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Spatial trade-offs in national land-based wind power production in times of biodiversity and climate crises

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Abstract:
Energy generated from land-based wind power is expected to play a crucial role in the decarbonisation of the economy. With the looming biodiversity and nature crises, spatial allocation of wind power cannot, however, any longer be considered solely a trade-off against local disamenity costs. Emphasis should also be put on wider environmental impacts, especially if these challenge the sustainability of the whole renewable energy transition. We suggest a modelling system for spatial allocation of wind power plants (WPPs) by combining an energy system model with a comprehensive GIS analysis of WPP sites and surrounding viewscapes. The modelling approach integrates monetary cost estimates of local disamenity and loss of carbon sequestration, and impacts on wilderness and biodiversity implemented as sustainability constraints on the model. Simulating scenarios for the Norwegian energy system towards 2050, we find that the southern part of Norway is the most favourable region for wind power siting when only the energy system surplus is considered. However, when gradually adding local disamenity costs (and to a lesser extent carbon costs) and the sustainability constraints, the more beneficial siting in the northern part of Norway become. We find that the sustainability constraints have the largest impact on the spatial distribution of WPPs, but the monetised costs of satisfying them are shown to be modest. Overall, results show that there is a trade-off between local disamenities and loss of biodiversity and wilderness. Siting wind power plants outside the visual proximity of households yield negative consequences for biodiversity and wilderness

Keywords: wind power, spatial analysis, energy system model, environmental costs, disamenity costs

JEL classification: C61, D62, Q24, Q42, Q48, Q51, Q57, Q58

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Sammendrag

Vindkraft på land kan forventes å spille en betydelig rolle i en lavutslippsøkonomi. Ved plassering av vindkraftverk bør det være en avveiing mellom de negative effektene på naturverdier og lønnsomhet. Vindkraftverk påvirker negativt både den estetiske verdien og bruksverdien av naturområder, som særlig berører de som bor i området (miljøkostnader for de lokale innbyggerne), og det biologiske mangfoldet og arealer av uberørt natur, som har en verdi for hele samfunnet (nasjonale miljøkostnader). Begge deler er det viktig å ta hensyn til en samfunnsøkonomisk analyse av vindkraftutbygging. I denne artikkelen tar vi som utgangspunkt at det skal bygges ut vindkraft på land, og ser på hvordan denne kan plasseres geografisk for å gi størst mulig samfunnsøkonomisk gevinst. Dette gjøres ved å kombinere en energisystemmodell med omfattende GIS analyser av potensielle vindkraftverkplasseringer, basert på innsendte søknader. Energisystemmodellen gir informasjon om hvordan plasseringen påvirker de rene økonomiske inntektene fra vindkraft, men GIS analysene gir oss informasjon om hvordan vindkraftverkene vil påvirke utsynet til husholdningene i området, samt hvilke naturområder som blir berørt. I modelleringen integrere vi monetære verdier på lokale miljøkostnader og kostnader ved karbonutslipp fra arealer, mens hensynet til uberørt natur og biologisk mangfold vil sette absolutte grenser på hvor vindkraftverkene kan plasseres. Ved å simulere modellen fram til 2050 finner vi at Sør-Norge er gunstig lokasjonen for vindkraft om en ikke tar hensyn til miljøkostnader. Dersom vi tar hensyn til både kostnader for de lokale innbyggerne og de nasjonale miljøkostnadene bør en større del av produksjonen flyttes mot den nordlige delen av Norge. Vi finner at hensynet til uberørt natur og biologisk mangfold har større innvirkning på optimal lokalisering enn om man bare tar hensyn til miljøkostnader som påvirker de lokale innbyggerne. Kostnadene av å utelukke noen områder er imidlertid små. Vi viser også at det generelt er en trade-off mellom hensynet til miljøkostnader for de lokale innbyggerne og nasjonale miljøkostnader. Dersom vindkraftverk skal plasseres langt unna synsfeltet for innbyggerne vil det bli større negative konsekvenser for biodiversitet og økt tap av uberørt natur.

