	Standard renovation of building envelope. Local renewable and energy efficient equipment as in ZEB – O ÷ EQ	ZEB-O[b]	Advanced renovation of building envelope. Local renewable and energy efficient equipment as in ZEB-O
2035–2050	Passive house	Advanced renovation	ZEB-O[b]	Advanced renovation of building envelope. Local renewable and energy efficient equipment as in ZEB-O	ZEB-OM[c]	Advanced renovation of building envelope. Local renewable and energy efficient equipment as in ZEB-OM

[a] ZEB–O ÷ E: Emissions related to all energy use for operation (O), except energy use for equipment and appliances (EQ), shall be compensated for with renewable energy generation.

[b] ZEB–O: Emissions related to all operational energy (O) shall be compensated for with renewable energy generation.

[c] ZEB–OM: Emissions related to all operational energy (O) plus embodied emissions from materials (M) shall be compensated for with renewable energy generation.

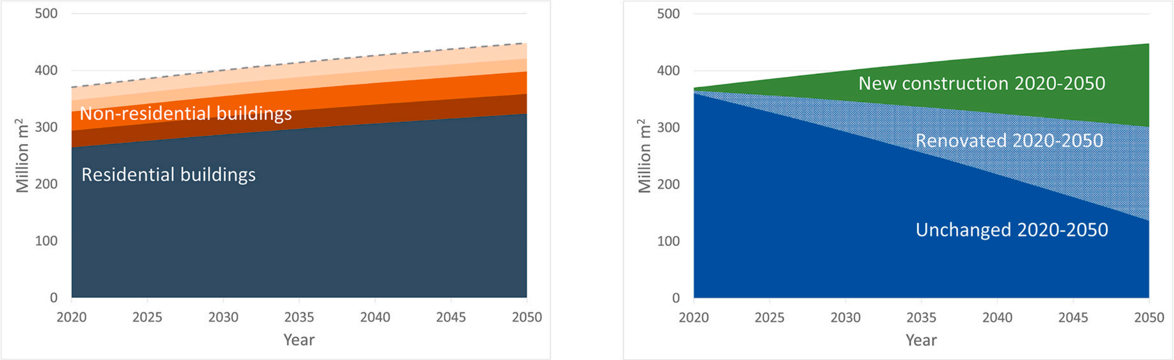

Fig. 2. Floor area in the Norwegian building stock 2020–2050 distributed to various building types (left) and to unchanged, renovated and new buildings (right).

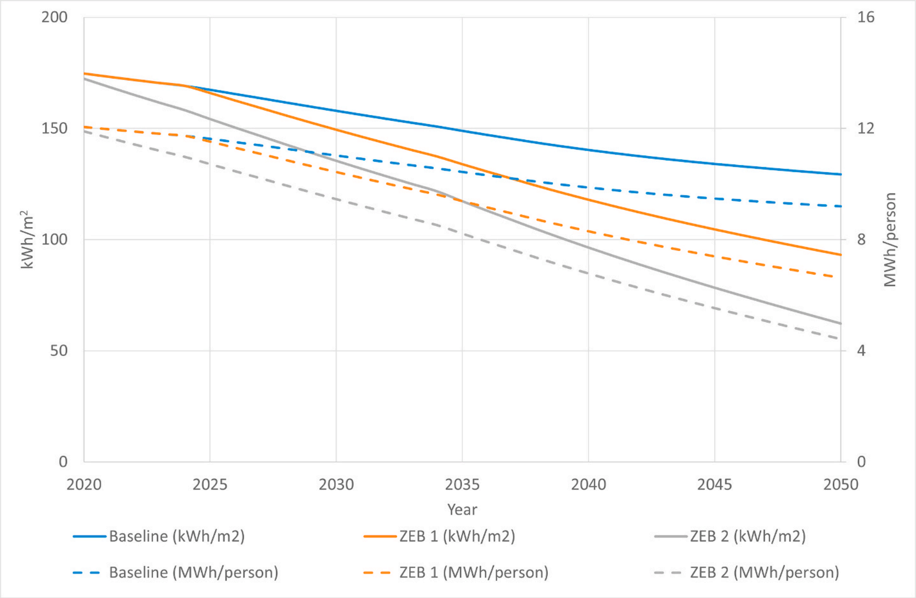

Fig. 3. Average energy intensity per square meter and per person in all scenarios.

4.2. Delivered energy to the Norwegian building stock 2020–2050

Fig. 4 shows the simulated delivered energy in 2020, 2030, 2040 and 2050 according to all three scenarios. Despite the expected 21% growth in the building stock size from 2020 to 2050, the total estimated delivered energy to the system decreases by 7 TWh even in the Baseline scenario. Furthermore, the additional savings in 2050, according to the alternative scenarios, are 16 and 30 TWh, respectively. In relative terms, the estimated delivered energy in the three scenarios in 2050 is 10%, 35% and 56% lower than in 2020. Fig. 4 also shows how the delivered energy is distributed to various building types. The share of delivered energy to residential buildings is 60–70% in all years and all scenarios. Shops are the non-residential buildings with the highest share of the energy demand, 12–15% across time and scenarios. Furthermore, office buildings and other buildings each account for 7–10% of the energy demand, and education buildings for 5–6%.

