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PAPER

Balancing act: the cost of wind restrictions in Norway's electricity transition

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Abstract

To meet its commitments under the Paris Agreement and reduce its dependency on energy imports, the pace, and scale of renewable energy deployment across Europe must increase dramatically over the next decade. Such a steep change in the net-zero transition will inevitably necessitate trade-offs with other societal priorities. Here we investigate a case study focused on the opposition towards onshore wind and the compromises that may need to be made to deliver its plans for deep electrification. Using an electricity system model, we explore the implications of key social and environmental dimensions shaping the future deployment of onshore wind on the costs and design of electricity systems for Norway in 2030. We find that under restrictions that allow for almost no additional onshore wind, demand cannot be met and load has to be shed. Yet, when reducing the restrictions on onshore wind or allowing for in-country transmission expansion, feasible system designs at a small fraction of that cost can be found. To meet the net-zero targets, compromises will need to be made on either wind power deployment, transmission expansion, non-electrification of industry or demand reduction.

1. Introduction

The decarbonisation of power production is key to achieving the Paris Agreement goal of limiting global mean surface temperature rise to well below 2 °C, particularly so given the drive to electrify industry, transport, and heat. Variable renewable energy technologies (VREs) such as wind and solar photovoltaics (PV) have decreased rapidly in cost and matured into cost-effective decarbonisation solutions (IPCC 2023). However, the location of VREs affects the technical feasibility and their impact on the environment and the communities where they are located. Thus, socio-environmental constraints can have a large impact on the overall capacity potential which influences the technology choices, changing costs and political viability of reaching decarbonisation goals. These constraints may also have an impact on ensuring a reliable electricity supply that meets current and future energy demand. The potential trade-offs and competing interests between technology, nature protection, social acceptance, energy prices and future demand needs to be evident in policies aimed at promoting VREs. There is an urgency for rapid action to close the emission gap, requiring global cuts of 42% of 2019s emissions by 2030 to get on track for 1.5 °C (Olhoff *et al* 2024). The European Union is not on track to meet its 2030 targets (Climate Analytics & NewClimate Institute 2024).

Norway comes with some of the best on- and offshore wind resources in Europe (Karlstrøm and Ryghaug 2014, Egging and Tomasgard 2018). If Norway aims to achieve net-zero emissions (Norway's current target is a reduction of 90%–95% of 1990s greenhouse gas emissions (Lovdata 2017)), this would lead to an increase in domestic electricity demand of up to 90 TWh from 127 TWh in 2023 (Statnett 2023b) to electrify sectors including transport, manufacturing, and oil and gas extraction. However, wind energy development has been contested and licensing has been revoked due to opposition from nature conservation groups, recreational activities and local communities (Karlstrøm and Ryghaug 2014, Gulbrandsen *et al* 2021). While renewable energy development, nature protection and social support may all be regarded as critical, an energy transition that balances all three is proving challenging in meeting Norway's future energy demand and achieving its decarbonisation goals. For instance, the construction of wind farms has been considered by the Sámi[5] Council as threatening the sustainability of reindeer herding (Lawrence 2014). In 2021, Norway's supreme court ruled that two wind farms built at Fosen in central Norway violated Sámi human rights under international conventions. The future of these wind farms is still unclear. This uncertainty sparked protests in February 2023, where Sámi activists blocked the entrance to Norway's energy ministry, demanding the cease of operations of the energy plants (Fouche and Klesty 2023). Therefore, socio-environmental constraints can have a large impact on the overall electricity generation capacity potential, which will in turn affect optimal technology choices, system costs and the social feasibility of reaching the Paris Agreement. The Norwegian power system is facing an increase in electricity demand from the electrification of transport, heating and industry, while the traditional generation source (hydropower) is not able to meet all of this increase due to environmental limits. While there has been a strong increase in onshore wind energy capacity from 860 MW in 2014 to 5 GW in 2021, there have been only 15 MW added since then (Statistics Norway 2024). This leads to concerns about a power deficit by 2030 (Statnett 2023a).

Energy systems and electricity system modelling has been a key policy tool for studying how to meet future demand and decarbonisation pathways (DeCarolis *et al* 2017). They can provide knowledge-based and systematic methods and solutions to reach decisions about which technologies and areas to invest in. Nevertheless, present-day models mainly integrate techno-economic input parameters, whereas social factors and environmental constraints such as local acceptance of new installations, are largely neglected (Pfenninger *et al* 2014, Gambhir 2019, Nikas *et al* 2020). Several studies (McKenna *et al* 2014, Höltinger *et al* 2016, Rinne *et al* 2018, Permien and Enevoldsen 2019) have acknowledged the importance of accounting for socio-environmental acceptance when modelling renewable energy potential and others call for integration of non techno-economic factors in energy system models (Hirt *et al* 2020, Hanna and Gross 2021, Süsser *et al* 2022). Without considering social factors that shape the renewable energy deployment, energy system models can therefore produce decarbonisation solutions that are neither publicly nor politically feasible (Trutnevyte 2016), risking missing carbon targets.

In the last 10 years, modellers have incorporated socio-technical assumptions which have increased the complexity of models through the inclusion of social aspects (Krumm *et al* 2022): Bolwig *et al* (2020) use an energy systems model to assess the costs of social acceptance limiting the expansion of onshore wind and transmission capacities for the Nordic–Baltic region in 2030 and 2050. They do not perform a spatial analysis but develop four scenarios where transmission and/or onshore wind energy can be expanded. Price *et al* (2018) assess how social and environmental restrictions on nuclear/renewables siting shape Great Britain's 2050 power system. Cheng *et al* (2024) assess the case for Norwegian hydrogen exports, developing three scenarios including socio-environmental factors such as land-use and electricity prices for 2050. Inderberg *et al* (2024) combine energy system optimisation modelling with political feasibility of different transition pathways. They develop a scenario for Norway towards 2050 that is unrestrained by assumptions about policy, and based on that identify areas where political choices are key to model outcomes. Grimsrud *et al* (2024) integrate monetised local disamenity and carbon sequestration costs and place constraints on areas of importance for wilderness and biodiversity for onshore wind deployment into a Norwegian energy system model for 2050. They only consider locations where concessions have been applied and limit expansion to an increase in onshore wind capacity of maximum 4 TWh annual production, adding to 15.5 TWh produced today.

Hirt *et al* (2020) identified the need for integrative research to provide more practical outcomes to meet energy and climate targets. As energy policy and infrastructure decisions are made on a national level and 2030 is within today's politicians' timeline, this study provides practical, short-term policy-relevant insights on trade-offs and compromises. This is also the reason for choosing 2030 as the target year of our analysis. It is a socio-political decision to select more expensive technologies, sites, or mitigation options to minimise the socio-environmental impacts of VRE development. Yet, a spatially explicit capacity assessment under different socio-environmental scenarios combined with energy system modelling is missing for 2030 to allow for such discussion. Further, most modelling approaches do not capture the spatial detail of capacity (i.e. how much can be built in a region) as well as spatio-temporal production (i.e. how much can be

[5] The Sámi are an Indigenous people with internal linguistic and cultural diversity who populate areas that today are within the national borders of Finland, Norway, Sweden, and Russia. Sámi communities' diverse sociocultural practices such as reindeer herding, fishing and handicrafts have been central in Sámi cultural history as an important way of subsistence (Broderstad 2011).

produced hourly in that location) to account for the spatio-temporal variability of renewables. Wu *et al* (2023) for example use a similar study design to examine implications of a net-zero goal for the western United States. They limit the optimisation to a sample of representative days. In contrast, Wu *et al* (2024) ran an hourly optimisation and dispatch model for the Southern Africa region for differing scenarios of legal, social and environmental protections.

Here, we close this gap by performing a nationally specific analysis: we first study the NVE (Norwegian Water Resources and Energy Directorate) framework, previous licences, literature, and newspaper articles to design three levels of socio-environmental acceptance exclusion areas (we call them 'None', 'Low' and 'High') for onshore wind. Based on the developed levels, we then conduct a GIS analysis to determine the spatially dependent capacity potential per level of each studied dimension (nature, fauna, Sami, neighbour). A description of the dimensions can be found in section 2.2.1. These dimensions contribute to building nationally specific socio-environmental scenarios that help decide which projects and locations can be considered, taking into account costs, future demand and decarbonisation goals. We use these spatially explicit scenarios in an electricity system model and run it at a high spatial resolution (30 km) for variable renewable production to capture the spatio-temporal variability. We identify trade-offs and support policymakers with quantification on alternative compromises.

Due to its considerable VRE potential, socio-environmental opposition, and expected future growth in electricity demand, the case study therefore contributes to addressing the significant gap in identifying and analysing social and environmental variables. These variables can affect system design, costs, and therefore prices and exports. We do this by answering the following research questions:

- What technical, environmental and social factors can impact the land availability for wind energy in Norway?
- How do spatially dependent technical, environmental and social scenarios change Norway's cost-optimal wind energy capacity potential?
- How do these scenarios impact the cost, optimal design, unmet electricity demand and electricity imports of Norway's energy system in 2030?

To answer these research questions, section 2 describes the methodology including the model, data and scenarios, section 3 shows the results and finally, section 4 discusses these findings and provides policy recommendations. While this paper draws on the Norwegian energy system, the globalised nature of both social and environmental restrictions and energy prices means that the research in Norway is likely to be relevant elsewhere.

2. Methodology

First, we describe the model, next the criteria for excluding areas from onshore wind instalment and distinguishing the different levels, and finally we show the area that remains available after applying those criteria.

All values with the unit Euro (€/EUR) refer to the value of that currency in the year 2023.

The input data, as well as results and the code used to generate them, are available. Details can be found under "Data Availability" at the end of this publication (Roithner *et al* 2025).

2.1. Model description

We separate between the model and its configuration in the first part and the generation of input data for the model in the second part of this section.

2.1.1. highRES electricity system model

We employ a modified version of the highRES electricity system model (Moore *et al* 2018, Price *et al* 2018, 2022, 2023, Price and Zeyringer 2022, Zeyringer *et al* 2018a; 2018b). highRES describes a linear optimisation problem implemented in the *General algebraic modelling system* and is solved using the off-the-shelf mathematical program solver suite CPLEX for minimal total system cost, consisting of annualised investment and operational cost. A set of technical, economic, meteorological and land use constraints ensures operational feasibility under the given circumstances. Using perfect operational foresight with an hourly time resolution, we adapt it to represent the Norwegian power system on a NUTS level 3 (based on 2021), which corresponds to 11 administrative regions at that time. Supply and demand are balanced at the NUTS level through the transmission grid, but the model can deploy wind and solar capacity in the most optimal 30 km × 30 km grid cells (based on ERA5 data). We assume a fully decarbonised power grid (as is the case with domestic generation) by 2030 and therefore only include feasible zero-carbon technologies. Wind, lithium-ion battery storage and solar power, are technologies that can be expanded, whereas hydropower and pumped hydro storage are fixed to current capacities due to small expansion potential by either 2030 or 2050, which lies in small scale hydropower plants.

The Norwegian parliament asked the Norwegian government in 2023 to set a target for new solar energy production of 8 TWh by 2030 (Meld. St. 4 (2023–2024) (2023)). Using estimated historical annual average solar capacity factors in Norway of ∼10% from Pfenninger and Staffell (2016), this equates to an installed capacity somewhere in the range of 9 GW. Yet, installation rates (as seen in figure A2 in the appendix) have not increased enough to support this target, even dropping in 2024. Current public statements by industry and interest organisations are pessimistic about the target being reached (Kalleberg 2025, Simonsen 2025) and the report itself specifies that due to grid constraints (especially of ground mounted PV) the target would have to be mainly reached by building integrated/roof mounted PV, which faces challenges with profitability (Norwegian Water Resources and Energy Directorate 2024). In a recent study that analysed the policy direction for solar installations in Norway, the authors '[…] find that the potential for utility-scale developments is likely to be fairly limited until 2030, and unlikely to reach the target. […] [they] also find that small-scale developments […] [are] also likely to fall well short of the 8 TWh target' (Inderberg and Opsahl 2025, p 12). For these reasons, we place an upper limit on solar deployment due to low installation volumes and rates, also compared to other technologies in the power system. The values can be found in table A2 in the appendix. Furthermore, we assume that solar cannot be built in areas that have protection level I–IV as defined by the *International Union for Conservation of Nature and Natural Resources* (IUCN), slope greater than 15 degrees, elevation of more than 2000 m above sea level. Also excluded are areas that belong to land cover categories, as supplied by the *Coordination of Information on the Environment* (CORINE) program, which are provided in table A1 in the appendix.

