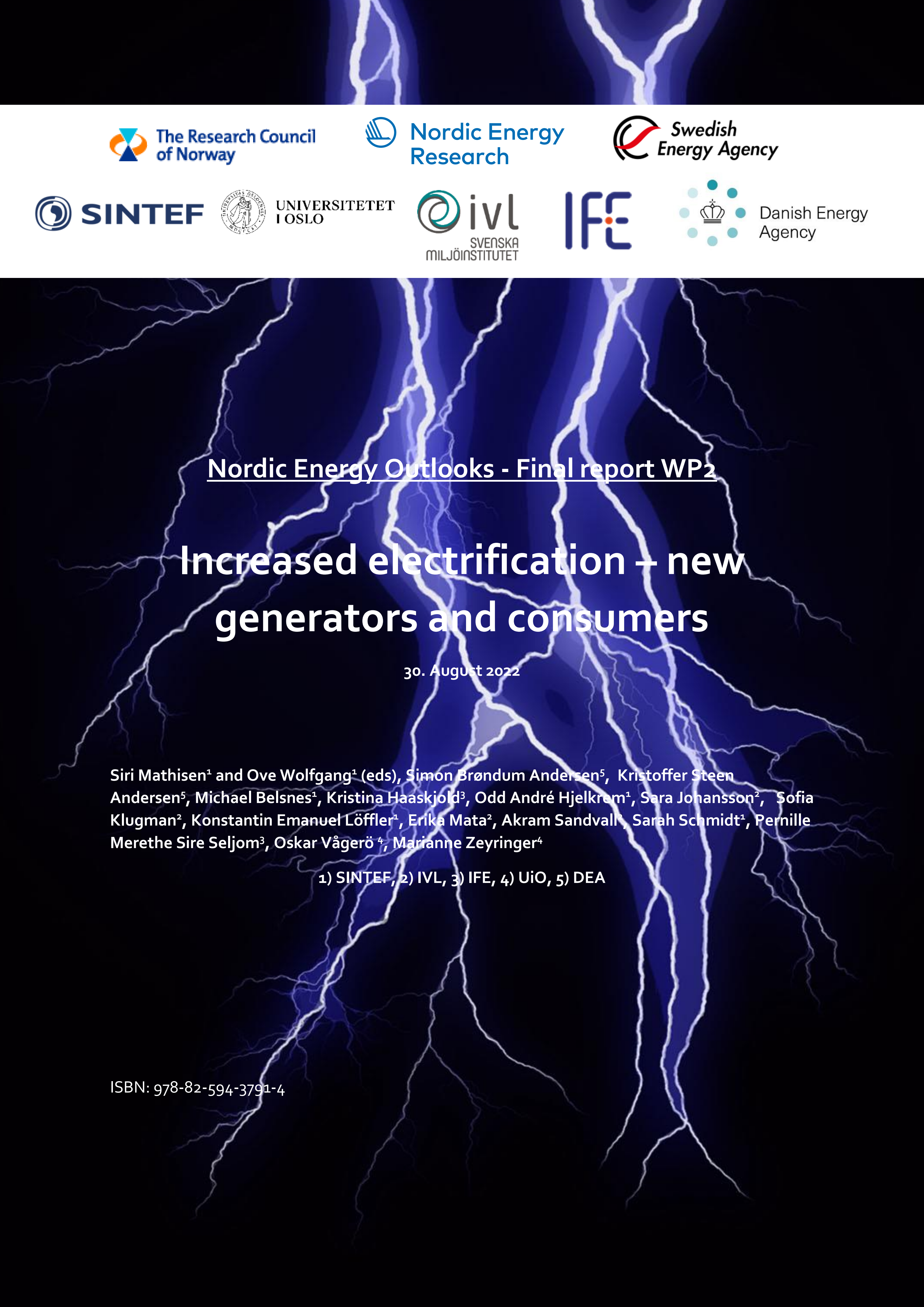


The Research Council of Norway
Nordic Energy Research
Swedish Energy Agency
SINTEF
UNIVERSITETET I OSLO
ivl SVENSKA MILJÖINSTITUTET
IFE
Danish Energy Agency

Nordic Energy Outlooks - Final report WP2

Increased electrification – new generators and consumers

30. August 2022

Siri Mathisen[1] and Ove Wolfgang[1] (eds), Simon Brøndum Andersen[5], Kristoffer Steen Andersen[5], Michael Belsnes[1], Kristina Haaskjold[3], Odd André Hjelkrem[1], Sara Johansson[2], Sofia Klugman[2], Konstantin Emanuel Löffler[1], Erika Mata[2], Akram Sandvall[2], Sarah Schmidt[1], Pernille Merethe Sire Seljom[3], Oskar Vågerö [4], Marianne Zeyringer[4]

1) SINTEF, 2) IVL, 3) IFE, 4) UiO, 5) DEA

ISBN: 978-82-594-3791-4

Acknowledgements

We gratefully acknowledge the financial support from Nordic Energy Research, the Swedish Energy Agency, the Research Council of Norway, and the Danish Energy Agency. We also want to thank Nordic Energy Research for advice and other support received through the project period.

Table of contents

1. Introduction

1.1. About the Nordic Energy Outlooks programme

Nordic Energy Outlooks [1](NEO) is a programme organised by Nordic Energy Research, and financed jointly by Nordic Energy Research, the Swedish Energy Agency, the Research Council of Norway, and the Danish Energy Agency.

The main aim of the programme is to *Strengthen Nordic research competence and cooperation in the field of energy systems analysis, by building on existing national research programmes*. By creating a forum for collaboration between different research groups and institutions, NEO helps to synthesise the results of current national research and put these into a Nordic context, but also help to clarify how the choice of analytical methods can create different results.

An additional aim of the programme is to discuss if and how the results from the programme can be used for following up on the integrated national energy and climate plans (NECP), and if the results can provide a regional perspective. Figure 1-1 illustrates the aims of the programme.

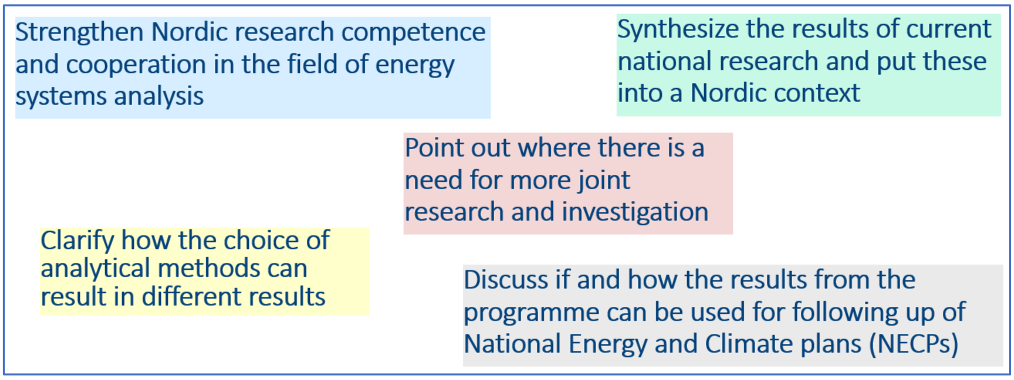


Figure 1-1: Aims of the Nordic Energy Outlooks programme

The programme is divided into four work packages (WPs), as shown in Figure 1-2, in addition to a separate project lead WP. Each WP is carried out by selected research institutes in collaboration with SINTEF Energy – which is the project lead institution for the programme. The outcomes from WP1 are documented in [2], whereas the outcomes from WP2 are documented in this report.

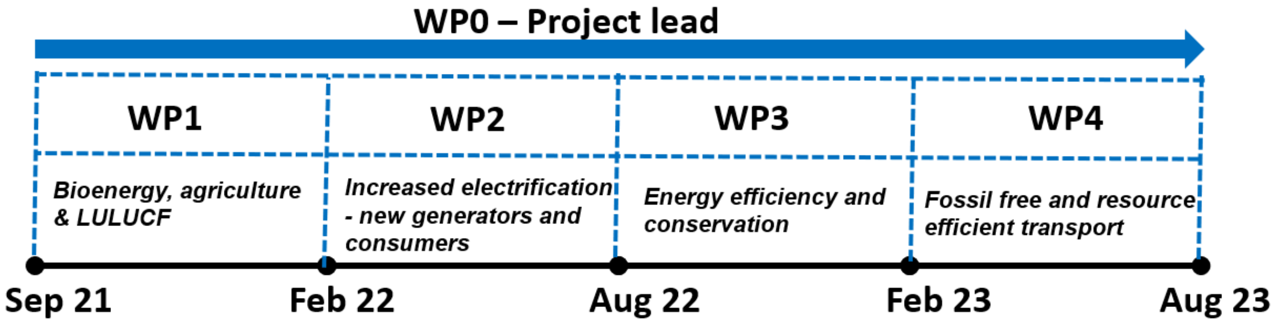


Figure 1-2: Overall structure and timeline for Nordic Energy Outlooks

1.2. WP2: Increased electrification – new generators and consumers

This document is the final report from WP2, which addresses carbon dioxide (CO_2) reductions through electrification of energy consumption based on fossil fuels, and possibilities for new electricity generation in the Nordic area. The research partners in WP2 are SINTEF Energy, IVL, UiO, IFE, and DEA. We have conducted a new comparative analysis and, additionally, each research partner has committed to specific tasks according to their contracts with their financing institution in NEO. The research questions pursued by each partner are described in Section 1.3.

European energy markets are in a state of emergency. Already before the war in Ukraine, European energy prices were high due to the recovery of economies after Covid-19 and the corresponding high prices for natural gas on the world market. As a response to the high energy prices and the war in Ukraine, the Commission proposed the REPowerEU [3] plan to cut import of large quantities of natural gas from Russia by switching to LNG import from other countries, by frontloading the existing Fit for 55 [4] renewable targets for 2030, among other things. Hence, the REPowerEU plan will probably have impacts also for the Nordic countries.

This report includes a dedicated REPowerEU scenario, which analyses a contribution to the ambitions in the REPowerEU plan by use of the models for the Nordic energy- and power-market in WP2. The models that are included in WP2 are:

- TIMES-type models
    - ON-TIMES (IVL)
    - IFE-TIMES-Norway (IFE)
    - IntERACT (DEA)
- GENeSYS-MOD (SINTEF)
- highRES-E (UiO)
- ECCABS (IVL)
- EMPS-W (SINTEF)
- Energy Map (SINTEF)

The models listed above are described in Section 2. The set of models used within WP2 are different in several respects. On the one hand, the general energy system models (TIMES-type models and GENeSYS-MOD), aims to include demand and supply for all relevant energy carriers, sectors, and technologies, with different levels of aggregation and simplifications of principles For those models the description in Section 2 emphasise how the electricity sector are represented.

On the other hand, the domain-specific models (ECCABS, EMPS-W and highRES-E) typically have a narrower focus allowing a more detailed representation. ECCABS facilitates the understanding of energy demand and CO_2 emissions in the buildings sector, EMPS-W is a power market model with detailed hydropower optimisation, and highRES-E is a model of the electricity market able to include various social constraints in the optimisation.

Section 3 presents the comparative model study of the impact of REPowerEU. Firstly, some of the main inputs and results for a base scenario for a decarbonised energy system by 2050 are shown for each model. Secondly, the impact of a Nordic contribution to REPowerEU through additional electricity export is shown. The following models are included in that study: ON-TIMES, IFE-TIMES-Norway, GENeSYS-MOD, and highRES-E. In addition, results for IntERACT is included for the base scenario.

Section 4 odescribes project outcomes from the research questions stated in Section 1.3, apart from the comparative study already described in Section 3. Comparing models and their input data makes it possible to provide more realistic views on the development of the Nordic energy system, and to understand limitations of models and data. In this way, the project has enabled the involved research groups to produce more relevant knowledge to understand the challenges ahead regarding the energy transition in the Nordic countries, and lay the foundation to further investigations in future projects.

Section 5 discusses existing NECPs for Sweden [5] and Denmark [6]. Norway does not have an official NECP, but we discuss the document Meld.St.13 Klimaplan for 2021-2030 [7]. We also consider if the results from the project and the expertise from involved researchers, can be used for following up NECPs by setting them into a Nordic perspective.

Some promising research topics for future cooperation between the research partners are described in Section 6. As illustrated by Figure 1-3, ideas and thoughts about improved methodology have been developed in a process where all partners shared information, which then was studied and discussed between the partners in workshops. Through this process, the research partners have gained increased mutual understanding of the corresponding energy system models for the Nordic area.

Section 70 concludes by providing a summary, and key takeaways from the work of this WP and Wp1.

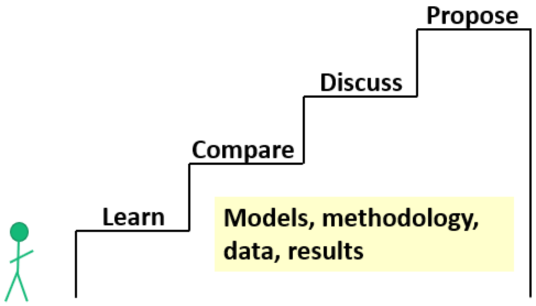


Figure 1-3: Process for mutual learning through WP2 activities

1.3. Research questions

IFE

The aim of IFE's work is to analyse the role of Norway in the green energy transition, both in terms of its own national energy system development, as well as how Norway can contribute to the REPowerEU plan. The new geopolitical and energy market reality requires a drastic acceleration of the European energy transition, with increasing independence from unreliable suppliers and fossil fuels. The elimination of Russian oil and gas import will require a large boost in renewable energy production to reduce the use of fossil fuels in homes, buildings, industry, transport, and the power system. This relates both to higher electrification rates, as well as the large volumes of green hydrogen needed to cover the European energy demand. At the same time, Norway needs to fulfil its own climate targets and ensure security of supply. This task will seemingly become more challenging as larger emphasis is put on local environment and preserving valuable nature areas. The future energy demand is also largely uncertain and will depend on multiple factors such as industry development, population growth, centralisation/decentralisation, technology development and energy efficiency. Consequently, Norway's contribution to the European energy transition, related to export of power, hydrogen, and other essential goods such as batteries and aluminium, needs to be balanced and coupled to domestic supply and demand.

IFE's analysis in WP2 builds on a decarbonisation pathway scenario definition developed in the Centre for Environment-friendly Energy Research (FME) NTRANS (RA4). The scenario reflects a net-zero emission society by 2050 which is modelled through a high CO_2 price, i.e. 200 €/t in 2030 and 438 €/t in 2050. The scenario assumes high technology learning rates, enabling large integration of renewable energy and fast development of hydrogen, batteries, and CCS for hard-to-abate sectors. Moreover, a high demand is assumed towards 2050 with increasing industry activity. Notably, production from oil and gas is assumed to decrease by 2/3 in 2050, relative to 2024, in which remaining fields are assumed to be fully electrified. The scenario focuses on economic growth, also allowing for high interaction with Europe.

The results of the work will provide insight into how the Norwegian energy system will develop in a decarbonisation pathway, and to what extent Norway can contribute to the intentions of the REPowerEU plan. To evaluate the robustness of the results, a sensitivity analysis will be performed on different uncertain parameters for future development. The focus of the results will mainly comprise the changes in generation capacity from renewable energy sources, changes in grid infrastructure and trade volumes and the additional cost of the Norwegian energy system under different system configurations.

UiO

The aim of UiO’s work is to reflect and discuss upon the societal implications of the increased electrification studied in this work package. What societal challenges come with increased electrification and what does that imply for energy systems modelling?

Energy and power system models are used to map transitions to low carbon societies and to advise policy and planning bodies on how to achieve them. While such models include high levels of techno-economic detail, they often only include social factors to a limited extent, which would be an important part of determining how much and where renewables can be deployed as well as the process and ultimate design of energy transitions. This may lead to designing solutions which are neither socially nor politically feasible.

Factors such as land use, changes in landscape aesthetics and local environmental impacts are found to influence the acceptance of energy infrastructure such as wind power plants [8], [9]. Another aspect of social acceptance is that the perceived fairness of energy infrastructure is highly important[10], [11], e.g. how the benefits and costs of these technologies are distributed. Addressing questions of justice may as such attend to both normative aspects of socially just energy systems and the instrumental role it has for legitimising energy system transitions and transformation.

The work will therefore explore how questions of justice may be implemented in modelling exercises and provide some concrete guidelines and pointers for modellers including such aspects in their studies.

IVL Swedish Environmental Research Institute

The aim of IVL’s work is to contribute to increased knowledge and understanding of electrification in different transition pathways for the Nordic industrial and buildings sectors towards climate neutrality, by gathering and sharing insights from two key models (ON-TIMES and ECCABS).

In the Nordic heavy industries, a vast part of CO_2 emissions relates to the processes themselves, which could be improved only with transformative changes. For instance, in the cement industry, about 65% of emissions originate from the calcination process. An electricity-heated clinkering process could remove the fossil fuels, making the off-gases a pure CO_2 stream, for which the CO_2 capture would be less energy demanding and expensive. In the iron and steel industry, about 50% of the CO_2 emissions originate from iron ore reduction in blast furnaces. The alternative HYBRIT process uses hydrogen from fossil-free electricity as reducing agent instead of coke and could cut CO_2 emissions by 10% in Sweden and by 7% in Finland. In the refinery industry, the CO_2 emissions relate to energy use at the refinery. Hence, both alternative feedstock to the existing refineries and alternative processes for fuels production are possible options for future production of liquid fuels.

Furthermore, in the buildings sector, electrification, demand-side flexibility, new electricity generation from renewable sources and sector coupling are key pathways to reach the climate targets. These measures, in both sectors, are approached differently depending on the capabilities of the models or methods used.

More specifically, the objectives of IVL's work are to:

- Map transformative options for Nordic heavy industry and built environment, and their representation in ON-TIMES and ECCABS models.
- Explore how different assumptions affect the results, e.g. future energy prices, and what consequences these new options will have for the energy system (in terms of demand of different energy carriers and emissions).
- Analyse measures and policy options to support the transformation.

SINTEF

The aim of SINTEF’s work is to understand potential improvement possibilities from increasing the level of detail for key power production descriptions in a general energy system model. The current version of the open-source energy system model GENeSYS-MOD[12] v3.1 is used as a reference. GENeSYS-MOD was originally developed with a Central European energy system focus, which does not contain the high share of hydropower, or regional market and grid coupling that we see in the Nordic power market. Results and input data from sector specific models can be used to bridge this gap.

Given an already almost completely renewable power system, Norway needs to focus on the electrification of the transport sector and industry to reach European and national emission reduction targets. This will lead to both an increase in electricity demand and to changes in the demand pattern, which can be met by a combination of increased generation and transmission capacities. Increased electrification in the transport sector is investigated based on results from the FuChar project [13], which can provide insight into the transport sector that could be used to improve transport sector modelling in GENeSYS-MOD. FuChar also aims to minimise the investment and operational costs of grid integration of electricity transport. Combined with results from the EMPS model, this can provide new knowledge regarding potential future power demands. GENeSYS-MOD, EMPS-W and FuChar have different spatial and temporal resolution, tailored for their application.

The main objective of SINTEF's work is to assess the consequences of future increase in electrification, embracing both the increased electricity demand and changing supply and demand patterns. By including the changes in the transport sector, increased generation from variable renewable energy and change in infrastructure, the work will evaluate the potential for integration of information from the domain specific models into GENeSYS-MOD. The secondary objective is to explore how Nordic cooperation can benefit the development of sector specific and energy system models and datasets within the field of increased electrification.

Under these premises, we want to answer the following research questions:

- How does the GENeSYS-MOD data relate to the data in FuChar or EMPS?
- How can the GENeSYS-MOD energy system model or dataset be improved by an inclusion of more detailed modelling of the transport or power sector?
- How do different assumptions on electrification in datasets for energy system models affect the results of the analysis?
- How can the combined insights from FuChar, GENeSYS-MOD and EMPS improve our understanding of the challenges defined by the NECP pathways?

DEA

The aim of the Danish Energy Agency (DEA) within the WP2 is twofold: 1) to seek insight from our Nordic colleagues on the effect of increased electrification on the Nordic energy system, and 2) to share the experience of the Danish Energy Agency doing energy system modelling with a focus on reaching climate neutrality by 2050.

2. Applied models

2.1. ON-TIMES

Introduction to ON-TIMES

The ON-TIMES (Open Nordic - TIMES) model includes the five Nordic countries in detail (Denmark two regions, Sweden four regions, Norway two regions, Finland two regions, Iceland one region), whereas the surrounding countries are represented by trade-links and price profiles for traded commodities. Sectors represented in the model are upstream/ fuel production, power and heat, heavy industry, residential, transport and other (i.e., manufacturing industries, services and agriculture). The model has a time horizon between 2015 -2050, in 5-year time steps. Each model year is divided into 32-time slices. ON-TIMES can be soft-linked to the BALMOREL model, which analyses dispatch and operation focusing on the electricity system. The BALMOREL model covers power systems in 18 European countries, including Denmark, Finland, Norway and Sweden [14]. The main model inputs to ON-TIMES are techno-economic data of existing energy conversion technologies, current and future resource and LULUCF potential, fuels prices and (if relevant) the associated CO_2 emissions, demands projections for different energy services, techno-economic data of new conversion technologies, which are used as investment options, and model constraints, e.g., CO_2 emissions cap. The entire ON-TIMES energy system model is available on GitHub – Nordic Energy Research NCES [15]. It contains all sector-level technology data and all demand projections with the associated references. The current version of the model contains three main scenarios designed to meet the carbon neutrality target by balancing carbon emissions and sinks in the Nordic countries as below (for more detail description of the scenarios please see Appendix A1):

- Carbon Neutral Nordic (CNN) seeks the least-cost pathway, considering current national plans, strategies, and targets. This scenario is used as base scenario in this report.
- Nordic Powerhouse (NPH) explores the opportunity for the Nordics to play a more prominent role in the broader European energy transition by providing clean electricity, clean fuels, and carbon storage.
- Climate Neutral Behaviour (CNB) reflects Nordic societies adopting additional energy and material efficiency measures in all sectors, ultimately leading to lower demand for both.

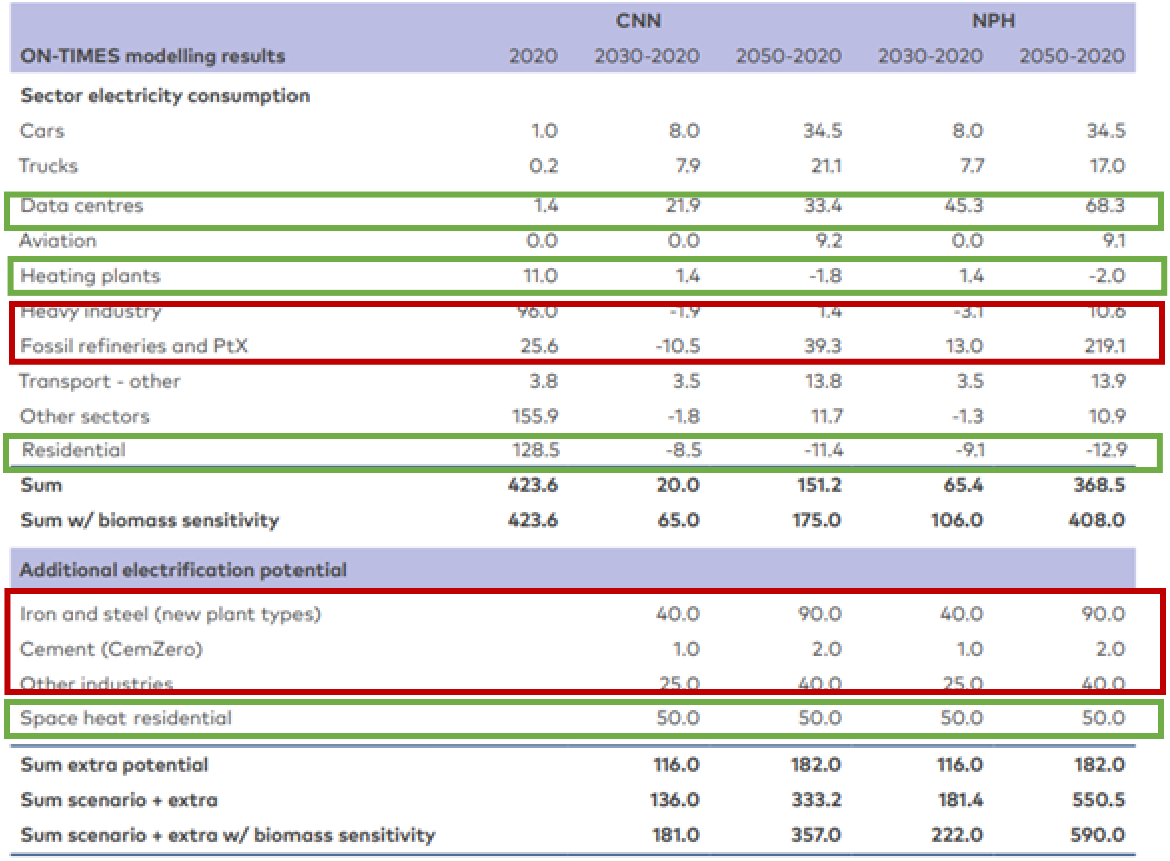
For each scenario and model year, the primary model outputs are installed capacities of energy conversion technologies, fuel use, production per conversion technologies and marginal energy and CO_2 prices. The model also generates results for primary energy supply by energy source, CO_2 emissions, investment capacities, carbon capture level, final energy consumption by energy source, final energy consumption by sector.

Building sector in ON-TIMES

The building sector is represented in ON-TIMES by exogenously giving current demand area for single-family and multifamily buildings, divided (based on heat supply technology) into individual, decentralised, and centralised buildings, in total in six main groups. Buildings not connected to district heating (DH) are assumed to have an individual heating system; buildings connected to DH are divided into centralised and decentralised based on connection to a corresponding DH system[1]. The existing technologies (heat devices) in the buildings with individual heating systems are boilers (fuelled by oil, natural gas, biomass or electricity), heat pumps and solar thermal collectors. During the model time horizon there are new investment options for the existing buildings such as heat-saving measures, new heat devices and connection to the DH systems. Simultaneously, some existing buildings are demolished and replaced with new and more efficient buildings. For the buildings, electricity demand for appliances is also included in the model per number of appliances for current and future single-family and multifamily buildings. See Appendix 0 for a schematic representation of the buildings sector for area demand for the case of Sweden in the ON-TIMES model.

Notably, production from renewable energy sources (RES) in the buildings (e.g. PV) and electric vehicles currently belong to the power and transport systems, respectively, in the model.

Table 2-1 Results of model runs and potential for electrification per sector, TWh per year. Results for the industrial sector are found in the red squares and for the building sector in green squares. (Source: Table 3.1, Nordic Clean Energy Scenarios 2021)



		CNN		NPH	
ON-TIMES modelling results	2020	2030-2020	2050-2020	2030-2020	2050-2020
Sector electricity consumption					
Cars	1.0	8.0	34.5	8.0	34.5
Trucks	0.2	7.9	21.1	7.7	17.0
Data centres	1.4	21.9	33.4	45.3	68.3
Aviation	0.0	0.0	9.2	0.0	9.1
Heating plants	11.0	1.4	-1.8	1.4	-2.0
Heavy industry	96.0	-1.9	1.4	-3.1	10.6
Fossil refineries and PtX	25.6	-10.5	39.3	13.0	219.1
Transport - other	3.8	3.5	13.8	3.5	13.9
Other sectors	155.9	-1.8	11.7	-1.3	10.9
Residential	128.5	-8.5	-11.4	-9.1	-12.9
Sum	**423.6**	**20.0**	**151.2**	**65.4**	**368.5**
Sum w/ biomass sensitivity	**423.6**	**65.0**	**175.0**	**106.0**	**408.0**
Additional electrification potential					
Iron and steel (new plant types)		40.0	90.0	40.0	90.0
Cement (CemZero)		1.0	2.0	1.0	2.0
Other industries		25.0	40.0	25.0	40.0
Space heat residential		50.0	50.0	50.0	50.0
Sum extra potential		**116.0**	**182.0**	**116.0**	**182.0**
Sum scenario + extra		**136.0**	**333.2**	**181.4**	**550.5**
Sum scenario + extra w/ biomass sensitivity		**181.0**	**357.0**	**222.0**	**590.0**

As seen in Table 2-1 (green marked), modelling results show a slight decrease in electricity consumption by 2050 in the residential sector for both scenarios. Generally, an increase in the number of appliances is being counteracted by improved appliance efficiency, traditionally causing a projection of zero to little change in electricity demand in the residential sector in the coming decades. Electricity consumption in heating plants is expected to stay in the current range. There is an

---

[1] Centralised DH systems are assumed to have annual heat deliveries of more than 400 GWh, decentralised otherwise.

estimation of additional electrification potential for residential space heating of 50 TWh, which is based on plans for future fuel consumption which could be replaced by electrification [16]. The number of data centres and following electricity consumption is expected to increase in both scenarios, with 33.4 TWh for the CNN scenario and 68.3 TWh for the NPH scenario by 2050.

Heavy industry in ON-TIMES

In the ON-TIMES model, industries are divided into Heavy industry (Pulp and paper, Mining, Iron and steel, Aluminium, Cement) and Manufacturing industries (Food, Chemical, Machinery, Wood products). Industries dealing with fuel production (Exploration/mining of fossil energy, Fossil and renewable refineries, PtX) is represented in the category Upstream/fuel production.

The energy demand in the industrial sector is represented by annual electricity demand and several conversion technologies that currently fulfil the sector's heat demand. There are different types of heat pumps, centralised and decentralised district heating, and heat-only boilers represented in detail. Fuel input to the heat-only boilers includes natural gas, coal, diesel, biogas, heavy oil, LPG, waste, and electricity. In addition, current diesel-fuelled tractors, trucks, fishing boats, forestry machines, LPG-fuelled forklifts, electric light appliances, and motors are also considered. Like for the buildings sector, the existing technologies are gradually replaced with new technologies (due to either reaching their lifetime or constraints on CO_2 emissions) given as new investment options in the model. These investments include hydrogen-based technologies in the iron and steel industry, woodchips boilers, heat pumps with waste heat recovery, electric boilers, mechanical vapor recompression, booster heat pumps, infrared heating, oil, gas and coal boilers, solar, centralised, and decentralised district heating.

As seen in Table 2-1 (red marked), the electrification of heavy industry is not seen to take off to the same extent as seen in transportation in the NCES scenarios [16] which use the ON-TIMES model. In heavy industries, iron and steel, aluminium, pulp and paper, and cement and mining, the biggest challenge for decarbonisation is in iron and steel, and cement. This is partly because certain industrial processes demand higher energy flow rates and higher temperatures where electrification of the processes are not applicable. However, for some industries, the least-cost option in the model is to keep using fossil fuels by incorporating CCS. The potential for electrification is therefore larger than what is seen in the NCES results and expansion of existing industry could especially lead to extra electricity demand.

2.2. IFE-TIMES-Norway

IFE-TIMES-Norway [17] is a long-term optimisation model of the Norwegian energy system that is generated by the TIMES (The Integrated MARKAL-EFOM System) modelling framework [18]. It is a bottom-up framework that provides a detailed techno-economic description of resources, energy carriers, conversion technologies and energy demand. TIMES models minimise the total discounted cost of a given energy system to meet the demand for energy services for the regions over the period analysed. The total energy system cost includes investment costs in both supply and demand technologies, operation and maintenance costs, and income from electricity export to and costs of electricity import from countries outside Norway.

Spatially, the model covers five geographical regions in Norway, corresponding to the current electricity spot market price zones. The model provides operational and investment decisions from the starting year, 2018, all the way to 2050. To capture operational variations in energy generation and end-use, each model period is divided into 96 subannual time slices, where four seasons are represented by 24 chronological hours.