The delivered energy in all scenarios in the years 2020, 2030, 2040 and 2050 is also presented in Fig. 5, now showing the distribution to buildings constructed before and after 2020. The estimated delivered energy in buildings constructed after 2020 (green bars) is significantly smaller in the ZEB scenarios than in the Baseline scenario. This demonstrates the important potential for energy savings in the system by large-scale implementation of ZEB buildings in new built, constructed after 2020. However, the potential energy savings is even higher in the share of the existing stock, constructed before 2020 (blue bars). Whereas the two ZEB scenarios in 2050 result in 3 and 10 TWh lower delivered energy than the Baseline scenario in the share of the stock constructed after 2020, more ambitious renovation lead to decreased delivered energy of 13 and 21 TWh in the two ZEB scenarios, respectively, compared to the Baseline scenario.

Fig. 6 shows the estimated total local renewable energy generation in all scenarios in year 2020, 2030, 2040 and 2050, and the shares from heat pump, PV, and new technology. New technology is here to be understood as the energy that is needed to be produced locally to meet the assumed ZEB ambition levels, but which cannot be generated by heat pump or PV on the buildings as they have already been utilized to the full capacity. This could be solutions on the neighbourhood scale, e.g. utilising space between buildings for PV, transfer technologies between buildings or seasonal and diurnal storage technologies.

The local energy generation increases over time in all scenarios. Somewhat surprisingly, the largest local energy generation is in the Baseline scenario, where no use of ZEB technology is assumed. This is we have defined the contribution from heat pumps to be local renewable energy and due to the larger share of energy generated from heat pumps in the Baseline scenario. In this scenario, there is a larger demand for energy for heating, because the average energy intensity for heating is higher in the Baseline than in the ZEB scenarios, hence the potential contribution from heat pumps is larger. Furthermore, the electricity

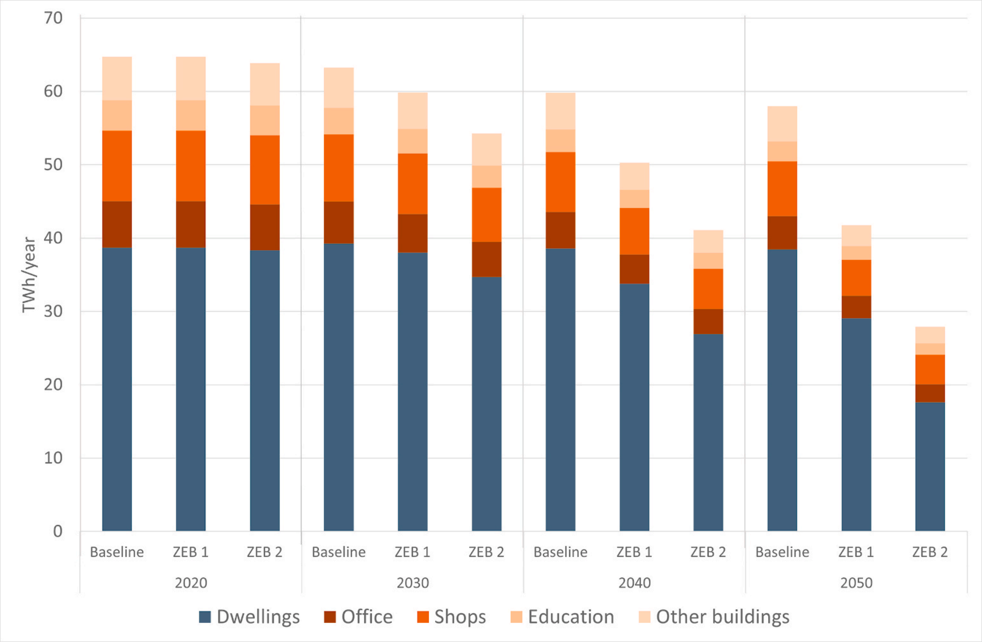

Fig. 4. Delivered energy in 2020, 2030, 2040 and 2050. Distribution to building types. All scenarios.

