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# The effect and value of end-use flexibility in the low-carbon transition of the energy system

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ABSTRACT

Flexibility at end-use level can lower both the costs of end-use sectors, such as the building sector and the investment and operational costs of the electricity sector. For planning purposes, it is however a need to understand how end-use flexibility influences the design of the future energy system. This paper analyses the role and value of end-use flexibility in the Norwegian low carbon energy system transition towards 2050. This is done by using a stochastic energy system model, IFE-TIMES-Norway, to quantify how end-use flexibility impacts the energy system design and the corresponding sectoral profits and costs. The results demonstrate that facilitating a techno-economic implementation of end-use flexibility lowers the cost of the energy transition towards 2050 between BEUR 4.4 and BEUR 8.3. This is primarily because end-use flexibility ensures a better match between local PV production and demand, lowers the capacity expansion needs of the electricity grid and increases profits from international electricity trade. Further, the results show that end-use flexibility reduces the need for hydrogen and thermal storage, where hydrogen storage capacity is lowered by 25 %–66 % in 2050, depending on storyline.

## 1. Introduction

With electrification and a more weather-dependent renewable electricity supply, there is an increased need for flexible solutions to adapt to variability and uncertainty in supply and demand [1]. There is a significant potential for flexibility at end-use level, including local batteries, demand response and electric vehicles [2]. For the electricity sector, end-use flexibility can contribute to avoiding curtailment, providing cost-efficient reserves for balancing markets and lowering the need for capacity expansion in generation and infrastructure [3]. Furthermore, for the end-use sectors, such as the building sector, end-use flexibility can help lower energy costs for end users [4]. However, the future role of end-use flexibility is uncertain, as it depends on energy behaviour and new market solutions, among other factors [5].

This paper presents a techno-economic analysis of the role of end-use flexibility in Norway's transition to a low-carbon energy system towards 2050, with 85 % $CO_2$ reduction in 2050 compared to 2018. We quantify how investment in, and operation of, end-use flexibility influences the revenues and costs of the different parts of the energy system, including electricity generation and electricity trade, district heat and buildings. Long-term energy system optimisation models (ESOMs), such as TIMES models [6], are well suited to capture the interaction between several flexibility solutions in different sectors and to address the impact of end-use flexibility on the techno-economic investments in and operation of the energy system. The analysis of this paper uses the IFE-TIMES-Norway model [7], which offers a detailed representation of the Norwegian energy system, including energy supply, infrastructure, end-use technologies and energy service demand. The focus of this paper is on flexibility options that affect the energy use of the building sector, encompassing stationary batteries, flexible electric heating of hot water and flexible charging of electric vehicles (EVs). Henceforth, these three flexibility options are termed *end-use flexibility*.

### 1.1. Background

There are numerous types of flexibility, and in an electrified building sector some of the most relevant flexibility options are studied in this paper; battery storage, electric water heaters, and charging of EVs.These flexibility options can lower the peak electricity demand and increase the self-consumption of PV through shifting the demand in time. Stationary batteries can both lower the peak electricity demand from the grid and increase the self-consumption of PV. For example, in Ref. [8], an analysis of buildings in the Bahamas shows that batteries can reduce the electricity supply from the grid by 58 %–83 %. Flexible electric heating of hot water can significantly lower the Norwegian morning

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**Abbreviations**

| | |
|---|---|
| CCS | Carbon Capture and Storage |
| ESOM | Energy System Optimisation Model |
| EV | Electric Vehicle |
| PV | Photovoltaics |
| IEA | International Energy Agency |
| TIMES | The Integrated MARKAL-EFOM System |
| ETSAP | The Energy Technology Systems Analysis Program |

peak. In Ref. [9], it is identified that the highest flexible power potential is 54 % at 8:00 a.m. for a duration of 61 min. As discussed in Ref. [10], EVs brings both new challenges and opportunities in the low-carbon transition, and a good integration with the electricity sector requires a good understanding of charging flexibility. An example of a benefit of EVs is quantified in Ref. [11], which shows that the predicted EV growth in India will not increase the peak electricity demand if it is combined with flexible EV charging.

Another source of flexibility in buildings, is to vary the indoor temperature while maintaining the thermal comfort of the occupants. According to Ref. [12], a commonly used approach to quantify this flexibility, Deterministic Model Predictive Control, tends to overestimate the flexibility potential as it ignores uncertainty. Due to the complexity of flexible space heating and limited data on a national level, this paper has not included this type of flexibility. Further, this study does not include the flexibility of moving the use of electric appliances, such as washing machines, that constitute only a marginal share of the energy demand of Norwegian buildings. Consequently, by not including all types of flexibility sources, this analysis is based on a conservative assumption of the total flexibility potentials of buildings.

There are several sources of flexibility in other sectors, that are also included in the analysis of this paper. In 2021, hydropower accounted for 91 % of the total Norwegian electricity generation [13], and the hydro reservoir capacity was equivalent to 70 % of the annual Norwegian electricity consumption [14]. Further, the Norwegian electricity grid is highly interconnected with the European power market, and in 2021, the max net export constituted 7.7 GW, corresponding to 30 % of the peak national electricity demand of 25.2 GW [15]. In addition, the district heating system offers flexibility [16], with both flexible supply and thermal storage and there is flexibility in the power-intensive industry [17]. In the transition to a low-carbon energy system, new sources of flexibility can be available, such as flexible hydrogen production and hydrogen storage [18].

The techno-economic profitability of flexible solutions has increased with higher and more variable electricity prices. With the increase in electricity prices from the fall of 2021 [19], Norwegian electricity demand has decreased. For example, the temperature corrected demand in the Oslo region was 8 % lower in the winter of 2021/2022 compared to the winter of 2020/2021 [20]. This implies that there is some flexibility in lowering and/or switching electricity use in the end-use sectors. Furthermore, since Norwegian electricity prices are highly dependent on European electricity prices [21], the future value of Norwegian flexibility depends on the development of the European power market.

Norwegian buildings constitute 37 % of the final Norwegian energy demand in 2022, whereas the share of electricity use in residential and commercial buildings was 81 % and 75 %, respectively [22]. Fig. 1 shows the Norwegian electricity use per month and sector. The electricity use in Norwegian buildings varies during the year due to that a high share of electricity demand is used for heating. The cooling demand represent 6 % of total energy use of commercial buildings [23] and this include cooling of goods and internal heat sources, that has less seasonal variation. Further, the cooling demand of households is marginal and is normally not included in the final energy demand [24]. Together, the

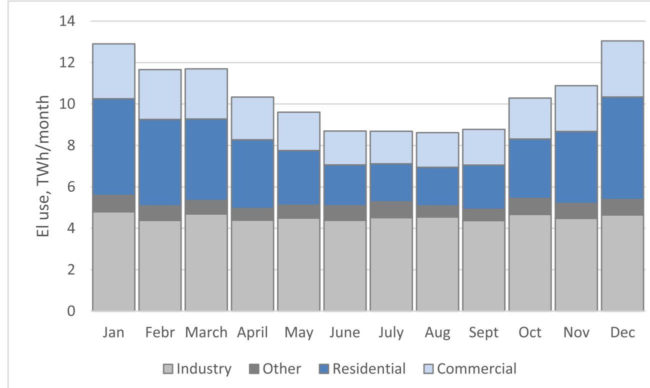



**Fig. 1.** Electricity use per month in 2022 by sector, TWh/month [25].

cooling demand corresponds to 2 % of the energy use in buildings. The electricity use in the industry is flat throughout the year since the electricity intensive industry have a continuous production. Furthermore, in 2022, 21 % of the Norwegian private cars were battery electric vehicles (EVs) and 79 % of the new cars were EVs.

Flexibility in buildings can provide flexibility at a low cost and contribute to lower the peak electricity demand. The cost of activating flexibility in the Norwegian industry is costly, as it often reduces the production of industrial products. In Ref. [26], the cost of the industrial sectors to be an hour without electricity ranges from 50 €/MW for the wood and paper industry to 900 €/MWh for the aluminium and metal manufacturing industry. Furthermore, as the electricity demand in buildings varies with seasons, the flexibility in buildings can have a great impact on the Norwegian peak electricity demand.

Since the Norwegian building sector is highly electrified, the energy demand of buildings can be representative for future situations of other countries in cold climates. Furthermore, seasonal differences in the electricity demand for buildings can also occur in countries that have a warmer climate due to a cooling demand. The scope of the paper is thus relevant for other countries to investigate the role of flexibility in buildings in a highly electrified building sector.

