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SINTEF RESEARCH 103

Flexbuild final report

THE VALUE OF END-USE FLEXIBILITY IN THE FUTURE NORWEGIAN ENERGY SYSTEM

SINTEF Research

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Preface

This report is a deliverable of the Flexbuild project, a knowledge-building project for industry (Kompetansebyggende prosjekt for næringslivet – KPN, in Norwegian) co-financed by the Research Council of Norway under the programme EnergiX, with grant agreement no. 294920/E20 for the period 2019–2024. The industrial partners in the project are: Statsbygg, Oslobygg, Boligbyggelaget TOBB, Norsk Fjernvarme, Elvia and Statnett; the public actors are: Norges vassdrags- og energidirektorat (NVE) and Enova; the research partners are: Institutt for Energiteknikk (IFE), Norges teknisk-naturvitenskapelige universitet (NTNU) and Danske Tekniske Universitet (DTU), together with SINTEF that is the project leader.

Project webpage: https://www.sintef.no/projectweb/flexbuild/

Oslo, 13/10/2023

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Sammendrag

Prosjektet Flexbuild har hatt som mål å forstå hvordan sluttbrukerfleksibilitet kan påvirke det fremtidige energisystemet i Norge. Flexbuild samlet industrielle partnere, offentlige organisasjoner, universiteter og forskningsinstitusjoner for å undersøke ulike aspekter ved energifleksibilitet. For å oppnå målet ble det tatt i bruk en kombinasjon av modeller med ulike fokusområder, og fire forskjellige energiovergangsscenarioer ble utforsket: Energinasjonen, Petroleumsnasjonen, Naturnasjonen og Klimapanikk.

Modellene som ble utviklet og brukt i prosjektet, inkluderer BUILDopt for enkeltbyggets energibruk, IFE-TIMES-Norway for det norske energisystemet, EMPIRE for det europeiske kraftmarkedet og EMPS for det norske vannkraftsystemet. Modellene ble koblet sammen gjennom en såkalt "soft linking", som innebærer at den ene modellens utdata blir brukt som den andres inndata, og vice versa, til noen forhåndsbestemte konvergenskriterier oppnås. Inndata og kalibrering i prosjektet innebar blant annet en regional oppdeling av den norske bygningsmassen, definering av potensial for utvidelse av fjernvarme og kalibrering av modeller mot statistiske data.

<u>Kapasitetsutvidelse av det europeiske kraftsystemet</u>
EMPIRE er en langsiktig investeringsmodell designet for å optimalisere teknologiporteføljer innenfor det europeiske kraftsystemet, samtidig som faktorer som karbondioksid (CO_2)-utslippsmål, tilbud-/etterspørselsbalanse og tekniske begrensninger tas i betraktning. Modellen representerer 31 europeiske land med hver sin respektive node, koblet gjennom koblingslinjer, med unntak av Norge, som er delt inn i fem markedsområder. EMPIRE ble utvidet for å inkludere etterspørselsrespons fra husholdningsapparater, noe som gjorde det mulig å vurdere fleksibiliteten i boligers spesifikke elektriske last. Etter denne utvidelsen, indikerte resultatene potensielle kostnadsreduksjoner på omtrent 1 % fra 2020 til 2055.

<u>Aktivering av fleksibilitet i sluttbruk i bygninger</u>
BUILDopt ble utviklet for å modellere fleksibiliteten i sluttbruk i bygninger. Den optimaliserer både drifts- og investeringskostnader for den enkelte bygnings energisystem med hensyn til faktorer som strømtariffer, spotpriser og fleksible lastprofiler. Modellen inkluderer fleksibilitetskilder som styring av innendørstemperatur, termisk lagring og lading av elektriske kjøretøy (EV). BUILDopts simuleringer viste potensial for en betydelig reduksjon av topplast samt kostnadsbesparelser gjennom aktivering av fleksibilitet. Valget av strømtariff var en kritisk faktor, der tariffer med effektledd ga mer kostnadseffektiv spisslastreduksjon. Modellen ble også brukt til å utforske investeringsoptimalisering av oppvarmingsteknologier, solcellepaneler og batterier. Resultatene viste at aktivering av eksisterende fleksibilitetskilder kan eliminere behovet for å investere i stasjonære batterisystemer, samtidig som det vil akselerere adopsjonen av solcellepaneler i bygninger, spesielt i småhus.

<u>Energisystem i Norge</u>
IFE-TIMES-Norway ble koblet sammen med både EMPIRE og BUILDopt for å forstå samspillet innenfor henholdsvis det norske og europeiske kraftsystemet og byggsektoren. Sammenkoblingen gjorde det mulig å få et helhetlig bilde av energiomstillingen. Resultatene understreker verdien av sluttbrukerfleksibilitet for å redusere kostnadene ved energiomstillingen. Fleksibilitet bidrar til å tilpasse lokal energiproduksjon – spesielt fra solcellepaneler – med etterspørselen, noe som reduserer behovet for nettutvidelse. Den øker også profitten fra internasjonal strømhandel. Sluttbrukerfleksibilitetens innvirkning på reduksjonen i toppbelastning varierer etter region og historie. Fremfor alt spiller den en rolle i å redusere behovet for både hydrogen- og termisk lagring.

<u>Vannkraftsystem i Norge</u>
EMPS-modellen fokuserte på å vurdere hvordan fleksibel sluttbruk av elektrisitetsbehov ville påvirke Norges vannkraftdominerte kraftsystem. Studien fant at sluttbrukerfleksibilitet hadde

minimale effekter på kraftsystemet: Resultatene viste små reduksjoner i energiforbruket og høyere energioverskudd i Norge. Små reduksjoner i strømprisene ble funnet, spesielt i 2050, mens vannkraftproduksjonen forble relativt stabil, med mindre endringer i gjennomsnittlig kraftproduksjon og bruk av vannreservoarer. Imidlertid førte det også til redusert inntekt for både vannkraft- og vindkraftprodusenter, spesielt i 2030.

Hovedmålet med prosjektet har vært å tilby kunnskap om hvordan sluttbrukerfleksibilitet tilgjengelig i bygningsmassen vil påvirke utviklingen av det samlede energisystemet. Hovedkonklusjonene fra Flexbuild er her oppsummert med hensyn til prosjektmålene.

Mål 1: Utvikle en ny og robust stokastisk modelleringsramme for det norske energisystemet som er i stand til å vurdere virkningene av sluttbrukerfleksibilitet i energisystemet.
Prosjektet opprettet BUILDopt-modellen for å vurdere sluttbrukerfleksibilitet i bygninger. I tillegg ble IFE-TIMES-Norway-modellen utvidet med stokastiske elementer for å ta hensyn til usikkerhet i investeringer i energilagringsteknologier. Videre ble det utviklet en metodikk for å koble disse modellene. Resultatene fra koblingen viser at bygninger i utgangspunktet forblir som pristakere, og selv om energibehovet blir fleksibelt i hele bygningsmassen, har dette kun marginal innvirkning på energiprisdannelsen.

Mål 2: Vurdere kostnadsoptimal investering og drift av energisystemet versus private bygningseiere, og adressere mulige misforhold mellom de to.
Sluttbrukerfleksibilitet ble funnet å være en teknoøkonomisk investering som forbedret samtidigheten mellom lokal solcelleproduksjon og etterspørsel, noe som reduserte behovet for nettutvidelse. Kostnadsoptimale valg av oppvarmingsteknologier favoriserte ofte varmepumper fremfor fjernvarme, noe som understreker et misforhold mellom individuelle bygningsvalg og energisystemperspektivet. Installering av solcellepaneler ble funnet å være kostnadsoptimalt når det ble kombinert med sluttbrukerfleksibilitet. I tillegg ble behovet for stasjonære batterisystemer til å lagre overskuddsenergien fra solceller betydelig redusert.

Mål 3: Vurdere virkningene av ulike strømtariffer for både sluttbruker og energisystemet.
Valg av strømtariff ble funnet å ha en betydelig innvirkning på topplast. En tariff bestående delvis av et effektledd, i tillegg til et energiledd, muliggjorde mer kostnadseffektiv spisslaststyring ved å sette tak på toppbehov.

Mål 4: Vurdere verdien av sluttbrukerfleksibilitet for å lette oppgradering av strømnettet.
Sluttbrukerfleksibilitet hadde potensial til å redusere topplast på enkeltbyggnivå med 20–50 %, med mindre effekter på aggregert nivå, rundt 16–20 % på markedsområdenivå. Det høye nivået av solcelleinstallasjoner reiste spørsmål om nettutfordringer i områder dominert av eneboliger.

Mål 5: Undersøke hvordan sluttbrukerfleksibilitet kan endre rollen til norsk vannkraft og investering i vind- og solenergi i nasjonale og europeiske kraftsystemer.
Sluttbrukerfleksibilitet ble vist å akselerere adopsjonen av solcellepaneler i Norge, øke total kapasitet og elektrisitetsproduksjon. Samtidig som vannkraftproduksjonen forble relativt stabil, var det små reduksjoner i strømpriser.

Fremtidig arbeid bør inkludere modellering av distribusjonsnett og "ancillary markets", med vekt på stokastiske etterspørselsprofiler i stedet for arketypebygninger for mer robuste representasjoner.

Oppsummert genererte Flexbuild kunnskap om sluttbrukerfleksibilitet samt modellering og potensielle virkninger på det norske energisystemet av denne. Det understreket betydningen av valg av strømtariff, kostnadseffektiviteten av sluttbrukerfleksibilitet og dens rolle i å akselerere adopsjonen av solcellepaneler, samtidig som behovet for nettutvidelse reduseres.

Executive summary

The Flexbuild project aimed to understand how end-use flexibility could impact the future energy system in Norway. This initiative brought together industrial partners, public organizations, universities, and research institutions to investigate various aspects of energy flexibility. To achieve its objectives, the project employed a combination of models and explored four different energy transition scenarios, or storylines, named as Energy Nation, Petroleum Nation, Nature Nation, and Climate panic.

The models developed and used in the project included BUILDopt for building energy use, IFE-TIMES-Norway for the Norwegian energy system, EMPIRE for the European power market, and EMPS for the Norwegian hydropower system. These models were interconnected through a soft linking approach, allowing them to influence each other's input and results, until some predefined convergency criteria are met. The project's input data and calibration involved regionally dividing the Norwegian building stock, defining potential for district heating expansion, and calibrating models against statistical data.

Capacity Expansion of the European Power System

EMPIRE is a long-term investment model designed to optimize technology portfolios within the European power system while considering factors like carbon dioxide (CO2) emissions targets, supply-demand balance, and technical constraints. The model represented thirty-one European countries connected through interconnectors, excluding Norway, which was divided into five market areas. EMPIRE was expanded to incorporate demand response from residential appliances, allowing it to consider residential electric load flexibility. This expansion indicated potential cost reductions of about 1% from 2020 to 2055.

Activation of End-Use Flexibility in Buildings

BUILDopt was developed to model end-use flexibility in buildings. It optimizes both operational and investment costs for a single building's energy system, considering factors like grid tariffs, spot prices, and flexible load profiles. The model incorporated flexibility sources such as indoor temperature control, thermal storage, and electric vehicle (EV) charging. BUILDopt's simulations revealed the potential for significant peak load reduction and cost savings through flexibility activation. The choice of grid tariff was a critical factor, with tariffs including a power fee component offering more cost-effective peak load reduction. The model also explored investment optimization in heating technologies, solar PV, and batteries. The results showed that activating existing flexibility sources could eliminate the need for investing in battery systems while it would accelerate the adoption of solar PV in buildings, particularly in houses.

Energy System in Norway

IFE-TIMES-Norway was linked with both EMPIRE and BUILDopt to understand interactions within the Norwegian and European power systems and the building sector, respectively. This linkage facilitates a holistic view of the energy transition. The results of this model emphasize the value of end-use flexibility in reducing energy transition costs. These flexibility options help align local energy production, especially from PV, with demand, reducing the need for grid expansion. They also increase profits from international electricity trade. End-use flexibility's impact on peak demand reduction varies by region and storyline. Importantly, it plays a role in lowering the need for hydrogen and thermal storage.

Hydropower System in Norway

The EMPS model focused on assessing how flexible end-use of electricity demand would affect Norway's hydropower-dominated power system. The study found that end-use flexibility had minimal effects on the power system, leading to slight reductions in energy demand and higher energy surplus in Norway. Power prices saw small decreases, especially in 2050, while hydropower production remained relatively stable, with minor changes in average power production and water reservoir usage. However, it also led to reduced income for both hydropower and wind power producers, particularly in 2030.

The main objective of the project was to provide knowledge on how end-use flexibility available in the building stock will impact the development of the overall energy system. The main takeaways of Flexbuild are here summarized with respect to the project's objectives.

Objective 1: Develop a robust and novel stochastic modelling framework of the Norwegian energy system capable of evaluating the impacts of end-use flexibility in the energy system.
The project created the BUILDopt model to assess end-use flexibility in buildings. It also expanded the IFE-TIMES-Norway model with stochastic elements to account for uncertainty in energy storage investments. Additionally, the project developed a methodology for linking these models. The results from the linking show that buildings remain fundamentally price-takers, and even if energy demand becomes flexible in the entire building stock, this has only a marginal impact on the energy price formation.

Objective 2: Assess cost-optimal investment and operation of the energy system vs. private building owner and address possible mismatch between the two.
End-use flexibility was seen as a techno-economic investment that improved the match between local PV production and demand, reducing the need for grid expansion. The cost-optimal choice for heating technologies often favoured heat pumps over district heating, highlighting a mismatch between individual building choices and the energy system perspective. Solar PV installation was found to be cost-optimal when combined with end-use flexibility, significantly reducing the need for batteries.

Objective 3: Assess the impacts of different power tariffs on both end-user and the energy system.
The type of power tariff had a significant impact. A tariff with a power fee component, in addition to an energy fee, enabled more cost-effective peak load management by setting caps on peak demand.

Objective 4: Asses the value of end-use flexibility for easing the power grid reinforcement.
End-use flexibility had the potential to reduce peak loads at the single building level by 20-50%, with smaller effects at the aggregate level, around 16-20% at market area level. The high level of solar PV installations raised questions about grid challenges in areas dominated by single-family houses.

Objective 5: Investigate how end-use flexibility may change the role of Norwegian hydropower and investment in wind and solar in the national and European power system.
End-use flexibility was shown to accelerate solar PV adoption in Norway, increasing total capacity and electricity production. While hydropower production remained relatively stable, there were slight reductions in power prices.

Future work should include modelling distribution grids and ancillary markets, with an emphasis on stochastic demand profiles rather than archetype buildings for more robust representations.

In summary, Flexbuild generated knowledge on end-use flexibility, its modelling and its potential impacts on the Norwegian energy system. It emphasized the importance of grid tariffs, the cost-effectiveness of end-use flexibility, and its role in promoting solar PV adoption while reducing the need for grid expansion.

Contents

1 Introduction and Storylines

Igor Sartori (SINTEF)

This is the final report of the Flexbuild project. It contains an overview of the main results of the project. In the first chapter, we introduce basic concepts that are needed to understand the content of the following chapters. Chapter 2 summarizes the main takeaways from Flexbuild, while Chapter 7 summarizes the lessons learned from the perspective of the non-research partners. Chapters 3 to 6 contain the detailed analysis and are all structured in the same way around the different models that were developed and used: a description of the model followed by the quantification of the input used, then the linking with the other models and a discussion of the results obtained. Finally, Chapter 8 presents a summary of the scientific publications produced in the context of Flexbuild.

1.1 Flexbuild project

The project "Flexbuild – The value of end-use flexibility in the future Norwegian energy system" is a knowledge-building project, running from 2019 to 2023 and financed with the support from the Research Council of Norway under the programme EnergiX, with grant agreement nr. 294920/E20 and the following industrial partners: Statsbygg, Oslobygg, Boligbyggelaget TOBB, Norsk Fjernvarme, Elvia and Statnett; and the public partners: Norges vassdrags- og energidirektorat (NVE) and Enova. The universities and research institute partners are SINTEF AS (Dept. Building and Infrastructure) who has been the Project Leader, IFE (Institute for Energy Technology), NTNU (Dept. of Industrial Economics and Technology Management) and SINTEF Energi AS from Norway, plus the participation of DTU Compute (Dept. of Applied Mathematics and Computer Science) from Denmark. The constellation of partners was chosen to cover the entire value-chain, from demand to supply of energy, that will be affected by implementing the end-use flexibility available in buildings.

The primary objective of Flexbuild was to provide knowledge on how end-use flexibility available in the building stock will impact the development of the overall energy system. The secondary objectives leading to the primary objective are:

- O1. Develop a robust and novel stochastic modelling framework of the Norwegian energy system capable of evaluating the impacts of end-use flexibility in the energy system.
- O2. Assess cost-optimal investment and operation of the energy system vs. the financial optimal operation of the private building owner and address possible mismatch between the two.
- O3. Assess the impacts of different power tariffs on both end-user and the energy system.
- O4. Asses the value of end-use flexibility for easing the power grid reinforcement.
- O5. Investigate how end-use flexibility may change the role of Norwegian hydro-power and investment in wind and solar in the national and European power system.

In chapter 2 the main takeaways from the project are summarized with reference to these objectives.

1.2 Terminology

It is useful to clarify some terminology, to avoid ambiguity and possible misunderstanding. Unfortunately, there is not a full consensus on how to use certain terms, and different fields (e.g., building physics, power system) may associate different meanings to common terms, such as demand, use, load. In this report, and in Flexbuild in general it has been agreed to use the following terminology (*Norwegian terms in italics*).

Terminology on the buildings:

- **Residential sector** (*husholdninger*), comprises the following building categories:
    - House (*småhus*), single- and bi-family houses and row-house
    - Apartment (*boligblokk*), apartments block
- **Commercial sector** / Service sector (*næringsbygg*), comprises the following building categories:
    - Office (kontorbygg)
    - Shop (forretningsbygg)
    - School (*skole*)
    - Nursing home (*sykehjem*)
    - Other (*andre*), which is a weighted average of all other commercial categories
- Energy efficiency levels, refers to the efficiency of the thermal envelope of a building and is classified as one on three levels (based on energy measurements):
    - **Regular**, average of the current building stock
    - **Efficient**, similar to the TEK10 building code, also an ambitious target for deep renovation
    - **Very Efficient**, similar to the Passive House standard and only possible for new buildings
- **SH**, Space Heating (*oppvarming*)
- **DHW**, Domestic Hot Water (*varmtvann*)
- **EL**, Electric specific (*el-spesifikk*)
- **EV**, Electric Vehicle (*elbil*)
- **PV**, Solar Photovoltaic (*solceller*)

Terminology on heating technologies:

- **WBH**, Waterborne heating distribution system, allows using the following technologies:
    - **DH**, District Heating; **EB**, Electric Boiler; **BB**, Biomass Boiler
    - **ASHP**, Air-Source Heat Pump (*luft-vann varmepumpe*)
    - **GSHP**, Ground-Source Heat Pump (*grunnvarmepumpe*)
- **PS**, Point Source heating (lack of waterborne system), allows using the following technologies:
    - **PH**, electric panel heater (*panelovn*)
    - **A2A**, Air-to-Air heat pump (*luft-luft varmepumpe*)
- **System Seasonal SCOP**, is the Seasonal COP (coefficient of performance) of a heat pump system, composed of a heat pump as base unit and a direct electric heater as top units, ev. with a buffer heat storage. The system COP is the ratio of the total heating energy in output of the system over the total energy in input to it (being it electricity or other carriers).

Terminology on energy:

- **Energy demand** (*energibehov*) for different needs, or energy services:
    - Space Heating, SH (*rom oppvarming*)
    - Domestic Hot Water, DHW (*varmtvann*)
    - Electric specific (fans, lighting, plug loads, …), EL (*el-spesifikk*)
    - Electric Vehicle (charging), EV (*elbil lading*)
- **Energy use** (*energiforbruk*) for different energy carriers:
    - Electricity (elektrisitet, strøm)
    - District Heating, DH (*fjernvarme*), and Local Heating, LH (*nærvarme*)
    - Fuels (*brensel*)

The difference between energy demand and energy use is that the energy demand for a specific need, e.g., space heating, may be met using different technologies, e.g., heat pump or gas boiler, thus resulting in different energy uses for different carriers, depending on the technology mix and the respective efficiencies.

The term **load profile** (*lastprofil*) is here meant as a generic term that refers to the hourly time series of any energy variable. So, for example, it is possible to speak of the load profile of DHW demand, as well as of the load profile of electricity use.

Finally, the following terminology is adopted in this report:

- **End-use flexibility** refers to the ability of a building to activate its «beyond the meter» flexibility sources, while safeguarding user needs and comfort
- Flexible energy thus results in hourly load profiles that deviate from a **baseline** (non-flexible)
- The **flexibility sources** available in the different models are shown in Table 1. BUILDopt, being a model dedicated to buildings only, offers more options as well as more detailed representations of the flexibility sources; this is described in more detail in chapter 4.1.2.

Table 1. Flexibility sources available in the different models.

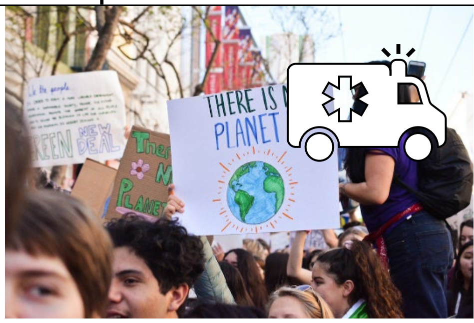
<table>
<tr><th colspan="2">EMPIRE</th><th colspan="2">IFE-TIMES-Norway</th><th colspan="2">BUILDopt</th></tr>
<tr><th>Baseline</th><th>Flexible</th><th>Baseline</th><th>Flexible</th><th>Baseline</th><th>Flexible</th></tr>
<tr><td rowspan="4">---</td><td rowspan="4">Residential only: Electric appliances, Electric water heaters for water and space heating, Air Conditioning, and EVs</td><td rowspan="4">---</td><td>---</td><td rowspan="4">Batteries**</td><td>Space heating (building envelope)</td></tr>
<tr><td>Electric water heater*)</td><td>Electric water heater*)</td></tr>
<tr><td>Electric Vehicle charging</td><td>Electric Vehicle charging</td></tr>
<tr><td>Batteries</td><td>Batteries</td></tr>
</table>

*) in this report the term Domestic Hot Water tank (DHW tank), or simply hot water tank, is sometimes used as synonym of Electric water heater.
**) only for the Full linking simulations, see §4.3

1.3 Storylines description

In the first year of the project, the partners agreed on the need to define long-term storylines, representing possible future developments for external variables influencing the modelling activities, such as the evolution of the building stock on the demand side and the availability and cost of different energy technologies on the supply side. This resulted in the identification of 4 storylines, named as shown in Table 2, that were given in a descriptive, qualitative way, as reported in Appendix A: Storyline descriptions.

Table 2. Concise summary of main characteristics of the Storylines. Images credits, from top-left and clockwise: Matthey Henry, Zachary Theodore, Oleksiiv Topolianskyl, Li-An Lim (all from Unsplash).

Energy nation	**Petroleum nation**
 • Large potential for land-based wind • High demand • Favour central solutions	 • Low technology learning • High demand • No new international trade
Nature nation	**Climate panic**
 • No new national grid or land-based wind • Low demand • Favour decentral solutions	 • As today until 2030, then radical measures • Low demand in 2050 • No new international trade

All storylines aim at a substantial decarbonization of the energy system by 2050 but follow different paths. Quantification of the storylines affects different variables in the different models, as described in the following chapters. All Storylines are quantified in a realistic way, i.e., none of them explores "maximum potential" scenarios for any technology.

Combining the four Storylines, the simulation years of interest 2030 and 2050, and the activation of end-use flexibility – compared to a baseline without flexibility – results in a matrix of all possible combinations, as shown in Figure 1.

Energy use in buildings	**2020**	**2030**				**2050**			
		Petroleum	**Energy**	**Nature**	**Climate panic**	**Petroleum**	**Energy**	**Nature**	**Climate panic**
Non-flexible	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
Flexible	-	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible

Figure 1. Matrix of all possible combinations of Storyline, simulation year and end-use flexibility activation.

The linking between the various models has been performed for all Storylines and simulation years with the Baseline (non-flexible) energy demand. This was necessary to align the models on the same set of assumptions and harmonized input, so that also the results, such as energy prices and investment in capacity for different technologies, would be consistent across the different models. However, after setting this common background, different features have been studied only in selected Storylines and/or different ways of activating the end-use flexibility.

This allowed focusing with more detail on specific aspects of interest while operating within the time and budget of the project. In the beginning of the following chapter and/or sub-chapters it is specified, with the help of similar figures to Figure 1, which combinations are explored and for what purpose.

1.4 Models and linking

Flexbuild uses a set of models to provide insights on the future role and value of end-use flexibility available in buildings from a Norwegian energy system perspective. Each of the four Flexbuild models has different sectoral coverage, and consequently captures different aspects of the future energy system:

- BUILDopt is a detailed model of energy use in single buildings. It considers both the operational flexibility of energy demand and the investment choice for the heating technologies, solar PV and battery. The input on typical (non-flexible) energy demand are taken from the PROFet model. To scale up the results at aggregated level BUILD-opt is used in combination with RE-BUILDS, which is a dynamic model simulating the long-term development of the Norwegian building stock. For simplicity, in this report we may use the term BUILDopt to refer to both the single building level and the aggregated level. Energy prices are an exogenous variable for BUILDopt that takes it as an input from TIMES, while energy use is endogenously calculated in response to the given energy prices and passed back to TIMES as an output.
- IFE-TIMES-Norway is a model of the energy system in Norway (sometimes referred to simply as TIMES, for simplicity). It contains all energy carriers, supply technologies (including hydropower, although not as detailed as in EMPS) and demand sectors (including the building sector, although not as detailed as in BUILDopt). TIMES models internally the energy use for industry and transport and takes from BUILDopt that of buildings; it calculates energy prices and investments in supply technologies in Norway, while import/export with neighbouring countries is obtained by linking with EMPIRE.
- EMPIRE is a long-term stochastic optimization model of the European power market, i.e., electricity only. It considers energy demand as an exogenous input, to calculate investments in supply and transmission technologies of all EU countries, Switzerland, Norway, the UK and some Balkan states. Moreover, it incorporates operational details that allows the determination of electricity prices and trading between countries. These operational results will be used in the linking with IFE-TIMES-Norway to ensure the Norwegian energy mix aligns with neighbouring countries.
- EMPS is a power market model of the Nordics with detailed representation of the Nordic hydropower system. In this project it is used to address how the developments of the future energy system influence the operation of the Norwegian power system inclusive hydropower. Thus, it takes the electricity use as input and generation capacities (incl. import/export) resulting from the linking of the other models, while it calculates the consequences for the operation in the power sector.

Each model is described in more detail in the following chapters, as well as the previous Flexbuild Annual Report 2 (Sartori et al., 2022). The models are linked two-by-two in a soft linking, as shown schematically in Figure 2.

Soft linking means that the models do not exchange information while processing, i.e., at each time step of the simulation. Rather, when one model has completed its simulation for the entire period of interest (in this project from 2020 to 2050) its results are used as input by the other model with which it is linked. Since (some of) the inputs of a model are (some of) the outputs of the other, the two models influence each other and there is the need to iterate between them until the key variables – those that form the mutual input/output soft link – converge to values that do not vary any longer between one iteration and the previous (within a margin of tolerance).

The reason for the two-by-two linking is that it was noticed, in early attempts, that the key variables affecting the international trade between Norway and Europe were not significantly affected by the key variables affecting the demand in the Norwegian building stock and vice versa. Thus, instead of iterating through all models at once, it was more convenient to iterate them two-by-two, without significant loss of accuracy. Furthermore, while the models IFE-TIMES-Norway, EMPIRE and REBUILDS-BUILDopt have been further developed in Flexbuild, altering or expanding their features to enable studying the effect of end-use flexibility, EMPS was simply used to verify the impact of the results on the Norwegian hydropower system. Thus, while the link between the other models is bidirectional, the link with EMPS is unidirectional, i.e., it simply takes some variable as input from TIMES (converged) outputs.

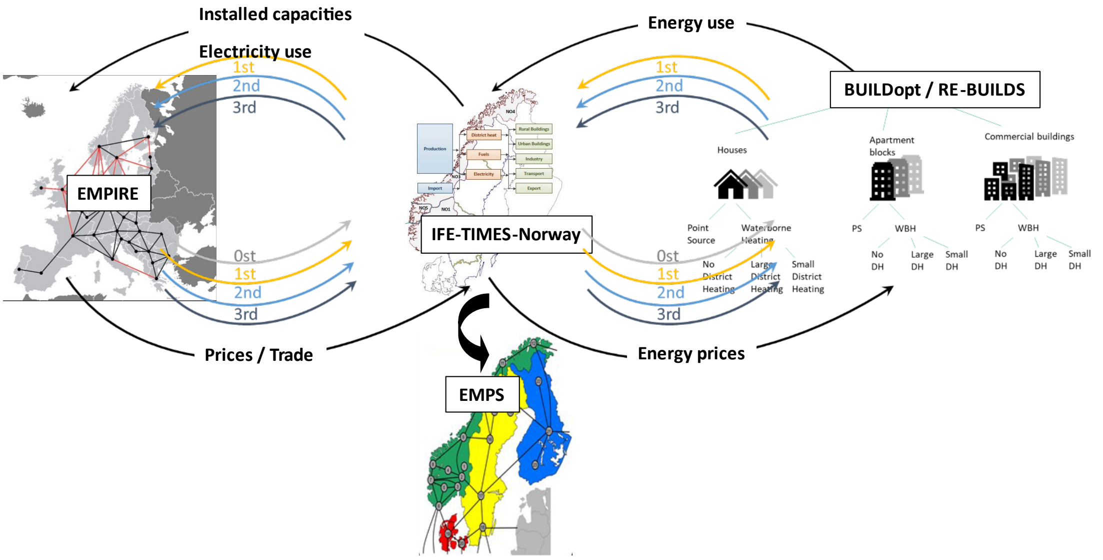


Figure 2. Schematics of the linking between the models, showing the bi-directional interdependencies with the respective key variables, and the iterations needed for their convergency.

Setting up and running the two-by-two soft linking between models was a time-consuming process. In the first place, the models needed to be modified to operate in this way, then extensive work of input data harmonization was necessary (as described in the next section), and finally, it requires time to process the iterations with its data exchange and analysis of result consistency. Therefore, not all linking was performed for all possible combinations of Storylines, simulation years and end-use flexibility activation shown in the matrix of Figure 1, as already commented in the previous section. Nevertheless, it was found that three iterations were enough, in general, to reach a satisfying convergence of the key variables.

The order in which the two-by-two linking was performed is also reflected in the order in which the chapter of this report are organised, and it was as follows:

- Simulate the “iteration #0”, as described in chapter 1.5
- Linking EMPIRE with IFE-TIMES-Norway, described in chapter 3.3 and 5.3
- Linking BUILDopt with IFE-TIMES-Norway (when the latter had converged with EMPIRE), described in chapter 4.3 and 5.4
- Linking EMPS with IFE-TIMES-Norway (when the latter had converged with both EMPIRE and BUILDopt), described in chapter 6.3.

1.5 Harmonization of inputs

Before starting the linking between the models, it was necessary to harmonize a large set of input and the structuring of such data. It was also necessary to calibrate the models for the starting of the simulation period, i.e., year 2020, and to define a starting point, or "iteration #0", for the linking between models.

Geographical distribution of the building stock

The Norwegian building stock has been regionally divided into the five spot price regions of Norway, NO1 to NO5, as shown in Figure 3. Since not all the geographical areas are served by, or can be served in future by District Heating, the following sub-area were defined with reference to population density and therefore suitability for District Heating (DH) systems:

- Large-scale DH, based on the Statistics Norway definition of "cities". Current district heating plants that generate > 100 GWh/year are defined as large-scale
- Small-scale DH, based on the Statistics Norway definition of "tightly populated areas". Current district heating plants that generate < 100 GWh/year are defined as small-scale
- No DH, based on Statistics Norway's definition of "sparsely populated areas". For these areas we assume that the heat density is too low to justify the development of thermal networks.