For offshore wind, we exclude Ia-IV of the World database of protected areas and areas deeper than 70 m where bottom-mounted can be built, leading to an upper limit of 125 GW installable bottom-mounted offshore wind capacity. Norway today has no commercial offshore wind and since the Norwegian stated target for 2030 is 3 GW, in the waters before Rogaland, we limit the model to this value (Buljan 2022, Aasland 2023, Lange and Pochhammer 2024). We do not include floating offshore wind because of the lead time of installations, which would make it difficult to finish large capacities until the target year of the analysis (2030).

In the partial greenfield optimisation of Norway we include existing infrastructure such as transmission, power generation capacities (in particular 5 GW of onshore wind power and 30 GW of current hydropower) and pumped hydro storage (1.3 GW which will be operational in 2030). For existing infrastructure, only variable O&M costs are part of the cost minimisation.

We assume a value of lost load of approximately €23 thousand/MWh, based on Ovaere *et al* (2016). The value of lost load tries to capture the economic impact of power deficits in the system.

We assume electricity demand to increase from 140 TWh (in 2022) to 178 TWh in 2030 based on forecasts by the transmission system operator Statnett (2023a). A more detailed description of this can be found in the appendix in section A.4.

While Norway has the potential to increase imports, being currently a net exporter (International Energy Agency 2022), the policy discussion is currently (and has been for some years) pointing in the other direction. An example is the NorthConnect subsea interconnector cable project to Scotland, which was put on hold indefinitely by the Norwegian government in 2020 (Moe *et al* 2021). Further, a commission instated by the Norwegian government advised the government to ensure a lasting power surplus to shield consumers from price fluctuations (Strømprisutvalget 2023). And currently the policy debate in Norway revolves around cutting existing links to Denmark by simply not renewing the ageing existing cable. This is driven by concerns about high power prices being imported from the connected European markets (Milne 2024). Given the limited time for grid expansion until 2030 both for in-country transmission and import capacity, and a (policy-mandated) desire to keep import volumes similar to current ones, we place an upper limit on the power capacity of both. The limit values can be found in table A2 in the appendix. A fixed price for imports of €34/MWh is assumed based on 2020 hourly electricity prices from the countries where there is an interconnection with Norway, weighted by the interconnector size.

More information on the modelling approach and assumptions can be found in section A.2 of the appendix.

2.1.2. Capacity factor modelling based on weather data

We use the open-source tool atlite (Hofmann *et al* 2021) to convert weather variables to power system variables (capacity factors, etc), weighted by geographical availability (topography, land use, and the restricted land use scenarios described in section 2.2.1).

To represent the influence of inter-annual weather variability on the system design (Grochowicz *et al* 2023), we pick a challenging year (i.e. high total system costs) for the Norwegian electricity system. The year

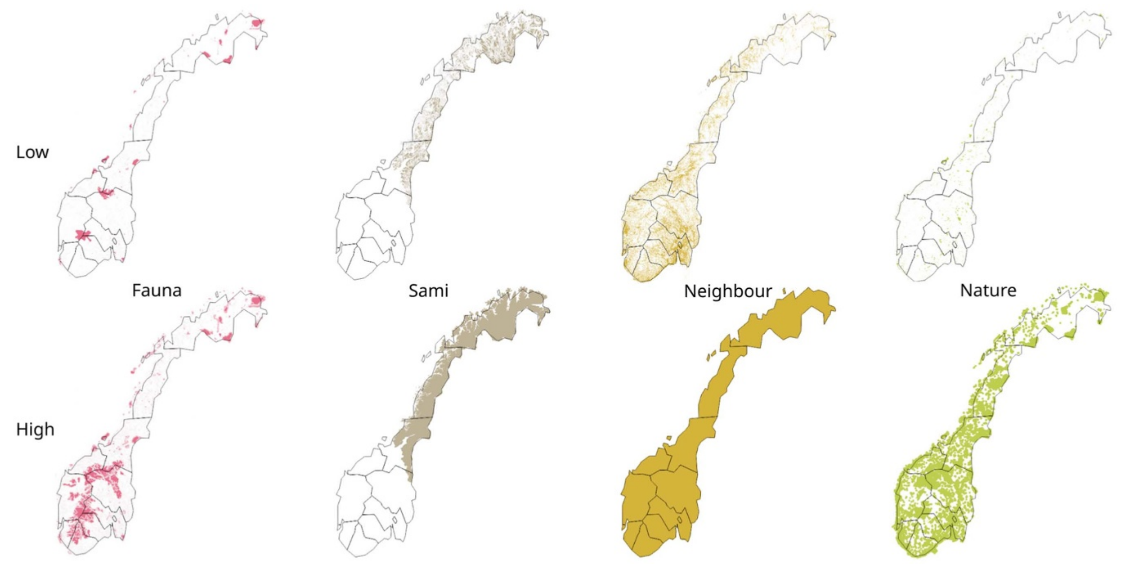

Figure 1. Onshore wind land availability in Norway under various land use scenarios. Coloured areas are not available for new onshore wind capacity. Upper row shows the Low level for each scenario dimension, lower row the High level. Columns show the scenario dimension.

2010 was characterised by low hydropower production and a very cold winter, leading to high electricity demand.

The complex topography of Norway means that the original ERA5 reanalysis weather data (Hersbach *et al* 2018) at 0.25° grid size cannot capture local variations in wind speeds, leading to *a priori* underestimation of wind power capacity factors in suitable locations. Therefore, we compute bias-correction functions for each 0.25° × 0.25° grid cell by comparing actual wind power production data and ERA5 wind speeds from 2019. The historical production data is sourced from the Norwegian Water Resources and `Energy Directorate (NVE) (2023) for Norwegian wind parks constructed up to 2021; for wind parks constructed after 2019 the production data reported by NVE is based on regional climate modelling. For each wind park, we compute the year-round distributions of capacity factors based on ERA5 wind speeds at that wind park and those from historical production data, and find a bias-correction function $f: [0,1] \to [0,1]$ such that the distribution of bias-corrected ERA5 capacity factors matches the distribution of historical capacity factors for that wind park. For every grid cell, we then take as the bias-correction function the inverse distance weighted average of the bias-correctors for the 10 closest wind parks.

We exclude areas with known low wind speeds (less than 6.5 m s^{-1} at 120 m height), defined as a hard exclusion 'wind speed' by NVE, and therefore low wind power production potential (Norwegian Water Resources and Energy Directorate 2019b).

2.2. Scenario design

We start by explaining the scenario dimensions and then detail how we combine the different levels of those dimensions into names for the resulting scenarios.

2.2.1. Land exclusion dimensions

We define three levels restricting the build-out of onshore wind in Norway until 2030 for four different restriction dimensions (technical, fauna, Sámi, neighbours). Level **None** considers only the technical constraints. Level **Low** adds environmental and social constraints to the existing technical factors, and level **High** considers even higher environmental and social constraints. Later, we create scenarios combining one expression for each dimension. Figure 1 shows the land that is excluded from development for the **Low** and **High** level for each of the restriction dimensions.

The selection is informed by policy documents including NVE's onshore wind power framework (Norwegian Water Resources and Energy Directorate 2019a), NVE's consequence report for offshore wind power (2013) and NVE's licence decision in onshore and offshore wind power cases. Furthermore, factors included in NVE licence decisions, and legal conventions that apply to the installation of renewable energy, such as the Bonn and Bern conventions.

Table 1. Restriction dimensions.

Low	High
Technical restrictions	
Roads and Railway—200 m buffer Airports 2 km buffer Watercourses, water bodies and glaciers Gradients steeper than 20 degrees	
Nature-related restrictions	
Low	High
Strict nature reserve (IUCN category 1a)	Strict nature reserve (all IUCN categories + 5 km buffer)
Coastal heather	Coastal heather + 5 km buffer
Fauna-related restrictions	
Low	High
Important bird areas (IBA) as defined by birdlife international	3 km buffer zone around IBA-areas
Four big predators (wolf, bear, lynx, and wolverine) and the mountain fox	Four big predators (wolf, bear, lynx, and wolverine) and the mountain fox
	All areas of important biodiversity as defined by the Norwegian Environment Agency All areas where wild reindeer live. All the 23 function areas for wild reindeer, including connected nature areas.
Reindeer-related restrictions	
Low	High
Migratory zone (ensure the migration between different grazing land during the year cycle)	All areas used by reindeer (Migratory zones,
Winter grazing land (Minimum grazing land areas)	all seasons grazing land, concession permit regions, expropriation areas, enclosed grazing sites, and gathering sites). Reindeer herding demands big, connected areas, where other activities can disturb the reindeer and affect the herding.
Core areas of the summer grazing land area Mating land/Autumn grazing land, unless during the reproduction time Calving area	
Neighbour-related restrictions	
Low	High
Noise (Buildings—a 400 m buffer zone to keep noise levels under 50 dB). Visibility (agglomerations): 1 km from cities and populated areas.	Noise (Buildings—a buffer zone of 10 times the height of the wind turbine to keep noise levels under 40 dB). Visibility (agglomerations): 50 km from cities and populated areas.
Walking routes, ski runs, biking routes other routes—20 m buffer Protected cultural heritage	

In table 1 we describe the constraints considered for each of the levels (**None Low, High**) for onshore wind power in Norway, followed by the reasoning behind the selection of each constraint. These include untouched connected nature areas, landscape, cultural heritage, outdoor life and tourism, nature types, fauna such as birds, bats, predators, wild reindeer and reindeer herding. Neighbour effects such as visibility and noise, and local and regional commerce development are also included.

2.2.1.1. Technical

A buffer of 200 m is applied to roads and railway in case a wind turbine falls or breaks (Enevoldsen and Permien 2018). For airports, a 2 km buffer was added due to safety. Watercourses, water bodies and glaciers were excluded since these would require offshore wind turbines and foundations. Gradients steeper than 20 degrees were also excluded due to the difficulties of accessing these sites (Permien and Enevoldsen 2019) and due to technical and fluid-mechanical reasons they are less suitable for wind turbines (McKenna *et al* 2014).

2.2.1.2. Nature

As well as having an intrinsic value, natural reserves benefit various social and environmental factors such as nature types, fauna such as birds, bats, predators and non-domesticated reindeer, landscape, cultural heritage, outdoor life (Outdoor Recreation Act 1957) and tourism. As well as being legally protected (Ot.prp. nr. 52 (2008-2009) 2009), conserving nature and the landscape for future generations is strongly rooted in Norwegian culture (Norwegian Environment Agency 2019a) and politics (Ministry of Climate and Environment 2015). Landscapes and nature types also define one's identity to a place and a cultural heritage (Norwegian Environment Agency 2019b). The visual effects on the landscape and for cultural heritage, along with noise, have been identified as some of the most important disadvantages of wind farms in Norway (Norwegian Water Resources and Energy Directorate 2012).

23 areas for the endangered nature type coastal heather are appointed for conservation and excluded according to the NVE's criteria (Norwegian Water Resources and Energy Directorate 2019a)

2.2.1.3. Fauna

Fauna, in the context of onshore wind power development, encompasses various species such as birds and other animals. Specifically, through the different levels, we have included birds, bats, wild reindeer and four major predators: wolves, bears, lynxes, and wolverines. Additionally, the fauna restriction includes mountain foxes, deer species like moose and deer, amphibians, and small rodents (Norwegian Water Resources and Energy Directorate 2018).

