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The REPowerEU policy's impact on the Nordic power system

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ABSTRACT

Energy system models provide us with scenarios for the future energy system, supporting our understanding of the impact of societal changes and adopted policies. To front-load the EU'Fit for 55' package for 2030 and targets of replacing imported natural gas with renewable electricity, the Nordic countries could contribute by exporting additional electricity to mainland Europe. This paper describes a comparative study including five energy system models – GENeSYS-MOD, ON-TIMES, IFE-TIMES-Norway, highRES, and IntERACT, exploring two decarbonisation scenarios leading up to 2050. The scenarios involved simulating an additional 30 TWh electricity export requirement from 2030. Key findings include Denmark and Norway emerging as major net exporters, with Denmark covering over 60% of the additional export. The models predict that 76%–82% of the new electricity production will come from wind power, split between onshore and offshore installations, highlighting significant investment requirements. These results underscore the Nordic countries' capacity to support the EU's renewable energy targets, with wind power being pivotal. This research offers a broad overview over different modelling tools and their behaviour and provides critical insights for policymakers, stressing the need for coordinated Nordic efforts to maximise the benefits of increased electricity exports while ensuring energy system stability and cost-efficiency.

1. Introduction

1.1. Motivation and background

The energy trilemma describes the difficulty of balancing energy affordability, sustainability and reliability. In the European energy markets, this has been challenged in the last couple of years. Starting with a raise in the prices for natural gas on the world market in 2021 as the economies were recovering after COVID-19, energy prices overall were high even before the war in Ukraine. The European market and the development of European electricity prices before the war in Ukraine are explained in [1]. After the Russian invasion of Ukraine in 2022, the European Commission proposed the REPowerEU policy package [2] to make Europe independent of Russian fuels before 2030: To achieve this, the import of large quantities of natural gas from Russia should be replaced by imports of liquefied natural gas (LNG) from other countries, but also by front-loading the existing Fit for 55 [3] renewable targets for 2030, aiming at a net-zero emissions society in 2050. To replace a large quantity of natural gas with power made from renewable energy sources before 2030, the renewable power production and transmission capacities must be expanded, with implications for all of Europe including the Nordic countries. While the final energy consumption in the Nordic area is around 10% of the total for EU, the corresponding inland consumption of natural gas is less than 2% [4,5]. A common European effort to substitute consumption of imported natural gas from Russia by front-loading renewable targets could therefore lead to increased electricity export from the Nordic area. A share of the new renewable power in the Nordic area could be supplied to areas where natural gas consumption needs to be phased out.

To analyse an energy system transition, energy system models are typically used to assess different storylines for future development of national and European energy systems. These storylines are parameterised to deliver quantified pathways, as e.g. in [6–12]. In [6], four socio-technical transition pathways for Norway have been developed based on varying degrees of change in socio-institutional and

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List of Acronyms

BEV	battery electric vehicle
CGE	computable general equilibrium
GHG	greenhouse gas
LNG	liquefied natural gas
NECP	National Energy and Climate Plan
NPV	net present value
PV	photovoltaic
RES	renewable energy sources

technological dimensions. The scenarios are evaluated through both a techno-economic model (IFE-TIMES-Norway) and a computable general equilibrium (CGE) model to provide insights on the development of the energy system and the economy. Similarly, the so-called Nordic Clean Energy Scenarios [7] mapped actions up to 2030 to reach carbon neutrality in the Nordic countries, through scenarios assessed using two energy system models, ON-TIMES and BALMOREL. The Open ENTRANCE project [8] assessed four low-carbon transition pathways of the European energy system, among others with the open source energy system model GENeSYS-MOD, primarily implemented through differences prices and their respective developments. While the scenarios agree in showing a decrease in primary energy use, further electrification of the energy system in several sectors, a slight increase of hydro-power generation and an increase of wind as well as photovoltaic (PV) generation up to 2050, the scenarios show quite different shares of wind (onshore and offshore) and PV. However, the study provides no insights for the Nordic countries (only at European level) nor on the electricity imports/exports between European regions. The pathways in the study, three of which comply with the (European fraction of the) 1.5 °C global temperature increase limit and a fourth one approaches the 2.0 °C limit, focus then on global climate goals. In that sense, by combining results from the same model and scenarios with a review of European energy transition scenarios, [9] focuses on realising the European Green Deal that aims to achieve 100% greenhouse gas (GHG) reductions by 2050. Three national scenarios for Sweden, so-called NEPP:s, are presented in [10] in which three modelling tools were used for the analysis; the energy system model TIMES-NORDIC, and two power system simulation models EPOD and Apollo. [11] integrates building stock energy models for 32 countries to create reference and decarbonisation scenarios by 2050, then comparing the scenarios with those from global models. The analysis concludes that the aggregation of national models complements assessments made by global models, providing a more detailed overview based on the incorporation of specific national/regional contexts, including building stock characteristics and socioeconomic trends. E.g., the comparison allows to identify that, to align with 1.5 °C scenarios, the national decarbonisation strategies are required to increase current annual renovation rates to a total of 2.4%, and to increase the share of electrification of buildings' final energy consumption by 4%–14% to an average of around 50% in all regions, to increase the share of renewable energy sources (RES) in the energy mix by 3%–30% to a global share of around 70%, and to decrease the carbon intensity of electricity production by 4–6 times (to at least below 40 g CO_2/kWh globally). [12] clarifies similarities and differences in approaches and results in terms of technological potential and competitiveness, by reviewing studies on global energy–economy modelling, nevertheless with focus on transport biofuels.

Similar resilience assessments, where variations of a reference scenario are compared, are presented in the literature using other models of the energy system or parts of it, on differently focused scenarios: In [13], the authors study the effect of H_2 electrification in combination with re-use and retrofitting of the existing natural gas transportation network in an effort to reduce CO_2 emissions. The study shows that hydrogen plays a significant role in the decarbonisation of the European power system while offering a much-needed flexibility when the share of variable RES increases. Hydrogen and other Power-to-X fuels and their use for transportation are also studied in [14], in addition to the impact of various degrees of hydrogen infrastructure on the energy system, including hydrogen storage. The study contributes to confirming the link between variable RES and storage, in this case producing the renewable fuels, and states that hydrogen infrastructure increases competitiveness but adds to the total system costs. A similar comparison was conducted in [15], comparing energy system modelling scenarios that focus on solar energy like PV and concentrated solar power in an arid climate. This study concluded that a sufficiently high natural gas price would trigger renewable-based investment plans for electricity generation, and that an increased CO_2 tax would contribute to the same goals.