Furthermore, it was agreed with the partners to simplify the modelling by excluding small houses from the connection to any form of district heating. This is because there is just a minor volume of district heating being delivered to single family houses, and at the same time this is not an attractive customer for district heating expansion. To keep overall consistency with the statistics on energy carriers use, the total volume of district heating going to residential buildings is thus allocated to Apartments.

The percentage of existing buildings having waterborne heating is ca. 40% for Apartments and ca. 60% for Commercial buildings, based on available statistics on heating technologies and consumed district heating. In new buildings, this is assumed to become ca. 90%, for both Apartments and Commercial buildings.

The combination of geographic sub-areas and waterborne heating led to the identification of the potential for District Heating expansion, showing an overall doubling potential from today's 5 TWh, see Flexbuild Annual Report 2 (Sartori et al., 2022) for further details. This aspect was later investigated also in the ZEN report 47 (Kauko et al., 2023) where further introduction of waterborne heating was considered as a renovation measure, leading to similar results. The potential for District Heating is discussed further in chapter 4.4.2.

Calibration and validation in 2020

In the starting of the simulation period, in year 2020, a breakdown of the building stock's floor area composition (from RE-BUILDS) and of its energy demand (from PROFet) is shown in Figure 4. Apart from the different weight of the building categories, either in terms of floor area or energy demand, it is worth noticing that more than half of the total energy demand goes into Space heating while just more than one third goes into electric specific consumption (with a negligible amount coming from EVcharging).

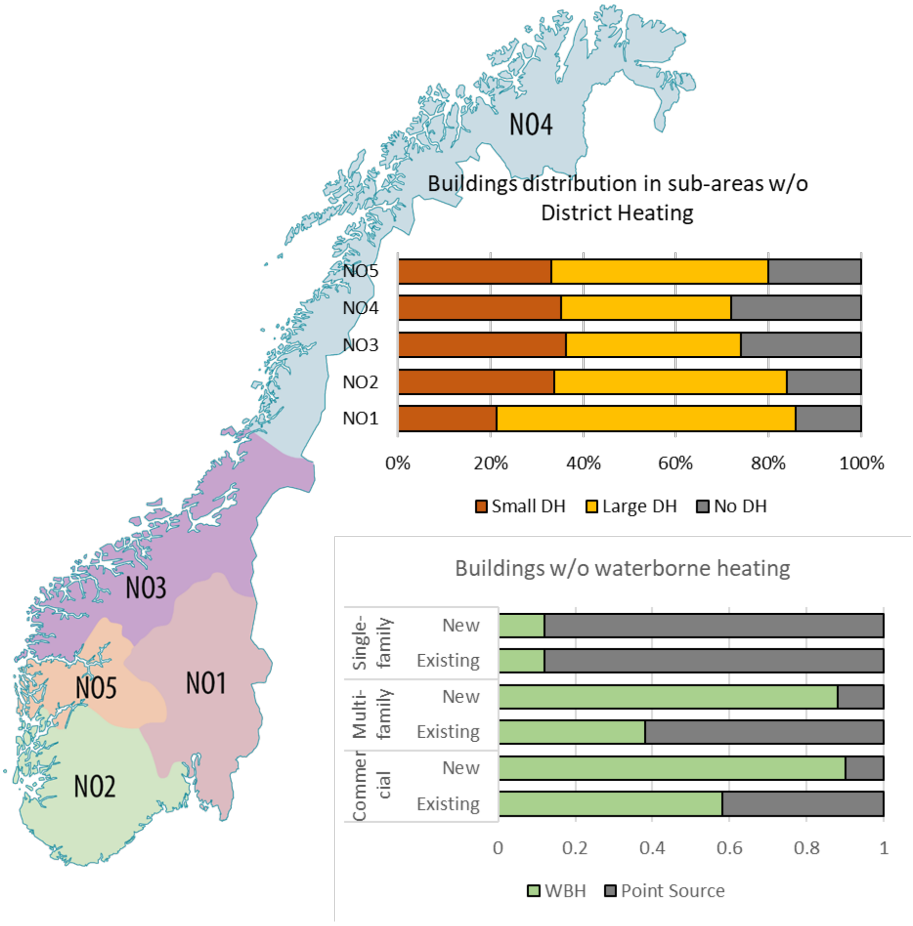


Figure 3. The five geographic areas corresponding to the electricity market areas of Norway (*left*); with the distribution of the building stock within each area and sub-area (*top-right*); and the availability of waterborne heating in building (*bottom-right*).

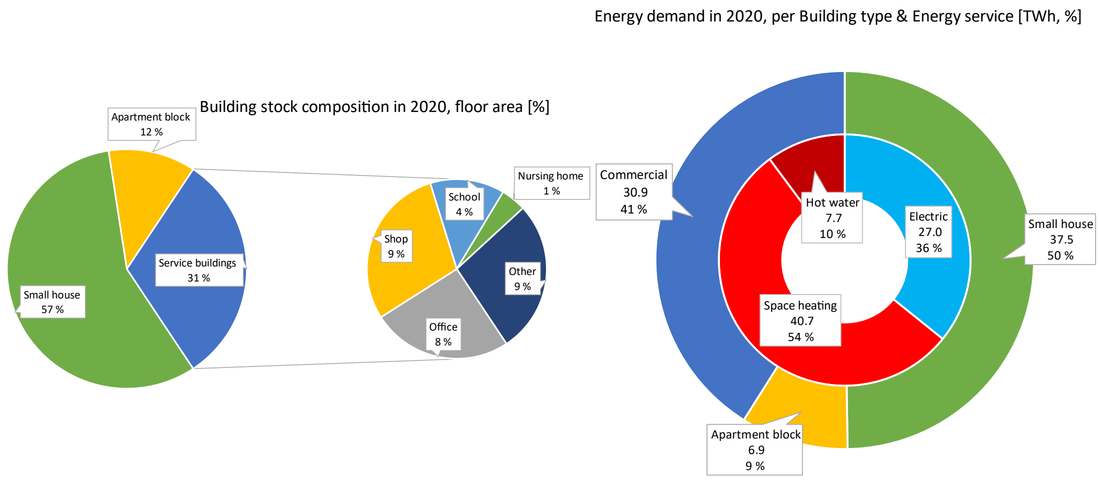
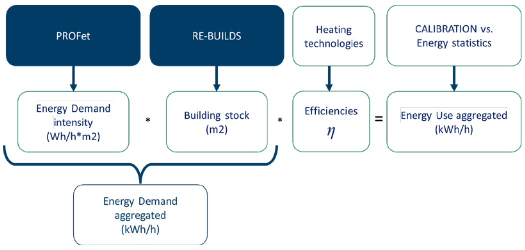
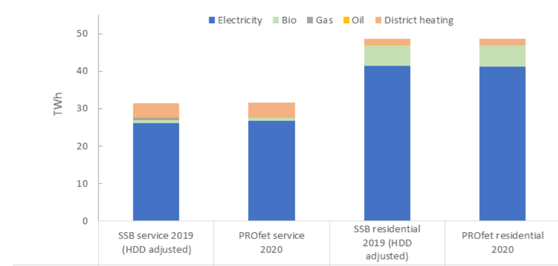


Figure 4. Breakdown of the building stock's floor area composition (*left*) and its energy demand (*right*).

To validate the building stock model for year 2020 against national energy use statistics (temperature adjusted), the load profile for the building mass has been generated by combining the models PROFet (energy demand load profile estimator) and RE-BUILDS with the best available information on installed heating technologies and their efficiencies, as shown schematically in Figure 5 (left). The model can be considered calibrated, considering that the difference is below 0.5 TWh/y in the total as well as in the breakdown per building category

(Residential and Commercial) and per energy carrier, over a total energy use of 80 TWh/y, see Figure 5 (right).





	SSB service 2019 (HDD adjusted)	PROFet service 2020	SSB residential 2019 (HDD adjusted)	PROFet residential 2020
SUM	31.5	31.7	48.7	48.7
District heating	3.8	4.2	1.6	1.7
Oil	0.3	0.0	0.1	0.0
Gas	0.5	0.0	0.1	0.0
Bio	0.8	0.7	5.5	5.8
Electricity	26.2	26.8	41.4	41.1

Figure 5. Schematics of how the models PROFet and RE-BUILDS are combined to give the aggregated Energy Demand in the building stock (*left*); and comparison between modelled energy use in 2020 and measured (temperature adjusted) energy use in 2019 from SSB (*right*).

Use of wood for space heating in residential buildings

The calibration shown in the previous section includes the annual consumption of wood, being the Biomass used exclusively in the Residential sector (Houses and Apartments), while pellets is assumed for Commercial buildings.

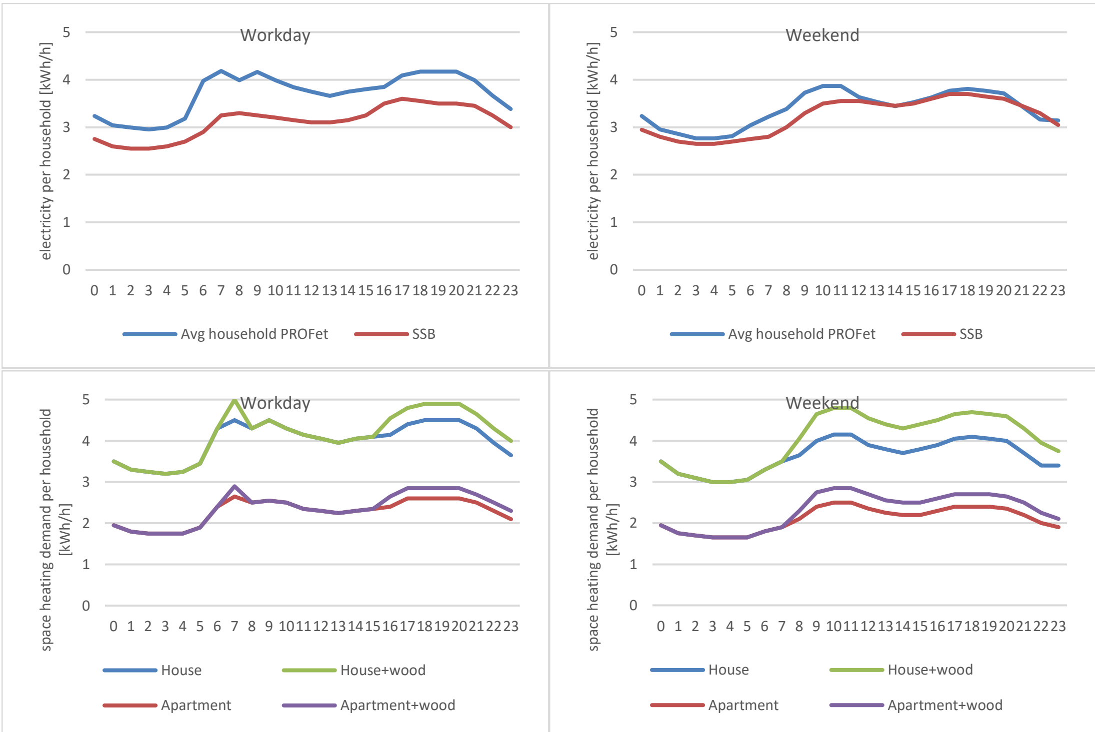


Figure 6. Comparison between the electricity load profiles from Ericson & Halvorsen (2008), SSB report, and PROFet weighted results for an average household (*above*); and the PROFet profiles w/o wood consumption (*bottom*), for the month of January.

The use of wood for space heating in residential buildings is treated differently than all other energy carriers and technologies. Firstly, it is assumed to be used in the form of wood logs in wood stoves. Secondly, it is assumed to be used with a regular daily and hourly pattern, proportional to the actual space heating demand. For this reason, wood stove is not one of the heating technologies subject to investment and operational optimisation in BUILDopt. Rather, the wood consumption pattern is subtracted from the space heating demand from PROFet before passing it to BUILDopt for its optimisation (technically, this is a pre-processing data handling done internally in BUILDopt).

It was therefore necessary to perform a calibration for the wood consumption considering both the total annual consumption and its daily and hourly profile. The total annual consumption was taken from SSB statistic, temperature corrected. For the load profile we used a report from SSB (Ericson & Halvorsen, 2008) that reported the average hourly electricity use from measurements by approximately 4,000 household (unspecified mix of small houses and apartment blocks) from the Vestfold region in year 2006.

Figure 6 shows a comparison between the SSB measured, average load profile and the PROFet profiles (weighted according to the national mix of houses and apartments) with and without the wood consumption, for the month of January.

The daily and hourly calibration so obtained gives an annual total wood consumption in 2020 from PROFet of 6.4 TWh, while SSB statistics for the same year registered 5.9 TWh, which become 6.7 TWh when temperature corrected.

Iteration #0 and Baseline cases

The same method of combining PROFet (with region specific climatic inputs) and REBUILDS was used also to calculate the development of the total energy demand in each Storyline, with hourly profiles for the building stock in 2030 and 2050. The aggregated energy demand so obtained was used as input by IFE-TIMES-Norway, which then internally calculated the corresponding energy use (i.e., without linking to BUILDopt), per each energy carrier. These results are presented in detail in Lien et al. (2022), who also compares it with several other models of energy use in the Norwegian building stock and discussed the calibration against statistics on energy consumption.

The energy use thus obtained formed what can be called the "Iteration #0" of the linking process between TIMES and the other models, see Figure 2. In the two-by-two linking between models, the Baseline case is defined starting from the Iteration #0 of IFE-TIMES-Norway, followed by a run of the other model.

1.6 References

Kauko, H., Delgado, B. M., Backe, S., & Sartori, I. (2023). *Energy efficiency and district heating to reduce future power shortage – Potential scenarios for Norwegian building mass towards 2050*. ZEN Report nr. 47. SINTEF. https://sintef.brage.unit.no/sintef-xmlui/handle/11250/3063886

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Ericson, T. & Halvorsen, B. (2008). *Kortsiktige variasjoner i strømforbruket i alminnelig forsyning – Forbrukskurver basert på timesmålte data fra Skagerak Nett*. Statistisk sentralbyrå (SSB) Rapporter 2008/50. Statistisk sentralbyrå.

2 Objectives and main takeaways

Main objective: To provide knowledge on how end-use flexibility available in the building stock will impact the development of the overall energy system.

Flexbuild has generated knowledge on the end-use flexibility available in the building stock, how to model it and on its potential impact on the future Norwegian energy system. This knowledge has been regularly disseminated both within and outside the project's consortium by means of annual workshops and reports and presentation of results at other events organised by the partners. These activities are reported in Cristin and in the Flexbuild website (https://www.sintef.no/projectweb/flexbuild/), while an overview of the scientific publications is given in chapter 8. All publications, scientific and non-scientific, are also registered in the Norwegian database Cristin. Furthermore, the project has contributed to the education of a PhD at NTNU.

The main takeaways from Flexbuild in relation to the project's secondary objectives are reported in the following sections.

2.1 Objective 1

Develop a robust and novel stochastic modelling framework of the Norwegian energy system capable of evaluating the impacts of end-use flexibility in the energy system.

BUILDopt (Buildings' optimal operation and energy system investment model) is the model that has been developed to enable modelling end-use flexibility in buildings for the needs, purpose and modalities of the Flexbuild project.

IFE-TIMES-Norway was expanded with a stochastic version, which demonstrates that the investments in energy storage depends on the modelling of uncertainty. For most instances, 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.

A methodology was developed for harmonizing a large set of input and structuring the data needed in the soft-linking between the models used in Flexbuild.

For the linking between the building stock (modelled with BUILDopt) and energy system (modelled with IFE-TIMES-Norway) two alternative linking approaches were used: a heuristic flexibility approach based on the goal of flattening a building’s load as much as possible, and a full linking approach based on the goal of minimising a building’s cost. In the latter approach it is necessary to iterate between the models because energy prices and energy demand influences each other, until convergence is achieved, thus significantly increasing the computational effort. In light of the significant differences in the KPI results between the two approaches, we can conclude that the flat profile goal does not represent a good heuristic for the cost minimisation goal. On the other hand, the first iteration of the full linking is a good approximation of the convergent case, suggesting that it is sufficient to limit the analysis to only one iteration. In other words, this means that buildings remain fundamentally price-takers, and even if the energy demand becomes flexible in the entire building stock, this has only a marginal impact on the energy price formation.

Linking the Norwegian energy system (modelled with IFE-TIMES-Norway) to the European power system (modelled with EMPIRE) led to increased utilization of transmission capacities and hence higher export volumes for Norway. As a consequence, increased investments in renewable energy were observed. This effect is more important in storylines with high degree of cross-national interconnection, such as the Nature nation storyline.

2.2 Objective 2

Assess cost-optimal investment and operation of the energy system vs. private building owner and address possible mismatch between the two.

End-use flexibility is a techno-economic investment from an energy system perspective. This is 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 the profits of international electricity trade. A consequence of these mechanisms is that the energy costs of the building sector is lowered.

For the heating technologies, from the buildings viewpoint the cost optimal choice is almost always the heat pump system, while district heating is seldom chosen. This is in contrast with the energy system perspective, where district heating is always a component of the energy mix. The mismatch arises from the fact that energy system models treat the building stock at aggregated level, where district heating contributes covering the base load of the heating demand. At single building level, instead, district heating may only be chosen as stand-alone technology (in the modelling it was not allowed using it for top heating) and is therefore outperformed by a heat pump system because of its SCOP. It shall be reminded that this is simply the outcome of a purely economic life cycle optimisation, with the given modelling inputs and assumptions. It does not reflect other aspects influencing decisions in real life, such as that district heating has a lower investment cost, it is easier to install and is both easier and cheaper to maintain than a heat pump system.

For apartment and commercial buildings, it is cost-optimal to install solar PV up to covering, in average, 50% of the roof area (which was the maximum allowed in the model); while for single family houses the cost-optimal level is somewhat lower.

End-use flexibility and solar PV become a win-win solution because flexibility increases the self-consumption – which is always economically advantageous from the end-user perspective – to the point that it becomes cost-optimal to invest in more solar PV; +13% installed capacity in 2050. It also accelerates the adoption of solar PV, making it a more attractive technology also for houses already in 2030; +58% installed capacity in 2030. At the same time end-use flexibility virtually eliminates the need to install batteries.

2.3 Objective 3

Assess the impacts of different power tariffs on both end-user and the energy system.

The main difference on the end-user was seen between a tariff based purely on an energy fee (*energiledd*) and a tariff that included also a power fee component (*effektledd*). A purely energy fee tariff cannot guarantee a reduction of the peak load; on the contrary, it may lead to an increase since it only has an incentive to shift loads into cheap hours, chiefly at nighttime, without restriction on the peak load other than the physically installed capacity. A tariff with power fee, on the other hand, allows finding the most convenient peak load levels, thus effectively setting a cost-optimal cap on the peak demand from a single building viewpoint.

2.4 Objective 4

Asses the value of end-use flexibility for easing the power grid reinforcement.

From the linking between the building stock (modelled with BUILDopt) and energy system (modelled with IFE-TIMES-Norway):
end-use flexibility can reduce the peak load significantly at single building level, in a wide span depending on the building's characteristics, roughly between 20–50%. At aggregated level the effect is reduced due to the coincidence factor (not all buildings demand their peak at the same time). At the level of NO-market areas, the peak load reduction ranges between

16–20% when looking only at the energy use from buildings, while for the total energy use (incl. industry and transportation) the range goes from 8% reduction to 8% increase.

In some building typology, namely houses and educational buildings, peak export / peak import ratio can become bigger than one. Whether this poses a challenge to the local grid depends on the mix of buildings connected in the same area. Attention should be paid for a residential neighbourhood dominated by single family houses, where a lower average solar PV installation per house may be desirable, lest risking incurring in problems for the local grid.

From the stochastic version of IFE-TIMES-Norway:
End-use flexibility lowers the peak electricity demand, and thus lowers the expansion need of the electricity grid. The largest impact is at the distributional grid level, where the electricity peak, occurring in winter, is lowered from 5 to 11%, depending on spot price region and future storyline. Our analysis indicate that end-use flexibility can replace parts of the expansion needs in the distributional grid. However, this requires incentives that ensures a predictable activation of end-use flexibility when it is needed from an electricity grid perspective.

2.5 Objective 5

Investigate how end-use flexibility may change the role of Norwegian hydropower and investment in wind and solar in the national and European power system.

In Norway, end-use flexibility enables to accelerate the adoption of solar PV and to increase the total capacity installed in the building stock (residential and commercial, excl. industrial and land-use buildings) from 7 to 11 GWp in 2030, and from 17 to 19 GWp in 2050. The corresponding electricity production is then 9 TWh in 2030 and 15 TWh in 2050.

On an aggregated level, only minor changes are seen in the total power production from hydropower and the seasonal storage in the hydropower reservoirs. The main impact of end-use flexibility is seen in a slightly lower power price, caused by a slightly lower total demand for electricity and reduced peak demand. Consequently, the yearly average income for hydropower producers is reduced, but only small to no impacts are seen on the value of flexibility for the hydropower producers.

Total costs in the European power system from 2020 to 2050 can be reduced by about 1% if residential flexibility is optimally scheduled. This flexibility is an alternative of costly lithium batteries. Also, the availability of shifting loads correlates with solar generation, thus residential flexibility may promote the adoption of this technology. Residential flexibility at the European level has limited impact in the development of the Norwegian energy system.

2.6 Need for future work

In the results of Flexbuild, it is assumed that that the electricity generation and electricity demand are always balanced by the energy market, corresponding to that there are no forecast errors in supply or the demand, nor bottlenecks in the grid. Our hypothesis is that this assumption underestimates the model results on the need for flexible solutions in energy system models. A suggestion for further work is to expand the modelling approach of Flexbuild to explicitly modelling distribution grids and ancillary markets. In such case it would also be beneficial to have a model of flexible demand in buildings that is able to generate stochastic, yet statistically representative load profiles rather than profiles from archetype buildings, which are representative at a high enough aggregation level, such as the market areas, but may not sufficiently represent the variability found at lower levels of building stock aggregation.

3 Capacity expansion of the European power system – EMPIRE

Raquel Alonso Pedrero (NTNU)

3.1 EMPIRE model description

The European Model for Power system Investment with Renewable Energy (EMPIRE) (Skar et al., 2014) is deployed in Flexbuild to capture the interaction between the European power system development and the Norwegian energy system. EMPIRE is a long-term investment model that optimises the optimal technology portfolios in Europe, considering the stochastic nature of short-term operations due to non-dispatchable generation. As such, the model finds the cost-optimal energy mix for Europe that guarantees meeting the CO_2 climate targets while ensuring supply-demand balance in the system. In addition to CO_2 and nodal balance constraints, EMPIRE includes technical details such as net transfer capacities (NTCs), up-ramping constraints for generation, capacity investments limitations, storage energy balance, energy asset lifetime and line losses, among others. The model components and structure are illustrated in Figure 7.

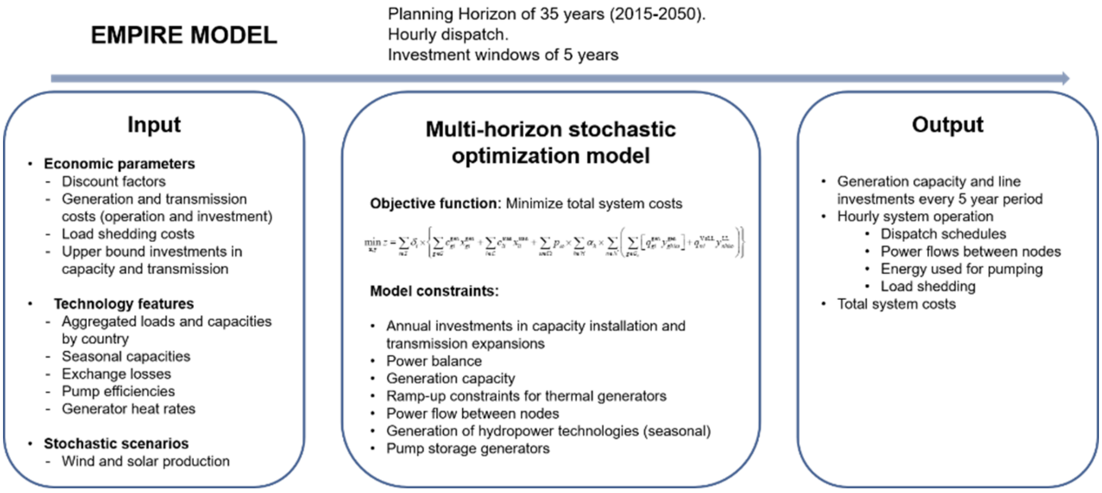

Figure 7. Overview of input, formulation and output of EMPIRE

Long-term models incorporating operations could comprise 8,760 hourly periods for each of the years considered. However, running models with such a time dimension usually lead to such a computational burden that ends up making the problem intractable. An approach to overcome this issue is to consider representative weeks and investment windows that helps to scale down the model. In EMPIRE, each season of the year is represented by one week. Also, in order to ensure that the model invest in enough generation for extreme demand situations (e.g., highest peak load with low RES) two days with extreme characteristics are included. Also, as part of the scaling down, the model considers investment windows of 5 years starting from 2020.

The geographical scope includes thirty-one European countries connected through 55 interconnectors. Each country is represented by a node which aggregates the projected electricity demands and expansion capacities. The only exception is Norway, which is dis-aggregated into five nodes, each for one market area (i.e., NO1, NO2, NO3, NO4 and NO5).

So far, EMPIRE has been used in multiple Norwegian and European projects and peer-reviewed journals (Crespo del Granado et al., 2020; Backe et al., 2021). We refer to Backe et al. (2022), for a detailed description of the model and for getting access to the open-source version.

3.1.1 Residential flexibility module

As part of the FLEBUILD project, EMPIRE was expanded to include demand response (load shifting) from residential appliances which include electric vehicles, air conditioning, dishwashers, washing machine, heat appliances (i.e., electric storage for water and space heating) and refrigeration. Each of their flexibility potential is modelled based on hourly load profiles, participation rates (willingness to offer flexibility services) and time windows (when flexibility may be offered) specific for each European country. The data for these parameters considered was provided by the European research project openENTRANCE.[1]

This expansion allows EMPIRE to account for residential electric load which can be shifted such that it reduces the overall cost of the power system. Alonso Pedrero et al. (2023) presents the details of the mathematical formulation of this extension as well as a comparison between the Energy nation and Nature nation storylines. Results on the impact of residential flexibility in Europe indicate that the total investment and operational cost of the power system can be reduced by around 1% from 2020 to 2055.

In the first and second year of Flexbuild, the goal was to implement carry out the link with TIMES with and without this flexibility expansion. Nevertheless, results showed that the parameters sent from EMPIRE to TIMES did not vary notably with or without accounting for this flexibility in Europe. In consequence, the link EMPIRE – TIMES was carried with the non-extended version. This allowed to put more focus on expanding the link to all four storylines (see chapter 3.3)

3.2 EMPIRE inputs and quantification of storylines

The EMPIRE model requires detailed data input on techno-economical features such as stochastic solar and wind profiles, ramp-up constraints of thermal generators, inter-temporal or seasonal constraints of water availability, among others. Thus, these parameters need to be aligned with the qualitative definition of the storylines. Most of these descriptions focused on the development of Norway, omitting the rest of Europe. To be aligned with the rest of the project, the parameters that apply to the rest of Europe were changed accordingly to the storyline for Norway. This includes, for example, the capital cost of renewable technologies or the adoption of CCS. Parameters specifically tailored to other countries remain stable (e.g., expansion capacity, transmission networks not connecting to Norway, total electricity demand)

Following this decision, the following parameters were considered to be modified to proceed with the TIMES-EMPIRE link:

- ✓ Transmission capacities with and within Norway.
- ✓ Carbon Capture and Storage (CCS) availability in Norway and all Europe.
- ✓ Nuclear expansion in Europe.
- ✓ Solar and battery technology learning curves, affecting their capital costs.
- ✓ Norwegian generation capacities (data provided by TIMES in each iteration).
- ✓ Norwegian electricity demand (data provided TIMES in each iteration).

Table 3 presents an overview how these parameters were considered in each storyline. The assumptions on expansion of transmission capacities were defined for interconnectors between European countries and national transmission lines within Norway. The CCS, nuclear expansion and technology learning curves apply to all Europe, including Norway.

[1] https://openentrance.eu/

Table 3. Overview of the parameters in EMPIRE

		Energy nation	**Nature nation**	**Climate panic**	**Petroleum nation**
Transmission capacities	Europe	Current capacity + 2000 MW	ENTSOE limits	ENTSO-E limits*)	ENTSO-E limits*)
	Norway	20% increase from current levels from 2030	Current levels	20% increase from current levels from 2035	20% increase from current levels from 2030
CCS	Both	No	Yes from 2035	No	Yes from 2035
Solar learning curve	Both	Moderate	High	High	Low
Batteries learning curve	Both	High	High	Low	Low
Nuclear	Both	Yes	Yes	No	Yes
*) Except the transmission capacity between Norway and neighbouring countries which they are kept to current levels					

Energy nation

The Energy Nation storyline is an extreme storyline characterized by high potential for renewable generation and transmission expansions in Norway and Europe. Nuclear expansion is assumed to be an optional technology in fourteen European countries (e.g., France, Bulgaria, Spain, Finland, UK, Romania, Sweden). However, CCS is not commercialized and implemented.

Electricity Demand: The European electricity demand used in Energy nation – and all storylines – is retrieved from the OpenEntrance. In this project, the European energy demand is projected until 2060 based on several storylines, similarly to Flexbuild. Based on their results, the projection of the demand used in Flexbuild was the resulted in a storyline with high reliance on technology and high electrification rates of the energy system (Techno-friendly). Note that this electricity consumption is applied to all storylines to be consistent and ease comparison at the Norwegian level. Hence, the electricity demand is only explained under the Energy Nation section. As can be observed in Figure 8, the largest electricity demand is reached by 2040 and from then forward it remains stable until 2060. The annual electricity demand in these years is almost 6500 TWh, which is around 85% increase from current levels.

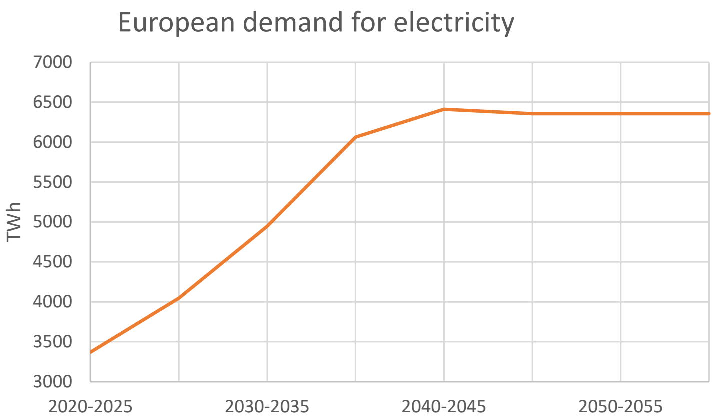

Figure 8. European electricity demand assumed in EMPIRE. Data from OpenEntrance.

Transmission capacities: The transmission capacity expansion in Europe for the Energy nation storyline assumes a total increase capacity of 2000 MW for all interconnectors. Under this assumption, Europe can count with up to 223 TW of international cables for exporting and importing power between countries. This is about 1.23 times higher than current capacity levels. Within Norway, the 20% increase since 2030 implies an increase of national transmission capacity from 10 TW to 12 TW.

Solar and battery costs development: The capital cost development of for utility solar panels and batteries in Europe are assumed to be slightly lower than those in Norway – assumed by TIMES. Figure 9 illustrates the development of prices for the Energy nation storyline.