There is little research indicating that wind power installations have negative effects on the bird species on the stock level (Norwegian Water Resources and Energy Directorate 2018), which is why bird-related restrictions are not included in Scenario Two. Studies indicate that the amount of birds that collide with wind turbines is very low compared to other mortality factors created by humans (Norwegian Water Resources and Energy Directorate 2018). Following the principle of precaution, the uncertainty about collision risk and repression results in restricting areas with a large bird population. Furthermore, IBA-areas are important bird areas which are not suitable for wind power (Rydell *et al* 2012). The effects on birds on an individual level will not be taken into consideration by NVE and are therefore not restricted in our map. Due to the lack of concrete Norwegian recommendations for buffer zones around bird areas, we use the 3 km used by the Swedish Environmental Protection Agency (Rydell *et al* 2012).

In protected national reserves, the presence of wild reindeer alone can be a sufficient reason to reject a concession application. As a result, areas with wild reindeer are excluded in Scenarios Two and Three. Non-Sámi domesticated reindeer herding is practised in parts of Innlandet county, with historical roots dating back to the 1700s. These reindeer herders operate within the framework of the Reindeer Herding Act (Reindeer Herding Act 2021).

2.2.1.4. Sámi reindeer herding (domesticated reindeer)

Migratory zones are protected according to the Reindeer Herding Act § 22. These areas ensure the migration between different grazing lands during the year cycle. NVE considers it unlikely to find acceptable alternative areas, so compensation could be difficult to establish (Norwegian Water Resources and Energy Directorate 2018).

2.2.1.5. Neighbour effects (includes local and regional commerce development)

In 2014 a million Norwegians lived in buildings with noise levels over the limit value for traffic noise (Lden 55 dBA). Still, studies indicate that noise from wind turbines can be more troublesome than noise from traffic (Katinas *et al* 2016). The recommended noise value by NVE and the Norwegian Environment Agency is 45 dBA (Ministry of Climate and Environment 2021). According to the Norwegian Institute of Public Health, annoyance starts at levels over 40 dB (Norwegian Water Resources and Energy Directorate 2018). To avoid this level, a buffer zone of 10 times the wind turbines' height was set (as is the case in countries such as Poland and Germany) (Norwegian Water Resources and Energy Directorate 2018).

For visibility impacts, the Norwegian topography minimises the consequences for neighbours, since flat terrain is rare. The restriction zone was set under 1 km, which considers at least three times the height of the wind turbine. Minimum standards in other countries are 500 m in Ireland, ten times the wind turbines' height in Poland and Bavaria, Germany, and four times the height in Denmark (Norwegian Water Resources and Energy Directorate 2018). The distance criteria should be determined in connection with the height of the wind turbine, this also ensures that the minimum distance is not too short for higher wind turbines (Norwegian Water Resources and Energy Directorate 2018).

Table 2. Exemplary translation table between the scenario name and the scenario dimension level values.

Land use display Name	Nature	Fauna	Sámi	Neigh
None	None	None	None	None
Low	Low	Low	Low	Low
Nature	High	Low	Low	Low
Fauna	Low	High	Low	Low
Nature, Fauna	High	High	Low	Low
…	…	…	…	…

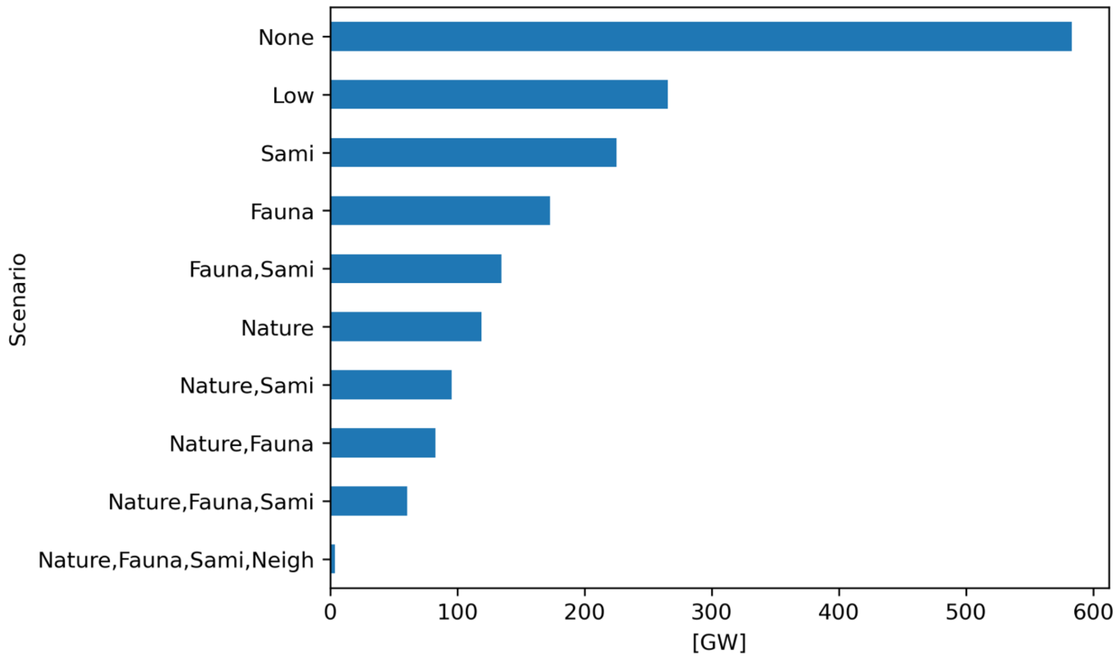

Figure 2. Energy equivalent land area of Norway available for wind power, after land use restrictions have been applied in gigawatts (GW).

2.2.2. Scenario naming

The figures in this paper use a scenario naming based on the different varying levels for each dimension (i.e. a scenario consisting of a selection of None/Low/High values for four different dimensions). Their meaning can be decoded following the examples given in table 2. It shows the pattern, which is just one word if all dimensions (Nature, Fauna, Sámi, Neigh) are at the same level (**None** if all of them are None, **Low** if all of them are Low). The default assumption for all other scenarios except for those two is that all dimensions are at the 'Low' level, and the display name contains the dimensions that are 'High'. To study the impacts of strict constraints on onshore wind, we ignore combinations of the levels 'Low' and 'None'. This results in the following ten scenarios: None; Low; Sami; Fauna; Fauna,Sami; Nature; Nature,Sami; Nature,Fauna; Nature,Fauna,Sami; Nature,Fauna,Sami,Neigh;

2.3. Area

Figure 2 shows the available area for onshore wind in each of the land use restriction scenarios. The unit is gigawatts (GW) to make it easier to compare this figure with the results later. We assume that one can install 3 MW km^{-2} (Price *et al* 2018). The total area of Norway in this metric would amount to roughly, 1150 GW. Most area (580 GW or 50%) is available for onshore wind in the least constrained scenario (**None**). In the **Low** scenario, 265 GW or 23% of the land area and in the most constrained scenario (**Nature,Fauna,Sámi, Neigh**) less than 4 GW (corresponding to 0.0035% of the land area) can be installed.

3. Results

The key metrics we consider, to evaluate the impacts of the different onshore wind land use scenarios on electricity generation and storage equipment deployment in Norway, are: the total cost of the resulting

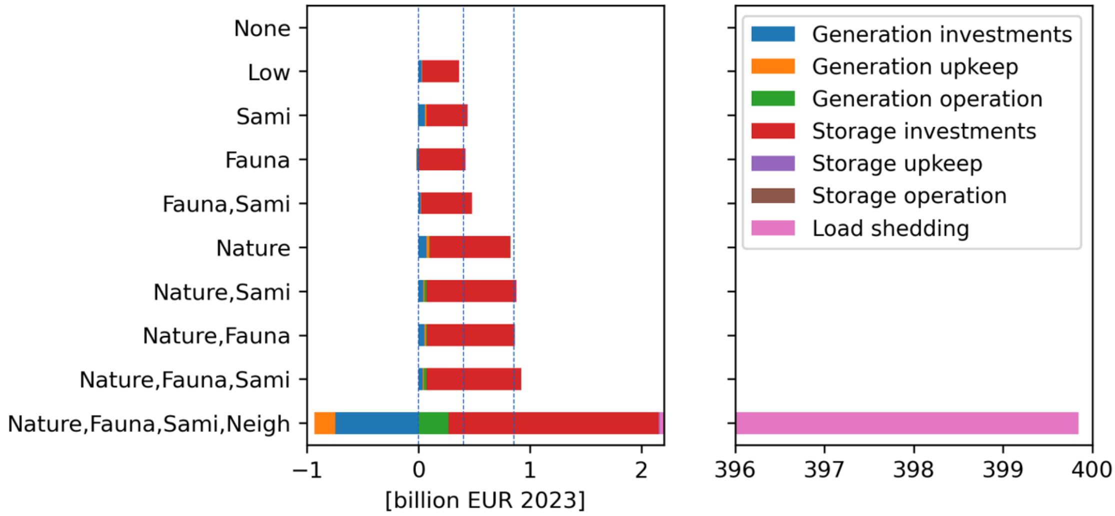

Figure 3. Change of each component of total system costs per scenario compared to the cheapest scenario plotted. Markers at 0%, 8% and 17% cost increase illustrate levels of similar cost increase between scenarios.

cost-optimal electricity system, its design in terms of generation and storage capacities and their spatial deployment patterns.

3.1. Electricity system costs

The scenario **None**, which applies only technical restrictions, serves as a baseline to which the other scenarios are compared to. **None** applies no land use restrictions for the four studied dimensions. In it, the total system costs are close to €5 billion. The largest component of these costs is generation upkeep (i.e. fixed and variable operations and maintenance costs), primarily due to the large existing stock of hydroelectric power plants, whose capital costs are not included.

Figure 3 breaks the total system cost down into components for all spatial restriction scenarios considered. In the most restrictive scenario (**Nature,Fauna,Sámi,Neigh**) all remaining cost components are overshadowed by the load shedding costs. This happens because the level **High** of the *Neigh* dimension allows for very little wind power generation investment. Lacking alternative expandable generation sources, the model is forced to shed some load, which comes at a cost. This indicates the significant societal impacts of this scenario. The reduction in generation investment, which also leads to reduced generation upkeep costs and combined make up €1 billion, do not offset this.

Figure 3 shows the cost increase of each component of the total system costs compared to the cheapest scenario, **None,** in absolute terms. The largest increase stems from storage investments in all but the **most restrictive scenario** where the cost of load shedding increases from negligible to almost €398 billion, making it the component increasing the most. Storage investment also more than doubles in scenarios with a High value for the nature dimension.

Storage investments, in increasingly restrictive scenarios, become necessary due to transmission grid limitations in Norway. This can be seen in figure a3 in the appendix, where Oslo (NO3) sees most battery capacity installed. Being the capital city, Oslo is an area with little electricity generation but a sizeable demand. A large part of the demand is satisfied through transmission from the enclaving neighbour region Viken (NO30), as depicted in figure A4. In figure A5, we see that in the **None** scenario, Viken (NO30) even sends electricity to its northern neighbour region Innlandet (NO34). But as scenarios become more restrictive, we can see in figure 7, that onshore wind generation capacity shrinks in Viken (NO30) and part of it moves to Innlandet (NO34). Now Oslo (NO03) and Viken (NO30) need to draw electricity from Innlandet (NO34), again seen in figure A5, and are sometimes limited by transmission grid capacity. This leads the model to provision storage capacity in large amounts in Oslo (NO03) to ensure demand is met at all hours.

To understand the monetary costs to society for imposing the land use restrictions in the different scenarios, figure 3 also shows how much more expensive (percentage wise) the scenarios are compared to the baseline scenario, **None**. Three categories form: scenarios with a cost increase of around 8% (∼€400 million), scenarios with an increase of roughly 17% (∼€860 million), and a scenario with an increase of 8007% (€398.9 billion) due to prohibitively expensive load shedding.