### 1.2. *Flexibility in energy system optimisation models*

A challenge of analysing the future role and value of flexibility is that model results are sensitive to the methodology used. On the other hand, as pointed out by Ref. [27], there is no one-size-fits-all solution for including flexibility options in energy models, and different research questions require different modelling approaches. According to Refs. [28,29], there is a trade-off with having a high resolution in time, space, techno-economic detail and sector coupling in energy system models.

We hereby present different approaches from the literature that are dedicated to improving the representation of flexibility in ESOMs.

A first approach is to increase the temporal resolution that is within a computational tolerance, as demonstrated in Ref. [30]. This study shows, for example, that increasing the temporal resolution from 12 sub-annual time slices to 192 time slices has a significant impact on the investments in stationary batteries when analysing capacity expansion of the European power system towards 2050.

A second approach is to use stochastic modelling, which is a tool to improve the representation of variable renewable energy, for example by capturing the need for backup capacity and flexible solutions [31]. As demonstrated in Ref. [32], a stochastic modelling approach can be used to provide investments that explicitly consider different operational situations that can occur due to different realisations of uncertain parameters, such as renewable electricity generation. Compared to a deterministic modelling approach, which assumes only one operational situation, a stochastic modelling approach can provide significantly different results by explicitly covering a set of operational realisations in the optimisation. For example, in Ref. [33], the deterministic model underestimates optimal battery capacity by 41 % compared to a stochastic model when analysing the decarbonisation of the European power market towards 2050. There is, however, a trade-off between increasing the temporal resolution and increasing the number of stochastic scenarios. The authors in Ref. [30] conclude that for the analysed modelling instance, a stochastic approach with a coarser temporal resolution provides better results with a lower computational time than a deterministic model with a higher temporal resolution.

A third approach is to use statistical methods to select representative days from an hourly time series of a year as model input. According to Ref. [34], such an approach can improve the operational accuracy of the results. Further, there are different methods for temporal selection, each with strengths and weaknesses, as illustrated in Ref. [35]. A limitation of the second approach, is however that most of these methods only evaluate the quality of the statistical methods on the input data itself, and not on the quality of the corresponding model results.

A fourth approach is to evaluate the feasibility of capacities from ESOM, by using the capacities as an input in a power market model, that optimizes the operation of the electricity sector over typically one year. Due to a lower sectoral coverage and exogenous capacities, power market models can, compared to ESOMs, use a higher temporal resolution, and include integer properties, such as start-up costs and minimum up time. However, a limitation of a power market model is they do not explicitly capture sector coupling nor capture how flexibility influences capacity expansion. Evaluating the feasibility of capacities from an ESOM in a power market model is done in Refs. [34,36]. A weakness of this approach is that the insights from the power market model do not directly improve the results of the ESOM, including investments in flexible solutions. To eliminate this weakness [37], demonstrates a bidirectional linkage between a Norwegian energy system and a European power market model, showing that the proposed linking strategy fails to converge when the development of the European power market deviates significantly from the current market structure. This underscores the challenges of using power market models to improve the investment strategies in ESOMs.

### 1.3. Energy modelling literature

Several long-term models that cover the power market have investigated the long-term effect of flexibility demand on the power sector. For example [38], analysed the impact of demand response on a stochastic capacity expansion model of the European power market. Their results show that demand flexibility can contribute to integrating more variable renewables and lowering the peak electricity demand, in addition to lowering the need for investments in battery storage. Another example is presented in Ref. [39], who analysed the economic effects and competition of various flexibility options for the selected European countries using the BALMOREL model. Their results demonstrate that the value of flexibility measures increases as climate targets become more ambitious, and investments in battery storage are outcompeted by demand response in 2030. Further, the authors of the latter paper suggest that a way to enhance the chosen modelling framework is to explicitly model end-use sectors to capture synergies and competition between sectors.

An advantage of ESOMS is that these models explicitly capture the interplay between different sectors in the energy system. The flexibility of smart appliances and EVs, with a detailed representation of the end-use sectors, is modelled in the UK TIMES energy system model [40]. Their analysis shows that by 2050, flexibility will enable greater integration of low-carbon electricity generation, such as nuclear and wind power, and lower the need for battery storage, as well as lowering the peak electricity demand and energy system cost. The study is cited as the first instance where demand-side flexibility has been analysed with a comprehensive ESOM that accounts for inter-temporal impacts across modelling years. The impact of flexibility options for the Swiss energy system, STEM, is also analysed using the TIMES modelling framework in Ref. [41]. The conclusion of this study is that a sustainable transition requires that several flexibility options, like storage, demand side flexibility and smart integration of EVs, interact with the overall energy system. The authors point out that their analysis could be improved with a higher granularity and with additional uncertainty analysis. Another study [42], analysed the future role of flexibility in the Swiss energy system in 2050 with a higher spatial granularity, where the power system is represented with 30 sub-national nodes and the Swiss residential heating sector with 24 nodes. Their results show, among other things, that flexible heat pumps, boilers and appliances increase the deployment of photovoltaic (PV) power.

### 1.4. Research questions and contributions

To address the future value of end-use flexibility, this study uses an ESOM, with a detailed representation of end-use, similar to Refs. [40, 41]. The methodology is chosen to capture how end-use flexibility in buildings can influence investments in all parts of the energy system, and to quantify how flexibility in buildings interact with other parts of the energy system. Further, a stochastic modelling approach, similar to the power market model in Ref. [38], is used to explicitly capture how the value of end-use flexibility in buildings depends on the uncertainty of future European electricity prices. The main argument for using a stochastic approach is to evaluate the role of end-use flexibility for different operational situations that can occur given the short-term uncertainty. This is in contrast to Refs. [40,41], which analysis end-use flexibility with a deterministic approach, assuming only one operational scenario.

A novelty of this paper is thus that a stochastic ESOM is used to analyse the role of end-use flexibility. Another novelty is the isolated focus on the role of flexibility in buildings in the energy transition. This gives insights into how the development of the building sector can be aligned with the needs of the energy transition. Another contribution is that the used stochastic modelling approach is compared with a deterministic modelling approach, to evaluate how modelling methodology influences the results.

The overall objective of the paper is to analyse the role and value of end-use flexibility in the low-carbon transition. In the analysis, the following research questions are addressed:

- How can end-use flexibility affect the design of the low-carbon energy system towards 2050?
- What is the economic impact of end-use flexibility on energy supply, infrastructure, and demand?
- How does the modelling of uncertainty impact the role and value of end-use flexibility?

The outline of this paper is as follows: Section 2 is devoted to the applied methodology, including a description of the TIMES model. The used storylines and case studies are presented in section 3, followed by section 4 which presents the corresponding results and discussion. In section 5, the conclusions are given.

## 2. Methodology

This section presents the structure of the IFE-TIMES-Norway model, including a description of end-use flexibility modelling, the generation of consistent European electricity prices and the stochastic modelling approach.

### 2.1. Energy system optimisation model

The TIMES modelling framework was developed during several decades and is continuously updated within ETSAP (the Energy

Technology Systems Analysis Program), an implementing agreement of the International Energy Agency (IEA) [6]. TIMES is a bottom-up framework that provides a detailed techno-economic description of resources, energy carriers, conversion technologies and energy demand. The framework is mainly used for medium and long-term analysis on global, national and sub-national levels, including the Energy Technology Perspectives [43] and World Energy Outlook [44] of the IEA. TIMES models minimise the total discounted cost of the energy system to meet the demand for energy services for the analysed model horizon.

IFE-TIMES-Norway [7] is a technology-rich model of the Norwegian energy system and is split into five regions corresponding to the current electricity spot price regions, NO1 to NO5. The model provides operational and investment decisions from the starting year, 2018, towards 2050, with model periods for every fifth year from 2020 to 2050. To capture operational variations in energy generation and end use, each model period is divided into 96 sub-annual time slices, where four seasons (winter, spring, summer, and fall) are represented by one day of 24 h in each season. The model has a detailed description of energy end use, and the demand for energy services is represented by numerous end-use categories within industry, buildings, and transport. Note that energy services refer to the services provided by consuming a fuel and not the fuel consumption itself. Each energy service demand category can be met by existing and new technologies using different energy carriers such as electricity, biofuel, hydrogen and fossil fuels. Other input data include fuel prices, electricity prices in countries with transmission capacity to Norway, renewable resources and technology characteristics such as cost, efficiency and availability.