This study investigates potential pathways for the Nordic countries in which additional electricity export is to be supplied to the remainder of Europe by 2030. The study also contributes to the existing literature by comparing results of different energy system models, with varying geographical, temporal and sectoral resolutions. Such comparisons offer important insights into the robustness of proposed developments, highlight potential trade-offs and identify the most resilient and sustainable ways for the Nordic countries to help Europe in achieving Russian independence. Different geographical scopes of models in a study provide insight in the challenges of optimising for national vs. regional energy system development. Different energy system models will, however, provide different solutions for the energy transition pathways. There are many reasons for this, which involve both the (mathematical) model framework and the corresponding data: The model can be a general model, able to capture spillover effects between markets, or a partial model formulation that typically allows for more details to be included. The temporal and spatial resolutions are important: Models with fine temporal and spatial resolution can capture time-dynamics and impacts of the geographical location of infrastructure. Another difference can be included mechanisms and assumptions: Many assumptions or premises are implicitly included in model frameworks. For instance, system optimisation models takes as a premise that markets are well-functioning (no market power, rational optimising agents, etc.). The different data-sources of the models, typically supplied with some own case-specific estimates, also causes differences in results. Finally, the scenario building is important. In any given study, there are many technical and political aspects that could either be included or left out. Due to differences between models, comparative studies can give insights into which findings are robust, and which results will vary considerably between different models. In addition, differences in the results can give insights into strengths and limitations for each of the models [16,17]. Other studies have also compared assessments of regional and national energy system scenarios: For example, [18,19] assessed the impacts of policy measures in North America using multi-model comparison, while [20] compares decarbonisation pathways of Europe until 2050 for five power market models. On a national level, [21] compares four high resolution power system models with different technology modelling approaches for the German power supply system in 2050, while [22] assesses the impact of high RES penetration across different energy system models for the United States. Lastly, [17,23] review comparison methods of energy system models, highlighting the importance of comparing energy system frameworks and models that consider sector-coupling.

However, as summarised in Table A.1, these studies – comparative or not – were performed in an energy landscape where Russia provided Europe with a high share of natural gas [24], and most do not have a Nordic scope. To provide solid results on the implications of the REPowerEU package for Nordic regions, storylines must be altered to accommodate the independence from Russian fossil fuels until 2030, including a comparative modelling exercise to gather insights from fully utilising the capacities of different models on the complex question. [1] raises the question of the affordability of an independence from Russian fossil fuels, which triggers the question of what impact the REPowerEU policy has on the total energy system costs.

1.2. Aim and scope

This study's central research question is: *How will a new constraint to ensure 30 TWh additional electricity export from the Nordic area from 2030 impact the Nordic electricity system; which overall findings are shared between the models, and where do models deviate?* As means to answer the main research question, and taking net-zero 2050 pathways for a set of models as a starting point, a set of sub questions are formulated:

1. How will the extra 30 TWh of exports from the Nordic area be allocated among the Nordic countries?
2. Which additional investments are carried out to provide the extra exports?
3. How are electricity balances for each country impacted?
4. How is the additional energy system cost of the extra constraint distributed between the Nordic countries?

The possible conflicts and synergies of the two goals, reducing climate gas emissions in the Nordic area and exporting extra electricity to Europe to reduce the dependency of imported natural gas, are analysed. For example, the level of electrification in the Nordic area may differ when the two goals are to be achieved simultaneously. Section 2 describes the methodology, with an overview of the models included in the comparative study in Section 2.1, and a description of the two scenarios used to analyse the impact of the additional export in Section 2.2. Results from the comparative study are portrayed in Section 3, whereas Section 3.3 discusses the relevance of the findings for the ongoing updates to the National Energy and Climate Plans (NECPs). Concluding remarks, key takeaways from the study and suggestions to future research are included in Section 5.

This paper adds important knowledge to the pre-existing literature, first by presenting new scenarios of increased electricity export in the Nordic countries obtained from five established energy system models, second by offering a comprehensive comparative analysis of the insights from the models while focusing on important issues of the European low-carbon transition. The comparative approach highlights robust findings across the different models, enhancing the reliability and applicability of the results for policy-making and strategic planning in the context of the EU's ambitious renewable energy goals. The work also stands out by quantifying the implications of increased interregional electricity trade and providing actionable recommendations for the Nordic countries' NECPs.

2. Methodology

2.1. Model comparison

Modelling exercises and associated results are sensitive to the input data used, but also to methodological approaches. Computational limitations constrain the level of complexity possible to include in a model. Decision such as choice of temporal resolution as well as geographical and sectoral focus [25] influence how well a model is able to capture different aspects of the energy system. For example, a model with high spatio-temporal resolution better represent the intermittency of variable renewable energy technologies and the how meteorological conditions vary across space. Similarly, models that do multi-stage/pathway optimisation consider existing infrastructure and inertia within the system (e.g. through build-out rates) while overnight/snapshot greenfield optimisations only consider the system at its end-state. In order to acquire results that are robust and consistent under a wider set of assumptions and methodological approaches, we apply a multi-model comparison approach in this work.

The model comparison is conducted by defining common scenarios, aligning the input data between the models where possible, and comparing the model results from the scenarios, e.g. [11,16,21]. In total, five different models are included, of which three are general energy system models; GENeSYS-MOD, ON-TIMES and IFE-TIMES-Norway, that aim to include demand and supply for all relevant energy carriers, sectors, and technologies. highRES is a domain-specific model that has the narrower focus of the electricity market and is therefore able to include a more detailed representation of the spatio-temporal sensitivity of variable renewables. IntERACT combines macroeconomic relationships with a description of the Danish energy system. ON-TIMES, IFE-TIMES-Norway and IntERACT rely on the TIMES model generator [26]. All five models are described further in Appendix B, and their spatial resolution is shown in Fig. 1. Although the power market is the focus of this paper, the general energy system analyses capture the effects in the whole energy system. While comparing the results across five different energy system models allows us to identify agreement and disagreement, it is important to acknowledge that the models only represent a small share of the different model structures one could utilise in such an exercise.

2.2. Scenarios

This paper compares the results from different models for the same scenarios, and the change in model results from one scenario to the next. The two scenarios that are analysed are:

- Scenario 1: Net-Zero emissions by 2050
- Scenario 2: Net-zero emissions by 2050 + 30 TWh additional electricity export from the Nordic area from 2030 and onwards, relative to Scenario 1

Scenario 1 is a decarbonisation scenario that assumes net-zero greenhouse gas emissions for each Nordic country in 2050. The scenario assumptions for Scenario 1 for all models are based on previous work, i.e. the Open ENTRANCE scenarios for GENeSYS-MOD [27], the NTRANS scenarios for IFE-TIMES-Norway [6], from [28] for IntERACT and from [7] for ON-TIMES. Table C.1 shows some of the key inputs to each of the models for the base case in 2050. Scenario 2, key novelty of this paper, is inspired by the REPowerEU plan and implemented with a constraint for extra electricity exports from the Nordic countries. The results focus on the electricity market. The electricity market is central for decarbonisation, which typically relies heavily on extra renewable power generation, electrification of demand sectors, and production of hydrogen and other zero emission fuels from electricity to substitute fossil fuels in sectors where electrification of demand is difficult. Iceland and the Faroe islands are a part of the Nordic region, but are not included in this study due to their remoteness and lack of integration with the rest of the Nordic and European electricity system. The size of the additional electricity export was chosen to create a feasible scenario, while still making the requirement binding in 2030. The net export volumes reached by 2030 in Scenario 2 is defined as the minimum level of export from the Nordics countries for the following years, i.e., it will never reach a level below this value. Since some of the models are country-specific, the 30 TWh are allocated to different Nordic countries, as shown in Table 1. The value is lower for Sweden than for Denmark and Norway due to existing bottlenecks with North–South transmission, and as Norway is usually a net-exporter already. IntERACT did not deliver results for the second scenario and will therefore not contribute to the comparison between the two scenarios.