Figure 4 illustrates the system cost impacts of the assumption we make about restrictions on the expansion (depicted in blue) of the transmission grid in Norway. In orange, we can see what the system

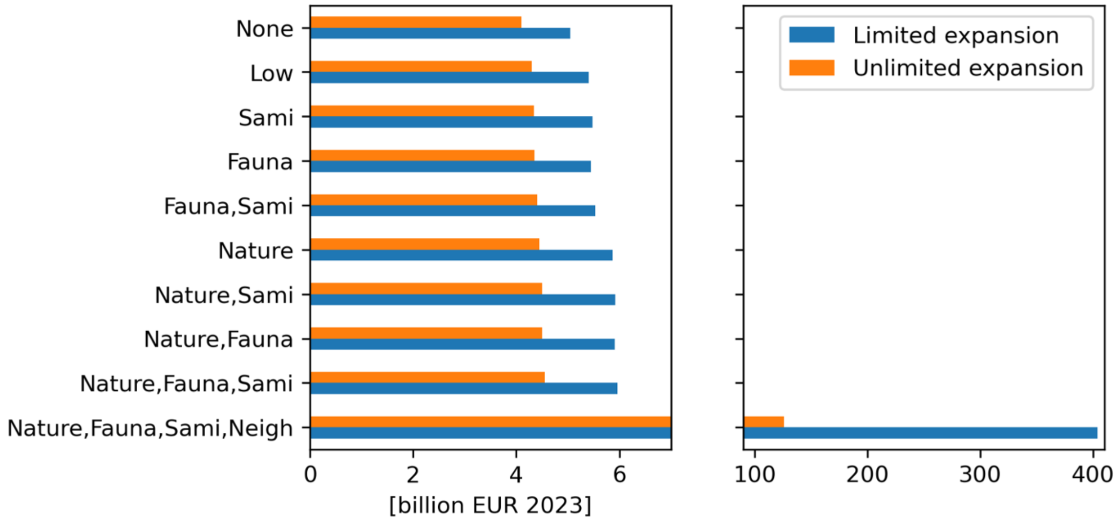

Figure 4. Total system cost when allowing for grid expansion vs. when running with projected 2030 grid.

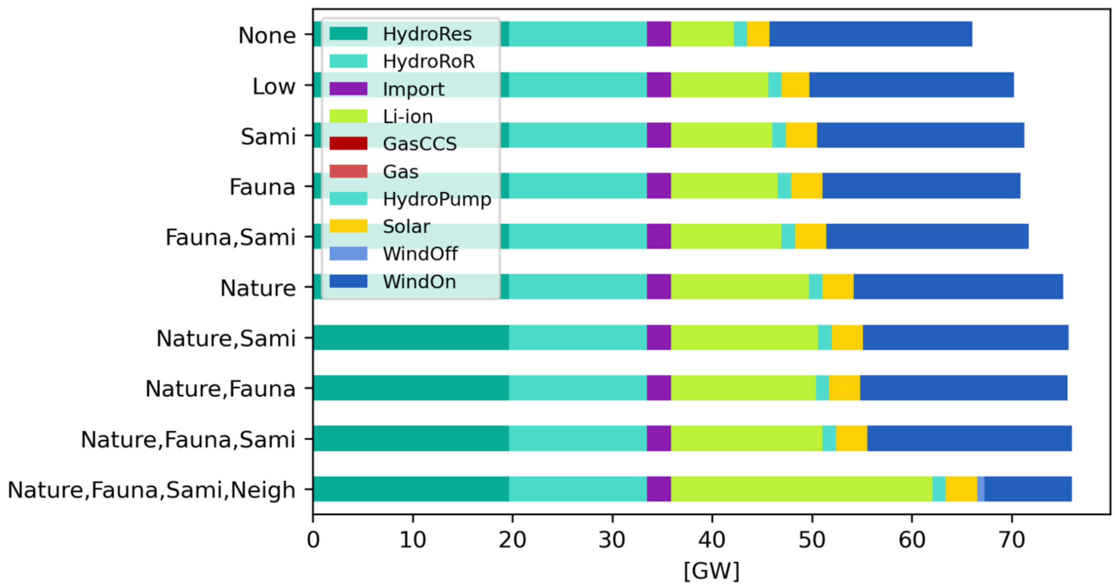

Figure 5. Norwegian installed generation and storage power capacity for reservoir hydropower, run-of-river hydropower, imports, lithium-ion battery storage, gas with carbon capture and storage, gas without carbon capture and storage, pumped hydropower, solar PV, offshore wind and onshore wind.

would cost if these assumptions were relaxed and investment into transmission expansion was possible. Total system cost levels would be lower by up to 30% (€1.4 billion) in most cases under unrestricted transmission expansion. Interestingly, we see that the substantial system costs in the most restrictive case have markedly reduced, demonstrating the immense value offered by extra flexibility when the system design is highly constrained.

3.2. Electricity system capacities

Figure 5 shows that with increasing limitations on the onshore wind deployment areas, battery storage capacity (Li-ion) increases. Note that hydropower capacity is pre-existing and, like import capacity, cannot be expanded by the model for the target year 2030.

Figure 6 shows that offshore wind power generation does not play a role in the designed energy system, except for a small amount in the most restrictive scenario. There is little variance in the results, with the usual exception of the **most restrictive** scenario. The reason there is variance at all is that the areas available to onshore wind change between scenarios, the installed capacity of it changes too. This means that the investments have to be slightly readjusted which either means the model has to substitute certain

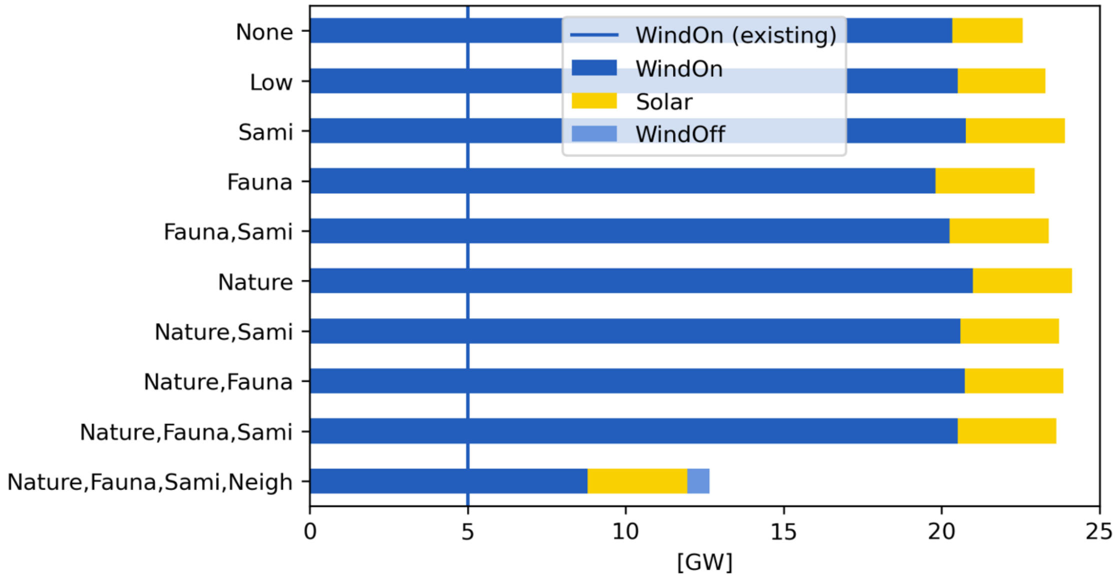

Figure 6. Norwegian optimal installed electricity generation capacity without hydropower and imports because they are fixed for 2030. The vertical line depicts the existing onshore wind capacity.

technologies in different regions (while keeping transmission in mind) or it has to turn to areas with slightly lower capacity factors, in turn increasing capacities. Still, as there is more area available than needed (see figure 2), many promising sites are still available in all scenarios except **Nature,Fauna,Sami,Neigh**.

In the most constrained scenario, for onshore wind and solar PV, all available area is being used. Due to bottom-mounted offshore wind having around twice the capital costs of onshore wind, it is outcompeted in all scenarios but the most constrained one. Due to limited transmission line capacity between the county where it makes landfall (Rogaland) and its neighbouring counties, the model cannot use the full offshore wind potential of 3 GW and only invests in 0.7 GW.

3.3. Spatial deployment of capacities

Figure 7 shows the amount of wind power *newly* installed in the eleven Norwegian counties and due to the model implementation the amount of currently installed wind power in the last scenario, as the model has to 'rebuild' the installed capacity. Even though the total amount of newly installed wind is fairly constant in almost all the scenarios, additional land use restrictions, force the model to shift the new wind installations into different counties. That is because locations with the best wind conditions are not available any more under progressively more restrictive land use scenarios, for which the model compensates by building more capacity in less windy regions. The model then generates more from solar energy combined with battery storage. This leads to increasing deployment in the south-eastern county 'Innlandet' (NO34). In general, the main regions that the model considers are 'Viken' (NO30), 'Troms og Finnmark' (NO54), 'Vestland (NO46)', 'Innlandet (NO34)' and 'Trøndelag' (NO50). The only scenario where the model does not install wind energy in Innlandet is None. In the other scenarios the model does not have enough land area and access to good capacity factors in the other regions and as a result it deploys more and more wind energy in Innlandet. Through the level High in the Nature dimensions, Innlandet ascends to the top three regions for new onshore wind.

Figure 7 also hints at why the model only chooses to invest in offshore wind in the most constrained scenario. There is almost no new onshore wind installed in Rogaland (NO11) (where most offshore wind could be built), as the region is self-sufficient on hydropower/imports in this model. This is due to the constrained transmission grid expansion, which leads to a bottleneck, so any additional generation in Rogaland cannot be moved out of the region.

4. Discussion and conclusions

In line with its climate goals, Norway's electricity demand is rising as a result of the electrification of transportation and industry. There are also efforts to diversify the economy away from oil and gas by fostering the growth of electricity-intensive industries. Norway is currently relying mostly on hydropower (30 GW) but the development potential is minimal. Over the last 10 years onshore wind has been expanded

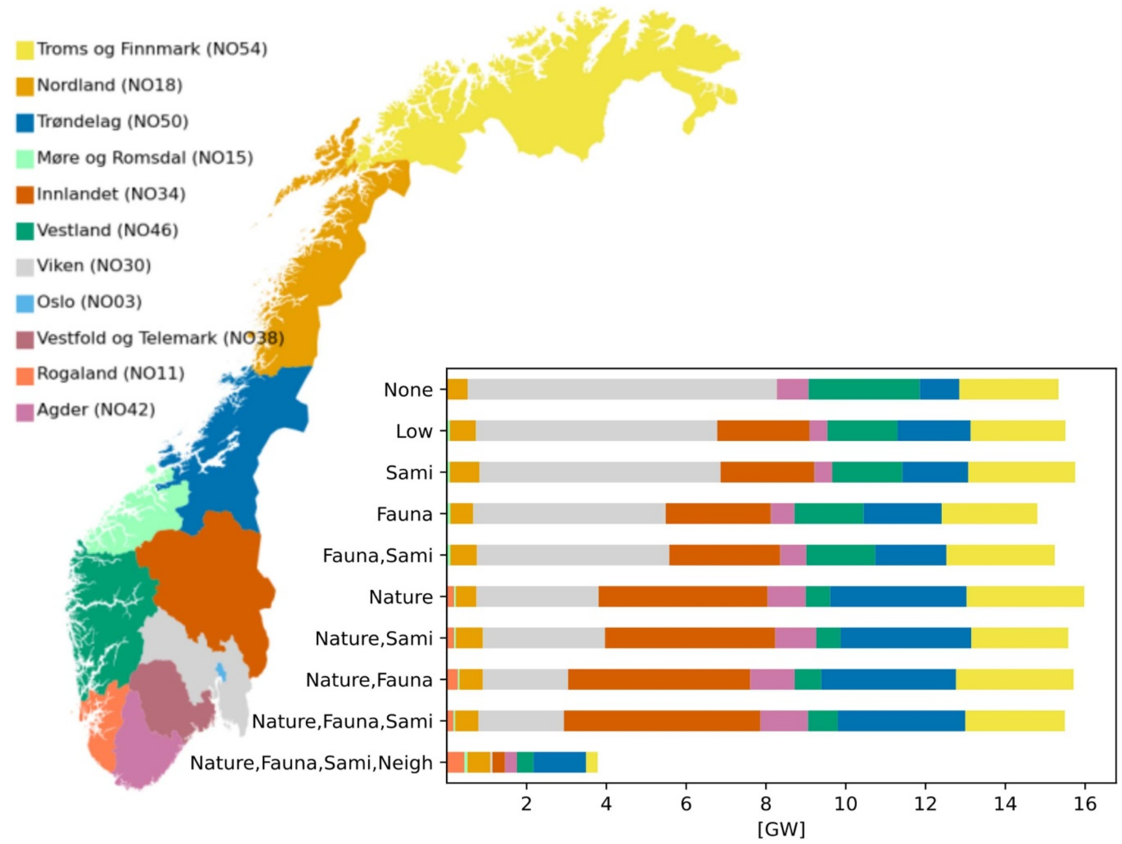

Figure 7. Spatial distribution of current (real) installed onshore wind generation capacity in GW [same as scenario Nature,Fauna,Sami,Neigh] and newly installed onshore wind generation capacity in GW per onshore wind restriction scenario.

to 5 GW; however due to strong opposition there have been no new projects built over the last 3 years. We explore the implications of key social and environmental dimensions, shaping the future deployment of onshore wind, on the costs and design of electricity systems for Norway in 2030.

