Energy & Buildings 268 (2022) 112186

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Comparing model projections with reality: Experiences from modelling building stock energy use in Norway

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ARTICLE INFO

Article history:
Received 14 March 2022
Revised 29 April 2022
Accepted 14 May 2022
Available online 19 May 2022

Keywords:
Energy use
Energy demand
Buildings
Building stock
Load profiles
Energy system models
Energy analysis
Scenario analysis

ABSTRACT

Projections of future energy use in buildings are a crucial tool in the tracking and attainment of political targets for energy efficiency and climate gas mitigation. In this article, a new methodology for projecting both the final energy use and the peak power demand for the Norwegian building stock is presented. The novelty of the methodology is to combine a set of existing, previously documented models in a novel way that integrates building stock models, hourly energy demand load profiles, and energy system modelling. The result is a coherent long-term projection of both annual and hourly energy use for different energy carriers, presented here with four scenarios of final energy use. The results show an expected decrease in total energy use for the Norwegian building stock between −2 and −12 TWh towards 2050, corresponding to a −3% to −14% of the energy use in 2020.

Models for projecting future energy use are helpful both to evaluate the potential effects of current policies and to help reveal the need for new or updated policies. However, to have the desired effect, the projections must be as realistic as possible and reflect the actual development in energy use in the building stock. This necessitates a methodology for evaluating historical long-term annual energy use projections to understand why some models succeed in predicting energy use development while others fail. In this article, a set of indicators for evaluating the calibration of different models are presented. The indicators evaluate the initial difference and the divergence in the annualised trend for energy use projection models, compared to statistical data. The indicators are used to compare selected historical energy use projections for the Norwegian building stock against energy use from statistics from 2000 to 2020. The comparison shows large differences between the different projections, where calibrated scenarios show energy savings that tend to be more optimistic in the reference projection but more conservative in the best case potential.

1. Terminology

Energy demand: In this paper, energy demand in buildings is a theoretical value used to describe the energy demand linked to energy services/energy needs in buildings – such as the energy demand for heating domestic hot water (DHW), space heating (SH), ventilation, lighting, and plug loads. When calculating the energy demand, losses in the heating and cooling systems are ignored. Depending on the system boundary, the calculated energy demand is referred to as net energy demand or gross energy demand [1].

Energy use: Often referred to as final energy consumption, delivered energy, or delivered energy use. Energy use is a measurable value which can be assessed for both energy services and energy carriers (such as electricity, fuels, district heating, etc.). The energy use in buildings considers losses within the building system boundaries, but not losses in the distribution grids.

Abbreviations: DHW, Domestic hot water heating; SH, Space heating; PV, Photovoltaic; CCS, Carbon Capture and Sequestration; HDD, Heating degree days; SSB, Statistics Norway; WBH, Waterborne heating.

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https://doi.org/10.1016/j.enbuild.2022.112186

2. Introduction

2.1. Background and context

Energy use in buildings accounts for 36% of domestic energy use in Norway [2], a third of the global final energy consumption [3], and greenhouse gas (GHG) emissions from buildings (including energy use and materials) account for about 40% of energy-related global GHG emissions [4]. The Paris Agreement requires a rapid decline in global GHG emissions [5], and the building sector can contribute significantly to climate change mitigation targets through energy efficiency measures and decarbonization of the energy supply. As part of the European Green Deal, with the European Climate Law, the EU has set a binding target of achieving climate neutrality by 2050 – with an intermediate target of cutting emissions by at least 55% by 2030 [6]. The EU 'Reference Scenario 2020′ for 2050 expects a 20% reduction in the final energy consumption of households compared to 2020. To fulfil this target, energy efficiency measures and implementation of local renewable generation in buildings is needed. These measures are mainly regulated through the EU directives on energy efficiency [7], energy performance of buildings [8], and renewable energy [9].

Making projections of the future energy use in buildings is crucial to follow up and reach the EU targets for energy efficiency and GHG emissions reductions. Several studies have attempted to make projections of the development of energy use in the Norwegian building stock, both total and separately for the residential and service sectors. An overview of selected studies from the past 20 years is shown in Table 1. The studies have various purposes, different number of years projected, and often include different scenario analyses. In many studies, a baseline or reference scenario is accompanied by alternative development scenarios. A baseline scenario often reflects the most likely (expected) outcome given recent trends and strict implementation of, and adherence to, policies, however the baseline scenario could also reflect a conservative development for renovation, building codes, and heating technologies. Other scenarios tend to reflect a more ambitious development or even the maximum theoretical potential for energy efficiency/energy use savings.

In 2020, the temperature corrected energy use in the Norwegian building stock was 30.9 TWh for the service sector and 50.3 TWh for the residential sector (81.2 TWh in total). Myhre 2000 [10] presented a projection on the residential energy use from the year 2000 until 2030 in three scenarios. The starting point in this study was 3 TWh higher compared to the temperature corrected energy use in 2000. The study predicted a growth in energy use towards 2020 of 5 TWh, which was close to the actual growth of about 4 TWh, but given the offset in the start year, the study failed to accurately predict the energy use of the residential building stock in 2020. Lavenergiutvalget (2009) [11] started with 80 TWh energy end-use for the total stock in 2009 (4 TWh more than the actual energy use), expecting a baseline of ca. 82 TWh by 2020 (+1 TWh off the actual energy use). The starting point for residential energy use in 2009 was lower than the actual energy use, while the starting point for energy use in service buildings was too high. Sartori et al. 2009 [12] projected the energy use of the entire building stock from 2005 to 2035. In their baseline scenario energy use was expected to become approximately 76 TWh in 2020, which is 6 TWh lower than the actual energy use consumed. Studies on the potential and barriers for energy efficiency in the building stock for Enova from 2012 [13,14] presented several baseline scenarios considering different developments in the energy pricing. Their starting point in 2010 was 81 TWh energy use for the building stock, which is 4–5 TWh higher than the actual energy used, mostly due to a high starting point for commercial buildings. In their baseline scenario with the highest energy price (0.8 NOK/kWh), the energy use in the total stock was expected to become 79 TWh in 2020. FME CenSES published an energy projection towards 2050 in 2015 [15]. Five scenarios were developed, where the energy demand in buildings had the same development in all scenarios, while industry and transport demand varied. In their projection the energy demand increased by 25% in residential buildings and by 18% in non-residential buildings towards 2050. Energy consumption in buildings increased by 13 TWh from 2010 to 2050 in the reference scenario. In a scenario with focus on energy efficiency, energy consumption reduced by 9 TWh compared to the reference scenario. In the project EPISCOPE from 2016 [16] energy consumption from residential ventilation, space heating, and DHW was projected in a baseline (trend) scenario, as well as in two scenarios showing the potential that could be reached through energy efficiency measures on the building envelope and technical installations. Energy use for electrical appliances and lighting was not considered. In their trend scenario, energy use in the residential stock was expected to decrease by 18% (36 to 29 TWh) from 2015 to 2050. NVE predicted a flat development in energy use in 2017 towards 2020 [17]. Their starting point was slightly below the actual energy use in 2016, giving a prediction of 78 TWh for 2020, 2–3 TWh lower than the actual energy used (temperature corrected). In 2018 they predicted that the development in energy use towards 2020 would be slightly lower [20], ending up at approximately 78 TWh in 2020.

Sandberg et al. 2017 [18] presented several scenarios for the development of energy use in the residential stock. Their baseline scenario reflected a continuation of trends, while the other scenarios assumed that more energy efficiency measures were introduced. In their baseline scenario, energy use was expected to increase slightly, by 3% from 2015 to 2050 (39–40 TWh), assuming that solar electricity is used in the residential sector. Seljom et. al. 2017 [19] predicted the demand for heat and electricity for the Norwegian building stock between 2010 and 2050 in five scenarios. In their reference scenario, the energy demand was expected to increase from 75 TWh in 2010 to 78 TWh in 2020. The projection only considers energy demand, not energy use, and is not comparable to statistics of energy end-use. A report about an 'energy roadmap 2050′ from 2020 [22] presented how a low carbon society could affect the Norwegian energy system and economy through three scenarios towards 2030 and 2050. The starting point for the total energy use in the buildings stock (incl. agriculture) in 2015 was 5 TWh higher compared to the measured energy use. The projection predicted a reduction of between 7 and 19 TWh towards 2030, before energy use was expected to have a slight change of between −2 TWh to + 3 TWh between 2030 and 2050. Sandberg et al. 2022 [23] presented a study of the expected energy consumption of the entire building stock given the continuation of recent trends, as well as the potential for reduction of energy use in the building stock from 2010 towards 2050. The development from 2010 to 2020 was calibrated and is in line with the measured energy use in building stock.

While projections of future annual energy use are crucial to follow up political targets for energy efficiency, projections of hourly load profiles are crucial for grid planning. The existing trend toward electrification is expected to continue or expand, which will both increase total electricity use and change the shape of the load profile, including peak loads [24–28]. According to Lindberg et al. [29], most long-term studies project either the annual energy/electricity use (e.g. [30,31]) or the annual/monthly peak loads (e.g. [32,33]). The European network of grid operators (ENTSO-E) [27] projects long-term electricity load, but the existing building stock is hidden in the historical load and is indirectly treated as a static body [34]. Few existing models for long-term electricity use consider both annual demand and peak loads, as well

Table 1
Overview of selected studies on projecting of energy use in the Norwegian building stock.