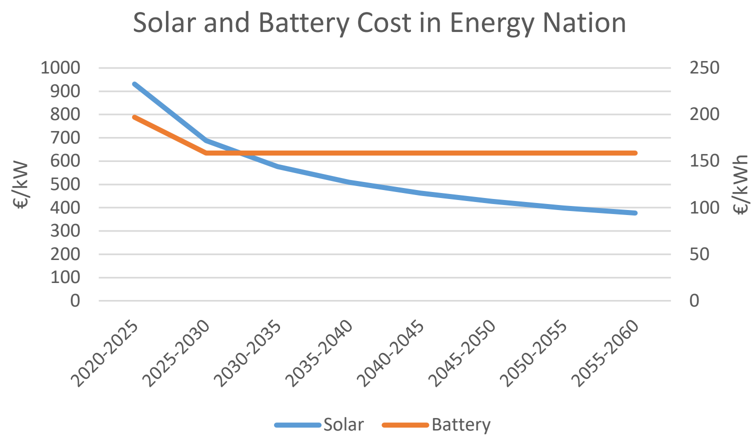

Figure 9. Cost development for utility solar and battery technologies in the Energy nation storyline

Petroleum nation

The storyline implies the ability to implement CCS by 2035 and there is political acceptance for expansion of nuclear technologies. This comes as a reaction to lower learning curves on solar and battery technologies.

Transmission capacities: Cross-border transmission capacity adds up to 220 MW and follows the same potentials as in Climate panic. This reduction is caused by the limitation imposed to the expansions between Norway and the rest of neighbouring countries (i.e., Germany, Netherlands, Denmark, Sweden and Great Britain).

Solar and battery costs development: The learning curves of batteries and solar is the lowest of all storylines, which may significantly affect their adoption.

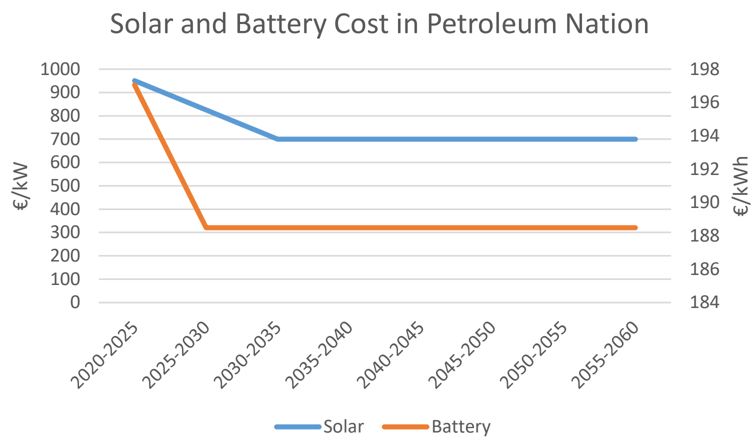

Figure 10. Cost development for utility solar and battery technologies in the Petroleum nation storyline

Nature nation

The Nature nation storyline is characterized by lower electricity demand in Norway, but also, slightly lower transmission and capacity expansion capacities compared to the Energy nation storyline. CCS is commercialized and nuclear expansion is also allowed in fourteen European countries.

Transmission capacities: The transmission capacity following the ENTSO-E roadmap sum up a total of 221 M. Nevertheless, the increase in capacity is not adopted in all Europe as in the previous case.

Cost of capital of utility solar and battery: While the battery cost in this storyline follows the same development as in Energy nation, the solar cost is reduced by 30% by 2050.

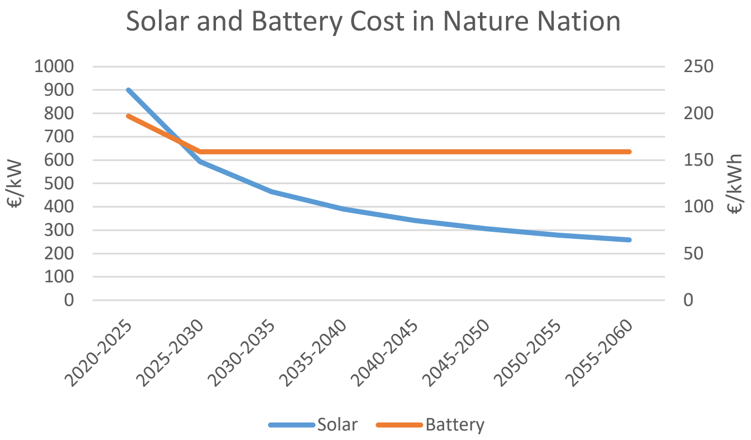

Figure 11. Cost development for utility solar and battery technologies in the Nature nation storyline

Climate panic

This storyline represents a extreme case where the capabilities for increasing transmission capacities in Norway and the potential for generation capacity is reduced. In all Europe, CCS technology and nuclear expansion is not happening. Also, in the Norwegian context, the energy demand is not as high as previous storylines.

Transmission capacities: Cross-border transmission capacity adds up to 220 MW, about 1 MW lower than in Nature Nation.

Solar and battery costs development: The technology learning curve of the solar technology in the Climate panic storyline is slightly higher than the assumed in the Energy nation. Contrarily, the cost development of batteries is not as optimistic as in the other two previous storylines.

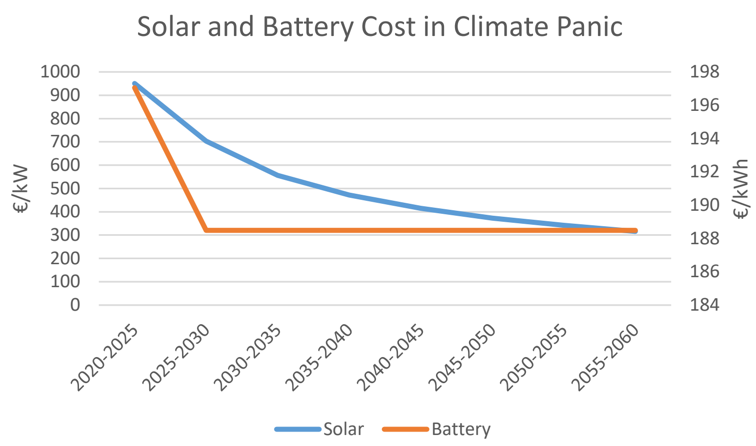

Figure 12. Cost development for utility solar and battery technologies in the Climate panic storyline

3.3 Linking EMPIRE with IFE-TIMES-Norway

The linking between EMPIRE and TIMES covered the non-flexible case, where energy flexibility in European households was not considered. As previously stated, considering the flexibility module in EMPIRE had a limited effect on market prices and trade volumes. Hence, the objective was on expanding the non-flexible case to the four storylines instead.

Energy use in buildings	2020	2030				2050			
		Petroleum	Energy	Nature	Climate panic	Petroleum	Energy	Nature	Climate panic
Non-flexible	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
Flexible	-	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible

Linking TIMES - EMPIRE
TIMES in deterministic mode

Figure 13. Matrix of combinations explored in the linking between TIMES and EMPIRE

Moreover, the soft-linking process of TIMES-EMPIRE is illustrated in Figure 14. First, the resulting Norwegian energy mix and electricity demands are sent from TIMES to EMPIRE. This data is delivered for each market zone and each investment period (five-year investment windows from 2020 to 2055). Then, these are set as fixed parameters in EMPIRE which optimises the generation portfolio of the rest of Europe considering the fixed Norwegian energy mix and demand. The solution of EMPIRE includes the market electricity prices and traded volumes in neighbouring countries (i.e., Great Britain, The Netherlands, Denmark, Germany, and Sweden) which are sent to TIMES. Then TIMES will adjust the energy mix and electricity demand according to the new prices and trades defined by EMPIRE.

This procedure is repeated until it leads to an equilibrium point, as each models' results diverge less and less with each iteration. The models are considered to be in equilibrium based on convergence criteria. When these criteria are met, the iteration stops. More details about the linking process are presented in chapter 5.3.

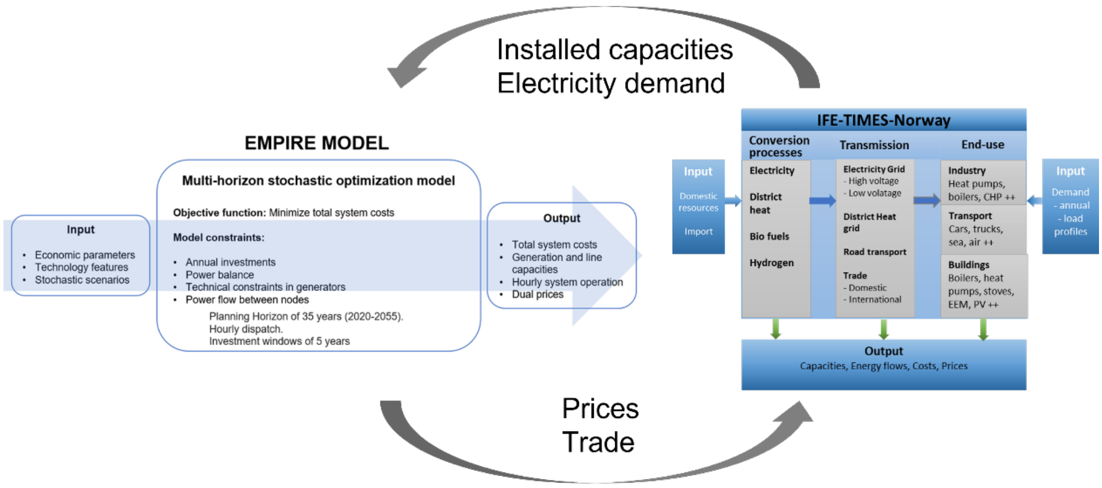

Figure 14. Bi-directional linking between IFE-TIMES-Norway and EMPIRE

3.4 EMPIRE Results and discussion

In the following section, the results for EMPIRE after completing the linking with TIMES – when the convergence criteria are met – are presented for each of the storylines. Further discussion on how the Norwegian energy system got affected by the European power system can be found in chapter 5.3.2.

3.4.1 Results at the European level

Table 4 presents the European results for each storyline by the year 2050. First, it can be observed that while the Energy nation, Climate panic and Petroleum nation storylines present similar system costs, Nature nation has significant lower cost. Specifically, this storyline has 11% lower cost than the Energy nation case. This may be expected given the favourable prices for solar and battery technologies as well as the possibility of introducing Nuclear and CCS technologies.

Table 4. Expected results for all Europe by 2050 after the completing the iterations with TIMES

	Energy nation	Nature nation	Climate panic	Petroleum nation
Long-term				
Total system cost (10^{12} €)	3.78	3.37	3.75	3.73
Transmission Capacity (GW)	216	219	219	212
Onshore wind Capacity (GW)	957	908	1784	1984
Offshore wind Capacity (GW)	138	73	647	761
Solar Capacity (GW)	2325	2545	2552	1606
Hydro Capacity (GW)	212	212	590	595
Li-Ion BESS Capacity (GW)	1107	1208	744	292
Gas Capacity (GW)	304	493	77	864
Nuclear Capacity (GW)	88	71	0	491
Coal Capacity (GW)	0	70	0	9
Operational				
RES Production*) (TWh)	6093	5418	6391	5633
RES Curtailment (TWh)	625	637	962	389
Average electricity price (€/MWh)	94.5	87.74	108	110
*) Including Wave, Geothermal, Hydro, Bio energy, Wind, Solar and Waste				

Additionally, Nature nation is characterized by high integration of solar and large investments in flexible technologies like Li-Ion storage and CCS. In particular, CCS permits the system to still rely on fuel-based technologies like coal and gas, which are characterized by low operational cost and high ramp up capacities. Although capacity in wind is noticeable lower than in the rest of storylines, the combination of technologies allows for a cost-effective transition pathway.

In contrast, the Petroleum nation storyline relies more on wind technologies than on solar technologies. This is explained by the low technology curves for solar assumed in for this storyline. Also, higher investments in wind reduces the need to invest in flexible technologies like Li-Ion batteries, although the system still invests in CCS for keep using gas-fuelled power plants. Also, there is a significant increase of hydro, particularly hydro-pump storage.

The Climate panic presents high investments in wind, hydro and solar promoted by their low costs of capital. In this case, there is no possibility to invest in CCS or nuclear technologies, which leads the system to compensate by massively expanding renewables and climate friendly flexible technologies like Li-ion storage and hydro pump storage. Consequently, we observe higher levels of RES production and curtailment than in other storylines. Interestingly and despite the restrictions on nuclear and CCS, the total cost of the system is comparable to the Energy nation and Petroleum nation storylines. Nonetheless, the average electricity price is about 20 and 13 €/MWh higher than in Energy nation and Nature nations storylines, respectively.

Lastly, the Energy nation storyline presents considerably high levels of renewables, although not at the level of Climate panic. Regarding the nuclear and gas, this storyline keeps both operative, despite not having CCS available. However, to increase the flexibility, Europe invests in utility scale batteries. Li-Ion batteries are prioritized over pump hydro due to the high learning curves assumed for this technology. Interestingly, despite this storyline still requiring flexibility, it does not lead to average electricity prices as high as in the Climate panic and Petroleum nation storylines.

In general, we observe similar transmission capacities in all storylines. Only Petroleum nation has lower investments in international cables as there is lower capacity of non-dispatchable technologies.

The development of the generation capacity in the European power system throughout time is presented in Figure 15. It is noticeable that in Petroleum nation, the total generation capacity is considerably below 4000 GW, whereas the rest of the storylines are above this number. It can be observed that the gas is kept in all storylines, However, in the Petroleum nation gas is utilised for baseload generation, while in the others gas is mostly used for flexibility provision. Moreover, from 2040 onwards, the Energy nation and Climate panic storylines adopt bio-energy to provide flexibility. Finally, some common feature in all storylines is a fast integration of solar panels between 2030 and 2040 which tends to decrease after that year. This is expected given that electricity demand stabilizes around 2040–2045.

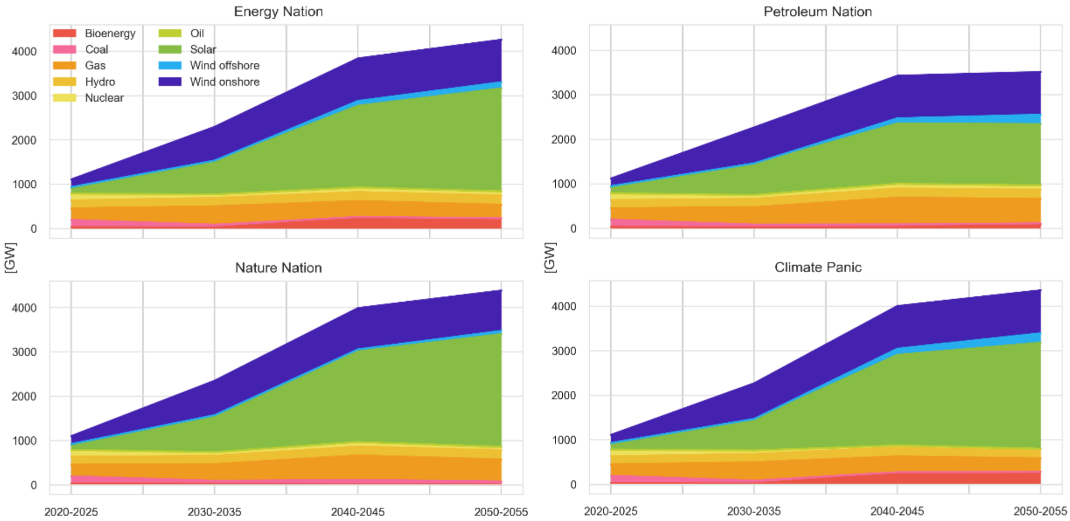

Figure 15. Development of generation capacity in the four storylines

3.4.2 Prices and capacity expansion in neighbouring countries

Given that the focus of Flexbuild is the effect of the European power system on the Norwegian energy system and vice versa, the following section presents the prices of neighbouring countries. Specifically, these are Sweden, Germany, Denmark, the Netherlands, and Great Britain.

Table 5. Annual average and standard deviation (in brackets) of the electricity prices of neighbouring countries by 2050.

	Energy nation [€/MWh]	Nature nation [€/MWh]	Climate panic [€/MWh]	Petroleum nation [€/MWh]
Sweden	81 (48)	72 (40)	84 (50)	90 (43)
Germany	90 (54)	80 (50)	99 (60)	97 (44)
Netherlands	93 (56)	84 (48)	106 (64)	100 (44)
Denmark	92 (54)	80 (43)	98 (55)	98 (43)
Great Britain	84 (48)	81 (47)	93 (54)	93 (47)

Average prices in the Climate panic and Petroleum nation storylines are particularly high. In the case of Petroleum nation, this is the result of non-variable technologies, with higher operational costs, contributing to covering a large share of the baseload. In the Climate panic storyline, high average electricity prices are derived from high variability in prices. The variability, in this case, is caused by a lack of flexibility options.

On the contrary, Nature nation, which adopts a wider range of flexible technologies, has the lowest average and variable prices of all storylines. Slightly higher prices can be observed in Energy nation, which cannot rely on cheaper technologies without CCS.

With respect to neighbouring countries, Sweden presents notably lower average prices than the rest of countries. As a country with a significant interconnection with Norway, the trading between these two countries helps to lower the electricity prices. Contrarily, the Netherlands have the highest average prices. These differences in prices have notable consequences for how the Norwegian energy system implements its trading with these countries. Detailed discussion on their effect is presented in Chapter 5.3.

3.5 References

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4 Activation of end-use flexibility in buildings – BUILDopt

Igor Sartori, Marius Bagle (SINTEF)

A large amount of flexibility is intrinsically available in the buildings' thermal mass and existing equipment, such as hot water storage and the charging of EV (which happens for more than 90% in connection to buildings; cf. NVE (2016)). What is lacking for an effective, large-scale exploitation of this latent end-use flexibility are automated control applications for the activation of these flexibility sources.

In the Flexbuild project the entire building stock is modelled with the ability to optimally activate its flexibility sources. From the buildings viewpoint this is the equivalent of imagining all buildings being equipped with automation and control system and deploying smart controls. From the energy system viewpoint this is the equivalent of imagining demand response available on a very large scale, virtually from the entire building stock. Furthermore, the linking between the energy system and the building stock modelled in Flexbuild resembles the mechanism of an ideal market clearing, where there is perfect forecast on energy demand and, through the linking iterations, repeated adjustments that fully capture the interdependency between energy supply, demand and prices. In other words, what is modelled in Flexbuild is the optimal exploitation of end-use flexibility from a holistic energy system perspective. At least, this is true for the "full linking" between BUILDopt and IFE-TIMES-Norway, described in chapter 4.3.2.

The focus in Flexbuild is on the effects of end-use flexibility, not on the characteristics of flexibility itself. For this purpose, it is important to model end-use flexibility as:

- activated in response to external signals in a predictive way (not reactive)
- used to schedule optimal building operation in pursue of different goals
- suitable for aggregators operating in day-ahead/intraday market

In other words, the end-use flexibility modelled in Flexbuild could also be called *dispatchable demand*.

4.1 BUILDopt Model description

BUILDopt (Buildings' optimal operation and energy system investment model) is the model that has been developed to enable modelling end-use flexibility for the needs, purpose and modalities of the Flexbuild project. However, BUILDopt has been co-developed within other projects too, namely the FME-ZEN centre[2] and internal funding at SINTEF Community.

BUILDopt performs both an operational and investment cost optimisation on the energy system of a single building. The cost is defined either as the global cost in a 30-years lifecycle, incl. investment in building technologies, or as operational cost. The operational cost, in turn, is composed of grid tariff (usually with a power charge component, *effektledd* in Norwegian) and spot-price.

The starting point is given by typical (non-flexible) energy demand load profiles taken from PROFet, based on a statistical analysis of hourly measurements from several buildings classified in different categories. The flexibility sources are modelled with internal variables (the model's *states*) such as indoor temperature, tank temperature, battery state of charge, and are subject to boundary conditions and constraints that represent user comfort and user needs, such as a comfort band for indoor temperature, a lower bound for the hot water tank's temperature, and the charging of electric vehicles within the connection time and capacity.

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[2] Forskningssenter for miljøvennligenergi (FME) Zero Emission Neighbourhoods in Smart Cities (ZEN), www.fmezen.no

Since BUILDopt operates at the level of single building (archetypes), the aggregation is done using the building stock model RE-BUILDS.

4.1.1 Typical load profiles and building stock aggregation

The main features of both PROFet and RE-BUILDS are summarized in the following sections, just for what is necessary to understand the results presented later in the chapter. For more details on the models refer to Flexbuild Annual Report 2 (chapter 2.3 and Appendix B for PROFet, chapter 3.1 and Appendix C for RE-BUILDS, Sartori et al., 2022a).

Typical load profiles – PROFet

PROFet (energy demand load profile estimator) is a model that can estimate average hourly load profiles for both thermal loads (space heating (SH), heating of domestic hot water (DHW)) and electric specific loads (EL), based solely on outdoor temperatures and building area. The temperature dependency has been extracted from a database, trEASURE, of monitored buildings, mostly connected to district heating. Because of this, the thermal loads estimated by PROFet represent the gross heating need (*brutto varmebehov*) of a building, inclusive of all system losses. For the thermal and electric specific loads PROFet distinguishes between 11 building categories, each given with three levels of energy efficiency (Regular, Efficient, Very efficient). For an example of the models' results, see Figure 16.

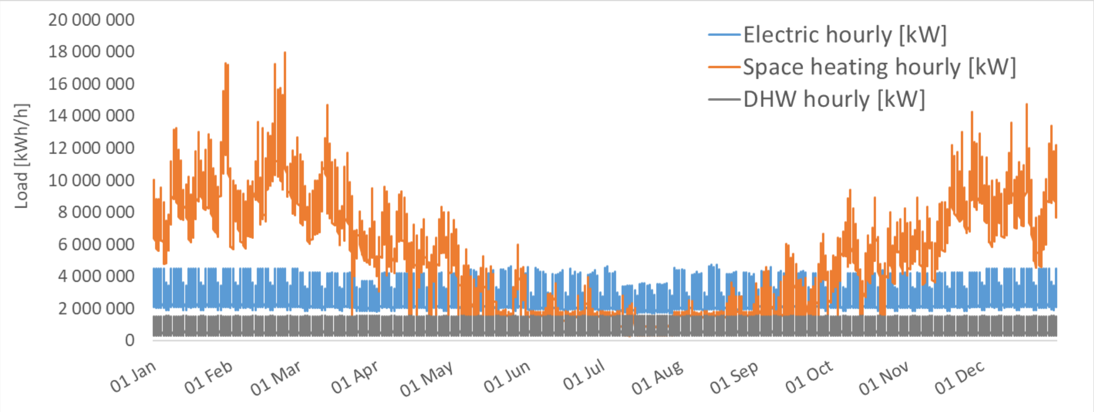

Figure 16. Load profiles generated by PROFet for the entire Norwegian building stock in 2020, using the standard reference Oslo climate from SN-NSPEK 3031 (2021).

An alternative improved statistical method – namely, the mixed effect model – for defining typical load profiles has been proposed, see Palmer Real et al. (2021), Leprince et al. (2022) and Palmer Real et al. (2022). However, this method has not (yet) been implemented in PROFet, so it has not been used in the modelling.

Building stock aggregation – RE-BUILDS

The RE-BUILDS model is used to simulate the building stock development from 2020 to 2050 according to an assumed development defined for the input parameters in each of the four storylines. The underlying concept in RE-BUILDS is the changing population size and the population's demand for buildings of various types. The model is slightly different for the residential and commercial building stocks, as there is more statistics available for the historical development of the dwelling stock (residential buildings) than for the service building stock. However, both parts of the model simulate the stock dynamics and development over time in terms of stock size and composition of types, cohorts, and renovation states. Compared to its detailed description as given in Sandberg et al. (2021), the model has been adapted in Flexbuild for being used in combination with PROFet and BUILDopt, see Flexbuild Annual Report 2 (Sartori *et al.*, 2022a). Figure 17 gives an overview of the model's structure to represent the Norwegian building stock in any given year.

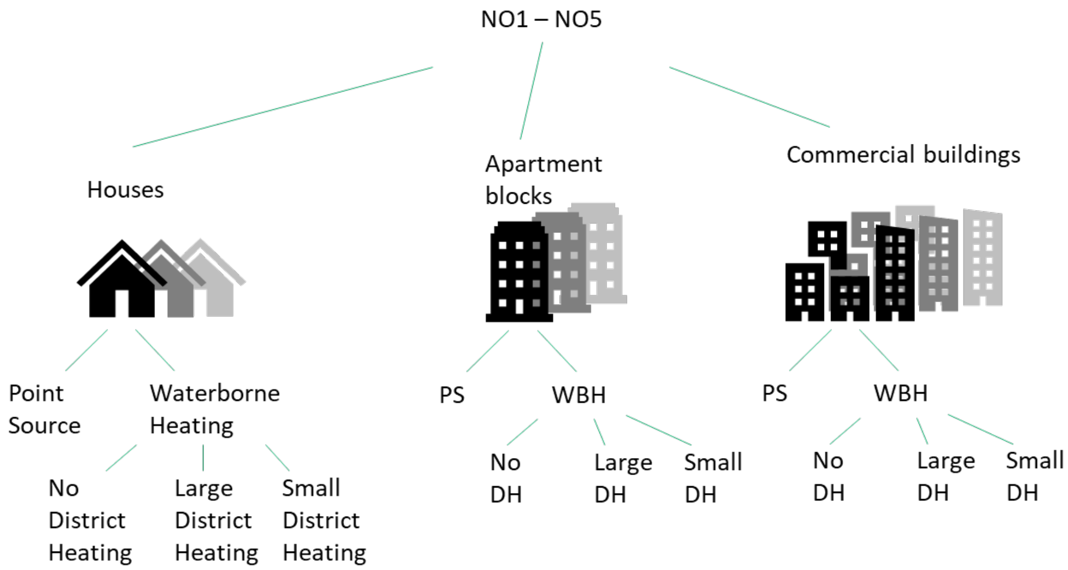

Figure 17. Representation of the Norwegian building stock in RE-BUILDS, in any given year, as used in Flexbuild. For each geographical/market area (NO1–NO5) the three main building categories are shown (House, Apartment, Commercial) with the three efficiency levels (shades of grey in the icons), the presence, or lack thereof, of a waterborne heating system, and for those with it the possibility, or lack thereof, to connect to DH depending on which sub-area the building is located.

4.1.2 Flexibility sources and operational optimisation

The activation of flexibility sources (described below) depends on the driver and the goal that is pursued (Sartori et al., 2022b). The flexibility driver considered here is a combination of energy price and grid tariff, applicable to either electricity or district heating. The energy prices are received from TIMES, while the grid tariff is a Peak Power Monthly (PPM). This is a grid tariff that, on top of a fix component and an energy-proportional component (*energiledd*), also has a peak power, or peak load component (*effektledd*). This component sets a penalty for hourly energy demand that exceed a reference (subscription) value that, in this case, is different each month; see more details in chapter 4.2.1. With a PPM tariff the optimizer finds the most convenient level for the monthly peak power values.

The flexibility goals considered are Cost minimization and Flat profile, discussed also in chapter 4.3. Minimization of (energy use related) cost is intended from the end-user's view-point. The Flat profile goal pursues a flattening of the load profile, as much as possible while limiting the associated energy losses. Thus, the Flat profile will, at the cost of some energy loss, not only smoothens the high peaks – in a similar fashion as a Cost minimization with PPM tariff – but also avoid "deep valleys" and sudden changes in the energy demand. These features might be desirable at an aggregated scale, for a smooth operation of a grid or energy supply system.

A mathematical description of the sub-models (or modules) of BUILDopt is given in the Appendix F of the Flexbuild Annual Report 2 (Sartori et al., 2022a). Further details on the modules development and testing are given in Delgado et al. (2022a; 2022b; 2023a; 2023b) and in Bagle et al. (2020; 2022).

Figure 18 shows a schematic of the interconnections between the modules that compose BUILDopt. The energy flow (represented by the thick blue lines) goes from left to right, while the calculation flow goes the opposite direction, from right to left. The calculations start with defining the Typical demand profiles that must be satisfied, obtained from PROFet, and continue through a series of flexibility options until obtaining the Flexible load profiles on the energy carriers that supply the building.

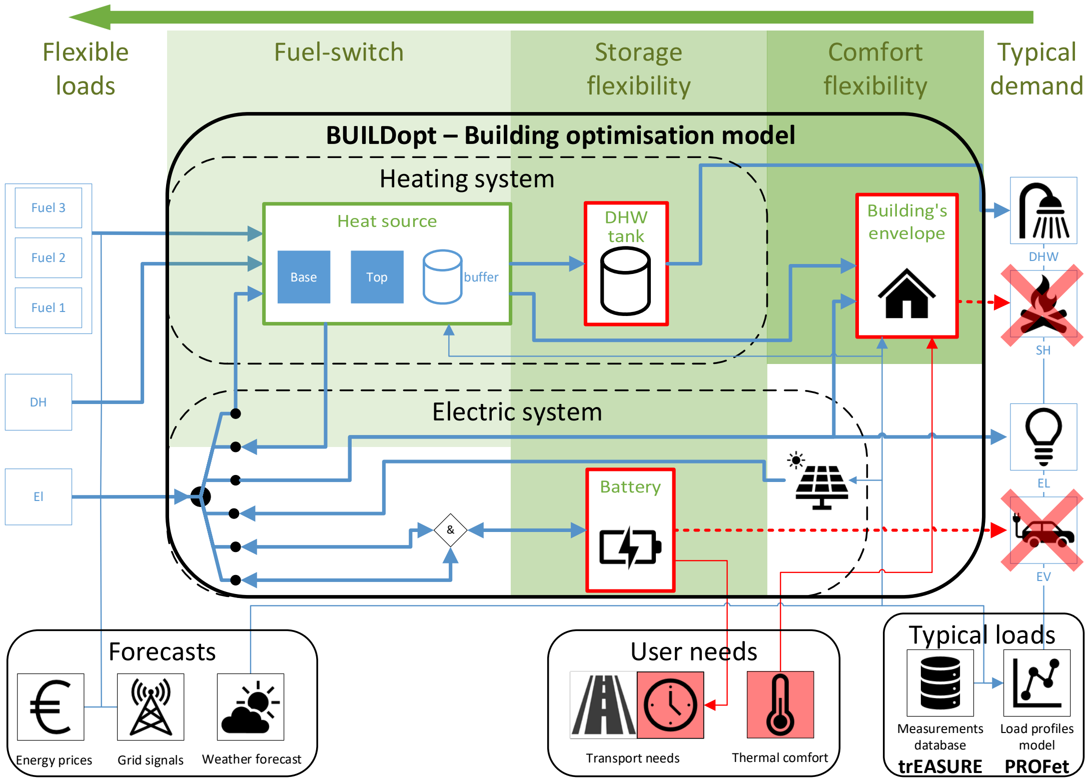

Figure 18. Schematic of the BUILDopt model showing the interconnections between the modules. Thick blue lines represent energy flows, thin ones information flows. Red boxes highlight the flexibility sources while red lines represent the possibility to deviate from typical profiles as long as user needs are satisfied.

The first flexibility option in the schematic is called "Comfort flexibility" because it is achieved by allowing the indoor temperature to fluctuate within a predefined comfort band. In this way the thermal comfort remains satisfied while the energy use deviates from the typical demand (that is the meaning of the red cross over the icon representing the Space Heating demand). This is activated by means of charging and discharging thermal energy in the building's envelope and exploiting its slow thermal inertia. Thus, by definition, this flexibility source is available in every building.

The second flexibility option is called "Storage flexibility" because it is achieved by controlling the charge and discharge of some physical storage component, whether thermal or electric storage. One thermal storage component, the DHW tank[3], is always present, while two electric storage components are possible: Electric Vehicles (EV) and stationary Batteries. EV are gradually introduced according to the storyline specifications, while stationary batteries are an investment option. The DHW tank can be preheated, so that its energy use can follow a different profile than that of DHW demand, which is always met without alteration. The same can be said for the electric battery, while the EV charging can be modulated but only within some constraints that safeguard the transport needs of the users.

The EV module is described in Delgado et al. (2022b) and the data used here as input for it are taken from measurement campaigns over prolonged periods that collected data from tens of thousands of charging sessions from several locations in Norway (Sørensen et al., 2021; 2023). Figure 19 shows the typical charging profiles and average connected capacity per EV unit. In the case of Residential buildings (House and Apartments) the EV unit is a single user

[3] A heating system often has a buffer, represented by the tank inside the Heat source box in Figure 19, which used to allow the base unit working at its nominal conditions also at part load. However, its effect is short term and therefore already included in the hourly profile (from PROFet).

(or car), while for Commercial buildings the EV unit is a single charging point, see further details in chapter 4.2.2.