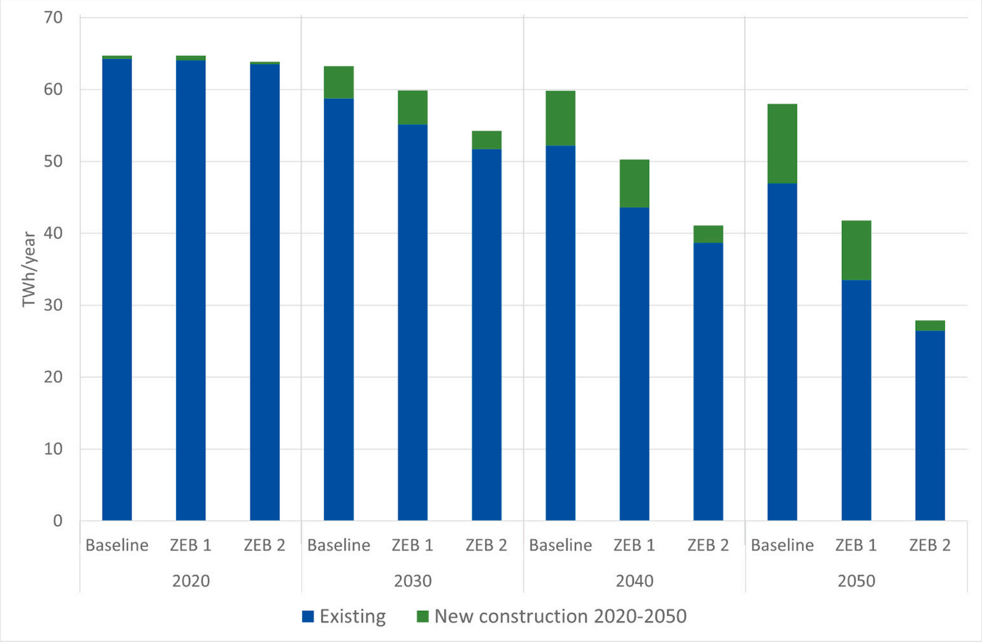

Fig. 5. Delivered energy in 2020, 2030, 2040 and 2050 in buildings constructed before 2020 and new construction 2020–2050. All scenarios.

generated from PV is rather similar in all scenarios, due to rather ambitious assumptions regarding use of PV also in the Baseline scenario. Finally, in the two ZEB scenarios, there is a growing share of energy from new technology, with largest share in the ZEB 2 scenario.

Fig. 7 shows the sum of net delivered energy and the local renewable energy generated in year 2020, 2030, 2040 and 2050, according to the three scenarios. The net delivered energy is distributed to the various energy carriers. The results demonstrate how the delivered energy to the Norwegian building stock is dominated by direct electricity. According to the model results, electricity will dominate the system also in the long term, equivalent to 85–90% in the three scenarios at various times. However, the absolute values decrease over time in all scenarios, and by 2050 the estimated electricity demand is 26% and 49% lower in the two ZEB scenarios than in the Baseline scenario, respectively. Hence, there is a large potential for electricity savings in the system. District heating has a share of 7–8% in all scenarios and years. The absolute value of the demand for district heating is rather stable at about 5 TWh throughout the period in the Baseline scenario. This is estimated to decrease from about 5 TWh in 2020 to 3 and 2 TWh in the two ZEB scenarios in 2050. Energy from biomass is assumed used only in residential buildings. In the Baseline scenario, the demand for biomass decreases slightly from 5 TWh in 2020 to 4 TWh in 2050. In the two ZEB scenarios, the demand in 2050 is decreased to 3 and 1 TWh.

Furthermore, Fig. 7 shows how local renewable energy generation can play an increasingly important role in the system towards 2050. In 2020, local renewable energy generation accounts for less than 10% of

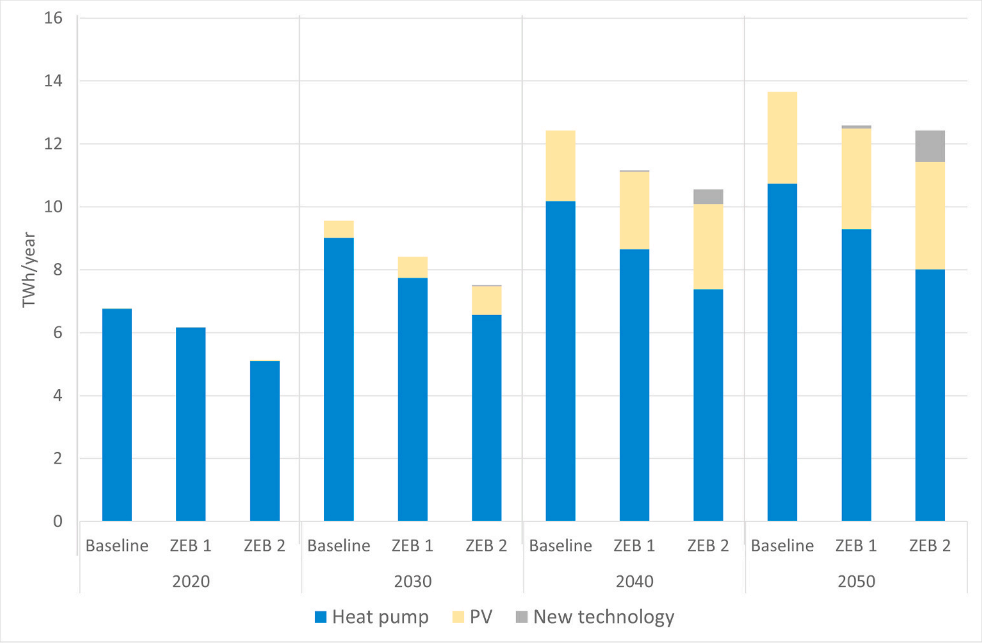

Fig. 6. Local renewable energy generation in 2020, 2030, 2040 and 2050. All scenarios.