1. Introduction

Energy generated from land-based wind power plants (WPPs) is expected to play a crucial role in the decarbonisation of the economy (IEA 2021). A challenging question facing regulators in many countries is how best to deploy WPPs geographically. The economic profitability of wind power differs spatially depending on the wind conditions and necessary investments in turbines, infrastructure, and associated grids. Differences in expected prices across the country will also affect the optimal spatial allocation of WPPs in countries with several electricity price zones. At the same time, the deployment of land-based wind power raises several disamenity and environmental concerns depending on the siting of the WPPs, such as noise, impaired landscape aesthetics, and loss of wilderness and biodiversity (see e.g., reviews by Saidur et al. 2011; Mattmann et al. 2016; Zerrahn 2017). In addition, the construction of WPPs in natural areas affects carbon storage through land-use changes, especially through the conversion of mires and forests.

From the regulator's point of view, when choosing a spatial deployment plan for WPPs both economic profitability, local disamenities and the wider environmental impacts of WPPs should matter. The total magnitude of the negative impacts of wind power production should be balanced against profitability and the climate contribution when choosing a specific siting of WPPs.

Research on spatial trade-offs in wind power deployment has to date focused primarily on negative effects for nearby residents (Zerrahn 2017; Mattmann et al. 2017; Wen et al. 2018), and just a few such studies have, to our knowledge, included some measure of (primarily local) environmental and disamenity costs into energy system models (e.g., Lehmann et al. 2021; Drechsler et al. 2017; Grimsrud et al. 2021; Salomon et al. 2020). However, with the latest assessment of the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES 2019) and the Dasgupta review (Dasgupta 2021), it has become increasingly clear that the degradation and loss of nature and biodiversity may be just as serious as the climate crisis. Hence, impacts of land use on wilderness and biodiversity need must also be thoroughly assessed and considered to achieve optimal renewable energy deployment. This paper contributes to filling this gap in the literature by analysing spatial trade-offs between the economic, local welfare and wider environmental aspects of siting WPPs on the national level in Norway.

The present paper contributes to the literature by suggesting how to evaluate and include various kinds of environmental impacts, more comprehensively assessed than previously, into the regulator's decisions on domestic siting of wind power production on land. By employing a, for the purpose, modified and updated energy system model for Norway (IFE-TIMES-Norway) (Loululu 2008; Loulou and Labriet 2008; Danebergs et al. 2021; Seljom et al. 2020), we can explicitly derive the socially optimal siting of WPPs, considering both energy system revenues and costs, local environmental costs and impacts on wilderness and biodiversity of WPPs. We analyse the optimal allocation of new potential wind power production capacity until 2050 based on concession proposals in the database obtained from the regulator The Norwegian Water Resources and Energy Directorate (NVE). We apply a production target of 4 TWh from new land-based wind power to assess which WPPs are most favourable for investments. The limiting target is conservative compared to NVE's projections of 7 TWh new wind power, as a three-year moratorium on new concessions has been in place until April 2022 due to resistance towards new land-based wind development resulting in a review of, among others, how environmental impacts should be assessed in future concession processes. The existing capacity in land-based wind power (ca. 15.5 TWh) is included as exogenous input, while we allow for the possibility of reinvestments (i.e., renewals of production concessions that are expiring at current sites).

The model analysis permits for the inclusion of cost parameters for the monetised local nuisance and disamenity costs and the cost of carbon emissions due to land-use change associated with each WPP in the IFE-TIMES-Norway model. The model analysis also permits for imposing indicator constraints to prevent loss of wilderness and biodiversity. Hence, this type of analysis follows e.g., the approach by Bateman and Mace (2020) arguing for use of strong sustainability constraints, and Bateman et al. (2013), where some environmental costs and benefits are monetised, while biodiversity impacts are analysed as a constraint in their spatial model of land-use scenarios in the UK. We derive the monetised local disamenity costs from a comprehensive GIS analysis of affected people within the viewscapes of the current and potentially new WPPs in the country multiplied by a per household cost derived from two local Norwegian valuation studies (Garcia et al. 2016; Dugstad et al. 2022). We also analyse alternative local cost specifications.

Impacts on wilderness and biodiversity are implemented in the model as unmonetised sustainability constraints. The constraints are derived based on an updated and modified GIS analysis from Nowell et al. (2020) identifying to what extent the sites of WPPs overlap land with different types of biodiversity and wilderness qualities. Finally, costs of carbon emissions from land-use change are calculated based on an extension of the above GIS analysis surveying affected mires and forests and monetised based on price scenarios for the EU emission trading system (EU ETS).