The model has a detailed description of end-use of energy, with demand for energy services divided into numerous end-use categories within industry, buildings, and transport. The demand can be met by both existing and new technologies using energy carriers such as electricity, bio energy, district heating, hydrogen, and fossil fuels. Consequently, in each time slice, the use of energy carriers such as electricity is a model result and not a model input, making sector coupling a part of the optimisation. For example, endogenous investments in heat pumps and electric vehicles couple the power sector with the heat and transport sector, respectively. Other input data include fuel prices; electricity prices in countries with transmission capacity to Norway; renewable resources; and technology characteristics such as costs, efficiencies, lifetime and learning curves.

Existing transmission capacity, both domestically and to European countries, is modelled exogenously and based on current capacity and ongoing capacity expansion. Moreover, the model allows for new investment capacity, both on existing and new connections. First year of investment is fixed to 2030 due to the long planning and construction process of building new transmission lines. The electricity prices in the model regions in Norway are endogenous, as they are the dual values of the electricity balance equation, while the electricity prices in the countries with trading capacity to Norway, including Denmark, Sweden, United Kingdom, Finland, Netherlands, and Germany, are a model input. Furthermore, we assume these electricity trade prices to be independent of the traded quantities to Norway. To capture the characteristics of the European power market under different future pathway scenarios, IFE-TIMES-Norway has been linked to various European power system models, such as EMPIRE (The European Model for Power System Investment with Renewable Energy).

In terms of renewable energy sources, the model differentiates between reservoir hydro plants and run-of-the-river (ROR) hydro plants, onshore wind and offshore wind, as well as building-applied PV on commercial, multi- and single-family house buildings. For new investments, several technology types are available with different costs, operational conditions, and upper potentials for each region.

2.3. IntERACT

The IntERACT model is a model used by the Danish Energy Agency for three overall purposes:

1. To determine industry and household emissions and energy use within policy scenarios (Danish Energy Outlook).
2. To assess the impact of different policy measures directed at households and industry.
3. For explorative scenarios dealing with different pathways to meet Danish long-term climate policy goals.

The IntERACT-model integrates a general equilibrium top-down (CGE) model with a technical energy system bottom-up model (based on TIMES-DK). The CGE model describes the macroeconomic relationships, i.e. economic flows between firms, households, the public sector and international trade. In comparison, the bottom-up model describes the Danish energy system using detailed technical modelling of both production and the use of energy and energy services.

The crux of IntERACT is an automated iterative link which allows the seamless exchange of information between the top-down and bottom-up model. That is information on cost of energy services, fuel cost shares and fuel tax rates from the bottom-up to the top-down model, and the subsequent exchange of updated energy service demand from the top-down to the bottom-up model. In essence, this allows IntERACT to utilise the strength of both the top-down and bottom-up models. In terms of bottom-up modelling, IntERACT relies on the same modelling framework as IFE-TIMES-Norway and ON-TIMES, i.e., the TIMES (The Integrated MARKAL-EFOM System) model generator, which is developed and maintained by the ETSAP (Energy Technology System Analysis Programme).

IntERACT covers the Danish energy system, geographically aggregated into the two Danish power regions, i.e. East and West Denmark. The model includes interconnections to neighbouring countries. IntERACT uses exogenously given projections of availability of transmission capacities and electricity prices. A comprehensive European electricity market simulation model (RAMSES) provides a dataset with hourly price profiles on import and export prices for each neighbouring region.

IntERACT offers two overall methods for defining time slice structure: a sequential and a non-sequential. Both methods rely on a comprehensive hourly dataset covering electricity demand profiles (e.g. for residential appliances and industry energy service) and renewable energy profiles (e.g. profiles for wind power production) are consistent both with respect to climate year (i.e. consistency between temperature, solar influx and wind profiles) as well as consistency in terms of the choice of the calendar year.

Both structures divide the year into four seasons, workday and non-workday. However, the two methods diverge when it comes to the hourly structure. Within the sequential hours, hours are chronological, and each time slice represents the average values (e.g., demand in a given hour by season and by type of day). This structure is helpful when trying to understand demand-side flexibility or the operation of storage processes. The current version of this time slice structure includes 192 time slices (4 seasons x 2-day-types x 24 hours).

The non-sequential time slice structure focuses on critical hours for the energy system. Within this structure, the model classifies each hour into one of four categories according to the historical variability of renewable energy resources and power load profile. These categories capture situations that are critical for the power system and include: A) «high wind production – low power demand», B) «high– low wind production», C) «no photovoltaics production» and D) «rest». All-in-all, this setup results in 32 time slices. The non-sequential structure allows IntERACT to take account of the variability in solar and wind power in the investment decision with only a limited number of time slices.

IntERACT includes five overall sectors: Supply, power and heat, industry, residential and transport. For each sector, IntERACT consists of a detailed investment portfolio, which matches the Danish Technology Catalogue. These cover technologies that replace existing ones to cover the defined demands, CCS technologies, PtX technologies and production of fuels e.g. heat pumps, hydrogen production, solar heating etc. Sector-coupling is a part of the model as end-use demands and supply are connected in IntERACT.

2.4. GENeSYS-MOD

The Global Energy System Model (GENeSYS-MOD) is an open-source, linear energy system model, minimising total system cost, including the different energy sectors transportation, electricity, and heat [12]. Through an optimisation procedure to minimise costs, the model outputs scenario pathway results for how the energy system could evolve to meet predefined demand and emission targets. Results from the model for four different European decarbonisation scenarios are openly available through the open Platform of the H2020 project openENTRANCE [19]. openENTRANCE investigates different pathways for the transition to a reduced-emission and low-carbon future. The GHG emission budgets for Europe needed for the 1.5°C and 2°C goals are results obtained from MESSAGE-Globium [20]. Data from the SET-Nav project is used as input to the demand projections for the scenarios. The quantitative scenario descriptions and simulation results are available in the openENTRANCE scenario explorer [21] and provide important information for companies and decision makers to support them in making more informed choices and investments on the way to reaching a climate neutral Europe in 2050.

GENeSYS-MOD is based on the Open-Source Energy Modelling System (OSeMOSYS) [22] framework. Energy demands for transport, final electricity, and heat are exogenously defined over the modelled timeframe, e.g. for each five-year timesteps from today to 2050. The details of the current energy system (2018) provide the starting point to the model, together with resource potentials, emission intensities and costs associated with the different fuels and technologies. GENeSYS-MOD finds the cost-efficient way to satisfy the provided energy demand over the years, respecting a set of constraints. In openENTRANCE, GENeSYS-MOD has been linked to various open source and proprietary models, among which the power-market simulator EMPS [23]. The current version of the openly available European dataset is developed within the openENTRANCE project and contains 4 different scenarios through which Europe can reach a decarbonised energy system in 2050, see [19] for details.

Initiated with a central European focus, the Nordic hydropower production has not been the focus of GENeSYS-MOD and its description is more simplified there than in the sector-specific models like EMPS. Still, power trade and power infrastructure are included in the model and investment in infrastructure will be adapted to the high degree of electrification that is predicted. In GENeSYS-MOD, the demand for heating and transport can be covered by different energy sources, and the model will calculate the optimal combination of sources and infrastructures. Hydropower from reservoirs is modelled in a simplified manner, not accounting for the inflows, restrictions on water levels or reservoir size, cascaded systems etc.

2.5. highRES-Europe

The high spatial and temporal Resolution Electricity System model for Europe (highRES-Europe) is a power system model specifically developed for analysing electricity systems with a large amount of variable renewable energy technologies (VREs) such as wind and solar. The model is a linear optimisation model, with the objective to minimise the total system costs, which includes both operation and annualised investment costs. highRES-E is a snapshot model at an hourly resolution (8760 time slices) with 31 zones represented (EU27 + Iceland, Norway, Switzerland and United Kingdom). The current version of highRES-E therefore represents countries at a national level, but can be disaggregated (as is done in highRES-Norway) or aggregated [24] depending on the spatial scope of the analysis and availability of data.

The model represents the transmission network through a linear transhipment formulation (see [25]) and includes a hybrid greenfield approach where neither existing transmission nor generation infrastructure is predetermined, with the exception of installed hydropower capacities (storage and generation). The demand-supply balancing equation ensures that the electricity supply in each of the zones, through local electricity generation, storage or import, is greater than the demand in every hour. Power plant operations are subject to technical constraints, such as ramping restrictions, minimum stable generation and start-up costs for thermal power plants. The annual electricity demand and carbon budget can be sourced from the output of long-time whole energy system models, such as the JRC EU-Times [26].

highRES-E uses historical meteorological data from climate reanalysis (e.g. ERA-5 reanalysis produced by ECMWF and processed by Atlite [27]) in physical power generation models to model capacity factors for wind, solar and hydropower. The variable and spatially unrestricted renewable energy technologies (i.e. wind and solar) can be modelled either at a grid-cell resolution of 30x30km, or aggregated on the applied zonal level of the model.

A more detailed description is provided in Price and Zeyringer [28] and the model structure is openly available on GitHub [29].

2.6. ECCABS

The building-stock model ECCABS [30], [31], was initially created to investigate potential reductions of energy use in Swedish residential buildings [32] and has since been further developed to map effects (in terms of energy demand, final energy consumption and corresponding CO_2 emissions) and costs of transforming the building sector through different actions (changes in consumption patterns, energy efficiency, installation of renewable energy), as well as to include the non-residential buildings. The model has been used to assess the transformation of Swedish residential [31] and non-residential [33] buildings (including urban applications [34], [35]), as well as that of several European countries [36].

Figure 2-1 shows the model structure. Input data includes physical building data (e.g., heated floor area, window area, heat loss coefficients, ventilation); climate data (outdoor temperature and solar radiation); existing energy system data; and further details to decide on scenarios and energy saving measures (ESMs) (e.g., constraints on costs, human labour).

In the simulation module, the energy performance of the building stock is calculated together with the potential energy savings, associated CO_2 emissions and costs. The module takes into account the thermal mass of the building at each time step (one-hour resolution) and extends the results to the building stock modelled (e.g. a building portfolio, city, region or country depending on the implementation). In the optimisation module, selected ESMs are implemented over a timeline following various technical and economical reasoning. The output from optimisation includes demands by end-uses and demands by fuels.

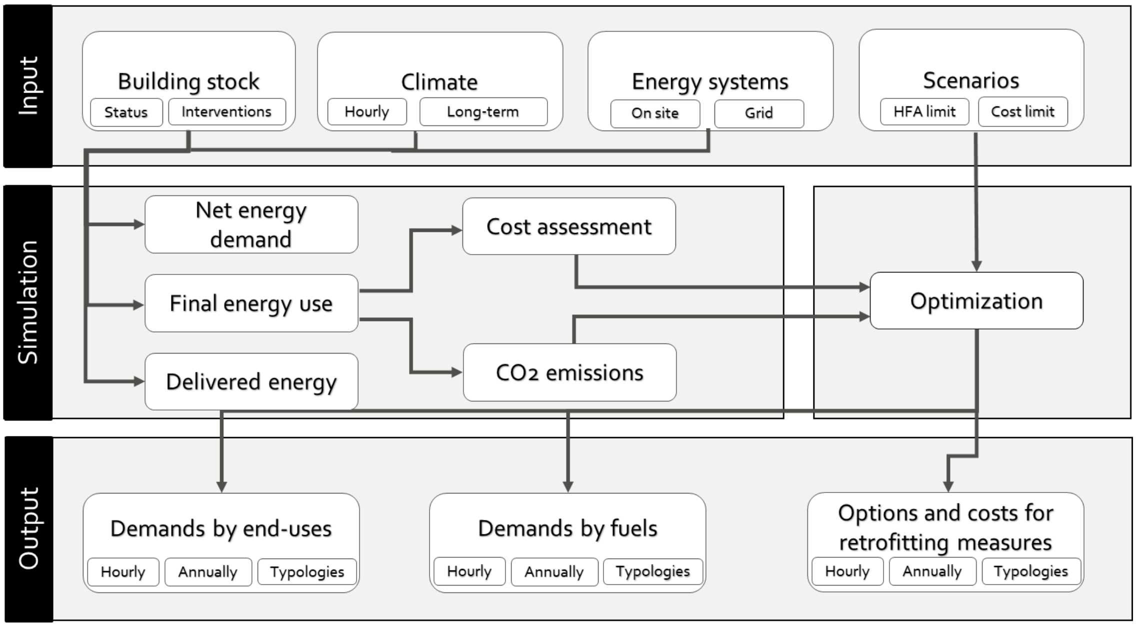


Figure 2-1 Structure and workflow of ECCABS Model [31].

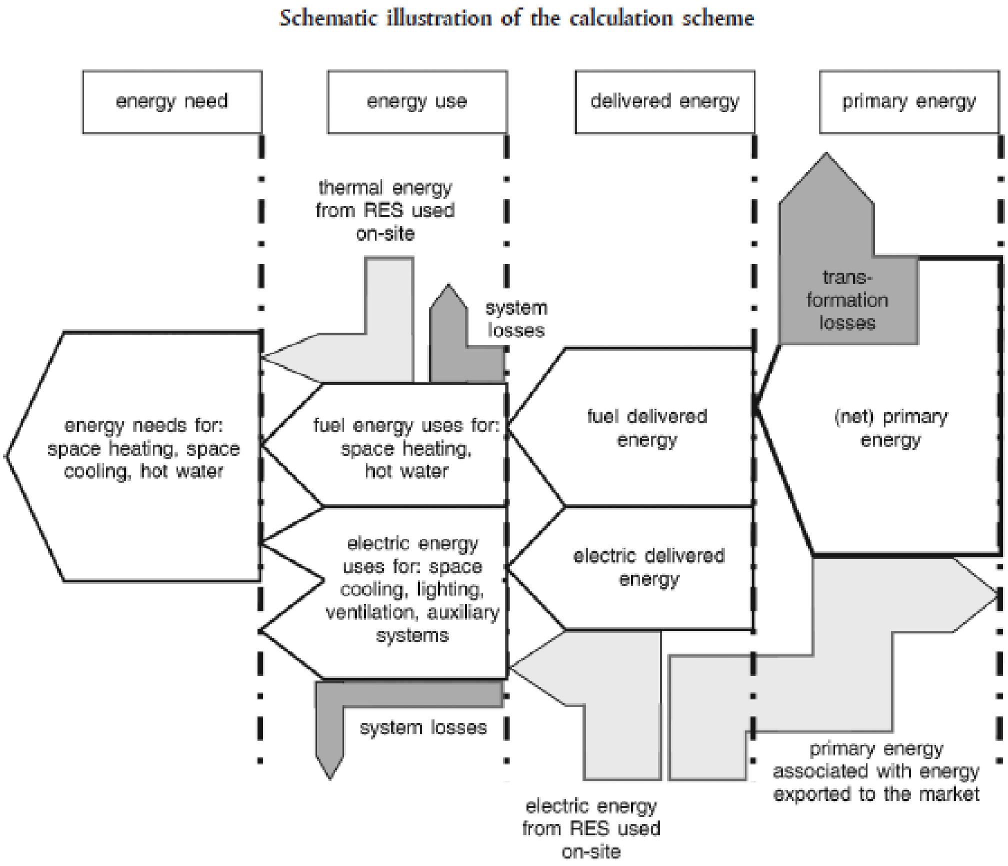


Figure 2-2 Schematic illustration of the calculation scheme used in ECCABS Model.

The model follows the calculation scheme suggested in the Energy Performance of Buildings Directive (Figure 2-2). The representation of electrification in ECCABS includes:

- At the energy need level, demands for hot water, and space heating and cooling are calculated.
- At the energy use level, the model calculates fuel uses for hot water, and space heating and cooling; electric uses for space cooling, lighting, ventilation, auxiliary systems; and thermal energy from RES used onsite.
- At the delivered energy[2] level, the model calculates fuel delivered energy, electric delivered energy, and electric energy from RES used on-site, e.g. PV panels.

As the modelling approach is dynamic and detailed, it allows to investigate DSM and other smart energy solutions, which are key for electrification of the buildings sector. Thus, the modelling approach enables input of hourly patterns, the same resolution as real-time pricing, of heat gains (occupants, lighting and appliances), and accounts for the thermal inertia of the building, while also allowing calculation of the indoor temperature.

2.7. Energy Map

The Energy map is a model developed at SINTEF that calculates the energy demand from the transport sector in Norway. It is based on road network data from NVDB (National Roads Database)

---

[2] *Delivered energy* is otherwise referred to in this report as *final energy* in this report. In this section we observe however the nomenclature of Figure 2-2.

and traffic data from Norwegian transport models. Given sufficient input data, it can be used to estimate the energy demand for past years, the current year, or projections for the future. The Energy Map model has been further developed in the FuChar project to convert the energy demand to a charging demand from vehicles by refining the temporal resolution and properties of the estimated trips. FuChar is a knowledge-building project financed by The Research Council of Norway and aims to minimise investment and operating costs related to the grid integration of electric transport. This includes e.g. analyses of transport patterns, user behaviour and charging profiles from electric vehicles and vessels.

The vehicle fleet (the distribution of various vehicle types) used in the Energy Map is based on country-wide vehicle statistics with an extrapolation based on both current developments and government policies to get predictions for future fleet distributions. The energy demand from the various vehicles in the Energy Map is calculated using physics-based vehicle models, which simulates driving the vehicles and vessels through a highly detailed description of the network geometry along a given route. The traffic data from the transport models is used to run the calculations on all roads in the Norwegian transport network. Traffic volumes and vehicle type distributions are used to aggregate the single vehicle energy demand on single routes into the full vehicle fleet energy demand for the entire network.

The Energy Map tool is constructed with a high level of detail, allowing users for instance to investigate energy demand on small sections of individual road links, or aggregate the demand up to municipalities or counties, or to substations and transformers. The resolution of the calculations is detailed in spatial and temporal dimensions, which calls for a similarly detailed set of inputs regarding transport network and vehicle characteristics.

2.8. EMPS

EMPS is a family of least-cost stochastic multi-area power-market models intended for forecasting and planning in electricity markets [23]. The models can be used to determine the optimal operation of the (hydro)power system and gives detailed insights into how the available water resources are best managed.

In a stochastic dynamic programming using aggregated models for each geographical area, a cost-optimal operation of the hydro-thermal power system is calculated and simulated. In an iterative procedure, a strategy for each area is calculated using an aggregated power station and equivalent reservoir representing all hydropower units in that area. The system is then simulated using the strategies found in the first step, before the strategy phase is repeated using updated hydropower values from the simulation results. Once convergence has been reached, a final, detailed simulation is carried out.

The model can contain detailed descriptions of hydropower production along with thermal production, wind power production, and solar power production in multiple geographical areas. The transmission capacity and availability transmission costs are exogenous variables that are specified for each line. The consumption curves are specified, and final demand will depend on prices and temperatures during the simulation. The outputs from the model include an optimal strategy for the aggregated hydropower system, and power prices for each area, that can be used as input in more detailed hydropower operation scheduling.

The model is in operative use by hydropower producers in the Nordic countries, usually with detailed descriptions of areas of interest and necessary information about peripheral areas. In the openENTRANCE project [19], the energy system model GENeSYS-MOD has been linked to the

EMPS-W model using a high time resolution (up to hourly). Demand profiles from GENeSYS-MOD were used as input to EMPS-W to get detailed time series for hydropower production in the different scenarios.

2.9. Relations and differences between models

The different models, as described above, are mapped into Figure 2-3 and Figure 2-4. In Figure 2-3, similarities and differences between the applied models are illustrated by a sun (reference properties), stars (extra features relative to reference), and moons (limitations relative to reference). Figure 2-4 shows the geographical coverage of each model and highlights how general or partial each model is.

The reference coincides with the features of the ON-TIMES model. ON-TIMES is a general energy system mode for the Nordic area. The model has some simplifications in the representation of hydropower and VRES, e.g. regarding stochastic optimisation and the number of within-year time-steps that are included, but both investments and operations are optimised. The two other TIMES-type models, TIMES-NO (i.e. IFE-TIMES-Norway) and IntERACT, are only for Norway and Denmark respectively.

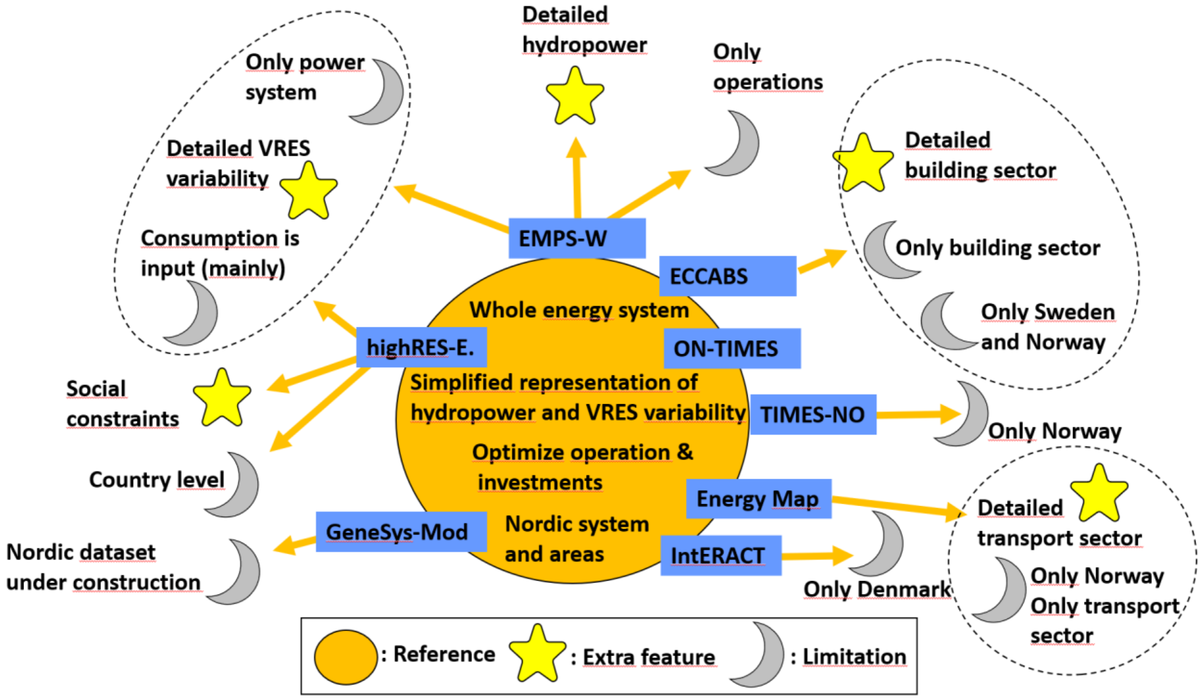


Figure 2-3: Similarities and differences between applied models

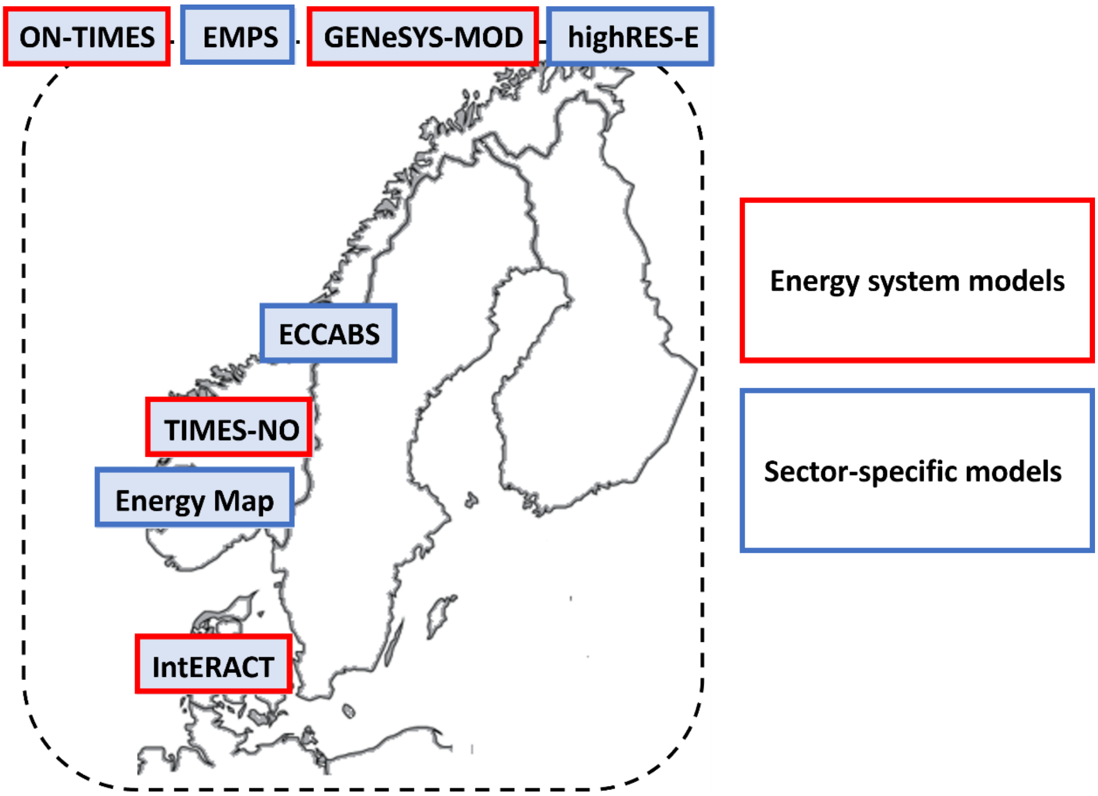


Figure 2-4: Geographical coverage and model type

GENeSYS-MOD is also a general energy system model, and it has many of the same overall properties as ON-TIMES, even though there can be considerable differences on the more detailed level. The full Nordic dataset for the GENeSYS-MOD model is still under construction.

The models highRES-E and EMPS-W are partial models for electricity markets. highRES-E has a lot of details regarding variability for renewable generation, and in the input-data to the model also for the geographical location of VRES – which is aggregated to country level. In highRES-E, it is possible to restrict the available areas for new electricity generation based on social, technical and environmental considerations. EMPS-W is an operational model for forecasting prices in hydropower-dominated power markets and includes a detailed representation of hydropower and the corresponding utilisation of reservoirs.

ECCABS considers the energy needs and supply of the building sector, and it has a detailed representation of that sector. Hence, in addition to providing specific results for the building sector, it can be used to provide inputs to e.g. TIMES-EMPS-W-type models.

3. Common scenario for parallel goals

3.1. Overview of model comparisons

In this chapter, we will compare quantitative simulation results between the different models, with a focus on electricity. To facilitate this, we have specified the following research question to be analysed by each model:

What will be the extra energy system cost in the Nordic area for complying with the targets in REPowerEU?

In addition to calculating the extra costs, we also compare other important results, including the additional renewable generation from different energy sources in the Nordic area.

To answer the research question above, we have formulated two scenarios: A base case consisting of a decarbonisation scenario leading to 2050, and a REPowerEU scenario having additional constraints on the net export volumes from the Nordic countries to continental Europe. Some of the inputs to the different models used in WP2 are aligned for this study, whereas others are not. We will thus:

- Describe parameters that are aligned for the two scenarios (Section 3.2)
- Compare some other key inputs between the models (Section 3.3)
- Compare and discuss model outputs for the base case for 2050 (Section 3.4)
- Compare and discuss the impact of REPowerEU, i.e. the differences between the REPowerEU scenario and the base case for 2030 (Section 3.5)

Although electrification is our focus, we will use energy system analyses to capture the effects on the whole energy system.

3.2. Two common scenarios: decarbonisation and REPowerEU

To compare model characteristics and outcomes, two scenarios have been developed and analysed by each model. As described below, the scenarios are focusing on decarbonisation and extra electricity export from the Nordic area to align with the REPowerEU plan. The decarbonisation scenario is the base case for the analyses. In this scenario det European energy system is decarbonised by 2050.

In March 2022, the European Commission proposed a plan [3] to make Europe independent from Russian fuels before 2030. This was made following Russia's invasion of Ukraine. Due to this changed situation, a common scenario aiming at reducing the European dependency on Russian fuels by 2030 has been studied as part of this project.

The possible conflicts and synergies of the two goals, reducing climate gas emissions in the Nordic area and contributing to the REPowerEU plan by exporting extra electricity to the continent, was analysed. For example, the level of electrification in the Nordic area may differ when the two goals are to be achieved simultaneously. Also, it could be possible to identify the narrowest bottlenecks that hinder increased electricity export from the Nordics to the European continent. In addition, it was possible to analyse how much more expensive it will be to reach climate neutrality and also comply with targets for increased electricity export.

For both scenarios, there are net-zero emissions constraints in each Nordic country by 2050. In the RepowerEU scenario, an additional requirement on net electricity to Europe has been defined, where net export from the Nordic area should be at least 30 TWh higher in 2030 compared to the obtained net export value in the same year for the base case. The new obtained value in 2030 will be defined as the minimum net export from the Nordics for the following years, i.e., it will never reach a level below this value. This is our quantification for a possible contribution to the REPowerEU plan for the Nordic area.

Since some of the models are country-specific, the 30 TWh are allocated to different Nordic countries as shown in Table 3-1. Those country-specific values are applied only in the country-specific models. The value is lower for Sweden than for Denmark and Norway due to existing challenges with North-South transmission, and due to a possible phase-out of nuclear power.

The results are compared between the different models, e.g. the extra energy system costs due to the required extra electricity export. The pace of development of new electricity generation may vary in the two scenarios, as may the location of new production units. In addition, the electrification of energy consumption in different sectors may be different in the two scenarios.

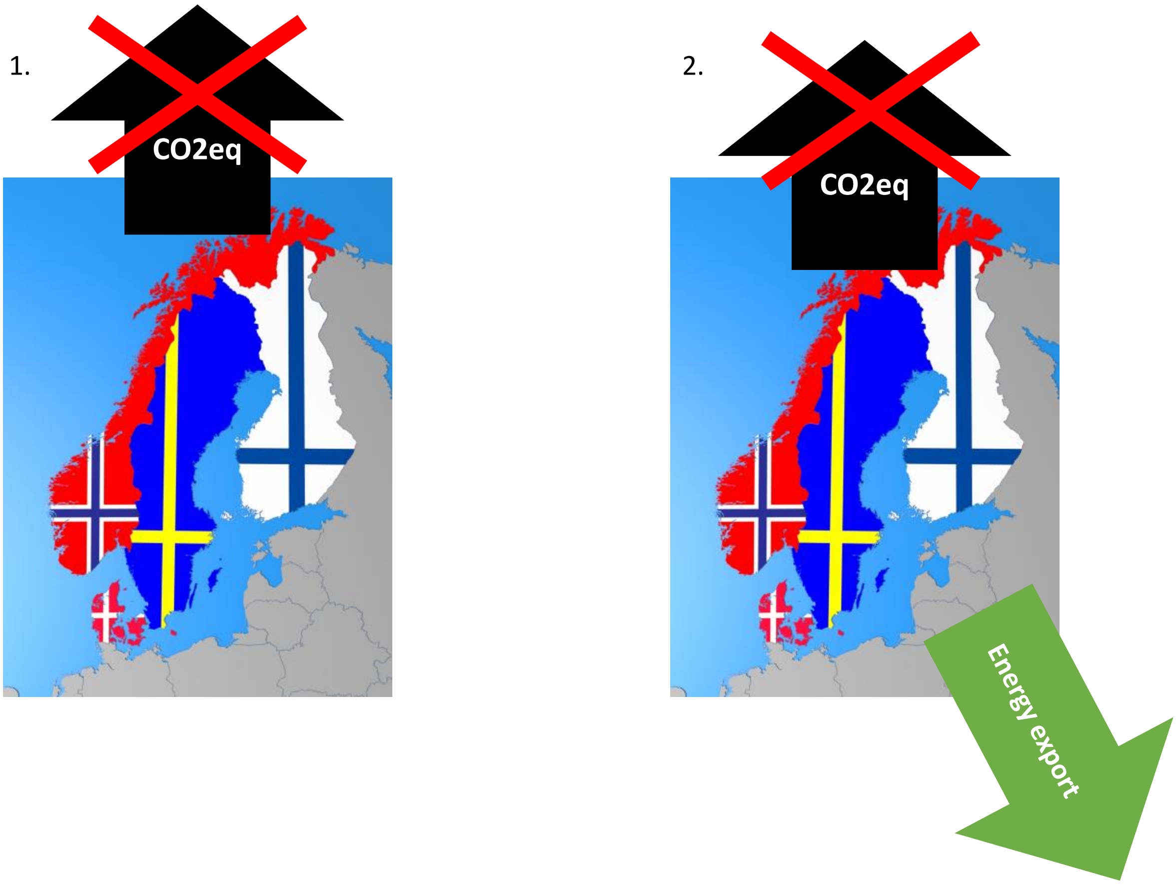


Figure 3-1: Common scenarios for the Nordic energy and power system until 2050. Panel 1.: Net-zero emission by 2050. Panel 2: Net-zero emission by 2050 + REPowerEU targets for 2030.