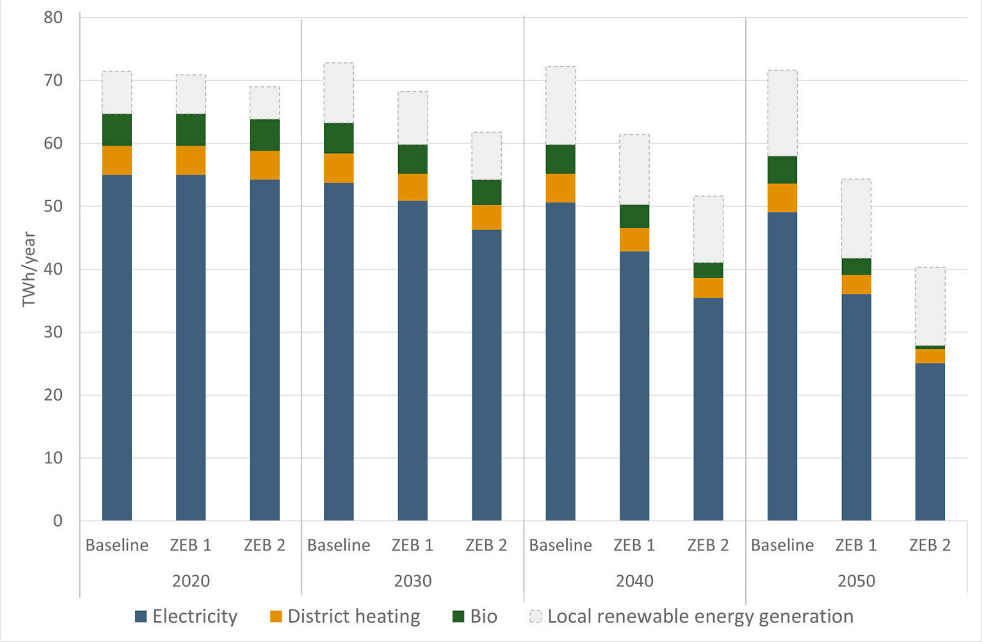

Fig. 7. Net delivered energy and local renewable energy generation in 2020, 2030, 2040 and 2050. All scenarios.

the gross delivered energy to the system, however, in 2050 this has increased to 19%, 23% and 31% in the three scenarios, respectively.

4.3. *Greenhouse gas emissions from energy demand in the Norwegian building stock 2020–2050*

The estimated greenhouse gas emissions resulting from the energy demand in 2020 and in the three scenarios in 2050 are calculated according to the five emission intensities presented in Table 1. Fig. 8 clearly confirms the high importance of the chosen emission intensity factor for electricity, for energy-related GHG emissions from Norway's building stock. The estimated emissions are about 6 times higher when assuming the European consumption mix with a constant average emission factor (alternative c) than when assuming the Norwegian consumption mix with a constant average emission factor (alternative a). When using the marginal perspective (alternative e), the estimated emissions are about 25 times higher than in alternative a. Furthermore, there is a substantial difference between the use of constant emission factors (alternative a and c) and the dynamic emission factors for the corresponding assumed consumption mixes (alternative b and d). The use of dynamic emission factors with rapidly decreasing values during the period naturally leads to both higher estimated emissions in the starting year and lower emissions in the end year, than if using the corresponding constant average factors. Hence, the estimated savings are also substantially larger when using the dynamic and decreasing emission intensity factors. The magnitude of such a difference between