Fig. 2 gives an illustration on how the building sector is represented in the model. The building sector is divided into residential single-family and multi-family houses and commercial buildings for each of the five model regions. All buildings are split into existing and new buildings, where existing buildings represent the building stock in 2020. The existing buildings have a stock of end-use technologies in the start year. The end-use demand is divided into central heating, point source heating, hot water and electricity-specific demand. Buildings with central heating can be connected to a district heating grid, but due to high costs it is assumed that single-family houses cannot use district heat [45]. The cost of the distribution grid is modelled by a distribution tariff, consisting of both an energy and a power component. Further, there are investment options in end-use technologies, such as heat pumps, direct electric heating, boilers etc. Investment options in building-applied PV are included for each building category.

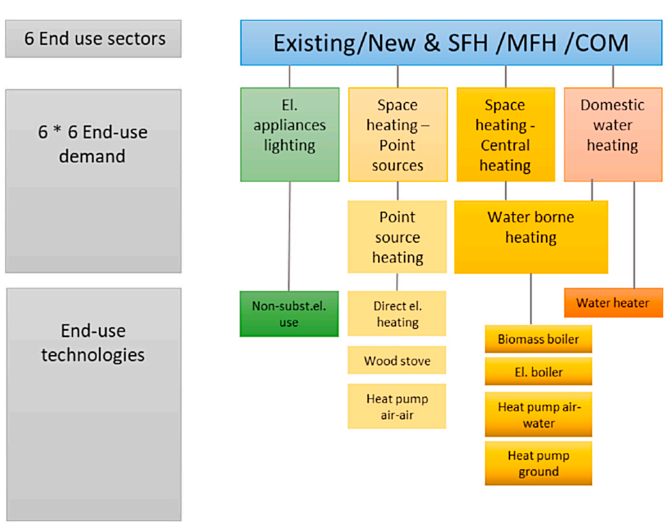



**Fig. 2.** Schematic overview of building end-use sectors, end-use demand, and end-use technologies. SFH = Single-family House, MFH = Multi-family house, COM= Commercial building.

## 2.2. End-use flexibility options

This paper focuses on analysing the effect and value of three flexibility options for buildings: 1) flexible electric heating of domestic hot water, 2) stationary batteries, and 3) flexible charging of EVs. Further, the interaction between these three flexibility options and other types of flexibility in the energy system is analysed, including reservoir hydropower production, thermal heat storage in district heat networks and flexible hydrogen production and storage, and electricity trade.

The electricity consumed by **domestic water** heaters are modelled with a flexible and a non-flexible share. The non-flexible part delivers at least 70 % of the total hot water demand, both for new and existing buildings. This is based on calculations of minimum temperature demand and on the study of [46]. The relationship between power output/input (kWh/h) and energy content (kW), is set to 0.28, based on existing storage heaters. The additional cost of installing a flexible water heater is assumed to be EUR 400 for a 13 kWh water heater based on [47], who cite the additional cost of a flexible heater, compared to a conventional heater, as about EUR 300–500.

**Electric batteries in buildings** are included as investment options in residential and commercial buildings. The maximum net output rate is assumed to be 30 min for batteries in buildings. It is assumed that the cost of batteries will decline from 675 €/kWh in 2020 to 400 €/kWh in 2050 as a result of technology learning. The maximum number of storage cycles is assumed to be 4,500, and the storage efficiency is set to 90 %.

**Flexible electric vehicle (EV) charging** of personal vehicles is modelled with three different charging options: residential, commercial (non-residential) and fast charging. It is assumed that the non-flexible charging pattern, for one day, follows the profiles illustrated in Fig. 3: Total power demand from EV charging, disaggregated for different charging locations, based on [51]. Further, it is assumed that 75 % of charging occurs in residential buildings, 15 % in commercial buildings and 10 % at fast charging stations, as described in Ref. [48]. In our study, flexibility is included in both where and when personal vehicles are charged. For **where**, the charging location is flexible, and it is assumed that up to 90 % can be charged in residential buildings and up to 50 % can be charged at commercial buildings, whereas fast charging remains at 10 % (no flexibility). For **when**, the flexible charging time, we assume 50 % flexibility in terms of when EVs are charging in either residential or commercial buildings, based on the charging profile of Fig. 3: Total power demand from EV charging, disaggregated for different charging locations, based on [51].

## 2.3. European electricity prices

Electricity prices in countries with transmission capacity to Norway is exogenous input to IFE-TIMES-Norway. To provide consistent exogenous electricity prices that captures the interplay between the Norwegian and European power system, IFE-TIMES-Norway is bi-

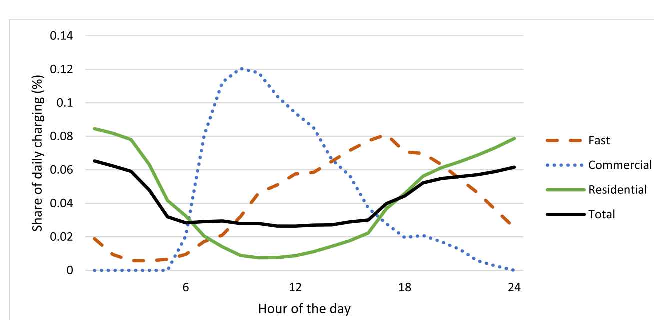



**Fig. 3.** Total power demand from EV charging, disaggregated for different charging locations, based on [48].

directionally linked to the European power system model, EMPIRE [49]. Note that the corresponding Norwegian electricity prices, in the five price regions, is a model result, and is the long-term marginal cost of electricity of IFE-TIMES-Norway.

The linking methodology between IFE-TIMES-Norway and EMPIRE is described in detail in Ref. [50]. First, common model assumptions are harmonised for both storylines. This includes existing capacity for electricity generation and transmission, future expansion potential, investment costs and technology learning towards 2050. Second, results from IFE-TIMES-Norway for Norwegian electricity generation capacity, transmission capacity, and electricity consumption are used as an input in EMPIRE for each of the five spot regions for every five years from 2020 to 2050. Third, the corresponding hourly electricity prices for countries with electricity trade to Norway are provided by EMPIRE for the same time periods and used as input for IFE-TIMES-Norway. Fourth, the annual availability of the transmission capacity from EMPIRE are used as an input to IFE-TIMES-Norway, to endogenous capture the trade dynamics between Norway and the European power market.

The linkage is performed iteratively until Norwegian electricity generation capacities and prices converge between the two models. Convergence is assumed if the difference in Norwegian electricity generation capacity is less than 0.25 % lower than in the previous iteration, and that the 90th percentile of difference in European electricity prices is less than EUR 5/MWh from the previous iteration.

The linkage provides inputs on both hourly electricity prices in countries with trade to Norway, and the annual availability capacity factor of these trade options. This includes electricity prices in Finland, Germany, the United Kingdom, the Netherlands, Sweden, and Denmark. The linkage ensures correlation in prices between the countries and between the hours of the day. To illustrate the input data, Figs. 4 and 5 show the 2050 electricity prices in Germany for Energy Nation and Nature Nation, respectively. The figures show the price range, first and third quantile and average of three weekly hourly price scenarios for each season from EMPIRE. Here, the deterministic blue line corresponds to the expected daily prices. As illustrated in Fig. 4, there are price variations within each season, with the greatest variation and highest expected price level occurring in winter. Also, for all seasons, there is a drop in prices during mid-day hours that is correlated to PV power production.

### 2.4. Stochastic modelling approach

To account for the uncertainty of European electricity prices, as illustrated in Figs. 4 and 5, a two-stage stochastic framework is applied, as described in Ref. [32], to provide investment decisions that explicitly consider various operational situations arising from the short-term uncertainty of the European electricity prices. The approach is designed such that the first-stage variables, investments, are set before knowing the outcome of the uncertain parameters, namely European electricity prices. The second-stage variables, operation of the energy system, are done in each scenario when the realisation of the electricity price is known. Consequently, the investments are identical for all scenarios, whereas the operational decisions are dependent on the realisation of the electricity price. The TIMES model minimises the investment costs and the average of the operational costs for all scenarios. This gives investment decisions that recognise the expected operational cost and ensure feasibility across all the model-specified realisations of electricity prices.

Model results from the stochastic European power market model EMPIRE are used to generate stochastic scenarios of European electricity prices, which are further used to provide good in-sample and out-of-sample stability as in Ref. [32]. To adjust for the difference in temporal resolution between the models, for each season, the 3 weekly hourly price scenarios from EMPIRE are converted into 21 stochastic daily hourly price scenarios in IFE-TIMES-Norway. Each of the 21 scenarios consists of electricity prices in all countries for all 96 sub-annual time slices, and it is assumed that each of the scenarios has the same probability of occurring. In the analysis below, we present results of both the stochastic, using all 21 price scenarios, and the deterministic, using the expected price, modelling approaches.