Table 3-1: Constraints for net electricity export, 2030 onwards

	Sweden	Denmark	Norway	Finland	Nordic*
Base case: Net zero emissions by 2050:	No constraint	No constraint	No constraint	No constraint	No constraint
REPowerEU:	+ 5 TWh relative to base case year 2030	+ 10 TWh relative to base case year 2030	+ 10 relative to base case year 2030	+ 5 relative to base case year 2030	+ 30 TWh relative to base case year 2030

*ON-TIMES and GENeSYS-MOD constraints.

3.3. Other key inputs in the models

Due to time-limitations in the project, other assumptions apart from the specification of scenarios in Section 3.2 were not aligned between the different models. However, in all models, high European energy prices were assumed based on the fact that energy prices have increased lately and are assumed to remain on a high level, at least in the medium term. Another common feature reflected by all models is that new LNG terminals will be built. Furthermore, to fit the characteristics of their existing energy models, each research institute developed ways to *incentivise the energy export.* Table 3-2 shows some of the key inputs to each of the models for the base case in 2050.

Table 3-2: Some key inputs per model for 2050. Nordic values for ON-TIMES and GENeSYS-MOD. Norwegian numbers for TIMES-NO and highRES-E

	Unit	ON-TIMES	GENeSYS-MOD	TIMES-NO	highRES-E
Renewable costs					
Rooftop PV	€/kW	Com:725 RES:850	Com: 397 Res: 537	Com: 300-520 RES: 300-770	Utility: 466
Wind onshore	€/kW	831	900	400-1340	851
Wind offshore	€/kW	1394	1353 - 1831	2170[2]-2787[3]	1562
Renewable potential					
Rooftop PV	GW	70.4	10.5	31.8	1120 (PV ground mont.)
Wind onshore	GW	54.4	42	15.2	190
Wind offshore	GW	154.3	158.9	31.6	210
Carbon regulation					
Constraint	Mt. CO2e	9265[1]	n.a.		87.5 annual[4]
Price	€/t		355	438	
Fuel prices					
Natural gas	€/MWh th	17	11.12	34.3	56-71
Oil	€/MWh th	Crude oil: 29	Crude oil: 18.7	-	
Bio	€/MWh th	Wood chips: 25	Average used: 18.8[5]		

[1] ON-TIMES accounts for LULUCF for achieving carbon neutrality in the Nordic region [$MtCO_2$-eq].

[2] Bottom-fixed offshore wind

[3] Floating offshore wind

[4] Only for the electricity sector

[5] There are several costs for biomass-sources in GENeSYS-MOD, the price here represents the average of the sources in the model that were used.

3.4. Results for base scenario, 2050

This section compares results for a decarbonised Nordic energy systems in 2050 between the different models. As shown in Table 3-4, the focus is on electricity. Table 3-4 to Table 3-8 show the results from the energy system models used in the comparative study, for the Nordic countries as a whole and for each of the studies countries.

GENeSYS-MOD

In the GENeSYS-MOD simulations, the Nordic area includes Norway, Sweden, Denmark and Finland, although the results for Finland are not further investigated in this report. The results from GENeSYS-MOD originally contained minimal capacities of offshore wind power production, as this is calculated as less profitable than onshore wind. However, due to political decisions (e.g. [37] [38]), the model was tuned to favour offshore wind despite less profitability, by changing the capacity factors for onshore wind. For 2050, we see that Denmark remains self-sufficient, but increases the production by 153%, mainly offshore wind, and increases demand by 53%, mainly increased electrolysis. No other Nordic country shows the same increase in either demand or production. Results also show that Norway is self-sufficient in 2050, whereas Sweden and Finland have a net import of about 30 TWh/year and 10 TWh/year respectively. In the Nordic area, no power production is expected from hydrogen, natural gases, coal or oil. The net exports from the Nordic area take a leap from 2045 to 2050, mainly due to increased exports from Denmark. The increased transmission capacities from 3.1 GW to 6.5 GW between Denmark and Germany, where much power is consumed, facilitates exports from Denmark, see Table 3-3.

Table 3-3: Power transmission capacity expansions along the base scenario from GENeSYS-MOD [GW]

Transmission lines (From-To)	Base scenario	
	2018	2050
SE-DE	0.6	0.6
SE-DK	2.4	2.4
SE-PL	0.3	0.3
SE-FI	2.3	2.3
SE-NO	3.7	5.3
DK-DE	3.1	6.5
DK-NL	0.7	1.5
DK-UK	1.4	1.4
DK-NO	1.7	1.8
DK-SE	2.4	2.4
NO-DE	1.4	1.4
NO-NL	0.7	0.7
NO-DK	1.6	1.7
NO-SE	3.4	5.4
NO-UK	2.8	2.8
FI-SE	2.0	2.0
FI-EE	0.4	0.4

IFE-TIMES-Norway

The results from the IFE-TIMES-Norway model provide insight on the demand, electricity production and net electricity export for Norway in a decarbonised transition pathway. Compared to the Nordic and European models, a higher demand for primary energy and electricity is reached in 2050. This is likely related to the scenario definition, in which an increase in industry activity is assumed for Norway. Moreover, the model largely favours onshore wind development due to its low production costs, reaching the full potential of 47 TWh. One of the largest differences in results is related to the rooftop PV installation, in which IFE-TIMES-Norway finds it profitable to invest in 13 TWh production. The reason for its high competitiveness is related to large cost reductions, but also to its advantage of being available on-site, reducing the need for new large-scale investments in grid infrastructure. Overall, the model invests in larger capacity for all renewable energy sources, because of higher electricity demand but also larger net export volumes. Notably, the degree to which Norway provides Europe with power depends largely on the price assumptions for the European power system, as will be showed in Section 4.1. Moreover, 58 TWh (61%) of the total net export is supplied by offshore wind production.

ON-TIMES

The model results for the ON-TIMES scenarios illustrate carbon neutrality pathways in all the energy sectors in the Nordic region. Our base case in this study is the CNN scenario (for the description of the scenario see the Introduction chapter for the ON-TIMES model). By 2050, wind and hydro will dominate Nordic electricity generation. Wind dominates investments in new power generation in all the scenarios, growing from about 15% of total Nordic electricity generation in 2020, to about 40% in the CNN scenario (chosen as base scenario in this study). Onshore wind is already the cheapest power generation option in the Nordic region. Hydropower also has low costs but has a limited growth potential. Sweden and Norway have particularly good wind resources in relatively less populated areas. Solar power is currently almost negligible in all Nordic countries except for Denmark, which had over one GW of installed capacity by end of 2019. By 2050, Nordic solar capacity could grow to about 30 GW in our base scenario. This growth in solar power is driven by its low levelised cost of energy. Since solar generation is concentrated over relatively few hours (900-1000 full-loads annually in the Nordic countries), its deployment is held back particularly in Finland, Norway, and Sweden. In the transport sector, electrification will not be limited to light-duty vehicles. Electrically chargeable cars reach 100% market share already around 2025, with battery-only cars dominating the market by 2030. Substantial electricity grid improvements are required to enable the transformation of Nordic industry and transport. This implies that a significant infrastructure build-out will be required.

highRES-E

For the base case (as well as the consequent REPowerEU), the model is constrained to a CO_2 budget of 12.4 MtCO_2 (2 gCO_2/kWh), which is consistent with a net-zero pathway [39]. The model results for highRES-E include capacity expansion in all 31 zones as well as operational decisions for a year at hourly resolution. Transmission expansion is restricted to the existing capacities plus what is planned by 2030 according to ENTSO-E Ten-Year Network Development Plan (TYNDP) 2020 [40](source). As highRES-Europe is a snapshot model, we do not see how the system develops, but only the final snapshot of 2050.

In addition to existing hydropower infrastructure, the model invests in moderate amounts of solar PV and significant offshore wind power in Sweden, Finland, and Norway, while Denmark invests in a moderate amount of onshore wind and solar PV. Both Denmark and Finland are net importers of electricity, while Sweden and Norway are net exporters. The Nordic area as a whole exports roughly 25 TWh in 2050. Large amounts of offshore wind and solar generation in Germany is likely a reason to why Denmark invests in such low amounts of electricity generation.

Table 3-4: Base case results for Nordic area, 2050

	Unit	ON-TIMES	GENeSYS-MOD	HighRES-E
Primary energy demand	TWh/yr	1310	1461.8	
Electricity demand	TWh/yr	571.9	739.7	730.7
Of which in transport	TWh/yr	139	59.2	
Electricity production				
Rooftop PV	TWh/yr	36.5[2]	77.2[1]	130.6[1]
Wind onshore	TWh/yr	146.4	113.8	38.1
Wind offshore	TWh/yr	155.6	378.6	325.8
Hydropower	TWh/yr	244.2	237.5	182.4
Bio-based	TWh/yr	29.7	2.5	
Natural gas with CCS	TWh/yr	0	-	24.6
Hydrogen-based	TWh/yr	0	-	
Net electricity export	TWh/yr	84.4	78.5	24.6

[1] Utility PV – no rooftop PV production available.

[2] All types of PV.

Table 3-5: Base case results for Norway, 2050

	Unit	TIMES-NO	highRES-E	GENeSYS-MOD	ON-TIMES
Primary energy demand	TWh/yr	279	-	243.4	274.2
Electricity demand	TWh/yr	188	220 (exog.)	156.3	168.3
Of which in transport	TWh/yr	19.7	-	12.3	33.6
Electricity production					
Rooftop PV	TWh/yr	13	28.6*	0.7*	0.03*
Wind onshore	TWh/yr	47	0.6	28.4	36.9
Wind offshore	TWh/yr	86	106.4	16.7	9.4
Hydropower	TWh/yr	155	113.2	162.0	158.9
Bio-based	TWh/yr		-	0.02	0.8
Natural gas with CCS	TWh/yr		0.8	-	0
Hydrogen-based	TWh/yr		-	-	0
Net electricity export	TWh/yr	96	29.7	56.8	38

*Utility PV – no rooftop PV production.

Table 3-6: Base case results for Denmark, 2050

	Unit	IntERACT[3]	ON-TIMES	GENeSYS-MOD	highRES-E
Primary energy demand	TWh/yr		232.5	425.4	-
Electricity demand	TWh/yr	74-97	107.5	188.4	63.7
Of which in transport	TWh/yr	12	29.7	12.0	-
Electricity production					
Rooftop PV	TWh/yr	14[2]	13.4[2]	18.7[1]	19.6[1]
Wind onshore	TWh/yr	22	25.9	17.6	30.8
Wind offshore	TWh/yr	44-65	96	212.6	-
Hydropower	TWh/yr	0	0	0.03	0.01
Bio-based	TWh/yr	1	0.6	0.5	-
Natural gas with CCS	TWh/yr		-	-	3.1
Hydrogen-based	TWh/yr		-	-	-
Net electricity export	TWh/yr	0	32	63.5	-10.2

[1] Utility PV – no rooftop PV production.

[2] All types of PV.

[3] Numbers from IntERACT are based on explorative scenarios made for the Climate Program 2021. Currently the IntERACT model is being update in order to provide new explorative scenarios for the Danish Government Climate Program 2022.

Table 3-7: Base case results for Sweden, 2050

Model	Unit	ON-TIMES	GENeSYS-MOD	highRES-E
Primary energy demand	TWh/yr	500.6	463.4	-
Electricity demand	TWh/yr	204.4	255.3	279.2
Of which in transport	TWh/yr	66.4	22.2	-
Electricity production				
Rooftop PV	TWh/yr	10.2[2]	40.5[1]	36.4[1]
Wind onshore	TWh/yr	59.4	9.3	-
Wind offshore	TWh/yr	50.3	111.1	143.4
Hydropower	TWh/yr	70.3	62.0	60.8
Bio-based	TWh/yr	4.4	0.5	-
Natural gas with CCS	TWh/yr	-	-	7.3
Hydrogen-based	TWh/yr	-	-	-
Nuclear	TWh/yr		37.8	
Net electricity export	TWh/yr	14.2	-29.2	6.6

[1] Utility PV – no rooftop PV production.

[2] All types of PV.

Table 3-8: Base case results for Finland, 2050

	Unit	ON-TIMES	GENeSYS-MOD	highRES-E
Primary energy demand	TWh/yr	303.1	329.6	-
Electricity demand	TWh/yr	91.4	139.7	168.1
Of which in transport	TWh/yr	9.4	12.6	-
Electricity production				
Rooftop PV	TWh/yr	13.2[2]	17.4[1]	46[1]
Wind onshore	TWh/yr	23.9	58.4	6.8
Wind offshore	TWh/yr	0	38.1	76
Hydropower	TWh/yr	14.7	13.5	8.4
Bio-based	TWh/yr	20	1.5	-
Natural gas with CCS	TWh/yr	-	-	13.4
Hydrogen-based	TWh/yr	-	-	-
Nuclear	TWh/yr		16	
Net electricity export	TWh/yr	0.27	-9.04	-1.5

[1] Utility PV – no rooftop PV production.

[2] All types of PV.

Electrification over time

Figure 3-2 shows how much electricity there is in the final energy consumption for each energy system model for the base year each model uses, which is around 2020, and for 2030, 2040 and 2050. HighRES-E does not show the temporal development, but the results for 2050 are compared to the results from the other models. All models show an electrification process for Denmark and both ON-TIMES and GENeSYS-MOD show electrification in Sweden (though GENeSYS-MOD much more so than ON-TIMES). For Finland, there is more electrification in GeneSys-Mod than in ON-TIMES. But ON-TIMES estimates a higher electrification in Norway than GENeSYS-MOD, with a lower consumption for the base year. HighRES-E estimates a remarkably higher consumption of electricity in 2050 than both ON-TIMES and GENeSYS-MOD for Sweden, Norway and Finland.

Figure 3-3 shows the electricity used for production of other energy carriers domestically, e.g. hydrogen through electrolysis, for each energy system model except InterACT, for the base year, 2030, 2040 and 2050. The produced energy carriers can then be exported or used domestically. The results for Denmark from GENeSYS-MOD stand out among the other results with a value for 2050 of more than 100 TWh, compared to values from the other models and for the other countries of less than 50 TWh. TIMES-NO and GENeSYS-MOD estimate about the same development for Norway, though GENeSYS-MOD starts later than TIMES-NO. ON-TIMES has estimates below all other models for all countries. No model estimates production of other energy carriers in Finland.

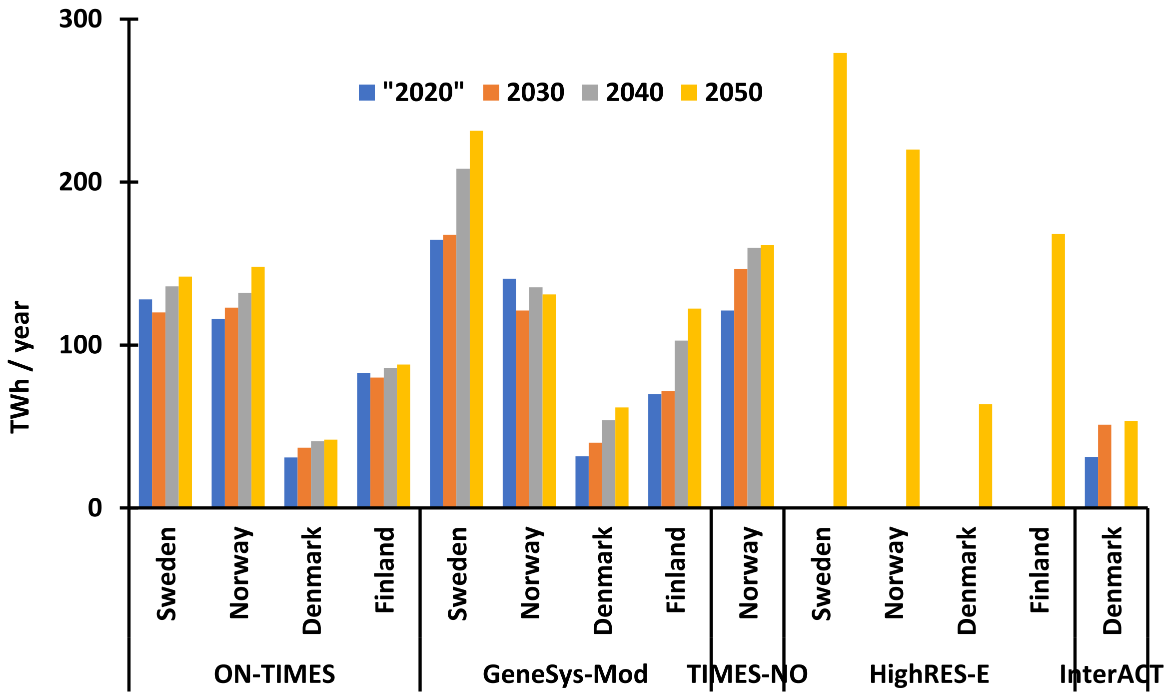


Figure 3-2: Electricity in final energy consumption[3]

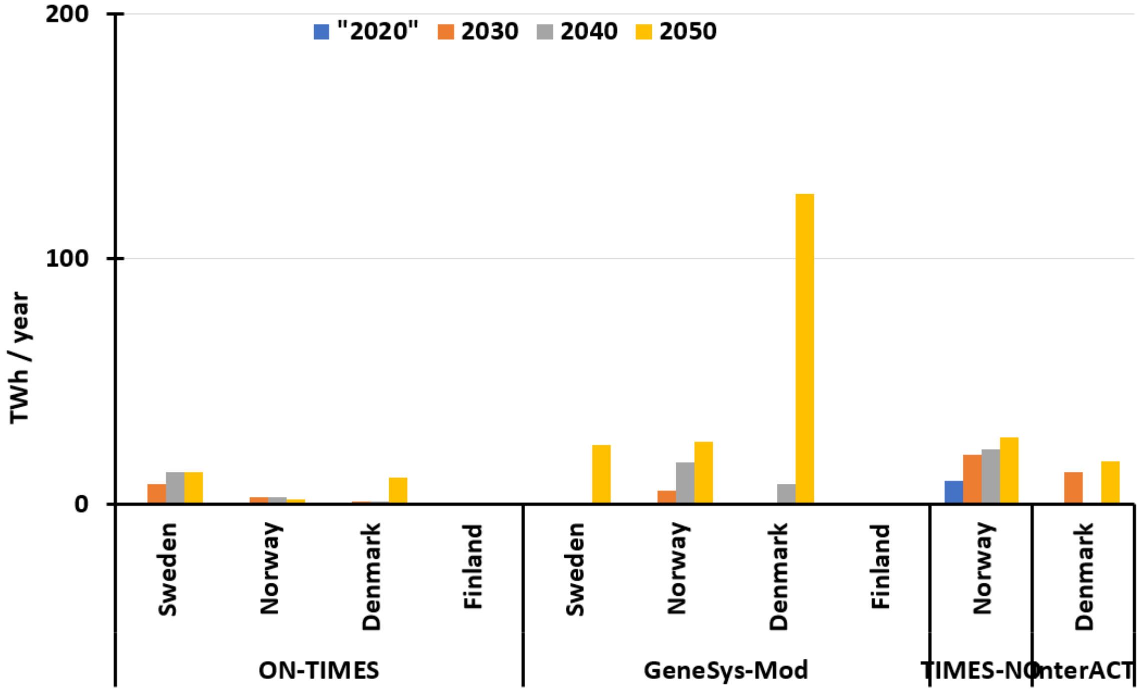


Figure 3-3: Electricity used for production of other energy carriers domestically[4]

---

[3] I.e. excluding losses, excluding electricity used to produced other energy carriers such as hydrogen, excluding net export and use in petroleum sector. "2020" is approximate, as it varies somewhat between models.

[4] I.a. production of hydrogen, district heating, and electrification in petroleum sector.

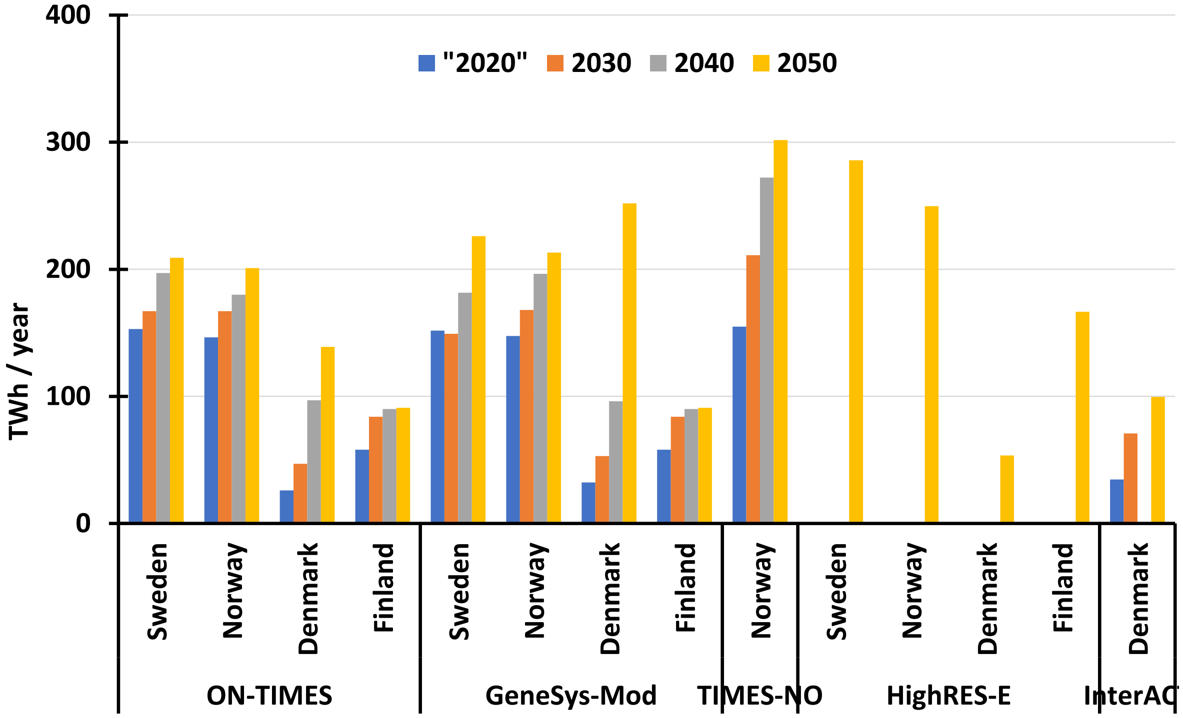


Figure 3-4: Electricity production

Figure 3-4 shows the electricity production for each country, model, and year from the base year, 2030, 2040 and 2050. These numbers show high amount of electricity used for production of other energy carriers in Denmark in 2050. TIMES-NO shows the highest production numbers for Norway, higher than the total electricity consumption. This reflects the high electricity exports shown in Table 3-5. HighRES-E continues to show higher numbers for Sweden, Finland and Norway than both ON-TIMES and GENeSYS-MOD. The Danish model InterACT provides the lowest number for Denmark's electricity production for 2050.

3.5. Results for impacts of REPowerEU, 2030

This section compares the impact of REPowerEU scenario relative to the base scenario, for the year 2030. Table 3-12 to Table 3-16 show the change introduced by the REPowerEU scenario.

GENeSYS-MOD

The results from GENeSYS-MOD show that to export 30 additional TWh/year from the Nordic countries, the power demand is left untouched while the production increases by 30 TWh/year. In addition to the values in Table 3-12, there is a 5 TWh/year increase of power production from coal in Finland and Sweden. The constraint is binding from 2030 to 2045, but not for 2050 – due to the net export leap from 2045 to 2050, similar to the net export leap from 2045 to 2050 that we see in the base case. In fact, the net export in 2050 is higher in the REPowerEU scenario than in the base scenario, although both export numbers would meet the constraint. This indicates that the extra export made in 2030 facilitates a new way to the decarbonisation goals for 2050 than the base scenario. However, there is a leap that happens when a constraint becomes binding: either net zero by 2050 or 30 TWh additional Nordic export by 2030. The increase in exported power in 2030 for the REPowerEU scenario compared to the base scenario, happens mainly in Denmark, Sweden and

Norway, in declining order. In Denmark, the increased production comes from offshore wind power. The energy system costs increase in total and especially in Denmark, but also in Norway and Sweden.

highRES-E

With demand being defined exogenously to the model, it does not change in any of the zones. The additional 30 TWh exported must stem from increased generation. The results show both technological and spatial diversification with additional generation from onshore wind and solar in Denmark, offshore wind in Sweden and Finland and offshore wind and solar in Norway (see Table 3-12 to Table 3-16 for more details). The changes in system cost is most significant for Denmark, both in absolute and relative terms. The increased onshore wind generation results in a system cost increase of 1.22%, while it only increases by 0.28%, 0.14% and 0.11% respectively for Norway, Sweden, and Finland.

IFE-TIMES-Norway

Results from IFE-TIMES-Norway indicate that the additional 10 TWh of export to Europe is covered mainly by new electricity production, with a small reduction in electricity demand of 1.6 TWh (SMR with CCS and biomass boilers substitute electrolysers and electric boilers). Most of the new production derives from rooftop PV, followed by hydropower and offshore wind. In this regard, it is important to note that the trade between Nordic countries is fixed in the model, meaning that Norway cannot provide Europe with additional power through increasing imports or reducing exports from/to Sweden, Denmark or Finland. Lastly, the long-term impact on the Norwegian energy system is close to negligible, as Norway initially reaches large net export volumes already from 2035. Consequently, the constraint of additional 10 TWh net export is only binding in 2030, leading to an accelerated investment in renewable capacity.

ON-TIMES

To enable the additional 30 TWh of net electricity export, new assumptions were needed in the ON-TIMES model compared to our base scenario. These assumptions were the lower average electricity prices in EU (see Table 3-9) and the higher power transmission capacity investments before 2050 between the Nordic region and continental Europe and also the higher transmission capacity between and within the Nordic countries (see Table 3-10 and Table 3-11, respectively). The transmission capacity investments in the base scenario are enough to handle the additional 30 TWh of net electricity export in 2030, but with the increased electricity demand within the Nordics after 2040, the transmission capacity needs to be expanded to a higher extent. Specifically, in comparison to the base scenario, the transmission capacity from Denmark to Germany and UK, and from Sweden to Germany, Poland, and Lithuania, need to be invested in.

The ON-TIMES model results for the additional 30 TWh of net electricity export from the Nordic region to Europe show that the extra electricity export is supplied, in decreasing order, by Denmark, Sweden Norway and Finland. The additional electricity in the Nordic region, to a large extent (16.4 TWh) is supplied by wind onshore in Denmark. The rest of the additional electricity export is covered mainly by offshore wind in Sweden (6.1 TWh), solar PVs in Denmark (4.2 TWh), offshore wind in Denmark (1.7 TWh) hydropower in Norway (1.4 TWh), onshore wind in Sweden (1.1 TWh), and biomass CHP plants in Finland (1.1 TWh).

Moreover, from the model results, the total system cost of energy supply for the entire model time horizon (2010-2050) increases in the Nordic region. However, the total system cost increases in some of the countries, i.e., in Denmark and Finland, while it decreases in the other countries, i.e., Norway and Sweden.

The ON-TIMES model results also illustrate that electricity demand decreases in most of the Nordic counties except for Finland, where it remains unchanged. The electricity demand is calculated as "delta electricity production" minus "delta net electricity export". From the model results, in 2030, electricity consumption in the industry sector in the Nordic region decreases by about 4.7 TWh, of which 2.5 TWh in Denmark. The reason could be explained by the fact that trade between the Nordic countries is not limited to electricity. Biomass, fossil fuels, hydrogen, etc., are also traded between the countries. This, in turn, could also affect electricity demand within the countries if extra electricity export is required from the Nordic region.

Figure 3-5 shows how the extra net electricity export in 2030 from the Nordic region to Europe can affect electricity production in the Nordic countries.

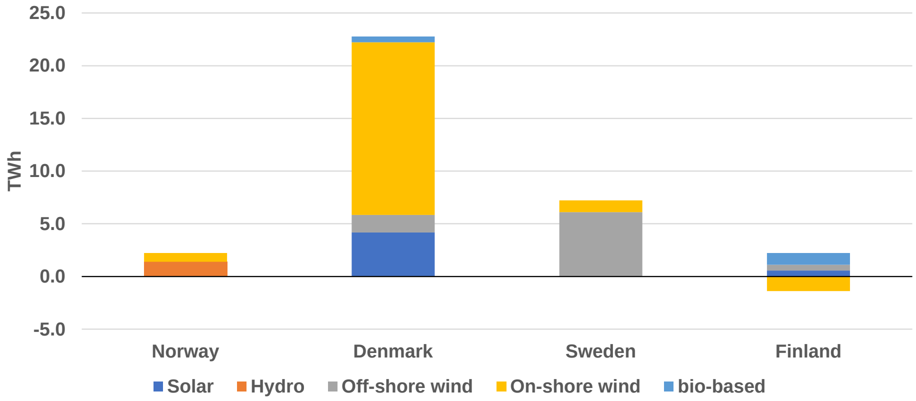


Figure 3-5: ON-TIMES model results for the electricity production mix in the REPowerEU scenario compared to the base scenario in 2030.

Figure 3-6 illustrates the ON-TIMES results for electricity consumption in the transport, residential and industry sectors for different regions from 2030 to 2050 for the base scenario. As it is shown, compared to the residential sector, electrification of the transport and industry sectors are identified by the model to be more cost-efficient solution to achieve the carbon neutrality goal in the Nordic region.

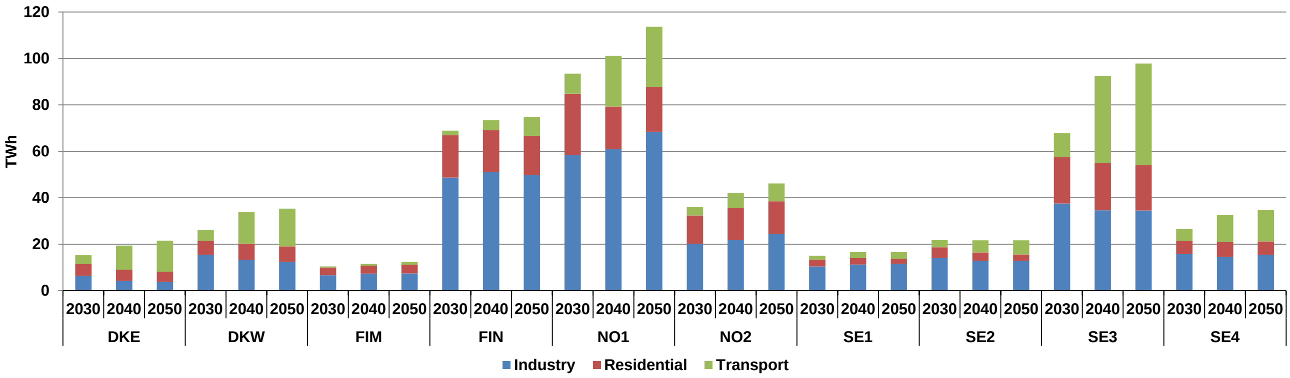


Figure 3-6: Electricity consumption by sector in the base scenario in ON-TIMES. Abbreviations: Denmark's two regions (DKE and DKW), Finland's two regions (FIM and FIN), Norway's two regions (NO1 and NO2), Sweden's four regions (SE1-SE4).