Study	Start year	End year	Residential	Service	Total stock	Per carrier	Scenarios
Myhre 2000 [10]	2000	2030	Yes	No	No	Electricity and other	4 scenarios
Lavenergiutvalget 2009 [11]	2009	2040	Only for potential	Only for potential	Yes	No	Baseline and potential
Sartori et al. 2009 [12]	2005	2035	Yes	Yes	Yes	Electricity and thermal	6 scenarios
Enova 2012 [13,14]	2010	2020	Yes	Yes	Yes	No	Several scenarios for energy prices and potentials
CenSES 2015 [15]	2010	2050	Yes	Yes	Yes	Yes	5 scenarios
EPISCOPE 2016 [16]	2015	2050	Yes	No	No	Yes, but excluding electricity for lighting and appliances	3 scenarios
NVE 2017 [17]	2015	2020	Yes	Yes	Yes	Yes	1 scenario with uncertainty
Sandberg et al. 2017[18]	2016	2050	Yes	No	No	Yes	7 scenarios
Seljom et al. 2017 [19]	2015	2050	No	No	Yes	Heating demand, el.spesific demand	5 scenarios
NVE 2018 [20,21]	2016	2035	Yes	Yes	Yes	Yes	Expected development with uncertainty
Norwegian Energy roadmap 2050 [22]	2015	2050	No	No	Yes	Yes	3 scenarios
Sandberg et al. 2022 [23]	2010	2050	No	No	Yes	No	3 scenarios

as the impact of building renovations and different end-use technologies, such as heat pumps, photovoltaic (PV) panels, and electric vehicles. Today, most energy use projections that consider hourly load projections for different sectors are used for short-term forecasts. Few exceptions exist for long-term modelling of both the annual energy use and hourly energy use per sector, such as [35] and [31], but these are limited to UK/Germany and Spain. Other models, such as [36] and [37], only consider the residential sector.

3. Research gaps and contribution of this study

A coherent long-term projection of building sector energy use and peak loads from different energy carriers, considering both heat and electric specific loads, is needed to accurately plan and inform current and future energy policy. The benefit of Sandberg et al. 2017 is the stock-driven approach and system dynamics applied to mimic the dynamic development of the building stock, including the demolition and renovation needed during the ageing process of the stock, as well as the construction needed to meet the growing population's changing demand for buildings. The benefit of Seljom et al. 2017, which relies on the load aggregation methodology in Lindberg 2017 [38], is the ability to investigate hourly peak loads. This paper presents a methodology that combines the benefits of the former two, the modelling framework developed in the Flexbuild research project [39] (the 'Flexbuild' study). This modelling framework provide a coherent long-term projection of both annual energy use and peak load for different energy carriers for the building sector separately, considering both heat and electric specific loads. Four scenarios towards 2030 and 2050 have been developed, and the results are compared to other studies on energy use projections.

All studies mentioned in Table 1 present models of future long-term or short-term annual energy use. The studies and scenarios have different purposes (some with the aim of predicting the most likely outcome, and others with the aim of outlining the energy efficiency potential), different starting years and end years. The studies give different results for the future annual energy use. This highlights the need for a new methodology to evaluate historical long-term annual energy use projections with different starting points, end points, and purposes. This can help to understand why some models succeed in predicting the development in energy use, while others fail. To do this, a set of indicators for evaluating the calibration of different models is presented. The actual development of energy use from the past years is compared against older energy projections to evaluate their differences and performance using these indicators.

3.1. Article structure

The article consists of two main parts, in Sections 4 and 5. Section 4 presents the methodology (4.1) and results (4.2) of the Flexbuild study. Section 5 presents the methodology (5.1) and results (5.2) of the comparison of the selection of energy projections for the Norwegian building stock and the actual development of energy use from statistics from 2000 to 2020, while the discussion section (6) and the conclusion (7) consider both these topics.

4. Flexbuild scenarios: methodology and results

4.1. Methodology: FlexBuild study

This section presents the methodology of the Flexbuild research project [39]. No new tools or models have been developed in the Flexbuild study, but the novelty of the methodology has been to combine a set of existing, previously documented models in a new way that benefits from both stock modelling, hourly load profiles of energy demand, and energy system modelling. The development in peak load and annual energy use of the service sector and residential sector has been estimated in four different scenarios for the years 2010–2050 by combining models for the development of the building floor area, the energy demand of different building typologies, and energy system analysis. Fig. 1 shows how the building stock projections from the dynamic building stock model RE-BUILDS [40] is used for aggregating the predicted energy demand in the aggregate load profile generator PROFet ([41,42,38]). The aggregate energy demand profiles are used as input to the energy system model IFE-TIMES-Norway[43], which finds the cost optimal solution for how energy demand shall be met – which energy technologies should be invested and what energy carriers will be used. Each of the models will be described in the following sub-sections, including the approach to calibration to national energy statistics.

4.1.1. Scenarios

Energy use for Norway is projected for 2030 and 2050 in 4 scenarios, named *Petroleum nation, Energy nation, Nature nation,* and *Climate panic*. The purpose of each scenario can be described as follows (see [44] for a more in-depth analysis):

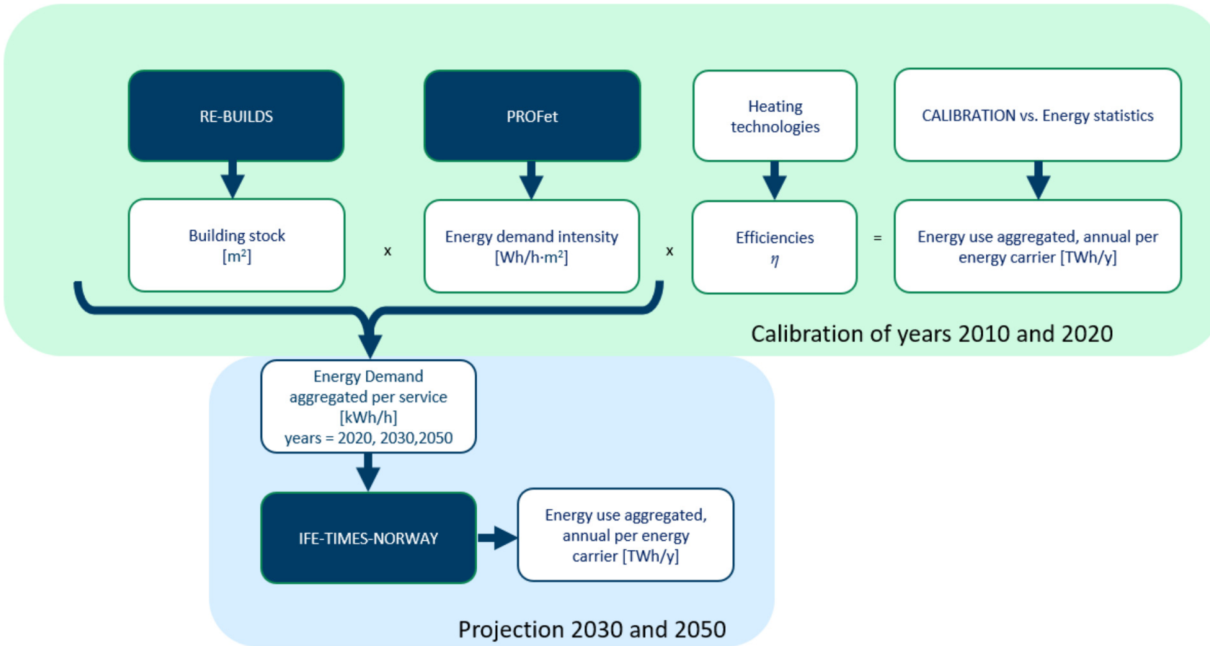


Fig. 1. Overview of the modelling framework, including the RE-BUILD, PROFet and IFE-TIMES-Norway models, and the linking between them.

The *Petroleum nation* serves as the baseline scenario, with a continuation of current trends regarding energy efficiency level of the building stock. Energy efficiency is only is implemented when economically profitable.

The *Energy nation* is mostly modelled in the same way as the *Petroleum nation*, but as there is a focus on making available energy and power for export. A slight increase in energy upgrades of renovated buildings and new passive house construction is assumed after 2030.

The *Nature nation* scenario assumes increased shares of *very efficient* new construction and *efficient* renovation from 2020. From 2030, all new construction is *very efficient*. Increased renovation rates and more urbanization with higher shares of apartments start in 2030.

The *Climate panic* scenario assumes the same development as in the *Petroleum nation* scenario from 2020 to 2030. After 2030 there are strong changes in most of the parameters, to reflect the climate situation the nation (and the world/EU) is in after realising that expected technological developments, such as Carbon Capture and Sequestration (CCS), will not be commercially deployable on large scale in useful time to meet the 2050 decarbonisation goal.

These are long-term scenarios for external variables influencing the modelling activities, such as the future developments of the building stock (new constructions, demolitions, energy-efficient renovations), technology development, EU directives, building norms, economic growth, consumer preferences, and political instability. All scenarios aim at a substantial decarbonization of the energy system by 2050 but follow different paths which affect both the supply and demand side.

4.1.2. Building stock representation and development

In this study, the energy use is projected for the entire Norwegian building stock. The building stock is distributed between residential and service building types. The residential building types include *Small house* and *Apartment block*. The service building types include *Office*, *Nursing home*, *Shop*, *School*, and *Other* (including kindergarten, university, hospital, sports facilities, cultural buildings, and light industry buildings). The buildings are further categorized according to three energy efficiency levels, *regular*, *efficient*, and *very efficient* as defined in [41].