3. Results

3.1. Nordic perspective

Model simulation results for the Nordic countries combined for Scenario 1 are shown in Table D.1, for 2050. Table D.2 shows the change in model results from Scenario 1 to Scenario 2 for the Nordic countries combined, for chosen key variables. The tables contain resulting primary energy demand and the electricity thereof, electricity

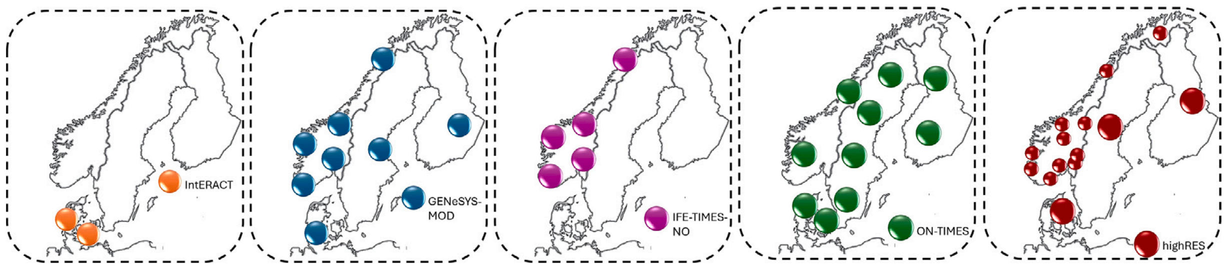


Fig. 1. Spatial resolution for the Nordic countries of the considered models: Some countries are represented by only one node in one model and with several nodes in other models.

Table 1
Constraints for net electricity export, 2030 onwards. TIMES-NO uses only the constraint for Norway, GENeSYS-MOD and ON-TIMES use the constraint for the total Nordic countries and highRES uses the country-wise constraints.

Scenario	Sweden	Denmark	Norway	Finland	Nordic*
1	No constraint	No constraint	No constraint	No constraint	No constraint
2	+5 TWh relative to base case year 2030	+10 TWh relative to base case year 2030	+10 TWh relative to base case year 2030	+5 TWh relative to base case year 2030	+30 TWh relative to base case year 2030

production and export, and the change in energy system costs between the two scenarios for Table D.2. The results from GENeSYS-MOD show that 30 additional TWh/year export from the Nordic countries lead to an increase in power production by 30 TWh/year, while the power demand is kept constant, signalising that the entirety of the additional export comes from a ramp up in new capacities and prolongation of the existing fossil power plant fleet. This is most apparent in the coal power plants, which provide an additional 5 TWh compared to the base case, since the renewable build-up is unable to provide the entirety of the added export. The export constraint in GENeSYS-MOD is binding from 2030 to 2045, but not for 2050. This reflects that the net export from the Nordic countries would increase towards 2050 for both scenarios, but the additional constraint causes the increase to initiate earlier. This also indicates that the extra export made in 2030 facilitates a new way to reach the decarbonisation goals for 2050, compared to the pathway found in Scenario 1. However, the large increase in export occurs whenever a constraint becomes binding: either reaching net-zero by 2050 or exporting 30 TWh additionally from the Nordic countries by 2030. For highRES too, the additional export is covered in its entirety by an increase in production, as the demand is an exogenous input. The change in energy system costs between the scenarios is in the same order of magnitude for ON-TIMES, GENeSYS-MOD and highRES. The ON-TIMES model results illustrate that electricity demand decreases by 12.5 TWh/year in total in the Nordic countries, of which 4.7 TWh are from the industry sector. This can be explained by the fact that trade between the Nordic countries is not limited to electricity, but also includes biomass, fossil fuels, hydrogen, etc. As an extra electricity export is required, intra-Nordic energy trade could cause some of the energy demand to be met by other energy sources.

3.2. Insights by country

The electricity production and the electricity used to produce other energy carriers domestically for each country in Scenario 1 for the start year, 2030, 2040 and 2050 are shown in Figs. 2 and 3, respectively. IFE-TIMES-NO shows the highest production numbers for Norway, higher than the total electricity consumption. This reflects the high electricity exports shown in Table D.3. HighRES shows a higher production 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. Results from GENeSYS-MOD indicate a 2–3 times higher Danish power production in 2050 than the Danish model InterACT, but both models expect that the production will mainly come from offshore wind. GENeSYS-MOD predicts that Denmark will use more than 100 TWh for production of other energy carriers like hydrogen through electrolysis in 2050, intended for export. Production of hydrogen or other Power-to-X is not seen in the same order of magnitude by any of the other models. IFE-TIMES-Norway expects a higher electricity production in Norway in 2050 than all other models: Although the model expects about the same hydropower production as GENeSYS-MOD and ON-TIMES, the value for wind production calculated by IFE-TIMES-Norway is about 3 times as high as the values for the other two models. However, the model also expects a higher electricity demand than GENeSYS-MOD and ON-TIMES for Norway.

The model results for the Nordic countries separately for Scenario 1 are shown in Table D.3, for 2050. The change in model simulation results from Scenario 1 to Scenario 2 for the Nordic countries separately for 2030 are shown in Table D.4. GENeSYS-MOD has an additional increase in power production from gas and coal of 5.6 TWh/yr in Sweden, Finland and Denmark. ON-TIMES, GENeSYS-MOD and highRES calculate an increase of 28 TWh/year, 19.2 TWh/year and 8.4 TWh/year, respectively, in net electricity export from Denmark due to the increased export constraint. ON-TIMES and GENeSYS-MOD expect the largest increase in electricity export to be covered by increased production in Denmark (61% and 62.5%, respectively, of the total increase for the Nordic countries), mainly from onshore and offshore wind and followed by a corresponding increase in energy system costs for Denmark (453% and 59.2%, respectively, of the total increase for the Nordic countries). As the production in Denmark for Scenario 1 is predicted to be low for 2030 for both models (about 50 TWh/year or lower), the increase is proportionally large. The expected increase in electricity production in Norway predicted by IFE-TIMES-Norway for 2030 is less than 5%.