Table 3-9: Average electricity import price assumption (to the Nordic region) for the REPowerEU compared to the base scenario [%].

	DE	LE	NL	PL	UK
2020	0	0	0	0	0
2030	-3.4	-1.4	-5.6	-1.3	-6.2
2040	-12.8	-6.9	-10	-9.7	-8.2
2050	-16.3	-6.4	-14.6	-11.4	-9.9

Electricity prices in EU are the Balmorel model results for the corresponding scenarios.

Table 3-10: Capacity of transmission lines between the EU and the Nordics countries [PJa][1].

Transmission lines	Base scenario[2]		REPowerEU scenario[3]	
	2030	2050	2030	2050
SE-DE	41	41	41	183
SE-LT	22	22	22	139
SE-PL	19	83	19	640
DK-DE	142	142	142	422
DK-NL	22	22	22	26
DK-UK	44	44	44	82
NO-DE	44	44	44	44
NO-NL	44	114	44	114
NO-RU	2	2	2	2
N-UK	44	119	44	120

[1] Annual availability of all the transmissions lines is 60%.

[2] Values are given as upper bound constraints in the model.

[3] These data are given exogenously to the model (i.e., outputs of the Balmorel model and as fixed constraints)

Table 3-11: Capacity of transmission lines between and within the Nordic countries [PJa].

Transmission lines	Base scenario[1]		REPowerEU scenario[1]	
	2030	2050	2030	2050
DKW-DKE	1200	1200	1200	2954
DKE-SE4	1700/ 1300[2]	1700/ 1300	1700/ 1300	1700/ 1300
DKW-NO1	1700	4027	1700	3546
DKW-SE3	740/ 680	1326/ 1266	740/ 680	6740/ 6680
NO1-NO2	2000	2000	2000	3641 / 6932
NO1-SE3	2145/ 2095	2145/ 2095	2145/ 2095	2145/ 2095
NO2-SE1	700/ 600	700/ 600	700/ 600	700/ 600
NO2-SE2	1600/ 2050	1823/ 2273	1600/ 2050	2301/ 2751
SE1-SE2	3300	3300	3300	3300
SE2-SE3	8700	8910	8700	8000
SE3-SE4	7200	7200	7200	6500/ 3200

[1] Values are given as upper bound constraints in the model and they are based on the Balmorel model [41]. Annual availability of all the transmissions lines is 60%.

[2] When the capacity is not equal from/ to a region, these values are given by "/ ".

Table 3-12: Impact of REPowerEU for the Nordic area in 2030

Model	Unit	ON-TIMES	GENeSYS-MOD	highRES-E[5]
Primary energy demand	TWh/yr	+38.9	+13.6	
Electricity demand	TWh/yr	-12.5	0.0	0
Of which in transport	TWh/yr	-0.3	-0.1	
Electricity production				
Rooftop PV	TWh/yr	+4.2[1]	0[2]	+1.2[2]
Wind onshore	TWh/yr	+16.9	+4.2	+7.5
Wind offshore	TWh/yr	+8.3	+20.5	+14.8
Hydropower	TWh/yr	+1.4	+0.1	+6.3
Bio-based	TWh/yr	+1.7	0	
Natural gas with CCS	TWh/yr	0	+0.5[3]	0
Hydrogen-based	TWh/yr	0	0	
Net electricity export	TWh/yr	+45.5	+30	+30
Energy system costs	NPV, M€	+537	+9459.5	+144[4]

[1] All types of PV.

[2] Utility PV – no rooftop PV production available.

[3] Power production from gas without CCS.

[4] Operating costs for one year only

[5] 2050 values for highRES-E

Table 3-13: Impact of REPowerEU for Norway, 2030.

Model	Unit	TIMES-NO	highRES-E[4]	GENeSYS-MOD	ON-TIMES
Primary energy demand	TWh/yr	0		+1.4	+3.1
Electricity demand	TWh/yr	-1.6	0	-0.1	-0.3
Of which in transport	TWh/yr	-0.14		0.0	0
Electricity production					
Rooftop PV	TWh/yr	4.9	+0.2[1]	-	0
Wind onshore	TWh/yr	0	-0.3	0	+0.8
Wind offshore	TWh/yr	1.4	+3.3	+3.2	0
Hydropower	TWh/yr	2.1	+6.9	0	+1.4
Bio-based	TWh/yr			0	0
Natural gas with CCS	TWh/yr		0	+0.1[3]	-
Hydrogen-based	TWh/yr			-	-
Net electricity export	TWh/yr	10	+10.1	+3.4	+2.5
Extra energy system costs	NPV, M€	468 M€	+28.8[2]	1752.2	-359

[1] Utility PV – no rooftop PV production available

[2] Operating costs for one year only

[3] Power production from gas without CCS.

[4] 2050 values for highRES-E

Table 3-14: Impact of REPowerEU for Denmark, 2030.

Model	Unit	ON-TIMES	GENeSYS-MOD	highRES-E****
Primary energy demand	TWh/yr	+26.7	+6.5	
Electricity demand	TWh/yr	-5	-0.3	0
Of which in transport	TWh/yr	0	-0.2	
Electricity production				
Rooftop PV	TWh/yr	+4.7**	0*	+0.7*
Wind onshore	TWh/yr	+16.4	-1.4	+7.6
Wind offshore	TWh/yr	+1.7	+17.3	0
Hydropower	TWh/yr	0	0	0
Bio-based	TWh/yr	+0.6	0	-
Natural gas with CCS	TWh/yr	-	-	+0.1
Hydrogen-based	TWh/yr	-	-	-
Net electricity export	TWh/yr	+28	+19.2	+8.4
Extra energy system costs	NPV, M€	+2429	5602.9	+72.4***

*Utility PV – no rooftop PV production.

**All types of PV.

*** Operating costs for one year only

****2050 values for highRES-E

Table 3-15: Impact of REPowerEU for Sweden, 2030.

Model	Unit	ON-TIMES	GENeSYS-MOD	highRES-E******
Primary energy demand	TWh/yr	+9.2	+1.5	
Electricity demand	TWh/yr	-7.2	0	0
Of which in transport	TWh/yr	-0.3	-0.2	
Electricity production				
Rooftop PV	TWh/yr	0***	0*	+0.2*
Wind onshore	TWh/yr	+1.1	+7.3	0
Wind offshore	TWh/yr	+6.1	0	+5.9
Hydropower	TWh/yr	0	0	0
Bio-based	TWh/yr	0	0	-
Natural gas with CCS	TWh/yr	-	+0.3**	0
Hydrogen-based	TWh/yr	-	-	-
Net electricity export	TWh/yr	+14.4	+4.2	+6.1
Extra energy system costs	NPV, M€	-3676	2292.1	+26.7*****

*Utility PV – no rooftop PV production.

**Power production from gas without CCS.

***All types of PV.

*****Operating costs for one year only

******2050 values for highRES-E

Table 3-16: Impact of REPowerEU for Finland, 2030.

Model	Unit	ON-TIMES	GENeSYS-MOD	highRES-E[5]
Primary energy demand	TWh/yr	+0.6	+4.2	
Electricity demand	TWh/yr	0	+0.5	0
Of which in transport	TWh/yr	0	+0.1	
Electricity production				
Rooftop PV	TWh/yr	-0.3[3]	0[1]	+0.1[1]
Wind onshore	TWh/yr	-1.4	-1.6	+0.2
Wind offshore	TWh/yr	+0.6	0	+5.6
Hydropower	TWh/yr	0	0	-0.6
Bio-based	TWh/yr	+1.1	0	-
Natural gas with CCS	TWh/yr	0	0	+0.1
Hydrogen-based	TWh/yr	0	0	-
Net electricity export	TWh/yr	+0.83	-0.1	+5.4
Extra energy system costs	NPV, M€	+2142	-187.7	+16.8[4]

[1] Utility PV – no rooftop PV production.

[2] Power production from gas without CCS.

[3] All types of PV.

[4] Operating costs for one year only

[5] 2050 values for highRES-E

3.6. Discussion

For the base scenario, ON-TIMES estimates a higher primary energy demand for the Nordic countries in 2050 than GENeSYS-MOD, and a lower electricity demand than GENeSYS-MOD and highRES-E. HighRES-E estimates a much lower hydropower production than ON-TIMES and GENeSYS-MOD, and a much higher rooftop PV production. GENeSYS-MOD estimates a higher power production altogether (about 800 TWh/yr) than ON-TIMES (about 600 TWh/yr) and highRES-E (about 700 TWh/yr), but both GENeSYS-MOD and highRES-E assume that about half of the production will come from offshore wind power, whereas ON-TIMES assumes that only one fourth of the production will come from offshore wind power. The Norwegian political signals at the moment are in favour of offshore wind (e.g. [37], [38]), which makes this a sensible result for the Norwegian models.

Model results from highRES-E appear to favour solar PV to a larger extent than the other models, particularly in Norway and Finland. Reasons *could* include the larger transmission network which connects the Nordics to all EU countries, allowing the model to hourly balance the generation which for only a few zones can be very intermittent and unreliable. In general, highRES-E features large shares of solar PV in non-Nordic countries such as Germany, France and Italy.

Comparing Table 3-4 to Table 3-12, we see that GENeSYS-MOD and highRES-E, who have favoured offshore wind power production in the base scenario, also choose to increase the electricity production to increase the electricity export in REPowerEU scenario. ON-TIMES sees an increase in onshore wind power production instead, and overall, a net electricity export which exceeds the constraint of 30 TWh/yr.

For the separate countries we see the same differences between the models, depending on the assumptions the models build their optimisations on. An interesting conclusion is that all models present feasible solutions for meeting the increased export due to REPowerEU. However, the overall cost for the energy system increases. TIMES-NO only looks at Norway, and it is therefore natural that the net energy system costs increases. For ON-TIMES and GENeSYS-MOD, the costs for the Nordic countries have the opportunity to balance each other out, which is largely the case for the ON-TIMES results, though not so much for GENeSYS-MOD.

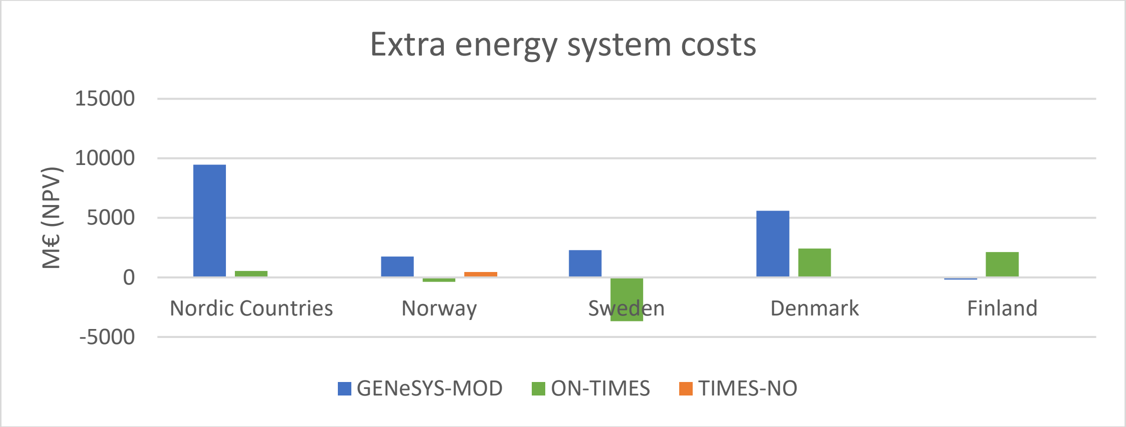


Figure 3-7: Extra energy system cost (NPV) because of the additional electricity export for the whole model time horizon.

Figure 3-7 shows the extra energy system costs due to the additional electricity export for the whole model time horizon, for each model and for each country. As the extra export comes at an added cost for the Nordic countries, other European countries would benefit from this. Also, Denmark with its proximity to the Central European demand centres, and good offshore potentials, carries the main share of the added exports, and therefore investment costs in new electricity production capacity. But what might not be explicitly in the model results is that this could mean a significant reduction of necessary domestic electricity production in e.g. Germany, which means less reliance on fossil fuels. If one would consider possible supply shortages and/or price shocks, it might very well be that the option of more renewable energy from the Nordics is in fact cheaper than the baseline, which might rely on more fossils in these other countries that can be replaced via imports from the Nordics.

In terms of transmission capacity, the results of the different models various considerably. For GENeSYS-MOD (see Figure 4-11), very limited new capacity is installed for the European connections and no new investments are made from and within Norway. In contrast, new transmission capacity is favoured in the TIMES-Norway model, both domestically and for international connections. Here we also see large new investments related to the export of offshore wind from Norway. For the ON-Times model, large investments are made from Sweden and Norway to the EU, in particularly for the RePowerEU scenario. Also, new transmission capacity is needed between the Nordic countries, in particularly between Norway and Denmark, and Denmark and Sweden. The differences between the models can be explained by different data inputs related to existing capacities and new capacity limits, as well as electricity price assumptions used for the European countries.

4. Individual project outcomes

4.1. Impact of the European energy crisis on the Norwegian energy transition

Sensitivity analyses

The interaction between Norway and Europe in the green energy transition depends on a large set of uncertain factors, such as technology development, economic growth, geopolitics, social acceptance, and energy policies. Capturing all these elements in decision making is difficult. However, energy system models can act as an important tool for evaluating the impact on future transition pathways. This section presents a sensitivity analysis on the role of Norway in the European energy transition under various parameter assumptions, evaluating the robustness of the results presented in Section 3.

European power prices

As mentioned in Section 2.3, electricity prices in countries with trading capacities to Norway are exogenously added to the IFE-TIMES-Norway model. The future development in prices is however highly uncertain and volatile, as Europe is currently experiencing, following the post-Covid recovery curve and the Ukraine invasion. Simultaneously, there have been challenges on the supply side related to the phase out of coal and low wind resources. Due to a combination of factors on both the supply and demand sides, both natural gas and electricity prices have surged in Europe. Moreover, future electricity prices will depend on the learning rates and deployment of renewable energy, as well as emerging technologies such as green hydrogen and CCS. The rate of decarbonisation is also largely affected by the carbon pricing.

To incorporate the uncertainty of European prices in this analysis, two different price sets have been applied, referred to as FP and PtX. The price sets are provided by DEA and are an output of the techno-economic model Ramses. The first scenario, FP, assumes a frozen policy in which climate and energy targets will be met within the framework of current regulation. This scenario reflects high gas prices but is still a conservative projection compared to what could be expected today. The PtX scenario allows for larger deployment of Power-to-X and renewable energy capacity. Moreover, the projections on fuel prices reflect the use of more sustainable fuels. The differences in prices are illustrated in Figure 4-1 and Figure 4-2.

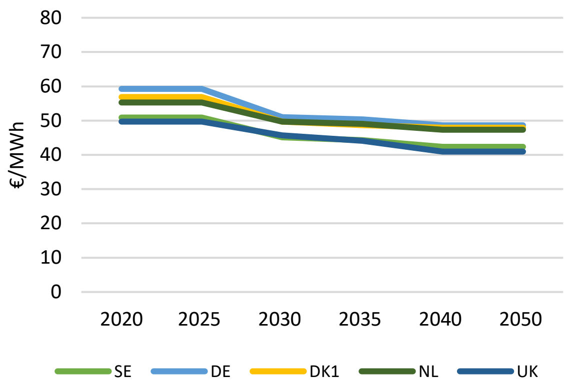


Figure 4-1: Average electricity price PtX scenario.

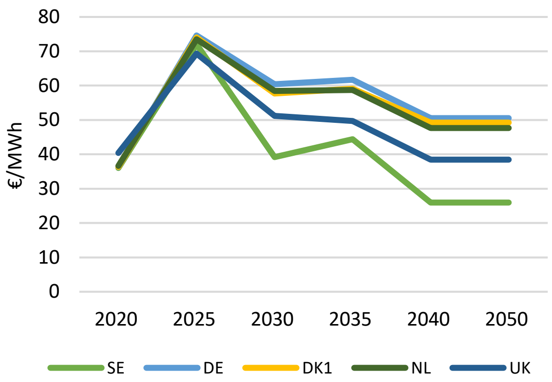


Figure 4-2: Average electricity price FP scenario.

A comparison of the results for the two price scenarios is presented in Table 4-1. One of the main differences between the scenarios is the profitability of export from the Norwegian energy system perspective. As can be observed from Figure 4-3 (S1), Norway becomes a net importer (6 TWh) in 2030 due to the lower electricity prices in Europe in PtX. Consequently, investments in new renewable capacity by 2030 are reduced by 9 GW, decreasing domestic production from 211 TWh in FP to 176 TWh in PtX. The main difference in deployment derives from the offshore wind sector, in which capacity is first installed in 2035 in the PtX scenario. At this point, Norway becomes a net exporter in both scenarios. However, the contribution to Europe remains significantly lower in PtX throughout the model horizon due to slower offshore wind deployment.

Table 4-1: Comparison of results for the two price scenarios with (S2) and without (S1) net export requirement in 2030

Model	Unit	S1 FP	S2 FP	S1 PtX	S2 PtX
Electricity demand	TWh/yr	166	165	168	167
Electricity production					
Rooftop PV	TWh/yr	1.8	6.7	0.2	1.8
Wind onshore	TWh/yr	25	25	25	25
Wind offshore	TWh/yr	30	31	0	11
Hydropower	TWh/yr	154	156	151	152
Net electricity export[5]	TWh/yr	32	42	-5	11
Additional system costs	NPV, M€		468		507

---

[5] Net export including Nordic countries

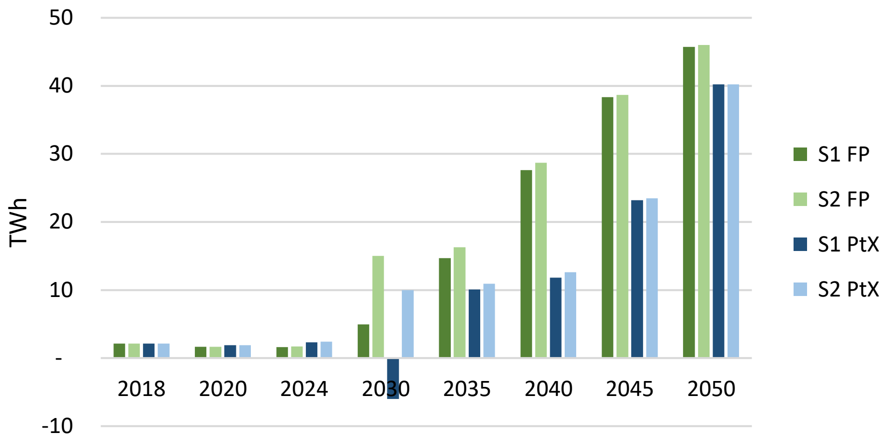


Figure 4-3: Net export to Europe (excluding Nordic countries) for all four scenarios.

For both price scenarios, the requirement of increased net export (S2) (described in Section 3.2) was enforced to evaluate the additional investments and restructuring of the Norwegian energy system needed to support Europe in the current energy crisis. In the case of Norway, it is assumed that the additional requirement on net export to Europe does not include the Nordic countries. Consequently, Norway cannot fulfil its commitment by increasing net export to Denmark, Sweden or Finland, nor can it increase import volumes from these countries to export back to Europe. Hence, trade volumes within the Nordic countries are fixed in the model. Notably, for the PtX scenario, the net export requirement is set to a total of 10 TWh in 2030, as Norway initially is a net importer in 2030. Hence, the additional net export is 16 TWh rather than 10 TWh. The assumption is based on the understanding that Norway should provide at least 10 TWh to Europe. The same tendency can be observed for both scenarios, in which the constraint is binding only in 2030. Consequently, the energy transition is only accelerated by five years, forcing a faster deployment of renewables.

The additional net export requirement is covered mainly by deployment of new renewable energy capacity. In the FP scenario, 59% of new production is derived from building applied PV (BAPV), followed by 25% hydropower and 16% offshore wind. Contrarily, offshore wind covered most of the new production requirement in the PtX scenario with 77%, while BAPV and hydropower only covered 11% each. This is related to offshore wind deployment in the southern part of Norway, which was initially profitable in S1 FP, but not in S1 PtX. The marginal cost of investing in offshore wind for the PtX scenario is therefore lower than that of new PV, but only for this specific offshore area. Noteworthy, investments in onshore wind have reached the maximum potential by 2030 and can therefore not contribute to supplying additional power. The remaining additional export is covered by a reduction in electricity demand, corresponding to 1.6 TWh and 1.5 TWh for FD and PtX, respectively. The reduction derives from substitution of electrolysers and electric boilers in favour of SMR with CCS and biomass boilers.

As the net export constraint mainly affects investments in 2030, the additional cost for the Norwegian energy system by 2050 is moderate for both scenarios, corresponding to 0.05% and 0.06% of total system costs (see Table 4-1). The additional system cost of the PtX scenario is slightly higher, but this is also related to the required increase in net export to *at least* 10 TWh. Consequently, it would in relative terms not be that expensive for Norway to provide Europe with additional 10 TWh net export in 2030. Nevertheless, results show that the total cost of the energy system is largely connected to the development of European power prices, in which the system cost increased by 12 b€ in the PtX scenario compared to the FP scenario. This clearly underlines the importance of the European energy system on the development of the Norwegian energy system.

Onshore wind power development

As presented in previous results, onshore wind power is one of the most favourable energy sources for the future Norwegian energy system, reaching full potential for all scenarios by 2030 and 2050. Nevertheless, large local resistance towards new wind power has largely limited the deployment in recent years, with no new license applications having been considered the last three years. In this regard, the government has announced a tightening of the licensing process in which more emphasis will be placed on nature, landscape, outdoor life, and cultural environment [42]. It is therefore expected that the initial potential estimated for onshore wind in Norway can be significantly reduced. This section therefore addresses the impact on the Norwegian energy system, and its power export capabilities, in a scenario where new onshore wind deployment is largely limited. To evaluate this, no new onshore wind is allowed, but reinvestments can be made in existing capacity.

The impact of restricting new onshore wind development is presented in Table 4-2. Results are presented for 2050 as this sensitivity has a more long-term impact compared to the price profile scenarios. Firstly, it can be observed from Figure 4-4 a large reduction in net export over the entire planning horizon, compared to the S1 scenario. In fact, the net export constraint is binding until 2040 in the low-price scenario, *S2 PtX nowind*, before exceeding 10 TWh. By 2050, the net export is reduced by 11 TWh and 12 TWh for the FP and PtX scenarios, respectively. These results highlight the importance of onshore wind on Norway's role as a large European power exporter.

Furthermore, both electricity demand and supply are largely reduced in this sensitivity scenario, with 21-25 TWh less power production and 10-12 TWh less electricity demand. On the demand side, 98% of the reduction is related to green hydrogen production, which is substituted by blue hydrogen. In terms of power production, offshore wind replaces parts of the onshore wind capacity, while investments in Rooftop PV and hydropower remains almost the same. For the short-term operation (2030), investments in offshore wind and solar PV are accelerated to comply with the net export requirement. However, in the long term, the model finds it more beneficial to invest in blue hydrogen to cover demand and reduce net export, rather than invest in more solar and offshore wind capacity. This is related to the technology definition in the model, in which each technology is categorised by several cost segments. Hence, when investments are maximised for the cheaper cost segments, other more favourable solutions are chosen than renewable expansion. Overall, the system cost is increased by 10-15 b€ when limiting new onshore wind investments. This is a substantial increase compared to the S2 scenarios presented in Table 4-1. Moreover, the electricity price in Norway is affected by the wind power limitation, in which the average price of 2030 increased by more than 80% in the FP scenario, from 62 €/MWh to 112 €/MWh. The same percentage increase applies for all regions, indicating that the population of Norway is equally affected by the restriction. Hence, even though Norway can benefit from high European electricity prices (FP scenario), it can also make the country more vulnerable in scenarios where it depends more on imports due to restrictions on new renewable expansion. Overall, the impact of local resistance towards onshore wind can become very expensive, as well as limiting Norway's role in the European green transition.

Table 4-2: Impact of no new onshore wind development in Norway, 2050. Results presented in relative terms to S1 scenario.

Model	Unit	S2 FP nowind	S2 PtX nowind
Electricity demand	TWh/yr	-10	-12
Electricity production			
Rooftop PV	TWh/yr	+0.7	+0.4
Wind onshore	TWh/yr	-33	-33
Wind offshore	TWh/yr	+10	+7
Hydropower	TWh/yr	+1.2	+0.5
Net electricity export[6]	TWh/yr	-11	-12
Additional system costs	M€	14 942	10 362

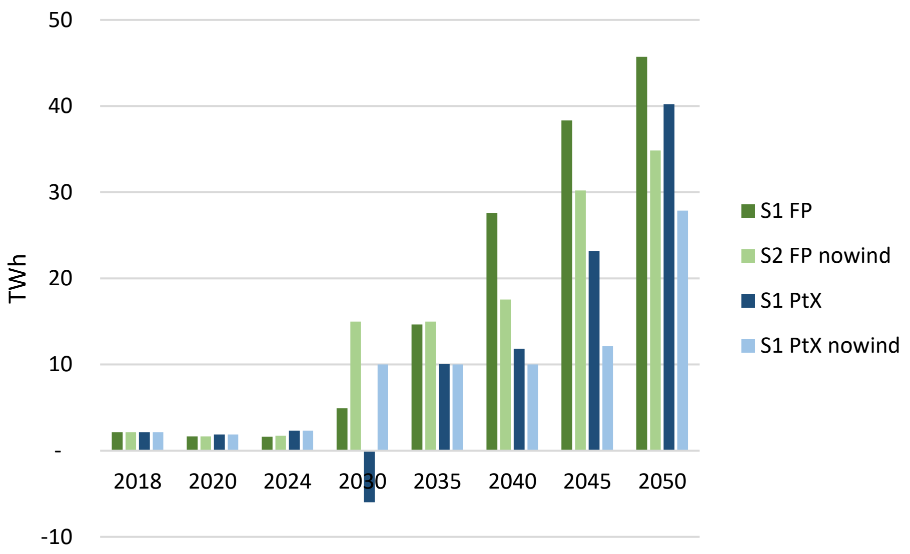


Figure 4-4: Net export to Europe (excluding Nordic countries) for scenarios with and without onshore wind

Transmission capacities

For the evaluated decarbonisation pathways in this analysis, new transmission capacity is needed both domestically and to neighbouring countries. In Figure 4-5 and Figure 4-6, the new capacities are presented for both price scenarios, FP and PtX, for the base case (S1). New investments of 1400 MW are made from Norway to Sweden, Denmark, Germany and the Netherlands by 2050 for both price scenarios, reaching the maximum potential added for these cables in the model. UK is the only country in which no new investments are made from the Norwegian mainland, however there is a substantial capacity investment from the offshore regions (>3000 MW). In terms of the RePowerEU scenario (S2), no additional capacity is needed to fulfil the net export requirement beyond what is installed in S1. For domestic trade, new capacity is needed on all lines except NO1-NO2. In addition to the connections presented in Figure 4-5 and Figure 4-6, new capacity is installed from offshore regions to NO2, NO3 and NO5 (>8000 MW). This is partly the reason for the high investment capacities between the domestic regions, to be able to distribute the large amount of offshore wind

---

[6] Net export including Nordic countries

production. This can be confirmed from the transmission flow trends, showing an increasing flow from the northern to the southern parts of Norway where transmission cables to Europe are connected. Results of this analysis are in line with the plans of the Norwegian TSO, which foresees a large investment need in new transmission capacity to meet expected growth in electricity consumption.

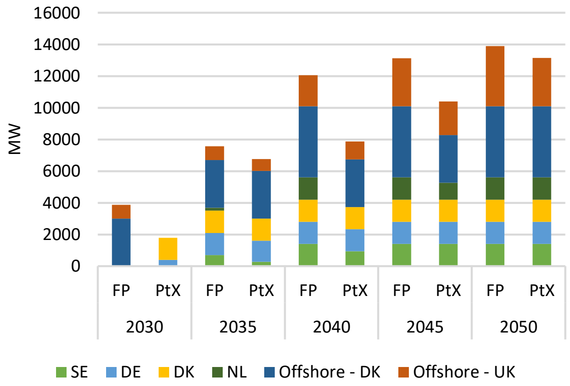


Figure 4-5: New transmission capacity to Europe

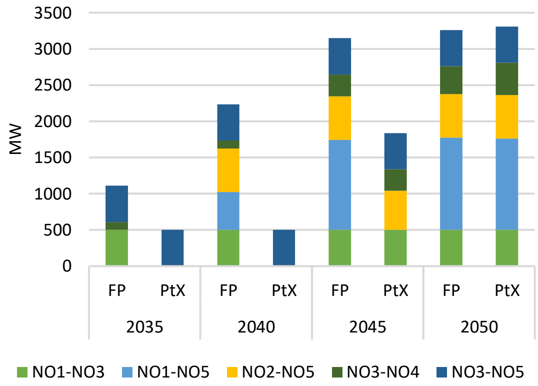


Figure 4-6: New domestic transmission capacity (excl. offshore areas)

4.2. Electrification of the built environment in the Nordics

The subsections below address the aims for IVL stated in Section 1.3 by providing a definition of electrification, presenting insights on electrification measures in the buildings from reviewed ongoing or recently performed projects that have used either the ON-TIMES or ECCABS models. Then, suggestions are provided to improve the representation of electrification measures in the built environment in the ON-TIMES model.

Definition

Below, we explain how electrification is modelled and accounted for in two relevant models.

Electrification in the building sector means i) increased/variations of energy need for electricity appliances (incl. also in offices; references are needed to define the trends; mention data centres specifically), ii) increased supply from electricity in all other end uses (space heating and cooling, cooking, water heating), and even surplus production of electricity (PV, rarely micro wind). This electrification of demand and supply is typically supported by digitalisation and by flexibility measures that facilitate the integration of on-site renewables in the energy system. Electrical vehicles are also included in the demand for electricity (when they are charged in the buildings area).

Insights on electrification measures for the Nordic countries

In Appendix A4, two tables are presented to summarise insights from previous studies using ECCABS to model energy use in buildings. The first table aims to summarise the measures studied, estimated potentials and conclusions of the previous studies. The second table is a summary on scenarios used in previous studies with details of time period, scenario narratives etc.

The Nordic Clean Energy Scenarios [43] developed using the ON-TIMES model show possible outcomes for residential electricity consumption until 2050 in three scenarios CNN, CNB and NPH (described in 2.1.). For all three scenarios, residential electricity consumption is expected to decrease by 10 TWh from 2020 to 2050 and the expected increase in consumption of solar power in the residential sector is 13 TWh. Electricity use in appliances (cooking, lighting, washing etc.) is expected to remain stable, while in all scenarios, the use of electricity in heating decreases by 8-9 TWh from 2020 to 2050.

Table 4-3 below presents the results for the base scenario in ON-TIMES model for 2015, 2030, 2040 and 2050, including the share of total heat supply/district heating production from different technologies. Additionally, demand for heating/electricity and installed PV capacity connected to buildings is presented.

Table 4-3- ON-TIMES model results in the base scenario for buildings related electricity use and supply in the Nordic countries. For for 2015 / 2030 / 2040 / 2050.