A modified version of the dynamic building stock model RE-BUILDS 2.0 [40] is used to simulate the building stock development from 2020 to 2050 according to the input parameters defined in each of the four scenarios. According to the classification described in [45], the RE-BUILDS 2.0 model is a hybrid model as it is technological in how it estimates the total building 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. The underlying concept in RE-BUILDS is the changing population size [46] and societal demand for buildings of various types. The model is slightly different for the residential and service building stocks, as there are more statistics available for the historical development of the residential building stock than the service building stock. However, both parts of the RE-BUILDS model simulate the stock dynamics and development over time in terms of stock size and composition of types, cohorts, and renovation states. The total demand for floor area is estimated as the population times the average floor area per person in various building types. For the dwelling stock, the floor area per person is determined by the assumed share of population living in various dwelling types, the number of persons per dwelling in various types, and the average floor area per dwelling. For the service building stock, the average floor area per person is assumed to be constant over the period 2020–2050 per building type. Demolition and renovation functions are applied to simulate the demolition and renovation activity in the system. Renovation may or may not lead to improved energy efficiency. For each year, the estimated new construction is equal to the sum of construction for new demand plus replacement of demolished buildings. In the dwelling stock model, we simulate the renovation activity in the system by use of *renovation cycles* (Rc), which corresponds to the average time between two major renovations that can include substantial improvement of the energy-efficiency of the building. The resulting renovation rate is a model output. The Norwegian building stock in start year 2020 includes 386 million m^2 of total heated floor area, distributed among small houses (57%), apartment blocks (12%), and service buildings (31%). Buildings constructed before

2010 are assumed have energy efficiency level *regular*. In line with the findings in Esser et al. [47], only 20% of buildings renovated after 2010 are assumed to be improved to energy efficiency level *efficient*, Buildings constructed in the period 2010–2019 are assumed to be *efficient*.

Scenario implementation, including inputs and assumptions, is described in detail in Sartori et al. [48]. When the four scenarios are implemented in the dynamic building stock model, most inputs are kept equal, but the shares of new construction being *efficient* and *very efficient*, the renovation rate, the share of renovated floor which is being upgraded to *efficient* and floor area per person in residential buildings are varied in the scenarios. None of the scenarios are meant to represent a sort of maximum energy conservation potential, although the 'Climate panic scenario' does adopt some radical measures, but only after 2030. Rather, all scenarios are meant to be realistic alternatives towards a substantially decarbonized energy system in 2050, though following different narratives. The specific values connected to the scenario assumptions for the building stock are summarized in Table 2.

4.1.3. Energy demand modelling

The Flexbuild study used the PROFet model to calculate energy demand load profiles. PROFet is an aggregated load profile generator which can predict hourly load profiles for both thermal loads and electric loads, based solely on outdoor temperatures and building area. Identifying the energy efficiency level is based on the building temperature dependency, i.e. the typical energy signature curves (ESC), which has been extracted from trEASURE, a database, of monitored buildings, mostly connected to district heating [41]. After the identification of efficiency level, PROFet uses fixed-effects panel regression analysis[49] to provide representative load profiles within each category, in Wh/h per m^2 [42]. The load profile considers the outdoor temperature, the hour of the day, the type of day (weekday vs. weekend), and the season. As the representative load profiles indirectly account for the coincidence factor[1], the aggregated load profile for an area is simply found by multiplying it with the building area in m^2 [38]. PROFet estimates the typical load profile of an area based solely on building area input (for 11 building categories and 3 energy efficiency levels as described in the categorization) and outdoor temperatures.

4.1.4. Initial calibration

Calibration of the modelling framework is based on energy use. The conversion between energy demand and energy use for the initial year is calculated using existing knowledge and statistics on installed technologies. This sub-chapter presents how the Flexbuild study is calibrated to provide energy demand for the current situation, while the sub chapter, *4.2.2 Energy use modelling* describes how the energy use is calculated using the TIMES (The Integrated MARKAL-EFOM System) model for the future scenarios. The starting year of the modelling framework (2020) is calibrated against national statistics on energy use in the building sector (residential and service) provided by Statistics Norway (SSB) [2] to provide a sound baseline (Fig. 1). A large share of Norwegian energy use is used for heating, which is highly dependent on the outdoor temperature. This can cause large variations in the energy use in buildings from year to year. To compensate for this, the model results are calibrated against temperature corrected energy use statistics using heating degree days (HDD), as given in [50] and further described in [48]. At the time of the calibration, energy use statistics for 2020 were not yet available, and the energy use statistics for 2019 was used.

[1] The peak load of individual buildings is not likely to occur at the exact same time, and so the peak load of the system is not equal to the sum of the peak loads of the individual buildings within the system. This is reflected in the coincidence factor. [59]

To obtain information on the use of various heating technologies, statistics on heating technologies have been extracted from the Norwegian Energy Label database system [51] and adjusted based on [52,53] as described in [48]. The share of service buildings with waterborne distribution systems was calculated as a weighted average for the *regular* and *efficient* buildings based on assumptions from [53] and was estimated as described Section 4.1.5. It is assumed that no houses are connected to district heating and that all firewood used in households is used in *small houses* with wood stoves, and that all bioenergy used in the service sector is used in pellet boilers. Due to the ban on the use of mineral oil for building heating, there are no oil or LPG boilers/burners in use in 2020. It is assumed that all categories of service buildings have the same distribution of heating technologies. The calibrated model results for energy use of different heating carriers as well as the temperature corrected statistical energy use for 2019 is shown in Fig. 2.

Post calibration, the energy use statistics for 2019 were adjusted by Statistics Norway (SSB), resulting in an increase in temperature corrected energy use for the service sector by 0.6 TWh and a decrease in the residential sector by 0.6 TWh, as shown in Fig. 3. The energy use for 2020 was later published showing a decrease in measured energy use from 2019 to 2020, most likely due to differences in the outdoor temperature. While 2019 was close to an average year (3650 HDD), 2020 was an unusually warm year (3260 HDD). The temperature corrected energy use shows a small increase from 2019 to 2020, as well as a surprising shift, where energy use in service buildings decreased while energy use in residential buildings increased. An explanation for this might be due to the COVID-19 pandemic. This shift may suggest that the model results will fit well with the total energy use for 2020, but that there will be a bigger mismatch for energy use in the residential and service sectors.

In addition to the calibration of 2020/2019, the modelling frameworks was calibrated for 2010 and 2015 using assumptions about the building area composition and the use of heating technologies in each building and energy efficiency category. The calibration of the years 2010 and 2015 is described in [23] and shown in the Appendix A, and shows a good fit with the actual (temperature corrected) energy used [2], with a 0.9%, −1.1% and −0.6% deviation in the years 2010, 2015 and 2020 respectively.

4.1.5. Regions and district heating availability

The building stock is split into the five electricity market spot price regions in Norway, NO1 to NO5 shown in Fig. 4*a* based on a population key from [46]. The energy use projections in the TIMES-model assume that buildings can be connected to a district heating system if they are in a densely populated area.

The building stock is further divided in three categories: 1. Cities/large district heating systems, 2. Smaller towns/local district heating systems, and 3. Rural areas, as shown in*Figure 4b*. Buildings with a waterborne heating system can be connected to a district heating grid at lower costs than buildings with point source heating, so it is assumed that only new buildings and existing buildings with central heating can be connected to a district/local heating grid. Based on data from the energy labels system [51] and Statistics Norway (SSB) [54], Flexbuild has estimated a share of buildings with waterborne heating systems, see*Figure 4c*. Due to high costs and low occurrence, it is assumed in the calibration and TIMES-model that small houses are never connected to district heating.

4.1.6. Energy use modelling

The total energy demand of each scenario in 2030 and 2050 is calculated using the resulting building stock projection from REBUILDS and the PROFet model with stochastic weather profiles. Resulting energy demand predictions for each scenario using a

Table 2
Assumptions of the building stock development in the different scenarios.

Scenario assumptions	Energy nation		Petroleum nation		Nature nation		Climate panic	
	2020–2029	2030–2050	2020–2029	2030–2050	2020–2029	2030–2050	2020–2029	2030–2050
Share of new being Efficient	100%	0%	100%	100%	50%	0%	100%	0%
Share of new being Very Efficient	0%	100%	0%	0%	50%	100%	0%	100%
Share of renovated being Regular after renovation	80%	67%	80%	80%	50%	50%	80%	0%
Share of renovated being Efficient after renovation	20%	33%	20%	20%	50%	50%	20%	100%
Renovation rate, service buildings	1.3%	1.5%	1.3%	1.5%	1.3%	2.1%	1.3%	2.6%
Renovation rate with energy upgrade, service buildings	0.3%	0.5%	0.3%	0.3%	0.7%	1.0%	0.3%	2.6%
Demolition rate, service buildings	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.4%
Construction rate, service buildings	1.1%	0.9%	1.1%	0.9%	1.1%	0.9%	1.1%	0.8%
Renovation rate, dwelling stock	0.9%	0.9%	0.9%	0.9%	0.9%	1.5%	0.9%	2.0%
Renovation with energy upgrade, dwelling stock	0.2%	0.3%	0.2%	0.2%	0.5%	0.8%	0.2%	2.0%
Demolition rate, dwelling stock	0.6%	0.7%	0.6%	0.7%	0.6%	0.7%	0.6%	0.7%
Construction rate, dwelling stock	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%
Average floor area per person, dwelling stock (m2)	50.7	52.1	50.7	52.1	50.6	51.2	50.7	51.4

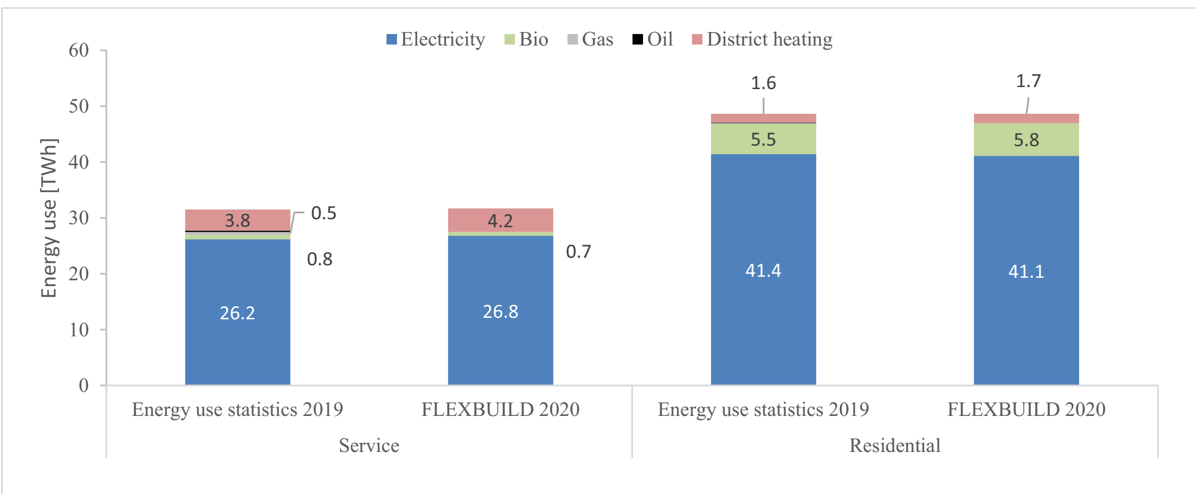


Fig. 2. Calibration of modelled energy use in the Flexbuild study against temperature corrected energy use statistics [2].