## 3. Storyline and case description

The storylines of this study are named Energy Nation and Nature Nation, and each has different assumptions related to technology development, demand projections and expansion opportunities for new transmission capacity and land-based wind power. Both storylines assume a low-carbon society by 2050, with significant $CO_2$ reductions of 80 % and 85 % in 2040 and 2050 respectively, according to the emissions from 2018. A summary of the model assumptions for the two storylines are included in Table 1.

**Energy Nation (Energy)** is a storyline that involves a significant growth in energy demand and a large expansion of Norwegian energy generation. This is enabled by high-technology learning for green hydrogen production, stationary batteries, and wind generation onshore and offshore. It is assumed that there is social acceptance of building new onshore wind power and expanding the national transmission grid beyond current plans. Further, there is an increased demand for energy

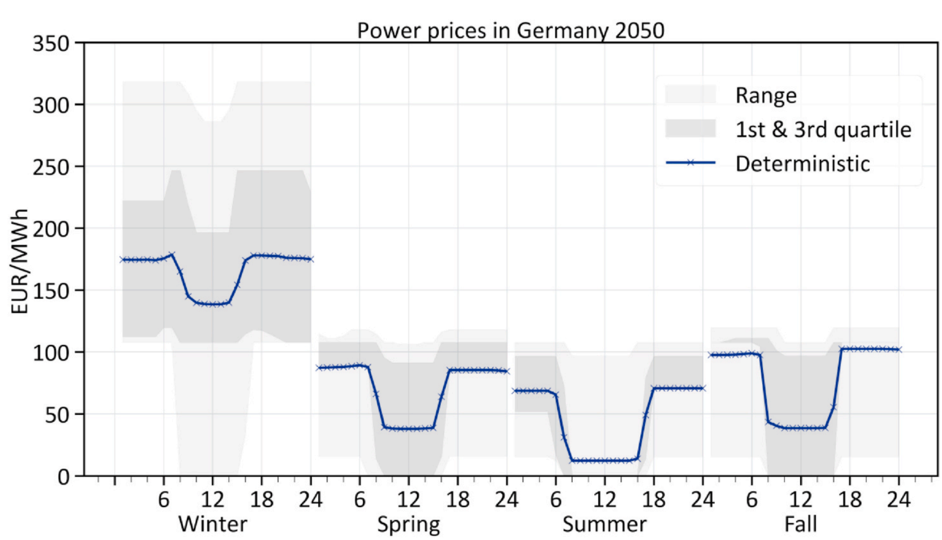



**Fig. 4.** Illustration of model assumptions for electricity prices in Germany in 2050 for Energy Nation.

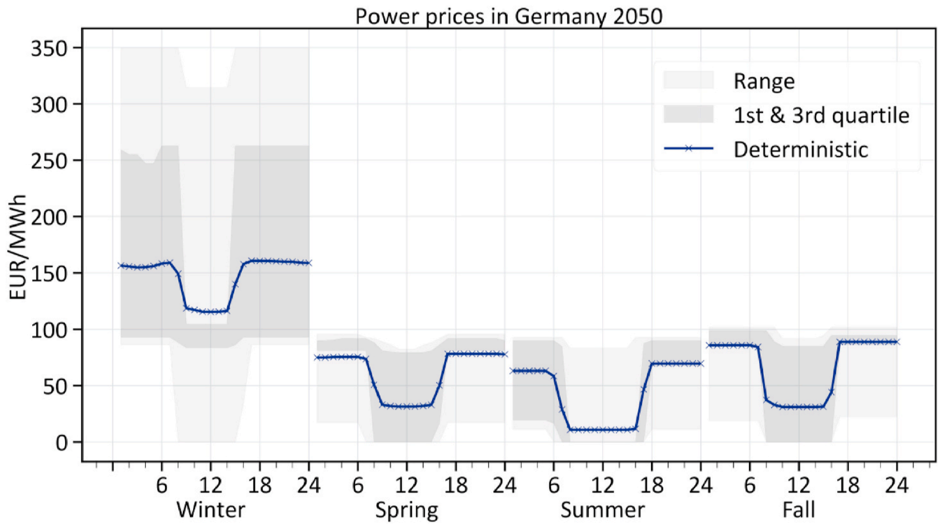



**Fig. 5.** Illustration of model assumptions for electricity prices in Germany in 2050 for Nature Nation.

**Table 1**
Summary of model assumptions for the two storylines. Technology learning and demand projections given as percentage difference from 2018 to 2050 and other numbers are given for 2050.

| Technology/ demand | Model assumption | Energy Nation (EN) | Nature Nation (NN) |
|---|---|---|---|
| Blue hydrogen | Carbon capture & storage Blue hydrogen | No | From 2035 |
| Green hydrogen | Technology learning: | High (−67 % to −81 %)[a] | Moderate (−58 % to −69 %)[a] |
| Stationary batteries | Technology learning: | High (−71 %) | High (−71 %) |
| Building applied PV | Technology learning: | Moderate (−57 %) | High (−68 %) |
| Building applied PV | Expansion potential | High (28 GW) | Low (14 GW) |
| Onshore Wind | Expansion potential | High (15 GW) | Limited new capacity (5 GW) |
| Offshore wind | Expansion potential | Moderate (16 GW) | Moderate (16 GW) |
| Transmission grid | National expansion potential | If profitable from 2030 | No |
| Transmission grid | International expansion potential | If profitable from 2030 | If profitable from 2030 |
| Transport | Demand projections | Moderate (+37 %) | Low (0 %) |
| Industry mainland | Demand projections | High (+82 %) | Moderate (−13 %) |
| Industry oil & gas | Demand projections | Low (−100 %) | Moderate (−69 %) |
| Building | Demand projections | Moderate (+2) | Low (−3 %) |

[a] The range depends on type (PEM or alkaline) and size of electrolyser (large or small).

services, mainly from the industry and transport sectors. Finally, it is assumed that there is no commercialisation of carbon capture and storage (CCS), and consequently no blue hydrogen production.

**Nature Nation (Nature)** is a storyline that limits intervention to Norwegian nature and favours decentralized solutions. Compared to Energy Nation, lower demand is assumed in the industry and transport sectors, as is lower technology learning for green hydrogen. It is further assumed that there will be no expansion opportunities for onshore wind power and the national transmission grid, while building-applied PV has a higher technology learning rate. Lastly, it is assumed that large-scale use of CCS and production of blue hydrogen are options from 2035.

A conceptual figure of the modelling framework is given in Fig. 6.

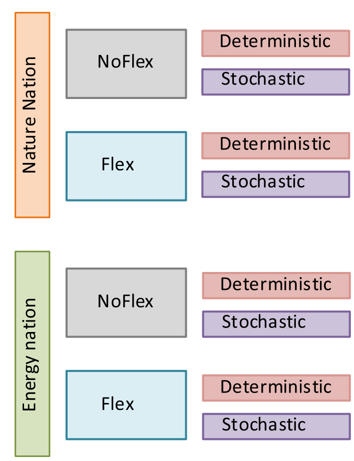



**Fig. 6.** Conceptual figure of the modelling framework.

This paper presents results from eight different model cases. The two storylines, Energy Nation and Nature Nation, are run and analysed with (Flex) and without (NoFlex) an option to invest in and operate end-use flexibility. Further, each of these four model runs is executed with both a stochastic and deterministic modelling approach for European electricity prices. When not specified, results from the stochastic modelling approach are reported. Note that the capacity is independent of the stochastic scenarios, whereas the operational decisions differ between the 21 operational scenarios.

The energy system effect of end-use flexibility, and the corresponding economic impact by comparing the difference in value and solutions, are quantified. Note that the investment costs of end-use flexibility are included in the flexible model case, and thus the difference between the flexible and non-flexible cases illustrates the value of facilitating a techno-economic implementation.

## 4. Results and discussions

This section presents the main results and discussions of the analysis with a focus on the use of end-use flexibility, energy system impacts and a quantification of the corresponding economic impacts on parts of the energy system, such as electricity generation, international transmission, and the building sector.