Technology name	Unit	Denmark	Norway	Sweden
Electric boilers**	[%]	0/ 0/ 0/ 0*	0.9/ 22.2/ 33.9/ 44.3	4.5/ 4.3/ 1.5/ 0
Air heat pumps**	[%]	8.9/ 36.8/ 52.6/ 49.2	18.8/ 38.9/ 29.4/ 18	27.6/ 43.9/ 49.8/ 43.3
Ground source heat** **pumps**	[%]	0.1/ 0.3/ 0.2/ 0.5	0/ 0.3/ 0.5/ 0.3	0/ 0.3/ 0.3/ 0.7
District heating supply	TWh	29.4/ 36/ 39.9/ 49.5	6.9/ 8.2/ 7.8/ 14.4	40.6/ 60.1/ 59.5/ 86.9
Large-scale heat pumps***	[%]	0/ 16.3/ 17.3/ 10.3	0/ 43.6/ 6.1/ 1.6	10.8/ 32.1/ 58.4/ 36.5
Electricity supply by PVs installed in buildings	TWh	0.3/ 1.1/ 9.8/ 13.4	0/ 0/ 0/ 0	0.1/ 0.1/ 0.1/ 0
Electricity use for charging electric cars	TWh	0/ 1.7/ 6.2/ 7.7	0.1/ 2.9/ 6.4/ 7.5	0/ 3.4/ 11.5/ 14.3
Electricity use in data centres	TWh	0/ 4.4/ 6.4/ 6.4	0/ 4.4/ 6.4/ 6.4	0/ 4.4/ 6.4/ 6.4

* Values are given for 2015/ 2030/ 2040/ 2050.
** share of total heat supply to buildings.
***share of total district heating production.

Improvement of ON-TIMES model

Very recently, output from ECCABS has been used as input in the TIMES-City model, e.g. to investigate building thermal storage and to investigate the influence of different time resolutions in TIMES models.

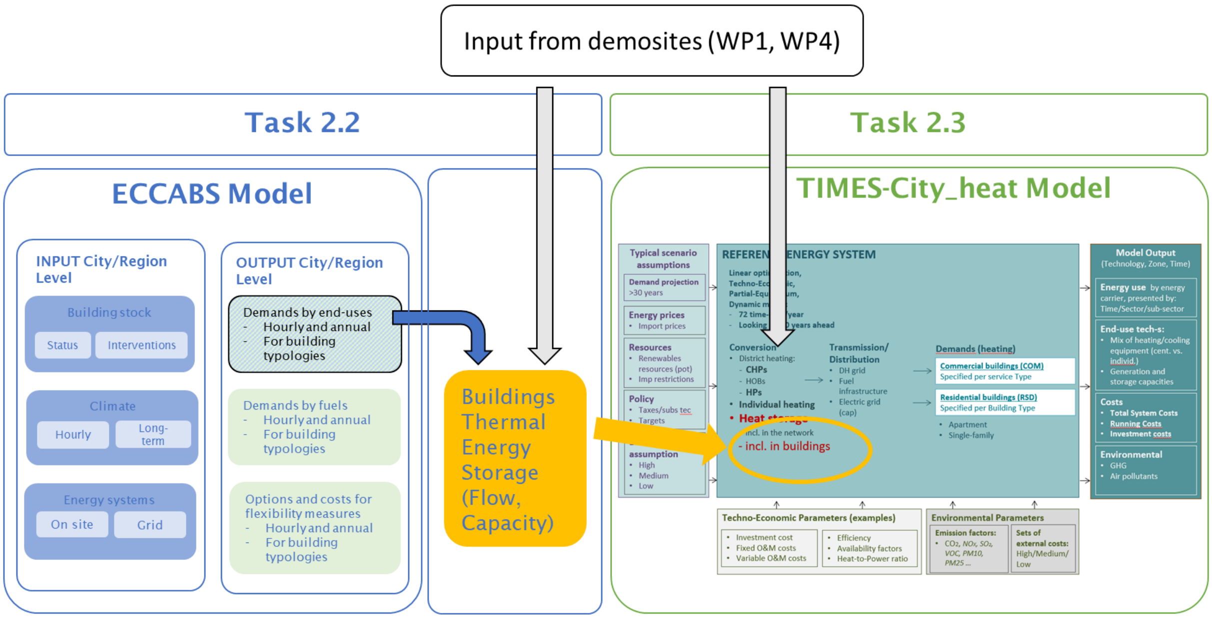


Figure 4-7 Flowchart with exemplary relationship between ECCABS and TIMES [44].

4.3. Electrification of heavy industry in the Nordics

In this section, the aim is to suggest how the transition of heavy industry in the Nordics towards climate neutrality can be represented in Nordic energy system models such as ON-TIMES. We start by defining the concept of electrification of heavy industry, then describe an earlier project that implemented industrial transformation into TIMES-Sweden, and finally suggest how to generalise that work to all Nordic countries in a Nordic energy system model.

The suggested improvements in ON-TIMES will however be performed beyond the scope of this project, in another ongoing project, MISTRA Electrification [45].

Definition – What to include in electrification of heavy industry?

Electrification of industry can be divided into two main parts: i) Energy demand is supplied by electricity instead of solid, liquid or gas fuels, and ii) Industrial processes are electrified.

Electricity replaces fuels

This measure can be either direct or indirect. Sometimes electricity is used directly, for example to melt steel with electrodes, and sometimes it is used to produce an intermediate energy carrier, such as steam or hot water, which in turn is used to heat an industrial process.

Electrification of industrial processes

In addition to the energy aspect of electricity, it can have a role in transition of industrial processes that themselves release greenhouse gases (GHG). For example, in primary steel production, oxygen needs to be reduced from iron ore. Traditionally this is made with coal in blast furnaces, which generate vast amounts of CO_2 emissions. By reducing the iron ore with hydrogen generated with renewable electricity, most of these emissions can be avoided. Hydrogen has potential to replace fossil raw material in several other industrial processes as well, not the least in chemical industry and refineries.

TIMES-Sweden Climate neutral industry

In a joint project between IVL and Luleå Technical University, the TIMES-Sweden model was developed to include alternative pathways for the Swedish industry to become climate neutral [46]–[48]. Focus was on the industries which contribute most to GHG emissions in Sweden: Iron and steel, Cement, Refineries and Chemical industry. For all these industrial sectors, the GHG emissions to a vast part origin from the processes themselves, not the energy use. Therefore, options to change industrial process were integrated in the model. Some of the most relevant option for industrial transformation involves electrification, as described below.

Cement

In the cement production process, no matter what fuel is used, CO_2 is emitted from the calcination process when creating clinker in the rotary kilns. The fossil fuels used for process heat can all be replaced by renewable alternatives but the emission from clinker production remains. To become CO_2-neutral, the cement industry therefore needs CCS. The CemZero process, which is developed by Cementa and Vattenfall in Sweden, aims to heat the clinker process with renewable energy [49]. Ensuring a clean electricity input to this process, the emissions from the clinker production will be a pure CO_2 stream which is less expensive and less energy demanding to capture. If CemZero is implemented at the biggest cement production facility in Sweden, Slite Gotland, the estimated increase in electricity demand is 2 TWh per year and the power capacity needs to increase by 260 MW by 2030.

Iron and steel

There are several alternative emission reduction processes for the iron and steel industry which could remove the vast part of the emissions from this industrial activity. The HYBRIT process which is developed in Sweden aims to produce fossil-free steel using hydrogen, produced with electricity from renewable energy sources, as reducing agent instead of coke [50]. The iron and steel industry currently consist of three blast furnaces in Sweden and two in Finland. The process has the potential to cut Swedish CO_2 by 10% and Finland's by 7% and would increase the Nordic electricity demand by an additional 20-30 TWh a year. On top of this, new plans for the industry in Sweden can increase electricity demand even more. LKAB has announced plans of scaling up production calling for another 20-30 TWh per year and finally H2 Green Steel has announced plans to start production using HYBRIT technology, increasing electricity demand another 30 TWh. If all these new plans are realised, it could increase the Nordic demand for electricity up to 70-90 TWh per year from 2030-40.

PtX fuels and chemicals

Power to X (PtX) means generating fuels or chemicals (X) from electricity (power). The key technology, electrolysers, produce hydrogen, which can be converted to fuels or chemicals. For example, by combining hydrogen with nitrogen from the air, ammonia can be produced. Hydrogen could also be converted into methane, methanol, e-diesel, or e-kerosene by combining with CO_2. If the CO_2 comes from biomass or is captured from the air, the fuel may be considered carbon neutral according to UNFCCC accounting principles or attributed with a low level of CO_2 emissions depending on the type of biomass and considered time horizon.

Today, most hydrogen is produced from fossil fuels, typically through steam methane reformation processes. An alternative pathway towards climate neutral hydrogen, in addition to electrolysers powered by renewable electricity, is planned for in Norway. By applying CCS to the process, most of the CO_2 emissions is eliminated, and so-called "blue" hydrogen is produced.

The industrial electrification measures mentioned above have not yet been implemented into ON-TIMES. In the following section, we suggest how this can be done for Sweden and then extended to all Nordic countries.

Implementation of electrification of Nordic heavy industry in ON-TIMES

Currently the energy demand in the industrial sector is fixed per year and subsector in ON-TIMES. Due to this, the transformative changes of industry in which the processes themselves are changed cannot be individually represented and monitored. In order to be able to model transformative changes of industrial processes, the energy demand in the industrial sector should instead be related to the industrial production, e.g. annual tonnes of cement, iron, steel, PtX fuels or chemicals as described above.

The starting point should be the current production in each sector and country. For Sweden, data for industrial production is publicly available from the development of TIMES-Sweden [51]. For the other Nordic countries, data need to be complemented. To avoid "export of emissions" to other countries by reducing production in the Nordics, it is required that the production levels remain at least the same in future scenarios. E.g. an increased production based on economic growth forecasts could be a relevant scenario.

The industrial structure in the five Nordic countries varies largely. The energy use in industry for each country is shown in Figure 4-8. The Finnish industrial structure is similar to the Swedish one, with large production of pulp and paper, and steel. Norway and Iceland have large production of primary aluminium. Also, both Denmark and Norway have a large share of refineries in their industrial sectors. The industrial production or capacity in each country and industrial subsector is shown in Table 4-4.

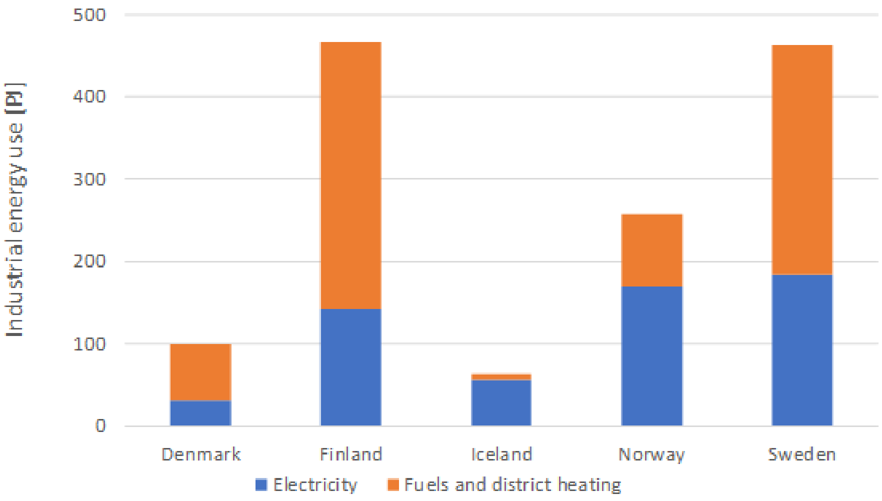


Figure 4-8 Industrial energy use in the Nordics. (Denmark, Finland and Norway 2019; Iceland 2015; Sweden 2018)

Table 4-4 Production in heavy industry in the Nordics. Unit is mega tonnes per year.

	Denmark	Finland	Iceland	Norway	Sweden
Iron and steel (ore based)		2.7		0.1	2.9
Iron and steel (scrap based)		1.4		0.5	1.5
Pulp and paper (chemical pulp)		7.2			7.6
Refineries[1]	28,000 m^3/day	33,000 m^3/day		32,000 m^3/day	84,000 m^3/day
Chemicals[2]		400 kt/y		560 kt/y	625 kt/y
Aluminium			0.85	1.3	0.13
Cement	2.4	1.5		1.9	3.2

[1] Total refinery capacity per country, m^3 crude oil per day.[2] Cracker capacity, ktonne ethylene per year [52]. A further division of production in each industrial sector is recommended. All special products may not be feasible to represent in a Nordic energy system model, but the division that has been used in TIMES-Sweden, as mentioned above, should be plausible.

4.4. Electrification in the Nordics – system toolchain for energy system modelling including transport model and power system model

A major part of the work in WP2 has been to understand how the general energy system model GENeSYS-MOD can be improved. The tool chain we have chosen to use for this consists of GENeSYS-MOD and a power system model EMPS and the transport model Energy Map. Both EMPS and Energy Map can generate insights on where to focus future GENeSYS-MOD improvements, by helping to identify the modelling areas and the missing data where the general energy system model falls short of the sector specific models.

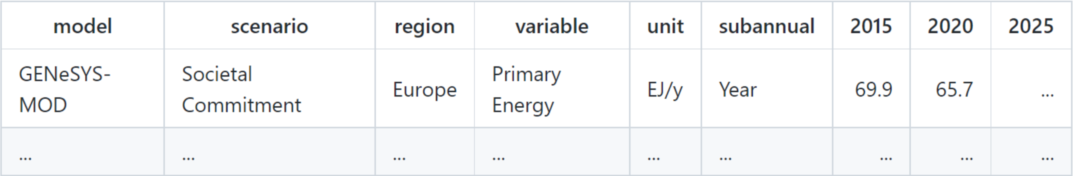
Linking GENeSYS-MOD and EMPS

To achieve an improved description of the Nordic and Norwegian energy system, the hydropower modelling in GENeSYS-MOD must be improved. To understand which improvements would be most important to implement, we have established a framework that links EMPS[7] and GENeSYS-MOD.

Given that both models are computationally heavy for a detailed European dataset and that they are inherently different on a conceptual level (GENeSYS-MOD is a capacity expansion optimisation, whereas EMPS optimises operation), we have chosen to soft-link the two models. Using the standardised nomenclature [53] and conversion tools developed in the openENTRANCE H2020 project, the results and necessary indata from GENeSYS-Mod have been converted to the IAMC format, see Figure 4-9.

---

[7] EMPS the way it is used from here on is including other models of the EMPS family such as EMPS-W and FANCI



model	scenario	region	variable	unit	subannual	2015	2020	2025
GENeSYS-MOD	Societal Commitment	Europe	Primary Energy	EJ/y	Year	69.9	65.7	...
...	...	...	...	...	...	...	...	...

Figure 4-9: The standardised nomenclature (IAMC) format developed further in the openENTRANCE project. Harmonised format and naming facilitate model linkages.

Then a toolbox has been developed that converts this format into the native EMPS input format. The main variables and parameters that are provided by GENeSYS-MOD describe the future power system setup, such as installed capacities (power plants, storage units, transmission lines), fuel costs and other variable costs as well as electricity demand profiles and levels. The detailed hydropower description, including inflows, reservoir sizes, operation restrictions, etc. is taken from the HydroCen EMPS dataset [54].

The GENeSYS-MOD dataset provides five nodes for Norway (the price regions) while the EMPS dataset divides Norway into 11 regions. To disaggregate the GENeSYS-MOD data to the EMPS regions, several different datasets from NVE (The Norwegian Energy Regulatory Authority) have been used [55]. Since EMPS cannot directly model batteries as a separate technology, their storage capabilities are modelled as pumped hydropower units with the same specifications.

After completing the linking, an optimal energy system for 2030 following the gradual development storyline [53] developed in Open ENTRANCE is computed with GENeSYS-MOD and then, via the linking framework established, used in EMPS to compute optimal system operation for 2030.

The main result obtained by this linking procedure is the transfer of realistic production levels from hydropower, here obtained by EMPS. These can now be used to improve the representation of hydropower in GENeSYS-MOD by adjusting the technology description resulting in matching production output. The secondary result is that allowing for 10% of flexible demand, i.e. 10% of the total annual demand can be satisfied at convenient timing and doesn't have to follow the demand profile curtailment avoided most of the time even given the variation described by the 36 simulated climate years.

Developing an improved understanding of the Norwegian energy transition

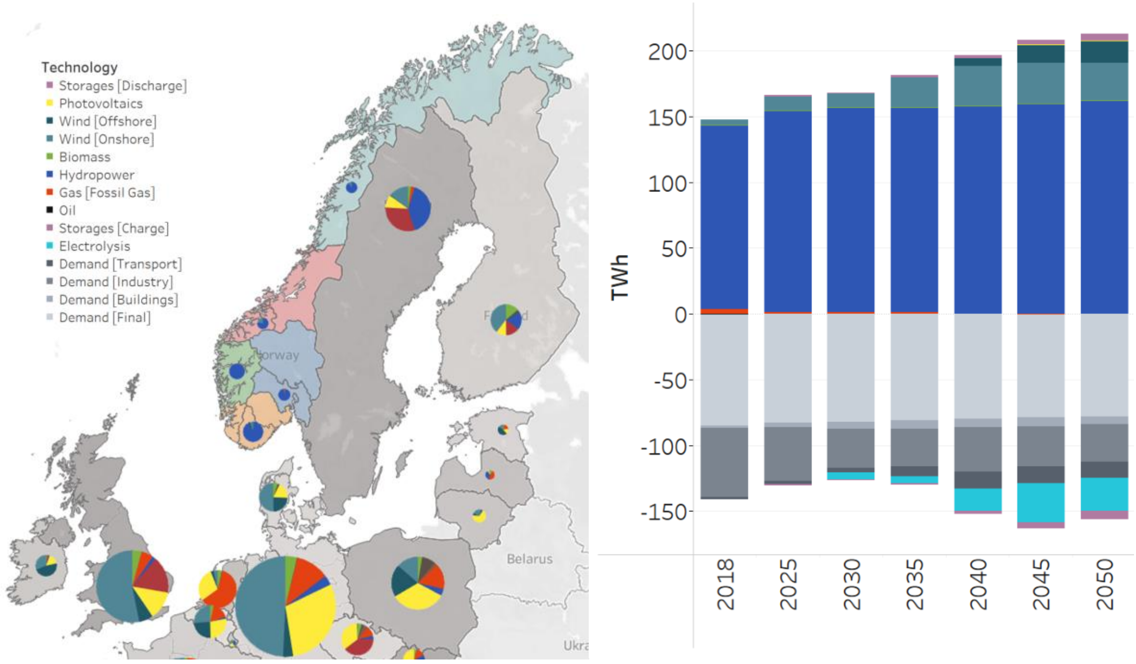
In WP1, an updated input dataset for GENeSYS-MOD with five nodes for Norway was created. In WP2, this dataset has been further improved to yield better insights on the energy system transition ahead. Several adjustments and updates have been made: First the dataset has been converted to the newest version of GENeSYS-MOD (V3.1), where a.o. a new technology – solar PV with axis tracking has been added. The most important data update, yielding the largest improvement in results are the renewable timeseries data.

Improving renewable timeseries data to understand electricity production developments

Until now, the same, average timeseries for both solar and wind power has been used. Now area specific timeseries data for on and offshore wind and solar, with and without axis tracking have been complied and used in the optimisation. Source data has been used from www.renewables.ninja, and an average of the best locations has been used to create a timeseries specific for the optimal locations for wind power deployment, the same for the average locations and locations with lower capacity factors.

The first major finding is that these updated timeseries combined with the cost assumptions detailed in Chapter 3 lead to accelerated onshore wind deployment. This is the most cost-efficient way to fuel the electrification process. Large scale deployments of onshore wind are controversial in Norway due to the current socio-political reality. Therefore, additional constraints were added to restrict further onshore wind developments until 2030. With the improved timeseries data, solar PV on rooftops, both commercial and residential, does not play a significant role in the energy transition in Norway. However, larger, utility scale developments of axis tracking solar (given its cheaper cost compared to rooftop installations) becomes a very small part of southern Norway's electricity mix.

Figure 4-10 illustrates the results obtained with the improved dataset. The first insight we obtain is that up until 2030, Norway's power production does not significantly increase. We see some improvements of the hydropower production and some investment in onshore windfarms (which are specified exogenously, to represent the latest developments). We also observe the continued unbalance between supply and demand within the different power price regions. Hydrogen production (from electrolysis) becomes a significant part of the energy system from 2030 and fourth, with a significant part of the production being done in Northern Norway, which is consistent with a hydrogen corridor from northern Scandinavia, as described in [56]. This production will be making use of cheaply excessed electricity produced from large onshore wind developments. Gas is present only on a minor scale to ensure that peak demand can be met and to reduce potential curtailment needs.



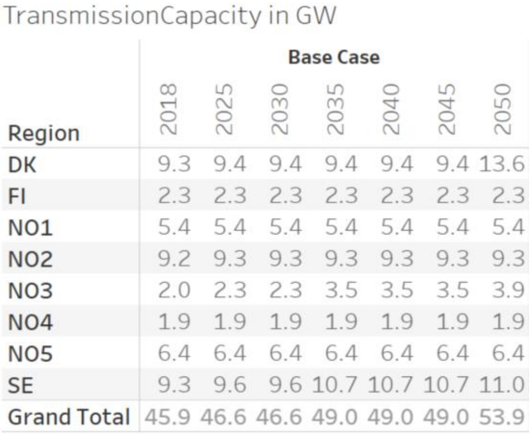
NO4

NO1

Figure 4-10 Left top: production mix in 2030 in Norway (5 regions) and relevant European countries. Right top: Norwegian power production (positive) and demand (negative) from today to 2050 (net-zero emissions from Europe, 2-degree compatible), including the hydropower production level improvements obtained from EMPS. Left bottom: Electricity production and consumption in NO4. The new timeseries shows that only onshore developments here are cost-efficient given the scenario assumptions. Right bottom: Electricity production and consumption in NO1, showing that here solar axis tracking is entering the production mix after 2040.

Transmission capacities

The development of the transmission system in the analysed scenario, see Figure 4-11, shows very few reinforcements and no completely new connections from and within Norway until 2050. This is not in line with Statnett's development plan, which foresees more investments in the grid due to higher consumption [57]. The only major upgrade is observed between NO3 and Sweden. Since Sweden is modelled as one single node, the possibility of transporting electricity from Northern Norway to Southern Norway through Sweden cannot be captured accurately. As for the other Nordic countries we see the largest upgrade between Denmark and Germany, but not before very late in the time horizon. Sweden in turn increases the transmission capacity to NO3 gradually.



TransmissionCapacity in GW

	Base Case						
Region	2018	2025	2030	2035	2040	2045	2050
DK	9.3	9.4	9.4	9.4	9.4	9.4	13.6
FI	2.3	2.3	2.3	2.3	2.3	2.3	2.3
NO1	5.4	5.4	5.4	5.4	5.4	5.4	5.4
NO2	9.2	9.3	9.3	9.3	9.3	9.3	9.3
NO3	2.0	2.3	2.3	3.5	3.5	3.5	3.9
NO4	1.9	1.9	1.9	1.9	1.9	1.9	1.9
NO5	6.4	6.4	6.4	6.4	6.4	6.4	6.4
SE	9.3	9.6	9.6	10.7	10.7	10.7	11.0
Grand Total	45.9	46.6	46.6	49.0	49.0	49.0	53.9

Figure 4-11: Transmission capacity development of the Nordic countries.

Electrification of transport sector

The transport sector in Norway is very interesting, as it differs significantly and in many ways from many other European and Scandinavian countries. Norway has been at the forefront of all countries when it comes to the deployment of electric vehicles. Efficient policy support, along with an income-strong population, have resulted in a 23% share of electric plug-in vehicles of the entire passenger car fleet. The Norwegian case hence constitutes a good foundation for understanding future power demand from further electrification in the transport sector, both in Norway and beyond. The FuChar project and the Energy Map model explore the Norwegian transport sector with high geographical and temporal detail and can take into consideration the timing of charging needs. In GENeSYS-MOD the electricity demand from transport is distributed evenly across all time slices and does not account for hourly variations in charging needs. This opens for interesting future improvements of the transport modelling in GENeSYS-MOD, by adding functionality to account for charging profiles and spatial needs for electric transport.

4.5. Societal challenges and implications of increased electrification[8]

Need for including social acceptance in energy system models

Although increased electrification comes with benefits of important GHG mitigation potential, there are also significant implementation challenges. Several European and Nordic countries are experiencing public opposition towards renewable energy technologies, partly due to conflicts around land use, changes in landscape aesthetics and local environmental impacts [8], [9]. Lack of social acceptance increase the financial risks for project developers and limits the rate of deployment of new electricity generating infrastructure. For the Nordic countries, such as Norway, electrification is considered an important GHG mitigation measure [58]. It is as such important to understand not only the techno-economic aspects of energy transitions and increased electrification, but also socio-political and cultural challenges and impacts. UiO's contribution to WP2 is therefore to reflect and discuss upon the societal implications of increased electrification as well as the relevance of justice and its potential integration with energy system models.

The cost-optimal power system modelled by e.g. the models in chapter 0 utilises resources, such as wind speeds, solar irradiance, in a technologically ideal way, but typically only take limited social aspects into account. Krumm et al. [59] identified five social and behavioural factors from the literature which are considered important for an energy transformation, namely; a) behaviour and lifestyle, b) heterogeneity of actors, c) public acceptance and opposition, d) public participation and ownership and e) transformation dynamics. Behaviour and the lifestyle of actors include things such as how behavioural changes (e.g. the mode of transportation [60]) can shift demand and the need for allocation of renewable energy, while heterogeneity of actors is concerning how diverse actors interact and influence the dynamics of an energy transition. As already mentioned, public acceptance and opposition can facilitate or obstruct specific technologies or a transition as a whole and the real-world deployment of technologies is both influenced by and influences attitudes of local communities and general society. The acceptance of local communities is considered to strongly relate to the degree of public participation and ownership, both in terms of how the decision-making process of the siting of renewable energy infrastructure is structured and the perceived benefits it yields for the community. Lastly, transformation dynamics relates to temporal pathways and speed of transformation.

Modelling results may indicate that there is a high potential for supporting Mainland-Europe with electricity from renewable energy sources. The rate of self-sufficiency of countries in a cost-optimal model solution using highRES-Europe[9] (see chapter 2.5), can be seen in Figure 4-12, where Denmark generates more than four times the amount of electricity it consumes in a year, largely from onshore wind (similar results and disparity between real-world generation and model results can be seen in [61]). However, this potential may not be realised if onshore wind power plants are rejected for various socio-political reasons.

---

[8] This work stems, in part, from work submitted for peer-review at the time of this report. The journal article can, in the case of acceptance, be found e.g. on ORCID (https://orcid.org/0000-0002-0806-0329).

[9] Note that these results are not the same as the base scenario in Chapter 3.4 as different CO_2 budgets are applied.

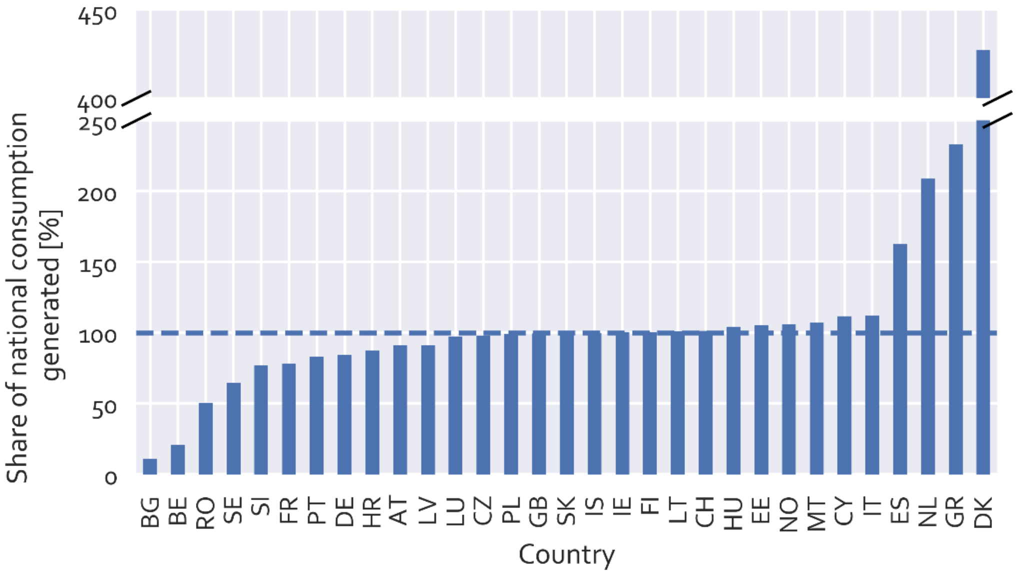


Figure 4-12 (im)balance between electricity generation and demand in 2050 from a cost-optimal model outcome in highRES.

The acceptance and political support for e.g. wind power plants is influenced by perceptions of how fair the distribution of benefits and burdens are as well as how decision-making processes are structured. Energy systems that are socially just may be considered a goal in itself (although that is a normative aspect that not everyone necessarily agrees with), but also instrumental for the realisation of low-carbon energy systems and high degrees of electrification in society.

Recent research has explored both new concepts for integrating insights from social sciences [62]–[65] and the current representation of social and behavioural factors [59], [66] into energy models, including energy system models. Systematic reviews of how justice perspectives have been included in energy systems modelling have not been done before but will help modellers understand what challenges and opportunities exists.

Modelling aspects of social justice

Justice is a wide concept with nuances that goes beyond only assessing the distribution of benefits and burdens. The framework of energy justice [67] considers three tenets (distributional, procedural and recognition justice) which help identify where energy injustice emerges, how processes are designed to include or exclude different stakeholders, and who is systematically ignored or misrepresented in decision-making. The framework aspires for wider systems thinking, considering both energy generation and consumption, as well as embodied energy injustices up- and downstream the life-cycle from e.g., the extraction, processing, transportation or disposal of energy resources [68].

From reviewing the literature and how modellers have incorporated aspects of justice [69], we find two larger categories within which we can place the literature. We find studies which tend to the procedural tenet of energy justice. While these studies may not explicitly assess justice aspects, they include an element of participation and allows for different stakeholders to be involved in different stages of the modelling process. While participatory processes may be desirable for various reasons, they may also be very time consuming, due to organisation and conduction of stakeholder interaction and ensuring the stakeholders stay engaged throughout the project. McGookin et al. [70] have conducted a review of participatory methods in energy systems modelling and planning, which we refer to for a more detailed understanding of e.g., which and how stakeholders have been engaged.

Distributional justice is perhaps more intuitive for modelling exercises, as the distribution of energy services and infrastructure is typically decision-variables in energy system optimisation models. Among the articles, we see studies exploring the spatial distribution of energy infrastructure [71], [72] and in particular wind power capacity [72], but also electricity access [73], [74] and electricity prices and changes in employment. While it is possible to extend the analysis to assess the distribution for different societal groups, spatial indicators and statistics are more readily available.

There are a variety of methods to implement justice aspects in the modelling process, but some are more common than others. According to Krumm et al. [59], general social aspects can be integrated either as part of the storyline, scenarios and assumptions of a modelling exercise, through modification of the modelling structure itself or by discussing the model outcome with the possibility to re-iterate with fine-tuned assumptions based on previous results. Socio-technical scenarios have been used, for example, in a Nordic-Baltic context [75] and the UK [76] to assess the implications of restricted deployment of renewable energy generation based on socio-political considerations. Storylines, scenarios and assumptions may be based on for example literature or co-produced together with stakeholders. Implementing justice aspects in the model itself is commonly done through the modelling to generate alternatives (MGA) methods [77], through which modellers are able to explore near-optimal system configurations and trade-offs between system cost and secondary objectives. The MGA method establishes a baseline from an initial cost-optimal solution, which in following modelling iterations can be deviated from by a certain percentage (slack), while the objective function changes to e.g., minimise new wind power capacity. Aside from the MGA method, we find studies which attempts to monetise environmental and social cost and including it into the model. For example, Grimsrud et al. [72] use the willingness-to-pay (WTP) and willingness-to-accept (WTA) to add a social cost for the allocation of wind turbines, based on the number of people directly and indirectly affected by it.