The charging profile is the average of the measurements, per EV unit, and is divided into inflexible, for the charging events that did not have at least one idle hour during the time the car was connected, and flexible, for all the others. The connected capacity indicates how much charging capacity is available, per EV unit, in average for every hour. In Residential buildings, EVs are mostly unavailable during daytime because people drive the car during daytime (mostly), thus disconnecting it from the charger; while when they come back home the car follows a plug-and-charge pattern until the battery is full again and the consumption drops to virtually zero in the night (when the connection capacity is at its maximum). In Commercial buildings, on the contrary, EVs get connected to the charging point during daytime, again following a plug-and-charge pattern, while the connection capacity is virtually zero at night and in the weekends.

The difference between the average connected capacity and the average charging profile express how much flexibility the EV unit has to offer. Therefore, in Residential buildings the flexibility potential is highest at night (good for postponing charging to cheaper hours) while in Commercial buildings it is highest in daytime (good for self-consumption of electricity from solar PV).

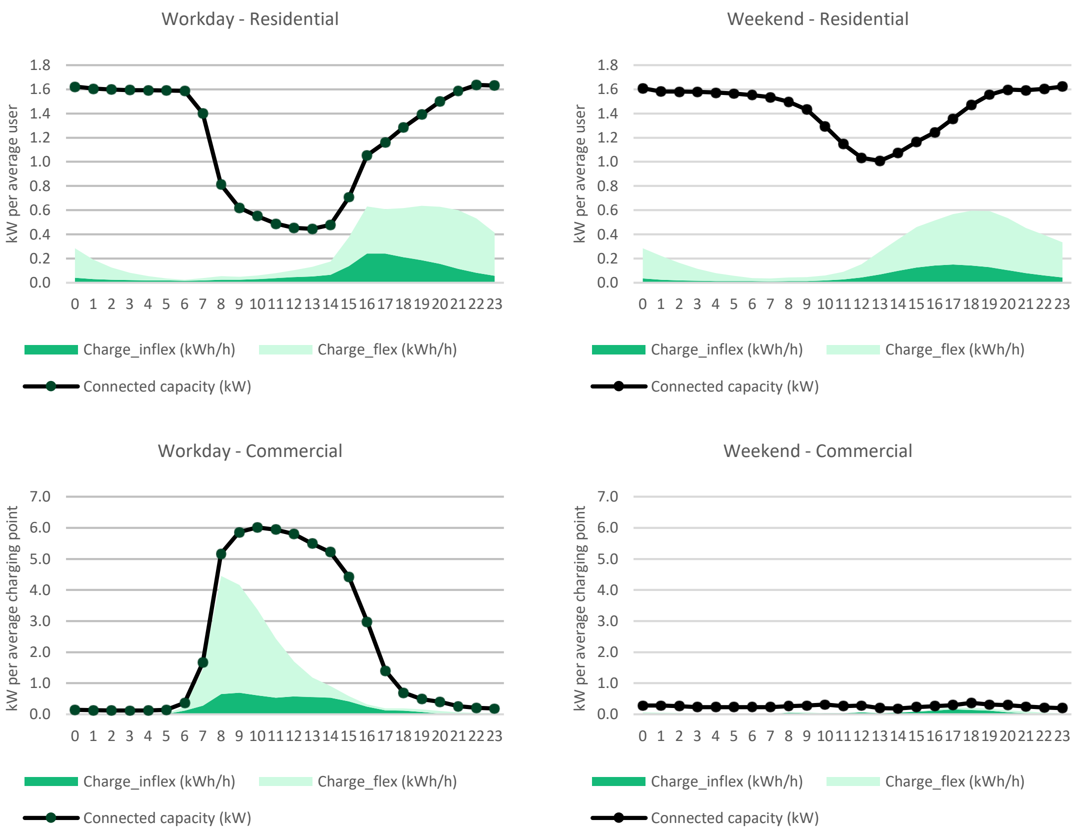

Figure 19. Electric vehicle (EV) typical charging profiles and connected capacity in Residential (*top*) and Commercial (*bottom*) buildings; for average workdays (*left*) and weekend days (*right*)

A further flexibility option would be provided by fuel-switching. However, this option is not really considered in this report because it never results that the heating system of a building uses multiple energy carriers, for different reasons. District heating is not allowed to be used for top heating – by modelling choice, on indication from the industrial partners: When DH is chosen it must cover the entire heating demand. In theory, an electric boiler could be the top heating unit for a biomass boiler (or vice versa) but this combination never happens to be chosen in the investment optimisation (and building-scale combined heat and power systems, CHP, were not considered at all in this project). Any form of fossil fuel use – already marginal in Norway in 2020, see Figure 5 – is not a modelling option for 2030 and 2050. Thus, each single (archetype) building turns out either having district heating or being all-electric, with a heat pump as base heating unit, topped up by either an electric boiler or electric panels.

It should be noted that all forms of flexibility come with associated energy losses.[4] For the battery this is because of inherent charge-discharge inefficiencies (the cycle losses). For the envelope and the DHW tank this is because only upward thermal flexibility is considered. This means that the temperature in the building and/or the tank is only allowed to become higher, never lower, than it is in the baseline. It is possible to preheat a building or tank, so that at a later time the energy use will be lower than in the baseline, but not the internal temperature in the module. This guarantees that the flexibility activation never comes to the detriment of user comfort. On the other hand, this causes additional heat losses and so, ultimately, a higher energy use.

4.1.3 Investment optimisation

BUILDopt can also optimise the investment in the energy system of a building. This means the choice of the heating technology as well as possible investments in solar PV and battery system.

Initially in the project it had been considered adopting the same optimisation method implemented also in the "stochastic mode" of IFE-TIMES-Norway; namely a 2-stages optimisation. This method consists in creating stochastic short-term 'scenarios' by arranging sets of historic data on weather, energy prices and energy demand, thus maintaining the correlation between these inputs. These short-term scenarios represent stage 2 of the optimisation problem, while stage 1 is given by the long-term investment optimisation, i.e., choosing when it is the optimal time to invest in a given technology and how much. Considering a set of stochastic operational scenarios, rather than a single deterministic one, leads to more robust investment strategies. This is explained in more detail in chapter 5.1.

However, closer considerations of the very nature of the problems at hand justified abandoning this solution in favour of a simpler and more effective one. For this reason, the original development of the model (called BUTLER) has been abandoned in favour of the present one, named BUILDopt.

The energy system of an entire country or region is large, complex and evolves slowly. Thus, a model must take into consideration existing infrastructures and assets, their expected time of retirement, and the most suitable timing and sizing for capacity expansion of several competing energy sources and technologies. In other words, investment decisions are modelled with "system memory" over several years of simulation. On the other hand, the many variables to be considered for the operation of such a large system makes it computationally untreatable to run simulations over a full year, especially when several years shall be simulated. That is why energy system models typically operate with representative days (or weeks). From here the need to introduce some stochasticity in the inputs, to avoid too rigidly deterministic outcomes.

The energy system of a single building, in comparison, is small, simple and short lived. And for the most part, single building models have stochasticity and robustness already embedded in the inputs (see next paragraph). At single building level it is realistic to consider only limited combinations of heating technologies, typically a base heating unit and eventually a peak heating unit, but no more. The lifetime of technologies at the building level is shorter than at

[4] With the exception of EV charging, since it is only a modulation of a unidirectional flow, the EV is only charged, never discharged.

the energy system level, typically around 10–15 years for heating technologies and up to 20–30 years for solar PV. While investment optimisation may be done considering the global cost over a 30-years lifecycle, it is common to make the investment "at once", at the year of simulation, without considering any "system memory" since there is no significant infrastructure to consider. The exception may be the presence of, or the need to introduce a waterborne heating system. But this is a parameter that is given exogenously to the model, being storyline dependent – likewise the rate of energy efficient renovation of the building envelope – rather than a variable to be endogenously treated in the model.

In the first place, building models focus on simulating the operation of the building for a full year to ensure the indoor comfort is always met under a variety of climatic conditions and to calculate the corresponding cost. Such climate inputs are constructed as a statistical composite of historic weather data, with the purpose of reproducing at once an average year, in terms of total annual energy demand, which include extreme conditions, in terms of coldest and warmest days, that define design conditions for proper dimensioning of heating and cooling systems. Thus, for what concerns climatic variables, the stochasticity is already embedded in the inputs.

For what concerns heating technologies, correlation between weather variables and energy prices is not crucial. Indeed, while the choice of a heating technology is influenced by the expected energy prices, especially for competing energy carriers, its dimensioning is hardly affected by it. The dimensioning is dictated, on one hand, by the need to satisfy demand under given design conditions, e.g., coldest day to be expected. On the other hand, there are techno-economic considerations of standard engineering praxis, e.g., to dimension the base heating unit (more expensive to invest in, cheaper to run, such as a heat pump) to cover only a part of the peak load. In this way both the investment and the operational costs are reduced because the unit can operate most of the time close to its nominal capacity, improving its performance and prolonging its lifetime. A peak heating unit (cheaper to invest in, more expensive to run, such as an electric boiler) takes care of covering the remaining load for the relatively few hours when that is necessary.

It is also unnecessary to consider hourly stochasticity or variability in the energy prices, which may imply different operational patterns in case of flexibility activation (in response to the price signal). This is because the dimensioning of heating technologies cannot be made reliant on presumed smart control strategies; it is the user comfort that is at stake, not merely a cost optimisation.

Different is the case for dimensioning a solar PV and battery system. This is a pure cost optimisation problem, so that both climate, energy prices and the overall operational control of the building should be considered.

In conclusion, it was decided that there was no need to develop a full 2-stage stochastic optimisation in BUILDopt. The very nature of the problem at hand does not justify the additional complexity, which under the given boundary conditions would have given substantially the same results. The investment optimisation in BUILDopt is implemented as follows.

The investment choices in BUILDopt are based on a global cost optimisation over a lifecycle of 30 years, where the operational costs are derived from a full year simulation, based on regional, statistically representative climatic conditions. For the heating technology the investment choice is made only in the Baseline case and such choice is inherited in the Flexible case. In this way the difference between Baseline and Flexible cases is solely due to differences in how the flexibility sources are controlled/activated and not on physical difference of what components are available in the building stock.

In the Full linking simulations (see chapter 4.3) the investment choice for the solar PV and battery system can be repeated in the Flexible case. The purpose, in this case, is rather the opposite: to test if and how much solar PV and/or batteries should be installed (or avoid installing) when the other flexibility sources are activated in the first place. The dual approach is justified by the fact that while a heating system is a must in a building, solar PV and batteries are optional. The comparison between Flexible and Baseline cases (within the same storyline and simulation year) will then reveal two important outcomes:

1. How much flexibility is possible to harvest by means of pure operational optimisation, i.e., smart controls, based on the same hardware available in the building stock.
2. How much the activation of existing flexibility source influences the installation of solar PV and batteries in the building stock.

4.2 BUILDopt inputs and quantification of storylines

4.2.1 Common to all storylines

Archetype buildings

All simulations in BUILDopt are based on archetype buildings that represent the average properties of a segment in the building stock. The results from single building archetypes are then aggregated at the level of climatic/market areas and up to the total national level, using the information from RE-BUILDS, see chapter 1.5 and 4.1.1.

This also means that the model works with the 11 building categories defined in PROFet, see chapter 4.1.1. However, the 9 categories representing commercial buildings are here summarized in the average Commercial building archetype. This is not an archetype used in the simulations per se, but it is a convenient way to present the information in a more concise way. Furthermore, some input such as technologies cost, grid tariff and Electric Vehicle properties are defined in the same way for all commercial buildings.

Table 6 shows the main geometric properties of the archetypes. These are important because they influence the dimensioning of both the heating system and the PV and battery system. In addition, also the DHW tank properties are given in this table since they are common to all storylines.

Table 6. Main properties of the archetype buildings' geometry and DHW tank.

	Geometry						DHW tank	
	Floor area (BRA) per dwelling [m^2]	Dwellings per building [#]	Floor area (BRA) per building [m^2]	BRA/BTA*) ratio [#]	nr. floors [#]	Roof area [m^2]	Size [m^3]	Coil power [kW]
House	128	1.3	160	0.85	2.1	90	0.3	2.5
Apartment	70	19	1 352	1.00	4.2	322	2.6	33
Commercial			837	1.00	1.6	523	0.8	13

*) BRA (*Bruksareal*) = utility floor area; BTA (*Bruttoareal*) = gross floor area.

Table 7 shows some main properties of the archetype buildings' envelope as well as the annual energy demand that results when applying the reference Oslo climate to the archetypes. None of these values is a direct input to the model but they are helpful to give a sense of differences between the three efficiency levels.

Table 7. Building envelope main properties and annual energy demand (in the reference Oslo climate from SN-NSPEK 3031) of the building archetypes.

Building type	*Energy efficiency level*	Building envelope properties: Thermal mass (from NS 3031)	H-value [W/m^{2}K]	**Annual energy demand [kWh/m^{2}y]**: Space Heating	DHW	El. specific	Total
House	Regular	Light	1.16	134	20	40	194
	Efficient		0.70	70	20	40	130
	Very eff.		0.48	53	20	40	113
Apartment	Regular	Heavy	0.92	128	40	40	209
	Efficient		0.56	68	40	40	148
	Very eff.		0.43	51	40	40	131
Commercial	Regular	Heavy	0.92	113	20	137	270
	Efficient		0.51	57	20	137	214
	Very eff.		0.40	36	20	122	179

Table 8 shows which heating technologies are available in each stock segment during the investment optimisation process. Obviously, all technologies requiring a waterborne heating system are not available for buildings with Point Source (PS) heating. Symmetrically, it was chosen to make electric panel heaters (PH) not available in buildings with waterborne heating (WBH). As already mentioned, District Heating (DH) is only available in two out of three sub-areas and is never an option for the House, see chapter 1.5. On the other hand, air-to-air heat pumps (A2A) are a possible choice only for Houses. Finally, ground-source heat pumps (GSHP) – requiring boreholes – are not allowed in the sub-area called Large-DH, which is representative of the most densely populated areas such as the city centres of the largest municipalities.

Table 8. Heating technologies available in the different geographical sub-areas, building types and kind of heating distribution system.

Building type / *Available heating technology* / *Heating distribution*	**House**: Point Source PS	**House**: Waterborne WBH	**Apartment / Commercial**: Point Source PS	**Apartment / Commercial**: Waterborne WBH
Electric panel heater (PH)	All	---	All	---
Electric Boiler (EB)	---	All	---	All
Biomass Boiler (BB)	---	All	---	All
District Heating (DH)	---	---	---	Large-DH, Small-DH
Air-to-air heat pump (A2A)	All	---	---	---
Air-source heat pump (ASHP)	---	All	---	All
Ground-source heat pump (GSHP)	---	No-DH Small-DH	---	No-DH Small-DH

As discussed in chapter 4.1.2, not all possible combinations of heating technologies (base- and top-heating) are possible, while others, although possible, turn out not being chosen in the investment optimisation. In particular, it turns out that only all-electric heating systems with a heat pump as base-heating unit appear as a combined solution. In these cases, either an Electric Boiler (EB, in WBH buildings) or electric panel heaters (PH, in PS buildings) is the top-heating unit. District Heating (DH) is only allowed as a stand-alone solution, while Biomass Boilers turn out never being chosen by the model.

Table 9 shows the efficiency or SCOP of the heating systems. It should be noted that since the input from PROFet represent the gross heating demand, it is correct to set the efficiency at 1 for boilers or direct heating systems. Heat pumps systems are actually modelled according to the Appendix F of the SN-NSPEK 3031 (2021),[5] so that the COP is different in every hour, depending on the outdoor conditions. The seasonal system COP is further influenced by the shape of the load duration curve and the amount of DHW; both things influencing how often the top-heater needs to be used. The values given in the table are just indicative numbers, obtained applying the model to the archetype Office-Regular in the climatic area NO1. The nominal COP values for the heat pump alone are taken as the average of several products reviewed from the market.

Table 9. Indicative Seasonal Coefficient of Performance (SCOP) or efficiency for the different heating systems

Efficiency level	Regular, Efficient (TEK10)		Very Efficient (Passive House)	
Heating system	Space Heating (SH)	DHW	Space Heating (SH)	DHW
GSHP + EB	2.7	2.4	3.5	2.4
ASHP + EB	2	2.3	2.7	2.3
A2A + PH	1.5	1	1.5	1
DH, EB, BB, PH	1	1	1	1

Heating technologies cost

The global cost over a life cycle of 30-years is calculated for each heating technology based on the input given in Table 10. The costs are different per each main building type and, within each type, vary according to the dimensioning of the system. Therefore, the cost is influenced by the size of an archetype.

For the specific case of heat-pump systems, it was set as an input that the heat pump unit should be dimensioned to cover 50% of the space heating peak load.

Table 10. Heating technologies costs per building type and heating distribution systems

Building type	**Life cycle** [years]	**Investment cost** [NOK / kW]	**Operation & Maintenance cost** [NOK / kW]
House			
	Waterborne		
Biomass boiler	15	12,618	919
Electric boiler	20	4,046	540
Ground source heat pump	20	18,589	40
Air source heat pump	15	14,373	40
	Point sources		
Air-to-air heat pump	15	5,498	30
Direct electric heating	25	2,042	31
Electric water heater	20	2,964	
Apartment			
	Waterborne		
Biomass boiler	15	7,739	919
Electric boiler	20	1,546	540
District/local heat exchanger	50	1,000	-
Ground source heat pump	20	12,514	40
Air source heat pump	15	5,432	40
	Point sources		
Air-to-air heat pump	15	2,540	30
Direct electric heating	25	2,042	31
Electric water heater	20	2,371	
Commercial			
	Waterborne		
Biomass boiler	15	7,739	510

[5] With the exception that the part-load effect is not considered because that would have made the optimisation problem non-linear.

Electric boiler	20	1,546	32
District/local heat exchanger	50	918	-
Ground source heat pump	20	12,514	32
Air source heat pump	15	5,432	32
	Point sources		
Direct electric heating	25	981	15
Electric water heater	25	2,371	60

Grid tariff

The grid tariff, which is applicable to either electricity or district heating, is a Peak Power Monthly (PPM) tariff made of an energy fee component (*energiledd*) and a peak load, or power fee component (*effektledd*). The latter component sets a penalty for hourly energy demand that exceed a reference (subscription) value that is different each month. The optimizer finds the most convenient subscription level for each month. Furthermore, both energy fee and power fee vary in the different spot-market areas. The values shown in Table 11 were agreed with the Flexbuild partners. It was agreed that for modelling purposes it was satisfying to use for all the building types the tariff scheme that usually apply to large commercial customers (not households); the only difference being that VAT applies to Residential buildings but not to Commercial ones. Furthermore, the same grid tariff is applied also to District Heating. These modelling choices were made because the main point is to underline the difference between a grid tariff with and without a power fee component (for both electricity and thermal grids), not to dwell in the details of how the power fee may be implemented. Other grid tariff schemes were considered earlier in the project, see the previous Flexbuild Annual Reports (Linberg et al., 2020; Sartori et al., 2022a), but have been subsequently disregarded since from 2022 all customers in Norway, including households, are subject to a grid tariff with a power fee component.

Table 11. Parameters of the Peak Power Monthly (PPM) grid tariff per market area, applied to both electric and thermal grids.

			Market area				
	Year	*Season*	NO1	NO2	NO3	NO4	NO5
Energy fee [øre/ kWh]	2030	Winter	7.4	9.0	9.3	8.6	8.3
		Spring	4.1	5.0	5.2	4.8	4.6
		Summer	4.1	5.0	5.2	4.8	4.6
		Fall	4.1	5.0	5.2	4.8	4.6
	2050	Winter	7.4	9.0	9.3	8.6	8.3
		Spring	4.1	5.0	5.2	4.8	4.6
		Summer	4.1	5.0	5.2	4.8	4.6
		Fall	4.1	5.0	5.2	4.8	4.6
Power fee [kr/ kW/ month]	2030	Winter	455	558	578	530	515
		Spring	254	312	323	296	288
		Summer	83	102	106	97	94
		Fall	254	312	323	296	288
	2050	Winter	814	1000	1035	949	923
		Spring	455	558	578	530	515
		Summer	149	183	190	174	169
		Fall	455	558	578	530	515

4.2.2 Storyline specific

Building stock evolution

In all storylines in 2050 the building stock will consist of ca. 70% of buildings already existing today, which will be responsible for ca. 80% of the energy demand, see Figure 20. It should be reminded that here we are talking of energy demand for specific services, such as space heating, domestic hot water and electric specific loads. The adoption of energy efficient technologies, such as heat pumps, affects the energy use (*energiforbruk*) but does not affect the energy demand (*energibehov*) of a building. The actual choice of which heating and other technologies to apply, is not a storyline input but is an output of the modelling work.

Figure 20. Aggregated energy demand in 2020 and in 2050 in the different storylines

Figure 20 shows the aggregated energy demand in both 2020 and in 2050 for the different storylines. It also shows the breakdown per energy service within each building type and energy efficiency level. More details on the building stock evolution and the underlying construction, demolition and renovation rates are given in chapter 3.1 and Appendix C of the Flexbuild Annual Report 2 (Sartori et al., 2022a).

District Heating

Modelling of District Heating required some harmonisation across the models used in Flex-build. As described in chapter 1.5, this has led to the subdivision of the building stock within each climatic/market area into three sub-areas: with (potentially) Large-DH network, with (potentially) Small-DH network, and with No-DH network, depending on the population density. This sets a constraint on the supply side. The potential utilisation of District Heating is subject also to constraints on the demand side. The first constraint is whether the building has or not a waterborne heating system; installation of waterborne heating is considered a costly and intrusive measure and it is therefore not modelled as an investment option for the optimisation process. Rather, it is treated as an option that is possible to introduce when a building is renovated (whether with or without energy efficiency upgrading) and is therefore a storyline dependent input. For further details refer to Flexbuild Annual Report 2 (Sartori et al., 2022a), and for a deeper investigation of district heating's role in the future Norwegian energy system refer to the ZEN report 47 (Kauko et al., 2023).

Other two demand side constraints were agreed with the project's partners, and these are:

1. DH is never an option for the House type. As mentioned in chapter 1.5, this is not an attractive customer type for district heating expansion; per today there is just a minor volume delivered to them, which in the modelling is allocated to apartments for simplicity.
2. DH cannot be used as top-heating unit. This too is not an attractive option for district heating expansion because it would add peak load demand but not bulk volume of heating demand. Thus, when DH is chosen it must cover the entire heating demand of a building.

   It should be noted that this marks an important difference between the modelling of DH in BUILDopt and TIMES (or in general, any energy system model). It has to do with the single building perspective vs. the energy system perspective, as commented also in chapter 4.1.3. At an aggregated level, seeing a large section of the building stock as "one large building" and having a complex, multi-carrier energy system with a given, existing infrastructure, it is possible to see DH as covering the base load up to its given (or planned) generation capacity. But this is not possible in a building model. It would be possible in theory, to have DH as base-heating unit and another technology (e.g., boiler and/or heat pump) as top-heating unit. But that is never chosen in practice because such a solution would be more costly than the alternatives, which are either to use DH as top-heating or not to use it at all. Since the top-heating option was not wanted by the project partners, it was decided to only allow DH to operate stand-alone. Either DH is chosen to be the only heating technology in that (archetype) building or it is not chosen at all; the choice depending on the investment optimisation, based on the global cost over a 30-years life cycle. This modelling option has some significant consequence on the results, as it is discussed in chapter 4.4.2 and 5.4.2.

A final consideration should be mentioned regarding the use of DH for Domestic Hot Water (DHW) only. This option was allowed since it would potentially expand the use of DH by serving buildings with Point Source (PS) heating (still, with the exclusion of Houses). Such an expansion may be desirable for district heating companies since it would add a base load that is approximately constant though the year, thus having a marginal impact in winter while increasing the summer demand. Several district heating networks, especially large ones, have a problem with surplus heat generation in summer as a consequence of a low demand and an obligation to burn municipal waste at a constant rate. Expanding to DHW-only customers may solve or alleviate this problem. However, it turns out that this option is never chosen by the optimiser because it implies an additional investment in the DH connection while it does not reduce the investment in the other heating system (whose cost is determined by the winter demand). Eventual operational savings, if DH energy price is cheaper than the alternative, do not compensate for the higher investment, so that the life cycle global cost for this solution never turns out to be the lowest.

Nevertheless, in the storyline Climate panic there is an exception to the constraint no. 2 above. After 2030, as a result of a climate crisis and the failure of some technologies, such as CCS, to deliver a scale necessary to deal with the crisis, there is a strong focus on maximal exploitation of resource, where central control and regulation stand strong, see Appendix A: Storyline descriptions. In this context it is implemented a "use obligation" for DH, meaning that all buildings that can, shall use DH as their (stand-alone) heating technology. It remains the supply constraint that DH itself is not available in all sub-areas, as well the demand constraint that only buildings with waterborne heating can make use of DH, with the exception of houses. But for all other cases there is no economic investment optimisation: where present, DH is used in all buildings (apartments and commercial) of any energy efficiency level.

Electric vehicles

The implementation of EV charging at single building level in BUILDopt is described in chapter 4.1.2. This must be aligned with the overall assumptions at national level about the development of EVs in Norway in future. This is a storyline dependent input; while it is assumed that the entire fleet of cars and vans will be electrified by 2050, some storylines have a higher overall demand than others, reflecting different development in transportation modes and needs. It is also needed to allocate where the charging happens, whether on road or in connection with buildings. these overall assumptions are presented in Table 12. The amount of energy charged "on road" is set at 10% for both 2030 and 2050. The amount charged in connection to Residential buildings per today can be estimated – to the best of the authors' knowledge, see for example NVE (2016) – at around 75%. This share was used for 2030 while for 2050 it has been reduced to 60%. This was chosen so to double the amount of charging happening in connection to Commercial buildings, from 15 to 30% by 2050. The assumption is motivated by the fact that the connected capacity in Commercial buildings is during daytime (see Figure 19) and thus is a natural match for self-consumption of solar PV electricity generated onsite in the building. Since PV self-consumption "beyond the meter" is always economically convenient from the building's perspective (the total electricity price is saved, incl. grid tariff and taxes, rather than only receiving the spot-price from exporting it to the grid) it sounds reasonable to assume that in future more EVs should be charged in Commercial buildings compared to today.

The EV demand charged on road is not modelled within BUILDopt but within IFE-TIMES-Norway, likewise the electricity and/or fuel needed by heavy trucks and other forms of transportation.

Table 12. Total electricity used for EV demand in 2050 and its distribution in relation to where the charging happens

		2050	
		Petroleum, Energy	Nature, Climate panic
Total EV demand [GWh/y]		7 532	5 870
	On road	10 %	
EV demand distribution [%]	Residential	60 %	
	Commercial	30 %	

Once the total EV demand has been distributed into the main building categories, it is necessary to allocate the corresponding number of EV units to each single archetype building. As described in chapter 4.1.2, the EV unit for Residential buildings is a single car, while for commercial buildings it is a charging point. Table 13 shows the resulting number of EV units per building, which is different in the storylines, depending on their respective total EV energy demand. So, what was modelled is that – given the average energy demand per EV unit and its load profiles as we know it per today, from Sørensen et al., (2021; 2023) – in the Energy nation and Petroleum nation storylines there are more EVs in circulation, and therefore more EVs being charged in buildings, than in the other two storylines, Nature nation and Climate panic.

Table 13. Number of EV units, and their main properties, allocated to the different archetype buildings

			no. EV units per building [#] 2050	
Building type	EV unit	Annual charge per EV unit [kWh/y]	**Petroleum, Energy**	**Nature, Climate panic**
House	car	2 372	0.80	0.62
Apartment	car	2 372	12.34	9.50
Commercial	charging point	5 831	2.39	1.86

Solar PV and batteries

The main specifications for the solar PV systems are given in Table 14. While the average tilt and orientation are common to all storylines, the maximum allowed roof area devoted to PV varies with the storylines. It should be noted that even the most conservative assumption of 25% of roof area dedicated to PV is relatively ambitious since this applies to all buildings in the stock, with all restrictions considered: unsuitable buildings, other uses of roof, shaded roof, ratio cell/panel area, inter-row and perimeter free space, etc. The most generous assumption of 50% roof area leads to a potential maximum installation of approx. 21 GWp, which should give indicatively 16 TWh of annual solar electricity generation. This is without considering the potential for PV neither from industrial and agricultural buildings (which are excluded from the RE-BUILDS building stock model) nor from ground-mounted system.

Table 14. Main parameters of solar PV systems for the different building types and storylines

Building type	Tilt angle [°]	Orientation distribution [%] Sør	Øst	Vest	Petroleum / Nature max PV roof area [%]	max PV per building [kWp]	Energy / Climate panic max PV roof area [%]	max PV per building [kWp]
House	30°	50%	25%	25%	25%	4.5	50%	9.0
Apartment	10°		50%	50%	25%	16.1	50%	32.2
Commercial	10°		50%	50%	25%	26.2	50%	52.3

Another parameter that is significant (not shown in the table) is the overall PV system efficiency, which determines the conversion between surface area (m^2) covered by PV and its capacity (kWp). This is an overall system efficiency that includes all forms of system losses in real conditions, i.e., not to be confused with the pure cell efficiency in testing environment. It was assumed to be 20% for all storylines and for the entire simulation period. That means that 5 m^2 of surface area are needed to install 1 kWp.

The cost for solar PV and Batteries system is expected to vary (diminishing) over time and at a different pace in the different storylines, as shown in Table 15.

Table 15. Investment costs for solar PV and battery system in different building types, storylines and years

Building type	2030 Energy	2030 Nature	2030 Petroleum Climate panic	2050 Energy	2050 Nature Climate panic	2050 Petroleum
			Investment cost [kNOK / kWp]			
			Solar PV			
House	9 300	8 200	10 500	6 900	6 000	10 500
Apartment Commercial	5 500	4 100	7 000	4 100	3 000	7 000
			Batteries			
House	3 702		6 641	2 450		6 641
Apartment Commercial	2 961		5 313	1 960		5 313

4.3 Linking BUILDopt / RE-BUILDS with IFE-TIMES-Norway

In the case of TIMES – BUILDopt / RE-BUILDS two alternative linking approaches were used. In some cases, a "**Full linking**" was applied. This consists in activating energy flexibility in response to the energy price, with the goal of cost minimization for the buildings. Energy prices, in turn, are those calculated by TIMES when using energy demand from BUILDopt / RE-BUILDS as an input. Therefore, the two models influence each other and there is need for a round of iterations.

Alternative to the "Full linking", the other approach is named "**Heuristic flexibility**". In this case the optimization in BUILDopt has a different goal than cost minimization; indeed, it has a goal that is price independent, just to avoid the need for iterations. Such a goal is named "**Flat profile**" and it means the flattening, as much as possible, of the load profile. In other words, it could be said that the flat profile combines "peak shaving" and "valley filling" with respect to the typical load profile (while safeguarding comfort and user needs in the buildings). This goal is based purely on physical quantities – energy used in each hour and its variation hour by hour – and is therefore price independent. Furthermore, a slowly and mildly fluctuating load should often be desirable from the energy system perspective since it avoids steep ramp-up and ramp-down of generation units on the supply side. However, it should be noted that the flattening refers to the own energy use of each single building, without regard of what happens in other buildings or in the rest of the grid in general. In this sense it can be said that the flat profile is a building-centric optimization.

The hypothesis behind the flat profile optimization is that this may be a good heuristic for the full linking, hence the name heuristic flexibility. This is because peak shaving and valley filling are typically desired outcomes of energy flexible demand. The hypothesis is that the load profiles resulting from the full linking, after convergence, will tend towards the flat profile. In chapter 4.4.2 and 5.4.2 this hypothesis is tested by comparing the results of the heuristic flexibility – applied to all combinations of Figure 1 – with those from the full linking – applied only to selected combinations.

In both approaches the following choices were made regarding short-term and long-term simulation time. In the short-term, both models operate with an hourly resolution but while BUILDopt simulates an entire year, thus 8760 hours, TIMES simulates only representative days, one per season, which are extrapolated as the average of the working days from the full year dataset from BUILDopt. In the long-term, BUILDopt simulates the years 2030 and 2050 independently, while TIMES performs a simulation for the entire period from 2020 to 2050, with 5 years interval, interpolating energy demand from BUILDopt for the years in between.