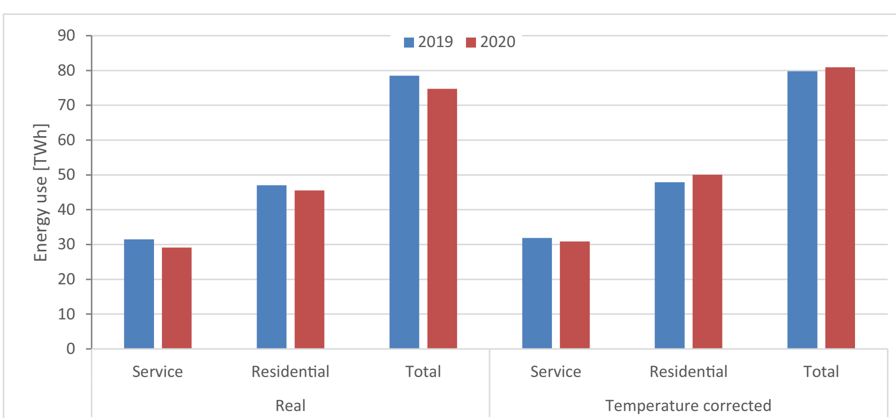


Fig. 3. Development in energy use from 2019 to 2020.

standard weather profile are shown in Appendix B. After calibration, the energy demand and load profiles are used as inputs into the TIMES-model to predict the energy use of the different scenarios. The energy demand for each building type and each end use category are exogenous model inputs from PROFet and RE-BUILDS to the energy system model IFE-TIMES-Norway [43] to derive the corresponding cost-optimal energy use for different technologies and energy carriers. IFE-TIMES-Norway is an optimisation model of the Norwegian energy system that is generated by the TIMES modelling framework [55]. TIMES models minimize the total discounted cost of a given energy system to meet the demand for energy services for the regions over the period analysed. The total energy system cost includes investment costs in both supply and demand technologies, operations and maintenance costs,

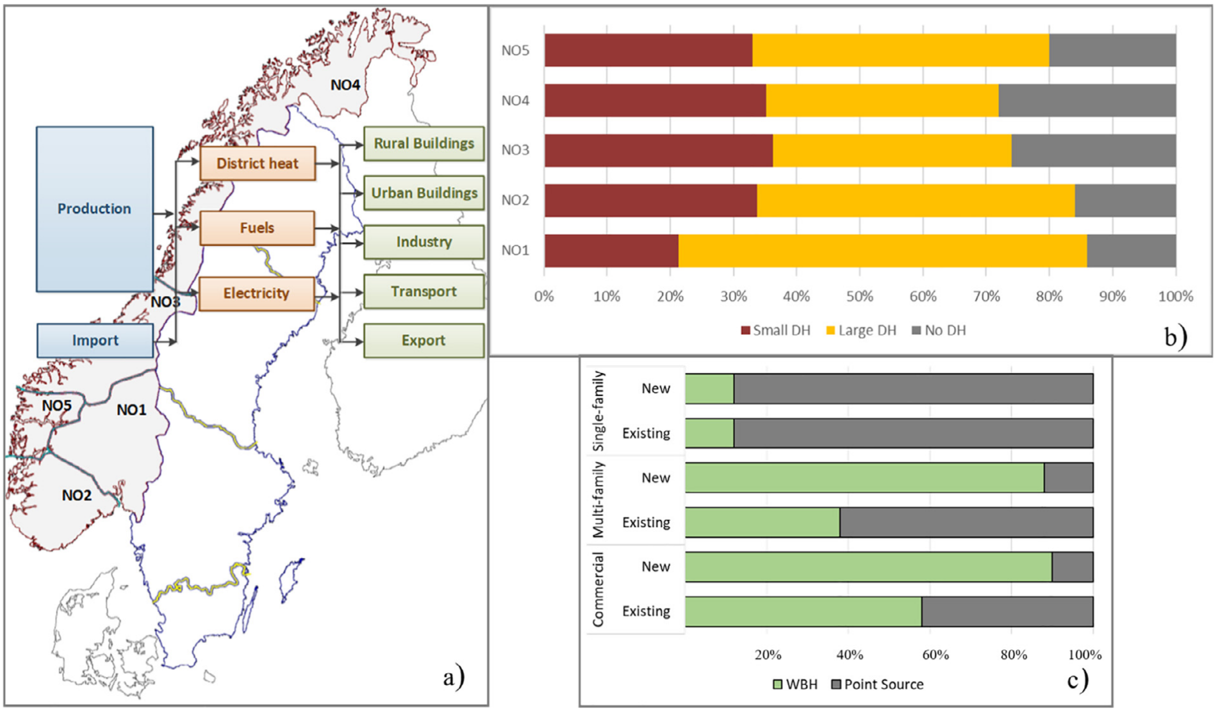


Fig. 4. a) Illustration of Flexbuild regions, b) Max share of buildings that could be connected to small, large, and no district heating systems per region, c) Current share of buildings with waterborne heating (WBH) and point-source heating. Additional shares and assumptions are given in [48].

income from electricity export, and costs of electricity import. Thus, the energy demand from PROFet and RE-BUILDS gives both annually demand and load profiles for each building category, end use demand and region in 2020, 2030, and 2050. The corresponding energy use of the building sector is thus a model result. IFE- TIMES-Norway is a technology-rich model of the Norwegian energy system divided into five regions corresponding to the five spot price areas. The TIMES model provides operational and investment decisions from the starting towards 2050, with model periods within this model horizon. To capture operational variations in energy generation and end-use, each model period is divided into four seasons, where each season has different energy production and demand profiles of 24 h.

4.2. Results: Flexbuild

4.2.1. Building stock development 2020–2050

The simulated building stock development using the RE-BUILDS model is shown in Table 3 for each of the four scenarios. More details on the RE-BUILDS results can be found in [48]. The building stock changes slowly in all scenarios, due to the long lifetime of buildings, and the long periods between renovations that can affect the energy efficiency level. The existing building stock from today will dominate the system and its energy use in decades to come. Still, important potentials for improvements of the building stock are revealed. In the most pessimistic scenario *Petroleum nation*, more than half of the stock is still *regular* in 2050, and none of the stock is *very efficient*. In the *Climate panic* scenario, 29% of the stock is still *regular* in 2050, 54% is *efficient* and 17% is *very efficient*.

An example of resulting building stock, for different renovated standards are shown in Fig. 5.

4.2.2. Projections: Energy use in 2030 and 2050

The resulting energy use in 2030 and 2050 in each of the different scenarios is shown in Fig. 6.

The figure shows that building stock electricity use decreases in all four scenarios towards 2050, due to more energy efficient buildings, more use of heat pumps, and increased district heating. The use of district heating from large-scale and small-scale systems increases for all scenarios towards 2030 and 2050. Towards 2050, the total energy use in the building stock is expected to decrease by 3% in *Petroleum nation*, 6% in *Energy nation*, 8% in *Nature nation* and by 14% in the scenario *Climate panic* (corresponding to a change between −2 TWh to −12 TWh compared to 2020).

4.2.3. Peak electricity loads 2030 and 2050

As the Flexbuild modelling framework creates long-term projections for energy use based on hourly loads, it can also be used to calculate the expected peak electricity use. Compared to 2018, the maximum electricity load of buildings in 2050 decreases in all four scenarios (Fig. 7), for the same reasons as the decrease in building stock electricity use. Similar to the reduction in annual electricity demand, the peak load reduction is largest for the *Climate panic* scenario, with a reduction in peak load of 14% for all regions combined, whereas *Petroleum nation* has the largest peak demand among the scenarios with a reduction of only 3% on the combined peak load, compared to 2018. The combined peak load is reduced by 11% in the scenario *Nature nation* and by 7% in the scenario *Energy nation*.

5. Comparing scenarios projections with statistics

5.1. Methodology: Indicators of energy projection calibration

The studies mentioned in Table 1 vary in both start year, duration, and purpose. To evaluate their performance on predicting the development in energy use towards 2020 there is a need for using indicators that account for differences in the starting year, scope, and the duration of the projection until 2020. To do this, a set of indicators have been proposed. The first indicator will evaluate how well the model fit with the actual measured energy consump-

Table 3
The composition of the building stock for the four scenarios in 2050.