The most constraining scenario (combined with assumed low PV expansion, limited importing capacity, difficult meteorological conditions for hydropower), which effectively means that wind energy is not visible from anyone's house (using a distance of 50 km between houses and wind turbines) reduces the possible maximum installed capacity for onshore wind from 580 GW to 4 GW. While this may look extreme, current opposition towards onshore wind, together with the desire for low electricity prices and the resulting policy discussion about limiting interconnectors (and therefore imports), could make such a scenario reality. The result of this heavily constrained scenario (which we designed to mimic current policy direction and public opinion), which opts to prioritise minimising the social and environmental impacts of onshore wind deployment, is that load needs to be shed. So the most restrictive scenario puts a high priority on local environmental protection, but that may impact Norway's efforts to mitigate climate change. This shed load is assumed to be highly costly, as it captures the socio-economic implications of not being able to serve demand. It means that the system is no longer reliable and in practice could mean leaving emissions targets behind, phasing out existing electricity-intensive industries, adapting behaviour, or importing energy. Imports are tight already, they reduce energy security and also increase emissions in practice as electricity from the rest of Europe is more CO_2 intensive and thus trade-offs between unpopular wind power and unpopular alternatives need to be considered. This situation is complicated by the layout and size of the grid in Norway and the fact that it is not possible to expand it beyond the plans in implementation until 2030. Relaxing any of those assumptions (e.g. speeding up PV deployment or allowing more imports) allows for cheaper system designs, emphasising the significant advantages of incorporating extra flexibility when the system design is tightly constrained.

Strong protection of nature leads to an increase in total system costs of about 9 percentage points in costs, as well as an increase in installed battery storage capacity. There is also a noticeable shift of the location of newly installed wind capacity from populous Viken to Innlandet. From the spatial perspective, the cost-optimal solution concentrates wind power in the windiest counties and close to demand, which is in the South of Norway as we assume transmission to be fixed to current limits. With increasing land use restrictions, wind power installation is forced to spread out to less windy regions further away from demand, combined with storage. When the model can invest in transmission expansion, total system costs are lowered even in the most stringent scenario.

Amongst others, limitations of this study are the simplified modelling of neighbouring countries and imports, the simplified modelling of demand side response (through load shedding), the fact that only Norwegian geodata is used for excluding areas. Especially in the high levels of many dimensions, buffers are applied, which may impact Norwegian territory, even if the source of the exclusion does not lie in Norway. Future research could use participatory approaches (e.g. workshops with stakeholders) to co-design the exclusion/restriction scenarios.

Cook (2024) describes how the Kaldor–Hicks model has been used in decision-making about energy infrastructure construction projects. This suggests that compensation payments from the project developer to impacted communities could allow for projects being built, as long as the compensation required is smaller than the benefit the project developer draws from the construction. Yet, the model only requires potential for compensation, not actual compensation flows, which Cook (2024) criticises. If applied with actual compensation, this could open areas previously unavailable and ease the system planning. This avenue merits further investigation.

Concluding from this, Norway will need more flexibility due to rising electricity demand. This is in part due to the planned electrification of oil platforms and a general diversification away from oil to other industries that are often energy intensive. By 2030 this flexibility could come from different sources: increased transmission capacity (as seen in the transmission expansion cases), increased wind generation capacity (as seen in most cases of this study, increased storage capacity (as seen in all cases of this study), increased import volumes/capacity, demand side flexibility/reduction, reduced electrification.

However, each of these choices will lead to different costs and socio-environmental challenges. What is evident is that restricting wind energy will likely make the electricity system more costly. Opting not to build new wind and limiting transmission expansion can lead to blackouts resulting in large societal impacts (modelled here as up to €400 billion per year based on the lost load assumption in our modelling). In reality, this could mean missing climate targets or failing to meet the objectives of industrial policy (the additional demand would not be allowed to come online after all (e.g. industry, oil & gas electrification)). The central insight of this analysis is that the strict level **High** of the neighbour dimension is completely incompatible with projected electrification. That is, some onshore wind will be needed one way or the other in order to meet demand by 2030, and the **High** level of the neighbour dimension does not leave enough land for that. Yet, when reducing the restrictions on onshore wind or allowing for in-country transmission expansion, feasible system designs at a small fraction of that cost can be found. As such, people might have to accept wind power closer to their homes than they would like.

The power deficit is likely to increase over the following decades with progressing electrification, therefore examining the situation for 2040 or 2050 is recommended for further research.

Yet, we are nearly five years away from 2030 and any infrastructure that we require to be online by then needs to be decided on today and implemented rapidly. Our analysis can help policymakers, regulators and the public make informed compromises as all options come at a monetary and socio-environmental cost. However, if no informed decision is made today, costs are likely to be very high.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.14621105.

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Appendix

A.1. Case selection: Why Norway?

The Norwegian power system is facing an increase in electricity demand from the electrification of transport, heating and industry, while the traditional generation source (hydropower) is not able to meet all of this increase due to environmental limits.

This leads to concerns about a power deficit by 2030 (Statnett 2024) which we choose as the target year of the analysis.

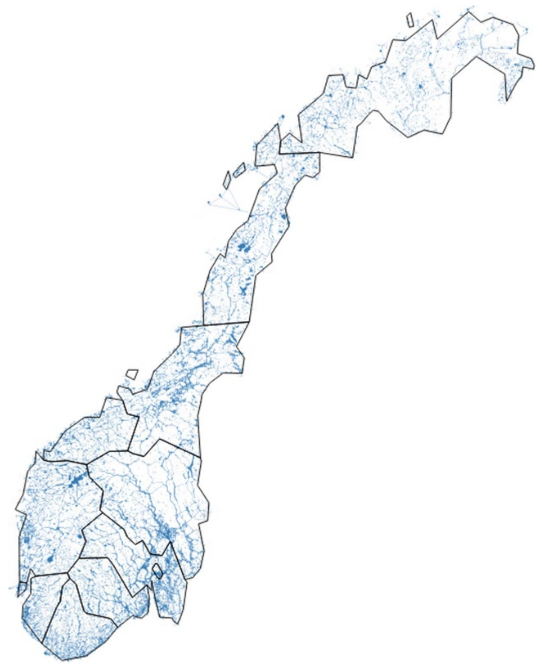

Figure A1. Technical restrictions.

The most cost-effective new sources of electricity generation are wind and solar power. Norwegian geography allows for some of the best on- and offshore wind resources in Europe (Karlstrøm and Ryghaug 2014, Egging and Tomasgard 2018). Norway has developed a great deal of expertise in offshore technology through the oil and gas sector, and is in a good position to play a role in the offshore wind sector. Both Equinor (the Norwegian state-owned petroleum company) and the Norwegian energy production industry are involved in the development of the largest offshore wind farms in Europe and the United States, including bottom-mounted and floating turbines. Nonetheless, floating wind power is a technology that is still transitioning from the demonstration stage to full-scale testing, and therefore cannot be considered a key technology to meet 2030 decarbonisation goals (emissions reduction by at least 50% and towards 55% compared to 1990 levels) (Meld. St. 13 (2020–2021) 2021).

Furthermore, even though licence applications have been opened for offshore wind renewable energy production in 2021, on average, applications take an average of five-and-a-half years (Gulbrandsen *et al* 2021). As a result, in Norway, onshore wind and solar power currently offer the greatest potential for new renewable energy production to reach its 2030 decarbonisation goals, as is also the case for other countries in the Nordic region.

However, onshore wind energy projects in Norway are facing opposition from nature conservation and recreational groups, and local communities (Karlstrøm and Ryghaug 2014, Gulbrandsen *et al* 2021). Wind farms, as well as solar power often require large areas that can have an impact on connectivity areas for fauna and ecosystems, which may cause disturbance and habitat fragmentation for mammals, birds and other animals (Gilad *et al* 2024).

In 2019, the NVE proposed a map of 13 major geographical areas regarded as most suitable for locating onshore wind power in Norway amounting to 29 000 km^2 (Norwegian Water Resources and Energy Directorate 2019b). These roughly 9% of the total land area of Norway could correspond to up to 290 GW of onshore wind power, if fully used according to the density mentioned in the framework. In this map, the NVE placed emphasis on avoiding conflicts with protected natural areas, outdoor life, noise, birds and wildlife, cultural heritage and reindeer husbandry. However, after a round of consultations with municipalities, ministries, the Sámi Parliament, nature conservation associations, and outdoor life associations among other organisations and individuals which were critical to the plan, the government decided to scrap the proposed framework (Gulbrandsen *et al* 2021). Instead, the NVE has published a white paper on measures for tightening the processing of wind power concessions, where more consideration is given to impacts on landscapes, the environment, society, and neighbours (Meld. St. 28 (2019-2020) 2020).

While it is a socio-political decision to choose more expensive technologies, sites or mitigation options to minimise the socio-environmental impacts of VRE development, a spatially-explicit capacity assessment under different socio-environmental scenarios is missing to allow for such discussion. Here, we close this gap by performing a nationally specific analysis: we first study the NVE framework, previous licences, literature, and newspaper articles to design three scenarios of socio-environmental acceptance for onshore/offshore wind and solar energy. Based on the developed scenarios, we then conduct a GIS analysis to determine the spatially dependent capacity potential per technology and scenario.

The NVE's onshore wind power framework consists of an updated basis of knowledge and a map where 13 areas are regarded as most suitable for locating wind energy. These consider factors such as untouched nature, nature types, fauna, landscapes, outdoor life, cultural heritage, Sámi interests and populated areas (Norwegian Water Resources and Energy Directorate 2019a). The framework is neither a development plan nor legally binding, but was meant to be a guiding document to select adequate areas to install wind farms. Net capacity and transmission grids are included in the framework.

The Energy Act regulates the planning of onshore energy production in Norway. The NVE does an assessment for every licence application based on whether the advantages of the project are higher than the effects on public and private interests. These interests include nature conservation, cultural heritage, landscape outdoor life, migration of birds, fish, Sámi interests and local communities[6]. As an example, nature's value is protected through the Nature Diversity Act[7] and shall ensure biological and geological diversity today and in the future[8].

A.2. Model changes

Compared to the version employed by Price *et al* (2018), we change the modelled battery technology from Sodium Sulphur to Lithium-ion batteries. We change the weather data from using the year 2006–2010, which we choose based on (Price *et al* 2023). The land use constraints also differ and are described in section 2.3. Water availability is not taken into account in this paper, as thermal generation is not very relevant in the Norwegian context.

The workflow management system snakemake (Mölder *et al* 2021) is employed to automate the process of preparing the required input data, running the model and converting the model output for each of the scenarios. We conduct the analysis in Python using Jupyter notebooks.

Version 0.2.4 of atlite is used. A slight modification is added, to be able to extract the weather data on a grid cell level (of the reanalysis data), compared to the default which is to aggregate over time or space.