HighRES shows the highest increase in electricity production for Norway (33.7% of the total increase for the Nordic countries, mainly from hydropower production), however, the increase in energy system costs is higher for Denmark (50.1% of the total increase for the Nordic countries). IFE-TIMES-Norway shows approximately the same increase in net electricity export from Norway as highRES does, but estimates that it will be covered by an increase in rooftop PV power production. The net export from IFE-TIMES-Norway is solely provided to Europe excluding the Nordic countries, meaning that the additional 10 TWh cannot be fulfilled by increasing imports or reducing exports from/to Sweden, Denmark or Finland. The long-term impact on the Norwegian energy system is close to negligible, as Norway initially reaches

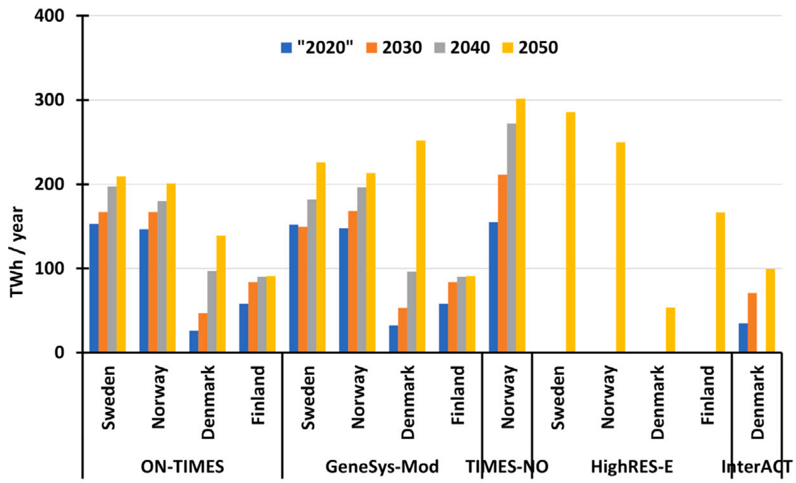


Fig. 2. Electricity production for Scenario 1: Net-Zero emission in 2050, for the start year(“2020”), for 2030, 2040 and 2050.

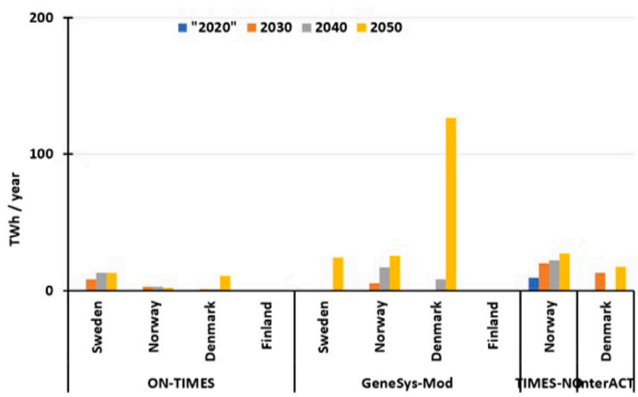


Fig. 3. Electricity used to produce other energy carriers domestically for Scenario 1: Net-Zero emission in 2050, for the start year(“2020”), for 2030, 2040 and 2050.

large net export volumes already from 2035. Consequently, for IFE-TIMES-Norway, the constraint of additional 10 TWh net export is only binding in 2030, leading to an accelerated investment in renewable capacity. The additional cost of enforcing the net export constraint for the Norwegian energy system is moderate, corresponding to 0.05% of total system costs. Due to the uncertainty in future development of European electricity prices, sensitivity was performed with two price sets, one with lower and more stable prices and one with higher and more volatile prices. With lower electricity prices in Europe, Norway becomes a net importer (6 TWh) in 2030 with significantly lower offshore wind investments. Enforcing an additional 10 TWh of export by 2050 leads to an increase in system cost of 12 b€ compared to the high price scenario, clearly underlining the importance of the European energy system on the development of the Norwegian energy system. None of the models expect Finland to be the main contributor to an increased power export from the Nordic countries, except for highRES, which, with its country-specific export constraint, expects Finland to cover 18% of the increased export, mainly from offshore wind and utility PV power production.

3.3. Impacts of the additional electricity export

Based on these numerical results, we can answer the research questions formulated in Section 1.2 and describe the impact of an additional 30 TWh electricity export requirement from the Nordic area, from 2030 onwards, on the Nordic electricity system.

3.3.1. How will the extra 30 TWh electricity export be allocated among the Nordic countries?

ON-TIMES and GENeSYS-MOD optimise the distribution of the additional electricity export among the Nordic countries, whereas highRES and IFE-TIMES-Norway used country-wise constraints specified in Table 1. Both ON-TIMES and GENeSYS-MOD choose to let Denmark cover more than 60% of the increased export, see Fig. 4. ON-TIMES expects only 5% and GENeSYS-MOD expects 11% to be covered by Norwegian power production. None of the models expect Finland to contribute much to the increased export. Indeed, GENeSYS-MOD expects Finland to be a net importer of electricity. ON-TIMES expects Sweden to cover 31% of the increased electricity export and GENeSYS-MOD expects Sweden to cover 26% of the increased export.

3.3.2. Which additional investments are carried out to provide the extra exports?

The distribution on energy sources of the additional investments carried out to provide the extra electricity export is shown in Fig. 6. For comparison, Fig. 5 shows the distribution on energy sources of additional production needed in 2050 to met the net-zero objective for Scenario 1. ON-TIMES and GENeSYS-MOD expect that 76% and 82% of the additional new electricity production in the Nordic countries should come from wind power production, with more onshore wind for ON-TIMES and more offshore wind for GENeSYS-MOD. Also HighRES expects a high share of wind production, though not as dominating as the other two models. The investment cost of onshore wind power for GENeSYS-MOD reflects a low societal acceptance and thus a high implementation cost, which leads to an increased investment in offshore wind power plants. In comparative studies in the literature, solar PV [1] or solar PV and wind power [13,14] are favoured for additional capacity expansion and production. HighRES expects that most of the additional power will come from additional hydropower investments and that the second highest investment is onshore wind power production (42% and 31%, respectively, of the additional new electricity production).

3.3.3. How are the electricity balances for each country impacted?

In addition to investments to provide extra exports, some models estimate a reduction in demand that enables electricity for export. HighRES assumes that the demand is constant for both scenarios. For the Nordic countries combined, ON-TIMES estimates a reduction in electricity demand that constitutes 27% of the additional net electricity export. This reduction happens mainly in Sweden and Denmark (58% and 40%, respectively, of the demand reduction). GENeSYS-MOD estimates a net constant electricity demand between the two scenarios, although Finland increases their electricity demand and Norway and Denmark reduces their electricity demand slightly.

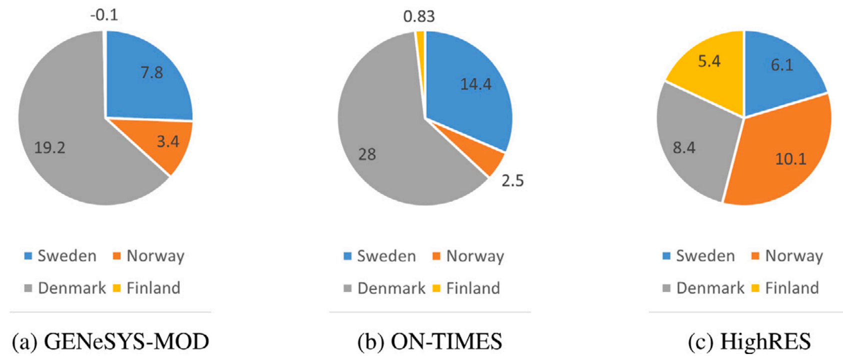


Fig. 4. Increase of net electricity export from Scenario 1 to Scenario 2 in TWh/year: Distribution on countries.