Our analysis demonstrates how an energy system model may be used to determine the best deployment of WPPs across Norway from a technological-social economic perspective while also taking into account the climate, wilderness and biodiversity concerns associated with land-based WPP deployment. We also derive the energy system surplus of new wind power for different scenarios, with and without externality costs and the sustainability constraints included. This is useful to demonstrate spatial trade-offs and the explicit costs of accounting for wilderness and biodiversity impacts. Although we conduct the analysis on Norwegian data, the analytical framework for finding an optimal spatial distribution of WPPs can be applied across all countries.

In the next section, we describe the analytical framework, while section three explains the empirical methods used, including the energy system model, IFE-TIMES-Norway, and how local disamenity costs and carbon emissions are estimated and monetised, and the sustainability constraints on the model derived. Section four first presents the most important and illustrative scenarios for the spatial distribution of WPPs, where we gradually introduce a more comprehensive inclusion of environmental costs and constraints. Second, we present the most important numerical results from model simulations and sensitivity analysis. Concluding remarks are given in section five.

2. Analytical framework

An elaborated dynamic numerical model is presented in section 3.1. This section presents a simplified analytical framework to explain the basic idea of the optimising problems considered in the paper. We first employ the analytical model to present the characteristics of a cost-effective deployment of WPPs from an energy system perspective, and then we modify this model to add the monetised environmental costs. Finally, we add strong sustainability constraints preventing the construction of new WPPs on land areas important for wilderness and biodiversity, as motivated by Bateman and Mace (2020). We chose this approach here, as it is often considered both controversial and methodologically challenging to value impacts on biodiversity and to determine the “extent of the market” of affected households where substantial non-use values are likely present. Hence, such impacts are sometimes included as (sustainability) constraints instead (e.g., Bateman et al. 2013). Let $i = \{1,2,\dots,J\}$ denote all new potential WPPs, where WPP$_i$ is characterised by its average annual electricity production (q_i).[1] We consider a target, Q, for new wind energy production, where

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[1] Not that the symbol J has a double interpretation as it denotes the total number of WPPs as well as the ultimate one of the WPPs.

$Q \leq \sum_{i \in J} q_i$. The optimisation problem is to choose the right WPPs to be developed among all the potential WPPs. The new wind energy production will affect the costs and revenues of the entire energy system in multiple ways and will depend on which of the WPPs that will be developed. The WPPs typically differ in investment costs in terms of scale, turbine characteristics, and grid connection. The production revenues of WPPs also depend on the geographical siting since we consider an entire energy system where there are several different price zones. Furthermore, investments in new WPPs also affect the electricity price and new grid investments, which in turn affect the profits of incumbent energy producers. We define the energy system surplus (*ESS*) as the system income in excess of expenses of producing *Q* units of new wind power. As discussed above, *ESS* will depend on the choice of which WPPs to be developed. Let $\Omega_1, \Omega_2, ..., \Omega_K$ denote the subsets of *J* for which the production target is satisfied. We can then write *ESS* as a function, *F*, of the chosen subset of WPPs. If Ω_k is the chosen subset, then $ESS(\Omega_k) = F\left(\sum_{i \in \Omega_k} q_i\right)$.

The selection of WPPs will also affect the total environmental costs, as the impact on the environment differ across WPPs. For each WPP$_i$, we assign a monetised environmental cost, denoted by $e_i = TD_i + TC_i$, where TD_i is the total disamenity cost for households during operation and TC_i is the total carbon cost caused by land-use-change from constructing a new WPP. Furthermore, let δ_i denote the percentage overlap between the land area required for WPP$_i$ and land areas that are considered valuable in terms of biodiversity richness and wilderness. The sustainability constraint requires that $\delta_i \leq d$, where d is a set restriction on the maximum irreversible loss of such land areas as required by societal goals. Let λ_{land} be the shadow price of the constraint, where $\lambda_{land} > 0$ implies that the constraint is binding.