The possibility exists that some existing wind power was built in areas that would be excluded from wind power development in this analysis. We therefore first add the locations of existing wind power to the exclusion zones. To guarantee that wind can be built by the model in those zones where wind power exists, we calculate a second exclusion zone that excludes all area except for area that hosts currently installed plants. Next, we add both matrices containing the exclusions to result in a matrix that excludes the desired areas according to the scenario guidelines, but also includes (in the buildable zones) areas where wind already exists.

Since the exclusion amounts are measured in area (km^2) but the existing wind power is quantified in installed power (MW) and the locations of existing parks are points without an area, we create a buffer around those points according to the assumed installation density (MW km^{-2}) and the installed capacity at this point. We feed the resulting area from this process into the workflow described in the paragraph above.

A.3. Data description

A.4. Electricity demand

Electricity demand is modelled according to a consumption prognosis by the Norwegian transmission system operator, Statnett (2023a). The methodology is previously described in (Hansson *et al* 2023) and only additional details follow here. The changes in electricity demand between 2022 and 2030 resulting from the prognosis is summarised in table A4.

Historical demand at hourly resolution for 1951–2021 is scaled so that the average yearly demand equals 140 TWh and yearly variation is kept. The 10 TWh from electric transport is distributed temporally, using an electric vehicle load curve from Sørensen *et al* (2022), and temporally as described in (Hansson *et al* 2023). The 12 TWh from industry is distributed spatially based on each county's share of total energy use in industry from (Norderhaug 2023). Of the 11 TWh from the petroleum sector, 4 TWh is allocated to electrification of onshore gas processing plants: 3.6 TWh in Troms og Finnmark (Hovland 2022) and 0.4 TWh in Vestland (Spilde *et al* 2020). The remaining 7 TWh is distributed evenly between twelve different offshore petroleum plants with potential for electrification: seven in Vestland, one in Møre og Romsdal, two in Trøndelag, and two in Troms og Finnmark (Statnett 2023a).

[6] Ot.prp.nr. 43 (1989–90) s. 84.
[7] Act relating to the management of biological, geological and landscape diversity [Nature Diversity Act].
[8] Ot.prp.nr. 52 (2008–2009) page 371.

Table A1. Overview of the Corine land cover classes which were excluded for solar PV deployment.

Incremental ID	Semantic ID	Top level category	Mid-level Category	Sublevel category
2	112	Artificial surfaces	Urban fabric	Discontinuous urban fabric
4	122	Artificial surfaces	Industrial, commercial and transport units	Road and rail networks and associated land
5	123	Artificial surfaces	Industrial, commercial and transport units	Port areas
6	124	Artificial surfaces	Industrial, commercial and transport units	Airports
10	141	Artificial surfaces	Artificial, non-agricultural vegetated areas	Green urban areas
11	142	Artificial surfaces	Artificial, non-agricultural vegetated areas	Sport and leisure facilities
12	211	Agricultural areas	Arable land	Non-irrigated arable land
13	212	Agricultural areas	Arable land	Permanently irrigated land
14	213	Agricultural areas	Arable land	Rice fields
15	221	Agricultural areas	Permanent crops	Vineyards
16	222	Agricultural areas	Permanent crops	Fruit trees and berry plantations
17	223	Agricultural areas	Permanent crops	Olive groves
18	231	Agricultural areas	Pastures	Pastures
19	241	Agricultural areas	Heterogeneous agricultural areas	Annual crops associated with permanent crops
20	242	Agricultural areas	Heterogeneous agricultural areas	Complex cultivation patterns
21	243	Agricultural areas	Heterogeneous agricultural areas	Land principally occupied by agriculture, with significant areas of natural vegetation
22	244	Agricultural areas	Heterogeneous agricultural areas	Agro-forestry areas
23	311	Forest and semi natural areas	Forests	Broad-leaved forest
24	312	Forest and semi natural areas	Forests	Coniferous forest
25	313	Forest and semi natural areas	Forests	Mixed forest
34	335	Forest and semi natural areas	Open spaces with little or no vegetation	Glaciers and perpetual snow
35	411	Wetlands	Inland wetlands	Inland marshes
36	412	Wetlands	Inland wetlands	Peat bogs
37	421	Wetlands	Maritime wetlands	Salt marshes
38	422	Wetlands	Maritime wetlands	Salines
39	423	Wetlands	Maritime wetlands	Intertidal flats
40	511	Water bodies	Inland waters	Water courses
41	512	Water bodies	Inland waters	Water bodies
42	521	Water bodies	Marine waters	Coastal lagoons
43	522	Water bodies	Marine waters	Estuaries
44	523	Water bodies	Marine waters	Sea and ocean

The electricity consumption of battery production and data centres is according to Statnett's prognosis expected to increase by 5 TWh from 2022 to 2030 (Statnett 2023a). However, we have identified planned battery factories that alone could make up more than 8 TWh of electricity demand in 2030. Four factories for battery production are planned in Norway, with annual production capacity of 43 GWh in Agder by 2028 (Morrow Morrow Batteries 2023), 200 GWh (we assume 50 GWh as this capacity might not be realised by 2030) in Nordland by 2030 (FREYR Battery 2022), 40 GWh in Trøndelag by 2030 (Elinor Batteries, 2023), and a factory in Rogaland with unknown production capacity (Beyonder, n.d.) (we assume 30 GWh by 2030). To go from the production capacity to electricity consumption, we apply an electricity use per GWh battery production of 50 GWh (Kurland 2019). Demand from battery production is distributed spatially

Table A2. Upper capacity limits per Norwegian county.

Zone	Import (GW)	PV (GW)
NO03	0	0.281
NO11	0.35	0.265
NO15	0	0.076
NO18	0.23125	0.024
NO30	0.53	0.728
NO34	0	0.276
NO38	0	0.386
NO42	0.7625	0.26
NO46	0.35	0.218
NO50	0.2	0.638
NO54	0.03	0.007

Table A3. Transmission capacities between Norwegian counties.

Zone 1	Zone 2	Link capacity (MW)
NO03	NO30	3000
NO11	NO38	900
NO11	NO42	1200
NO11	NO46	750
NO15	NO34	500
NO15	NO46	3000
NO15	NO50	1350
NO18	NO50	1350
NO18	NO54	600
NO30	NO34	7000
NO30	NO38	500
NO30	NO46	3900
NO34	NO50	600
NO38	NO42	1200

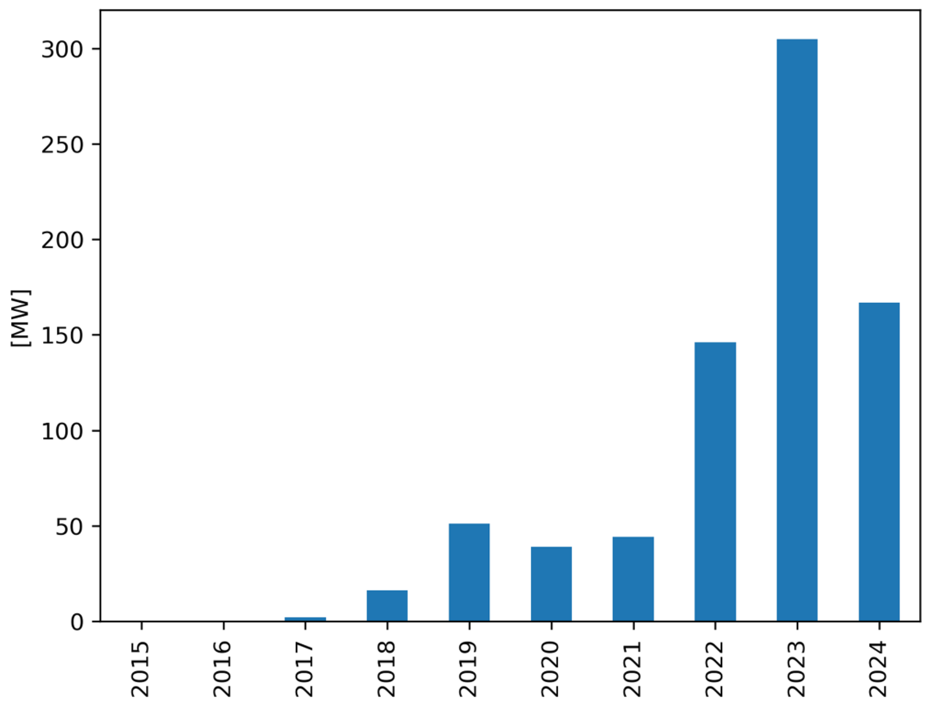

Figure A2. Solar capacity additions in Norway from 2015 to 2024 in megawatts (MW).

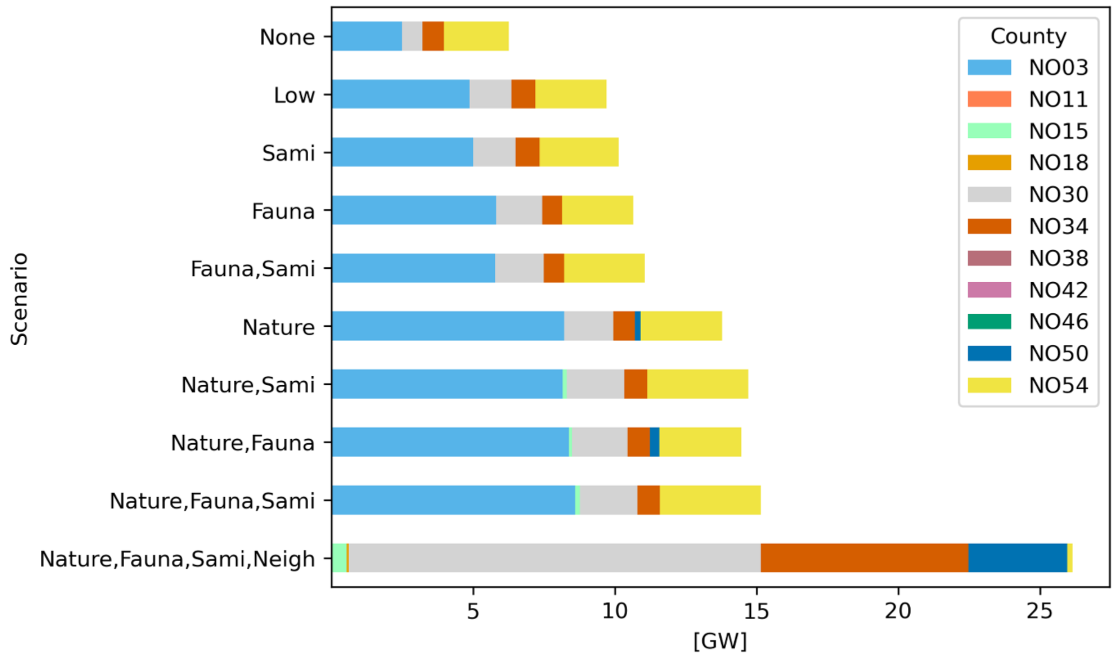

Figure A3. Spatial battery capacity investments in Norway for the scenarios.