Throughout these studies, the way justice is interpreted or defined changes a bit, but not much. Sasse and Trutnevyte [78] mention four so-called equity principles which can be used to guide the assessment of how socially just an energy system is. These four principles are:

1. Cost-efficiency - The cost-efficiency/cost-optimality principle builds on utilitarianism, where minimising the total system cost and in turn maximising the sum of utilities in society is the guiding principle. Although it may not explicitly address equity concerns, it aligns with the objective of optimisation models.
2. Equality - The equality principle strives for an equal share of benefits and/or burdens across the factor being evaluated. Perhaps most commonly, it can be understood on a per capita basis, where the aim is for equal benefits/burdens for every individual.
3. Responsibility - The responsibility principle applies a temporal perspective on the distribution, for example allocating additional burdens to regions/societal groups which have had historical benefits by for example burning fossil fuels, consequently leading to high cumulative GHG emissions.
4. Capability - The capability principle, sometimes referred to as 'ability-to-pay', takes socio-economic indicators into account for the distribution, for example ascribing more burdens to a region with a high gross domestic product (GDP).

Despite these four different equity principles, assessments of distributional justice typically only compare the first and second principles, comparing normal model results to one where the equity factor (e.g., installed energy generation capacities) is distributed equally across space based on either the population or electricity consumption of a region.

Normative justice principles and constructions of justice in modelling

As the definition of a just distribution can be different based on philosophical principles, there is also a risk that modelling results largely depend on which definition is applied to assess the system. Although both Sasse and Trutnevyte [78] and Neumann [61] mention that there are alternative equity principles than what they apply, there is limited reflection on the significance for the modelling results.

We therefore perform a similar modelling exercise with the MGA method, to showcase how different modelling results may be given the application of different equity principles. With highRES-Europe, we generate a small sample (N=10) of MGA scenarios where generation infrastructure is minimised/maximised within a solution space of 7% more expensive total system costs compared to a baseline scenario. We apply two justice principles; 1) one based on egalitarianism, where a fully socially just system should contain the same amount of installed generation capacity per capita in every zone; 2) one based on capability, where a fully socially just system instead should contain the same amount of installed generation capacity per nominal GDP of a zone. Based on these two different principles, it is possible to identify which of the MGA scenarios performs best given the different justice principles.

The modelling results (see Appendix A5) show that the MGA scenario where onshore wind is minimised shows the least amount of inequality when defined as installed generation capacity per capita and the scenario minimising solar power shows the least amount of inequality when defined as installed generation capacity per nominal GDP.

Note that the results are based on an example with a small sample of MGA scenarios and justice principles, which should be explored more thoroughly and robustly in a larger-scale study. Nonetheless, it indicates that exploring elements of justice using the MGA method in modelling are largely reliant on the formal definition applied. This would be important to explicitly mention and discuss in any study attempting to study socially just energy systems.

4.6. Understanding the challenge of electrification in a Nordic context from a Danish perspective

Electrification involves many subsets of the overall energy system, i.e., residential heating, industry, transport and fuel conversion. Further electrification cannot be understood within a pure national setting but also necessitates broader inter-country planning and coordination, particularly related to expanding transmission capacity. The section below discusses future electrification, as seen from a Danish perspective touching on key sectors.

Today approximately 400.000 and 60.000 households use natural gas and oil, respectively, and the current expectation is that this number will decrease by more than half by 2030. This decrease is driven mainly by the conversion to district heating and individual heat pumps.

For industry, there is also a focus on electrification, e.g., promoting the use of heat-pump technology for industrial processes. In addition, new industry electricity demands are expected, particularly regarding the proliferation of data centres. A considerable focus relates to energy-intensive industries since converting heavy-emitting industries such as cement and refineries towards electricity is difficult and expensive, requiring carbon and storage capture technologies (CCS).

Personal transport today largely relies on fossil fuel energy. However, a substantial shift towards electrified transportation of both cars and railways is underway in Denmark. It is still less clear how to reduce fossil fuel use associated with heavy transport such as long-haul trucks, ships and air transport, both from a Danish and a global perspective. Direct electrification will likely play an important role here as well. However, alternative fuels such as hydrogen, biofuels or electro-fuels may also be essential in decarbonising heavy transport and international transport.

Biofuels are expected to come from biomass sources such as straw, wood chips and wood pellets. In comparison, electro-fuels could be the product of hydrogen combined with carbon sources from carbon capture technologies. The demand for hydrogen based on electrolysis will necessitate an expansion of renewable electricity production capacity. On the other hand, hydrogen production could offer additional flexibility regarding the overall electricity demand, thereby potentially complementing the variability of renewable electricity production. In addition, the large-scale production of biofuels and electro-fuels could increase excess heat supply, providing a future source of renewable district heating.

The expansion of renewable electricity production, notable wind and solar power, further directs focus to the increased importance of transmission capacity. In particular, as a means of mitigating the variability of renewable electricity production across multi regions.

The Danish Energy Agency has approached this project to learn from the other models and partners of the project. In addition, the Danish Energy Agency has shared data and knowledge related to the modelling electricity trade in a European context. WP2 has provided the Danish Energy Agency with valuable insights, both i) generally regarding energy system modelling in Nordic countries and ii) more concretely, regarding how to improve flexibility modelling within the IntERACT model.

5. Inputs to the update of National Energy and Climate Plans (NECPs)

5.1. Background

About NECPs

The following discussion is based on information provided at the corresponding websites for the Commission, where submitted NECPs till the EU can be downloaded, and the Florence School of Regulation[10].

NECPs are part of the EU's work to ensure the fulfilment of the Energy Union and the achievement of the 2030, as well as long-term objectives and targets of the Energy Union in line with the Paris Agreement. In existing EU regulation, there are binding targets specified for the union as a whole, with respect to cuts in GHG emissions, share of renewable energy in final energy consumption, energy efficiency, and electricity interconnections. Specific goals are also stated for 2030. The NECPs for 2021 – 2030 show how each Member State contributes to jointly reach those targets, by describing the national targets and measures for energy and climate policies that are expected to be implemented in the 10-year period to achieve those targets.

Unlike what was the case for the EU 2020 targets, the national 2030 targets and measures described in the NECPs are non-binding, except for the non-ETS GHG-emission target. However, the commission may identify a need for additional efforts by Member States, as well as for EU policy and measures after having assessed the NECPs.

NECPs for 2020-2031 shall be updated by 30 June 2023 (draft) and 30 June 2024 (final). This is to account for significant changing circumstances, during the 10-year period, and reflects the need for stocktaking, since the NECPs were submitted to the EU by the end of 2019 and both EU targets and many national policies may have been amended since then.

WP2 inputs to NECPs

One aim of the Nordic Energy Outlook programme is to discuss if and how the results from the programme can be used for following up on the integrated national energy and climate plans (in 2023 and 2024), and if the results can provide a regional perspective – notably a Nordic perspective - to the updated integrated NECPs submitted by the Nordic countries. In this report, we focus on the Nordic countries represented in WP2 i.e. Denmark, Sweden, and Norway.

REPowerEU

REPowerEU as defined in [3] indicates an acceleration within the areas of renewable energy solutions that also will impact the Nordic energy perspectives towards 2030 and 2050. One main ambition is the doubling of solar and wind power production by 2025 and tripling by 2030. This means a change from the current level of ~360 GW to ~1240 GW in 2030. This will require a huge restructuring of the power sector and huge investment in both renewables and electric infrastructure. Norway as an EEA country has concrete targets of 30 GW offshore wind, but not same offensive strategy on

---

[10] https://fsr.eui.eu/national-energy-and-climate-plans-necps/.

implementation of roof-top solar as REPowerEU. The roof-top solar strategy in REPowerEU states that all new buildings should integrate solar power by 2029 resulting in implementation of large volumes of distributed generation that will require new solutions for management of local power grids. it will also have a huge impact on the Nordic energy balance with effects across the Nordic borders. In the Nordic countries solar seasonal generation is in anti-phase with the consumption and therefore also requires implementation of flexible assets to help balance the power system. As facilitator of this change towards variable renewable energy REPowerEU points to energy storage and in particularly hydrogen and hydrogen storage. Today the hydrogen production in Europe is about 0.15 Mtoe, but the ambition is to increase beyond the 5.6 Mtoe agreed in FIT for 55 to 20.6 Mtoe in REPowerEU by 2030. Half of the hydrogen shall be produced within Europe which means that half shall be imported. The increase in wind and solar capacity will change the supply curve for power while the hydrogen strategy potentially will impact both the supply and demand curves for electricity depending on its origin and use. As a low hanging fruit, REPowerEU focuses on increased energy efficiency both through electrification, low energy build environment and increased application for heating based on incineration of waste and district heating in addition to largescale application of heat pumps. As the existing build environment in the Nordics has a significant heat demand a change away from direct electric heating will impact the demand curve and lower the end-users dependency on electricity prices. An accelerated update of the NECPs should consider how these changes can be done while inflicting minimal damage to other objectives.

An especially important aspect in a Nordic perspective are the proposed hydrogen corridors from the North Sea to Belgium/Germany and from the northern Sweden through Finland and the Baltics. This will call on cooperation between the Nordic countries and impact the possible futures for the Nordic energy system and NECPs. Realisation of these infrastructural plans will depend on fair distribution of wealth and cost, an aspect that should also be elaborated in the NECPs.

5.2. Nordic perspective in NECPs for Norway, Sweden, and Denmark

Regional and Nordic perspective in existing plans

According to standard economic theory, a uniform CO_2 emission tax (all sectors, all countries, all GHG gases) will lead to cost-efficiency GHG mitigation. Hence, one can expect extra energy system costs for decarbonisation of the energy system if the CO_2 price is not uniform between e.g. between the Nordic countries, or regulated differently.

In the EU, mitigation efforts are divided between sectors that are included in the EU's emission trading system (ETS), and sectors that are not included. The included sectors will in principle see the same CO_2 price, i.e. the price for buying emission permits. Hence, that system should facilitate pan-European cost-efficiency at least for the included emissions. In practice the system has not been perfect, e.g. because there has been so many permits available within the system that the carbon price did not give a high incentive for mitigation. However, this will still be the main tool for the EU to reach a decarbonised energy system – with the participation of all Nordic countries.

However, some sectors are not included in EU-ETS. There are probably many different reasons for this, also including the existence of many small emitters in transport sector and concerns for carbon leakage due to higher costs when emissions are taxed. In [79] barriers are grouped into 1) there exist already a considerable legal framework and schemes to obtain several policy goals, 2) financial aspects, 3) behavioural changes due to changed regulation.

This report focuses on electricity, and for this sector the Nordic countries have a long tradition for cooperation. The common Nordic electricity market was one of the first deregulated markets in the world, and the Nordic TSO's cooperated within Nordel. Today, the EU is an important arena for European cooperation within the electricity system, e.g. through ENTSO-E.

There is already a considerable transmission capacity between the Nordic countries. Still, there are examples of considerable price-differences between areas due to congestion. Towards 2050, there will be a need for considerable enhancements in the transmission grid of the Nordic area due to electrification of consumption and investments in new renewable power generation. A description of the coordination of the planning of transmission grids could therefore be a way to increase the pan-Nordic perspective in the existing NECPs.

5.3. Norwegian NECP

The Ministry of Climate and Environment (Klima- og miljødepartementet) informs, Appendix A3, that Norway is not obligated to submit any NECP to the EU. However, in 2019 the Government made a plan [80] that shows how Norway shall comply with obligations in regulations for non-ETS sectors and LULUCF, which was submitted on a voluntary basis. This plan has not been updated, but in 2021, a more comprehensive climate plan for Norway for the period between 2021-2030 [7] was issued. This climate plan is not an updated NECP, but it is the more relevant plan, newer of age and including more detailed plans across the different energy sectors and technologies. In the following we have made comments to that plan.

Electrification in industry

The climate plan underlines the need for electrification of the industry sector for Norway to reach its climate goals. However, the increase in electricity demand for industry is largely uncertain, and different future pathway projections show a substantial sample space depending on the assumptions. For example, NVE's "Langsiktige kraftmarkedsanalyse 2020-2040" [81] present an electricity increase from industry of 14 TWh in their low scenario, compared to 53 TWh in the high scenario. Similarly, other projections from Prosess 21 [82], *DNV GL* [83] and *Statnett* [84] show large variations. The large differences demonstrate the importance of having a coordinated plan for industrial development, and to connect this to new power production and grid development.

Considering the current situation in Europe, with shortage of gas supply and high gas and electricity prices, it is becoming even more important to understand Norway's role in the production and supply of hydrogen. The climate plan states that hydrogen is an area with large potential for long-term value creation in Norway, however, no concrete target on production has been established. Meanwhile, REPowerEU plan for an additional 15 million tonnes (mt) of renewable hydrogen by 2030, on top of the 5,6 mt foreseen under the Fit for 55, of which 5 mt should be produced in Europe. In the update of the climate plan, it should be considered how much of this Norway could contribute to and the amount of electricity it would require.

In terms of blue vs. green hydrogen, a new revisal is needed, taking the bottlenecks into account in gas infrastructure and the high price of natural gas in the current energy crisis. As mentioned in the climate plan, Norway could potentially have a competitive advantage for blue hydrogen production at the Norwegian shelf, being a leader in CO_2 management with significant CO_2 storage capacity and a well-developed regulatory regime for CO_2 storage. The current high gas price can however limit the potential for blue hydrogen, and even make green hydrogen a more competitive solution.

Electrification of transport

The climate plan states that emissions from the transport sector constitute about 60% of Norwegian emissions from the non-ETS sectors, and transport is therefore one of the focus areas in the plan. The plan refers to emission-free vehicles, but electrification of the transport sector implies electrification beyond electric cars. The plan describes demands for emission-free public procurement as an important means, along with facilitation for the infrastructure development needed for long-distance transport. For new and refurbished buildings, the plan demand inclusion of charging infrastructure. The increased demand for power and power infrastructure due to electrification of the transport sector is not mentioned, as well as the increased electricity demand in the building sector due to charging of short-range transport. The production of and infrastructure for hydrogen for decarbonisation of the heavy transport will require faster technology development facilitated by the government. The choice between blue and green hydrogen will depend on the market situation.

New electricity generators

While the Climate Plan emphasise the need for increased production of renewable energy, in particularly from offshore wind and solar, it does not include any concrete target for renewable deployment by 2030. On the other hand, Fit-for-55 and Repower EU propose to double the capacity of photovoltaics and wind power in the EU by 2025 and triple it by 2030, reducing faster the dependence on fossil fuels. The recent announcement by the Norwegian government of 30 GW offshore wind by 2040 [37] is in accordance with these targets and is a positive development beyond that expressed in the Climate plan. However, a concrete plan for deployment and distribution should be specified to ensure that the target is realised. Similarly, a target for solar PV, in particular rooftop PV, should be specified to be in line with RepowerEU and to follow the fast pace of deployment of our neighbouring countries.

While the Climate Plan emphasises the need for increased production of renewable energy, in particularly from offshore wind and solar, it does not include any concrete target for renewable deployment by 2030. On the other hand, Fit-for-55 and Repower EU propose to double the capacity of photovoltaics and wind power in the EU by 2025 and triple it by 2030, reducing faster the dependence on fossil fuels. The recent announcement by the Norwegian government of 30 GW offshore wind by 2040 [37] is in accordance with these targets and is a positive development beyond that expressed in the Climate plan. However, a concrete plan for deployment and distribution should be specified to ensure that the target is realised. Similarly, a target for solar PV, in particular rooftop PV, should be specified to be in line with RepowerEU and to follow the fast pace of deployment of Norway's neighbouring countries.

One of the main highlights from the EU commission is to accelerate the roll out of green energy technologies by enabling faster permitting of renewable energy projects. They underline that the lengthy administrative procedures have been identifies as one of the key obstacles for investments, which can be related to the three-year hold in licensing process for onshore wind power developments in Norway. Suggestions to accelerate permitting processes are to swiftly map, assess and ensure suitable land and sea areas available, and to avoid as much as possible environmentally valuable areas. Considering the current situation in Norway today, it will be important to establish good frameworks for faster permitting. Moreover, the climate plan does not include possible negative consequences of new regulatory schemes for hydropower due to new concessions, which could have significant impact on the energy and power balance towards 2030.

Lastly, the climate plan does not address the increasing need and value of flexibility as the power sector moves toward larger shares of variable renewable energy by 2030. This is a major drawback as flexibility and energy storage is recognised as important in a European context.

Recommendations based on project results

Results from IFE-TIMES-Norway show that Norway can indeed contribute with large export volumes by 2030, however an accelerated deployment in renewable energy capacity is needed. Based on current and future cost projections and resource potential, deployment of new onshore and offshore wind seems most favourable to supply Norway and Europe with power. For the case of this analysis, a potential of 6 GW offshore wind at Sørlige Nordsjø II was allowed by 2030. In scenarios representing the current European market, this potential was reached. This indicates that additional investments in the Southern North Sea, beyond the 3 GW currently planned for by the government, can be profitable without subsidies. Allowing for hybrid connections will further benefit these investments.

Onshore and offshore wind are however energy sources that require large infrastructure, characterised by long and complex permitting processes. Hence, the extent to which these technologies can support with additional export volumes by 2030 is limited. Onshore wind has also experienced large resistance due to its impact on local environment and nature, which can potentially limit its future deployment. Results from IFE-TIMES-Norway indicate a substantial increase in costs for the Norwegian energy system if no new onshore wind power were to be allowed, also largely restricting export volumes to Europe. Despite the proposal by the EU commission for accelerated treatment of wind power licenses (and renewable energy deployment in general), it will be important for Norway to balance more efficient processes with the involvement of local democracy to avoid new moratorium on wind power development. Additionally, with the uncertain role of onshore wind as a supplier of new renewable energy, the government should consider other sources of renewable energy to accelerate supply of green energy to Europe.

In this regard, the Commission promote an increased development of solar power in the building sector as part of the REPowerEU plan [85]. Results from this study show that building applied PV is indeed a competitive energy source also for the Norwegian energy system and can play an important role for both domestic supply and enabling larger export volumes to Europe. The advantages of rooftop PV for the consumers are especially relevant now, as these installations can shield consumers from high energy prices, contributing to public acceptance of renewable energy. Moreover, they can be deployed rapidly, utilising existing infrastructure, and avoid conflicts with other public goods like the environment. The Norwegian government should therefore push for an accelerated deployment of rooftop PV in the years to come. An established robust support framework for such systems, including hybrid systems with energy storage, will be important in this process.

Although the results from GENeSYS-MOD show a slight decrease (7.5%) in total energy demand to the Norwegian transport sector in 2030 relative to 2018, the power demand for the transportation sector will continue to increase and constitute 3.3 TWh in 2030 and 12.3 TWH in 2050, or 2,6% in 2030 and 7.9% in 2050 of the total power demand. In the GENeSYS-MOD results, this demand is met with an increased production coming mostly from onshore and offshore wind, but also from biomass and solar PV. In the first results from GENeSYS-MOD, only onshore and no offshore wind was built, as this was not seen as profitable. Due to the political incentives, the GENeSYS-MOD capacities were adjusted to allow for more offshore wind also in Norway. Public opinion influences political decisions, and it is important to balance power demand against nature conservation.

In its final chapter, the climate plan debates the level for the CO_2 tax – whether the level for 2030 should be doubled to 4000 NOK/tonnes CO_2 to reduce the non-ETS emissions to 50% in 2030 – and the CO_2 price dynamics. However, the plan does not mention any development in the CO_2 price between 2030 and 2050. In the GENeSYS-MOD results, the CO_2 price-increase accelerates as shown in Appendix A2. However, in [86], the implementation of the REPower EU action plan [56] is described and to a large extent, and the short-term measures to reduce dependency on Russian fossils will be demand-side behavioural measures. Though Norway is not part of the EU, we have considered the same front-loading of the *Fit-for-55*-goals for the Norwegian climate plan with convex CO_2 price dynamics as a possibility to achieve the climate goals faster with better opportunity to export power. This will mean a higher CO_2 price sooner, but without any significant increase in the end.

The snapshot results from highRES-Europe provides some insight into the contributions of Norway to supply mainland Europe with an additional 30 TWh of electricity from the Nordic countries. The model was allowed to choose freely how much additional electricity would be generated and exported in the Nordic countries. The results show Norway generating 6.8 TWh of additional electricity from hydropower (despite not being allowed to invest in additional capacity) and 3.3 TWh from offshore wind. The increased generation results in 0.28% additional costs.

5.4. Swedish NECP

Sweden had to present an integrated NECP to the European Commission by 31 December 2019 in accordance with the Governance Regulation. The following comments are made to that plan.

In 2016 Sweden adopted The Energy Agreement, a broad agreement on energy policy which aims to combine sustainability, security of supply and competitiveness. In 2017 a climate policy framework was adopted, including national climate targets, which is considered a key component of the nation's efforts to comply with the Paris Agreement. The current Swedish NECP is based primarily on these existing frameworks, and the energy and climate targets included in them. A few key targets for the Swedish energy and climate policy are:

- Sweden must cut net-zero GHG emissions to zero by 2045 (base year: 1990).
- 70% reduction in emissions in the transport sector by 2030 (base year: 2010).
- 100% renewable electricity generation by 2040.

Other existing national energy policies, measures and scenarios associated with the existing frameworks are also elaborated on in the plan.

A general comment on the plan, is that the net-zero GHG emissions goal may sound misleadingly ambitious. The goal is already close in sight[11], since negative emissions due to land use (LULUCF) were already equivalent to more than 80% of the positive emissions. In sectorial climate plans, the ambitions are higher than this. An option could be to set separate goals to the positive and negative emissions. That would signal that both aim high, and that one cannot rely on the other. For example, the transport sector cannot relax and hope that land owners re-establish wetlands.

---

[11] Table 26 in NECP Sweden.

Electrification goals

The Swedish NECP does not present overarching targets aimed specifically at electrification. Rather, electrification is incorporated as part of the measures taken to reach previously mentioned targets within the energy and climate frameworks.

Electrification measures are mentioned in the NECP mainly for the transport sector and the industry sector, as part of the transition to net-zero emissions. The two sectors are stated as powerful driving forces, and major uncertainties, for future electricity consumption. For the transport sector, an electrification commission has been formed to help accelerate investments in electric roads, charging infrastructure etc. and to investigate the effects of transport electrification on electricity supply. For the industry sector Industriklivet (Industrial Evolution initiative) has been initiated to support the transition in Swedish industry towards zero emissions of GHG in 2045. Projects such as the HYBRIT (HYdrogen BReakthrough Ironmaking Technology) framework are expected to contribute to net-zero emissions through fossil-free production of steel.

Electrification in transport and industry

Reaching zero emissions through electrification of transport and industry will require more electricity generation and stronger transmission capacity. Technological shifts in heavy industry will lead to significant increase in electricity demand, for example in the HYBRIT case mainly for hydrogen production. A comment to the NECP is that it mentions the financial support for the industrial transition *but does not elaborate on the expected power requirement for the fossil-free industries.* In energy scenarios developed by the Swedish Energy Agency in 2021 (ref), the issue is further studied. In 2019, the electricity demand of the industry sector was 48 TWh. According to the new scenario for high electrification, the electricity demand in industry will be 60 TWh in 2030 and 98 TWh in 2050.

Likewise, the transport sector is expected to have reduced GHG emissions by 70% in 2030, partly through electrification measures mentioned in the plan. However, the expected increase in electricity demand related to this transition is, besides being mentioned as an uncertainty for future demand predictions, not described in detail. In 2019 the annual electricity demand for the transport sector was 3 TWh and can according to a high electrification scenario reach 10 TWh by 2030 and 28 TWh in 2050.

These shifts and the following electricity demands could be of great importance for the electrification and net-zero transition of the Nordics at large and would therefore be of great interest for the updated NECP.

According to the Swedish Energy Agency's EU Reference Scenario (Figure 3 in the Swedish NECP) the installed capacity 2020-2030 increases by 38 - 45 GW. This is likely to meet the electricity demand in the new high electrification scenario (with especially the increased electricity demand for transports and industry). The major electrification occurs beyond 2030, when great challenges in capacity demand could come. Since largescale infrastructure projects have a long planning phase, the electricity capacity expansion needs to be addressed as soon as possible.

Electrification in the built environment

The sector of housing and services is expected to move towards national climate goals assisted by several policies and measures mentioned in the NECP such as energy and carbon tax, national building regulations and education programmes for low-energy buildings.

Similarly to the previously mentioned sectors, regulations and programmes are aimed at the building sector to achieve net-zero emissions and do not dictate electrification as a goal for the sector. This means the outcome in terms of changing use of energy sources, which could lead to a change in electricity demand, is not certain. Electrification in the built environment could for example be switching to heat pumps from other heat sources like oil or district heating.

Scenarios for future electricity demand in the housing and services sector project that the electricity demand will be between 79 TWh (low electrification) and 83 TWh (high electrification) in 2050. This can be compared to the demand in 2019 of 74 TWh, concluding that the electricity demand for housing and services is not expected to increase as strongly as transport and industry sectors. However, it should be noted that a substantial part of the transport electrification it expected in the form of electric vehicles which will be charges in connection to the built environment, which will indirectly increase the electricity demand and needed infrastructure in the built environment.

The built environment is also expected to play a role on the electricity generation side, as it is one of the most suitable places for renewable electricity generation in the form of PV panels. To this aim, in the Swedish NECP large investments in PV start from 2040. Considering the expected increase in electricity demand, due to the several expected developments previously stated, earlier investments in PV to increase the capacity significantly by 2030 would be more in line with other shifts. Additionally, the pace of PV investments in the NECP is lower than in the RePowerEU strategy. The later declares PV installation as an important measure to reduce dependency on Russian energy before 2030, and correspondingly sets targets for the EU photovoltaic and wind capacities should be doubled in size by 2025 and tripled by 2030.

The role of Nordic cooperation

Nordic cooperation is emphasised in several regards in Sweden’s NECP, not the least in relation to energy research. Some other examples, closely related to electrification, are presented in the following.

Regarding market integration, the role of Nordic cooperation is emphasised. A model for the balancing of the Nordic power system is to be developed and implemented by 2023.

Regarding transmission capacity, a new connection to Finland (900 MW) planned by 2027. No further plans for interconnection from 2027 onwards are presented. Reflecting on the results from the Nordic scenarios for climate neutrality and especially on the results from the RePowerEU scenario with increased electricity export to the European continent, see Table 3-11, this seems to be insufficient. Transmission capacity needs to be strengthened largely, both within countries and in-between.

The ambition to cooperate on sustainable Nordic cities and smart grids is emphasised. Also, the Nordic Environment Finance Corporation is highlighted. It enables Nordic operators to carry out climate measures in cooperation with the fund.

Nordic cooperation as described in Sweden’s NECP will be of increasing importance for several reasons. On one hand to be able to tackle an increased share of intermittent electricity generation, and other hand to strengthen the resilience in world with climate change and military conflicts. In the Nordic Clean Energy Scenario report [16], the results from ON-TIMES model runs, implied the importance of Nordic energy collaboration (Chapter 8.5 in NCES). Four target areas for collaboration were highlighted:

- Stronger coordination of and commitments to Nordic power infrastructure planning.
- Nordic cooperation on integrated offshore wind and grid development.
- Common vision for the role of PtX production in the Nordics.
- A common Nordic CCS strategy.

It is stated that climate neutrality can be obtained without this collaboration, but collaboration will make it more efficient solutions and substantially lower costs.

5.5. Danish NECP

From an energy system perspective, the NECPs are an essential tool, as it requires each member state to take a holistic approach to climate and energy policy. It does so by not only focusing on national GHG reduction. Instead, it also requires member states to consider additional key policy objectives such as renewable energy, energy efficiency, security of supply, infrastructure and markets and R&D and overall level of competition. At the same time, these policy objectives should be considered in a broader regional context.

The Danish NECP strongly focuses on the electrification of transport, industry, and society in general. However, it also highlights how increasing the level of electrification puts pressure on the electricity supply and challenges the security of supply, as more appliances, especially cars and heating systems, will run on electricity. The increased electricity demand implies that generation and grid adequacy will require attention and plans to construct large data centres will further challenge the generation and grid adequacy.

The security of electricity supply will be affected as the renewable energy sources providing the electricity are primarily wind and solar power, which are highly fluctuating energy sources. That will lead to periods of low electricity generation, which would previously have been covered by running the thermal power plants, but which in the future will have to be covered by other means. Hence, the focus is on developing interconnections to ensure sufficient interconnections with our neighbouring countries. That is, by becoming more interconnected, Denmark can sell electricity when there is a lot of wind and buy electricity when there is less.

Another objective for the future Danish energy system is to make sure that the demand for electricity does not rise to levels that cannot be met by the supply and to make the most efficient energy investments in line with the energy efficiency first principle. As an example, electrification and a higher degree of distributed generation will support the incorporation of fluctuating renewable energy sources in the electricity system. With increasing shares of decentralised production and new consumption due to the electrification of heating and transport, the Danish grids will become challenged on a more local scale. The plan is to meet local challenges primarily through market-based arrangements to achieve the most cost-effective solutions.

The NECP also describes the Danish policy focus on developing a common strategy with the North Sea nations for a significant expansion and exploitation of the offshore wind potential and supporting the large-scale power-to-X technologies.

The variation in model outcome in WP2 on a national and regional level highlights the potential for further collaboration between Nordic research institutions. An interesting perspective is that despite our cultural similarities in the Nordic Region, each country's energy system is quite different. However, this difference means that by improving our understanding and modelling of the Nordic region, we may provide insights into synergies achievable through closer cooperation to the possible benefits of every country.

In practice, this could be done by having more resources available for aligning the model scenario assumptions, allowing for a better comparison and more profound insights from the model output which could perhaps serve as input into future NECPs. And perhaps also increase the footprint of Nordic region on future European energy and climate policy.

6. Needs for more joint research and investigation

The work in WP2 has led to good discussions between the various modelling groups involved, resulting in the analysis of the joint scenario case RePowerEU, which could constitute a first step on a more complete joint research project between Nordic research institutes on that topic.

This endeavour has also led to the insight that many important but difficult to investigate research questions have resurfaced, driven by the opportunities that international and interdisciplinary collaboration open for. In the following we describe a set of promising research topics.

6.1. Improvement of the datasets

Rationale:

High quality time series data are crucial the capacity expansion needs for both power production capacities as well as transmission capacities. Including partners from all Nordic countries provide additional insights, understanding and data for their respective countries regarding potentials and locations for potential future installations, which when combined into a Scandinavian model, on sub-country/country level, could provide a much more realistic understanding of capacity expansion needs and costs. Also projected cost assumptions for these technologies could then be differentiated on national or sub-nation level, accounting for the specific requirements/challenges of each country/region.

Expected outcome:

A new database with open datasets across the Nordics. The value of joint datasets will be higher by joint modelling efforts across the Nordic countries. Improved data will eventually lead to more coherent and robust insights from modelling exercises, consistent results between the countries, and increased likeliness of optimal joint energy system between the Nordic countries. These improved modelling will in turn better inform real world politics, by also communicating limitations and shortcomings of both the modelling frameworks and the data – detail and quality - the studies rely on.

Scope:

Key data are renewable resources, such as wind and solar, weather data, energy prices, demands of energy/products, population, GDP. Use digitalisation as a supporting tool to energy system models – develop methods that use AI to derive and continuously improve datasets based on the available open data. E.g. similar to IAASA database for climate modelling, but for Nordic Energy System modelling. It could be a requirement of NER calls that scenario results are added by each modelling group to the database. Policies such as FIT for 55, changes due to REPowerEU and the individual Nordic NECP should be included in the common datasets.

6.2. Nordic resilience in a changing world

Rationale:

As shown in this project when addressing the RePowerEU, there is great usefulness of energy system models to increase the understanding of resilience in the Nordic countries and highlight the value of international cooperation between the Nordic countries.

Expected outcome:

New quantitative and qualitative studies that compare national and coordinated strategies. Development of a methodology for Nordic resilience assessment covering components such as of energy, power, and infrastructure. These new studies and methods will eventually lead to increased resilience in the Nordic energy system by diversified use of energy resources, energy carriers and, energy infra-structures across the Nordic countries.