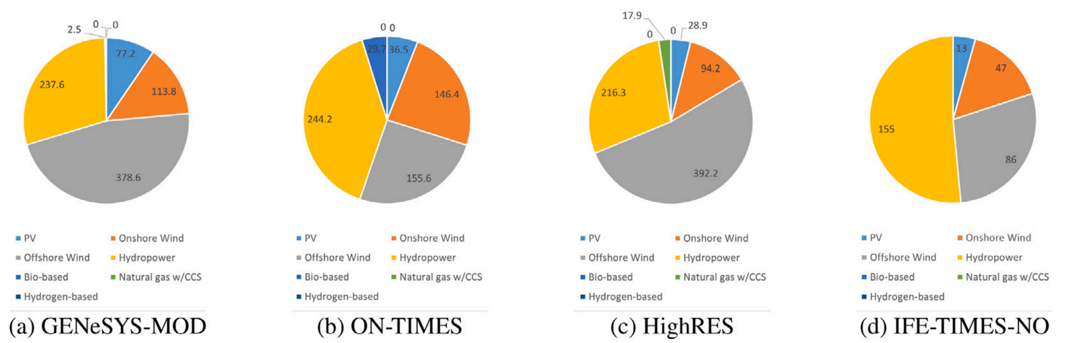


Fig. 5. Energy production in 2050 for Scenario 1: Distribution on technologies, in TWh/year.

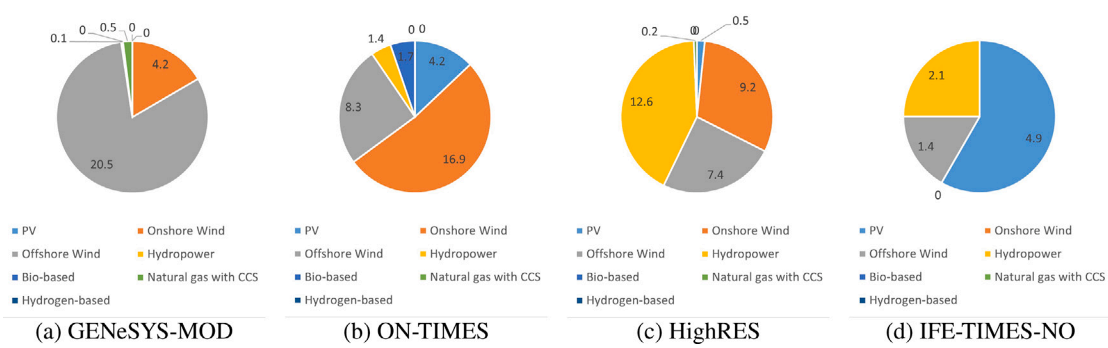


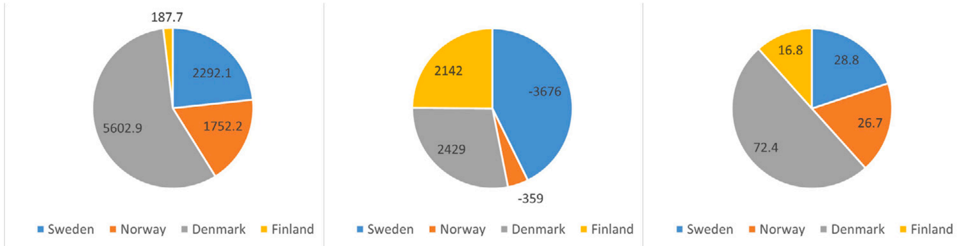
Fig. 6. Change in production in 2030 between Scenario 1 and 2: Distribution on technologies, in TWh/year.

3.3.4. How is the additional energy system cost of the extra constraint distributed between the Nordic countries

The distributions of additional energy system costs on the Nordic countries for GENeSYS-MOD, ON-TIMES and HighRES are shown in Fig. 7. In Scenario 2, all models indicate a net increase in total energy system costs compared to Scenario 1. Notably, ON-TIMES estimates that the costs for Sweden are drastically reduced, while Denmark and Finland holds the additional costs. On the other side, GENeSYS-MOD assigns the highest cost to Denmark which is the largest contributor to the additional export volumes. This aligns with the findings in [14], where hydrogen export must be compensated by a sufficiently high hydrogen price to avoid an increase in energy system costs. On an overall Nordic level, the additional system costs from ON-TIMES are only 6% of that projected by GENeSYS-MOD. Nevertheless, it is worth noting that the assumptions change for the ON-TIMES model between the two scenarios which can explain the small change in costs. The costs from highRES are limited to one year, making direct comparison challenging, but it provides a similar geographical distribution as the costs from GENeSYS-MOD: Highest costs for the Danish energy system, lowest for Finland and medium-sized costs for Sweden and Norway. Due to the differences between the models, it is difficult to provide a clear answer to this research question, however it is possible to draw the conclusion that the additional requirement on the energy system leads to higher energy system costs. Moreover, the distribution of costs differ depending on whether optimisation is performed separately for each country or jointly at a Nordic level. The most comparable cost numbers are between GENeSYS-MOD and ON-TIMES. The higher costs for on-shore wind-power in GENeSYS-MOD shows the considerable impact of the availability of that resource.

3.3.5. Case study of increased electricity export to mainland Europe from Norway

While the other models optimise the system from a Nordic perspective, the IFE-TIMES-Norway model focuses on the role of Norway in providing additional electricity export to Europe. For the country specific development perspective, new electricity investments to provide additional exports from Norway will be covered mainly by rooftop PV and hydropower (58% and 25%, respectively, of the additional new electricity production). Notably, the potential for onshore wind investments is maximised for both scenarios as this is considered the cheapest



(a) GENeSYS-MOD (b) ON-TIMES (c) HighRES

Fig. 7. Additional energy system cost in M€: Distribution on Nordic countries.

generation technology. Moreover, the additional export volumes are mainly enabled through increased production rather than reduced consumption, in which electricity demand decreases by 1.6 TWh. This constitutes 16% of the additional net electricity export from Norway. These results differ from that of the Nordic models, emphasising the impact of having country-wise models versus Nordic models, and the importance of different data and assumptions as discussed.

The additional export restriction only induce a minor increase in total costs for the Norwegian energy system. In comparison to GeneSYS-MOD, the additional cost is only 5% of the estimated cost for Norway from a Nordic perspective. This difference is likely due to the constraint's binding nature, which only takes effect in 2030 for IFE-TIMES-NO, whereas it generates longer impacts in GENeSYS-MOD.

4. Discussion and policy implications

Analysing the energy system with an energy system model is an approach that can be used in regional, national or overarching planning of an energy system, as the models reveal a pathway to a future that can be described mathematically. In this section we discuss the implication of our results for policy making, and in particular, how well these new pathways are aligned with the National Energy and Climate Plans. The NECPs are part of the governance regulation of EU's *Clean energy for all Europeans* package [29], and shall ensure the fulfilment of the long-term objectives and targets of EUs energy union, in line with the Paris Agreement and the clean energy transition. The NECPs were originally made for the period 2020–2031, but are due to be updated every other year, starting with a draft version that has been delivered by many member states in 2023 and a final version due in June 2024. The updates are intended to account for significant changing circumstances that have occurred since the initial submission to the EU by the end of 2019. It reflects the need for stocktaking, as both EU targets and many national policies may have been amended since then, including the introduction of the REPowerEU plan. As Norway is not a member of the EU, it is not required to deliver any NECP. However, a comprehensive climate plan for Norway for the period between 2021–2030 was issued in 2021 [30]. The energy and climate plans consider the plans and situation in each country. However, looking at several countries in one region could generate cost reduction or easier implementable solutions. For the electricity sector, the Nordic countries have a long tradition for cooperation. Today, the EU is an important arena for European cooperation within the electricity system, e.g. through ENTSO-E.