We consider different scenarios for an optimal choice of WPP development, given a target of new wind energy production (*Q*), with and without internalising the monetised environmental costs and with an additional sustainability requirement.

2.1 Cost-effective solution. Maximising energy system surplus without internalising environmental costs.

Let Ω_B denote the subset of WPPs that maximise the energy system surplus of *Q*. We refer to this outcome as the cost-effective spatial distribution of WPPs, i.e., environmental costs are not internalised in the optimisation. The net energy system revenue (ESS^B), the total monetised environmental costs (E^B), the total production, and the monetised welfare (MW^B) for this distribution are, respectively, given by:

$$
\begin{aligned}
&ESS^B = F\left(\sum_{i\in\Omega_B} q_i\right),\\
(1)\qquad &E^B = \sum_{i\in\Omega_B} e_i,\\
&Q = \sum_{i\in\Omega_B} q_i,\\
&MW^B = ESS^B - E^B.
\end{aligned}
$$

2.2 Socially efficient solution. Maximising energy system surplus with internalised monetised environmental costs but without strong sustainability requirements.

Let Ω_N denote the subset of WPPs which maximise the energy system surplus of Q, *less of* monetised environmental costs. The net energy system revenue (ESS^N), the total monetised environmental costs (E^N), the total production, and the monetised welfare (MW^N) of this distribution are, respectively, given by:

$$
\begin{aligned}
&ESS^N = F\left(\sum_{i\in\Omega_N} q_i\right),\\
(2)\qquad &E^N = \sum_{i\in\Omega_N} e_i,\\
&Q = \sum_{i\in\Omega_N} q_i,\\
&MW^N = ESS^N - E^N.
\end{aligned}
$$

2.3 Socially optimal solution. Maximising energy system surplus with internalised monetised environmental costs and strong sustainability requirements.

Let Ω_S be the subset of WPPs that maximise the energy system surplus of Q, *less* of monetised environmental costs, and that *satisfies* the strong sustainability constraint. Under the condition of a binding sustainability constraint, the net energy system revenue (ESS^S), the total monetised environmental costs (E^S), the total production, and the monetised welfare (MW^S) of this distribution are given by:

$$\begin{aligned}
&ESS^S = F\left(\sum_{i\in\Omega_S} q_i\right),\\
&E^S = \sum_{i\in\Omega_S}(e_i),\\
&Q = \sum_{i\in\Omega_S}(q_i),\\
&MW^S = ESS^S - E^S,\\
&\lambda_{land} > 0.
\end{aligned} \tag{3}$$

2.4 Anticipated results from the numerical analysis

As the environmental costs are not included in the cost-effective solution, the WPPs included in Ω_B are expected to differ substantially from the WPPs included in Ω_N, which again differ from the WPPs included in Ω_S. As the model gradually incorporates new costs and the analysis becomes more constrained, it is expected that $ESS^B > ESS^N > ESS^S$.

Furthermore, since the socially efficient solution internalises the environmental costs in the optimisation problem, opposed to the cost-effective solution, it is expected that

$$MW^B < MW^N.$$

Both the socially efficient solution and socially optimal solution internalise the monetised environmental costs, but the latter is imposed an additional sustainability constraint. As the positive welfare impact of avoiding WPP development of valuable nature is not included in our measurement of monetised welfare, we expect that $MW^N > MW^S$. We can interpret $MW^N - MW^S$ as the monetised welfare cost of the sustainability constraint.

In the cost-effective solution, the energy system costs will be the determining factor for the location of WPPs. The monetised environmental costs include inter alia quantifiable welfare loss of neighbouring households. Hence, the solution that only includes environmental costs that are monetised will typically lead to less development of WPPs in locations near residential areas, and thus shift the WPP development into land areas that are valuable in terms of their biodiversity and wilderness (nature areas). Adding the sustainability constraints will, on the other hand, shift WPPs out of nature areas and nearer the more populated areas. Hence, we expect there to be a trade-off between reducing the neighbouring households' discomfort and preserving valuable natural areas, for the benefit of the wider society. Our modelling approach permits us to estimate this trade-off by assessing $MW^S - MW^B$ and $E^S - E^B$.

3. Empirical methods

Given the analytical model above, we first explain the empirical modelling framework (the IFE-TIMES-Norway model) and, second, how monetised impacts and the sustainability constraints are calculated and integrated into the model.