The key variables exchanged in the linking between BUILDopt / RE-BUILDS and IFE-TIMES-Norway are, as shown in Figure 2:

- Energy prices, TIMES → BUILDopt / RE-BUILDS
- Energy use, BUILDopt / RE-BUILDS → TIMES

These are meant per each energy carrier and aggregated per each NO-area, within each storyline and simulation year.

4.3.1 Heuristic flexibility

The following set of actions and data exchange between the models was performed to establish the Baseline for the Heuristic flexibility analysis:

1. TIMES takes the typical (non-flexible) energy demand from PROFet and makes its own investment choices to convert energy demand into energy use. Thus, it calculates the corresponding energy prices and pass it to BUILDopt.
2. BUILDopt takes the energy prices from TIMES and the typical (non-flexible) energy demand from PROFet and makes its own investment choices to convert energy demand into energy use. The single building level results are aggregated per NO-area and passed back to TIMES.
3. TIMES takes these energy use datasets from BUILDopt (thus without doing any investment choice for the building sector) and recalculates the corresponding energy prices.

Technology choices regard only heating system and solar PV; batteries are not considered in the heuristic flexibility cases. Since differences in energy prices, especially for competing energy carriers such as electricity and district heating, influences only the choice of the heating technology in BUILDopt but not its dimensioning (as discussed in chapter 4.1.3), there is no need for further iterations, unless end-use flexibility gets activated. Therefore, the energy use and energy prices so calculated are coherent with one another and form the Baseline case, for each storyline and simulation year.

In the heuristic flexibility there is no need for actual linking between BUILDopt and IFE-TIMES-Norway beyond establishing the Baseline. By definition, a flat profile optimisation is price independent, so that in the heuristic flexibility there is only a re-run of BUILDopt:

- BUILDopt takes the baseline energy prices from TIMES and inherits the technology choices from the baseline. Then it makes the operational optimisation activating the flexibility sources with the goal of a flat load profile.

The optimisation is purely operational since there is no re-investment in the flexible case. All storylines and simulation years are simulated, as shown in Figure 21.

Energy use in buildings	2020	2030				2050			
		Petroleum	Energy	Nature	Climate panic	Petroleum	Energy	Nature	Climate panic
Non-flexible	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
Flexible	-	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible

Linking TIMES - BUILDopt
TIMES in deterministic mode
Flexibility heuristic (Flat profile) – "one shot" models linking

Figure 21. Matrix of combinations explored using BUILDopt and the heuristic activation of flexibility

4.3.2 Full linking

The Baseline for the Full linking analysis was established in the same way as for the Heuristic flexibility, with the difference that also batteries were considered in the investment choices.

In the full linking the iterations between BUILDopt and IFE-TIMES-Norway proceed as follows:

- BUILDopt takes the energy prices from TIMES from the previous iteration (beginning from the Baseline) and inherits only the heating technology choices from the baseline. Then it makes the operational optimisation activating the flexibility sources and re-sizing the solar PV and battery system, with the goal of Cost minimisation (global cost over a 30-years lifecycle). This can be regarded as a deterministic 2-stage optimisation, with only one operational scenario. The single building level results are aggregated per NO-area and passed back to TIMES.
- TIMES takes the energy use from BUILDopt and re-calculates the new, corresponding prices. If convergence is not reached (difference between new and previous prices is bigger than a given threshold) the process is repeated until convergence is reached (or it stops after 3 iterations for practical reasons).

The optimisation is not purely operational since there is re-investment in the solar PV and battery system. This is to test if and how much PV and/or batteries is necessary to install when the other flexibility sources are activated in the first place. Since the iteration process proved time consuming to properly set up and the actual runs had to be made after testing the consistency of the linking mechanism in the simpler case of the Heuristic flexibility, the Full linking was only simulated for the Energy nation storylines, as shown in Figure 22.

Energy use in buildings	2020	2030				2050			
		Petroleum	Energy	Nature	Climate panic	Petroleum	Energy	Nature	Climate panic
Non-flexible	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
Flexible	-	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible

Linking TIMES - BUILDopt
TIMES in deterministic mode
Flexibility (Cost minimisation) – iterations until convergency

Figure 22. Matrix of combinations explored in the full linking between TIMES and BUILDopt

4.4 BUILDopt / RE-BUILDS results and discussion

Thousands of simulations were run in BUILDopt to obtain the aggregated results, weighted according to the RE-BUILDS model, to be passed to IFE-TIMES-Norway. By combining:

- 5 climatic areas *x*
- 3 sub-areas *x*
- 11 building archetypes *x*
- 3 efficiency levels *x*
- 2 heating distribution system *x*
- 2 simulation years *x*
- 2 flexibility options (baseline/flexible) =

we get 3,960 simulations per each storyline in the Heuristic flexibility mode; while in the Full linking mode only one storyline is simulated but it required *x3* iterations with TIMES. Thus, in total ca. 28,000 BUILDopt simulations were necessary to generate the results commented in this chapter and in chapter 5.4.

It would be untreatable to give a comprehensive overview of the results at the single building level. Therefore, we rather choose to focus on the results aggregated at the total building stock level in chapter 4.4.2, with a special focus on solar PV and batteries in chapter 4.4.3. In the following chapter 4.4.1, we first give an account of results obtained earlier in the project, from building level case studies, and then focus on the results of just one BUILDopt simulation for a single building. This allows us to show in detail how the end-use flexibility sources are activated.

4.4.1 Single building level

Analysis on single buildings have been carried out throughout the duration of the project and some results are presented in the previous Flexbuild Annual Reports (Lindberg et al., 2020 and Sartori et al., 2022a) as well as in other work, such as Sartori et al., 2022b. The latter paper also defined KPIs (Key Performance Indicators) to quantify relevant effects of end-use flexibility activation. The following load flexibility KPIs were defined (where Δ, delta, means the difference between flexible and baseline values, given in %):

- **Δ Energy**, the difference in total energy use
- **Δ Cost**, the difference in operational cost due to energy use
- **Δ Peak**, the difference in peak load (usually referring to imported energy but may apply also to exported energy)
- **Δ Energy stress**, the difference in energy use during hours that are predefined as stressful for the energy system, e.g., peak load hours for the grid, typically occurring in early morning and late afternoon during workdays, in Norway

These previous results showed that in terms of flexibility sources, space heating (SH) and EV charging have rather large and similar potential, especially in terms of Δ Peak, achieving results in the order of -20% when activated singularly (either SH or EV), while domestic hot water tanks (DHW) achieve more modest results at -8%. Activating all these flexibility source together the effects of the single sources cannot be expected to add up directly, but the overall result was in the order of -35%.

In terms of flexibility KPI, it was observed that activating flexibility can bring reductions in Δ Cost (in the range of 0 to 20%), in Δ Peak and Δ Energy Stress (in the range 20 to 50%, or even as high as over 80%, as in Knudsen et al. (2021)) even if this is accompanied by a modest increase in Δ Energy (in the range 0 to +5%) due to some energy losses.

In terms of flexibility drivers, when the goal is minimization of operational costs for the end-user, an important outcome was clear regarding the grid tariff adopted. The main difference was seen between a tariff based purely on an energy fee (*energiledd*), such as the energy pricing (EP), and a tariff that included also a power fee component (*effektledd*), such as the Peak Power Monthly (PPM), see chapter 4.2.1. The EP tariff cannot guarantee a reduction in ΔPeak; on the contrary, it may lead to an increase since it only has an incentive to shift loads into cheap hours, chiefly at nighttime, without restriction on the peak load other than the physically installed capacity. The PPM tariff, on the other hand, allows finding the most convenient level for the monthly peak power values, thus effectively setting a cost-optimal cap on the peak demand from a single building viewpoint.

These results are visualized in Figure 23 for the case study of an apartment building. Here also a flat profile optimization is presented (see chapter 4.1.2 and 4.3.1), achieving peak load smoothening similar to a PPM tariff while also avoiding "deep valleys" and sudden changes in the energy demand.

Only in the last year of the project both the BUILDopt model and the linking methodology had matured to the point of allowing a systemic simulation of all necessary building level combinations, and a coherent exchange of the aggregated data with IFE-TIMES-Norway, including going through the necessary iterations in the case of Full linking. The simulation results presented below only refer to the case of an Efficient Office building with an Air-Source Heat Pump (ASHP) system in the NO1 area for the Energy nation storyline in 2050. The results are shown for both the Heuristic flexibility and the Full linking simulations; in the latter we show the converged results, i.e., from the 3rd iteration. The purpose it to visualize and describe the mechanisms by which end-use flexibility is activated at single building level.

Figure 24 shows a zoom-in for three consecutive working days in winter. The graphs are arranged in pairs on each row, where the two columns show results from the Heuristic flexibility (left) and Full Linking (right) simulations.

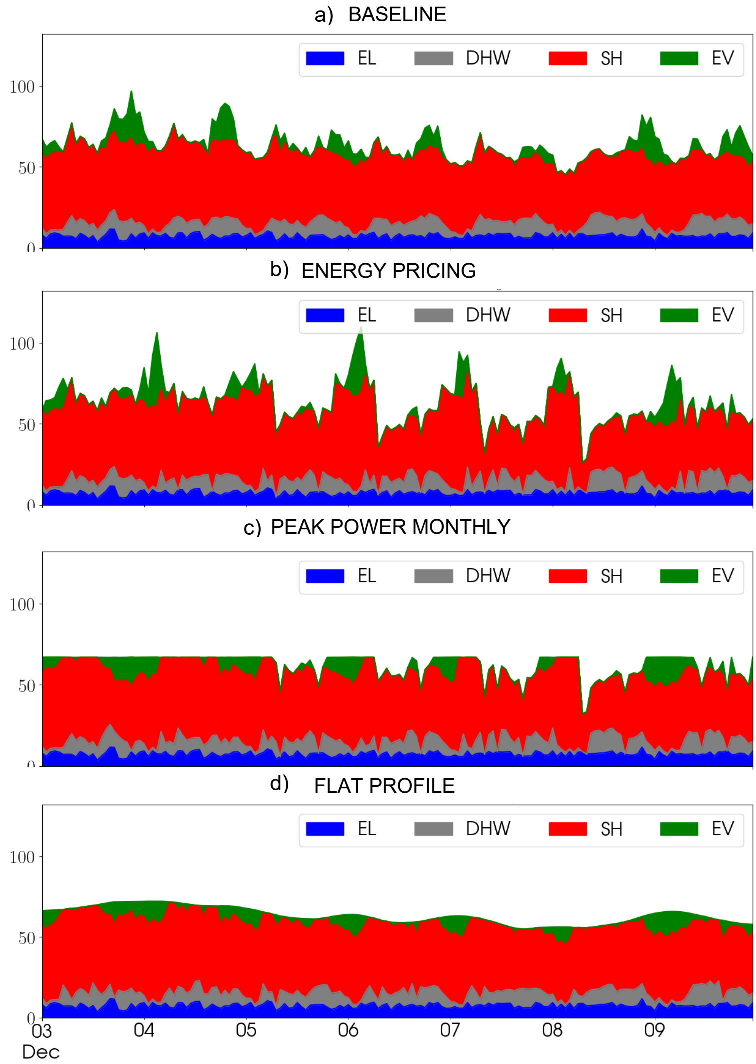

Figure 23. Hourly profile of electricity use (kWh/h) for the archetypical Apartment with Regular efficiency and electric panel heaters, in a December week, Oslo climate. The top plot shows the typical demand (a) Baseline; while (b)–(d) show the result of activating end-use flexibility with different goals: Minimization of cost with two different grid tariffs (b, Energy Pricing, or c, Peak Power Monthly), or minimization of profile variation (d, flat profile). Source: Sartori et al. (2022).

The first row shows the total electricity load profile for the building. Here we can see that the two baselines are not identical and that is because in the Full linking simulation the optimiser could invest in batteries, see Table 1. This creates an asymmetry between the two simulations: *a)* Heuristic flexibility vs. *b)* Full linking; but it was done with the intent to investigate how much the activation of existing flexibility source influences the installation of batteries, as discussed in chapter 4.1.3. Nevertheless, the main characteristic of the Baseline electricity profile (solid green line) is visible on both sides, and that is that the load is higher during daytime, being this an office building. The dotted blue line shows the Flexible load. In *a)* it is visible how effectively the flexibility sources are activated to flatten as much as possible the total load. Indeed, this flattening is rather aggressive because there is no explicit constraint on how much thermal losses are acceptable to pursue the goal of load flattening. The only implicit limitation is given by either the installed capacity of the heating source or, mostly, by the fact that the indoor temperature is only allowed to swing up to 2 °C above the baseline. In *b)* it is visible the effect of the PPM grid tariff, which is the major driver for cost minimisation in these days where the electricity price is rather stable (black line in the bottom graph).

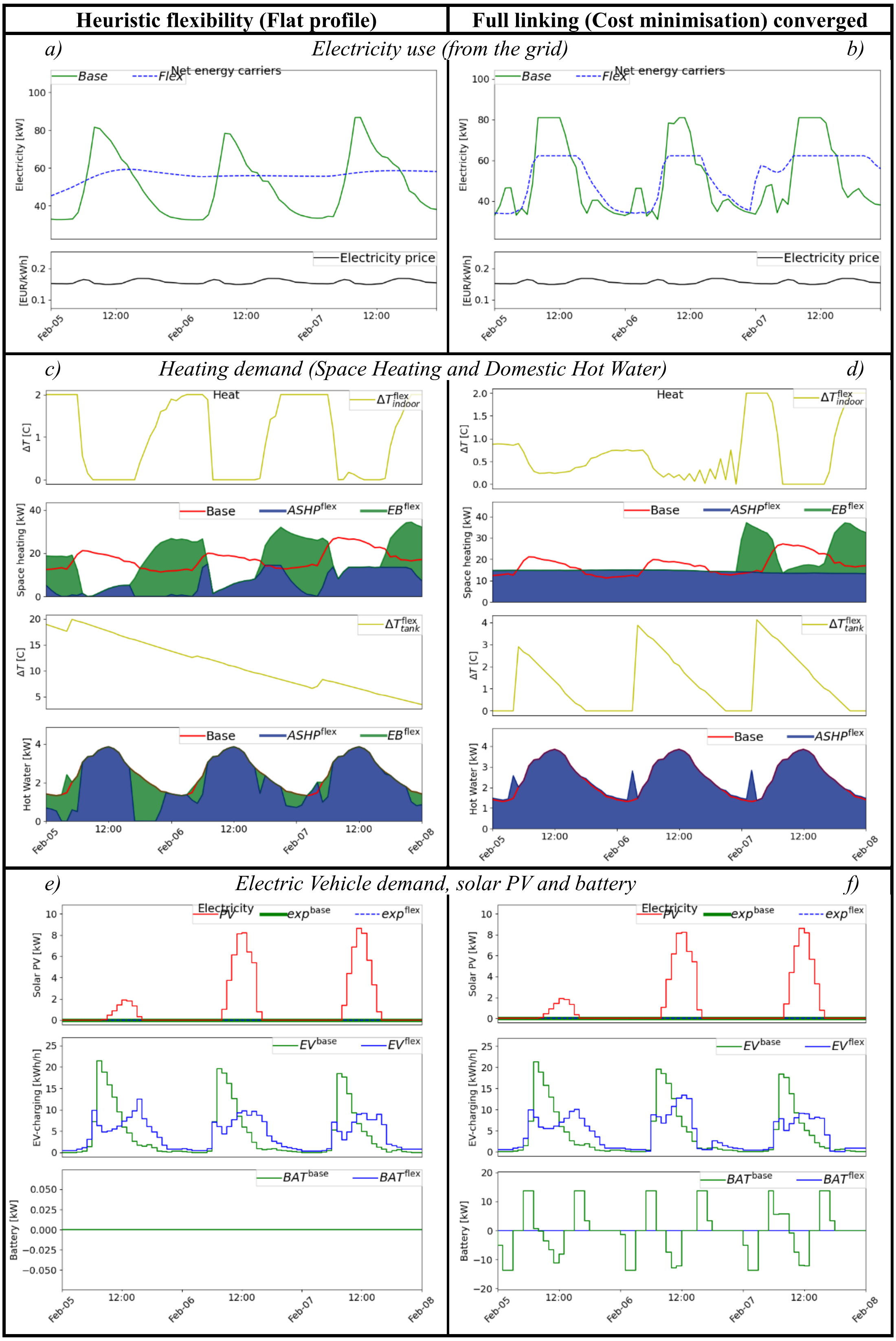

Figure 24. Zoom-in on the load profiles of an Efficient Office building with ASHP system in NO1 area for three working days. Results for the Energy nation storyline in 2050. The two columns show results from the Heuristic flexibility (*left*) and Full linking (*right*) simulations.

The second row shows how the thermal loads contributes to the overall result (the building is all-electric). Space Heating is shown in the first two graphs and DHW in the bottom two. The graphs with a yellow line show the Δ T (temperature difference) between the flexible and the baseline cases. For space heating Δ T refers to the average indoor temperature of the building; it is only allowed to deviate upward and for a maximum of 2 °C. In this way the thermal comfort is safeguarded because the building is never colder than in the baseline; it may eventually be warmer in some hours but only within a 2 °C comfort band. For DHW Δ T refers to the average internal temperature of the tank; it is only allowed to deviate upward and for a maximum of 20 °C. In this way the thermal comfort is safeguarded because the tank is never colder than in the baseline. For both space heating and DHW such upward flexibility is responsible for some thermal losses, but it serves the purpose at hand: either to flatten the electricity load profile or to minimise the operational cost. The other graphs show the baseline load (red line) and the flexible load for the base-unit (ASHP, blue area) and the top-unit (EB, green area) of the heating system. Comparing *c)* and *d)* it is clear that the two simulations follow a different strategy for the activation of the thermal flexibility source; that is precisely because they pursue two different goals. Note the difference in magnitude between space heating (*y-axis* end of scale is 40 kW) and DHW (*y-axis* end of scale is 40 kW).

The third row shows the electric loads. The electric specific demand is not shown because it is inflexible; however, it should be reminded that it is implicitly considered in the optimisation because it is part of the total building's electricity load. The first graph shows the solar PV generation (inflexible, red line) and the part of it that is exported in the baseline (solid green line) and the flexible case (dotted blue line). In both *e)* and *f)* the export is null. This is partly because this is a winter week and therefore the generation is low (the installed PV system has a capacity of 63 kWp, see Table 17) and therefore easily self-consumed by the building. But partly it is because there is in general enough flexibility available – at least with the ideal control conditions of the simulations – that the building is almost always able to self-consume the solar electricity generated onsite, if this helps achieving the goal. This is true for most building types, see Table 17.

Furthermore, the third row shows the EV charging where in both *e)* and *f)* we can see that the flexible load (blue line) is shifted from the morning to the afternoon, compared to the baseline load (green line). This increases the solar PV self-consumption as well as it helps flattening the total electricity load (within the PPM limit, in the Full linking simulation).

Finally, the third row shows the charging and discharging of an eventual battery. The Heuristic flexibility simulation does not have the option to invest in a battery, while the Full linking simulation does (see Table 1) but it invests in a battery only in the Baseline case (green line). The Flexible case (blue line) has no battery, and this is because the activation of the other flexibility source makes it unnecessary to invest in it.

This effect is better visualized in Figure 25 that shows a zoom-in on the activation (charge and discharge) of the flexibility sources. While in *a)* there is no option battery investment, in *b)* the flexible case does not chose to invest in a battery because the same function is performed (even better) by activating the other flexibility options, which are investment free. Having the possibility to control smartly the existing flexibility sources (Space Heating, DHW tank, EV charging) eliminates, or drastically reduce, the need to invest in a battery as a source of flexibility, see Table 16 and Table 17.

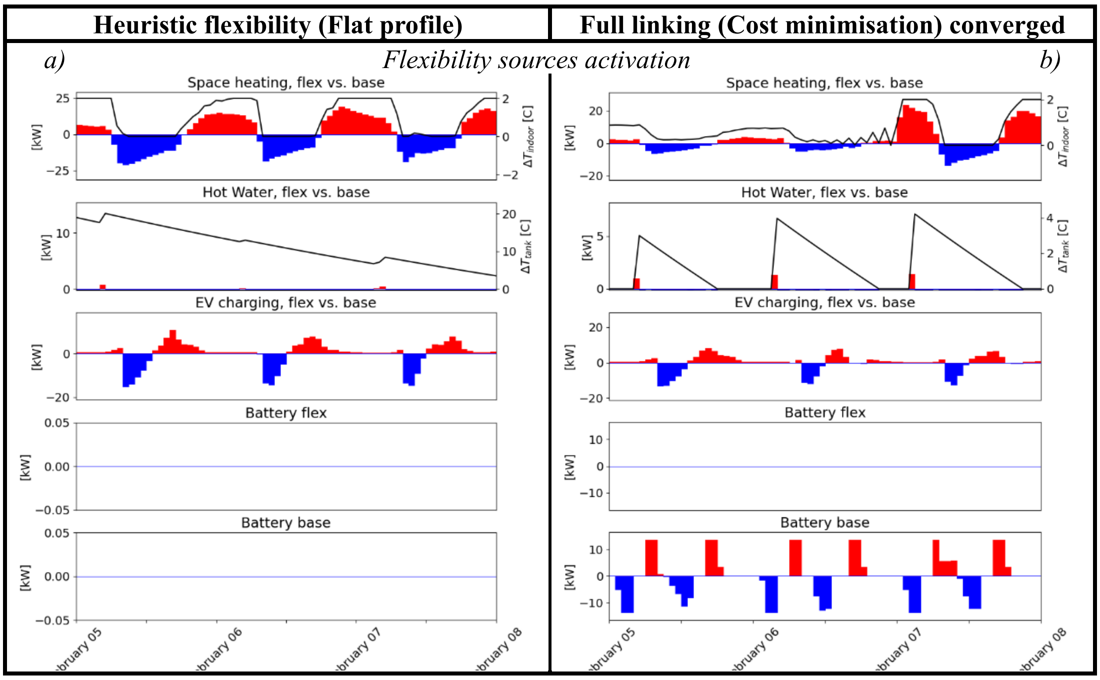

Figure 25. Zoom-in on the flexibility sources activation of an efficient office building with ASHP system in NO1 area for three working days (same building as in the previous Figure). Results for the Energy nation storyline in 2050. The two columns show results from the Heuristic flexibility (*left*) and Full linking (*right*) simulations.

4.4.2 Building stock level

The results at aggregated level are obtained by combining BUILDopt results at single (archetype) building level with the building stock structure from RE-BUILDS.
Figure 26 shows the heating technologies that are installed in 2050 in the different storylines and linking modes, with a breakdown per building type. The graphs are arranged in rows showing the results per storyline, and two columns showing results from the Heuristic flexibility (left) and Full linking (right) simulations, where the latter only has results for the Energy nation storyline.

As already commented in chapter 4.1.2 all buildings turn out either having district heating or being all-electric. What stands out is that while District Heating has a certain capacity in *a)* the iteration #0 from TIMES (see chapter 1.5), when the investment decisions are made in BUILDopt District Heating is almost not chosen at all, totalling a negligible capacity at national level in all storylines except *f)* Climate panic, where there is an obligation to use DH wherever it is possible, see chapter 4.2.2.

The reason for it is that BUILDopt has a building perspective while TIMES has an energy system perspective in their investment optimisation, as discussed in chapter 4.1.3.

Energy system models such as IFE-TIMES-Norway, when used self-standing – e.g., like in the iteration #0 – treat the entire building stock as a single, large building (or few large ones, if there is a split between residential and commercial sectors and/or between existing and new buildings). With this setup it is meaningful to have a mix of heating technologies serving the building stock. Therefore, district heating is always a component in the energy mix; partly because it is an infrastructure whose value is considered in the "system memory" and partly because, at an aggregated level, District Heating is seen as contributing to covering the base load of heating demand. This makes sense form an energy system perspective.

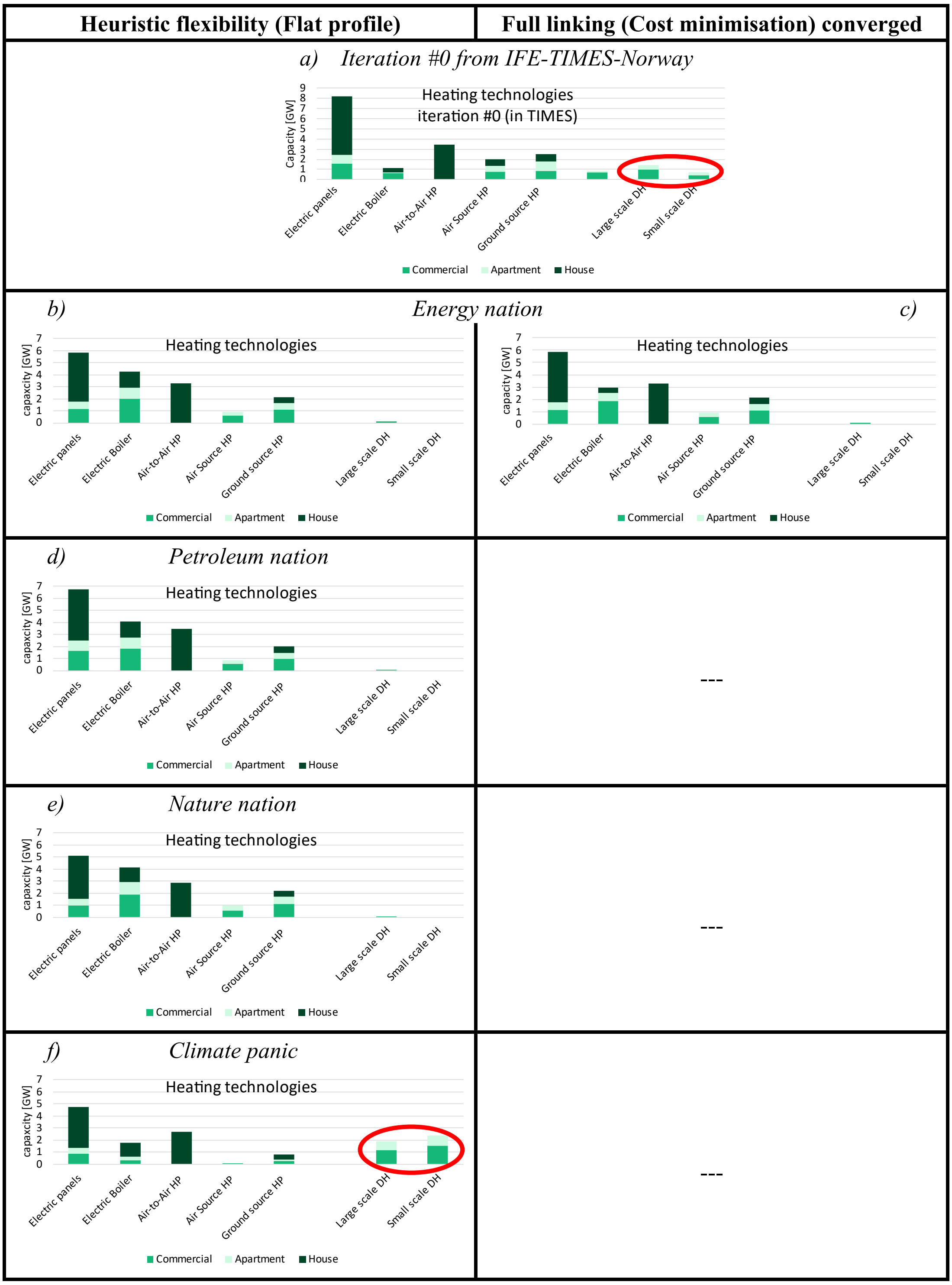

Figure 26. Aggregated results on heating technologies installed capacity in 2050 for the different storylines. The two columns show results from the Heuristic flexibility (*left*) and Full linking (*right*) simulations, where only the Energy nation storyline was simulated.

Building models such as BUILDopt, on the other hand, make a choice for a single building at a time – or more precisely, for an archetype building representing an entire segment of the stock. This choice is made "at once" based on a pure lifecycle cost-optimal principle. Considerations on whether this is a plausible representation of end-user investment choices are out of the scope of this report, and of the project altogether. What is interesting to notice is that, consequently, District Heating may suddenly disappear from the energy mix serving a building stock, given certain conditions. This is because each building is optimised independently, and with the constraint – agreed with the partners – that DH shall not be chosen as peak heating unit only, the choice is either to use DH for the total heating demand or not to use it at all. If, for every archetype building in a region, an alternative choice results more convenient in the cost-optimisation (e.g., a heat pump system), the aggregated result is simply zero demand for DH in that region. This may sound illogical from an energy system perspective, but it is a logical consequence of applying investment choices on the single building level.

There are two mechanisms that determine this outcome. The first and most important is the ratio between electricity and DH prices in comparison with the SCOP of a heat pump system. Since the DH price from TIMES is almost always similar to the electricity price, just a little lower, the price ratio electricity/DH is just above one (meaning DH is just a little cheaper than electricity). But the SCOP of a heat pump system is significantly higher, especially for ASHP + EB and GSHP + EB (see Table 9), which are the technology that compete with DH in apartment blocks and commercial buildings with waterborne heating (see Table 8). In turn, the heat pump system consumes ca. 2,5 times less energy than a DH system. We have performed a sensitivity analysis in our simulations, and we have seen that when the price ratio becomes approximately equal to the competing SCOP (meaning when DH becomes ca. 2.5 times cheaper than electricity) then there is a switch and DH becomes the chosen heating technology.

The second mechanism in place is given by the PPM tariff. Electric specific and EV-charging demand already set a minimum level of power subscription that the heating system can "benefit from" without causing additional cost. Only when the heat pump system demands 1 kW more than this minimum level, then it starts adding a cost on the power component (*effektledd*) of the tariff. DH, instead, is disadvantaged because it will start adding cost from the very first 1 kW it demands. This is because the DH tariff is modelled the same way as the electricity grid tariff, see Table 11. However, the grid tariff effect is secondary to the SCOP effect, which is the real determining factor why a heat pumps system is the chosen heating technology in most simulations.

It shall be reminded that this is the result from a single buildings perspective, and simply the outcome of a purely economic optimisation on a 30-years life cycle, with the given modelling inputs and assumptions. It does not reflect other aspects influencing decisions in real life, such as that DH has a lower investment cost, it is easier to install (virtually plug-and-play) and is both easier and cheaper to maintain (virtually connect-and-forget). A heat pump system, on the contrary, is more expensive and complex to install, especially for GSHP that require boreholes, and needs a regular, qualified maintenance service to perform well throughout its lifetime.

Nevertheless, when using DH is an obligation as it is in the Climate panic storyline – wherever available for apartments and commercial buildings with waterborne heating, see chapter 4.2.2 and Table 8 – the installations of DH in BUILDopt exceeds those in TIMES; compare *f)* with *a)*. This is reflected in the aggregated use of district heating shown in Figure 27 *e)* where the combined large-scale and small-scale consumption in 2050 is 13 TWh for the Baseline and 14 TWh for the Flexible case. This is in line with other results, such as from Kauko et al. (2023).

Figure 27 shows the aggregated energy carriers use for the entire national building stock. The terminology in these graphs mean:

- Electricity import = from the grid to the buildings (i.e., delivered electricity from the grid's viewpoint)
- Electricity export = from the buildings to the grid (i.e., feed-in or reverse power flow from the grid's viewpoint)

and it shall not be confused with the meaning of import/export in the sense of power exchange between countries.

Looking at the Baseline results, the Climate panic storyline achieves the lowest electricity import, which is as low as 41 TWh in 2050, partly thanks to the 13 TWh of district heating use. The highest electricity import is at 61 TWh in Petroleum nation, where solar PV generation is at its minimum (see chapter 4.4.3), while Nature nation and Energy nation, in both *a)* and *b)*, are at ca. 50 TWh. Compared to the modelling starting year 2020 where the electricity use is 68 TWh, the saving potential from the building stock is thus in the order of 17–27 TWh by 2050. Similarly, the potential savings are in the order of 9–14 TWh by 2030 (not shown in the graphs below).