In that sense, the results show that the Nordic countries 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 the Nordics and Europe with power. Indeed, ON-TIMES, GENeSYS-MOD and highRES estimate that wind power production will cover 53%, 67% and 50%, respectively, of the Nordic electricity demand in 2050, InterACT estimates that wind power production covers around 90% of the Danish electricity demand in 2050 and IFE-TIMES-Norway estimates that wind covers 71% of the electricity demand in Norway in 2050. In comparison, [13] shows that wind power will constitute less than 40% of the electricity supply in the EU for 2050. For the case of this analysis, IFE-TIMES-Norway allows a potential of 6 GW offshore wind at Sørlige NordsjøII (Southern North Sea) by 2030. In scenarios representing the current European market, the model reached this potential. 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. Further recommendations for updates of the Nordic NECP based on this study are shown in [31]. Of course, there will be a consistency gap between a model and the actual energy system. Hence, the qualitative results are easier to use directly than the quantitative model results. Increasing the accuracy of a model will decrease the consistency gap and make the results easier to apply in policies.

The energy sources described above as the most favourable supply options, i.e. onshore and offshore wind, will however require large infrastructure, characterised by long and complex permitting processes. Hence, the extent to which these technologies can support 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 licences (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 a new moratorium on wind power (and other renewable energy) 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 [32]. 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. General recommendations for updates of the Nordic energy and climate plans based on the work performed in this study are shown in [31].

While this study focuses on the expansion of the power sector in enabling additional exports from the Nordics, other studies have also explored how energy exports can depend on other societal and political developments. In particular, the NTRANS [6] and Open ENTRANCE [8] scenarios illustrate the importance of domestic industry development, as well as societal commitment to reduce energy consumption. In scenarios with high degree of behavioural change, including flexible demand, energy efficiency measures, and the use of local energy storage, the demand for energy services decreases. This can free up energy generation capacity for export without necessitating substantial amounts of new renewable energy expansion. This is also beneficial in terms of land-use limitations and ecological impacts related to large energy infrastructure. In addition, the adoption of hydrogen-derived fuels could be another effective strategy to reduce dependency of Russian natural gas in Europe. The Nordic countries are well-positioned to supply both blue and green hydrogen [33] to support the decarbonisation of Europe. This could enhance flexibility in electricity usage [34–36], proving especially beneficial during periods of high electricity production across Europe or during transmission grid bottlenecks. Noteworthy, also this approach would require substantial expansion in electricity generation sources.

Compared to previous model results obtained from GENeSYS-MOD Europe (compare [8,9,37]), the introduction of the additional constraints outlined in Section 2 lead to a significant shift in renewable electricity generation to the Nordic countries. However,this mostly represents a shift in geographic location of electricity generation, as overall electricity consumption remains at similar levels across the European Union. Instead, the surplus electricity from the Nordics substitutes other electricity sources across Europe, mainly in Central Europe, which now imports the added wind energy from the Nordics. This leads to a reduction in use of natural gas, and therefore an overall reduction in Emissions.

The Nordic area had an annual electricity surplus of 12 per cent in 2022, expected to decrease to 6 per cent by 2030 due to faster consumption growth compared to production [38]. Increasing wind or solar power in the Nordic grid (MWh/h) necessitates higher net export combined with adjusted utilisation of price-flexible options, and in some cases curtailment. Nevertheless, the total impact over a full year (TWh/yr) would result in additional net export. In cases of frequent grid constraints, enhancing the grid often reduces total system costs. Examples of new interconnectors to/from the Nordic area in 2021/22 include the North Sea Link to England and the North Link to Germany, both originating from Norway. Through these new cables, extra electricity trade to/from the Nordic area was made possible. Norway also became more exposed to high European power prices during this period, which received significant attention.

5. Concluding remarks and key take-aways

This paper describes the implications of an additional electricity export requirement for the Nordic countries for 2030 and onwards in a decarbonised scenario towards 2050: how this impacts the electricity balance, which additional investments are needed, the geographical allocation of the additional export and the additional energy system costs.

Results from GENeSYS-MOD show that Denmark will export the most power of the Nordic countries, closely followed by Norway. In Scenario 2, Denmark will provide almost two thirds of the additional export, which will mainly be produced from offshore wind power. Wind power production will cover a large share of the additional energy export. 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 Scenario 2 than in Scenario 1. According to ON-TIMES, the largest amount of new electricity capacity will be wind power from Denmark. To some extent, the additional export in Scenario 2 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 the GENeSYS-MOD optimisation results are based on a 100% decarbonised scenario for Europe, whereas 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. Increased wind power will also come from Finland, Sweden and Norway. IFE-TIMES-Norway results indicate that onshore and offshore wind power are the most cost-effective technologies for new renewable energy deployment to meet Norway's future electricity demand. The net electricity export from Norway to Europe can 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 mean that Norway will largely benefit from exporting electricity. In order to contribute to the targets in the REPowerEU plan by 2030, Norway will still need to accelerate the deployment of new renewable energy. It is noteworthy that the additional cost for the energy system of enabling 10 TWh increased electricity export is relatively small.

This study shows that the impacts of the REPowerEU plan, here delimited to an additional electricity export from the Nordic countries to mainland Europe, on the Nordic power system are increased investments in wind power production, mainly from Denmark, but also from Sweden. The study also shows that when the models can distribute the additional export freely among the countries, Denmark is assigned the majority share. However, all models agree that Denmark has the highest increase in energy system costs. ON-TIMES is the only model that predicts a demand reduction as a result of the additional requirement, the other models assume an overall constant demand between the two scenarios. For more information about the comparative study, please see Mathisen et al. [39].

As shown in his 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. This case study shows how the Nordic countries can unite forces to help Europe front-load the green shift by exporting more power. Pathways for the transformation of the Nordic energy system can be studied to inform policy making, prioritise infrastructure development and common Nordic engagement. This study shows a comparison between different energy system model results, and we therefore provide suggestions about how to choose the more suitable energy system model for a task. One of the models provides high resolution results for one year, and the others provide a pathway from a start time to an end horizon, often far in the future. Then, the model must contain your geographical and sectoral area of interest and that area's level of detail must fit your task. The model dataset must be changed according to the conditions and scenarios used in each case, which requires experience and domain- and policy knowledge by the model users. The variation in model outcomes in this study, on a national and regional level, highlights the potential value of collaboration between Nordic research institutions. Notably, improving and aligning data and scenario assumptions would allow for a better comparison and more profound insights from the model output which could perhaps serve as input into future NECP. Moreover, collaboration could increase the footprint of the Nordic region on future European energy and climate policy.