3.1. Energy system model (IFE-TIMES-Norway)

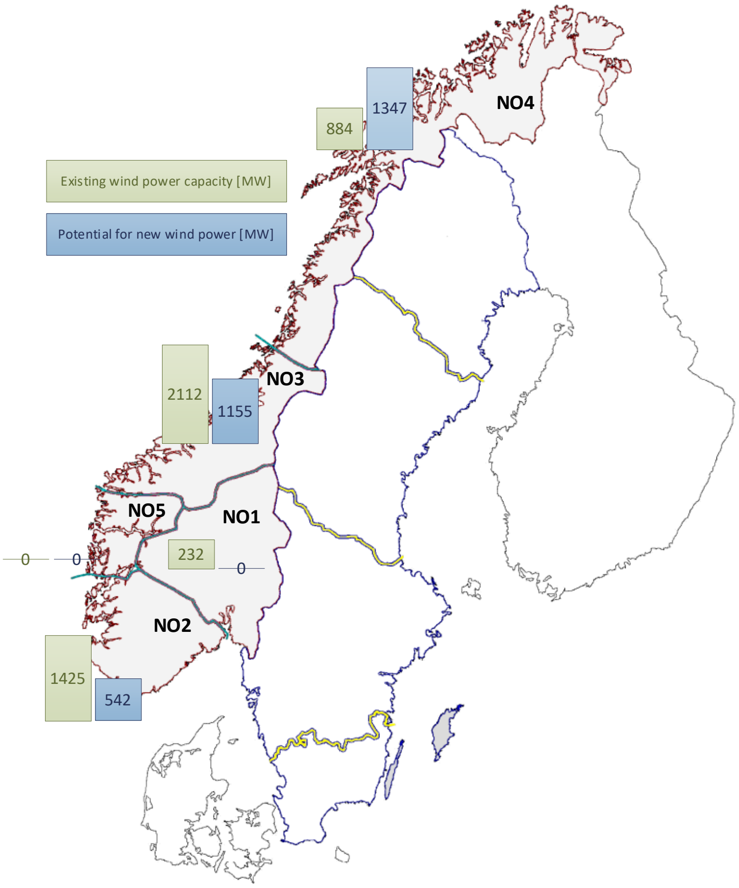
3.1.1. About the model - general characteristics

IFE-TIMES-Norway (Loululu 2008; Loulou and Labriet 2008; Danebergs et al. 2021) is a long-term optimisation model of the Norwegian energy system that is generated by TIMES (The Integrated MARKAL-EFOM System) modelling framework. It is a bottom-up framework that provides a detailed techno-economic description of resources, energy carriers, conversion technologies and energy demand. TIMES models minimise the total discounted cost of a given energy system to meet the demand for energy services for the regions over the period analysed. The total energy system cost includes investment costs in both supply and demand technologies, operation and maintenance costs, and income from electricity export to and costs of electricity import from countries outside Norway.

The model has a detailed description of the end-use of energy, with demand for energy services divided into numerous end-use categories within industry, buildings, and transport. The demand can be met by both existing and new technologies using energy carriers such as electricity, bio energy, district heating, hydrogen, and fossil fuels. Other input data include fuel prices; electricity prices in countries with transmission capacity to Norway; renewable resources; and the characteristics of the technology such as costs, efficiencies, lifetime and learning curves.

Spatially, the model covers five geographical regions in Norway, corresponding to the current electricity spot market price zones. Figure 1 provides an illustration of the price zones, with respective existing wind power capacity and potential. The model provides operational and investment decisions from the starting year, 2018, towards 2050. To capture operational variations in energy generation and end-use, each model period is divided into 96 sub-annual time slices, where four seasons are represented by 24 chronological hours.