Looking at the Flexible results, it is striking that in all Heuristic flexibility simulations the use of electricity from the grid (Electricity import) is higher for the Flexible case than it is for the Baseline, while it is lower in the Full linking simulations.

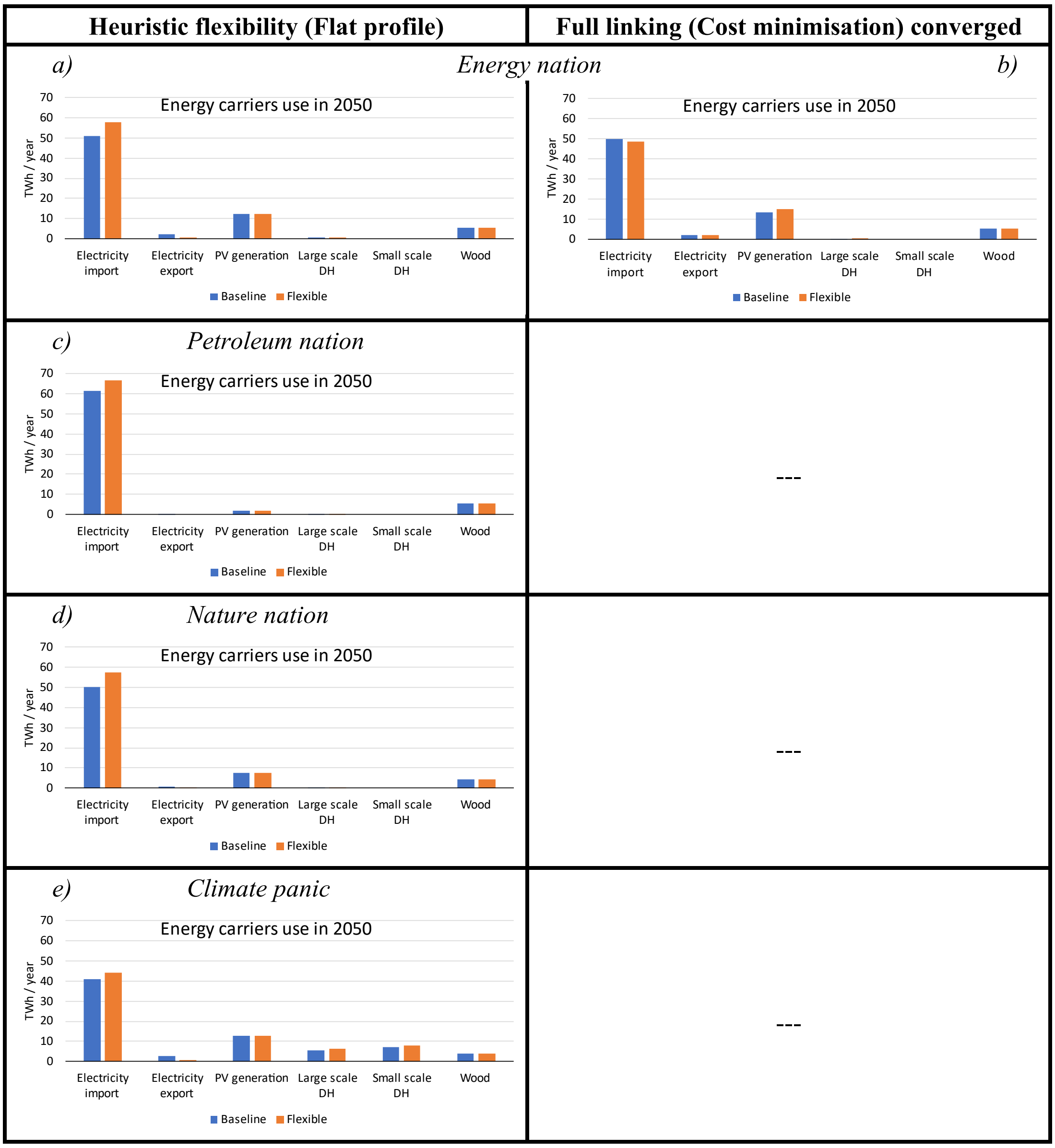

Figure 27. Aggregated results on energy carriers use in 2050 for the different storylines. The two columns show results from the Heuristic flexibility (*left*) and Full linking (*right*) simulations, where only the Energy nation storyline was simulated.

This is explained by the very nature of the goal for which flexibility is activated. In the Heuristic flexibility simulations the goal is to flatten the load profile, and as commented in relation to Figure 24 such goal is pursued without explicit limitations on the energy losses it may cause (only the implicit limitation given by installed heating capacity and the 2 °C upper boundary for temperature swings).

On the other hand, in the Full linking simulations one may expect to see still a moderate increase in energy use for the Flexible case due to the thermal losses. And that is correct, but since the cost minimisation goal also achieves a better utilisation of the solar electricity produced onsite, the resulting Electricity import is lower than in the Baseline.

We see that the PV generation varies in the different storylines and is very similar in the Heuristic flexibility and Full linking simulations, being respectively 12 TWh in *a)* and 13 TWh in *b)*. The Flexible case remains the same in *a)* because all investments are inherited from the Baseline (see §4.1.3), while in *b)* the generation increased to 15 TWh. This is mainly due to more installation capacity in houses, as shown and commented below in reference to Figure 30. Electricity export is only a small fraction of the total PV generation, below 2 TWh in all storylines, because of the generally high self-consumption level (see Table 17 below).

Figure 28 shows the hourly load profile, for a full year, of the two timeseries of electricity use that are passed to IFE-TIMES-Norway in the Full linking: Electricity import (from the grid) *at top* and Electricity export (to the grid) *at bottom*. The two models exchange data aggregated at the market NO-area level, while Figure 28 shows the overall aggregation at national level. What is important to notice is that while at the single building level there cannot be simultaneous import and export of electricity – one of the two timeseries must be zero when the other one has a non-zero value – at the aggregated level this is what happens. Some buildings are net importer of electricity from the grid while, simultaneously, other buildings are net exporters to the grid. We see that the Flexible case achieves both lower electricity import in winter and lower electricity export in summer.

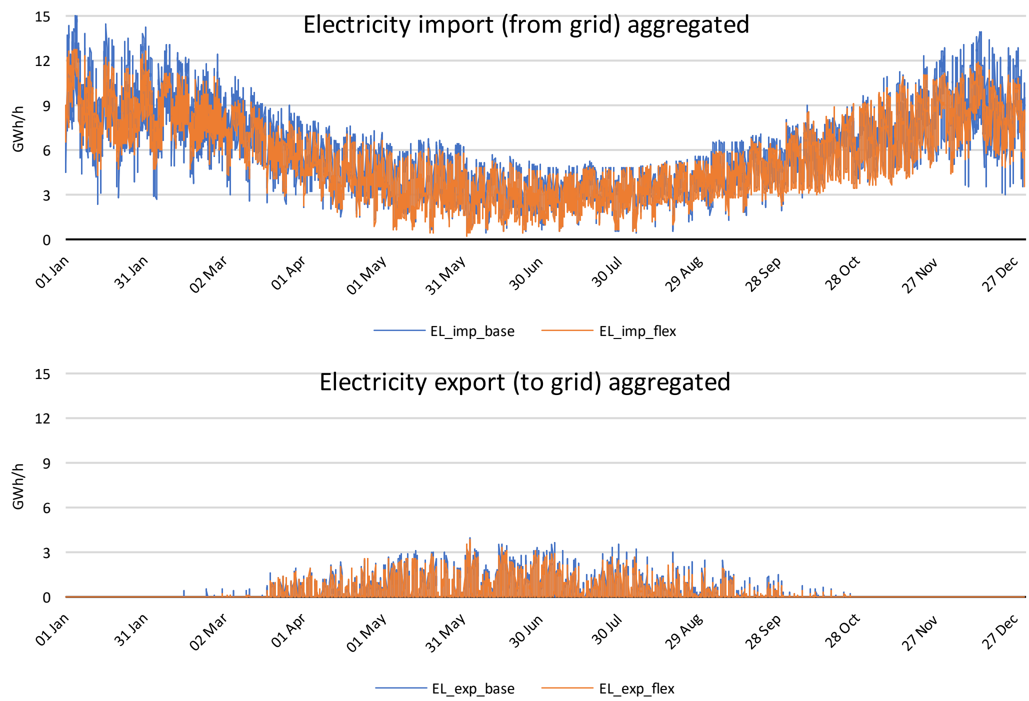

Figure 28. Aggregated hourly electricity load profile for a full year: *(top)* import from the grid, *(bottom)* export to the grid. Results for the Energy nation storyline in 2050, from the Full linking simulations.

Table 16 summarizes the differences between Flexible and Baseline cases in 2050 using some of the KPIs already introduced for the single buildings in chapter 4.4.1, while adding two more: the variation in installed capacity for solar PV and Battery, which apply only for Full linking simulations. These KPIs show that the Flexible case achieves a higher installation of solar PV capacity than the Baseline, Δ Solar PV = +13% (converged iteration #3), while plummeting the installation of Battery capacity, Δ Battery = -93%. These results are further commented in chapter 4.4.3.

Table 16. Key Performance Indicators (KPIs) at aggregated building stock level, for the Heuristic flexibility simulations (all storylines) and for the Full linking simulations (Energy nation, all three iterations).

	Flexible vs. Baseline in 2050						
	Heuristic flexibility				**Full linking**		
Storyline	Climate panic	Nature nation	Petroleum nation	**Energy nation**	**Energy nation** iteration nr.		
KPI					**#3**	#2	#1
Δ Energy	7 %	14 %	9 %	**14 %**	**-3 %**	-3 %	-3 %
Δ Cost	2 %	6 %	4 %	**4 %**	**-4 %**	-4 %	-4 %
Δ Peak	-15 %	-20 %	-19 %	**-21 %**	**-16 %**	-15 %	-16 %
Δ Solar PV	-	-	-	-	**13 %**	13 %	8 %
Δ Battery	-	-	-	-	**-93 %**	-93 %	-93 %

In the Heuristic flexibility simulations, the KPIs show a similar pattern through all the storylines, and likewise across the iterations in the Full linking simulations. So, let's focus the attention on comparing the results for Energy nation to highlight the differences between the two linking approaches (bold numbers in Table 16).

Both approaches achieve a significant reduction in Δ Peak, as expected being this one of the major potential benefits of end-use flexibility. The reduction is less marked than what observed at single building level (see chapter 4.4.1), and this too is as expected because of the coincidence factor amongst different building types. The Heuristic flexibility approach scores better on this KPI, with -21% vs. the -16% of the Full linking simulations.

However, the better performance on Δ Peak is more than counteracted by the poorer performance on the other two KPIs, Δ Energy and Δ Cost. Because of the unchecked energy losses of the Flat profile goal, the Heuristic Flexibility simulations achieve a much higher overall energy use, Δ Energy = +14%, which is accompanied by a higher cost, Δ Cost = +4%. The Cost minimisation goal of the Full linking simulations, instead, achieves a reduction also in these two KPIs, with Δ Energy = -3% and Δ Cost = -4%.

Table 16 shows the results aggregated at national level. A closer look at the market area level shows that Δ Peak, in the Full linking simulations, varies from a minimum of 16% in NO3 to a maximum of 20% in NO2.

Finally, looking at the results for the three iterations of the Full linking approach, we see that the KPI results from the first iteration are already very similar to those from the (converged) third iteration. The similitudes between the iterations are discussed in more detail in chapter 5.4.2, in relation to the load profiles and price variations in typical days.

In light of the significant differences in the KPI results between the two approaches, we can conclude that the Flat profile goal does not represent a good heuristic for the Cost minimisation goal. So, while the Baseline results for all storylines are valid, only the Flexible results from the Full linking simulations should be regarded as valid.

4.4.3 Focus on solar PV and batteries

Figure 29 shows the installed capacity for solar PV in all storylines for the Heuristic flexibility simulations, where the investment decisions are made only in the Baseline case. In 2030 the total installed solar PV capacity ranges from 3 to 7 GWp, while the range expands from 3 to 16 GWp in 2050. The main reason for this is that investment cost go down in all storylines except Petroleum nation, see Table 15, while energy prices generally go up from 2030 to 2050. In particular, solar PV is not yet cost-optimal for Houses in 2030, except in Nature nation storyline.

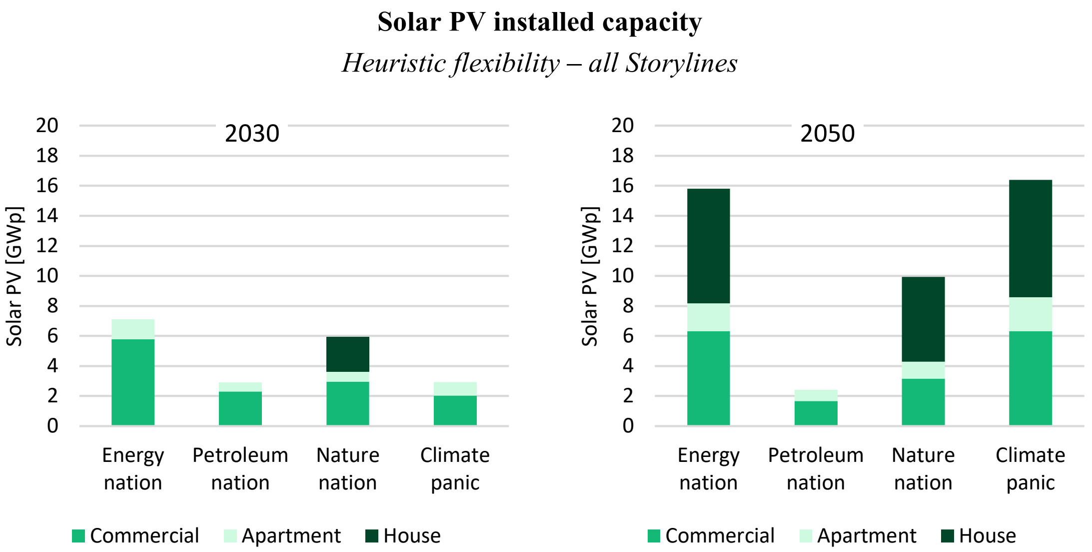

Figure 29. Solar PV capacity installed in 2030 (*left*) and in 2050 (*right*) for all storylines, from Heuristic flexibility simulations, with breakdown per building type

Figure 30 shows the results for the Full linking, where only the Energy nation storyline was simulated, where the investment decisions are made separately in the Baseline and Flexible cases, and where also a Battery system was an investment option. For solar PV the results in the Baseline are similar to those from the Heuristic flexibility, while in the Flexible case the installation capacity increases in 2050 from 17 to 19 GWp (+13%). More significantly, activation of end-use flexibility makes solar PV cost-optimal also for Houses already in 2030, increasing the installed capacity from 7 to 11 GWp (+58%). House is the only building type where the results show it is not cost-optimal to install as much solar PV as allowed (cf. Table 14). However, in the Flexible case the total installed capacity on Houses is 32% of the maximum potential in 2030 (vs. 0% of the Baseline) and 83% in 2050 (vs. 67% of the Baseline).

For a comparison with other studies, the results presented here are more optimistic than those from the FM-ZEN Report no. 50 (Sandberg et al., 2023). Both studies simulate the activation of end-use flexibility but while in this study the maximum solar PV system capacity allowed for a single House is set at 9 kWp (Table 14) – the actual choice being left to the investment optimisation – while in Sandberg et al. (2023) Houses are simulated, not optimised, with a fix amount of 5 kWp per building – while the other building types have comparable capacities to those shown in Table 14. Thus, it is the difference in the House installations that determines the different results between the two studies. In Sandberg et al. (2023) the annual production from solar PV on buildings is estimated at 4 TWh in 2030 and 12.5 TWh in 2050; here it is already at more than 8 TWh in 2030 and at 15 TWh in 2050.

Solar PV and Battery installed capacity

Full linking – Energy nation

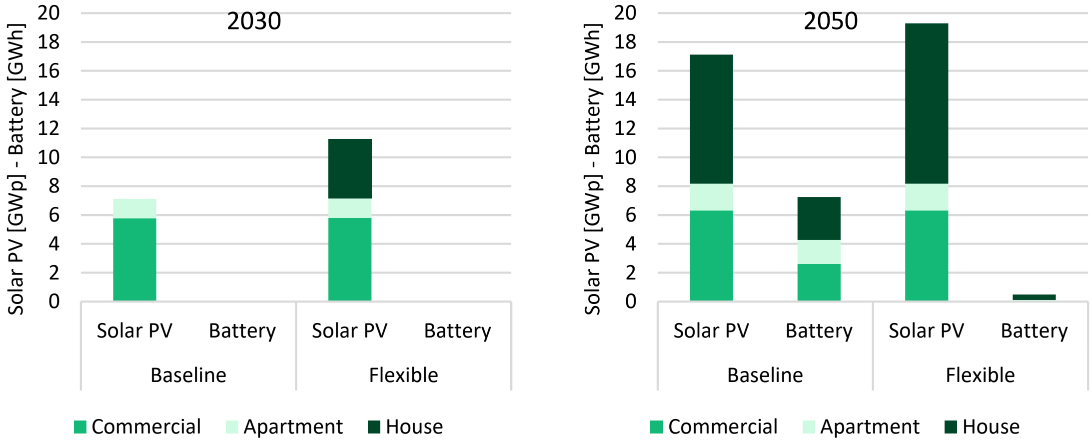

Figure 30. Solar PV and Battery capacity installed in 2030 (*left*) and in 2050 (*right*) for the Energy nation storyline, from Full linking simulations, with breakdown per building type

The other important result seen from Figure 30 is that Batteries, while non convenient in 2030, are installed in buildings in 2050, for a total of 7 GWh, only in the Baseline case. In the Flexible case the installed capacity is negligible, being below 0.5 GWh (mainly in Houses). This is because activation of end-use flexibility already achieves the cots-optimal performance that is possible to achieve, leaving almost no room for improvement by installing batteries. In other words, end-use flexibility eliminates the need to install batteries in buildings while achieving better overall results, see Table 16. In absolute terms, activation of end-use flexibility is worth 1.2 billion NOK in avoided installation of Batteries by 2050.

Finally, Table 17 shows the main properties of the solar PV systems for all building types. In the thousands simulation needed to model the entire building stock, those properties result with different values, depending on the climatic area, the efficiency level, the chosen heating technology and so on. Table 17 reports both the minimum and the maximum values observed in the results of all simulations.

All building types in 2050 install as much solar PV as allowed, i.e., 50% of their roof area (Table 14), except Houses for which the result varies from zero to the maximum, totalling 83% of the potential as commented above (32% in 2030). This means that in average every House has installed ca. 7 kWp in 2050 and 3 kWp already in 2030.

Table 17. Results for the main properties of solar PV systems in the various building types. Minimum and Maximum results for the Energy nation storyline in 2050, from Full linking simulations.

	Building type	max PV allowed [kWp]	**PV installed [kWp]** Min	Max	**Self-consumption [%]** Min	Max	**Peak export / Peak import [-]** Min	Max
House		9	0	9	0 %	100 %	0.0	**1.5**
Apartment		32	32	32	96 %	100 %	0.0	0.4
Commercial	Office	63	63	63	97 %	100 %	0.0	0.3
	Shop	61	61	61	96 %	100 %	0.0	0.5
	Hotel	21	21	21	82 %	100 %	0.2	**1.4**
	Culture & Sport	35	35	35	81 %	100 %	0.1	**1.4**
	Kindergarten	56	56	56	75 %	93 %	0.5	**1.4**
	School	56	53	56	65 %	95 %	0.4	**1.9**
	University	116	116	116	100 %	100 %	0.0	0.1
	Hospital	167	167	167	100 %	100 %	0.0	0.0
	Nursing home	61	61	61	97 %	100 %	0.0	0.6

More interesting are the results for the self-consumption and the peak export / peak import ratio. Self-consumption means the amount of electricity generated by the solar PV system that is "immediately" consumed in the same building, i.e., within the same hour since the simulation have hourly resolution. The calculation is done with hourly resolution while the share refers to the cumulative value over the year. The peak export / peak import ratio compares the highest value of electricity exported from the building to the grid (in summer) over the maximum value of electricity imported from the grid (in winter). A value higher than one may be problematic because it indicates that for that building archetype the grid connection should be dimensioned based on the summer export rather than the winter import.

Regarding self-consumption we see that for all building types except Houses the values are rather high. Partly this is due to the geometry at hand: often these are building with large volumes and relatively little roof area (multistorey buildings), so that the installed solar PV capacity is relatively small compared to the high building's energy demand. Thus, it is easy to self-consume most of it. However, the maximum value, hitting 100% in most cases, is usually achieved in the Flexible simulations. In Houses there is large variability. The building's geometry is rather the opposite, offering a high surface to volume proportion, so that a relatively large solar PV capacity is available compared to the small building's energy demand. In addition, the actual installed capacity ranges from min to max in the various archetypes. Consequently, also the self-consumption varies from 0 to 100%, but here too the highest values of self-consumption are achieved in the Flexible cases.

Flexible loads in Houses allow to increase the self-consumption of onsite generation, which is always economically advantageous from the end-user viewpoint. Indeed, it is beneficial enough for the optimiser to invest in extra solar PV capacity in the Flexible simulations; see the Δ Solar PV = +13% in Table 16. Thus, end-use flexibility and solar PV becomes a win-win situation where one thing calls for more of the other. Nevertheless, this positive spiral does not lead to saturation but finds it optimum at ca. 80% of the maximum allowed: the average 7 kWp per house, as commented above. Meaning that, in average, we could say that the cost-optimal roof area to cover with solar PV in a house is 40% of its roof, in 2050. On one side, this may look like an untapped potential (since 50% was considered as the average technical potential), but the peak export / peak import ratio tells us another story.

House is one of the building types where the peak export / peak import ratio can become bigger than one. The other typologies are all educational buildings, see the bold values in Table 17, most markedly Schools that reach a value of 1.9 because of their low energy demand during summer. For all such buildings the grid connection should then be dimensioned based on the summer export rather than the winter import. Whether this poses a challenge to the local grid depends on how much this effect is dampened down at the local aggregation level, e.g., at the level of a feeder, due to the coincidence factor between different buildings. For an area with mixed typologies of buildings one may expect no problem would arise since most other buildings show low enough ratios that it means, very likely, they would be able to absorb the extra generation form the nearby school, so that the reverse power flow would not propagate in the grid. Different is the case for a residential neighbourhood dominated by small houses, such as single- and bi-family houses and row-houses. In such an area, where virtually all buildings are houses connected to the same feeder and/or low voltage transformer, the entire neighbourhood is well approximated by the House archetype and may thus incur in either reverse power flow or curtailment. Such considerations are outside the scope of the Flexbuild project and outside the simulation capabilities of the models used in it, which model the energy system in macro regional areas. A dedicated analysis modelling the distribution system would be needed to investigate further on these issues.

Nevertheless, the results presented here tells us that while the cost-optimal level of solar PV installation in a house is, in average, less than 50% of its roof area, the desirable level for a residential neighbourhood may be even lower, lest risking incurring in problems for the local grid.

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5 Energy system in Norway – IFE-TIMES-Norway

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5.1 IFE-TIMES-Norway Model description

IFE-TIMES-Norway (Haaskjold et al., 2022) is a technology-rich model of the Norwegian energy system, divided into five regions corresponding to the current electricity market areas (NO1–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. Operational variations in energy generation and end use are captured by dividing each model period into 96 sub-annual timeslices, where each season (spring, summer, fall, winter) is represented by one day of 24 hours. The model has a detailed description of end-use of energy, and the demand for energy services is divided into numerous end-use categories within industry, buildings, and transport. Each energy service demand category can be met by existing and new technologies using different energy carriers such as electricity, biofuel, district heat, 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 costs and efficiencies.

5.1.1 Building sector

The building sector is divided in three categories, residential single-family and multi-family houses, and commercial buildings. All building types are split into existing (as of 2020) and new buildings for each of the five model regions. The end-use demand includes central heating, point source heating, hot water and electricity specific demand. It is assumed that buildings with central heating can be connected to a district heat grid, while single-family houses cannot be supplied by district heat due to the high cost (Lien, S.K., et al., 2022). All end-use sectors connected to the distribution grid will have to pay a grid tariff, composed by both an energy and a power component. Investments in building applied PV is modelled as an option to reduce the energy demand of the building, where PV can be used either for own consumption or sold to the grid to serve other low-voltage electricity consumption.

5.1.2 End-use flexibility options

In IFE-TIMES-Norway, three flexibility options are included; 1. flexible electric hot water tanks, 2. electric batteries in buildings, and 3. flexible charging of electric vehicles (EVs).

Flexible electric hot water tanks are modelled by allowing for a flexible and non-flexible share. Of the total hot water demand, the non-flexible part delivers at least 70% for both new and existing buildings. The additional cost of installing a flexible hot water tank is assumed to be EUR 400 for a 13 kWh hot water tank. This is based on (Enova, 2022), where the additional cost of a flexible tank is estimated to approximately EUR 300–500, compared to a conventional one.

Electric batteries in buildings are included as investment options in both residential and commercial buildings. It is assumed that the batteries can be fully charged/discharged in 30 minutes, equivalent to a c-rate of 2. The cost of batteries is assumed to be reduced due to technology learning, from 675 €/kWh in 2020 to 400 €/kWh in 2050. The maximum number of storage cycles are assumed to be 4500, and the storage efficiency is set to 90%. In contrast to the BUILDopt model, electric batteries are only included in the flexible model run, and hence not considered an available technology in an inflexible storyline.

Flexible EV charging is included for personal vehicles, with three charging options: at residential buildings, at commercial buildings or fast charging. In the non-flexible case, it is assumed that charging occurs 75% in residential buildings, 15% in commercial buildings and 10% at fast charging (Skotland et al., 2016). The non-flexible charging pattern follows the daily profile illustrated in Figure 31. The flexible case allows for flexibility in both where and when the cars are charged. In terms of charging location, it is assumed that up to 90% can be charged in residential buildings and up to 50% in commercial buildings, while fast charging remains at 10% (no flexibility). In terms of charging time, the EVs have a flexibility of 50% on when to charge in residential and commercial buildings, relative to the profile in Figure 31.

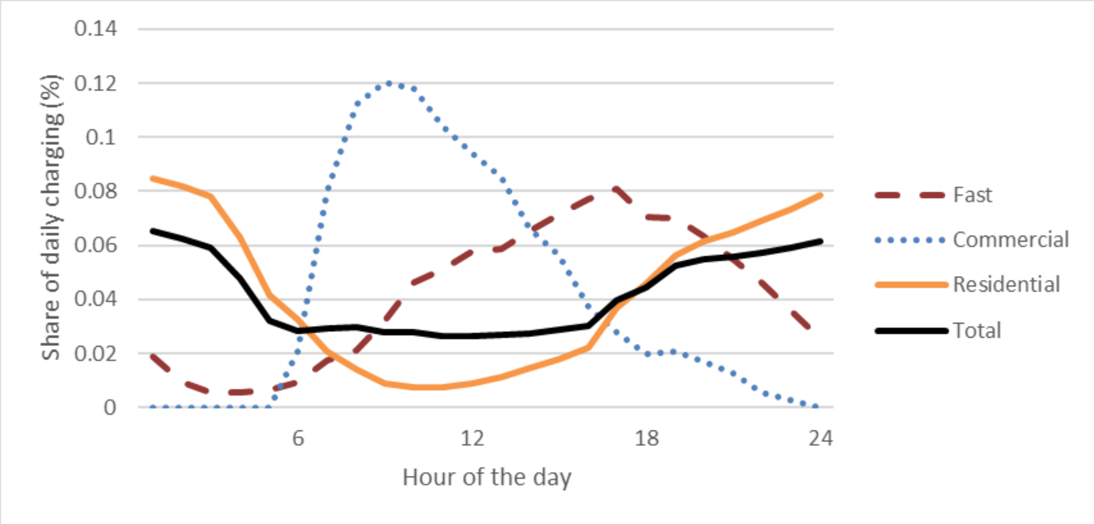

Figure 31. Non-flexible charging pattern, aggregated and disaggregated by charging location. Based on (Skotland et al., 2022).

5.2 IFE-TIMES-Norway inputs and quantification of storylines

The qualitative description of the four storylines has been quantified to be used for analyses with the IFE-TIMES-Norway model. Important quantification needed are the development of energy demand per sector, technology data and limitations on energy production and transmission, energy resources and end-use technologies. All storylines aim at decarbonizing the energy system by 2050, with 85–90% CO_2 reduction targets by 2050 according to the emissions from 2018. The assumptions of the storylines are described in the following. An overview of the assumptions and differences between the storylines is presented in Table 18.

Table 18. Summary of model assumption for the four storylines.

Technology/ demand	Energy nation (EN)	Nature nation (NN)	Climate panic (CP)	Petroleum nation (PN)
		Technology learning		
Blue hydrogen	No	From 2035	No	From 2035
Green hydrogen	High (-67% to -81%)	Moderate (-58% to -69%)	Low (2030), High (2050)	Low
Stationary batteries	High (-71%)	High (-71%)	Low (2030), High (2050)	Low
Building applied PV	Moderate (-57%)	High (-68%)	Moderate (-57%)	Low (-29%)
		Expansion potential		
Building applied PV	High (28 GW)	Low (14 GW)	High (28 GW)	Low (14 GW)
Onshore Wind	High (15 GW)	No new capacity (5 GW)	Moderate (2030) High (2050)	Moderate (8 GW)
Offshore wind	High (16 GW)	High (16 GW)	Moderate (2030), High (2050)	Moderate (12 GW)
National transmission grid	If profitable from 2030	No	If profitable from 2035	If profitable from 2030
International transmission grid	If profitable from 2030	If profitable from 2030	No	No
		Demand projections		
Transport	Moderate (+37%)	Low (0%)	Moderate (2030) Low (2050)	Moderate (+37%)
Industry	High (+5%)	Moderate (-38%)	Moderate (-38%)	High (+5%)

Energy nation

The Energy nation storyline involves a significant growth in energy demand, enabled by high technology learning for green hydrogen and stationary batteries, as well as large expansion potential and cost reductions in building applied PV, onshore wind, and offshore wind. The storyline also allows for large transnational collaboration, with potential to expand both national and international transmission grid. Moreover, there is an increased demand for energy services, mainly from the industry and transport sector. Due to large technology learning and innovation for other new technologies, it is assumed that CCS is not commercialized as it is not a zero-emission solution, and hence blue hydrogen is not available.

Petroleum nation

The Petroleum nation storyline assumes a continuation of current trends with no large breakthroughs in technology innovation and learning. Hence, both renewable generation technologies, hydrogen production and storage solutions remain expensive. Simultaneously, there is an increase in demand from both transport and industry sector, making Norway more dependent on imports from Europe. No new international transmission capacity is assumed, but existing capacity can be utilized, and new domestic investments can be made if profitable. As with the Nature nation storyline, CCS and blue hydrogen is available.

Nature nation

The Nature nation storyline limits intervention to the Norwegian nature, and hence no expansion opportunities is assumed for onshore wind power and national transmission grid. On the other hand, decentralized solutions are favoured, and both building applied PV and stationary batteries has a high technology learning rate. Due to the limited potential for new energy production, a lower demand in the industry and transport sector is assumed, as well as lower technology learning for green hydrogen. To reach a low emission society by 2050, technologies such as CCS and blue hydrogen is made available from 2035.

Climate panic
The Climate panic storyline assumes the same development as the Petroleum nation storyline towards 2030, in which climate panic occur and maximum exploitation of resources is in focus towards 2050. Hence, climate panic adopts both high technology learning and expansion potential from 2030 onwards, while energy demand reduces due to rationing and implement-tation of energy efficiency measures and circular economy. CCS does not succeed to reach the large-scale commercialization necessary to handle the climate crisis, and hence blue hydrogen production is not available.

5.3 Linking IFE-TIMES-Norway with EMPIRE

To provide a consistent equilibrium that captures the interactions between the Norwegian and European power system, IFE-TIMES-Norway is bi-directionally linked to the European power system model, EMPIRE. As mentioned in chapter 3.3, the linking TIMES-EMPIRE expands through the period 2020 to 2050 and includes the four storylines of Flexbuild. Nonetheless, it only entails the non-flexible case where any model considers flexibility at the end-user level.