Scenario		Existing (constructed before 2020)			New (constructed after 2020)		Sum
		Regular	Efficient	Very efficient	Efficient	Very Efficient	
		million m^2	million m^2	million m^2	million m^2	million m^2	million m^2
Nature nation	Small house	112	64	0	10	26	212
	Apartment block	20	20	0	6	49	95
	Service buildings	65	42	0	5	24	136
	Sum	197	126	0	21	99	443
	Share of 2050 stock	**44%**	**28%**	–	**5%**	**22%**	–
Petroleum nation	Small house	137	39	0	64	0	239
	Apartment block	24	16	0	38	0	78
	Service buildings	76	29	0	31	0	136
	Sum	236	84	0	133	0	453
	Share of 2050 stock	**52%**	**19%**	–	**29%**	–	–
Climate panic	Small house	77	100	0	20	15	213
	Apartment block	12	29	0	10	44	95
	Service buildings	39	69	0	9	18	136
	Sum	129	198	0	40	77	444
	Share of total stock	**29%**	**45%**	–	**9%**	**17%**	–
Energy nation	Small house	131	45	0	21	42	239
	Apartment block	23	17	0	12	26	78
	Service buildings	76	29	0	10	20	136
	Sum	230	91	0	43	88	453
	Share of 2050 stock	**51%**	**20%**	–	**10%**	**20%**	–

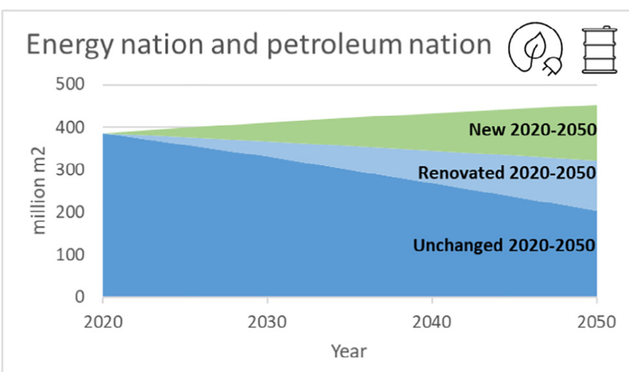


Fig. 5. Building stock development 2020–2050, according to the Energy nation and Petroleum nation scenarios from: [48]

tion in the model's start year, and is called the "Initial offset" and is given as follows:

$$Initialoffset = \frac{E_{model,initialyear}}{E_{measured,initialyear}} - 1$$

Where $E_{measured,initialyear}$ is the temperature corrected energy use of the initial year, while $E_{model,initialyear}$ is the modelled energy use of the starting year.

The average annual change in energy use from the initial model year to 2020 is evaluated using the "Initial trend error", to see how well the modelled trend line fit with the measured trend line. This indicator is calculated as follows:

$$Initialtrenderror = \frac{\Delta e_{model,2020-initalyear}}{\Delta e_{measured,2020-initalyear}} - 1$$

Where $\Delta e_{2020-initalyear}$ is the change between 2020 and the initial year divided by the number of years from the initial year and 2020.

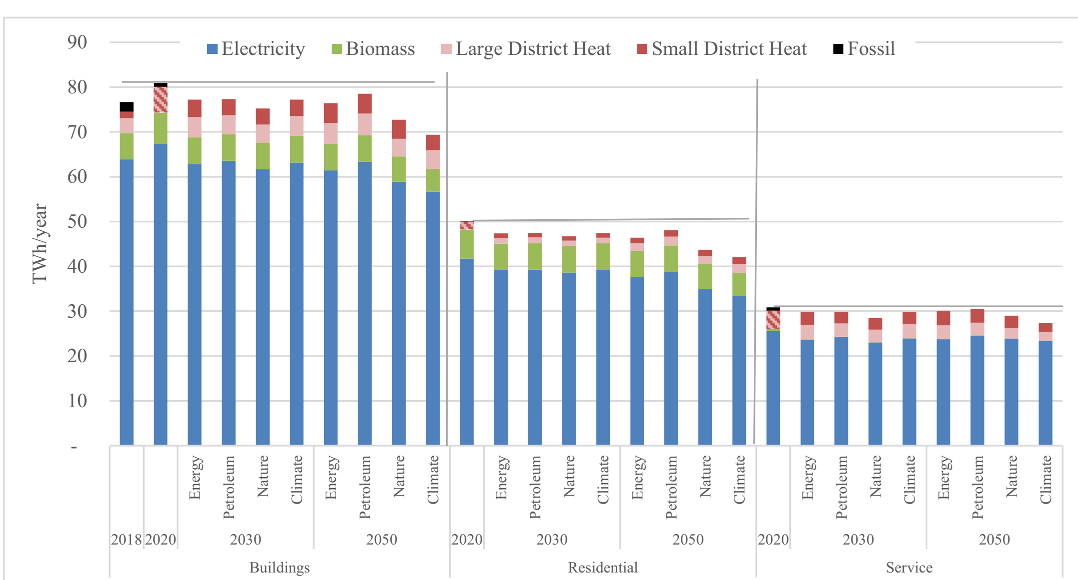


Fig. 6. Energy use in buildings (TWh/ year) in 2018, 2020, 2030 and 2050 for the four scenarios.

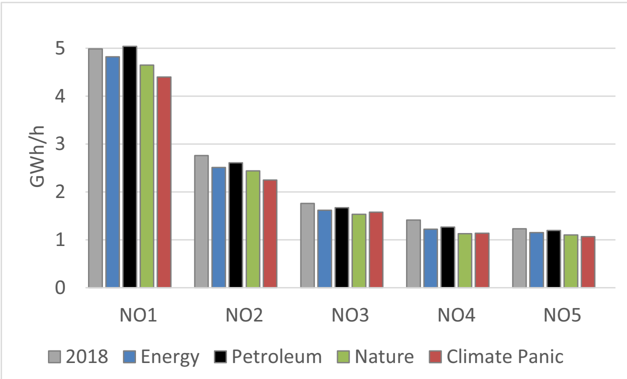


Fig. 7. Maximum power load (GWh/h) of buildings in 2050 per region and scenario.

5.2. Results: measured vs. projected energy use in different studies

A comparison between the measured (and temperature corrected) energy use of the building stock in the years 2000–2020, the projected energy use from the Flexbuild study, as well as the modelled results from the studies presented in Table 1, are shown in Fig. 8-Fig. 10. The figures indicate large differences between the studies, both with regards to their scenario durations, how well they are calibrated in the starting years and the trend in the energy consumption in the different scenarios. For the total building stock, Lavenergiutvalget 2009 [11] present the scenarios with both the highest expected increase in expected energy consumption (in their reference scenario), as well as the largest potential (in their best case scenario). The figures show that many of the studies have a starting point which is not calibrated with the measured energy use. The Norwegian Energy roadmap 2050 [22], for instance, predicts a reduction in energy use from their baseline scenario which is quite similar to the development of the Flexbuild scenarios. However, since the starting point for this study was higher than the actual energy consumption, the reduction until 2030 is just equal to the offset between the modelled and measured energy use in 2020. The Flexbuild scenarios indicate a smaller change in energy use in all scenarios compared to some of the other studies.

An overview of the calculated indicators for each of the different scenarios from Figs. 8–10 are shown in Table 4. The purpose of the various scenarios is indicated in the table (column 'type'), where they are marked with an 'R' if they are Reference scenarios with the intent of showing the most probable scenario and/or the continuation of current trends, and with 'BC' which are Best Case scenarios to outline the potential for energy efficiency. The reference studies are marked as “Calibrated” if the Initial offset is less than 5% (in absolute value) and the Initial trend error is less than 50% (in absolute value). The latter may seem as a generous benchmark: to classify as “calibrated” a scenario that is 50% off the measured value. However, this is the intention: to separate the scenarios that are considerably far off from those that lay within a range that is, at least, not larger than the observed trend itself, i.e. ±50% around it. The BC scenarios are not labelled as “Calibrated” or not since the purpose of these scenarios is to intentionally deviate from the expected trends in order to outline the potential for energy savings in the building stock.

The column “Annualised trend” shows the linear trend of the total energy use variation over the entire period of the scenario (from initial to end year), in TWh/y. This is a uniform way to express the scenario results, allowing to compare them even though the various studies focused on different periods. It is worth remarking that this is different from the trend considered in the Initial trend error, which is calculated only over the observed period between each scenario's initial year and 2020.

Table 5 summarizes the average Annualised trend – and its spread, meaning the difference between minimum and maximum values, given in parentheses () – for the Reference scenarios, together and split in “Calibrated”-True and “Calibrated”-False, as well as for the Best Case scenarios. All groups consist of small subsets of the scenarios listed in Table 4; too small for an appropriate statistical analysis. That is the reason for providing only the average and the spread. Even so, some group such as Service R-True and Service-BC consist of only two scenarios each, meaning the average and the spread may be highly biased by the values of a single scenario. This being said, it may still be possible to attempt the following observations.

Looking at the different sectors, the annualised trend average values of all the Reference scenarios appear to be consistent, in the sense that the Total average value is equal to the sum of the Residential and Service average values, despite the values coming from different subsets. The same cannot be said for the Best Case scenarios where, notably, the projected average energy savings are similar in all three sectors (between −0.44 and −0.55 TWh/y) despite the different size of the sectors: the total stock is by definition the sum of residential and service stocks. This may be explained by the fact that Reference scenarios are different attempts to represent the same reality, namely the continuation of the *status quo* (or business as usual), and so less subject to the assumptions of the various studies. In Best Case scenarios, instead, the modellers have more freedom in defining possible future evolutions, giving rise to higher variability and making the resulting averages not directly comparable across sectors.

Looking at the difference between “Calibrated”-True and “Calibrated”-False within the Reference scenario, we see that the Total stock average appears to be solid, in the sense that both True and False scenarios give the same average value (0.06 TWh/y). This is no longer true for the Residential and Service sectors where large differences are observed between the -True and -False groups themselves and with respect to the All group. This would suggest that the Reference scenarios average is somewhat less robust in the Residential and Service sectors than it is in the Total stock. This, in turn, may indicate that it is somewhat simpler to construct scenarios on the total stock than it is on parts of it. Several studies, though not all, consider both sectors and present results both separately and together. In these cases we see that they might result as “Calibrated” only in the Total and/or only in one of the two sectors, but overall, the highest proportion of “Calibrated”-True scenarios is found in the Total stock. Separating the stock into residential and service does introduce additional assumptions on how to classify the stock and its evolution, as well as on the available energy statistics and how to split it between the two sectors. This increase the complexity of the modelling and so the freedom and the variability of the modellers choices. Thus, it does not sound unreasonable that scenarios on the total stock may be somewhat more robust than those on separated sectors.