Figure 0-1: Illustration of spot price zones in Norway together with existing and potential wind power capacity (MW)



3.1.2. *Assumptions and methods for incorporating WPPs in TIMES*

To investigate the most efficient geographical siting of new WPPs, the IFE-TIMES-Norway model has been modified to include a more detailed representation of existing and potentially new land-based wind power parks in Norway. Information about each WPP is obtained from NVE (2022). In the data gathering process, wind parks have been categorised according to their status: "in operation", "license granted" and "under assessment". The latter category includes WPPs that have applied for a license or have announced plans. Applications that have been rejected are therefore not part of the investment potential in new wind power. The same applies to applications that are put on hold, as most of these are quite old and will require new applications and that licenses will be granted. Lastly, applications that were submitted before 2010 and where no updates have been reported since, have been excluded. In total, 4.6 GW capacity is already in operation, with the first WPP installed in 1998. Regarding the potential for new wind power capacity, 26 WPPs have been included in the analysis with 1.2 GW having granted licensing while 1.9 GW is under assessment. This corresponds to approximately 15.5 TWh of existing wind power production and 11TWh from potential new WPPs investments. Noteworthy, all the future potential for new WPPs included in the analysis is found in areas NO2, NO3 and NO4, meaning that no new wind capacity is assumed to be built in NO1 and NO5. These regions will henceforth be referred to as South (NO2), Central (NO3), and North (NO4). Reinvestments in existing capacity are allowed at a 20% lower cost than the initial investment cost, due to reduced costs for new infrastructure and wind turbines[2]. The possible capacity of reinvestment is restricted by regulations on the existing WPP capacity.

An overview of the existing and new WPPs included in this analysis, along with respective specifications, can be found in Appendix A, Tables A1 and A2 and their location in Figure A1. Model input data include the investment and operational cost, existing/applied capacity, and the associated capacity factor for each WPP. Investment costs are based on data from NVE and the respective municipality/developer, while operational costs are assumed to be equal for all plants at 10 €/MWh[3]. The year of investment for new WPPs is fixed to 2025, with a technology learning of 16% from the starting year of 2018 to 2025 (IRENA 2019). Moreover, as investment costs tend to be estimated at the submission of the concession application, and these often trace back many years, a yearly cost reduction of 3% from the cost year to 2018 is applied to wind turbines that are yet not in operation. These technology learning rates are based on projections from IRENA (IRENA 2019). Lastly, all cost inputs to the model are in 2020 prices. The WPPs have a lifetime of 25 years, and plants with reinvestments can operate for an additional 25 years. The assumption that all wind parks are installed in the same year is made to simplify the environmental cost calculation, as the carbon price differs depending on the year of installation.

Since the purpose of this analysis is to assess the optimal spatial distribution of new wind power, we assume that only a portion of the potential of 11 TWh is implemented. Considering the strong opposition towards land-based wind power development in Norway and the 3-year-long hold in the licensing process, a target of 4 TWh annual production from new land-based wind power is assumed. This is added as a restriction in the IFE-TIMES-Norway model, in which the annual wind power production from new WPPs is constrained at 4 TWh in all years following 2025. Note that production

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[2] Assumption is based on a review of the cost breakdown from different license applications in NVE’s database.

[3] Variable O&M assumptions are based on (IRENA 2019; IRENA 2020): around 30% of average LCOE (0.03- 0.05 $/kWh in 2030).

from reinvestments is not included in this restriction, meaning that wind power production by 2050 can potentially reach 19.5 TWh (i.e., 15.5 + 4) if reinvestments occur for all existing plants. This is considered a reasonable assumption as reinvestments will not require new land-use change.

In IFE-TIMES-Norway, the electricity price in Norway is a result of the model, but its magnitude and development depend largely on the assumptions of different parameters. In particularly, the electricity price in Norway follows to a large extent the market prices in Europe. With higher CO_2 prices and larger penetration of variable renewable energy, prices are expected to become higher and more volatile (Statnett 2020). The impact is, however, uncertain and will depend on several factors such as gas price, CO_2 price, industry development and renewable expansion. The development in electricity prices in Norway, also on a regional level, will further impact the optimal spatial distribution of WPPs. The analysis therefore builds on two different price sets for neighbouring countries with transmission cables to Norway[4]. A baseline scenario is used for the initial analysis, while a sensitivity case is performed with a high electricity price scenario. The electricity price profiles for European countries are created using the same carbon price path assumptions as presented in Table B1, Appendix B. The average price development for the two scenarios for some selected countries are presented in Figure B1.