### 4.1. End-use flexibility

The analysis demonstrates that end-use flexibility is a techno-economic solution in a low-carbon transition of the Norwegian energy system. The energy system cost, covering the period from 2025 to 2055, is lowered by 8.3 BEUR and 4.4 BEUR for Energy Nation and Nature Nation, respectively, when investments and operation of end-use flexibility are an option. To put the numbers in context, the Norwegian state budget to support consumers facing high energy prices in 2023 is 4.0 BEUR [51]. Compared to the stochastic energy system costs, deterministic modelling gives a slightly different value of end-use flexibility, with 0.3 BEUR lower and 0.4 BEUR higher value for Energy and Nature Nation, respectively.

Stationary batteries in buildings and flexible water heaters are techno-economic solutions in both storylines. Fig. 7 shows the investments in stationary batteries and flexible electric heating in 2030 and 2050, for a deterministic and stochastic modelling approach, split by residential and commercial buildings. The results reflect that far from all buildings have a stationary battery. The battery capacity for Energy Nation in residential buildings in 2050, at 2.7 GWh, corresponds to 31,765 batteries @85 kWh, whereas there are about 2.5 million residential buildings in Norway in 2021 [52].

The storage capacity in buildings is larger for Energy Nation than Nature Nation. In 2050, the battery capacity and the flexible water heater capacity are 28 % and 30 % higher, respectively, in Energy Nation than in Nature Nation. Further, there is significantly higher storage capacity in the residential sector compared to the commercial sector. For example, for Energy Nation in 2050, 74 % of the battery and 77 % of the flexible water heater capacity is in residential buildings. There are several reasons for the higher value of end-use flexibility in residential buildings compared to commercial buildings. First, the demand profiles of commercial buildings align better with local PV production than residential buildings. Second, as opposed to commercial buildings, residential buildings are subject to value added tax (VAT) on purchased electricity, creating stronger incentives for self-consumption of electricity.

The investments in stationary batteries and flexible water heaters are lower for most cases when using a deterministic approach as compared to a stochastic modelling approach. The largest percentage difference is for flexible water heaters in residential buildings in 2030 for Energy Nation, and for batteries in commercial buildings in 2050 for Nature Nation, for which the deterministic approach gives 40 % and 30 % lower capacity compared to the stochastic approach. On the other hand, the deterministic modelling results show 28 % more investment in batteries in residential buildings for Nature Nation in 2050.

Figs. 8 and 9 illustrate the electricity charging pattern of EVs, with and without flexibility, for commercial and residential buildings in 2050 for Energy Nation. The EV charging pattern of Nature Nation follows similar trends. Here, the blue line represents non-flexible charging, the red line represents the expected flexible charging profile, and the grey area represents the feasibility area for flexible EV charging. Except for winter, EV charging in commercial and residential buildings shifts to the middle of the day when the sun is shining. This can be both due to increased self-consumption of PV or because electricity prices are correlated to PV production, with lower prices in the middle of the day. Another driver of flexible charging can be to lower the total peak demand of the buildings, i.e., lower the cost of the distribution grid expansion. For winter, charging shifts away from the morning peak for both residential and commercial buildings.

### 4.2. Energy system impact

Fig. 10 shows the electricity generation by type in Energy Nation and Nature Nation in 2030 and 2050, with end-use flexibility (Flex) and without end-use flexibility (NoFlex). The results indicate that end-use flexibility has a limited impact on electricity generation. Of all the electricity generation technologies, investments in PV are most affected. Note that PV corresponds to building applied PV and does not include utility scale PV. With end-use flexibility, the PV capacity is increased by 23 % and 1 % in 2030 and 4 % and 5 % in 2050 for Energy Nation and Nature Nation respectively. End-use flexibility also lowers investments in onshore wind power and hydropower marginally in 2050. Wind power generation is lowered by 1 % in both storylines, whereas run-of-the-river hydropower is lowered by 0.5 % and 1 % for Energy and Nature Nation respectively.

The use of a stochastic or a deterministic modelling approach has significantly impact on the electricity generation. The biggest influence is on the expansion of offshore wind power, where the deterministic capacity is 60 % and 30 % higher in 2050 compared to the stochastic capacity. This indicates that the expected profits from offshore wind power are lower when using a stochastic approach.

End-use flexibility lowers peak electricity demand and smooths the daily profile of electricity demand. Fig. 11 illustrates how the low voltage electricity demand profile of the Oslo region, NO1, for all seasons, is influenced by end-use flexibility for Energy Nation and Nature Nation in 2050. In winter, electricity demand is flattened by using flexible solutions to lower peak demand. For the other seasons, the demand in the middle of the day is increased to better correlate with PV production and lower electricity prices. For low voltage electricity demand, the expected peak demand reduction, given as an average of all stochastic scenarios, ranges from 11 % in NO2 to 5 % in NO4 for Energy Nation, and from 8 % in NO3 to 5 % in NO1 for Nature Nation. The

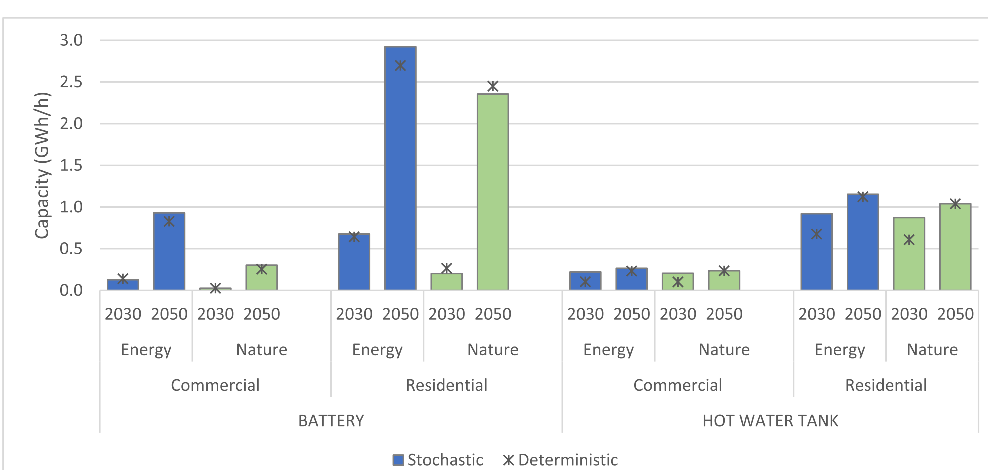



**Fig. 7.** Stationary batteries and flexible water heater capacity in Energy Nation and Nature Nation for 2030 and 2050 split by commercial and residential buildings.

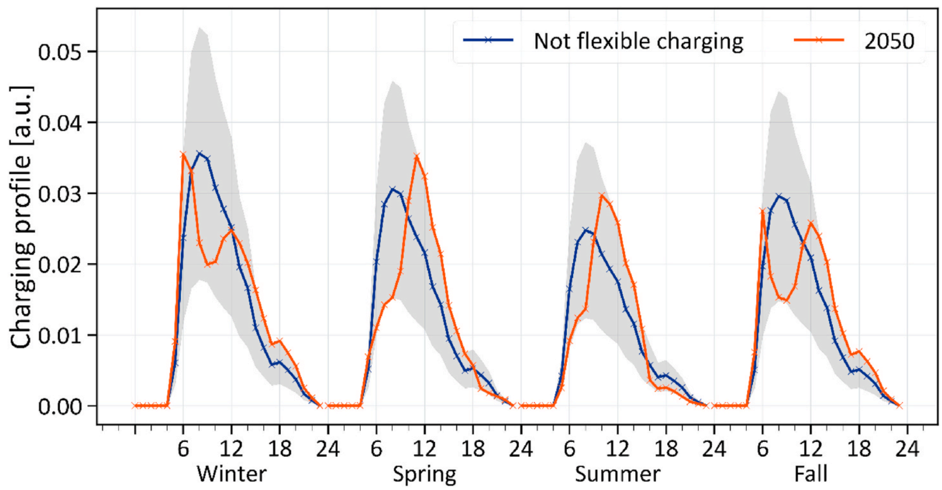



**Fig. 8.** Flexible (red line) and non-flexible (blue line) EV charging pattern of commercial buildings in 2050 for Energy Nation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