Energy use in buildings	2020	2030				2050			
		Petroleum	Energy	Nature	Climate panic	Petroleum	Energy	Nature	Climate panic
Non-flexible	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
Flexible	-	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible

Linking TIMES - EMPIRE
TIMES in deterministic mode

Figure 32. Matrix of combinations explored in the linking between TIMES and EMPIRE

5.3.1 Linking methodology

The methodology to link TIMES and EMPIRE follows three sequential steps:

1. Harmonization: The initial step is to harmonize the data input in the model that are stable during the linking iterations. This data includes maximum solar and wind generation capacities, cross-border capacities between Norway and neighbouring countries, adoption of CCS, capital cost for batteries and solar technologies and the adoption of nuclear.
2. Linking: The second step implies sending output from one model to the other and vice versa. Each linking iteration starts with TIMES providing electricity generation capacity and electricity demand for each market area (i.e., NO1, NO2, NO3, NO4 and NO5) to EMPIRE. The data is provided for every five years from 2020 to 2050. Once EMPIRE is solved, the electricity prices and trading capacities are sent to TIMES. illustrates the linking process for both models.
3. Convergence criteria: Finally, the linking step will finalize once the convergence criteria are reached. Two criteria are selected to ensure alignment in generation capacity and prices. The first states that convergence is reached if the difference in capacity for each generation technology between iterations is lower or equal to 0.25%. The second criterium is that the 90th percentile of difference in hourly prices should be below 5€/MWh in all periods.

Further details about the methodology applied is presented in Haaskjold & Alonso (2023).

5.3.2 Results from linking

5.3.2.1 Convergence criteria

The convergence criteria are met after 3 iterations for the Energy nation and Petroleum nation, and 4 iterations for the Nature nation and Climate panic. Note that Baseline case refers to the run of EMPIRE without input data from TIMES but considering the harmonized parameters. Figure 33 shows the maximum level of difference in generation capacity and the maximum 90th percentile of price differences detected between iterations. As can be seen, the most significant changes in generation capacities and prices occur in the first iteration. For the Petroleum nation and Climate panic storylines, wind offshore capacity in Norway fluctuates considerably between iteration #1 and #2, which explains the high rate of change in the figure. Also, all storylines converge in prices after the first iteration. However, the generation capacity criteria imposed further restrictions that lead to perform more iterations.

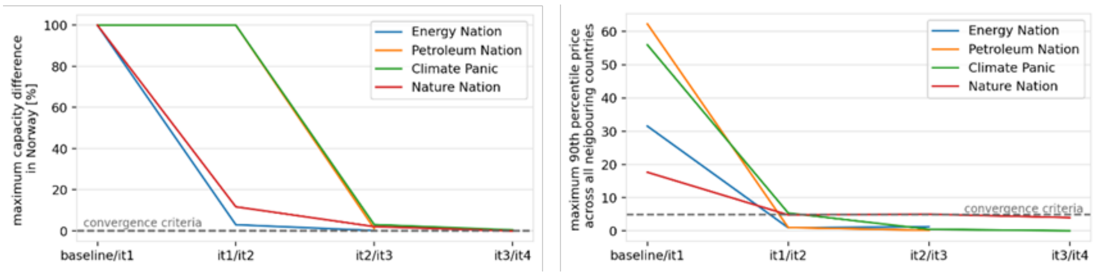

Figure 33. Convergence criteria results for the four storylines. The figures plot the maximum capacity difference (on the left) and the maximum price difference (on the left).

5.3.2.2 Changes in generation mix

For the Norwegian energy system, the linkage leads to higher PV, onshore and offshore wind production. As can be observed from Figure 34, the most significant difference occurs for offshore wind in the Nature nation storyline, with a 6.9% increase in production. For all storylines, the annual electricity consumption varied less than 0.5% across all periods and regions between the model iterations. Instead of serving domestic demand, the increase in production enabled larger export volumes. This is also confirmed by assessing the difference in electricity prices between the iterations, which on a national basis was lower than ~ 3 €/MWh in all storylines.

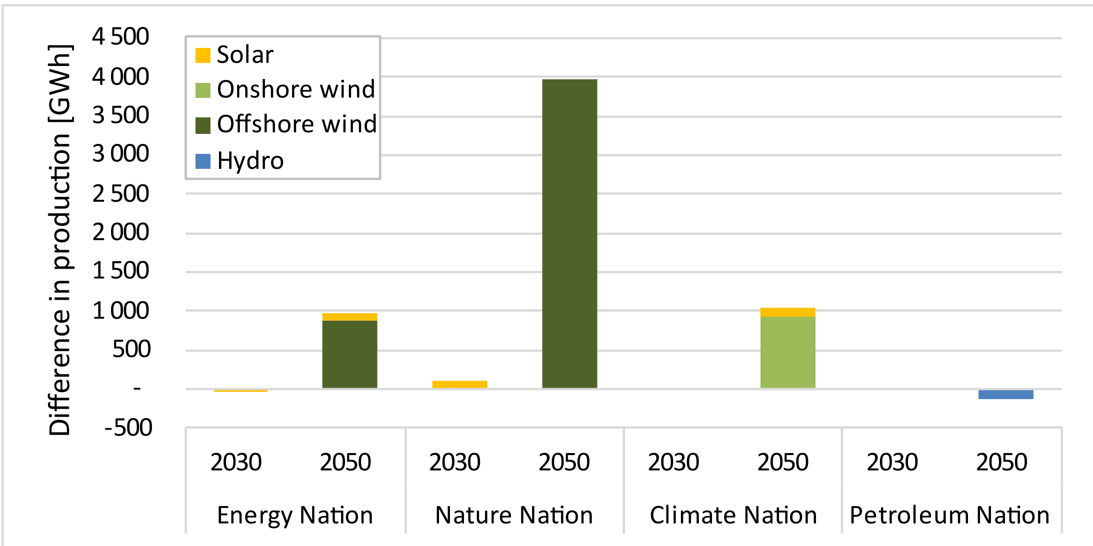

Figure 34. Difference in production from renewable technologies in Norway between first and last iteration for each storyline

For the European power system, the bi-directional linkage impacts the generation mix of the countries connected to Norway. In the Energy nation storyline, the most noticeable differences are in Denmark's capacities for offshore and onshore wind, which are reduced by 12 and 17 GW, respectively. Also, Germany increases its solar capacity by 62 GW after the linking. The changes in the generation mix are smaller in Nature nation. The most significant impact is in Sweden with a decrease in offshore wind capacities of 23 GW and in the UK with an increase in gas capacity of almost 8 GW.

5.3.2.3 Net export from Norway

The net export volumes from Norway are positive in all storylines, except for Petroleum nation. In this storyline, Norway is heavily depending on imports from Europe due to limited expansion of new generation in combination with high demand development. Moreover, the linkage has negligible impact on the volumes. For the other three storylines, the net export volumes after the linkage increases. The largest increase occurs in Nature nation with 8.4%, followed by Energy nation with 4.2%.

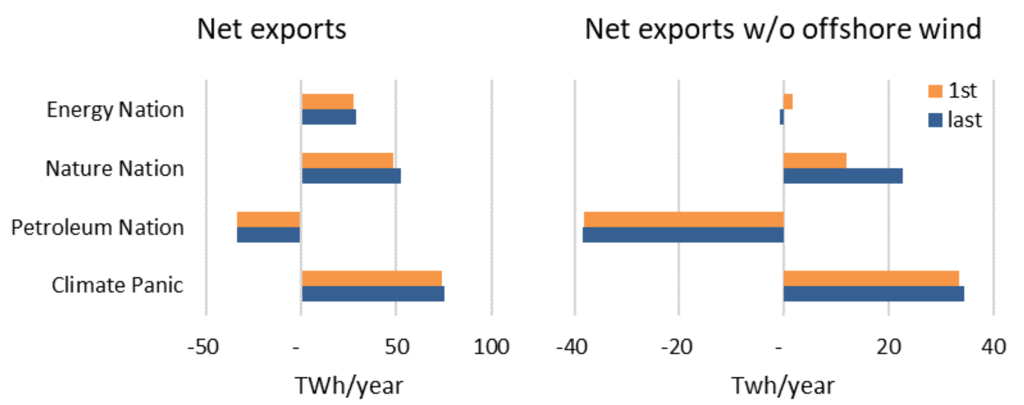

Figure 35. Norwegian net exports by 2050 with (left) and without (right) offshore wind production

As can be observed from Figure 35, offshore wind largely contributes to the net export volumes in all storylines, emphasizing the importance of this energy source for Norwegian value creation. The increase in export between iteration is not caused by higher transmission capacities, but increased utilization of the existing transmission cables between Norway and connected countries. The more efficient utilization is caused by the adaptation in the generation mix in Europe. Neighbouring countries are either decreasing its generation capacity or transitioning to generation sources that better synergize with Norwegian production, ultimately facilitating greater exports from Norway. In terms of country specific trade, Norway mainly increases its export to Denmark, the UK and the Netherlands after the linkage due to generally higher prices observed in these countries.

5.3.2.4 Prices in Europe

Table 19 presents the average prices in neighbouring countries for the baseline case and the last iteration by 2050. It can be observed that the Petroleum nation and Climate panic storylines significantly affect the prices in neighbouring countries. In Pentroleum Nation storylines, there are no changes in prices. This is explained by no changes in imports from Norway. In this and the Climate panic storyline, these countries require to cover their demands from more expensive generation sources, which higher up prices. However, in Nature nation, the net exports from Norway to these countries increases, helping to reduce the average electricity price.

Table 19. Day-ahead prices in neighbouring countries in 2050 for the baseline and last iteration

	Energy nation		**Nature nation**		**Petroleum nation**		**Climate panic**	
	Baseline	Last it.	Baseline	Last it.	Baseline	Last it.	Baseline	Last it.
Denmark	89	3%	82	-1%	80	0%	98	0%
Germany	90	0%	80	-1%	79	0%	99	0%
Great Britain	85	-1%	81	0%	79	0%	93	0%
Netherlands	94	-1%	87	-3%	80	0%	106	-1%
Sweden	75	8%	73	-2%	78	0%	83	0%

5.3.2.5 Key takeaways

The results from linking enables TIMES and EMPIRE to calibrate their outputs considering the strengths of each other. From these quantitative results obtained for the different storylines, several key takeaways are included in Table 20.

Table 20. Key takeaways from the linking between IFE-TIMES-Norway and EMPIRE

Storyline	**Takeaways**
Energy nation	✓ High demand in Norway increases prices and lowers net-export ✓ High self-sufficiency is achieved despite the large interconnection with Europe
Petroleum nation	✓ CCS lowers fluctuations in European electricity prices ✓ CCS promotes the adoption of wind in all Europe ✓ High demand in Norway and low generation and transmission capacity expansions leads to high prices in Norway ✓ Norway becomes a net importer given their high demand and restrictive production capacity
Nature nation	✓ CCS lowers fluctuations in European electricity prices ✓ CCS promotes the adoption of wind in all Europe ✓ Norway becomes a net exporter
Climate panic	✓ Self-sufficiency and low demand keep steady and low prices ✓ Large net exporter due to offshore wind expansion ✓ These outcomes are achieved by 2050, but there is a low transition until becoming net exporter and reach low prices and large renewable investments.

5.4 Linking IFE-TIMES-Norway with BUILDopt

The overall linking methodology is described in chapter 3.3. This section presents details of the data exchange and results by IFE-TIMES-Norway for the Full linking simulations only, as shown in Figure 36.

Energy use in buildings	2020	2030				2050			
		Petroleum	Energy	Nature	Climate panic	Petroleum	Energy	Nature	Climate panic
Non-flexible	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
Flexible	-	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible

Linking TIMES - BUILDopt
TIMES in deterministic mode
Flexibility (Cost minimisation) – iterations until convergency

Figure 36. Matrix of combinations explored in the full linking between TIMES and BUILDopt

5.4.1 Linking methodology

The entire building sector in IFE-TIMES-Norway is replaced by demand of energy carriers per time slice calculated from results of BUILDopt, see Figure 37. This includes space heating, heating of domestic hot water, electric appliances, cooling, stationary batteries and charging of private cars at home or work. In addition, electricity production from building applied PV is excluded from the optimization of IFE-TIMES-Norway and replaced by input data from BUILDopt. Charging of VANS (light commercial vehicles) remains as a part of IFE-TIMES-Norway, as well as all other transportation, industry, energy production and infrastructure.

The input data from BUILDopt used by IFE-TIMES-Norway in the linking were energy carriers per hour for two years (2030 and 2050). The demand and profile of the following energy carriers were used:

- Electricity from grid
- Electricity to grid (sold PV)
- Large district heating
- Local district heating
- Wood firing in stoves

Bio energy boilers in residential and commercial buildings is excluded from the linking analyses and the only use of bio energy is use of wood in stoves in residential houses.

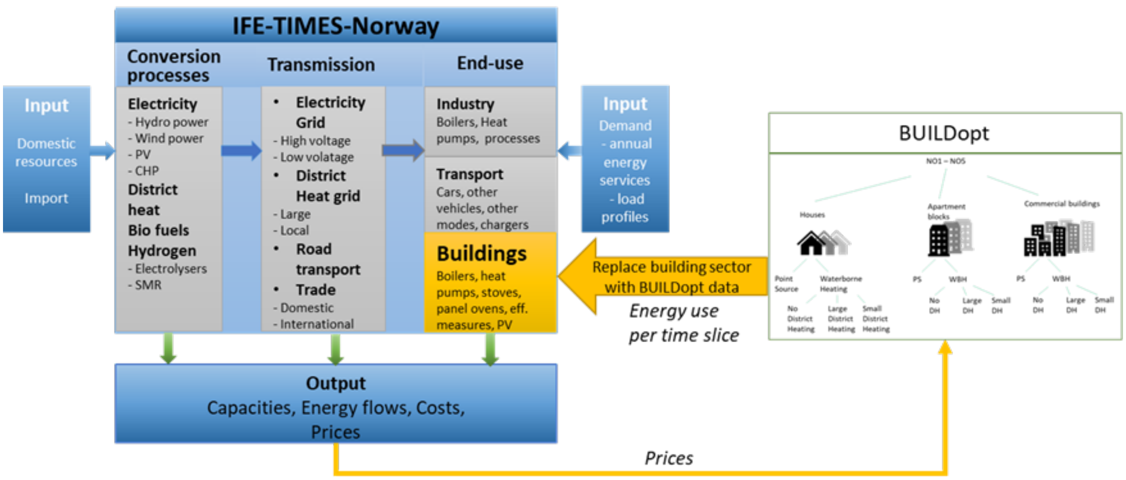

Figure 37. Schematic overview of linking between IFE-TIMES-Norway and BUILDopt

5.4.2 Results from linking

In the linking process, all building technologies in IFE-TIMES-Norway is replaced by load profiles from BUILDopt. Hence, it is not possible to compare the differences on a technology level in the building sector in IFE-TIMES-Norway, only on an aggregated level of load profiles and energy prices. The total energy system cost is also impossible to compared since the cost of the entire building sector is missing. No notable effect on the Norwegian energy generation system is observed, due to the linking with BUILDopt. The electricity generation from hydro and wind is unchanged and since the building part of PV is replaced by input data from BUILDopt, it is difficult to compare the PV generation.

Load shaving and valley filling is observed in all seasons and the convergence occurs after the first iteration in all seasons but winter. The load in a winter day shows a more complicated picture. During nights the peak "jumps" between 2 and 4 o'clock, but in all iterations it is a valley filling compared to the base case. The rest of the winter day shows a convergence after two iterations with a peak shaving during evenings. Overall, the iteration gives a load profile with the same peak as before and with a reduced valley during nights. The hypothesis of a flat load profile is not achieved, although it is less variable than in the base case. As an example, the electricity load profile in 2050 in NO1 is presented in Figure 38.

The peak load in NO1 is almost unaffected in a winter day, but in the other seasons it is considerable reduced (19% reduction in a spring day, 21% in summer and 10% in fall). In NO2 there is observed an increase in peak load by 8% in the winter. In the other regions, the winter peak load is decreased by 5% in NO2, 3% in NO3 and in NO5 the decrease is 8%.

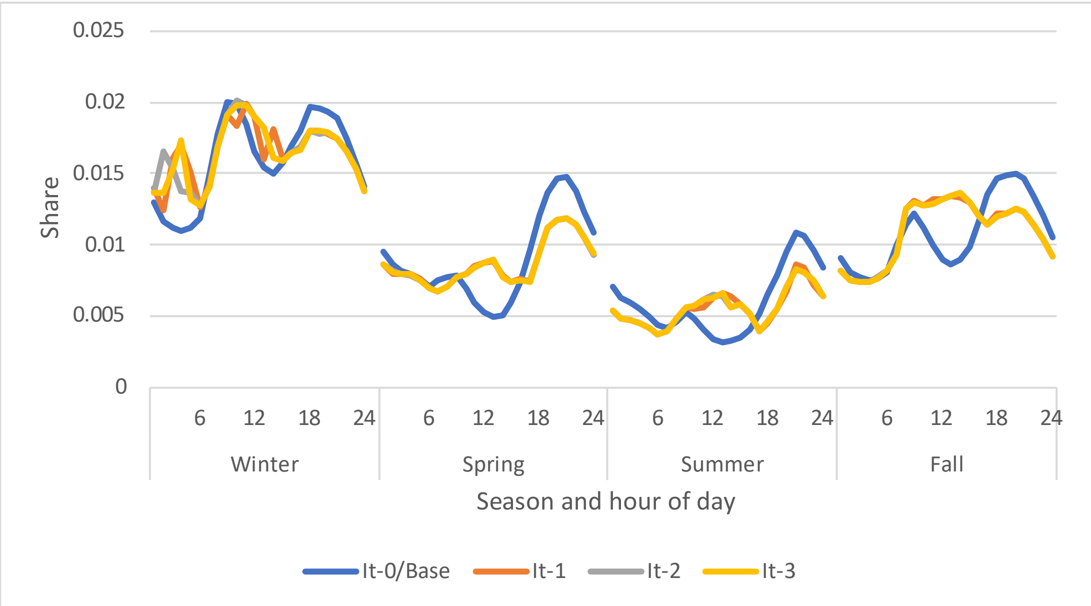

Figure 38. Electricity load profile 2050 in NO1 for the base case and three iterations, per season and hour of day

The electricity prices have a peak in the morning in region NO3 and NO5 in the base case, and this is removed completely after two iterations, see example of NO5 in Figure 39. In NO5 there was also a peak in the evening that is removed after the first iteration. In the other regions, the effect of the electricity price is much less. The price level a winter day in 2050 in NO1 is in average 3% less than in the base case, but the profile is unchanged, see Figure 40. The price during spring daytime is reduced in regions NO1, NO2 and NO5 by 20% (NO1), 16% (NO2) and 23% (NO5).

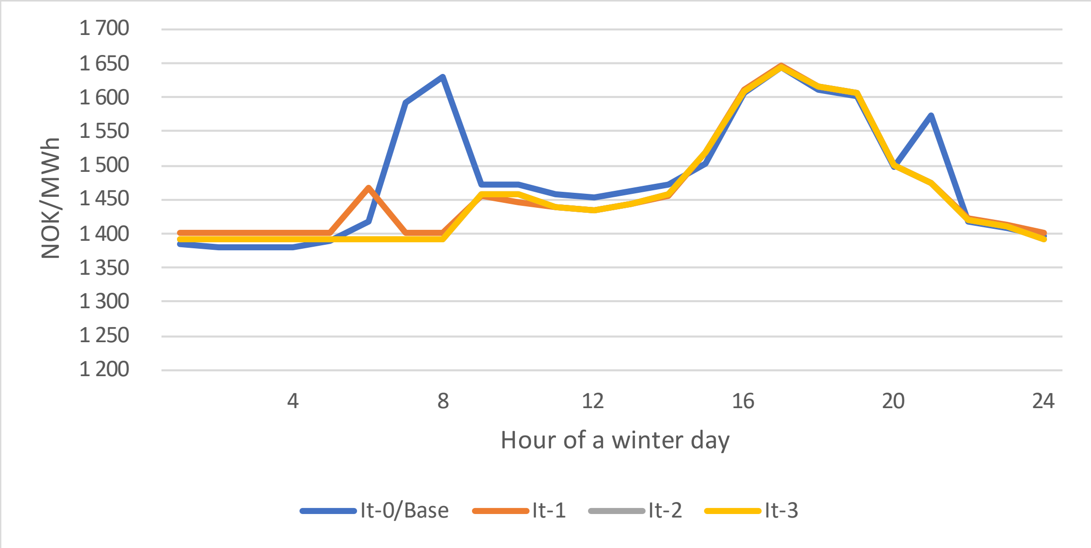

Figure 39. Electricity price a winter day in 2050 in NO5, NOK/MWh

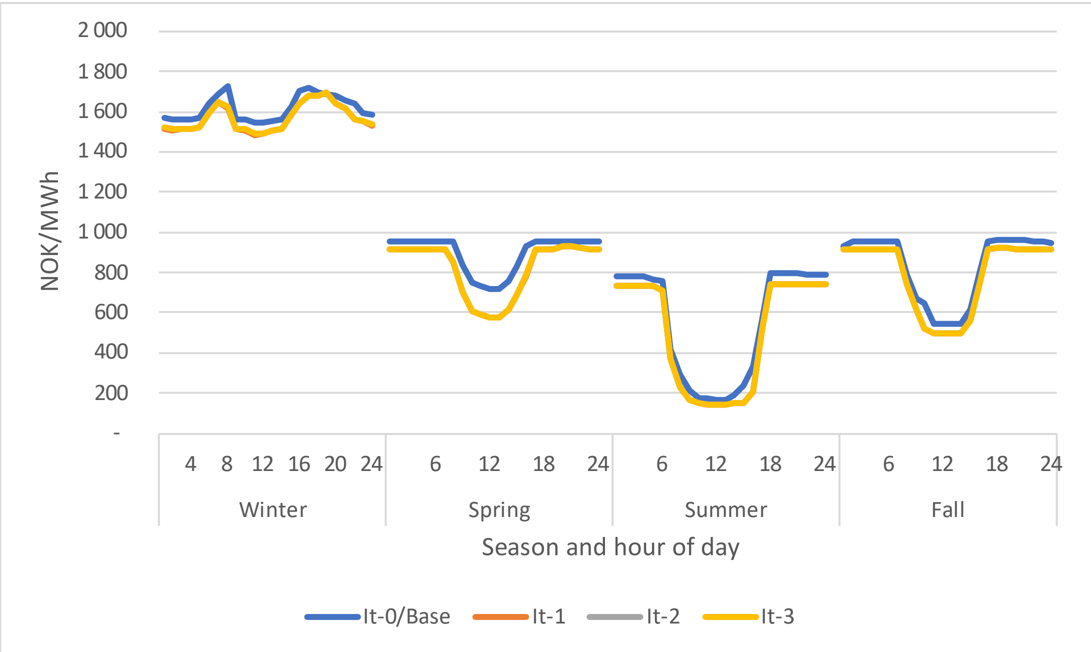

Figure 40. Electricity price in 2050 in NO1, NOK/MWh

The total system cost of IFE-TIMES-Norway as a result of the heuristic linking increased due to the enforcement of a flat profile that caused increased energy use as input from BUILDopt to TIMES (energy not being used). The heuristic linking gave a reduced peak in all seasons but also caused other unexpected results such as increase prices.

The first iteration of the full linking is a good approximation of the convergent case, suggesting that is sufficient to reduce the analysing time of the linking process to only one iteration. In other words, this means that buildings remain fundamentally price-takers. The fact that energy demand becomes flexible for the entire building stock (not for just a single or few buildings) has only a marginal impact on the energy price formation, as shown in Figure 39 and Figure 40.

On the contrary, the hypothesis of a flat load profile in the heuristic linking did not work as intended, and therefore the results of the heuristic linking gave less results than expected.

5.5 IFE-TIMES-Norway results and discussion

A stochastic version of IFE-TIMES-Norway is used to analyses the role and value of end-use flexibility in the Norwegian low carbon energy system transition towards 2050. The results demonstrate that end-use flexibility lowers the cost of the energy transition significantly. This is primarily due to that end-use flexibility ensures a better match between local PV production and demand, lowers the capacity expansion needs of the electricity grid and increases the profits of international electricity trade. Further, we show that end-use flexibility lowers the need for hydrogen and thermal storage and lowers the district heat production.

This section gives a brief summary of the methodology and results from Seljom et al. (2023), which focuses on the Energy nation and Nature nation storylines, as shown in Figure 41.

Energy use in buildings	2020		2030				2050		
		Petroleum	Energy	Nature	Climate panic	Petroleum	Energy	Nature	Climate panic
Non-flexible	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
Flexible	-	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible

TIMES in stochastic mode
Flexibility internal to TIMES

Figure 41. Matrix of combinations explored using the stochastic mode of TIMES

5.5.1 Methodology

To address the future value of end-use flexibility, we use IFE-TIMES-Norway, with a detailed representation of end-use and that captures the sector coupling between the surrounding energy system. We use a stochastic modelling approach to explicitly capture how the value of end-use flexibility changes under short-term uncertainty in European power prices that is aligned with EMPIRE. Further, the analyses are executed for two different storylines, Energy nation and Nature nation.

We focus on analysing the effect and value of three flexibility options of buildings; 1. flexible electric heating of hot water tanks, 2. stationary batteries, and 3. flexible charging of electric vehicles. We quantify the energy system effect of these end-use flexibility options, and the corresponding economic impact, by comparing the difference in the value and solution between the model cases with and without end-use flexibility. Note that the investment costs of the end-use flexibility are included, and thus the difference between the flexible and non-flexible case illustrates the value of facilitating a techno-economic implementation.

5.5.2 Results

Implementation of 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 towards 2050. The energy system cost, covering the period is lowered by 8.3 BEUR and 4.4 BEUR for Energy and Nature nation respectively when investments and operation of end-use flexibility is an option.

Stationary batteries in buildings and flexible hot water tanks are techno-economic solutions in both storylines, where the storage capacity is larger for Energy than Nature nation. However, 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.

Except for winter, the EV charging is moved to the middle of the day when the sun is shining. This is both due to that end-use flexibility enables increased self-consumption of PV, but also because the electricity prices are correlated to the 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, the charging is moved away from the morning peak for both residential and commercial buildings.

Energy system impact
The results indicate that end-use flexibility has a limited impact on the optimal capacity expansion of the electricity sector, but that is increases the investments in building applied PV and marginally lowers the investments in onshore wind and Run-of-the-River hydropower.

End-use flexibility lowers the peak electricity demand and smoothens the daily profile of the electricity demand. The electricity demand in a winter day is flattened with end-use flexibility, whereas for the other seasons, the demand in the middle of the day is increased to better correlate the demand with the PV production and lower electricity prices. For the low voltage electricity demand, the expected peak demand reduction, ranges from 5 to 11%, depending on spot price region and storyline.

In general, end-use flexibility has a limited effect on the electricity prices. Nevertheless, for some operational situations, end-use flexibility contributes to flatten the prices, both by increasing the prices when they are low, and decreasing the prices when they are high.

End-use flexibility influences the investments in other storage options in the energy system, including hydrogen storage and thermal storage in the district heat sector. For example, the hydrogen storage capacity is lowered by 35% to 65% depending on storyline. However, the results demonstrate that a stochastic modelling approach is necessary to analyse the future storage needs, as a deterministic modelling approach underestimates investments in energy storage.

Impacts in profits and costs
For electricity generation, the end-use flexibility impacts on profits are marginal, and varies with storyline and types of electricity generation. For both storylines, end-use flexibility increased profits for run-of the river hydropower and onshore wind power. The income of international trade increases with end-use flexibility, as enables Norway to sell more electricity when prices in Europe are high, and to buy more electricity when prices in Europe are low. For the building sector, the end-use flexibility lowers the energy costs of the building sector with 4 to 5%.

5.6 References

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6 Hydropower system in Norway – EMPS

Linn Emelie Schäffer (SINTEF)

6.1 EMPS model description

In this project, the EMPS model is used to assess the impact of flexible end-use of electricity demand on the hydropower dominated Norwegian power system.

6.1.1 Brief description of the EMPS model

The EMPS model is a fundamental hydro-thermal power market model with a detailed representation of the Nordic hydropower system (Helseth, 2020). The model optimizes power production to meet electricity demand at the lowest possible socioeconomic cost considering uncertainty in inflow, wind power, solar power and temperature. The model provides optimal operational decisions for power production, reservoir management and electricity exchange for a 3-hour resolution given a stationary system description of the North-European power system over a yearly planning horizon. The Nordic region is particularly detailed modelled, including a complete description of the Norwegian hydropower system with more than 1000 hydropower reservoirs and plants. Uncertainty is modelled for weekly stochastic stages. The model is used extensively in the Nordic countries for price forecasting, transmission expansion planning, and analysis of security of supply (Wolfgang, 2009).

6.1.2 Representation of electricity demand

Electricity demand is modelled by defining a yearly average expected quantity, seasonal weekly-demand profiles, and intra-weekly profiles for demand variations for each week of the planning horizon. Different types of electricity demand can be modelled by different seasonal and weekly profiles. Each type of electricity demand can be defined to be temperature dependent (stochastic) and/or price-dependent (price elastic). It is also possible to define separate price-dependent contracts, e.g., to represent specific types of industry demand in a region.

6.2 EMPS inputs and quantification of storylines

Operation of the Energy nation storyline in 2030 and 2050 is modelled using the EMPS model. Two different cases are simulated: with and without end-use flexibility in the Norwegian building stock. The quantification of the storyline is based on an existing dataset (Schäffer, 2019) for a low-emission European power system in 2030 and input data from the model-runs and linking of the IFE-TIMES-NORWAY, BuildOpt and EMPIRE models.

Energy nation

To harmonize the assumptions in EMPS with the storyline, fuel- and CO_2-prices from the EMPIRE simulations are used. Besides this, no changes to the European power system outside Norway have been made from the original dataset. To align with the Energy nation storyline the description of the Norwegian power system is based on the results from the IFE-TIMES-NORWAY model. This is further described in the next section.

6.3 Linking EMPS with IFE-TIMES-Norway

The EMPS simulations of the Energy nation storyline are based on the results from the full linking between the IFE-TIMES-NORWAY and BuildOpt models. The optimal configuration of the Norwegian power system for the Energy nation storyline is included in the EMPS model by conducting a one-directional linking between the EMPS model and IFE-TIMES-NORWAY model. The one-directional linking of the EMPS and IFE-TIMES-NORWAY models have been used for the cases shown in Figure 42. As previously discussed in chapter 1.4, end use-flexibility is modelled in BuildOpt and reflected in the IFE-TIMES-NORWAY results through the linking between IFE-TIMES-NORWAY and BuildOpt. Consequently, the resulting optimal investments in the Norwegian power system towards 2050 from the IFE-TIMES-NORWAY model, may change slightly due to different levels of end-use flexibility available in BuildOpt.

In the EMPS model, wind and solar power generation, transmission grid capacities, electricity demand and seasonal and weekly demand-profiles for Norway are defined based on the results from IFE-TIMES-NORWAY linked with BuildOpt. The results from the linking between IFE-TIMES-NORWAY and BuildOpt are discussed in chapter 4.4 and 5.4.

Energy use in buildings	2020	2030				2050			
		Petroleum	Energy	Nature	Climate panic	Petroleum	Energy	Nature	Climate panic
Non-flexible	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
Flexible	-	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible

Linking TIMES - EMPS
TIMES in deterministic mode
Flexibility (Cost minimisation)

Figure 42. Matrix of combinations explored using EMPS with inputs from TIMES (when linked with BUILDopt)

6.3.1 Modelling of electricity demand and end-use flexibility

The electricity demand in EMPS is assumed to be fixed, i.e., not dependent on the power price, as the price sensitivity of the demand already has been considered in BuildOpt and IFE-TIMES-NORWAY. This implies that end-use flexibility is not modelled explicitly in the EMPS model. Instead, the EMPS model is used to evaluate the impacts on the operation of the Norwegian hydropower system of considering end-use flexibility in the BuildOpt and IFE-TIMES-NORWAY models. This is done by using the resulting electricity demand and yearly profiles for household demand from the other models as input to the EMPS model. These profiles represent the main difference between the Flex and Base case.