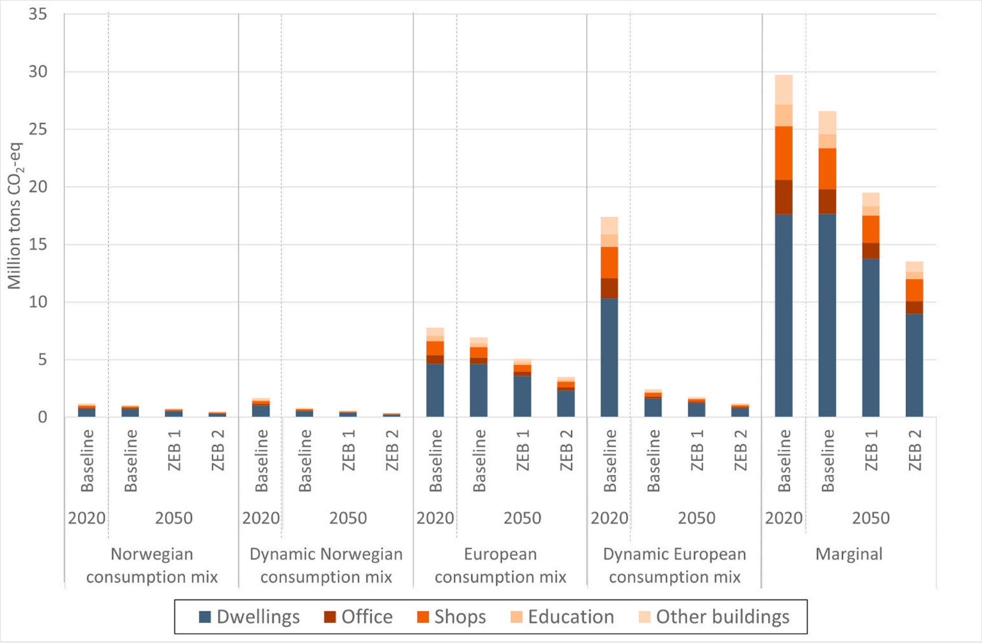

Fig. 8. Greenhouse gas emissions (GWP100) from delivered energy to the Norwegian building stock in 2020 and 2050, according to all scenarios and calculation methods.

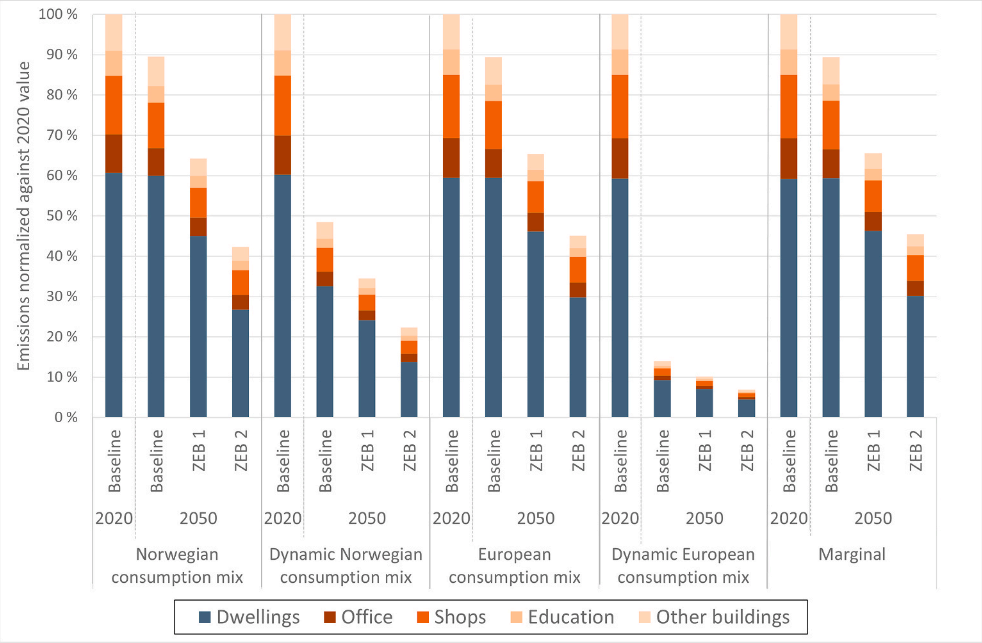

Fig. 9. Greenhouse gas emissions (GWP100) from delivered energy to the Norwegian building stock in 2020 and 2050, according to all scenarios and calculation methods. Normalized against 2020 results for each calculation method. Contributions from various building types.

the alternatives is not a surprise, due to their large difference in emission factors, however, its dynamic nature and high long-term importance for a given single country with a national building stock that is largely electricity dependent, and hydropower dominated, is not previously demonstrated in such a way in the literature.

As seen in Fig. 8, the model simulations result in reductions in greenhouse gas emissions from 2020 to 2050 in all scenarios and emission intensity variants, even if the size of the building stock increases by 21%. In Fig. 9, the GHG emissions in 2050 are compared to the emissions in 2020 for all scenario and calculation variants. For each variant, the 2050 emissions are normalized against the total Baseline 2020 value in the same variant, for better comparison of the relative savings. When using the constant factors (alternative a, c, and e), the estimated relative savings are similar for all three calculation methods. The baseline scenario gives 10% savings from 2020 to 2050, whereas the two ZEB scenarios give about 36% and 58% savings, respectively. Hence, when using a constant emission intensity factor for electricity, the chosen factor is therefore not important for the resulting *relative* savings in GHG emissions from the system, even though it is highly important for the *absolute* values, as seen in Fig. 8. However, using a dynamic and decreasing emission intensity factor for electricity makes a large difference also in the estimated relative reductions in GHG emissions. In alternative b, where we use the dynamic factor for the Norwegian consumption mix, the estimated GHG emissions in the three scenarios are 52%, 66% and 78% lower in 2050 than in 2020. In alternative d we use the dynamic factor for the European consumption mix, and this factor itself has a strong decrease from 309 g CO_2-eq/kWh in 2020 to 45 g CO_2-eq/kWh in 2050. This results in estimated emission reductions of 86%, 90% and 93% from 2020 to 2050 in the three scenarios, respectively.