Table A.1
Reviewed literature. All but [17] and [23] concern energy system analysis results.

Reference	Comparisons type	Concerned model	Role of battery electric vehicle (BEV)	Study case
[6]	Scenarios	IFE-TIMES-Norway, REMES	Minor	Norway
[7]	Scenarios	ON-TIMES	Flexibility potential	The Nordic countries
[8]	Scenarios	GENeSYS-MOD inter alia	Minor	Europe
[9]	Scenarios	GENeSYS-MOD	Requirement for green transition	Europe
[10]	No	TIMES-NORDIC,EPOD, Apollo	Possible flexible demand	Sweden
[11]	Models and scenarios	several	several	
[12]	Review	several	Included in study	several
[13]	Resilience	COMPETES	demand response, storage	Europe
[14]	Resilience	Balmorel, SpineOpt	High electrification, transport focus	Nordic countries
[15]	Resilience	EnergyPLAN	None	Iran province
[16]	Models	Balmorel, GENESYS-2 GENeSYS-MOD, oemof, urbs	None	Germany
[17]	Review	Balmorel, GENESYS-2 GENeSYS-MOD, oemof, urbs	None	–
[18]	Models	17 models	None	North American countries
[19]	Models, resilience	8 models	None	North American countries
[20]	Models	DIMENSION, EUREGEN E2M2, urbs, HECTOR	None	Europe
[21]	Models, scenarios	REMix, PowerFlex, SCOPE, ELMOD	Flexibility potential	Germany
[22]	Models, scenarios	Several	None	US States
[23]	Review	several	None	–

CRediT authorship contribution statement

Siri Mathisen: Project administration, Conceptualization, Writing – original draft, Visualization. **Marianne Zeyringer:** Conceptualization, Writing – review & editing. **Kristina Haaskjold:** Conceptualization, Writing – review & editing, Data curation. **Konstantin Löffler:** Conceptualization, Writing – review & editing, Data curation. **Érika Mata:** Conceptualization, Writing – review & editing. **Akram Sandvall:** Conceptualization, Data curation, Writing – review & editing. **Kristoffer Steen Andersen:** Conceptualization, Data curation, Writing – review & editing. **Oskar Vågerö:** Conceptualization, Data curation, Writing – review & editing. **Ove Wolfgang:** Project administration, Conceptualization, Writing – review & editing.

Declaration of competing interest

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

Data availability

This article contains confidential Data, Data available on request and openly available Data.

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Appendix A. Literature review

To structure and organise the cited literature from other energy system analyses, see Table A.1.

Appendix B. Model descriptions

ON-TIMES

The ON-TIMES (Open Nordic - TIMES [40]) 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 time horizon is 2015–2050, in 5-year time steps, with 32-time slices per year. The model contains three scenarios designed to meet the carbon neutrality target by balancing carbon emissions and sinks in the Nordic countries, one of which (Carbon Neutral Nordic) is the base scenario in this study, and seeks the least-cost pathway considering current national plans, strategies, and targets. The model outputs are installed capacities of energy conversion technologies, fuel use, production per conversion technologies and marginal energy and CO_2 prices, primary energy supply by energy source, CO_2 emissions, investment capacities, carbon capture level, and final energy consumption by both energy source and sector. The model uses the TIMES model framework and the mathematical formulation can be found in the documentation part [26].

IFE-TIMES-Norway

IFE-TIMES-Norway [41] (labelled TIMES-NO in results tables and plots) is a long-term optimisation model of the Norwegian energy system. The model covers five geographical regions in Norway, corresponding to the current electricity spot market price zones, and provides operational and investment decisions from the starting year, 2018, to 2050 with 5-year time steps. 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 various energy carriers, making sector coupling a part of the optimisation. 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. For new investments, several technology types are available with different costs, operational conditions, and upper potentials for each region. Existing transmission capacity, both domestically and to

Table C.1
Key inputs per model for 2050. Nordic values for ON-TIMES, GENeSYS-MOD. Norwegian numbers for TIMES-NO and highRES, Danish numbers for IntERACT.

	Unit	ON-TIMES	GENeSYS-MOD	TIMES-NO	highRES	IntERACT
Renewable costs						
Rooftop PV	€/kW	Com:725Res:850	Com:397Res:537	Com:300-520Res:300-770	Utility: 402	Utility: 314Small: 628
Wind onshore	€/kW	831	900	400–1340	1259	1028
Wind offshore	€/kW	1394	1353–1831	2170-2787[a]	2347	1884
Renewable potential						
Rooftop PV	GW	70.4	10.5	31.8	2577[b]	Utility: 25.5
Wind onshore	GW	54.4	42	15.2	265	7.6
Wind offshore	GW	154.3	158.9	31.6	104	41.5
Carbon regulation						
Constraint	Mt. CO_{2e}	9265[c]	n.a.		87.5 annual[d]	net-zero
Price	€/t		355	438		
Fuel prices						
Natural gas	€/MWh_{th}	17	11.12	34.3	56–71	27
Crude Oil	€/MWh_{th}	29	18.7			38
Bio	€/MWh_{th}	Wood Chips: 25	Average: 18.8			29

Com: Commercial rooftop installations, Res: Residential rooftop installations.

[a] Using only bottom-fixed offshore wind or also floating offshore wind.

[b] Only ground-mounted utility-scale PV considered.

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

[d] Only for the electricity sector.

European countries, is modelled exogenously and based on current capacity and ongoing capacity expansion. Moreover, the model allows for new investment capacity to ensure that new renewable production can be distributed across Norway and to Europe. The model uses the TIMES model framework and the mathematical formulation can be found in the documentation part [26].

IntERACT

IntERACT [28,42,43] is a model used by the Danish Energy Agency to determine industry and household emissions and energy use within policy scenarios [44], to assess the impact of different policy measures directed at households and industry and for explorative scenarios dealing with different pathways to meet Danish long-term climate policy goals. IntERACT integrates a general equilibrium top-down model with a technical energy system bottom-up model based on TIMES-DK with the cost of energy, fuel cost shares and tax rates and the subsequent exchange of updated energy demand as an iterative link. The top-down model describes the macroeconomic relationships and the bottom-up model describes the Danish energy system using detailed technical modelling of both production and energy use. IntERACT uses exogenously given projections of the availability of transmission capacities and electricity prices from neighbouring countries, and models the electricity price within Denmark endogenously. A comprehensive European electricity market simulation model (RAMSES) [45] provides hourly price profiles on import and export prices for each neighbouring region. IntERACT includes various sectors and sector-coupling is a part of the model as end-use demands and supply are connected in IntERACT. The mathematical formulation can be found in a prior publication [28].