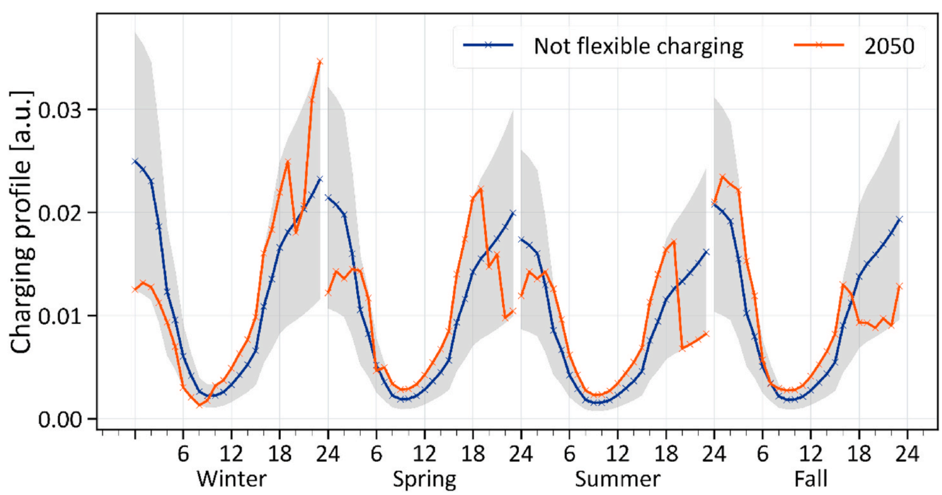



**Fig. 9.** Flexible (red line) and non-flexible (blue line) EV charging pattern of residential buildings in 2050 for Energy Nation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

impact on the total peak electricity demand is lower, as this demand includes base load demand of the power-intensive industry in Norway. The corresponding peak demand reduction in the total electricity demand ranges from 5 % in NO1 to 2 % in NO4 for Energy Nation and from 4 % in NO1 to 3 % in NO3 for Nature Nation.

New transmission capacity changes marginally with end-use flexibility. For example, the new capacity is 149 MW (3 %) lower for national transmission and 417 MW (2 %) higher for international transmission for Energy Nation in 2050. Similarly for Nature Nation, international transmission capacity increases by 13 MW (2 %) with end-use flexibility.

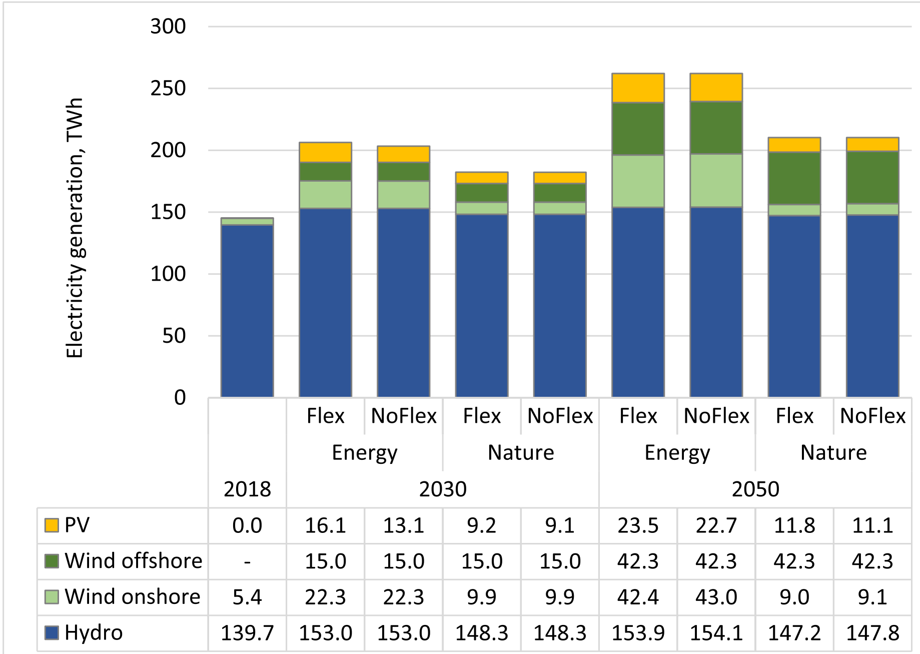
End-use flexibility has a limited effect on electricity prices, but for some stochastic scenarios, end-use flexibility flattens prices. As an illustration, for Energy Nation for NO1 in 2050, end-use flexibility lowers the price in winter for stochastic scenario 17 as shown in Fig. 12, and is increased in spring for stochastic scenario 3 as shown in Fig. 13.

End-use flexibility influences investment in other storage options in the energy system, including hydrogen storage and thermal storage in the district heating sector. Fig. 14 shows the storage capacity for hydrogen and district heat with and without end-use flexibility for Energy Nation and Nature Nation in 2050. Both stochastic and deterministic model results are indicated. With end-use flexibility, hydrogen storage capacity is lowered by 66 % and 35 % for Energy Nation and Nature Nation respectively. For thermal storage, the impact of end-use flexibility varies with the storyline, with storage capacity decreasing by 0.4 MWh for Energy Nation and increasing by 0.2 MWh for Nature Nation. Finally, the results demonstrated that a deterministic modelling approach underestimates the storage capacity. In Nature Nation, a deterministic approach gives zero investments in storage for thermal and hydrogen storage, which is not the case for the stochastic modelling approach.

### 4.3. Impacts of profit and cost

This section presents how end-use flexibility influences the profits and costs of specific sectors in the energy system. The results for 2050 are summarised in Table 2 and described in more detail below. Profits are derived by summing up the energy generation multiplied by the corresponding energy price over all time slices for each stochastic scenario. Similarly, costs are derived by summing up the energy consumption multiplied by the corresponding energy price over all time slices for each stochastic scenario.

For electricity generation, the impact of end-use flexibility is marginal and varies with the storyline. Profits from electricity generation increase by 0.2 % for Energy Nation and decrease by 0.5 % for Nature




| | 2018 | 2030 Energy Flex | 2030 Energy NoFlex | 2030 Nature Flex | 2030 Nature NoFlex | 2050 Energy Flex | 2050 Energy NoFlex | 2050 Nature Flex | 2050 Nature NoFlex |
|---|---|---|---|---|---|---|---|---|---|
| PV | 0.0 | 16.1 | 13.1 | 9.2 | 9.1 | 23.5 | 22.7 | 11.8 | 11.1 |
| Wind offshore | - | 15.0 | 15.0 | 15.0 | 15.0 | 42.3 | 42.3 | 42.3 | 42.3 |
| Wind onshore | 5.4 | 22.3 | 22.3 | 9.9 | 9.9 | 42.4 | 43.0 | 9.0 | 9.1 |
| Hydro | 139.7 | 153.0 | 153.0 | 148.3 | 148.3 | 153.9 | 154.1 | 147.2 | 147.8 |

**Fig. 10.** Electricity generation by technology for Energy Nation and Nature Nation in 2018 and expected generation for 2030 and 2050.

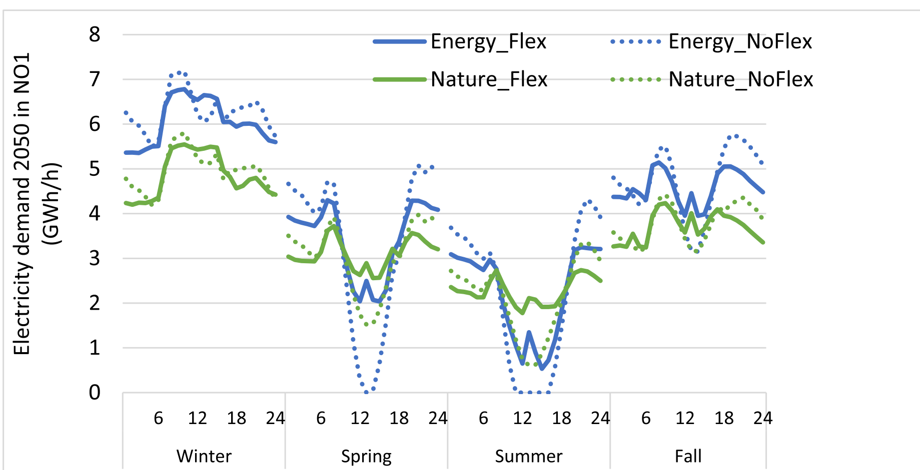



**Fig. 11.** Demand profile of low voltage electricity for Oslo region, NO1, in 2050 with and without end-use flexibility for Energy Nation and Nature Nation.

Nation. Furthermore, the impact of profits varies among the different types of electricity generation. For both storylines, end-use flexibility gives increased profits for run-of the river hydropower and onshore wind power.