Furthermore, Figs. 8 and 9 both show how the GHG emissions are distributed to various building types. According to all alternatives, energy consumption in residential buildings account for about 60% of the GHG emissions in 2020. In 2050, this share has increased to 62–66% in the various scenarios and alternatives. Shops have the second largest share with 11–16% of the total emissions, whereas office buildings contribute with 7–10%, education buildings with about 5% and other buildings with 6–9%.

Fig. 10 shows how the relative GHG emissions from Fig. 9 is distributed to the various energy carriers according to the various scenarios and emission intensity alternatives. When using the constant and dynamic Norwegian consumption mix emission intensity factors (alternative a and b), electricity accounts for about 80% of the emissions. When assuming the constant and dynamic European consumption mix factors (alternative b and d), electricity accounts for more than 90%, and when using the marginal assumption (alternative e), electricity accounts for 98% of the emissions both in 2020 as well as in all scenarios in 2050.

5. Discussion

The RE-BUILDS 2.0 model is further developed from a previous model version to include non-residential buildings in addition to the residential building stock. The presented principles for dynamic simulation of a building stock are general and can in principle be applied to any building stock. The details in the applied input data could even be adjusted based on data access, e.g. regarding assumptions on renovation and demolition or local renewable energy generation. However, it is of high importance always to make sure that there is realism in the applied assumptions – even in the most optimistic scenarios, otherwise the resulting energy and GHG emission savings will also be unrealistic. Assumed renovation rates of 2.5–3% may result in a rapid improvement of the stock and high saving potential, but the value of these results is questionable if the applied renovation rate is unlikely to be possible to implement. We assumed a renovation cycle with average time between renovation of 40 years for the residential buildings and a renovation rate of 1.5% for the non-residential buildings.

According to the revised EPBD, the Member states in the EU are required to establish long-term renovation strategies to support the renovation of the national stocks of buildings into highly energy efficient and decarbonized building stocks by 2050, by setting out roadmaps with a view to the long-term 2050 goal of reduction in greenhouse gas emissions. The use of detailed and thorough building stock energy models is crucial in this work, and the present study has demonstrated how such models can be used to indicate the aggregated impacts of various policies.

In this study, the RE-BUILDS 2.0 model was applied to the Norwegian building stock. The results demonstrate that the model is well-suited to simulate the future development in a building stock and provide detailed information about the resulting stock size and composition, which is an important starting point for a well-grounded scenario analysis on energy use and GHG emissions.

In the Norwegian case study, the building stock is estimated to grow by 21% from 2020 to 2050. Model results show how the stock is divided in new, renovated and unchanged stock, and that each of the shares in 2050 are roughly 1/3 of the total stock. The energy-efficiency potential is mainly related to buildings that will either be constructed or renovated in future. It turns out that a ZEB transition leads to large energy savings in the stock, beyond the savings expected even in the Baseline scenario, by making use of the ZEB ambitions and technologies by the Norwegian ZEB Research Centre. The two ZEB scenarios reduce the delivered energy by 28% and 52% compared to the Baseline scenario in 2050, respectively. This shows that there are large possible (theoretical) aggregated impacts resulting from ambitious policy on energy efficiency of building stocks.

The presented ZEB scenarios, and in particular the ambitious ZEB 2 scenario, may be claimed to be too ambitious. It is indeed ambitious, but only in the energy performance level that is assumed for new construction and renovated buildings. The frequencies of replacement of