GENeSYS-MOD

The Global Energy System Model (GENeSYS-MOD) [46,47] is an open-source, linear energy system model, that minimises total system costs for the entire energy system, including the different energy sectors electricity, buildings, transport, and industry. GENeSYS-MOD focuses on sector-coupling and the computation of long-term scenarios, usually towards 2050, for the development of the energy system. It outputs pathways describing how the energy system needs to evolve to meet predefined energy demands and climate targets, such as deep decarbonisation of the energy system and its sub-sectors, through renewable shares or emission limits. While GENeSYS-MOD has been applied for a wide range of different regional settings [48], the model version used in this comparative analysis uses a European setting with five nodes in Norway. Results from the model for multiple European decarbonisation scenarios are openly available [37]. The details of the current energy system (in our case 2018) provide the starting point to the model, together with resource potentials, pre-existing capacities, and energy demands. Power trade and power infrastructure are included in the model, which plans investments in infrastructure, generation, and storage to minimise the overall operational and investment costs. The model source code and documentation can be found at GitLab [49] (GAMS version) and GitHub [50] (Julia version, data, and tools). GENeSYS-MOD is a linear program (LP), minimising total system costs of the energy system, while meeting exogenously defined demand constraints, political targets, and resource availabilities. The mathematical formulation can be found in several prior publications, such as Löffler et al. [46], Burandt et al. [47], and Burandt et al. [51].

highRES

The high spatial and temporal Resolution Electricity System model for Europe (highRES) is a linear power system optimisation model developed for analysing electricity systems with a large amount of variable renewable energy technologies. It minimises the total system costs of the desired end-state with high time resolution, including both operation and annualised investment costs. highRES does not include intermediate system designs, but operates the desired end-state at a high temporal resolution and capture the system variability. 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. highRES uses historical meteorological data from climate reanalysis (e.g. ERA-5 reanalysis produced by ECMWF and processed by Atlite [52]) 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 30 × 30 km, or aggregated on the applied zonal level of the model. A more detailed description is provided by [53] and the model structure is openly available on GitHub [54]. In this project, highRES represents 27 European zones on a country level, while Norway is modelled more in detail through 11 regions. The mathematical formulation can be found on GitHub [54] and in the documentation [55].

Appendix C. Key inputs per model for 2050

Some of the key inputs per model for 2050 are found in Table C.1.

Appendix D. Results tables

The model simulation results from Scenario 1 are shown in Table D.1 for the Nordic countries combined, and in Table D.3 for the Nordic countries separately. The change in model simulation results

Table D.1
Scenario 1 simulation results for Nordic area combined, for 2050.

	Unit	ON-TIMES	GENeSYS-MOD	highRES
Primary energy demand	TWh/yr	1310	1461.8	
Electricity demand	TWh/yr	571.9	739.7	718.0
of which in transport	TWh/yr	139	59.2	
Electricity production				
Rooftop PV	TWh/yr	36.5[a]	77.2[b]	28.9[b]
Wind onshore	TWh/yr	146.4	113.8	94.2
Wind offshore	TWh/yr	155.6	378.6	392.2
Hydropower	TWh/yr	244.2	237.6	216.3
Bio-based	TWh/yr	29.7	2.5	
Natural gas with CCS	TWh/yr	0	–	17.9
Hydrogen-based	TWh/yr	0	–	
Net electricity export	TWh/yr	84.4	78.5	41.5

[a] All types of PV.
[b] Utility PV- no rooftop PV production available.

Table D.2
Change in simulation results from Scenario 1 to Scenario 2 for the Nordic area combined, for 2030.

	Unit	ON-TIMES	GENeSYS-MOD	highRES[d]
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	−0.2	
Electricity production				
Rooftop PV	TWh/yr	+4.2[a]	0[b]	+0.5[b]
Wind onshore	TWh/yr	+16.9	+4.2	+9.2
Wind offshore	TWh/yr	+8.3	+20.5	+7.4
Hydropower	TWh/yr	+1.4	+0.1	+12.6
Bio-based	TWh/yr	+1.7	0	
Natural gas with CCS	TWh/yr	0	+0.5[c]	0.2
Hydrogen-based	TWh/yr	0	0	
Net electricity export	TWh/yr	+45.5	+30	+30
Energy System costs	NPV,M€	+537	+398	+419

[a] All types of PV.
[b] Utility PV - no rooftop PV production available.
[c] Power production from gas without CCS.
[d] 2050-values for highRES. Operating costs for one year only.

Table D.3
Scenario 1 simulation results for the Nordic countries for 2050.

	Unit	IFE-TIMES-NO	highRES	GENeSYS-MOD	ON-TIMES	InterACT[a]
Electricity demand						
Norway	TWh/yr	188	220 (exog)	156.3	168.3	
Sweden	TWh/yr		298.0	255.3	204.4	
Denmark	TWh/yr		69.0	188.4	107.5	74-97
Finland	TWh/yr		131.0	139.7	91.4	
Electricity production[b]						
Norway	TWh/yr	301	243.2	207.7	206.03	
Sweden	TWh/yr		324.6	223.4	194.6	
Denmark	TWh/yr		72.0	249.4	135.9	81-102
Finland	TWh/yr		119.7	128.9	71.8	
Net electricity export						
Norway	TWh/yr	96	23.2	56.8	38	
Sweden	TWh/yr		26.6	−29.2	14.2	
Denmark	TWh/yr		3.0	63.5	32	0
Finland	TWh/yr		−11.3	−9.04	0.27	

[a] Numbers from IntERACT are based on explorative scenarios made for the Climate Programme 2021.
[b] Including Rooftop or utility PV, Wind onshore and offshore, hydropower, bio-based, natural gas with CCS, hydrogen-based. This delimitation may cause a deviation between production and demand combined with export.

Table D.4
Change in simulation results from Scenario 1 to Scenario 2 for the Nordic countries separately, for 2030.

	Unit	IFE-TIMES-NO	highRES[a]	GENeSYS-MOD	ON-TIMES
Electricity demand					
Norway	TWh/yr	−1.6	0	−0.1	−0.3
Sweden	TWh/yr		0	0	−7.2
Denmark	TWh/yr		0	−0.3	−5
Finland	TWh/yr		0	+0.5	0
Electricity production[b]					
Norway	TWh/yr	+8.4	+10.3	+3.3	+2.2
Sweden	TWh/yr		+6.1	+7.9	+7.2
Denmark	TWh/yr		+8.4	+16.0	+23.4
Finland	TWh/yr		+5.4	−1.6	+5.4
Net electricity export					
Norway	TWh/yr	+10	+10.1	+3.4	+2.5
Sweden	TWh/yr		+6.1	+7.8	+14.4
Denmark	TWh/yr		+8.4	+19.2	+28
Finland	TWh/yr		+5.4	−0.1	+0.83
Energy system costs					
Norway	NPV,M€	+468	+28.8	+1752.2	−359
Sweden	NPV,M€		+26.7	+2292.1	−3676
Denmark	NPV,M€		+72.4	+5602.9	+2429
Finland	NPV,M€		+16.8	−187.7	+2142

[a] 2050-values for highRES. Annuitised investment costs and operating costs for one year only.
[b] Including Rooftop or utility PV, Wind onshore and offshore, hydropower, bio-based, natural gas, hydrogen-based.

between Scenario 1 and Scenario 2 are shown in Table D.2 for the Nordic countries combined, and in Table D.4 for the Nordic countries separately.

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