Scope:

One example is to investigate the role of Norway and Sweden for Finland's disconnection to Russian energy supply. The works should consider energy infrastructure that improve the joint resilience of the Nordics. Environmental impact and circularity shall be part of the work for generation and infrastructure alike.

6.3. Nordic energy system modelling

Rationale:

Modelling across the Nordic countries, possible also the Baltics will benefit the region leading to robust and more cost-effective energy system development.

Expected outcome:

Create a Nordic TIMES modellers++ modelling group to undertake a joint Nordic modelling effort that can be used as a tool to create a common strategy on how Scandinavia, and possibly the Baltic countries, can contribute to the European green transition. Hereinunder, investigate the impact and role of Norway and Finland in the new industry development in North of Sweden and Finland in the triangle of new industry consumption, power potential and the hydrogen corridor from north Scandinavia to Europe.

Scope:

To create coherent and robust insights form modelling exercises, that have value to inform real world politics, it is important to first understand limitations and shortcomings of both the modelling frameworks used and the data – detail and quality - the study relies on. The work includes considering the value and modelling of hydropower and the increasingly stronger connection to European. The socio-political perspective should be included amongst other as. interviews and discussions activities with inhabitants, politicians and decision makers based on the results, before adapting the modelling effort according to the feedback.

6.4. Modelling improvement

Rationale:

More thorough model comparisons, both in terms of structure and what data is used. Is needed. The understanding of fundamental characteristics of what assumptions that are explicitly stated in the models/reports and what is implicit should be the basis for suggesting and undertake necessary modelling improvements.

Expected outcome:

Improved models that can provide realistic results in energy systems with variable sources and high levels of uncertainty. This includes technology constraints that impact on optimal development of the energy system enabling investment decisions in technologies, infrastructures leading to affordable energy cost for the citizens as well as representing and industrial advantage.

Scope:

Increased understanding of the role of demand for optimising the energy system Comparative analysis of socio-political aspects of the models. How much wind, solar, nuclear can be deployed from a techno-economic point of view and from a socio-political point of view. It must include social acceptance and circularity in Nordic energy system models.

6.5. Increasing the level of temporal and spatial detail for new electricity consumers in the Nordic transport sector

Rationale:

The model results for the transport sector are in general aggregated for large regions and summarised for an entire year. However, this sector inhabits large variations over time (both seasonal, weekly, and hourly) and space regarding energy demand. Cross-sectorial issues are apparent, particularly for private electric vehicles that can be charged either as a domestic appliance (e.g. as a mobile telephone), a building service (e.g. as the lifts) or an infrastructural service (e.g. as road lighting). With an expected increase of electrification in all transport modes, charging infrastructure will pose a large challenge for the energy system.

Expected outcome:

An analysis of potential distributions of charging demand in space and time based on assumptions about an estimated future transport sector to help identify any logical shortcomings at the supply side, as well as any coinciding demands from other electricity consumers. This could help in guiding decisions regarding both future planning of charging infrastructure and grid expansion or improvement, with also substantial impact on spatial planning of the existing and new residential, commercial, and industrial areas in the Nordic region (both urban and rural).

Scope:

An overall goal should be to set the system boundaries for the whole Nordic region, but it might be practical to begin with a smaller region for the initial methodical development. In addition, all modes should be included, such as maritime (ports), aviation (airports), road (private and freight) and rail, especially to pinpoint potential for crossmodal charging infrastructure.

6.6. Increasing resolution of new electricity production and consumption in Nordic buildings

Rationale:

Substantial electrification of the building sector is expected in the sustainable transition of the Nordics. in the analysis of this WP it has been observed that the energy system models differently represent the electrification measures (changes and flexibility in demand, fuel switch, production from RES in the buildings, cross-sectorial spill overs such as electric vehicles and urban farming). Results from these models differ substantially from those of sectorial models. Yet, the influence of changes in the temporal and spatial resolution, as well as in the resolution of physical and technical data, has not yet been studied.

Expected outcome:

Improved model structure, improved data, leading to better assessments.

Scope:

Improved temporal (intra-year timesteps, target years), spatial (size of building categories, technologies, and climate zones) and technical resolution (sizes, potentials and costs of sectorial data); demand (interactions between end-uses, demand side management) and supply (RES in buildings, electric vehicles, urban farming, data centres).

6.7. The role of wind energy – opportunities and challenges

Rationale:

Model results show the large contribution wind energy plays in reaching our climate targets. However, there are challenges both on the acceptance side as well as on the spatial-temporal variability when integrating large shares.

Expected outcome:

Better understanding of the challenges of reaching high shares of wind energy into the Nordic energy system and ways to solve them.

Scope:

1. Analysis of the social acceptance and ecological impacts, options to improve acceptance and minimise impacts,
2. Understanding of weather and climate and how to best integrate large shares of wind energy into the system.

7. Conclusions

7.1. Summary

Models in WP2 of NEO

This report describes the work and results from WP2 of Nordic Energy Outlooks. It describes five general energy system models and three domain specific models, all developed by institutes within the Nordic area, as well as the connections between them.

The five energy system models are:

- ON-TIMES (IVL)
- GENeSYS-MOD (SINTEF)
- IFE-TIMES-Norway (IFE)
- highRES-E (UiO)
- IntERACT (DEA)

The three domain-specific models are:

- ECCABS (IVL)
- EMPS (SINTEF)
- Energy Map (SINTEF)

Comparative study

To compare models, we have studied how the Nordic power system will be impacted by the REPowerEU plan and, in particular, a Nordic contribution to the fulfilment of that plan. Two scenarios were specified: a base scenario for a transition to a decarbonised energy system by 2050, and a REPowerEU scenario, which requires that the Nordic area exports an additional 30 TWh of electricity to other European countries from 2030 onwards, in relation to the base scenario. This will contribute to reducing their dependency of Russian gas. We presented and compared the results from the different models for those two scenarios. The input data to the different models was not aligned apart from implementation of scenario definitions.

The base case is already a decarbonised scenario for 2050. Therefore, the impact of the REPowerEU scenario relative to the base case does not show how the energy system needs to change between today and 2050. Instead, it shows the *extra* effort that is needed on top of the decarbonised scenario in order to export an additional 30 TWh of electricity to other European countries. An important finding across the models is that extra offshore wind power generation is needed, notably in Denmark.

Results from GENeSYS-MOD show that Denmark will export the most power of the Nordic countries, closely followed by Norway. In the scenario with additional export, Denmark will provide almost two thirds of the additional export, which will mainly be produced from offshore wind power. The additional energy system cost per country will be affected by the extra export, as indicated by high additional costs in Denmark and lower costs in Finland, which exports less in the REPowerEU scenario than in the base scenario. For Norway, it will be cost efficient to increase onshore wind power.

However, due to the current political situation, the model is not allowed to add much onshore wind power. Therefore, the model presumes extra offshore wind power instead.

Results from ON-TIMES show that the extra 30 TWh electricity from the Nordic area can be managed without additional transmission capacity up to 2040. However, after 2040, when several sectors in the Nordics are assumed to have been electrified, extra transmission capacity will be needed. According to this model, the largest amount of new electricity capacity will be wind power from Denmark, which is also the case in the GENeSYS-MOD results. Another finding from ON-TIMES is that, to some extent, the additional export in the REPowerEU scenario will prohibit electrification as a measure to reach climate neutrality in the Nordic area, and instead favour other energy transition solutions.

When comparing electrification and use of electricity between ON-TIMES and GeneSys-Mod, the latter shows more electrification and more production of other energy carriers such as hydrogen. One explanation can be that GeneSys-Mod simulation are based on a 100% decarbonized scenario for Europe, wheres ON-TIMES is based on a 80% reduction scenario for Europe.

The HighRES model provides results for 2050, but does not include a year-by-year transition from the current situation. However, the modelling results provide insights into the spatial and technological distribution in the Nordic countries. According to this model, the highest increase in power generation between the scenarios will also be wind power from Denmark, which will therefore also experience the highest increase in energy system costs. However, increased wind power will also come from Finland, Sweden and Norway.

The IFE-TIMES-Norway is a model for Norway. Results indicate that onshore and offshore wind power are the most cost-effective technologies for Norway. If Norway must contribute to the targets in the REPowerEU plan by 2030, it needs to accelerate its deployment of renewable capacity. However, the additional cost of the energy system would be small.

Individual project outcomes

The report also describes other project results and modelling carried out by the involved research institutes, in accordance with their research questions in WP2, and some promising future research topics have been outlined as a result. Furthermore, a dedicated section discusses if the work in WP2 can produce suggestions for updating the NECPs for Nordic countries.

IFE has focused on studying a decarbonisation transition pathway, i.e. a base case in comparative study, and results for renewable energy expansion, transmission grid investments, electricity demand growth and electricity trade with Europe. Sensitivity on different parameters have been calculated to evaluate the robustness of the results, taking into consideration current uncertainties in the Norwegian and European energy system. Results indicate that onshore and offshore wind power will be the most cost-effective technologies to meet Norway’s future electricity demand, where most of the offshore wind power production is exported to Europe. Moreover, solar PV panels on buildings will play an important role, with capacities exceeding 13 GW by 2050. The net electricity export from Norway to Europe will be significant from 2035 onwards, but the magnitude will differ depending on European power prices and social acceptance of electricity generation sources. Results indicate that high and volatile power prices in Europe, as with the current situation (August 2022), mean that Norway will largely benefit from exporting electricity. The results also show that social acceptance of wind power will have a large impact on Norway's potential to support Europe by supplying electricity in the energy crisis. With no new wind power development, the electricity export to Europe will have decreased by 11-12 TWh in 2050, while the electrification of the Norwegian energy system is reduced.

SINTEF describes a toolchain linking the power market model EMPS to GENeSYS-MOD and discusses further linking such as including linking between the transport model Energy Map and GENeSYS-MOD.

IVL has developed insights into the electrification of heavy industry and the built environment in the Nordic energy system, and specified a method for developing the ON-TIMES model for these sectors. Since a large transition of the heavy industry into electrification is at hand, both in terms of energy supply and transitioning to new processes, the industrial sector needs to be modelled to reflect these opportunities. A suggestion on how to integrate the ON-TIMES and ECCABS models has also been discussed.

UiO has discussed the social considerations of energy infrastructure in relation to modelling, including aspects of justice, which has been found to be instrumental for the realisation of energy infrastructure projects. By assessing how socially just a power system design is through different lenses, it has been found that the applied formal definition is an important factor for the consequent results and analysis. When working with questions of justice in a quantitative manner, it is therefore important to clearly state the assumptions and definitions applied around the subjective nature of social justice.

During this project, the DEA has contributed with support in terms of sharing experience and data from different modelling aspects. We believe that this has created a better understanding of both the IntERACT model and the Danish experience within energy system modelling. An understanding of the different model opportunities and limitations has been highlighted throughout the project, through interaction, during meetings, discussions, and knowledge sharing. We also believe that by participating in this project, we have helped to create a larger network and establishing new connections throughout the Nordic area within energy system modelling. We furthermore believe that we have helped raising the understanding of the differences between our different models by, among others, sharing data with the TIMES-NO. Here calculated prices from a Danish perspective, from the in-house techno-economic RAMSES-model, were used in the Norwegian model. By supplying two types of datasets, one representing a frozen-policy aspect and one representing a non-frozen policy PtX-development scenario, the Norwegian model could gain new insights into how different inputs could affect their model outputs compared to their current assumptions.

7.2. Important take aways from the collaboration

As shown in this project when addressing REPowerEU in a common scenario, energy system models are extremely useful for increasing our understanding of the energy system transformation in the Nordic countries in a changing world, e.g. in terms of climate mitigation, climate change, energy price fluctuations, energy security, and energy deliveries that can be used as a means of military pressure. Pathways for the transformation of the Nordic energy system can be studied to inform policy making, prioritise infrastructure development and common Nordic engagement.

Cooperation with researchers from neighbouring countries has been fruitful. Despite geographical proximity and a common aim of a climate neutral future, we have structural and cultural differences. One example is the industrial differences caused by the importance of the petroleum sector in Norway, the agricultural sector in Denmark, and forestry in Sweden. Such differences influence the options considered in climate action plans. Working together has increased our understanding of how other Nordic countries think and inspired us to broaden our perspective on ways forward and synergies that can be obtained by extended collaboration.

Cooperation with experts from different disciplines has been rewarding. For example, it has highlighted how social aspects can be considered when developing energy system models, and how knowledge about the energy development in sub-sectors can be used to make the high-level energy models more accurate. Likewise, the sub-sector experts can learn from the widened system perspective how changes will affect the larger system, which is important to avoid sub-optimisation.

Participants in the project have increased their knowledge about important Nordic energy system modelling communities and corresponding energy system models. The improved overview of where different expertise within different aspects of energy system modelling can be found in the Nordics will help us in future work with knowing who to ask for collaboration and advice on specific modelling aspects.

References

[1] ‘Nordic Energy Outlooks’, *Nordic Energy Outlooks*, 2021. https://www.nordicenergy.org/project/nordic-energy-outlooks/

[2] O. Wolfgang *et al.*, ‘Nordic Energy Outlooks - Final report WP1. Bioenergy and links to agriculture & LULUCF in a Nordic context’, SINTEF, 1, Feb. 2022. [Online]. Available: https://www.nordicenergy.org/publications/nordic-energy-outlooks-final-report-wp1-bioenergy-and-links-to-agriculture-lulucf-in-a-nordic-context/

[3] ‘REPowerEU: Joint European Action for more affordable, secure and sustainable energy’, European Commission, Mar. 2022. [Online]. Available: https://energy.ec.europa.eu/system/files/2022-03/REPowerEU_Communication_with_Annexes_EN.pdf

[4] ‘Fit for ’55: delivering the EU’s 2030 Climate Target on the way to climate neutrality’, European Commission, Jul. 2021. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0550

[5] The Ministry of Infrastructure, Sweden, ‘Sweden’s Integrated National Energy and Climate Plan’, European Commission - National energy and climate plans, Jan. 2020. [Online]. Available: https://energy.ec.europa.eu/topics/energy-strategy/national-energy-and-climate-plans-necps_en

[6] Danish Ministry of Climate, Energy and Utilities, ‘Denmark’s Integrated National Energy and Climate Plan’, European Commission - National energy and climate plans, Dec. 2019. [Online]. Available: https://energy.ec.europa.eu/topics/energy-strategy/national-energy-and-climate-plans-necps_en

[7] ‘Klimaplan for 2021-2030. Meld. St. 13 (2020-2021).’ Det kongelige Klima- og miljødepartement, 2021. [Online]. Available: https://www.regjeringen.no/contentassets/a78ecf5ad2344fa5ae4a394412ef8975/nn-no/pdfs/stm202020210013000dddpdfs.pdf

[8] A. Dugstad, K. Grimsrud, G. Kipperberg, H. Lindhjem, and S. Navrud, ‘Acceptance of wind power development and exposure – Not-in-anybody’s-backyard’, *Energy Policy*, vol. 147, p. 111780, Dec. 2020, doi: 10.1016/j.enpol.2020.111780.

[9] P. Devine-Wright, ‘Beyond NIMBYism: towards an integrated framework for understanding public perceptions of wind energy’, *Wind Energy*, vol. 8, no. 2, pp. 125–139, 2005, doi: 10.1002/we.124.

[10] M. Wolsink, ‘Wind power implementation: The nature of public attitudes: Equity and fairness instead of “backyard motives”’, *Renewable and Sustainable Energy Reviews*, vol. 11, no. 6, pp. 1188–1207, Aug. 2007, doi: 10.1016/j.rser.2005.10.005.

[11] C. Gross, ‘Community perspectives of wind energy in Australia: The application of a justice and community fairness framework to increase social acceptance’, *Energy Policy*, vol. 35, no. 5, pp. 2727–2736, May 2007, doi: 10.1016/j.enpol.2006.12.013.

[12] K. L. Thorsten Burandt and Karlo Hainsch, ‘GENeSYS-MOD v2. 0-Enhancing the Global Energy System Model: Model improvements, framework changes, and European data set. No. 94. DIW Data Documentation’, 2018.

[13] ‘FuChar - Grid and Charging Infrastructure of the Future’, *NRC ENERGIX programme project*, 2022. https://www.sintef.no/prosjekter/2019/fuchar/

[14] EA Energy Analyses, ‘Electricity price projections’, EA Energy Analyses, Copenhagen, Denmark, 2021. [Online]. Available: https://www.ea-energianalyse.dk/en/publications/electricity-price-projections/

[15] https://github.com/NordicEnergyResearch/NCES2020, .

[16] ‘Nordic Clean Energy Scenarios’, 2021. https://www.nordicenergy.org/wordpress/wp-content/uploads/2021/09/nordicenergyresearch2021-01.pdf

[17] J. Danebergs, E. Rosenberg, P. S. Seljom, L. Kvalbein, and K. Haaskjold, 'Documentation of IFE-TIMES-Norway v2', ISSN: 2535-6380, 2021.

[18] Richard Loulou, Antti Lehtilä, Amit Kanudia, Uwe Remme, and Gary Goldstein, 'Documentation for the TIMES Model: Part II Reference Manual', 2016.

[19] 'openENTRANCE', *EU Horizon 2020 programme project*, 2022. https://openentrance.eu/

[20] V. Krey et al., 'V. Krey et al., MESSAGEix-GLOBIOM Documentation – 2020 release.', Technical Report, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 2020.

[21] 'openENTRANCE Scenario Explorer'.

[22] 'OSeMOSYS', 2022. http://www.osemosys.org/

[23] O. Wolfgang, A. Haugstad, B. Mo, A. Gjelsvik, I. Wangensteen, and G. Doorman, 'Hydro reservoir handling in Norway before and after deregulation', *Energy*, vol. 34, no. 10, pp. 1642–1651, 2009.

[24] J. Price, I. Keppo, and P. Dodds, 'The role of new nuclear power in the UK's net-zero emissions energy system', 2021, doi: 10.48550/ARXIV.2109.15173.

[25] W. Matar and A. M. Elshurafa, 'Electricity transmission formulations in multi-sector national planning models: An illustration using the KAPSARC energy model', *Energy Reports*, vol. 4, pp. 328–340, Nov. 2018, doi: 10.1016/j.egyr.2018.04.004.

[26] J. R. Centre *et al.*, *The JRC-EU-TIMES model : assessing the long-term role of the SET plan energy technologies*. Publications Office, 2014. doi: doi/10.2790/97799.

[27] F. Hofmann, J. Hampp, F. Neumann, T. Brown, and J. Hörsch, 'atlite: A Lightweight Python Package for Calculating Renewable Power Potentials and Time Series', *JOSS*, vol. 6, no. 62, p. 3294, Jun. 2021, doi: 10.21105/joss.03294.

[28] J. Price and M. Zeyringer, 'highRES-Europe: The high spatial and temporal Resolution Electricity System model for Europe', *SoftwareX*, vol. 17, p. 101003, Jan. 2022, doi: 10.1016/j.softx.2022.101003.

[29] 'https://github.com/highRES-model/highRES-Europe'.

[30] É. Mata, A. S. Kalagasidis, and F. Johnsson, 'A modelling strategy for energy, carbon, and cost assessments of building stocks', *Energy and Buildings*, vol. 56, pp. 100–108, Jan. 2013, doi: 10.1016/j.enbuild.2012.09.037.

[31] É. Mata, J. Wanemark, M. Österbring, and F. Shadram, 'Ambition meets reality – Modeling renovations of the stock of apartments in Gothenburg by 2050', *Energy and Buildings*, vol. 223, p. 110098, Sep. 2020, doi: 10.1016/j.enbuild.2020.110098.

[32] É. Mata, A. Sasic Kalagasidis, and F. Johnsson, 'Energy usage and technical potential for energy saving measures in the Swedish residential building stock', *Energy Policy*, vol. 55, pp. 404–414, Apr. 2013, doi: 10.1016/j.enpol.2012.12.023.

[33] É. Mata and F. Johnsson, 'Cost-Effectiveness of Retrofitting Swedish Buildings', in *Cost-Effective Energy Efficient Building Retrofitting*, Elsevier, 2017, pp. 343–362. doi: 10.1016/B978-0-08-101128-7.00012-5.

[34] M. Österbring, É. Mata, L. Thuvander, and H. Wallbaum, 'Explorative life-cycle assessment of renovating existing urban housing-stocks', *Building and Environment*, vol. 165, p. 106391, Nov. 2019, doi: 10.1016/j.buildenv.2019.106391.

[35] É. Mata, J. Wanemark, V. M. Nik, and A. Sasic Kalagasidis, 'Economic feasibility of building retrofitting mitigation potentials: Climate change uncertainties for Swedish cities', *Applied Energy*, vol. 242, pp. 1022–1035, May 2019, doi: 10.1016/j.apenergy.2019.03.042.

[36] É. Mata, A. S. Kalagasidis, and F. Johnsson, 'Contributions of building retrofitting in five member states to EU targets for energy savings', *Renewable and Sustainable Energy Reviews*, vol. 93, pp. 759–774, Oct. 2018, doi: 10.1016/j.rser.2018.05.014.

[37] Statsministerens kontor, Finansdepartementet, Nærings- og fiskeridepartementet, and Olje- og energidepartementet, 'Kraftfull satsning på havvind', Regjeringen.no, May 11, 2022. [Online]. Available: https://www.regjeringen.no/no/aktuelt/kraftfull-satsing-pa-havvind/id2912297/

[38] Statsministerens kontor, 'Hurdalsplattformen 20221-2025', Regjeringen.no, Oct. 2021. [Online]. Available: https://www.regjeringen.no/no/dokumenter/hurdalsplattformen/id2877252/

[39] Committee on Climate Change, ‘The Sixth Carbon Budget - The UK’s path to Net Zero’, 2020. Accessed: Aug. 17, 2022. [Online]. Available: https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf
[40] ENTSO-E, ‘Ten-Year Network Development Plan 2020 - Main Report’, 2021. Accessed: Aug. 12, 2022. [Online]. Available: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/TYNDP2020/FINAL/entso-e_TYNDP2020_Main_Report_2108.pdf
[41] ‘https://www.ea-energianalyse.dk/en/publications/electricity-price-projections/’.
[42] Olje- og energidepartementet, ‘Historisk innstramming av vindkraftpolitikken’. Jun. 19, 2020. [Online]. Available: https://www.regjeringen.no/no/dokumentarkiv/regjeringen-solberg/aktuelt-regjeringen-solberg/oed/pressemeldinger/2020/historisk-innstramming-av-vindkraftpolitikken/id2714900/
[43] ‘https://cleanenergyscenarios.nordicenergy.org/tab6’.
[44] É. Mata and et al, ‘D2.3: Energy system cost-optimization of flexibility potentials’, ERA-NET Flexi-Sync project, 2022.
[45] ‘https://mistraelectrification.com’.
[46] Klugman et al, ‘A climate neutral Swedish industry - An inventory of technologies (ivl.se)’, IVL, 2019.
[47] E. Sandberg, A. Toffolo, and A. Krook-Riekkola, ‘A bottom-up study of biomass and electricity use in a fossil-free Swedish industry’, *Energy*, vol. 167, pp. 1019–30, 2019.
[48] E. Sandberg, ‘Capturing Swedish Industry Transition towards Carbon Neutrality in a National Energy System Model’, 2020.
[49] Wilhelmsson, B, et al., ‘A feasibility study evaluating ways to reach sustainable cement production via the use of electricity’, Cemzero, 2018.
[50] ‘Hydrogen Breakthrough Ironmaking Technology, Genomförbarhetsstudie’, HYBRIT, Slutrapport HYBRIT Energimyndighetens projektnr 42684-1, 2018.
[51] ‘TIMES modelling files with industrial technology data’. https://doi.org/10.5281/zenodo.5702722
[52] ‘Cracker Capacity - Petrochemicals Europe’. https://www.petrochemistry.eu/about-petrochemistry/petrochemicals-facts-and-figures/cracker-capacity/
[53] openENTRANCE, ‘Quantitative Scenarios for Low Carbon Futures of the pan-European Energy System’, 2020. [Online]. Available: https://openentrance.eu/wp-content/uploads/openENTRANCE-D3.13.pdf
[54] L. E. Schäffer and I. Graabak, ‘Power Price Scenarios - Results from the Reference scenario and the Low Emission scenario’, SINTEF, 5. [Online]. Available: https://www.ntnu.no/hydrocen/hydrocen-rapport
[55] ‘Historical hydrological data’. https://www.nve.no/vann-og-vassdrag/hydrologiske-data/historiske-data/
[56] ‘REPowerEU Plan’, European Commission, May 2022. [Online]. Available: https://energy.ec.europa.eu/system/files/2022-05/COM_2022_230_1_EN_ACT_part1_v5.pdf
[57] Statnett, ‘Grid development plan and power system plan’, 2021. https://www.statnett.no/en/for-stakeholders-in-the-power-industry/our-analyses-and-assessments/grid-development-plan-and-power-system-plan/ (accessed Aug. 09, 2022).
[58] Norwegian Environment Agency, ‘Klimakur 2030: Tiltak og virkemidler mot 2030’, p. 1197, 2020.
[59] A. Krumm, D. Süsser, and P. Blechinger, ‘Modelling social aspects of the energy transition: What is the current representation of social factors in energy models?’, *Energy*, vol. 239, p. 121706, Jan. 2022, doi: 10.1016/j.energy.2021.121706.
[60] G. Perlaviciute, L. Steg, and B. K. Sovacool, ‘A perspective on the human dimensions of a transition to net-zero energy systems’, *Energy and Climate Change*, vol. 2, p. 100042, Dec. 2021, doi: 10.1016/j.egycc.2021.100042.
[61] F. Neumann, ‘Costs of regional equity and autarky in a renewable European power system’, *Energy Strategy Reviews*, vol. 35, p. 100652, May 2021, doi: 10.1016/j.esr.2021.100652.

[62] F. W. Geels, F. Berkhout, and D. P. van Vuuren, ‘Bridging analytical approaches for low-carbon transitions’, *Nature Clim Change*, vol. 6, no. 6, pp. 576–583, Jun. 2016, doi: 10.1038/nclimate2980.

[63] F. W. Geels, A. McMeekin, and B. Pfluger, ‘Socio-technical scenarios as a methodological tool to explore social and political feasibility in low-carbon transitions: Bridging computer models and the multi-level perspective in UK electricity generation (2010–2050)’, *Technological Forecasting and Social Change*, vol. 151, p. 119258, Feb. 2020, doi: 10.1016/j.techfore.2018.04.001.

[64] D. Süsser, B. Pickering, S. Chatterjee, G. Oreggiono, V. Stavrakas, and J. Lilliestam, ‘Integration of socio-technological transition constraints into energy demand and systems models. Deliverable 2.5. Sustainable Energy Transitions Laboratory (SENTINEL) project’, Potsdam Institute for Advanced Sustainability Studies (IASS), Oct. 2021. Accessed: Oct. 28, 2021. [Online]. Available: https://publications.iass-potsdam.de/rest/items/item_6001259_2/component/file_6001261/content

[65] E. Trutnevyte *et al.*, ‘Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step’, *One Earth*, vol. 1, no. 4, pp. 423–433, Dec. 2019, doi: 10.1016/j.oneear.2019.12.002.

[66] D. Huckebrink and V. Bertsch, ‘Integrating Behavioural Aspects in Energy System Modelling—A Review’, *Energies*, vol. 14, no. 15, Art. no. 15, Jan. 2021, doi: 10.3390/en14154579.

[67] K. Jenkins, D. McCauley, R. Heffron, H. Stephan, and R. Rehner, ‘Energy justice: A conceptual review’, *Energy Research & Social Science*, vol. 11, pp. 174–182, Jan. 2016, doi: 10.1016/j.erss.2015.10.004.

[68] N. Healy, J. C. Stephens, and S. A. Malin, ‘Embodied energy injustices: Unveiling and politicizing the transboundary harms of fossil fuel extractivism and fossil fuel supply chains’, *Energy Research & Social Science*, vol. 48, pp. 219–234, Feb. 2019, doi: 10.1016/j.erss.2018.09.016.

[69] O. Vågerö, ‘Inclusion justice modelling’. https://github.com/OskarVagero/inclusion_justice_modelling/tree/master

[70] C. McGookin, B. Ó Gallachóir, and E. Byrne, ‘Participatory methods in energy system modelling and planning – A review’, *Renewable and Sustainable Energy Reviews*, vol. 151, p. 111504, Nov. 2021, doi: 10.1016/j.rser.2021.111504.

[71] F. Neumann and T. Brown, ‘The near-optimal feasible space of a renewable power system model’, *Electric Power Systems Research*, vol. 190, p. 106690, Jan. 2021, doi: 10.1016/j.epsr.2020.106690.

[72] K. M. Grimsrud, C. Hagem, A. Lind, and H. Lindhjem, ‘Efficient spatial allocation of wind power plants given environmental externalities due to turbines and grids’, Statistics Norway, Discussion paper 938, 2020. [Online]. Available: https://www.ssb.no/en/forskning/discussion-papers/_attachment/430436?_ts=174494097a0

[73] V. Menghwani *et al.*, ‘Planning with justice: Using spatial modelling to incorporate justice in electricity pricing – The case of Tanzania’, *Applied Energy*, vol. 264, p. 114749, Apr. 2020, doi: 10.1016/j.apenergy.2020.114749.

[74] D. Nock, T. Levin, and E. Baker, ‘Changing the policy paradigm: A benefit maximization approach to electricity planning in developing countries’, *Applied Energy*, vol. 264, p. 114583, Apr. 2020, doi: 10.1016/j.apenergy.2020.114583.

[75] S. Bolwig *et al.*, ‘Climate-friendly but socially rejected energy-transition pathways: The integration of techno-economic and socio-technical approaches in the Nordic-Baltic region’, *Energy Research & Social Science*, vol. 67, p. 101559, Sep. 2020, doi: 10.1016/j.erss.2020.101559.

[76] J. Price, K. Mainzer, S. Petrović, M. Zeyringer, and R. McKenna, ‘The implications of landscape visual impact on future highly renewable power systems: a case study for Great Britain’, *IEEE Transactions on Power Systems*, pp. 1–1, 2020, doi: 10.1109/TPWRS.2020.2992061.

[77] J. F. DeCarolis, ‘Using modeling to generate alternatives (MGA) to expand our thinking on energy futures’, *Energy Economics*, vol. 33, no. 2, pp. 145–152, Mar. 2011, doi: 10.1016/j.eneco.2010.05.002.

[78] J.-P. Sasse and E. Trutnevyte, ‘Distributional trade-offs between regionally equitable and cost-efficient allocation of renewable electricity generation’, *Applied Energy*, vol. 254, p. 113724, Nov. 2019, doi: 10.1016/j.apenergy.2019.113724.

[79] H. Bragadóttir, R. Magnusson, S. Seppänen, D. Sundén, and E. Yliheljo, ‘Sectoral expansion of the EU ETS - A Nordic perspective on barriers and solutions to include new sectors in the EU ETS with special focus on road transport’, Nordic Council of Ministers, 2015.

[80] ‘Norway’s National Plan related to the Decision of the EEA Joint Committee No. 269/2019 of 25 October 2019’. Norwegian Ministry of Climate and Environment, 2019. [Online]. Available: https://www.regjeringen.no/contentassets/4e0b25a4c30140cfb14a40f54e7622c8/national-plan-2030_version19_desember.pdf

[81] NVE, ‘Langsiktig kraftmarkedsanalyse 2020 – 2040’, 2020. [Online]. Available: http://publikasjoner.nve.no/rapport/2020/rapport2020_37.pdf

[82] Prosess21, ‘Kraftmarkedet - Prosess21 Ekspertgrupperapport’, 2020. [Online]. Available: https://www.prosess21.no/contentassets/39713b28868a41858fc2c8a5ff347c0b/nf_prosess21_ekspertgrupperapport_kraftmarkedet_def_131020.pdf

[83] DNV GL, ‘Energy Transition Norway 2021’, 2021.