There is a large difference in the income effects of international transmission between the two storylines. End-use flexibility enables Norway to sell more electricity when prices in Europe are high and to buy more electricity when prices in Europe are low. Income from international trade increases by 8 % and 1 % for Energy Nation and Nature Nation respectively. This difference can be explained by the fact that Nature Nation is a more constrained storyline than Energy Nation, with no expansion of national transmission and onshore wind power.

End-use flexibility lowers profits from district heat production: 3 % for Energy Nation and 4 % for Nature Nation. An explanation for this is that end-use flexibility lowers the corresponding district heat production by 2 % and 3 %, and that end-use flexibility competes with district heat as a provider of flexibility for the building sector.

The results further indicate that end-use flexibility lowers costs for the building sector. Energy costs are lowered by 5 % for Energy Nation and 4 % for Nature Nation. However, while costs for the residential sector are lowered, they are increased for the commercial sector. This is due to the fact that we include a flexibility option for the charging location of EVs; the results indicate that it is optimal to prioritise charging in commercial buildings as the charging profile matches better with the PV production. The impact of end-use flexibility on each building type for Energy Nation in 2030 and 2050 is further illustrated in Fig. 15.

Table 2 shows the corresponding results of the deterministic modelling approach. The numbers confirm that the results depend on the modelling methodology. However, although the magnitude varies with the methodology, the effect on the profits and costs tends to be in the same direction. One exception is the profits from electricity generation: whereas the deterministic results suggest that end-use flexibility has a negative impact on electricity generation profits, the stochastic results indicate that this is not always the case.

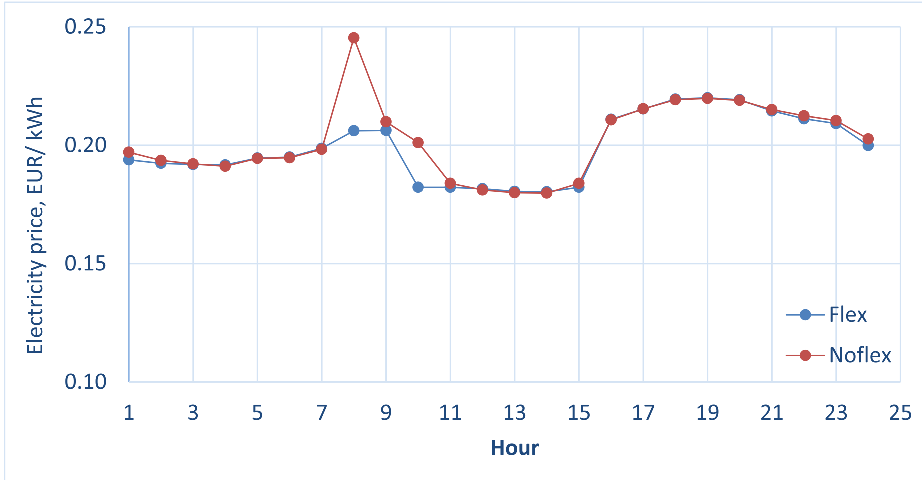



**Fig. 12.** Illustration of winter electricity prices, with and without end-use flexibility, for Energy Nation in 2050, NO1 spot price region and stochastic scenario 17.

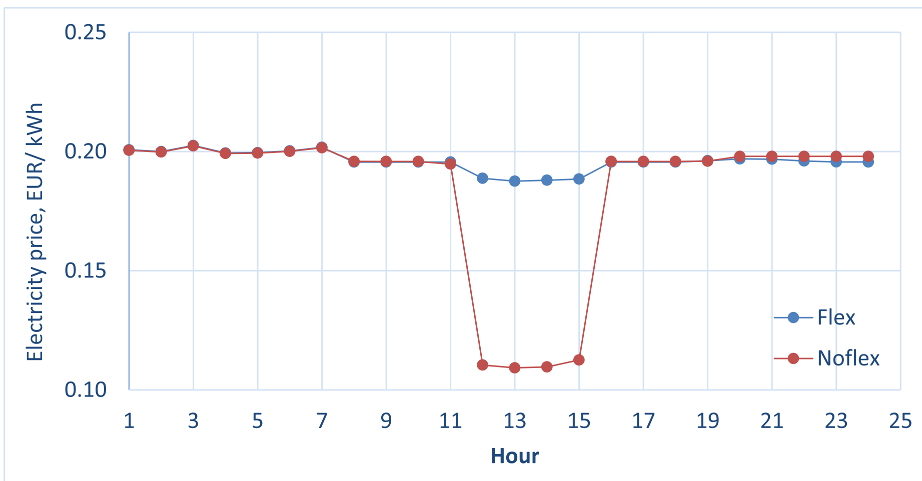



**Fig. 13.** Illustration of spring electricity prices, with and without end-use flexibility, for Energy Nation in 2050, NO1 spot price region and stochastic scenario 3.

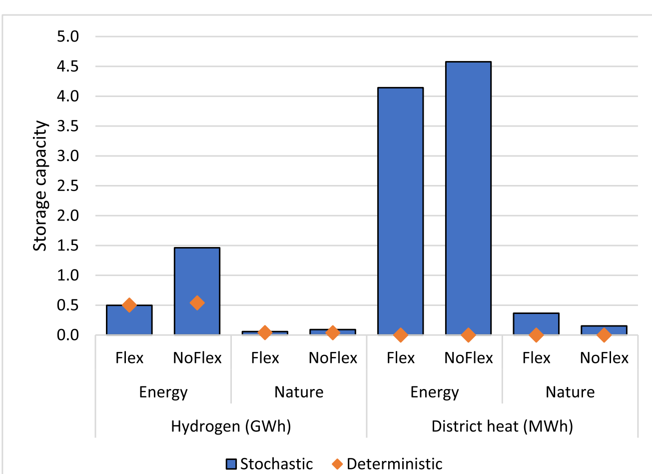



**Fig. 14.** Storage capacity for hydrogen and district heat, with and without end-use flexibility, for both storylines in 2050.

### *4.4. Discussions*

This section is dedicated to compare main similarities between the results from Section 4.1 to 4.3 with results from the literature that are described in Section 1.3. Note that there are no clear contradictions with the results and the literature, and the major differences are on the scope of the analysis. A contribution from an analysis perspective from this paper, is the quantification of costs and profits for different sectors, and the comparison between deterministic and stochastic results.

The results of this paper, emphasizing that end-use flexibility lowers the need for other types of flexible solutions in the energy system, is supported by several studies. In Ref. [38], demand response in buildings and industry reduces the capacity of peak power plants by 11 % and the battery capacity with 86 %. In Ref. [39], demand side management, with demand response and flexible EV charging, competes with battery storage. Their analysis show that battery storage is only utilised when the demand side management is used to its full potential. Also in Ref. [40], additional investment in storage technology and back-up power is reduced with demand-side flexibility, avoiding, investments of around 1.5 GW of storage systems. Further [42], shows that demand response lowers the investments in battery storage with 17 %. A difference of the listed literature and the analysis of this paper is that we include only stationary batteries in the Flex model runs, and thus this study cannot explicitly quantify the effect of investments in batteries.

**Table 2**
Impact of end-use flexibility on expected profits and costs in 2050 (MEUR/year) and % change, for Energy Nation and Nature Nation and for deterministic and stochastic modelling approaches.

| | Deterministic | | Stochastic | |
|---|---|---|---|---|
| | Energy Nation | Nature Nation | Energy Nation | Nature Nation |
| Profits | | | | |
| **Electricity generation** | **−83 MEUR (-0.3 %)** | **−80 MEUR (-0.4 %)** | **+ 24 MEUR (+0.2 %)** | **−89 MEUR (-0.5 %)** |
| - Regulated hydropower | −48 MEUR (−0.4 %) | −28 MEUR (-0.3 %) | ~0 MEUR | −88 MEUR (-1 %) |
| - Run-of River hydropower | −20 MEUR (-0.5 %) | −3 MEUR (-0.1 %) | +16.5 MEUR (+0.4 %) | +26 MEUR (+0.75 %) |
| - Onshore wind power | −7 MEUR (-0.2 %) | −2 MEUR (-0.2 %) | +7 MEUR (+0.2 %) | +5 MEUR (+0.7 %) |
| - Offshore wind power | −8 MEUR (-0.1 %) | −46 MEUR (-1 %) | +0.6 MEUR (+0.01 %) | −32 MEUR (-0.7 %) |
| **District heat production** | **−16 MEUR (-5 %)** | **−8 MEUR (-3 %)** | **−9 MEUR (-3 %)** | **−10 MEUR (-4 %)** |
| **International transmission** | **+ 490 MEUR (+ 10 %)** | **+ 236 MEUR (+ 4 %)** | **+ 336 MEUR (+ 8 %)** | **+ 121 MEUR (+ 1 %)** |
| **Energy costs** | | | | |
| **Building sector** | **−764 MEUR (-6 %)** | **−593 MEUR (-7 %)** | **−693 MEUR (-5 %)** | **−488 MEUR (-4 %)** |
| - Residential | −588 MEUR (−7 %) | −466 MEUR (-7 %) | −927 MEUR (-11 %) | −616 MEUR (-9 %) |
| - Commercial | −177 MEUR (-4 %) | −127 MEUR (-3 %) | +234 MEUR (+4 %) | +127 MEUR (+3 %) |