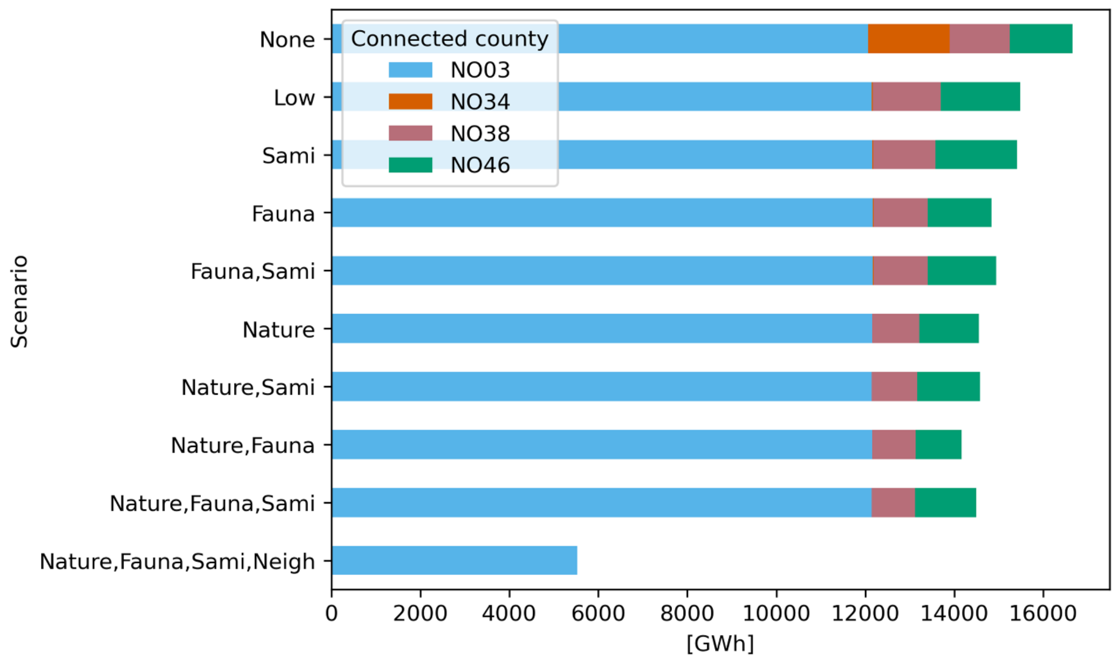

Figure A4. Electricity flow from NO30 (Viken) to adjacent counties.

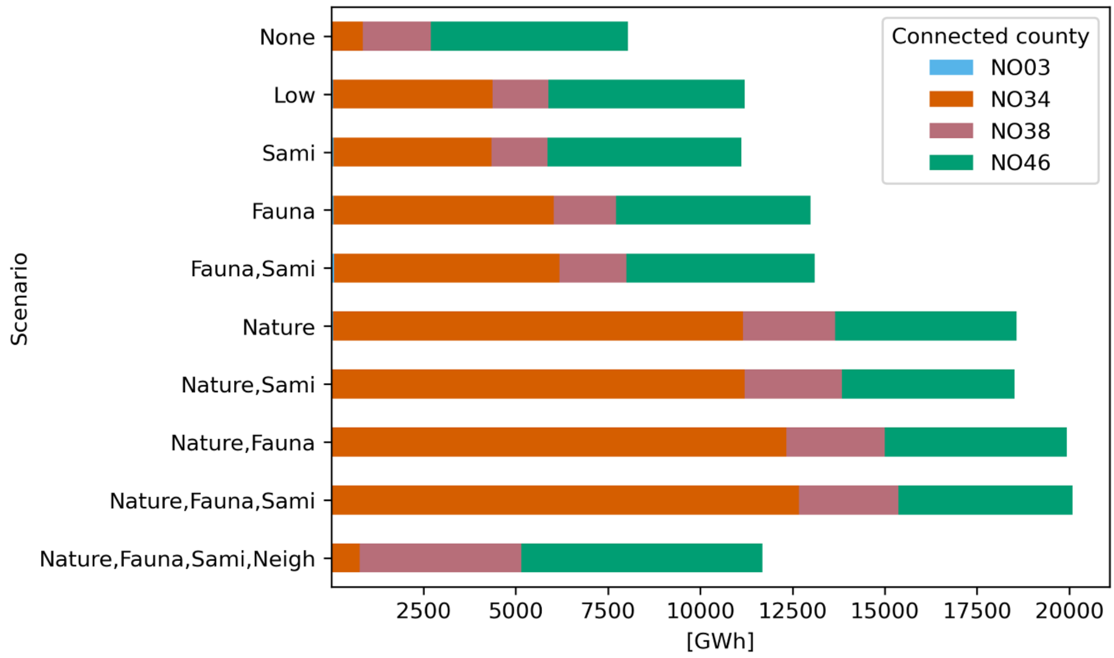

Figure A5. Electricity flow to NO30 (Viken) from adjacent counties.

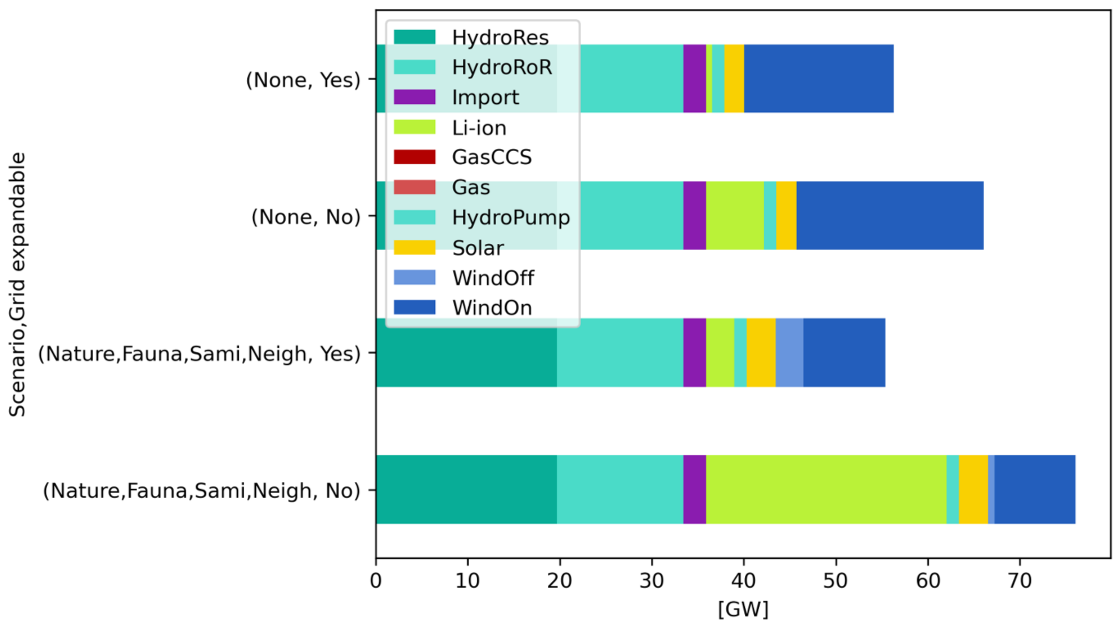

Figure A6. Norwegian installed generation and storage power capacity compared for scenarios with no transmission grid expansion and scenarios with transmission grid expansion.

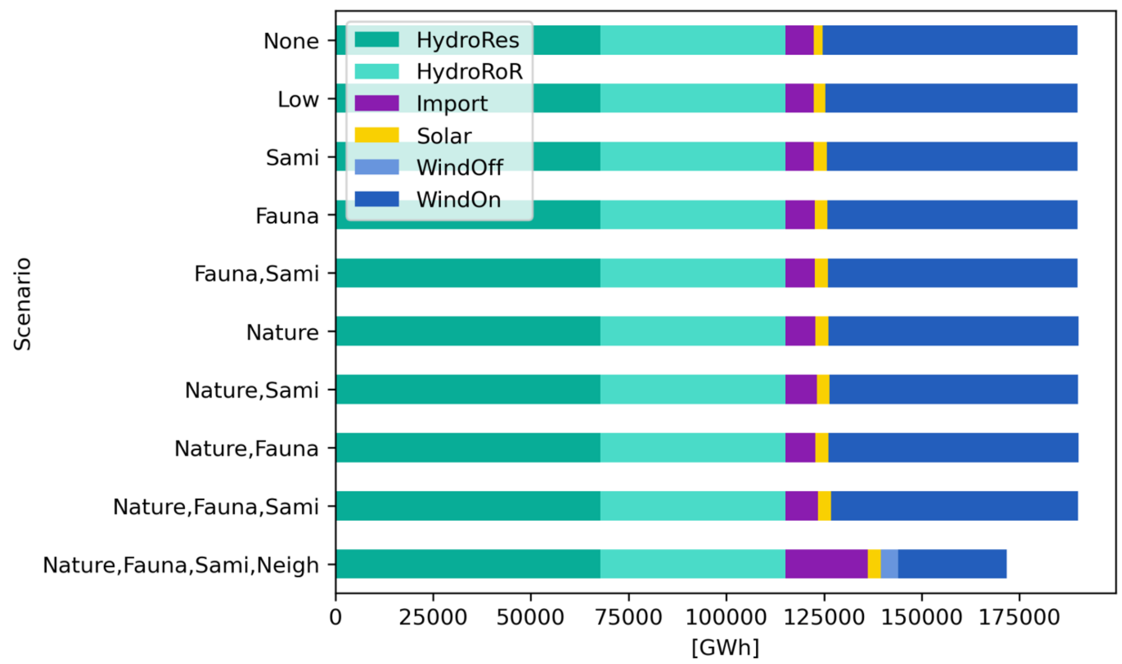

Figure A7. Electricity generation from different technologies per scenario.

Table A4. Electricity consumption in 2022 and prognosis for 2030, from Statnett (2023a).

Sector	2022 (TWh)	2030 (TWh)	Change (TWh)
Battery production and data centres	1	6	5
Petroleum	9	20	11
Industry	47	59	12
Electric transport	3	13	10
Other consumption	80	79	−1
Total	140	178	38

based on the identified factories. Of the 2 TWh from data centres, 1.3 TWh is allocated to Innlandet based on a planned data centre (Vogt *et al* 2023) while the rest is evenly distributed between the other counties.

A.5. Geodata

Technical constraints	
Variable	Data set
Roads—200 m buffer	https://kartkatalog.geonorge.no/metadata/kartverket/vbase/96104f20-15f6-460e-a907-501a65e2f9ce Title: Vbase Format: shape
Railway 200 m buffer	https://kartkatalog.geonorge.no/metadata/bane-nor-sf/jernbane-banenettverk/c3da3591-cded-4584-a4b1-bc61b7d1f4f2 Title: Jernbane–Banenettverk Format: GML
Airports 2 km buffer	https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download Select by attribute: clc18_kode = 124 Data explanation: https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html/index-clc-124.html

Water courses	https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download Select by attribute: clc18_kode = 511 Data explanation: https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html/index-clc-511.html
Water bodies	https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download Select by attribute: clc18_kode = 512 Data explanation: https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html/index-clc-512.html
Glaciers	https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download Select by attribute: clc18_kode = 335 https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html/index-clc-335.html
Gradients steeper than 20 deg	https://hoydedata.no/LaserInnsyn/ Click: Nedlasting -> Landsdekkende -> Velg UTM-sone 33 -> DTM50 Needed to merge the data
Neighbours	
Low exclusion	
Variable	Data set
Buildings—400 m buffer	https://kartkatalog.geonorge.no/metadata/kartverket/n250-kartdata/442cae64-b447-478d-b384-545bc1d9ab48 Title: N250 Kartdata Format: SOSI Folder: Arealdekke Select by attribute: OBJTYPE = BymessigBebyggelse
Agglomerations—1 km buffer	https://kartkatalog.geonorge.no/metadata/kartverket/n250-kartdata/442cae64-b447-478d-b384-545bc1d9ab48 Title: N250 Kartdata Format: SOSI File: Arealdekke Select by attribute: OBJTYPE = Tettbebyggelse
Walking routes, ski runs, biking routes other-routes—20 m buffer	https://kartkatalog.geonorge.no/metadata/uuid/d1422d17-6d95-4ef1-96ab-8af31744dd63 Title: Tur- og friluftsruter
Cultural heritage: • Sikringssoner • Brannsmitteområder • Lokaliteter	https://kartkatalog.geonorge.no/metadata/riksantikvaren/kulturminner-sikringssoner/0a3251bb-2a50-45d3-8674-58bade2fe673 Title: Kulturminner—Sikringssoner Fortmat: FGDB https://kartkatalog.geonorge.no/metadata/riksantikvaren/kulturminner-brannsmitteomrader/73f863ba-628f-48af-b7fa-30d3ab331b8d Title: Kulturminner–Brannsmitteområder Format: FGDB https://kartkatalog.geonorge.no/metadata/riksantikvaren/kulturminner-lokaliteter/c6896f24-71f9-4203-9b6f-faf3bfe1f5ed Title: Kulturminner–Lokaliteter Format: FGDB