[84] Statnett, ‘Langsiktig Markedsanalyse 2020-2050 - Oppdatering våren 2021’, 2021. [Online]. Available: https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/planer-og-analyser/lma/2021-06-30-lma-oppdatering.pdf

[85] European Commission, ‘EU Solar Energy Strategy’. May 18, 2022. [Online]. Available: https://eur-lex.europa.eu/resource.html?uri=cellar:516a902d-d7a0-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF

[86] ‘IMPLEMENTING THE REPOWER EU ACTION PLAN: INVESTMENT NEEDS, HYDROGEN ACCELERATOR AND ACHIEVING THE BIOMETHANE TARGETS’, European Commission, May 2022. [Online]. Available: https://energy.ec.europa.eu/implementing-repowereu-plan-swd_en

[87] É. Mata, A. Sasic Kalagasidis, and F. Johnsson, ‘Cost-effective retrofitting of Swedish residential buildings: effects of energy price developments and discount rates’, *Energy Efficiency*, vol. 8, no. 2, pp. 223–237, Apr. 2015, doi: 10.1007/s12053-014-9287-1.

[88] É. Mata, J. Ottosson, and J. Nilsson, ‘A review of flexibility of residential electricity demand as climate solution in four EU countries’, *Environ. Res. Lett.*, vol. 15, no. 7, p. 073001, Jul. 2020, doi: 10.1088/1748-9326/ab7950.

[89] E. Nyholm, S. Puranik, É. Mata, M. Odenberger, and F. Johnsson, ‘Demand response potential of electrical space heating in Swedish single-family dwellings’, *Building and Environment*, vol. 96, pp. 270–282, Feb. 2016, doi: 10.1016/j.buildenv.2015.11.019.

[90] V. M. Nik, E. Mata, A. Sasic Kalagasidis, and J.-L. Scartezzini, ‘Effective and robust energy retrofitting measures for future climatic conditions—Reduced heating demand of Swedish households’, *Energy and Buildings*, vol. 121, pp. 176–187, Jun. 2016, doi: 10.1016/j.enbuild.2016.03.044.

[91] J. Ewald, T. Sterner, E. Ó Broin, and É. Mata, ‘Saving energy in residential buildings: the role of energy pricing’, *Climatic Change*, vol. 167, no. 1–2, p. 18, Jul. 2021, doi: 10.1007/s10584-021-03164-3.

[92] V. M. Nik, E. Mata, and A. S. Kalagasidis, ‘Assessing the Efficiency and Robustness of the Retrofitted Building Envelope Against Climate change’, *Energy Procedia*, vol. 78, pp. 955–960, Nov. 2015, doi: 10.1016/j.egypro.2015.11.031.

A. Appendix

A1. Description of the ON-TIMES scenarios

Carbon Neutral Nordic (CNN)

Climate and energy policy
It develops according to the Nordic countries' national plans, strategies, and targets to reach carbon neutrality. The Nordic countries become climate neutral by 2050. Rest of Europe also see a strong cut in CO_2-emissions leading to approximately 80% reduction in emissions by 2050. The green transition in this scenario is driven by high CO2 prices equal to those applied in the Sustainable Development scenario of the IEA's World Energy Outlook 2020. This creates a need to transform the power system by applying renewable energy sources such as solar PV panels and wind turbines.

Technology
Decarbonisation of energy consumption will require fast actions in all sectors. The amount of renewable power and heat production must increase to provide clean energy to end-use sectors. BECCS will compensate some of the most expensive CO_2 emissions abatement options. Onshore wind development will be limited below the technical potential due to acceptability and land use issues.

In the Nordic countries we see a significant increase in the demand for PtX to decarbonise long-distance transport and industries. In the rest of Europe PtX demand is more modest reflecting a lower willingness to pay for GHG reductions.

Fuel / energy use
Nordic countries will increase electricity exports to Central Europe, but the amount will not increase much above current projections as electrification of Nordic heating, transport, and industry will require a large supply of low carbon electricity. Biomass imports from outside the Nordics will be limited to current or slightly higher levels to ensure sustainability of bioenergy use.

Nordic Powerhouse (NPH)

Climate and energy policy
All activities increase demand for electricity and/or other energy products.

Technology
In addition to their efforts to reduce Nordic emissions, the Nordic countries host larger number of data centres, produce more batteries, and manage to increase the exports of electricity, electro fuels, and carbon free steel and aluminium. The Nordic economy would benefit from the export of new products. The additional electricity and electro fuels would be produced by offshore wind hubs, continuing the lifetime of nuclear power plants, ground-based PV power plants, and by onshore wind, assuming high acceptance for onshore wind.

Fuel / energy use
The Nordic countries can provide cheaper clean energy than Central Europe and manage to host more low carbon services and industries and increase their exports of low carbon products and energy carriers. There would be more excess heat from industry and services that can be used in district heating generation.

Climate Neutral Behaviour (CNB)

Climate and energy policy

Strong political and citizen engagement. politicians and citizens adopt additional energy and material efficiency measures in all sectors that lead to lower energy demand. Focus of society is not on GDP but on sustainability, circular economy, and securing biodiversity.

Technology

A rapid decrease in costs of distributed energy generation and other low carbon technologies. decentralised generation technologies become much more common, and they further cut the energy delivered through grids and lead to prosumers and districts as energy suppliers.

Fuel / energy use

Energy demand for transport decrease due to modal changes, remote working, car sharing, and lower and more efficient heavy transport of goods.

A2. CO_2 prices used in the GENeSYS-MOD scenarios

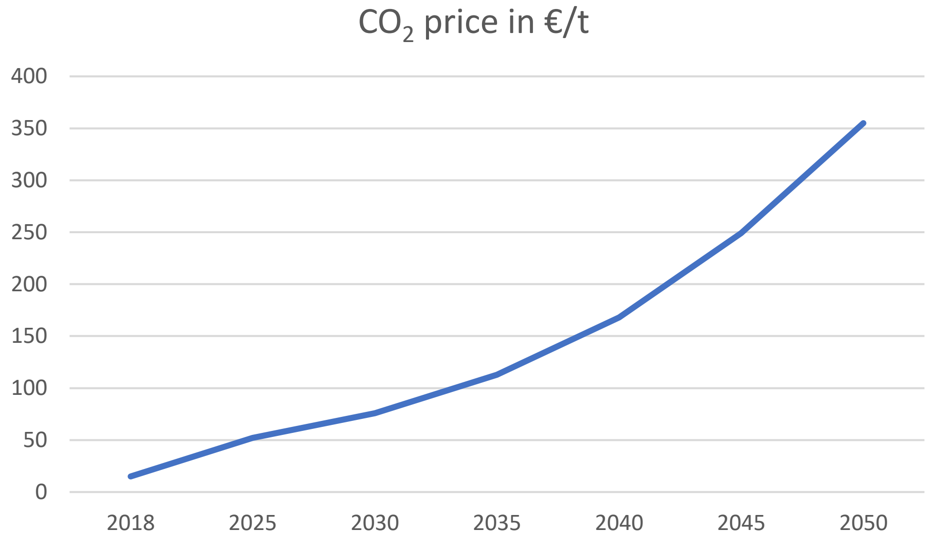


Fig A- 1: CO_2 price calibrated to ensure net-zero GHG emissions (energy-use and partly process) by 2050, emission budget is 2-degree scenario compatible.

A3. Communication with the Norwegian Ministry of Climate and Environment

"EU-landene skal I henhold til EUs styringssystem (Governance Regulation EU 2018/1999) levere National Energy and Climate Plans (NECPs). Denne rettsakten er ikke tatt inn i EØS-avtalen i sin helhet, og Norge er derfor ikke forpliktet til å utarbeide NECPs i tråd med reglene i forordningen. Med andre ord, Norge har ikke formelt sett en NECP. Da Norge inngitt den såkalte «klimaavtalen med EU» tok vi imidlertid inn enkelte bestemmelser fra EUs styringssystem som gjelder klimarapportering. I tillegg ble det enighet om at Norge og Island på frivillig grunnlag skulle vise hvordan vi vil nå forpliktelsene i regelverket for ikke-kvotepliktig utslipp (innsatsfordelingsforordningen) og regelverket for skog- og arealbruk (LULUCF-forordningen). Planen du viser til under var den planen forrige regjering sendte inn til ESA i desember 2019. Hva en slik frivillig plan skulle inneholde følger av en frivillig erklæring som er tatt inn i EØS-komitébeslutningen om «klimaavtalen med EU»: 269-2019.pdf (efta.int). Den forrige regjeringen la også i 2021 frem "Klimaplan for 2021-2030". ESA har laget en «progress report» for Norge og Island som også baserer seg på Norges rapportering på klimaavtalen, rapporten er tilgjengelig her: ESA Climate Progress Report 2021 Final version.pdf (eftasurv.int).

For å oppsummere: Norge leverer ikke en NECPs, men har på frivillig grunnlag levert en «plan» som skal vise hvordan Norge skal nå forpliktelsene i regelverket for ikke-kvotepliktige utslipp og skog- og arealbruk i 2019. Siden Norge ikke er formelt forpliktet til å levere en oppdatert plan, har ikke «Klimaplanen for 2021-2030» blitt levert som Norges nye plan, men ESA er orientert om at den finnes. I praksis vil ESA få informasjon om Norges klimapolitikk og fremgang mot våre forpliktelser gjennom klimarapporteringen som vi er forpliktet til å levere til ESA 15. mars annethvert år. "

A4. Buildings sector in ON-TIMES model

Fig A- 2 shows schematic representation of the buildings sector for area demand for the case of Sweden in the ON-TIMES model. Buildings' area demand has been represented in the same way for Denmark and Norway, but buildings' construction year may differ from the ones in Sweden. Fig A- 2 also illustrates that:

- all the buildings constructed before 2012 have the possibility for making energy saving measures corresponding to different cost levels.
- all the buildings have the possibility to invest in individual heat devices (e.g., heat pumps, boilers, etc.) if it is cost-effective from a system perspective.
- not all the buildings have the possibility to invest in a connection to district heating (i.e., a district heating substation)

The area demand projection for buildings (in Mm^2) for the case of Sweden, for instance, follows the methodology outlined in the Swedish Energy Agency (SEA) report[12]. From 2020, for the new buildings, the shares of single-family houses and apartments are assumed to be 42% and 58 %, respectively. For 2020-2025, the demand projection for new buildings is based on the forecast from the National Board of Housing, Building and Planning (Boverket)[13]. From 2026, the projection has been calculated by extracting population forecast from Statistics Sweden (SCB)[14]. Then, it is assumed that the average number of people per household remains unchanged while single-family houses and apartments have an area of 149 m^2 and 65 m^2, respectively.

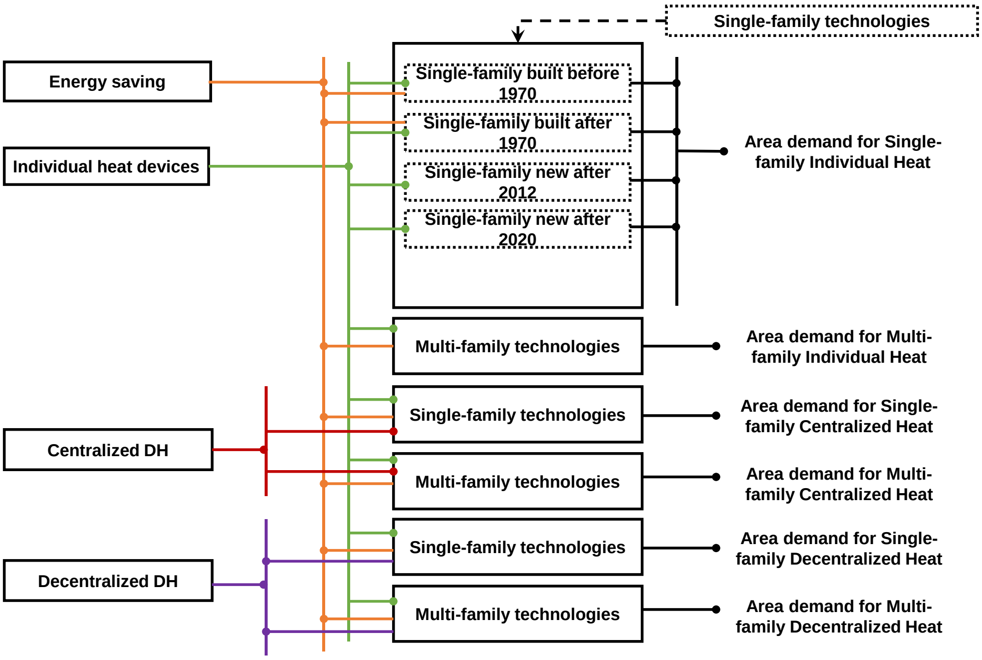


Fig A- 2: Schematic representation of the buildings sector (the case of Sweden) for heat demand in ON-TIMES.

---

[12] Swedish Energy Agency (2019) report, "Scenarier över Sveriges energisystem 2018" (ER 2019:07).

[13] Boverkets byggbehovsprognos

[14] https://www.scb.se/en/finding-statistics/statistics-by-subject-area/population/

Energy demand in new buildings is based on regulations from Boverket, in which the buildings were constructed before 2020 are based on "BBR22 from 1 July 2015" standards[15], whereas the ones built after 2020 are based on "Near zero energy buildings" standards[16].

Representation of appliances demand (per number of appliances for single-family and multi-family buildings) is shown in Fig A- 3 .

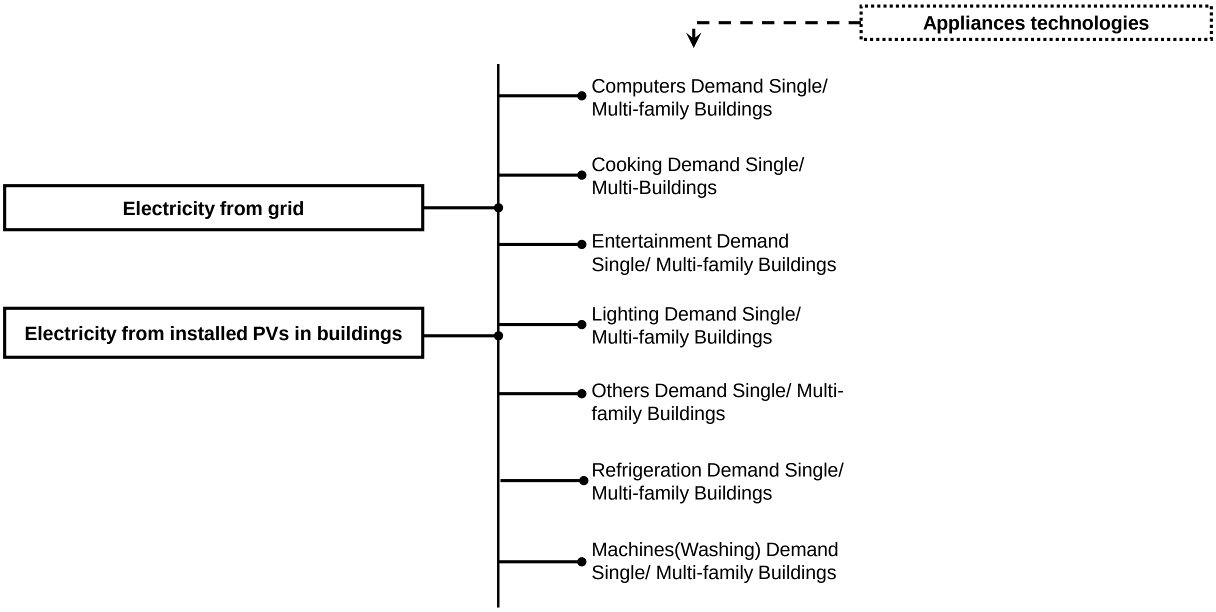


Fig A- 3: Schematic representation of the buildings sector for appliances demand in ON-TIMES.

---

[15] https://rinfo.boverket.se/BBR/PDF/BFS2015-3-BBR-22.pdf

[16] Förslag till svensk tillämpning för näranoll energibyggnader: http://www.boverket.se/sv/om-boverket/publicerat-av-boverket/publikationer/2015/forslag-till-svensk--tillampning-av-nara-nollenergibyggnader/

Table A- 1: Previous studies - measures studied, estimated potentials and conclusions. Whereas the scope of most of the compiled studies goes beyond electrification, the table shows only electrification measures when possible.

Ref	Country, sector	Measures	Estimated potentials	Main conclusion
Mata et al, 2014 [87]	Sweden, residential buildings	Twelve energy-saving measures	**Change in electricity demand** from installing heat recovery system: Single-family dwellings: Increase 0.7 TWh (3 kWh/m2) Multi-family dwellings: Decrease 0.25 TWh (1 kWh/m2)	«The most profitable measures identified for all the scenarios are application of energy-efficient lighting and appliances, reduction of the indoor temperature to 20 °C through improved control systems and installation of ventilation systems with heat recovery."
Mata et al, 2018 [36]	Five EU member states (UK, Sweden, Spain, Germany, France)	Ten energy conservation measures (ECM)	**Electricity demand reduction potential** from doubling efficiency of lighting and appliances: 6% - 7% **Energy savings from installing solar panels** for hot water production: 2% - 6%	«The modeling also indicates that the reduction in electricity demand linked to more-efficient lighting and appliances can be offset by the increased demand for space heating, as less heat is released to the indoor air.»
Mata et al, 2020 [88]	North/central Europe (France, Germany, Sweden, and UK) Building sector	Electric vehicles Heat pumps RES Appliances Storage heating	**Flexibility potentials** in residential electricity load Largest potential Germany (6%–29%) Lowest potential Sweden (1%–5%)	"flexibility for the total residential electricity load varied greatly among the countries investigated" "The literature identifies substantial economic, technical, and behavioural benefits from implementing flexibility measures."
Nyholm et al, 2015 [89]	Sweden, single-family dwellings	Shifting of the electric space-heating load in time, demand response (DR), for six different types of electrical heating systems.	**Electricity demand response potentials** Single-family dwellings: 7.3 GW	"The power available for DR in the heating system is found to be substantial (7.3 GW)." "…if large-scale DR of electric space heating is to be implemented other indicators than the day-ahead electricity price are needed given the current system."

Table A- 1 continued

Ref	Country, sector	Measures	Estimated potentials	Main conclusion
Mata et al, 2020 [31]	Gothenburg, Sweden Building sector (multifamily buildings)	Ventilation with heat recovery Lighting Appliances Hot water PV panels	**Energy-saving potential (by 2050)** Driven by technical renovation needs: Reduced energy demand of 85% Driven by cost-efficiency: Reduced energy demand of 15%.	"…current limitations of reaction capacity to implement these cost-effective measures would only allow a reduction in the energy demand by 4%–23% during the same period." "In both scenarios, workmanship capacity was more constraining than investment capacity…"
Nik et al, 2015 [90]	Three cities (Stockholm, Gothenburg, Lund), Sweden, residential buildings	Nine energy retrofitting measures	**Electricity demand for lighting and appliances** decrease with 50% by installing more efficient equipment	"Upgrading the ventilation system (N5 and 6) decreases the heating demand on the hourly scale between 6% to 12%. Not surprisingly, reductions in the power for lighting and appliances (N7, N8 and P3) increase the space heating demand due to less amount of heat that is dissipated from these sources…"
Mata et al, 2012 [32]	Sweden Residential building stock	Twelve energy saving measures (ESM)	**Electricity saving potentials** Upgrade of ventilation systems with heat recovery for single-family dwellings 3.5 TWh/yr Upgrade of ventilation systems with heat recovery for multi-family dwellings 1 TWh/yr Reduction by 50% of power for lighting 1,5 TWh/yr Reduction by 50% of power for appliances 4 TWh/yr Decrease of indoor air temperature to 20'C 4 TWh/yr	"It is shown that application of the selected ESMs has the potential to reduce the final energy demand of the Swedish residential sector by 53%." "The level of CO2 emissions from the Swedish building sector could be reduced by 63% by applying all the ESMs studied."

Table A- 1 continued

Ref	Country, sector	Measures	Estimated potentials	Main conclusion
Österbring et al, 2019 [34]	Gothenburg, Sweden Multi-family building stock	Eleven energy saving measures (ESM)	Energy savings reduction in GHG- emissions	"Results show possible energy savings of up to 23% and a corresponding 31% reduction in greenhouse-gas emissions." "Current trends in uptake of ESMs will have little effect in reaching targets for reductions in GHG emissions set by the municipality which would have to rely on reductions from other sectors."
Mata et al, 2019 [35]	Four cities in Sweden Residential buildings	Thirteen retrofitting measures	Energy saving potentials + Economic feasibility	"Although few measures appear as cost-effective in terms of either their energy saving or mitigation potentials, the Net Cost Conserved Energy values are generally rather low."
Ewald et al, 2021 [91]	European Union Residential	Changes in energy prices and income, effects on residential energy demand	Price elasticity Change in residential energy demand	"We find a long-run price elasticity of −0.5. The total long-run income elasticity is around 0.9, but if we control for the increase in income that goes towards larger homes and other factors, the income elasticity is 0.2. These findings have practical implications for climate policy and the EU buildings and energy policy framework."
Nik et al, 2015 [92]	Gothenburg, Sweden Residential building stock	Change in U-value of: *cellar/basement *facades *attics/roofs *replacement of windows	Decreased heating demand	"…, the uncertainties induced by different climate scenarios and different time periods (20-year periods) do not affect the relative performance of the considered retrofitting measures. Therefore it is possible to rely on one 20-year period and one climate scenario for assessing the relative performance of the retrofitting measures…"

Table A- 2: Scenarios in previous studies – aim and features.

Ref	Baseline/Final year	Aim	Scenario name and number of scenarios	Scenario narrative
Mata et al, 2020 [31]	2015/2050	Aims to * propose an improved method for building-specific stock modeling by incorporating the realities of building renovations * explore renovation scenarios for existing multifamily buildings * identify locally optimal renovation strategies and key determinants of the long-term deployment of renovation strategies	2 scenarios Scenario 1: end of lifetime Scenario 2: cost-efficiency	In the two scenarios renovation is driven by either technical renovation needs (the building components are updated at the end of their lifetimes, regardless of the cost-efficiency of the associated energy saving measure) or cost-efficiency (energy saving measures are implemented only if they are deemed cost-effective, with renovations occurring at the end of the lifetime of the building component renovated)
Nik et al, 2015 [92]	1961/2100	Assessing efficiency and robustness of retrofitting measures against climate change	Five climate scenarios RCA3 (regional climate model) 50 km horizontal resolution.	Retrofitted vs. non-retrofitted buildings compared in different climate futures
Mata et al, 2014 [53]	2010/2020, 2030, 2040, 2050	Explore how the cost-effectiveness of different energy-saving measures in buildings is dependent upon assumptions of energy prices and discount rates.	3 energy price development scenarios: 1.Baseline 2.High-price-increase 3.Low-price-increase	The scenarios are a description of possible future development of the energy system in terms of energy prices for the different energy carriers used in the buildings.

Table A- 2 continued

Ref	Baseline/Final year	Aim	Scenario name and number of scenarios	Scenario narrative
Nyholm et al, 2015 [74]	2012 (normal-price year)/ 2010 (high-price year)	Investigating the demand response potential, in terms of time frame for load shifting as well as capacity and energy of the shifted load, for electric space heating in Swedish SFDs through using the thermal inertia of the building stock. The study examines both how DR influences the electricity load curve and the magnitude of the economic benefit from the resulting reduction in the cost of electricity.	2 DR scenarios: 1.No DR occurs. 2.Optimization of DR by minimizing annual electricity cost.	Optimization of demand response shows potential monetary savings in load shifting. Comparison normal/high-price year shows the range of savings potential.
Mata et al, 2019 [28]	1961/2100	Assess the impact of input uncertainties on future climate scenarios in the evaluation of different retrofitting measures, particularly the (1) criteria potential for CO2 mitigation (2) economic feasibility	Five climate scenarios RCA3 (regional climate model) 50 km horizontal resolution.	Uncertainties related to future climate and the possible effect on evaluation of different retrofitting measures Comparison of uncertainties related to climate and other uncertainties such as geographical location and energy prices
Nik et al, 2015 [75]	1961/2100	Assessing the effectiveness and robustness of retrofitting measures for uncertain future climatic conditions of three cities in Sweden.	Five climate scenarios RCA3 (regional climate model) 50 km horizontal resolution.	Uncertainties related to future climate and the possible effect on evaluation of efficiency and robustness of different retrofitting measures.
Mata et al, 2012 [24]	2005/-	Assessing the effects of applying a set of energy saving measures to all residential buildings in Sweden.	2 scenarios comparison: 1. Baseline 2. Implementation of energy saving measures	Reduction of final energy demand of the Swedish residential sector by application of energy saving measures

Table A- 2 continued

Ref	Baseline/Final year	Aim	Scenario name and number of scenarios	Scenario narrative
Österbring et al, 2019 [27]	2015/2050	Explore the environmental impact of future development of an urban housing stock	Two types of dynamic scenarios	Renovation logic (end of life, cost-efficiency) effects on potential in energy savings and reduction in greenhouse-gas emissions
Ewald et al, 2021 [77]	1990/2018	Examine the importance of changes in energy prices and income on residential energy demand	Varying energy price	Different economic determinants of energy demand for future modelling and policymaking.
Mata et al, 2020 [72]		Assessing how digitalization of the grid edge contribute to climate mitigation from residential buildings	3 scenarios for carbon intensity of electricity C1, C2 and C3	Scenarios for carbon intensity of electricity influencing potential reduction in CO2 emissions from load shifting
Mata et al, 2018 [29]	2009-2012/2030, 2035, 2050	Primary aim is to provide homogenous mapping of the potential for energy savings in EU buildings.	Review with multiple scenarios For each member state: Reference Implementation of ECMs	Multiple narratives
Camarasa et al, 2022 [76]	2020/2050	Share insights from national building sector models to describe carbon mitigation scenarios by 2050 and compare them to results from global models in line with 1.5°C–2°C scenario goals	Multiple scenarios created for regions and countries 1.Reference scenario 2.Decarbonization scenario	Multiple narratives

A5. Modelling results for different justice principles

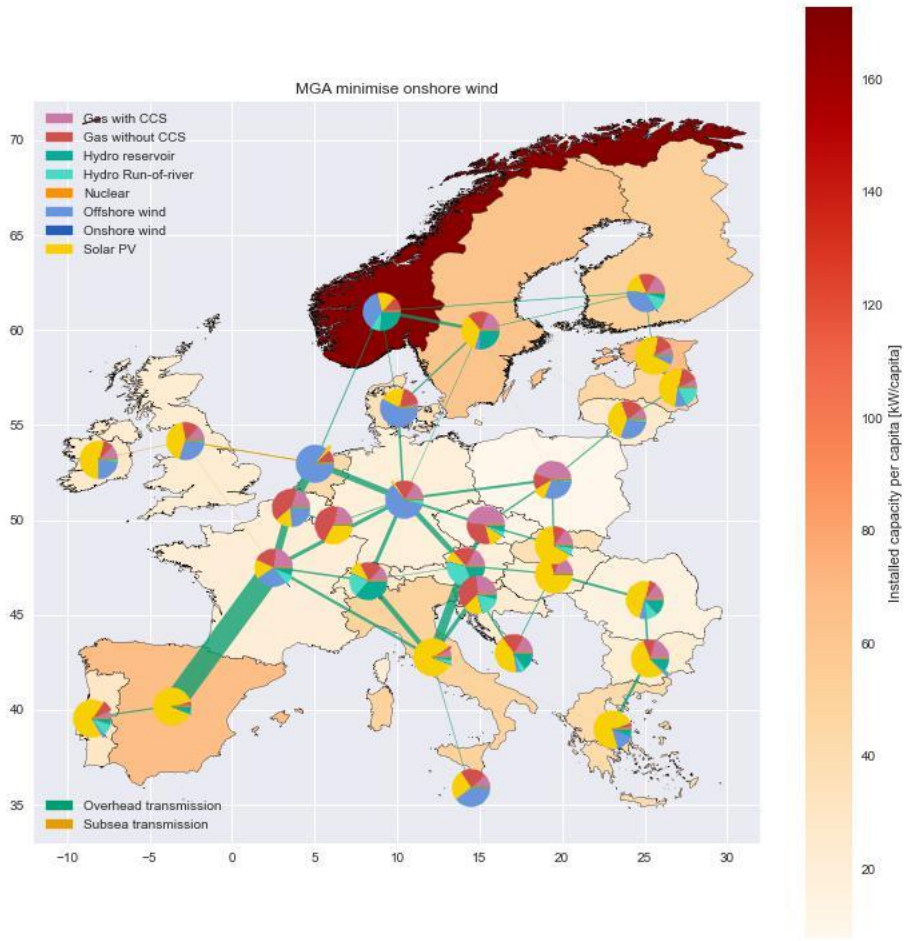


Fig A- 4: MGA scenario with the least distributional inequality when defined as installed capacity per capita

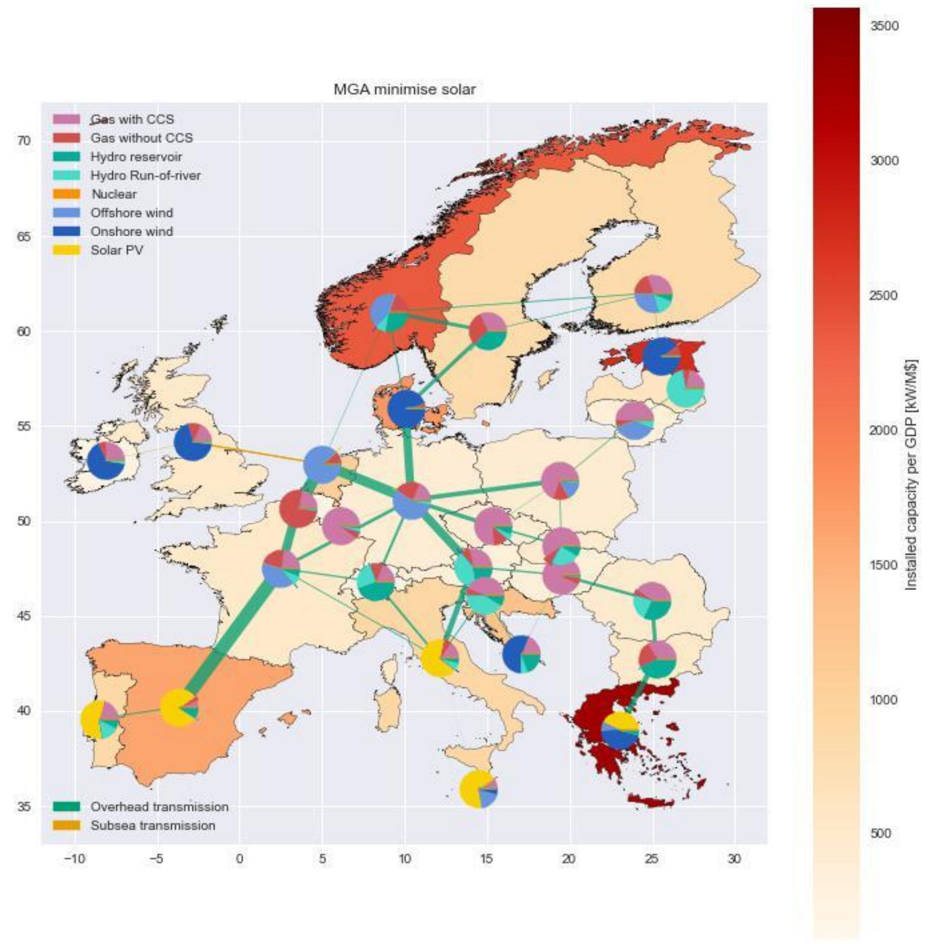


Fig A- 5: MGA scenario with the least distributional inequality when defined as installed capacity per GDP