Figure 43 (left) shows total demand on a 3-hour resolution over one year in the Flex and Base cases together with the duration curve for demand for year 2030, in the EMPS model. Figure 43 (right) shows the variation from one time-step to the next (3-hour time steps). The same is shown for 2050 in Figure 44, the plots illustrate the total electricity demand in NO1 which is the price area with the largest building-stock. For 2030, the entire demand curve is shifted downwards in the Flex case, reducing both the maximum and minimum demand compared to in the Base case. The short-term variation in demand (from timestep to timestep) is also reduced in the flex case as can be seen by the flatter duration curve in Figure 43. In 2050, the duration curve for the demand is slightly flattened in the Flex case compared to in the Base case, indicating that there are slightly fewer hours with both very high and very low demand (Figure 44). Like in 2030, the short-term variation in demand is reduced in the Flex case compared to in the Base case. It should be noted that the household demand constitutes a smaller share of the total demand in 2050 than in 2030 potentially reducing the overall impact of end-used flexibility on the total demand.

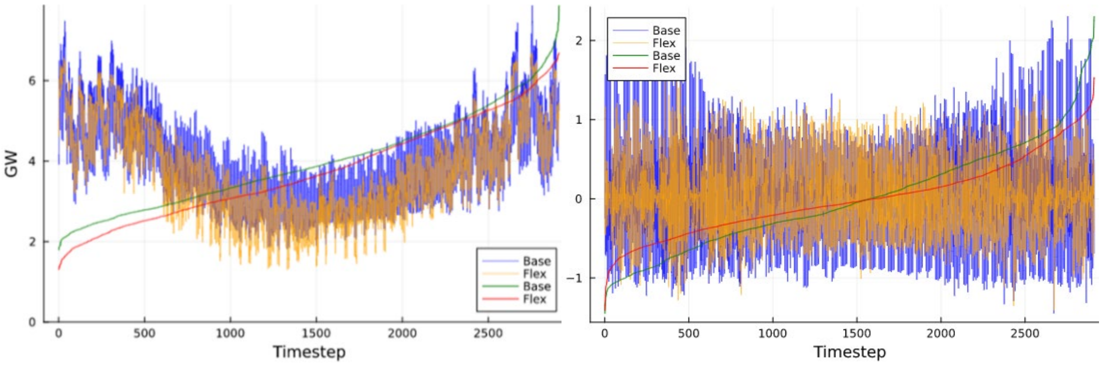


Figure 43. Total demand in NO1 for the Energy nation storyline in 2030 in the EMPS model, on a 3-hour resolution plotted for an example year (left) and variations in total demand from each 3-hour timestep to the next (right). The blue and orange lines show the Base and Flex cases, respectively. The green and red lines show the duration curves for the Base and Flex cases, respectively.

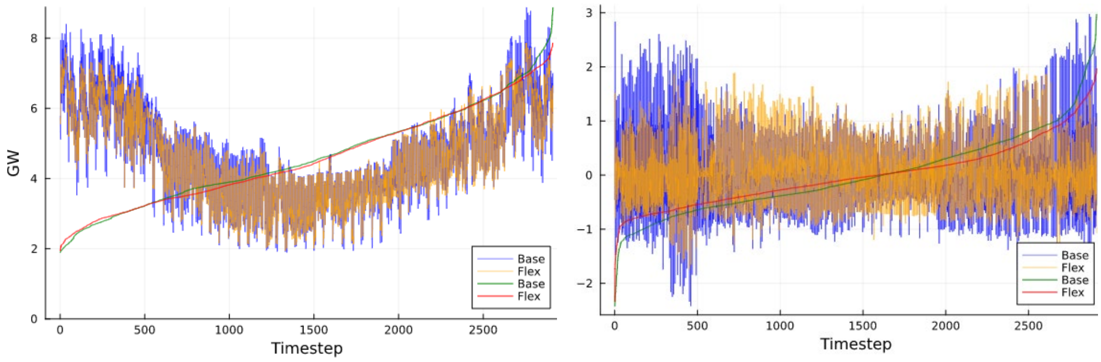


Figure 44. Total demand in NO1 for the Energy nation storyline in 2050 in the EMPS model, on a 3-hour resolution plotted for an example year (left) and variations in total demand from each 3-hour timestep to the next (right). The blue and orange lines show the Base and Flex cases, respectively. The green and red lines show the duration curves for the Base and Flex cases, respectively.

6.4 EMPS results and discussion

In general, end-use flexibility is found to only induce small changes on the power system level. The results from IFE-TIMES-NORWAY show that there is a slight reduction in energy demand in 2030 and 2050 when end-use flexibility is considered, which results in a slightly higher surplus of energy in Norway. The largest difference is seen in the demand-profiles for household demand from the BuildOpt model.

The results from the EMPS model simulations evaluate the implications of end-use flexibility on the operation of the hydropower-dominated Norwegian power system given the optimal electricity demand-profiles and power system investments from BuildOpt and IFE-TIMES-NORWAY. This section discusses the changes in hydropower operations and economics induced by considering end-use flexibility compared to when end-use flexibility is not included.

6.4.1 Power prices

A main result from the EMPS model is the expected power price. The results give a large difference in the resulting average power prices in 2030 and 2050 for the Energy nation storyline, as shown in Figure 45. This is mainly due to the price impact from other European countries and the differences in the assumed fuel and CO_2-prices in 2030 and 2050.

We are in this study mainly interested in the difference between the Flex and Base case to evaluate the impact of end-use flexibility. In general, there are only small changes in the power price in the Flex case compared to the Base case. The average power price is slightly reduced in the Flex case compared to the Base case in 2030 and 2050. In 2030, there is a slight reduction in the amount of high price hours and a slight increase in the number of low-price hours as shown in Figure 46. The lower power prices are likely a result of the slightly higher energy surplus in the Flex case compared to the Base case and the reduction in peak demand. In 2050, the difference is smaller but there is a slight reduction in the number of hours with high power prices in the Flex case compared to the Base case. Furthermore, there is a slight reduction in the number of low-price hours, indicating that the end-use flexibility is giving a small reduction in number of hours with extreme prices (low and high). This is in line with the slightly flatter demand curve in the Flex case in 2050, as shown in Figure 44.

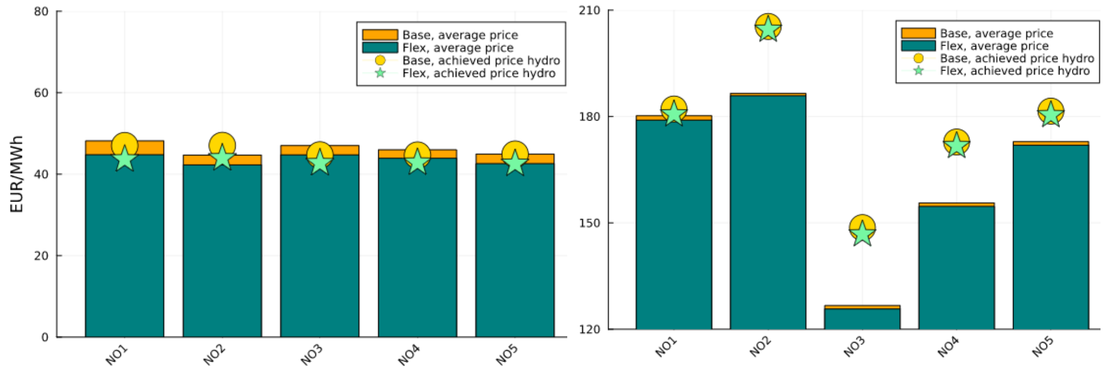


Figure 45. The bars show the average power price in each price area in Norway in 2030 (left) and 2050 (right) for the Base and Flex cases, while the circle and star give the achieved power price for hydropower in the same area for the Base and Flex case, respectively.

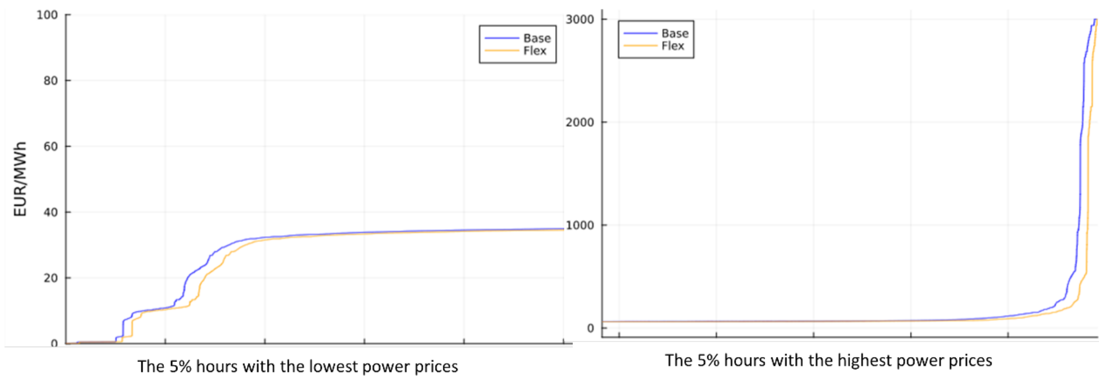


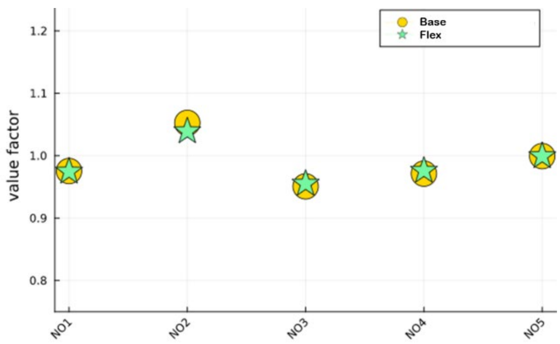
Figure 46. The 5% hours with the lowest power prices (left) and the 5% hours with the highest power prices of (right) of all simulated timesteps for NO1 in the Energy nation storyline for 2030 on a 3-hour resolution. The blue line plots the simulated prices in the Base case and the orange line in the Flex case.

6.4.2 Impacts to hydropower producers

Only minor changes are seen in the power production from hydropower on an aggregated level and on the storage of water in the reservoirs between the Base and Flex case. In 2030, the total power production from hydropower is reduced or increases with less than 0.1% in the different areas. In 2050, the total power production is slightly reduced, but still the changes are minor with a reduction in average power production below 0.3% in all areas.

Flexible hydropower plants can often achieve a higher average power price per unit of produced energy (EUR/MWh) over the year compared to the average price of energy produced by all technologies because of the hydropower plant's flexibility to increase and decrease production depending on the price. The achieved power price of hydropower is plotted in Figure 45 together with the average power price for the Base and Flex cases in 2030 and 2050. In 2030 there is not a large difference between the average power price and the achieved power price for hydropower, but in 2050 the achieved power price for hydropower is considerably higher in some of the areas. Both in 2030 and 2050, the achieved power prices are slightly lower in the Flex case than in the Base case.

The value factor (also sometimes referred to as the flexibility factor) is found by dividing the achieved power price on the average power price. The value factor can be used to evaluate the added value of being able to adjust production, i.e., the value of flexibility. The value factor for hydropower in 2030 and 2050 is plotted in Figure 47, respectively. In 2030, the value factor lies between 0.9–1.1 which indicated that there is not a large added value of flexibility for hydropower compared to an average production profile. Furthermore, the value factors in the Base and Flex cases are about the same, except for in NO2 where the value factor is slightly reduced in the Flex case. In 2050, the value factor lies between 1–1.2 in all areas, indicating a higher value of flexibility than in 2030. Still, the value factors in the Base and Flex cases are about the same, except for in NO3 where the value factor is slightly lower in the flex case. These results indicate that the changes in the electricity demand caused by considering end-use flexibility, has very small implications on the value of flexibility for the hydropower plants. The main impact is seen by the reduction in power price and high-price periods, which reduce the value of power production and thereby also the achieved power price for hydropower producers. It should be noted that these calculations are based on the aggregated hydropower production in each area. For individual hydropower plants larger changes may occur.



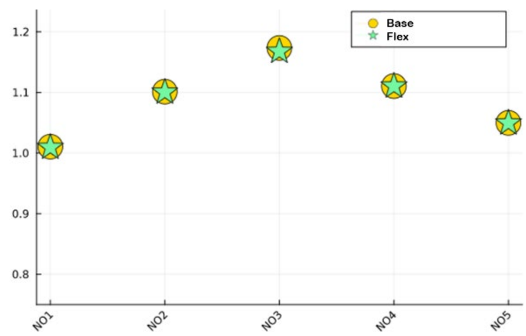


Figure 47. The value factor for hydropower in each price area in 2030 (left) and 2050 (right) for the Base case (yellow circle) and Flex case (green star).

6.4.3 Change in income

As discussed in the previous section, the achieved power prices for hydropower are slightly reduced in the Flex case compared to the Base case. However, the value factors are about the same in the Flex and Base case, indicating that the slightly lower achieved power prices in the Flex case mainly is a result of the reduced power prices and not necessarily represent a reduced value of flexibility.

The change in income in the Flex case compared to in the Base case for selected technologies are given in. In general, there is a reduced income for both hydropower and wind power producers in the Flex case, Table 21. The larger relative differences are seen for 2030 for all technologies, but especially for hydropower.

Table 21. Change in average yearly income in the Flex case compared to the Base case in 2030 and 2050 for hydropower, onshore wind and offshore wind

	Hydro	Wind onshore	Wind offshore
2030	-0.374 billion EUR/yr (-5.6%)	-0.039 billion EUR/yr (-3.5%)	-0.002 billion EUR/yr (1.2%)
2050	-0.184 billion EUR/yr (-0.7%)	-0.041 billion EUR/yr (-0.63%)	-0.045 billion EUR/yr (-0.54%)

6.4.4 Discussion

We only see small implications to hydropower producers on an aggregated power system level of considering end-use flexibility in the building stock. This is reasonable, as there only are minor changes in the optimal configuration of the power system in the Base and Flex case from IFE-TIMES-NORWAY. The main differences between the Base and Flex case definitions in the EMPS-analysis are the seasonal and intra-week demand profiles and a slight reduction in the total electricity demand in the Flex case. The results show that the reduced electricity demand gives a slightly lower power price and reduced average yearly income from hydropower production. Still, only small to no changes are seen in the total power production from hydropower and the use of the reservoirs to store energy, on an aggregated level.

The results show large differences between the 2030 and 2050 results. The power prices and the value of flexibility for hydropower producers are considerably higher in 2050 than in 2030. The higher power prices in 2050 are mainly due to the assumed fuel- and CO_2-prices in Europe. In combination with larger shares of wind power in the Norwegian power system, the price variability in the Norwegian power system in 2050 is much higher than in 2030, which gives a higher value of flexibility. However, both in 2030 and 2050 there are only small difference between the Base and Flex cases. The largest relative impacts of considering end-use flexibility are seen in the reduction in income for hydropower producers in the 2030 Flex case. The larger relative impact of end-use flexibility in the 2030 case compared to the 2050 case is reasonable as the electricity demand from the building stock constitutes a larger share of the total demand in 2030 than in 2050. End-use flexibility in the building stock therefore has a larger impact on the total demand in the power system in 2030. Furthermore, variability in electricity demand is a smaller contributor to the total variability in the power system in 2050 than 2030, due to larger shares of wind power in 2050. Overall, the impact of activating end-use flexibility in the building stock therefore has a larger relative impact on the system in 2030 than in 2050, even though there is a higher value of flexibility in 2050.

Finally, the representation of end-use flexibility in the conducted EMPS-analysis can be discussed. The flexibility in electricity demand was optimised in BuildOpt and IFE-TIMES-NORWAY, which have more detailed representations of electricity demand than the EMPS model. The resulting electricity demand profiles were then taken directly into the EMPS models as an input, and the price elasticity of the demand in the EMPS-model was deactivated (to not consider end-use flexibility twice). This approach allowed us to analyse the impact of different profiles for electricity demand using the EMPS-model. However, the demand-flexibility was not optimised towards the other assumptions in the EMPS-model, such as variability in the wind- and solar-power series. A larger impact of end-use flexibility could therefore be seen if end-use flexibility was modelled directly as a price-elasticity in the EMPS-model, based on the results from the BuildOpt and IFE-TIMES-NORWAY. This approach should be considered for future analyses of end-use flexibility on the power system.

6.5 References

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7 Reflections and Prospects in enhancing End-use flexibility

Pedro Crespo del Granado (NTNU) based on interviews with the non-research partners

Considering the multifaceted outcomes and insights derived from the Flexbuild project, non-research project partners – grid companies, building developers, and public authorities – have shared some reflections and inputs on the role of end-use flexibility in Norway's future energy system considering this report. This chapter summarizes some contributions from these discussions.

7.1 The impact of short-term flexibility

Flexbuild objectives 3 and 4 (see Chapter 2) outlined the impacts of varied power tariffs on both end-users and the energy system, and the value of end-use flexibility for mitigating power grid reinforcement, respectively. The distinction between tariffs based purely on an energy fee and those incorporating a power fee component was stark, with the latter facilitating the identification of the most convenient peak load levels, effectively setting a cost-optimal cap on the peak demand from a single building viewpoint. It was noted that that end-use flexibility could notably decrease the peak load by a significant margin at a single building level and at an aggregated level, although the effect might be diminished due to the coincidence factor.

Likewise in Objective 5, the primary impact was a slightly lower power price due to a marginally reduced total demand for electricity and reduced peak demand, which resulted in a minor decrease in the yearly average income for hydropower producers. These finding are very important according to industrial and user partners (e.g., Statnett and NVE) of the Flexbuild project. That is, end-use flexibility impacts short term operations of the power system with the following noteworthy implications:

- *Peak hours reduction:* Although some of the conclusions and central take aways highlight the overall average reductions, the report also illustrated the role of end-use flexibility on creating large reductions ("big jumps") in price due to flexibility. This is a very noteworthy highlight and finding of the project.
- *Flexibility duration:* Valuing end-use flexibility will also depend on how many hours flexibility can last, i.e., how long flexibility stays in the market duration? According to Statnett projections the total potential of flexibility from buildings can be around 5 TWh.

7.2 Power grid infrastructure investments

It was noted that end-use flexibility might influence investments in power grid infrastructure by its ability to synchronize local photovoltaic (PV) production with demand, consequently alleviating the pressure for capacity expansion within the electricity grid. According to the insights project results, end-use flexibility not only enhances the profitability of international electricity trade but also diminishes the energy costs within the building sector, proving its merit as a techno-economic investment from an energy system perspective. Hence, as a byproduct this will potentially reduce the necessity for hefty investments in grid expansion, especially in scenarios with a high degree of cross-national interconnection.

A clear finding is end-use flexibility capability to considerably reduce peak load – at a single building level by roughly between 20-50%, and at the NO-market areas level by between 16-20% for building energy use. End-use flexibility mitigates the stress on the power grid, thereby potentially minimizing the need for substantial infrastructural investments. For instance, in the stochastic version of the IFE-TIMES-Norway model, end-use flexibility was demonstrated to alleviate peak electricity demand and consequently diminish the expansion need of the electricity grid, particularly at the distributional grid level where electricity peaks in winter were lowered from 5 to 11%. Moreover, the report highlighted that the total costs in the European power system from 2020 to 2050 could be reduced by about 1% if residential flexibility is optimally scheduled. Based on these results, industrial and user partners raised the following points in relation to the effect of infrastructure investments:

- *Energy Efficiency:* Statnett and TOBB noted the importance of energy efficiency as an alternative to grid and related infrastructure investments. Incentives for buildings refurbishment can go hand-by-hand with end-use flexibility. That is, Energy efficiency, complemented by end-use flexibility, optimizes power consumption patterns, reducing peak demand and alleviating stress on the power grid. There are important questions on understanding deeper how flexibility solutions come along with energy reductions.
- *Heat vs electricity analyses:* Flexbuild partners noted that electricity is cost effective and hence brings a higher importance on developing schemes for the smart use of end-use flexibility. That is, higher electrification in the next decades will make end-use flexibility *even more* valuable.

7.3 Regulatory perspectives on end-use flexibility

Regulatory aspects of end-use flexibility are critical in determining the effectiveness and efficiency of the energy system. In Flexbuild, the introduction of stochastic modelling in assessing energy storage investments, particularly end-use flexibility, highlights the importance of capturing uncertainty in decision-making. A traditional deterministic approach may undervalue investments in flexibility and other storage solutions. This has significant implications for regulatory frameworks that guide energy investments. If regulatory decisions are based on deterministic models, there's a risk of under-investing in end-use flexibility, potentially leading to less optimal outcomes for the energy system. These deep technical understanding are not always straightforward to comprehend for all partners and maybe the general public. But it underscores the complexity of understanding the energy system dynamics (sectors, grids, power producers, etc.) and hence the significant effort (developing highly sophisticated modelling frameworks) that the Flexbuild project work took to draw the main findings.

An important regulatory implication based on the project insights was the importance of tariff structures in driving end-user behaviour and system outcomes. A tariff based purely on an energy fee might inadvertently lead to increased peak loads, as users may be incentivized to shift loads to cheaper hours without any restrictions. In contrast, a tariff that includes a power fee component can effectively set a cost-optimal cap on peak demand. This underscores the role of regulatory interventions in shaping tariffs that not only reflect the true costs and benefits of electricity consumption but also drive desired behaviours that align with broader system objectives (peak load reduction). But realizing these benefits requires a regulatory environment that encourages predictable activation of end-use flexibility. Without the right incentives, the potential to replace parts of the expansion needs in the distribution grid with end-use flexibility may remain untapped. These insights and discussions raised these additional aspects where regulation needs more alignment:

- *Aggregators:* Aggregators play a pivotal role in harnessing end-use flexibility; hence regulation must ensure that aggregators operate transparently and fairly, protecting the interests of end-users while also ensuring that their activities align with broader grid management and policy objectives. Regulatory policies should facilitate the integration of aggregators into energy markets and grid operations, establishing clear rules and mechanisms that enable them to participate in various energy and ancillary service markets, thereby ensuring that the value of aggregated end-use flexibility is

fully realized. NVE noted that there might be also a need to develop incentives for aggregators that provide heat-based flexibility.
- *Dimension and further understand the potential of end-use flexibility:* From NVE perspective, Flexbuild has *"helped greatly view into the potential of end-use flexibility and should be eye-opening for companies and the overall sector"*. Hence, understanding more about the dimension and impact will bring more arguments to introduce incentive and friendly regulatory frameworks. This is central on accelerating the development of new regulatory frameworks.

7.4 Research priorities and future ideas for end-use flexibility

As noted in previous chapters, there were some pointers on the next research areas or priorities that end-use flexibility could have in the next years. Based on the discussion with partners (mainly from Statnett, NVE, Statsbygg, Oslobygg, TOBB), the following points have been discussed and proposed:
- *Energy solutions without compromising the comfort.* Understand the dynamics of consumer engagement and how behavioural aspects influence the adoption and effective utilization of flexibility options.
- *More research on quantifying the dimension and potential of end-use flexibility.* As highlighted in this chapter, this has been a recurring point of discussion that requires more validation and research.
- *Surplus of energy in buildings.* Large intake of renewables will create a greater share of positive buildings that will need new ways to integrate into the energy system beyond the existing prosumer regulation.
- *EVs and End use flexibility.* There is an important relationship between Electrical Vehicles and end-use of flexibility. Given higher electrification rates in the future more synchronization and V2G should be enabled.
- *Energy Efficiency.* As noted in this chapter, this was noted as an important area of research and further development, e.g., understanding substitution effects. This is especially important within Norway's energy policy and environmental goals.
- *Large RES deployment (wind and solar PV) in Europe.* These developments require more research on a portfolio of flexibility options, hence greater opportunity for end-use flexibility.
- *Hands-on piloting and demos:* Partners noted the importance of testing in real-life buildings and demo-sites, show how end-use flexibility will work in practice.
- *Energy security:* The power system being intricately woven into the fabric of national energy security, hence the role of end-use flexibility in effectively modulating the delicate balance between energy supply and demand will likely play a greater role.

In conclusion, end-use flexibility has potentials in shaping Norway's energy future. The reflections and insights from grid companies, building developers, and public authorities highlight a collective acknowledgment of the potential that flexibility holds, while also underlining the complexities and challenges in its implementation. Future research, thereby, plays a crucial role in unearthing solutions, innovations, and strategies that can navigate these complexities, ensuring that end-use flexibility is not merely a theoretical concept but a tangible, impactful reality in Norway's energy landscape.

8 Scientific publications

WP1 Scenarios and inputs
Bagle, M., Maree, P., Walnum, H. T., & Sartori, I. (2021). *Identifying grey-box models from archetypes of apartment block buildings*. Proceedings of Building Simulation 2021: 17th Conf. of IBPSA. DOI: https://doi.org/10.26868/25222708.2021.30162
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Lien, S. K., Sandberg, N. H., Lindberg, K. B., Rosenberg, E., Seljom, P., & Sartori, I. (2022). Comparing model projections with reality: Experiences from modelling building stock energy use in Norway. *Energy and Buildings*, (268) 112186. DOI: https://doi.org/10.1016/j.enbuild.2022.112186
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WP2 Modelling framework
Andersen, I. M. & Lindberg, K. B. (2021). *Optimal investment decisions for a Zero Emission Building under uncertainty: Stochastic BUTLER*. 2021 International Conference on Smart Energy Systems and Technologies (SEST), Vaasa, Finland. DOI: https://doi.org/10.1109/SEST50973.2021.9543287
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Sartori, I., Lien, S., Bagle, M., Walnum, H. T., & Manrique, B. (2022). Development and testing of load flexibility KPIs in the ZEN definition. *E3S Web of Conferences*, (362) 13004, BuildSim Nordic 2022. DOI: https://doi.org/10.1051/e3sconf/202236213004
WP3 Results analysis and dissemination
Alonso Pedrero, R. & Crespo del Granado, P. (2023). Assessing the impact of energy communities on retailers' balancing positions in the power market. *Energy*, (283) 128384. DOI: https://doi.org/10.1016/j.energy.2023.128384
Alonso Pedrero, R., Vicent de Lestrade, V., Spetch, J., & Crespo del Granado, P. (2023). *Value and effects of adopting residential flexibility in the European power system*. DOI: https://doi.org/10.1109/PESGM52003.2023.10252872
Seljom, P., Rosenberg, E., & Haaskjold, K. (2023). *The effect and value of end-use flexibility in the low-carbon transition of the energy system*. In publication, available at SSRN: http://dx.doi.org/10.2139/ssrn.4523740
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Sartori, I., Alonso Pedrero, R., Bagle, M., Haaskjold, K., Rosenberg, E., Seljom, P., Schäffer, L. E., & Crespo del Granado, P. (2023). *Flexbuild Final Report – The value of end-use flexibility in the future Norwegian energy system*. SINTEF Academic Press. (This report)
Sartori, I., Lindberg, K. B., Bagle, M., Sandberg, N. H., Lien, S. K., Haugen, M., Seljom, P. M. S., Kvalbein, L., Alonso, R. P., Ahang, M., Crespo del Granado, P., Tomasgard, A., Palmer, J., Kloppenborg, J., & Madsen, H. (2022). *Flexbuild Annual Report 2. Technical report with results analysis*. SINTEF Academic Press. https://hdl.handle.net/11250/3026974

Appendix A: Storyline descriptions

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Energy nation

There is wide political will in both Norway and Europe to tackle the climate crisis. Both regulations and market mechanisms such as the EU ETS (Emission Trading System) stand strong. The society is increasingly electrified since CCS technology never becomes commercial. This also means that by 2050 the Norwegian oil and gas will be completely out of the market and the petroleum sector will be phased off the Norwegian economy.

Norway supports in large scale the deployment of renewable energy, mainly offshore and onshore wind but also building integrated PV. Solar cells become the common roofing in new buildings and roof renovations. Energy efficiency is not supported with subsidies but is implemented where profitable. It is focused on freeing generation capacity that can be exported.

In addition to exports, the increased energy volumes make Norway an attractive country for energy-intensive industries. Norway becomes a major exporter of energy products (goods with a high energy content). The increase in electricity demand comes mainly from industry.

Without fossil fuels the transport sector is based on battery electric vehicles, hydrogen and supplemented by biofuels. Power-to-X technologies receive increased attention and provide increased flexibility in the power sector. Othe sources of flexibility are active consumers and flexible buildings and neighbourhoods.

The energy system has increased decentralised energy production, but transmission lines are used to provide the system with flexibility, including export cables.

Petroleum nation

There is wide political will in both Norway and Europe to tackle the climate crisis. Both regulations and market mechanisms such as the EU ETS (Emission Trading System) stand strong. CCS technology becomes commercial during the next decade. This means that by 2050 there is still demand for Norwegian oil and gas and we have found large quantities of new gas. CO_2 is a commercial product and CCU (Carbon Capture and Utilization) stands strong. Hydrogen is considered one of the major sources of flexibility. The focus is on centralized large-scale solutions for energy production. Renewable energy grows sharply, although in Norway it is mainly wind power and mostly offshore.

The transport sector uses mainly hydrogen and battery electric vehicles. Households' consumption is approximately at today's level or slightly increased. Energy efficiency has economic motivation. The Norwegian power export is moderate, and there is less need for wind power. This is market driven, and there is political acceptance that for several years there is power deficit and net import. In addition to industry CCS, we see an increasing electrification of industry.

Nature nation

The national identity is in focus and the protection of nature gets increased support. Intervention on nature is minimized. This creates increased focus on energy efficiency, renovation, circular economy and other resources utilization, such as waste heat.

In the energy sector, the focus is on reducing demand and there is acceptance for lower economic growth. Development and new industrial activity are mainly created in other sectors than renewable energy production. Densification and urbanization lead to more efficient systems for transport and energy supply.

CCS is commercialized before 2030 and centralized solutions in the local environment or cities play a large role in energy security and energy supply. Hydrogen production with CCS and power generation from natural gas with CCS play a role in the European power system and the Norwegian economy depends on this. Waste incineration and heat production with CCS play an important role in the transformation of large cities.

At the same time there is less acceptance for transmission lines and large intervention on nature, except for export cables and offshore wind.

Personal CO_2 quota are being discussed, politicians propose establishing markets for it, preferably at a European level. An EU Emission Trading System – Personal is established for all European countries.

Climate panic
Norway, Europe and the rest of the world spend the next 10 years discussing climate solutions. There is broad agreement that the 1.5-degree target will be reached with the help of negative emissions and CCS. In 2030, two important and surprising events take place. First, large parts of the Antarctic ice melt in a short time as a result of changes in ocean currents. At the same time, we see sudden and dramatic climate changes that turn parts of Europe into desert, while other parts are experiencing huge increases in precipitation or disappearing into the sea. CCS technology does not succeed on a scale necessary to deal with the crisis.

All western countries introduce a climate minister who is the supreme decision-making authority over government and parliament. This leads to strong state control in the period 2030–2050.

In the new situation, energy demand drops dramatically, but so does energy production since coal and gas are phased out overnight. New nuclear power plants are being planned but will not be in place before 2050.

For end users, this means rationing and all end-user flexibility is exploited. We see a dramatic increase in wind and solar in a short time from 2030. Transmission and energy storage become important. Hydrogen plays a major role in absorbing surplus production.

In Europe, energy deficits lead to nationalization of energy systems and markets and to focus each on its own country and resources. Central control and regulation stand strong. In Norway we see the merging of NVE + Statnett + Enova + Statkraft + Equinor. The focus is on maximal exploitation of resources, but it comes too late. All measures are implemented: energy efficiency, recycling, waste heat, renewables, circular economy, rationing.

Flexbuild final report

THE VALUE OF END-USE FLEXIBILITY IN THE FUTURE NORWEGIAN ENERGY SYSTEM

This report is a deliverable of the Flexbuild project, a knowledge-building project for industry (Kompetansebyggende prosjekt for næringslivet – KPN, in Norwegian) co-financed by the Research Council of Norway under the programme EnergiX. The Flexbuild project aimed to understand how end-use flexibility could impact the future energy system in Norway. This initiative brought together industrial partners, public organizations, universities, and research institutions to investigate various aspects of energy flexibility. To achieve its objectives, the project employed a combination of models and explored four different energy transition scenarios, or storylines, named as Energy Nation, Petroleum Nation, Nature Nation, and Climate panic.

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