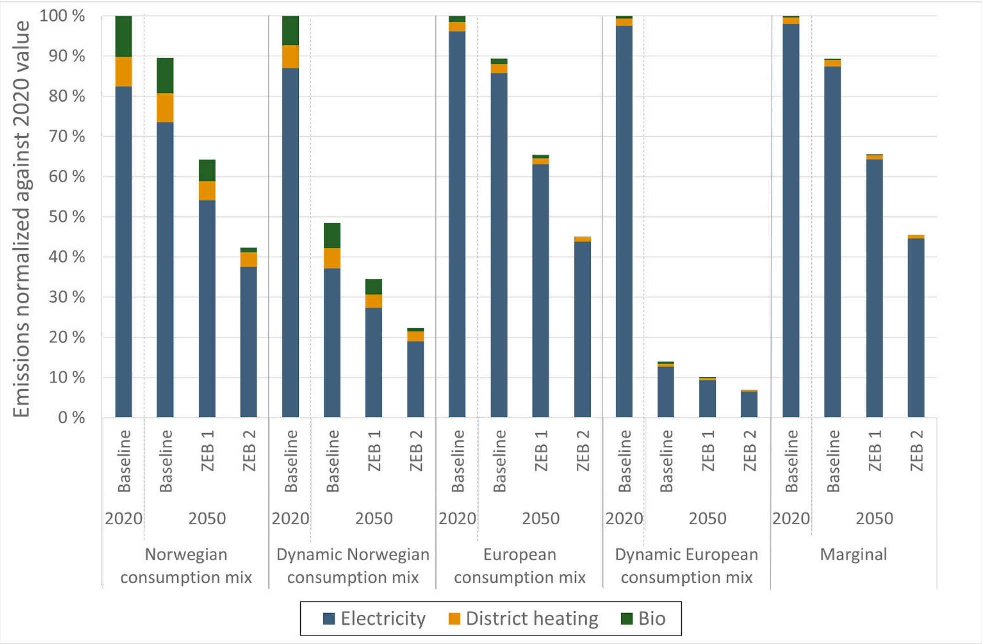

Fig. 10. Greenhouse gas emissions (GWP100) from delivered energy to the Norwegian building stock in 2020 and 2050, according to all scenarios and calculation methods. Normalized against 2020 results for each calculation method. Contributions from various energy carriers.

buildings and renovation of the existing stock are assumed equal to the quite modest assumptions in the Baseline scenario, and the future renovation rates follow recent trends. The ambitious assumptions for energy performance levels of new and renovated buildings are in fact based on available technology and solutions in use today in Norway. We therefore claim that the scenarios are not impossible and represent at least a potential for energy savings. The extent, to which the best available solutions are taken into use, depends on policy, costs and the future choices of building developers and owners. Policy makers can influence this by introducing ambitious requirements for new construction and renovation in future building codes, and by use of e.g. financial policy measures to encourage building owners to choose the best available solutions when renovating their building.

Fig. 5 shows how the energy saving potential is distributed to buildings constructed before and after 2020. Even though the relative difference between the Baseline and ZEB scenarios is largest in new construction after 2020, the absolute difference is larger in the existing stock. This means that the overall energy saving potential is larger in renovation of existing buildings than in new construction. Hence, policy instruments should encourage more energy-efficient renovation and must be an important part of future policy, although focus is often given to innovative solutions for new built projects. Lock-in effects make the implementation timeline of policies and measures highly important for the aggregated energy and emission savings towards 2050. A rapid introduction of ZEB solutions is considered necessary if the Norwegian building sector is to reach its future climate change mitigation potential.

The revised EPBD highlights the important role of the building stock regarding charging solutions for electric vehicles, which is also important for the decarbonisation of the society. Since energy consumption in the Norwegian building stock is heavily dominated by use of direct electricity, energy savings in the building sector will make electricity available to other sectors. Norway has already the worlds' largest share of electric vehicles, and a political goal of further rapid electrification of the transport sector. The modest ZEB 1 scenario results in energy savings of 23 TWh from 2020 to 2050, of which 19 TWh is reduced demand for electricity. This is almost equal to the estimated need for electricity to the Norwegian transport sector in 2050, if all vehicles used for road transport, rail, boats and ships are by then run by electricity. Large-scale energy efficiency of the building stock should therefore politically and technologically be considered a vital part of the electrification of transport. It may also be a highly relevant alternative to future onshore wind power in Norway, which today is associated with growing conflicts regarding location as well as nature and biodiversity impacts (Gullberg et al., 2014). This paper does not aim to contribute as a political statement in the wind power debate, and probably both wind power and energy efficiency of the building stock will be needed to reach the required reductions in GHG emissions. However, this study demonstrates the importance of using a holistic approach and detailed analyses of the future development and potentials in the building sector when planning the future development of the energy system. This is in contrast to what is often done, e.g. as Spilde et al. (2019) who for Norway towards 2040 assume that "a small reduction in the electricity use is expected in the household and service sectors", without carefully discussing the potential for savings in the building stock energy demand when analysing the future development in electricity use in mainland Norway.

Finally, the results show the large potential for reducing GHG emissions from energy use in the Norwegian building stock, despite stock growth. There is a reduction potential in all scenarios, but with large differences in both the absolute and relative saving potential, between the scenarios and between the five alternatives for electricity emission intensities that are examined. The analysis clearly demonstrates how important the choice of emission intensity is for the resulting savings in the system. In particular, this is the fact in a country like Norway with a high share of direct electricity in space heating for buildings. There are three main differences: 1) the use of Norwegian versus European consumption mix, 2) the use of constant versus dynamic factors and 3) the use of average versus marginal technology. Due to the dominant share of hydropower, the Norwegian electricity mix is substantially less carbon intensive than the European consumption mix. The estimated absolute emissions are therefore substantially higher when assuming the European consumption mix rather than the Norwegian. The relative future emission reduction potential is, however, similar for both consumption mixes, when using constant factors. When using dynamic factors, the relative emission reductions are higher when assuming European consumption mix than when assuming Norwegian consumption mix. The assumption of marginal technology, however, results in absolute emissions that are 70–3500% larger than the emissions calculated by using the other factors.