3.2. Monetised local disamenity and carbon costs and sustainability constraints

A WPP affects the environment in several ways. We distinguish between disamenity impact specifically affecting the households in the vicinity of WPP and more general environmental impacts affecting the whole society (wider environmental costs). The latter category includes monetised carbon emissions from land-use-change due to WPP establishment, and impacts on land areas important for wildlife and biodiversity included as sustainability constraints in the model.

3.2.1. Local disamenity costs

Adjacent households face noise pollution, light flickering, ice fall incidents, deterioration of local nature and recreational areas, and reduced visual aesthetics of the local landscape (Zerrahn 2017). We estimated a total local disamenity cost for each WPP attempting to capture this “bundle” of impacts.[5]

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[4] The price set for European power prices used in this analysis does not represent the current price levels caused by the energy crisis.

[5] For simplicity and to avoid any issues of double counting, we do not include externalities related to construction or upgrade of power lines, locally, regionally nor nation-wide. These costs are hard to estimate and normally not included in modelling studies of wind power development. An exception is Grimsrud et al. (2021), which distinguishes between local and national externalities of power lines.

The total local disamenity costs, TD_i, is a function of the disamenity costs for the sum of the households, h_i, affected in the vicinity of WPP$_i$:

$$(4) \qquad TD_i = C_d h_i,$$

where C_d is the disamenity cost. We assume that the affected housholds are *all* housholds located at a distance less than 4 km from the WPP$_i$ and all housholds with a distance between 4 to 30 km from the WPP$_i$, where the WPP is in their viewscape.

To capture the disamenity costs of households in the vicinity of existing and potential new WPPs, GIS analysis on land registry data were used to identify the number of households in each residential building. In addition, there can be recreational homes in the vicinity of WPPs. A recreational home is typically occupied by one household for a certain percentage of the year. GIS analysis was used to identify which of the residential buildings and recreational homes that are in the viewscape of each WPP, both existing and new ones. For existing WPPs the viewscape analysis relied on information from NVE which provides data on the placement of the turbines in the landscape and the turbine height for each WPP. For potential new WPPs, the viewscape analysis is more challenging as the number of turbines and their placement are not available. The total capacity (MW) applied for in the concession application of each new WPP is however given by NVE. For WPPs coming into operation in 2021, the average capacity of turbines is 5 MW[6] and the average turbine height is 171m. We used this information to estimate the number of turbines for each potential new WPP. In the viewscape analysis for potential new WPPs, we assumed that the estimated number of turbines would have a height of 171m and would be distributed evenly in the land area indicated in the concession application for the WPP.

While households in residential buildings are assumed to be affected all year round, households in recreational homes are assumed to be affected in correspondence to the share of the year they use their cabin. For this, we used a mean estimate of 15%, based on survey data from the last five years on the number of days Norwegians use their recreational homes/cabins (Prognosis Centre 2021).[7]

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[6] WPP concession applications only indicate a certain MW to be produced and not the number of turbines or how the turbines might be placed in the landscape.

[7] This number has increased during the Covid pandemic, so to be more representative of a normal year, we used the average from the last five years. There is no information about how cabin owners value disamenity impacts of wind power, hence, we chose this simple approximation.

To get an estimate of the total local disamenity cost for each WPP, we apply a constant cost per household per turbine per year, independent of the number of turbines at the site and the distance from the site. It is included in the model as €/MW/year. In our base case, we use an average, annual mean willingness to pay (WTP) per household to avoid one turbine of EURO €23.10 taken from the only two local non-market valuation studies we are aware of from Norway. Both are choice experiment studies: One from a proposed WPP in the municipality of Sandnes on the west coast (Garcia et al. 2016, WTP estimate used in Grimsrud et al. 2021) and one from a proposed WPP in the municipality of Aurskog-Høland of eastern Norway (Dugstad et al. 2022). Due to well-known concerns related to hypothetical bias in choice experiment and other stated preference methods, we choose conservative estimates from these studies. Since they do not specifically analyse or demonstrate distance decay in their data and their estimates are based on mean WTP from the sampled municipality population, we assume in our base case a constant per turbine cost applying to all households and recreational homeowners in the viewscape of each WPP.