However, looking at the spread (values reported in parentheses in Table 5) there clearly is a large variability between the scenarios in each subset, so that the average values are highly uncertain and no conclusion can be withdrawn with confidence. Within the Reference “Calibrated” scenarios, the True subsets have a lower spread than the corresponding False subsets, as it should be expected. The Reference scenarios altogether present a spread that is in absolute values lower than the spread of the Best Case scenarios, in all sectors. However, when put in proportion to the average value, the spread in the Reference scenarios looks higher than in the Best Case scenarios; for example the spread is about 11 times the average value in the R-scenarios while it only about 3 times the average value in the BC-scenarios. On one side, this is the effect of the aver-

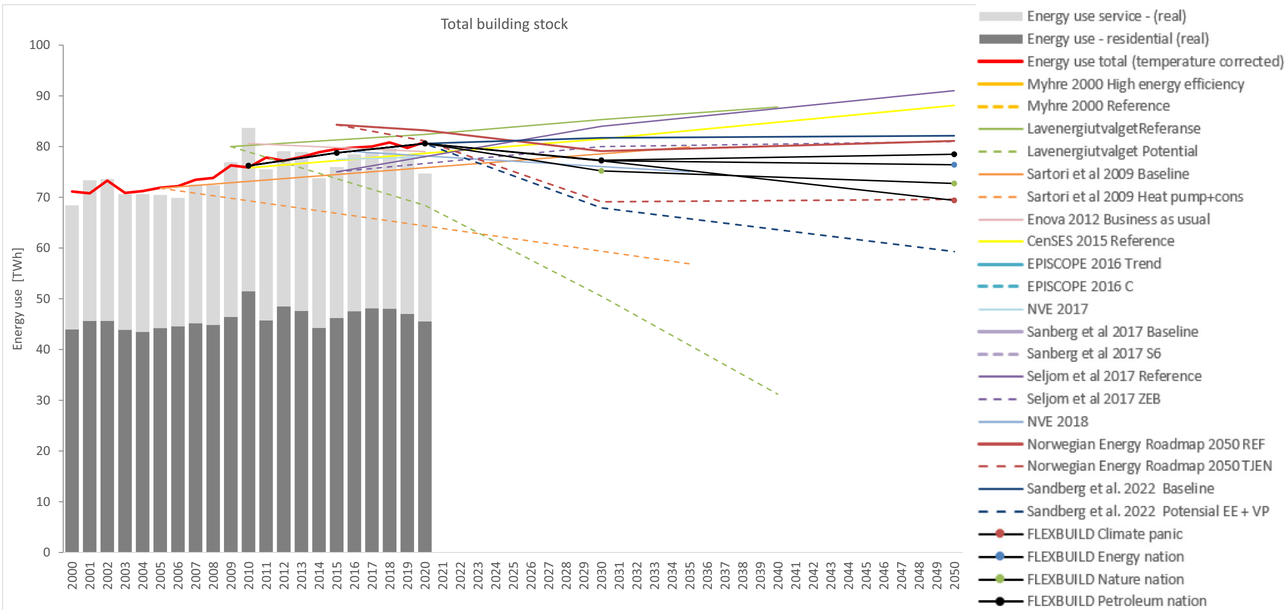


Fig. 8. Measured energy use and expected development in the energy use for the building stock from different studies.

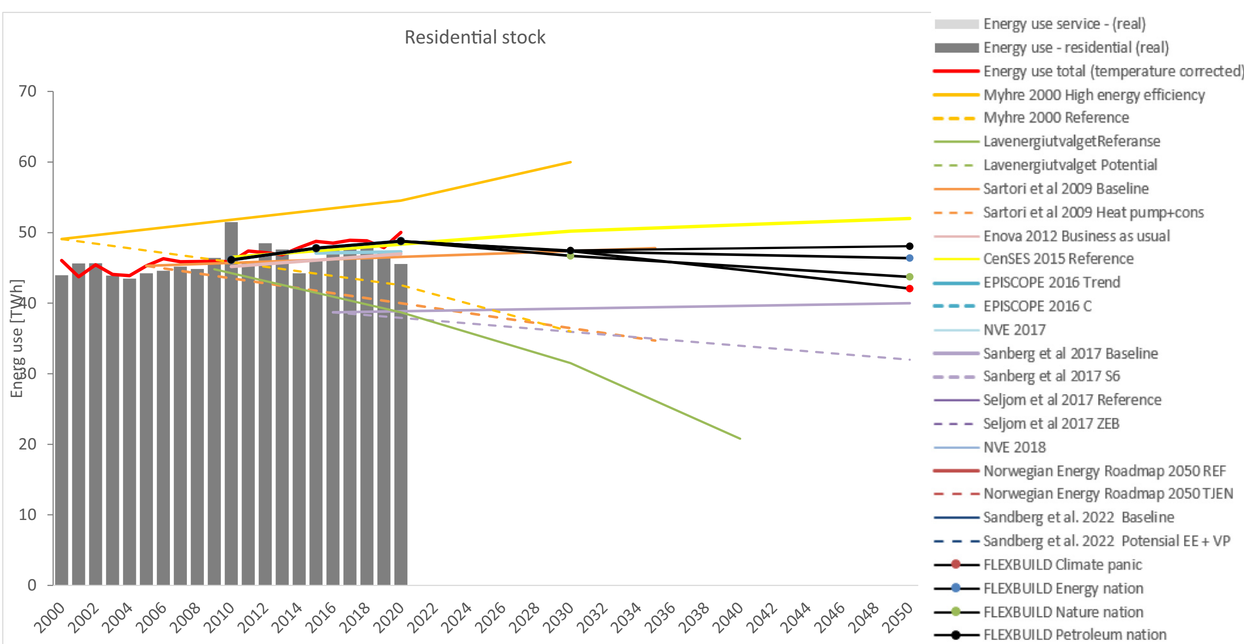


Fig. 9. Measured energy use and expected development in the energy use for the residential stock from different studies.

age value being smaller in absolute terms; on the other side it should serve as a reminder that uncertainty is high in all scenario groups.

With all the due precautions aforementioned, the Total stock results appear as the most robust in the R-scenarios, given that the "Calibrated" True and False average values are equal, and the most conservative in the BC-scenarios, given that the projected savings are similar in all sectors while the total stock is the largest in size by definition. The R-scenarios point at an average annualised trend of 0.06 TWh/y, which would mean an increase in energy use of about 2.5 TWh over a 40 year period, while the BC-scenarios point at potential energy savings that progress at an average pace of −0.55 TWh/y, which would mean a reduction in energy use of about –22 TWh over the same 40 years period.

Focusing on the Flexbuild scenarios, they are all classified as Reference scenarios because they are constructed to represent possible outcomes for the development of energy use in the building stock (see §6.1) and in the context of the Flexbuild project all the scenarios (named 'Storylines' in the project) achieve a substantial decarbonisation of the energy system by 2050 (with different mixes of demand side and supply side contributions to the goal) [44,48]. The Flexbuild scenarios are identical in the initial period 2010–2020, in which they result as "Calibrated" according to the classification here adopted, and their average annualised trend in the entire time horizon of the study, 2010–2050, is −0.05 TWh/y.

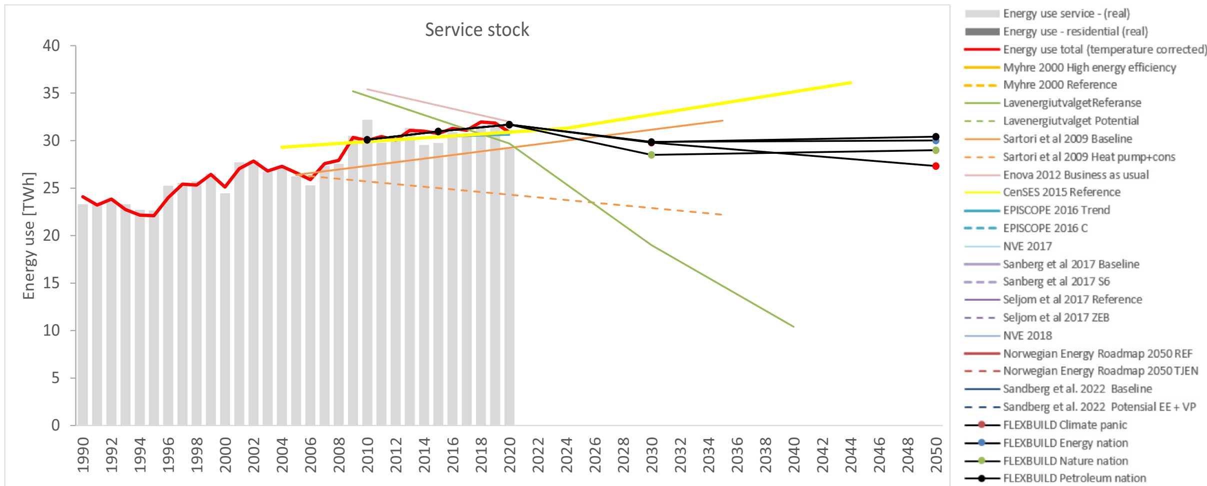


Fig. 10. Measured energy use and expected development in the energy use for the service building stock from different studies.

This is in the same order of magnitude as the overall average for Total-R scenarios but reversed in sign, i.e. indicating savings rather than increased energy use, that would cumulate to about −2 TWh by 2050. The study by Sandberg *et al.* (2020) [23] is based on substantially the same model and assumptions as the Flexbuild scenarios for its initial period (thus also resulting “Calibrated”), while it projects a best case scenario for the future development between 2020 and 2050. In this case the average annualised trend is −0.42 TWh/y; in the same order of magnitude as the overall average for Total-BC scenarios, although somewhat more conservative. This would lead to cumulative savings of about −17 TWh by 2050.