Fauna	
Low restriction	
Variable	Dataset
IBA—Important Bird Areas	Needed to request data from http://datazone.birdlife.org/site/requestgis
Very important nature for biodiversity	https://kartkatalog.miljodirektoratet.no/Dataset/Details/10 Chose Norge uten Svalbard and select viktige naturtyper. Select by attribute: BMVERDI = S

Nature	
Low exclusion	
Variable	Dataset
Strict nature reserve—IUCN = 1a	https://kartkatalog.geonorge.no/metadata/uuid/5857ec0a-8d2c-4cd8-baa2-0dc54ae213b4 Title: Naturvernområder Format: SOSI Select by attribute: IUCN = 1

Sámi reindeer herding	
Low exclusion	
Variable	Dataset
Winter grazing land (Minimum grazing land)	https://kartkatalog.geonorge.no/metadata/landbruksdirektoratet/reindrift-arstidsbeite-vinterbeite/63f655ef-f625-43cf-a512-bb8164bf53a4 Title: Reindrift–Årstidsbeite–Vinterbeite Format: SOSI
Calving area	https://kartkatalog.geonorge.no/metadata/landbruksdirektoratet/reindrift-arstidsbeite-varbeite/fa02a652-cd6d-4828-9fb5-7bd4515aa6d0 Title: Reindrift–Årstidsbeite–Vårbeite Format: SOSI Select by attribute: kodenavn = Vårbeite I

PV	
Low exclusion	
Variable	Dataset
Land used for agriculture	https://kartkatalog.geonorge.no/metadata/norsk-institutt-for-biookonomi/arealressurskart-ar50-jordbruk/76255ebe-2a0e-401e-87c8-7618dd196cf2 Title: Arealressurskart–AR50–Jordbruk Format: SOSI, GML SOSI: Akershus, Aust Agder, Buskerd, Finnmark, Hordaland, MøreRomsdalen, Oslo, Rogaland, Romsa Troms, Sogn Fjordane, Telemark, Vest Agder, Vestfold, Østfold GML: Hedmark, Nordland, Oppland Select by attribute: Artype = 20
Very good soil quality	https://kartkatalog.geonorge.no/metadata/norsk-institutt-for-biookonomi/jordkvalitet/35c38144-c0a0-4ed9-a66f-21b80bc17fa7 Title: Jordkvalitet Format: SOSI Needed to download every region by itself and then merge them Select by attribute JORDKVALIT = 1

Offshore	
Low exclusion	
Variable	Dataset
3 km buffer around coast and islands	https://kartkatalog.geonorge.no/metadata/kartverket/n250-kartdata/442cae64-b447-478d-b384-545bc1d9ab48 Title: N250 Kartdata Folder: Arealdekke Select by attribute: OBJTYPE = Kystkontur
Marine Protected Areas (IUCN = 1a)	www.protectedplanet.net/c/monthly-updates/2019/july-2019-update-of-the-wdpa Select by attribute: MARINE = 1 AND IUCN_CAT = Ia
Coral Reef	https://kartkatalog.geonorge.no/metadata/fiskeridirektoratet/korallrev-forbudsomrader/3be8f59c-cf30-47b5-ab5d-61abab25942b Title: Korallrev–forbudsområder Format: SOSI
Naturetypes: Slåttmark and Slåttmyr	https://kartkatalog.miljodirektoratet.no/Dataset/Details/10 Chose Norge uten Svalbard and selected viktige naturtyper Select by attribute: NATURTYPE = Slåtte—og beitemyr and Slåttemark
Ship traffic buffer: 500 m (Other boat routes, car ferry, passenger ferry)	https://kartkatalog.geonorge.no/metadata/kartverket/n250-kartdata/442cae64-b447-478d-b384-545bc1d9ab48 Title: N250 Kartdata Folder: Samferdsel Files: Annen-Båtrute, Bilferjestrekning, Passasjerferjestrekning
Fields and pipeline	Download data from: http://factpages.npd.no/ReportServer?/FactPages/geography/geography_all&rs:Command=Render&rc:Toolbar=false&rc:Parameters=f&IpAddress=1&CultureCode=nb-no Data description (Attributter): http://factpages.npd.no/factpages/Default.aspx?culture=nb-no&nav1=wellbore

Neighbours	
High exclusion	
Variable	Dataset
Cultural heritage: Kulturmiljøer, sikringssoner, lokaliteter, brannsmitteområder	https://kartkatalog.geonorge.no/metadata/riksantikvaren/kulturminner-kulturmiljoer/17adbcac-bbb2-4efc-ab51-756573c8f178 Title: Kulturminner–Kulturmiljøer Format: FGDB
Walking routes, ski runs, biking routes other-routes—2 km buffer	

Fauna	
High restriction	
Variable	Dataset
IBA—Important Bird Areas 3 km buffer	
All areas important for biodiversity	https://kartkatalog.miljodirektoratet.no/Dataset/Details/10 Chose Norge uten Svalbard and select viktige naturtyper.
All wild reindeer areas	https://kartkatalog.geonorge.no/metadata/miljodirektoratet/villreinomrader/fc59e9a4-59df-4eb3-978a-1c173b84bf4e Title: Vilreinområder Format: FGDB
Arter av veldig stor og stor forvaltningsinteresse (Species of very important and important management)	https://kartkatalog.geonorge.no/metadata/miljodirektoratet/a8456aed-441a-40c4-831f-46bcbe4e6ff1 Format: GDB Select by Attribute: BM_TAKSON_BMFORVALTNINGSKATEGORI = 1 (very important) = 2 (important)

Nature	
High exclusion	
Variable	Dataset
Strict nature reserve— IUCN = 1a, 1b II 5 km buffer + all IUCN categories	https://kartkatalog.geonorge.no/metadata/uuid/5857ec0a-8d2c-4cd8-baa2-0dc54ae213b4 Title: Naturvernområder Format: SOSI
Kystlinghei 5 km buffer	https://kartkatalog.miljodirektoratet.no/Dataset/Details/10 Chose Norge uten Svalbard and selected viktige naturtyper. Select by attribute: NATURYPE = Kystlinghei

Sámi reindeer herding	
High exclusion	
Variable	Dataset
All areas used by reindeer: Migratory zones, All seasons grazing land, Concession permit regions, Expropriation areas, Grazing zones, Enclosed grazing sites, gathering sites	https://kartkatalog.geonorge.no/metadata/uuid/f9c1e228-892f-4f1a-9e4e-b6d6149f373c Title: Reindrift–Flyttlei Format: SOSI https://kartkatalog.geonorge.no/metadata/landbruksdirektoratet/reindrift-arstidsbeite-vinterbeite/63f655ef-f625-43cf-a512-bb8164bf53a4 Title: Reindrift–Årstidsbeite–Vinterbeite Format: SOSI https://kartkatalog.geonorge.no/metadata/landbruksdirektoratet/reindrift-arstidsbeite-hostbeite/6383f5a8-3a4d-48fc-8c67-f1eeec24fd8b Title: Reindrift–Årstidsbeite–Høstbeite Format: SOSI https://kartkatalog.geonorge.no/metadata/landbruksdirektoratet/reindrift-arstidsbeite-hostvinterbeite/85a4c5e3-25ab-427c-b664-bbac2d0c9e79 Title: Reindrift–Årstidsbeite–Høstvinterbeite Format: SOSI https://kartkatalog.geonorge.no/metadata/landbruksdirektoratet/reindrift-arstidsbeite-varbeite/fa02a652-cd6d-4828-9fb5-7bd4515aa6d0 Title: Reindrift–Årstidsbeite–Vårbeite Format: SOSI https://kartkatalog.geonorge.no/metadata/landbruksdirektoratet/reindrift-arstidsbeite-sommerbeite/d5d1e2d4-7dc0-47ce-8776-ff64b07d788e Title: Reindrift–Årstidsbeite–Sommerbeite Format: SOSI https://kartkatalog.geonorge.no/metadata/landbruksdirektoratet/reindrift-konsesjonsomrade/49efb2b2-93 × 103-4175-b10b-65b509d73c2a Title: Reindrift- Konsesjonsområde Format: SOSI https://kartkatalog.geonorge.no/metadata/landbruksdirektoratet/reindrift-ekspropriasjonsomrade/1c64c5ff-0069-4f8e-9a2b-948c7ce3d527 Title: Reindrift- Ekspropriasjonsområde Format: SOSI https://kartkatalog.geonorge.no/metadata/landbruksdirektoratet/reindrift-reinbeiteomrade/d02dc4bd-77d5-4b3b-a316-5a488b6fe811 Title: Reindrift–Reinbeiteområde Format: SOSI https://kartkatalog.geonorge.no/metadata/landbruksdirektoratet/reindrift-beitehage/df2db95d-adbc-4807-bb46-00b729caed7c Title: Reindrift-Beitehage Format: SOSI https://kartkatalog.geonorge.no/metadata/landbruksdirektoratet/reindrift-oppsamlingsomrade/a02e84ec-322c-47a7-a626-ca02d57d1f7e Title: Reindrift- Oppsamlingsområde Format: SOSI

PV	
High exclusion	
Variable	Dataset
Land used for agriculture	https://kartkatalog.geonorge.no/metadata/norsk-institutt-for-biookonomi/arealressurskart-ar50-jordbruk/76255ebe-2a0e-401e-87c8-7618dd196cf2 Title: Arealressurskart—AR50—Jordbruk Format: SOSI, GML SOSI: Akershus, Aust Agder, Buskerd, Finnmark, Hordaland, MøreRomsdalen, Oslo, Rogaland, Romsa Troms, Sogn Fjordane, Telemark, Vest Agder, Vestfold, Østfold GML: Hedmark, Nordland, Oppland Select by attribute: Artype = 20
All soil qualities	https://kartkatalog.geonorge.no/metadata/norsk-institutt-for-biookonomi/jordkvalitet/35c38144-c0a0-4ed9-a66f-21b80bc17fa7 Title: Jordkvalitet Format: SOSI Needed to download every region by itself and then merge them Select by attribute JORDKVALIT = 1 and 2

Offshore	
High exclusion	
Variable	Dataset
10 km buffer around coast and islands	https://kartkatalog.geonorge.no/metadata/kartverket/n250-kartdata/442cae64-b447-478d-b384-545bc1d9ab48 Title: N250 Kartdata Folder: Arealdekke Select by attribute: OBJTYPE = Kystkontur
All marine Protected Areas IUCN = 1a, 1b, 2 with 5 km buffer	www.protectedplanet.net/c/monthly-updates/2019/july-2019-update-of-the-wdpa Select by attribute: MARINE = 1 AND IUCN_CAT = Ia, Ib and II
Coral Reef	https://kartkatalog.geonorge.no/metadata/fiskeridirektoratet/korallrev-forbudsomrader/3be8f59c-cf30-47b5-ab5d-61abab25942b Title: Korallrev–forbudsområder Format: SOSI
Nature types: Slåttmark and Slåttmyr	https://kartkatalog.miljodirektoratet.no/Dataset/Details/10 Chose Norge uten Svalbard and selected viktige naturtyper Select by attribute: NATURTYPE = Slåtte—og beitemyr and Slåttemark
Ship traffic buffer: 500 m (Other boat routes, car ferry, passenger ferry)	https://kartkatalog.geonorge.no/metadata/kartverket/n250-kartdata/442cae64-b447-478d-b384-545bc1d9ab48 Title: N250 Kartdata Folder: Samferdsel Files: Annen-Båtrute, Bilferjestrekning, Passasjerferjestrekning
Fields and pipeline	Download data from: http://factpages.npd.no/ReportServer?/FactPages/geography/geography_all&rs:Command=Render&rc:Toolbar=false&rc:Parameters=f&IpAddress=1&CultureCode=nb-no Data description (Attributter): http://factpages.npd.no/factpages/Default.aspx?culture=nb-no&nav1=wellbore
Fishing Areas	https://kartkatalog.geonorge.no/metadata/uuid/c6082425-8133-4f4d-bc46-8960c78232ce

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