The differences in the results from the five alternative factors might be claimed to be common sense – different factors lead to different results. Although this is indeed true, comparisons like this are rarely done in analyses of the future emissions from energy consumption. One factor is commonly chosen and applied for each energy carrier, and the importance of the choice of factor is rarely discussed. When applying the five alternative factors, we demonstrate how the choice of factor in this case totally determines the magnitude of the resulting emissions. The implications of the chosen factor should be discussed in such analyses.

Future energy savings in Norway's building stock are likely to change the import/export balance of the national power grid. This effect is better captured by applying a dynamic emission factor based on a European relative to Norwegian consumption mix. However, when analysing long-term technology changes at scale, that are in fact politically driven, such as in this case when phasing in ZEB technologies in order to achieve substantial GHG emission reductions, the use of a marginal emission intensity is even more appropriate. Saved electricity in the Norwegian building sector makes available renewable hydropower electricity that can either substitute fossil electricity production in Europe or the use of fossil fuels in the transport sector in Norway.

Even though Norway is a particular case in terms of the already largely renewable electricity production and the large share of direct electricity for heating, this study is also interesting in an international perspective. It demonstrates the power of using a well-grounded building stock model to understand the details of the possible future development of the building stock and its energy demand, as well as the importance of including detailed analyses of the building stock energy use in planning of the future energy system. This finding is important also for other countries even though the energy mix is different.

There is uncertainty in all models that simulate future development, and indeed also in the presented results for the Norwegian building stock energy use. This uncertainty is not analysed per se, but as we present a range of variants and ambition levels for various important factors in the analysis, we find that the study serves well to describe possible effects of various future developments in the system.

6. Conclusions and policy implications

The building sector contributes to substantial parts of global energy use and GHG emissions. Improving the future energy performance of building stocks and developing zero emission building concepts are crucial to reduce energy use and GHG emissions in 1.5 °C scenarios. Until now, no bottom-up studies have quantified potential effects of a large-scale ZEB introduction at the national level. Our study has demonstrated how a well-defined and detailed building stock model is suitable for analysing the possible future aggregated impacts from policies leading to a large-scale energy-efficiency improvement in the building stock. Realistic and reasonable estimations and assumptions about future building stock development are crucial to be able to obtain realistic and reasonable results in the energy analysis.

For the first time, this paper applies a dynamic building stock model to quantify and assess aggregated effects on energy use and GHG emissions of a future large-scale introduction of novel ZEB building standards on a national building stock, here exemplified with a Norwegian case study. We use the Norwegian Research Centre on Zero Emission Buildings' recently developed guideline for how to plan, design and build zero emission buildings. Several ambition levels have been proposed. We study the possible aggregated effects of implementing the Norwegian ZEB definition in future building regulations for new construction and common practice for renovation, and find that there is indeed a potential for substantial reductions in energy demand and GHG emissions in the Norwegian building stock towards 2050. Even though there is an expected 21% growth in the building stock size from 2020 to 2050, the total estimated delivered energy to the system decreases by 7 TWh even in the Baseline scenario, and 23 and 36 TWh in the more ambitious ZEB scenarios, in 2050 compared to 2020. Ambitious policies towards a ZEB transition will have an important impact on the future aggregated energy system.

With such a large potential for energy savings, the building sector should be carefully included in the analysis of the future development of the whole energy system. Especially, in Norway it will particularly affect the electricity system, as electricity in Norway, in contrast to most other countries, is by far the dominant energy carrier supplying the building sector. Ambitious use of known zero emission building technologies in new and renovated building could e.g. make available enough electricity to electrify the whole domestic transport sector, and hence, possibly also reduce the need for increased onshore wind power production. A holistic approach is needed, and our results indicate that proactive energy efficiency strategies for the building sector should be thoroughly analysed and considered before conclusions are made regarding future development in policies and regulations affecting the overall energy system in a country.

In our case, the results show that there is indeed a very promising potential for reduced GHG emissions from energy use in the Norwegian buildings stock. The *absolute* savings strongly depends on the chosen emission intensity factors, but there is a large *relative* saving potential across factors. Stricter future regulations (building codes) would in future have a strong aggregated effect, as there is a large potential for energy and GHG emission savings towards 2050. Due to the long lifetime of buildings and the potential lock-in effect, there is an urgency of a rapid ZEB policy implementation if the climate change mitigation potential of the Norwegian building stock is going to be reached.

CRediT authorship contribution statement

Nina Holck Sandberg: Conceptualization, Methodology, Software, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Jan Sandstad Næss:** Conceptualization, Methodology, Software, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing. **Helge Brattebø:** Conceptualization, Methodology, Resources, Writing - original draft, Writing - review & editing, Supervision, Project administration. **Inger Andresen:** Resources, Data curation, Writing - original draft. **Arild Gustavsen:** Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2020.112114.

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