6. Discussion

Developing a model of the building stock and its energy use is linked to many uncertainties. There are currently no detailed, accurate statistics on many important aspects of the Norwegian building stock, including basic data about the heated floor area, the composition of building archetypes, or renovation rates and types. Statistics on the shares of heating technologies are limited. The Flexbuild scenarios show a good fit with the historical development for the total building stock energy use, but a worse fit for energy use in the residential and service sector when considered separately. The models in the Flexbuild study were originally calibrated against energy use measurements from 2019 as statistics for 2020 were not available. If compared to 2019, the model results show a better fit with both the total stock and the service stock, but a worse fit wit the residential stock. When the energy use statistics for 2020 were later published, the temperature corrected energy use for the service sector appeared to have been reduced while the energy use for residential buildings had increased. A reason for this could be a change in habits and behaviour and restrictions due to the COVID-19-pandemic, and in particular the increased use of home offices. Energy use in the Norwegian building stock is highly dependent on the outdoor temperature, as a large share of the energy use is used for heating purposes. Due to this, the energy use statistics must be temperature corrected before calibrating the models. As shown in Fig. 3, the annual energy use is highly sensitive to the temperature correction, and the choice of calibration year can affect the model results. This affect all studies, and as we can observe in Table 4, more studies are *calibrated* on the development of energy use from 2010 to 2020 for the total building stock then for the residential and service sector separately.

The Flexbuild scenarios show a small error in the initial offset indicator, as well on the initial trend indicator between 2010 and 2020 on the total building stock, but with a larger error on the service and residential sectors when they are analysed individually. Calibrating the model against measurements from several years can be useful for assuring the model does not over- or underestimate the rapidness of changes in the building sector. Towards 2050, the Flexbuild scenarios indicate a reduction in energy use in a range from 2 TWh (in *Petroleum nation*) to 12 TWh (in *Climate panic*) compared to 2020. The differences between the results in the scenarios are affected by differences in energy demand, energy supply, and costs of energy technologies. The difference in the scenarios indicate that the building stock could provide either smaller or larger reductions in energy use and electricity, which could help reduce emissions linked to energy generation, and “free up” electricity for other purposes, such as electrification of the transport and industrial sectors. Studies such as Sandberg et al. 2022 [23] suggest that the potential for energy efficiency in 2050 is even higher, but the Flexbuild scenarios aim to present the possible development of the building stock given different political, economic, and social development. The scenarios do not indicate that we will reach the potential for energy efficiency which is outlined in many of the other scenarios. A reason for this could be due to assumptions of a slow renovation rate (with energy upgrades), which appears realistic as only 20% of renovations of buildings are expected to result in energy upgrades [47].

Table 4 indicates that the Flexbuild scenarios, Lavenergiutvalget *Reference* [11], Sandberg et al. 2022 [23], and CenSES 2015 [15] are all *calibrated* and show a good fit for the development of the energy use in the total building stock between 2010 and 2020. For the residential stock, only the Flexbuild scenarios are *calibrated*, while for the service sector only CenSES 2015 [15] *Reference* scenario and Sartori et al. 2009 [12] are *calibrated*. The Flexbuild scenarios are not *calibrated* for the service sector due to the *Initial trend error* being at 85%.

The starting point of the different projections do in some cases differ from the energy use statistics [2], and though some of the studies start their projections in the same year, the starting point may still differ. Explanations for this may be differences in HDD temperature correction of the measured energy use, lack of calibration of the starting year, changes in the actual energy use statistics between the publication years, or differences in the system boundaries (e.g., which buildings and energy carriers are included). For instance, energy use for fuels for military vehicles may be assumed

Table 4
Indicators of the fit between modelled and measured energy use between the initial year and 2020 for the total stock scenarios.

Scenario		Model				Indicator of calibration (2020)		
		Scenario type	Initial year	End year	Annualised trend [TWh/y]	Initial offset	Initial trend error	"Calibrated"
Total	LavenergiutvalgetReferanse	R	2009	2040	0.25	5%	−48%	True
	Sartori et al. 2009 Baseline	R	2005	2035	0.27	0%	−55%	False
	Enova 2012 Business as usual	R	2010	2020	−0.16	6%	−132%	False
	CenSES 2015 Reference	R	2010	2050	0.24	4%	−43%	True
	NVE 2017	R	2015	2020	0.08	−3%	−71%	False
	Seljom et al 2017 reference	R	2015	2050	0.46	−6%	116%	False
	NVE 2018	R	2016	2035	−0.21	−1%	−175%	False
	Norwegian Energy Roadmap 2050 REF	R	2015	2050	−0.09	6%	−179%	False
	Sandberg et al. 2022 Baseline	R	2010	2050	0.15	0%	−13%	True
	Flexbuild Climate panic	R	2010	2050	−0.17	0%	−13%	True
	Flexbuild Energy nation	R	2010	2050	0.00	0%	−13%	True
	Flexbuild Nature nation	R	2010	2050	−0.09	0%	−13%	True
	Flexbuild Petroleum nation	R	2010	2050	0.06	0%	−13%	True
	LavenergiutvalgetPotential	BC	2009	2040	−1.57	5%	−352%	-
	Sartori et al. 2009 Heat pump+cons	BC	2005	2035	−0.50	0%	−183%	-
	Seljom et al 2017 ZEB	BC	2015	2050	0.17	−6%	20%	-
	Norwegian Energy Roadmap 2050 TJEN	BC	2015	2050	−0.42	6%	−331%	-
	Sandberg et al. 2022 Potensial EE + VP	BC	2010	2050	−0.42	0%	−13%	-
Residential	Myhre 2000 Reference	R	2000	2030	0.36	7%	37%	False
	Sartori et al. 2009 Baseline	R	2005	2035	0.08	0%	−74%	False
	Enova 2012Business as usual	R	2010	2020	0.18	−1%	−57%	False
	CenSES Reference	R	2010	2050	0.09	5%	−55%	False
	NVE 2017	R	2015	2020	0.04	−3%	−84%	False
	Sanberg et al 2017 Baseline	R	2016	2050	0.04	−20%	−90%	False
	Flexbuild Climate panic	R	2010	2050	−0.10	1%	−36%	True
	Flexbuild Energy nation	R	2010	2050	0.01	1%	−36%	True
	Flexbuild Nature nation	R	2010	2050	−0.06	1%	−36%	True
	Flexbuild Petroleum nation	R	2010	2050	0.05	1%	−36%	True
	Myhre 2000 High energy efficiency	BC	2000	2030	−0.44	7%	−265%	-
	Lavenergiutvalget Potensiale	BC	2009	2040	−0.77	−3%	−250%	-
	Sartori et al. 2009 Heat pump+cons	BC	2005	2035	−0.35	0%	−212%	-
	Sanberg et al 2017 S6	BC	2016	2050	−0.20	−20%	−152%	-
Service	Sartori et al. 2009 Baseline	R	2005	2035	0.19	−1%	−33%	True
	Enova 2012 Business as usual	R	2010	2020	−0.34	18%	−495%	False
	CenSES Reference	R	2010	2050	0.15	1%	16%	True
	NVE 2017	R	2015	2020	0.04	−1%	67%	False
	Flexbuild Climate panic	R	2010	2050	−0.07	0%	85%	False
	Flexbuild Energy nation	R	2010	2050	0.00	0%	85%	False
	Flexbuild Nature nation	R	2010	2050	−0.03	0%	85%	False
	Flexbuild Petroleum nation	R	2010	2050	0.01	0%	85%	False
	LavenergiutvalgetPotensiale	BC	2009	2040	−0.80	16%	−1100%	-
	Sartori et al. 2009 Heat pump+cons	BC	2005	2035	−0.14	−1%	−149%	-

to be a part of the service sector in some studies [56], while other studies ignore fuels for vehicles used in the service and residential sector when analysing the energy use of buildings. Some projections only project the energy demand in buildings ([19]), and not energy use, and do not consider the effects of energy losses in the buildings, or the choice of heating solutions. Other approaches [16] do not include energy used for electrical appliances and lighting.

The differences in the projected future energy use may be caused by several factors. The development of building area is largely affected by population projections, which have their own uncertainties, are dependent on several factors, and are updated annually. There is a large potential for reducing the energy use in existing buildings, which may explain the large variations in future energy demand and energy use. Projections operating with more cohorts/age groups seem to assume that a larger portion of the energy efficiency potential is realized, and hence, that future energy use is expected to decrease more. Assumptions about renovation rates and the share renovations which involve energy-upgrades have a large impact on the development of energy use as well as the share of heating technologies and the assumptions of efficiencies, especially for heat pumps. Other factors which may affect the results are based on theoretical energy use in buildings from simulations (such as calculations for the energy demand (for example with Enova 2012 [13,14], NVE 2017[17] and NVE 2018 [20,21]) or based on measured energy use/energy demand, from for example PROFet (used in Flexbuild and Sandberg et al. 2022[23]). When using simulated energy use models, the user

Table 5
Average annualised trend in different types of scenario, and related spread in parentheses.

Sector	Annualised trend [TWh/y](spread* [TWh/y])			
	Average of Reference scenarios – R			Average of Best Case scenarios – BC
	All	"Calibrated"		All
Total	0.06 (0.67)	True	0.06 (0.42)	−0.55 (1.75)
		False	0.06 (0.67)	
Residential	0.07 (0.46)	True	−0.03 (0.15)	−0.44 (0.58)
		False	0.13 (0.33)	
Service	−0.01 (0.53)	True	0.17 (0.05)	−0.47 (0.66)
		False	−0.07 (0.38)	

* Difference between minimum and maximum values within each group.

behaviour of residents as well as the rebound effect of upgraded buildings, could result in smaller energy use reductions than expected. By basing the models on measured results, the rebound effect is considered. The shares for different heating technologies in the Flexbuild scenarios are a result of economical optimization combined with scenario assumptions. In other scenarios, such as Sandberg et al. 2022 [23], this is purely based on scenario assumptions.