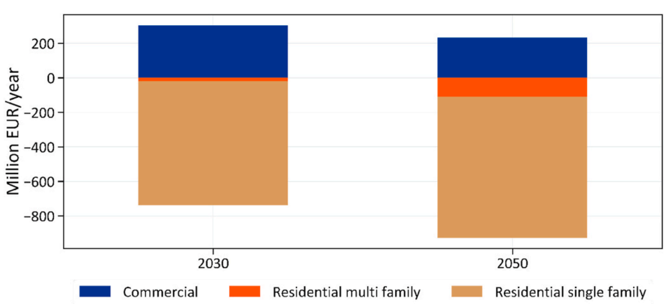



**Fig. 15.** Energy savings in 2030 and 2050 by building type in Energy Nation.

Nevertheless, from the results from this paper and the described literature, it can be concluded that flexibility in end-use sectors is a cost-competitive solution in a transition to a low-carbon energy system, that can contribute to lower the need for batteries, both on a grid level and in buildings.

Another result is that end-use flexibility lowers the cost of the energy transition. This is supported by Ref. [39], that concludes that the flexibility options lowers the system cost by 60 % in a deep decarbonisation pathway. Note that the latter paper includes more types of flexibility than this paper, including transmission investments and sector coupling with district heat. Another example is [40], that uses an ESOM similar to this study, where the demand side management lowers the cost of the energy system with 1 %, corresponding to 4.6 billion GBP. Also [41] states that flexibility options reduces the annual system operational cost. To conclude, the results and the literature, supports that flexibility in the end-use sectors contributes to lower the cost of the energy transition. Indeed, this indicates that it is valuable to push for the utilisation of these solutions through policy and support schemes.

A third results is that end-use flexibility increases the profitability of building applied PV through shifting the demand in time. This is aligned with [41], where all flexibility options are deployed to absorb the excess electricity during the hours with high PV production. Further in Ref. [42], the flexible options increases the PV deployment, with 22 %–66 %, and the self-consumption of PV, with 21 %–26 %. In Ref. [38], demand response enables more PV capacity in the European electricity sector by 1 %. To summaries, the results and the literature agrees that flexibility at end-use level is an enabler for the integration of larger shares of PV in the energy system.

## 5. Conclusions

This study analyses the role and value of end-use flexibility in the decarbonisation of the Norwegian energy system towards 2050. End-use flexibility is defined as flexibility options that are available in buildings, encompassing stationary batteries, flexible electric heating of hot water and flexible charging of electric vehicles. The analysis uses a long-term energy system model to assess the impact of end-use flexibility on investments, operations, costs, and revenues for different parts of the energy system. Further, to ensure robust insights, the analysis is executed for two different storylines, with different assumptions regarding technical and societal change towards 2050.

The research questions of the paper are hereby addressed in the following.

**Research question 1:** How can end-use flexibility affect the design of the low-carbon energy system towards 2050?

End-use flexibility accelerates and increases investments in building applied PV. This is primarily because end-use flexibility facilitates better matching of local PV production to demand. As a result of higher PV investments and shifts in the demand profile, our results indicate that end-use flexibility marginally lowers investment in onshore wind power and hydropower. It should, however, be noted that since electricity generation in Norway relies heavily on flexible reservoir hydropower, the impact of end-use flexibility may have a larger impact on the electricity sector in other countries.

End-use flexibility lowers the peak electricity demand and thus the need to expand the electricity grid. The largest impact is at the distribution grid level, where the electricity peak in winter is lowered from 5 % to 11 %, depending on the spot price region and future storyline. Furthermore, the results demonstrate that end-use flexibility increases the investment in international transmission as it enables greater export of electricity from Norway when European prices are high and import of electricity from Europe when the prices are low.

End-use flexibility reduces the need for other flexible energy storage options in the energy system, for example, hydrogen storage and thermal storage in the district heating sector. In our analysis, the hydrogen storage capacity is lowered by 25 %–66 % with end-use flexibility, depending on the storyline.

**Research question 2:** What is the economic impact of end-use flexibility on the energy supply, infrastructure and demand sectors?

End-use flexibility lowers the cost of the low-carbon energy system transition. Investments and operation of stationary batteries, flexible electric heating of hot water and flexible charging of electric vehicles are considered profitable solutions to facilitate carbon neutrality towards 2050. The economic gains from end-use flexibility depend on future storylines and vary between 4.4 BEUR and 8.3 BEUR. The results imply that there is value in having energy system policies, incentives and regulations in place that facilitate the activation of end-use flexibility.

The building sector is the major winner when end-use flexibility is implemented as it lowers the energy costs for this sector. This is due to several factors: end-use flexibility shifts demand to periods with lower energy prices, increases self-consumption of local PV and lowers the cost of the distribution grid by lowering peak demand. Furthermore, end-use flexibility contributes to smoothing out the variation in electricity prices. By lowering energy costs, the activation of end-use flexibility contributes to increasing the public acceptance and feasibility of the energy transition.

The impact of end-use flexibility on electricity generation profits depends on externalities that influence the future energy system. Both storylines show increased profits of run-of-river hydropower and onshore wind power. The impact of regulated hydro and offshore wind power varies between a negative effect in the storylines with no expansion of Norwegian transmission capacity and a positive effect in the storyline with more energy supply and demand. Furthermore, both storylines show that the profits from district heat production are lowered by end-use flexibility. This can indicate that end-use flexibility competes with district heating as a flexibility provider for the building sector.

> **Research question 3.** How does the modelling of uncertainty impact the role and value of end-use flexibility?

To accurately capture the future role and value of end-use flexibility, it is crucial to use a realistic model of uncertainty. This study demonstrates that investments in energy storage depend on the modelling approach used to represent short-term uncertainty. In most cases, investments in end-use flexibility and other storage options, such as hydrogen storage, are lower when using a traditional deterministic modelling approach compared to a stochastic approach. Consequently, to provide insights on how end-use flexibility influences other flexibility options in the energy system, it is necessary to have a realistic representation of the operational situation that can occur in the energy system given the presence of short-term uncertainty. In this paper, the short-term uncertainty of European electricity prices is considered. The analysis could be further improved by including other types of short-term uncertainty, such as weather-dependent renewable electricity generation and heat demand. However, this is not necessarily straightforward as it is important to ensure a correlation between uncertain parameters, which will significantly increase the computational complexity.

There are several other **further research needs** related to addressing the role and value of end-use flexibility in the energy transition.

First, in this study, and most ESOMs, it is assumed that electricity generation and electricity demand are always balanced by the energy market, also known as 'perfect foresight'. This corresponds to assuming that there are no forecast errors in either the supply or the demand. A hypothesis is that the assumption of perfect foresight can underestimate the need for flexible solutions in ESOMs. A suggestion for further work is to expand the model approach of this paper to include an explicit modelling of ancillary markets. However, this requires a quantification of the current balancing markets and a modelling methodology that endogenously defines the future need for reserves based on investments in energy supply and future demand.

Second, although techno-economic analysis demonstrates its value, end-use flexibility is not necessarily implemented, despite being a cost-optimal solution from an energy system perspective. It is therefore necessary to better understand the barriers and drivers of these solutions to facilitate a cost-efficient energy system transition.

Third, when analysing the competition between different flexibility sources, it is relevant to consider the resulting material use. This is because limiting materials can give a prioritisation of flexibility options that are not material intensive. Also, such analysis, can quantify the benefits of flexibility if it entails a lower use of materials. For example, if flexibility lowers the grid expansion needs.

## CRediT authorship contribution statement

**Pernille Seljom:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Eva Rosenberg:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Kristina Haaskjold:** Writing – review & editing, Writing – original draft, Visualization, Methodology.

## 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.

## Data availability

Data will be made available on request.

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