Table 5 showed that the scenarios on the Total stock appear more robust in the Reference scenarios and more conservative in the Best Case scenarios, compared to the scenarios on the Residential and Service sectors. The Best Case scenarios for the total stock project an average energy saving potential, expressed as annualised trend, that proceeds at a pace of −0.55 TWh/y, while the Reference scenarios show an increase of 0.06 TWh/y. The Flexbuild scenarios, and likewise the similar scenarios in [23] – which are all calibrated over an extended observation period – point at a more moderate situation, where the Best Case scenario in [23] progresses at −0.42 TWh/y while the average of Flexbuild Reference scenarios progresses at −0.05 TWh/y.

6.1. Scope of present work and need for future work

The Flexbuild scenarios are constructed to represent possible outcomes for the development of energy use in the building stock. In some ways, these scenarios represent a narrow range of possible futures. For instance, all of these scenarios assume the same changes in population (the median population projection from Statistics Norway [57]). The energy demand load profiles are created based on the composition of different building categories, but it is assumed that all service building categories use the same heating technologies. In reality, there would be some differences in the heating technologies used in the different building categories.

As our modelling framework provides coherent long-term projections of both annual and hourly building sector energy use for different energy carriers separately, the modelling framework can provide peak load projections in addition to energy use projections. The results for peak load projections for building stock electricity use are presented, but are not a main topic of this article. In further work, the peak load projection results should be compared against peak load projections from other studies.

The purpose of the indicators of calibration has been to show how well the results from different projection model studies compared with the historical development in energy use. In some cases, these indicators can be misleading or not possible to compare. For example, since the Episcope study excludes energy use for electrical appliances and lighting, is the results not directly comparable with measured energy use, especially not for the *Initial offset* indicator, as similarly differentiated energy use statistics are not available.

The *Initial trend error* indicator works well at indicating the difference in growth in energy use, but the year 2020 is a unique year due to the COVID-19 pandemic, which may be a reason why some studies receive low values for this indicator on the residential and service sectors especially. The purpose of the different scenarios is important for the development of the projected energy use. A baseline scenario will often reflect the most likely outcome given today's policies and trends, or it might reflect a conservative development for renovation, building codes, and heating technologies. Other scenarios tend to reflect a more ambitious development or even the maximum theoretical. For these scenarios, comparing the trend in the energy use development until the year 2020 does not make sense, as the purpose of these scenarios is to outline a future potential for energy use, and not reflect historical development of energy use. A large deviation on these scenarios could also imply that these scenarios are unlikely, or indicate that it was not possible to extract the existing potential. The indicators of calibration should be limited to their main purpose of evaluating the reference scenarios against historical development.

7. Conclusion

The novelty of the methodology proposed in this article has been to combine a set of existing, previously documented models in a new way that benefits from the integration of stock modelling, hourly energy demand load profiles, and energy system modelling, thus providing a coherent long-term projection of both annual and hourly energy use for different energy carriers for the building sector. The Flexbuild modelling framework has been used to project the energy use and the peak power load for the Norwegian building stock in four scenarios towards 2030 and 2050. Towards 2050, the total energy use in the building stock is expected to decrease by 3% in *Petroleum natio*n, 6% in *Energy nation*, 8% in *Nature nation* and by 14% in the scenario *Climate panic* (corresponding to a change between −2 TWh to −12 TWh compared to 2020). The maximum electricity load of buildings in 2050 decreases in all four scenarios compared to 2018, due to more energy efficient buildings, more use of heat pumps and an increased use of district heating.

Models for projecting future energy use can provide insights about the effectiveness of current policies while illuminating areas that may benefit from new or updated policies. However, to have the desired effect, the projections must be as realistic as possible and reflect the actual development in building stock energy use.

This necessitates a methodology for evaluating historical long-term annual energy use projections to understand why some models succeed in predicting the development in energy use while others fail. In this article, a set of indicators for evaluating the calibration of different models has been presented. The indicators evaluate the initial difference and the deviation in annualised trend for energy use projection models. A comparison of a selection of energy projections for the Norwegian building stock and the actual development of energy use from statistics from 2000 to 2020 is presented and evaluated using the suggested indicators. The comparison shows a large spread in the results of the analysed scenarios from different studies, with the results on the total stock appearing somewhat more reliable than those on residential and service sectors. The Flexbuild scenarios point at energy savings that are, in average, more optimistic than the average value from all the reference scenarios. However, a best case scenario that is based on the same initial calibration methodology as in Flexbuild, shows a potential for energy savings that is more conservative than the average value from all the best case scenarios.

Declaration of Competing Interest

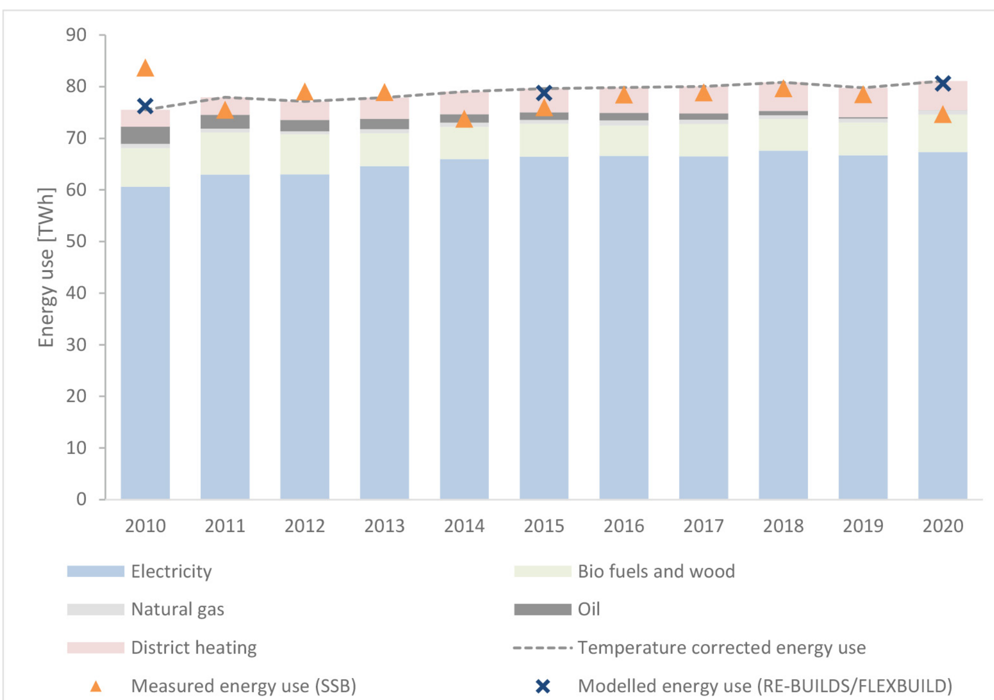
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper is a deliverable of the Flexbuild project. The authors kindly acknowledge the support from the Research Council of Norway under the programme EnergiX, with grant agreement nr. 294920/E20 and the following industrial partners: Statsbygg, Omsorgsbygg (Oslobygg), Boligbyggelaget TOBB, Norsk Fjernvarme, Hafslund nett (Elvia) and Statnett; the public actors are: Norges vassdrags- og energidirektorat (NVE) and Enova.

Appendix

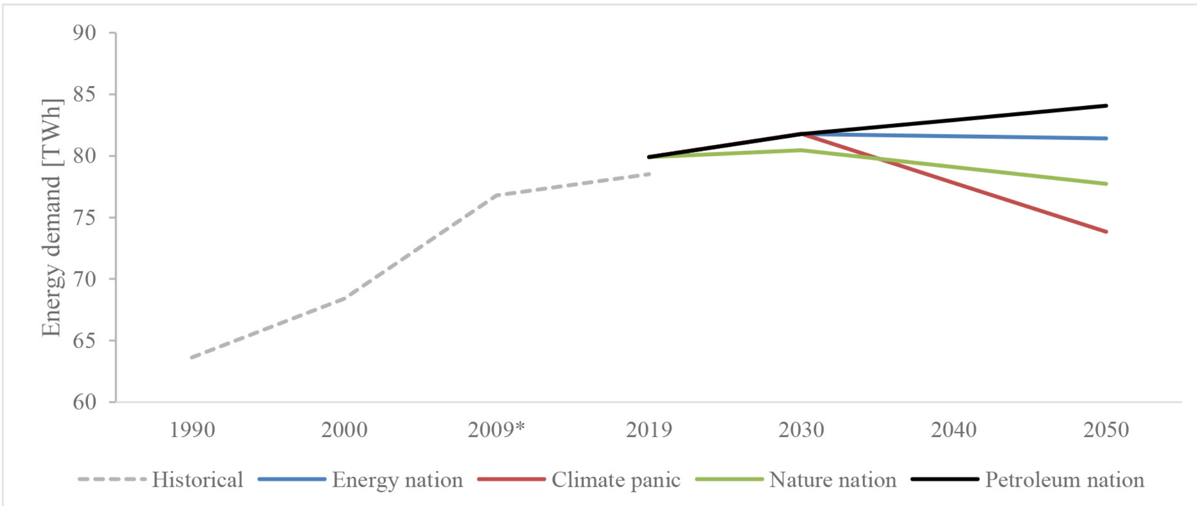
Appendix A: Energy demand in scenarios 2020–2050



Modelled energy use in the building stock compared to the measured and temperature corrected energy use. Reference: [23]

Appendix B: Energy demand in scenarios 2020–2050

The energy demand of each scenario in 2030 and 2050 is calculated using the PROFet model using a standard weather profile (NS 3031:2014 [58]). The sum of energy demand (for space heating demand, domestic hot water demand and electricity demand) is shown in the figure below.



Modelled development of energy demand in the building stock 2020-2050 and the historic development of energy use 1990–2020 [2].

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