There is uncertainty related to the local disamenity cost specification. Both theoretical and empirical studies generally show ambiguous results on distance decay effects, determining boundaries for affected populations (e.g., Glenk et al. 2020) and scope effects (e.g., Dugstad et al. 2021) of environmental impacts. This is also the case for wind power externalities, e.g., Wen et al. (2018) and Mattman et al. (2016). Some studies apply a distance decay function (e.g., Lehmann et al. 2021) and/or use a close boundary around each WPP (e.g., Krekel and Zerrahn 2018[8]). We, therefore, use three alternative specifications for sensitivity. First, we base our distance decay function on Lehmann et al. (2021),

$$(5) \qquad c_h^{dis}(d_h) = 90\ EUR\left(\frac{1054\,m}{d_h - 543\,m} - 0.3\right),$$

and translate their distance decay function which calculates per monthly disamenity costs in € from German studies as a function of a household’s distance (m) to a wind turbine to an annual disamenity cost distance to a WPP. We assume, as do Lehman et al. (2021), that the per turbine cost is linear in the number of turbines (located as part of the same WPP or adjacent ones). The disamenity costs used in the sensitivity analysis with distance decay are higher than the cost in our base case if the distance of the household to the WPP is less than 3822 m, and lower than the base case for distances beyond

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[8] This study has shown based on a subjective wellbeing valuation approach that the negative effect of wind power drops substantially beyond 4 km from the WPP in Germany.

3833 m. For households at a farther distance than 4000 m, no environmental cost is included in this sensitivity analysis. For sensitivity, we also use low and high alternatives where we set the boundary to 4 km and a doubling of the cost for the full viewscape, respectively. As in the main analysis, we assume that each household incurs this full cost and that only 15% of this cost is incurred if the building is a recreational home.

3.2.2. Carbon emission cost of land-use change

When building a WPP, only a small share of the land set aside for the power plant will be converted from undeveloped to developed land. According to NVE (2019), p. 18, around 4 % of the area of a WPP concession is directly affected by infrastructure. Some of this may be restored after the roads have been built, and management practices would affect land-use changes and subsequent CO_2 emissions. We do not have access to information about carbon emissions due to the felling of trees and drainage of mires, but by using GIS analysis, we have access to the amount of biomass stored in the forests, below and above ground, the forested area, and the area of mires for each of the WPPs' concession area (Nowell et al. 2020). For all WPPs we assume that a share of 4 % of all the types of land in the concession area is converted to developed land. Furthermore, we assume that the loss of biomass due to the felling of trees will not be replaced and that the excavation of mires to achieve a firm foundation for infrastructure leads to direct (and immediate) emissions of CO_2. The emissions from the removal of mires correspond to the carbon content of the mires. Excavating mires and converting forests into developed land also implies that a source for carbon sequestration is removed, see inter alia Nayak et al. (2010) and de Wit et al. (2015). This impact is assumed to last "forever". The total carbon costs for WPP$_i$ (TC_i) thus consist of four elements:

$$TC_i = CE_{iF} + CE_{iM} + CS_{iF} + CS_{iM} , \tag{6}$$

where CE_{iF} is emissions costs from loss of stored carbon in forests (measured in ton biomass above ground and below ground), during the construction year, CE_{iM} is the carbon costs of emissions from loss of mires, also in the construction year, and CE_{iM} and CS_{iF} are the carbon costs of loss of future CO_2 uptake in mires and forests, respectively. For the monetary social cost of the emissions from land-use changes, we use scenarios for the EU-ETS-prices, presented in appendix B. The base prices are used for the initial analysis, while a sensitivity analysis is performed with the high carbon price pathway.

As we do not have information on the depth of the mires on each site, we rely on average numbers for Norway and set the dept to 1.5 m (de Wit et al., 2015, reports 1.7 m, whereas Gorham, 1991, reports 1.1 m). For the average carbon content per meter dept, we use the same average factor as in the official report to the UNFCCC, which is set to 0.1683 tons of CO_2 (Stokland et al., 2022). For calculation of the carbon costs of lost sequestration in forests and mires, we use the estimates of carbon accumulation in peatland soils, trees and forest soil provided by de Wit et al. 2015. Appendix C provides a detailed description of the calculations of carbon costs.

By employing the carbon price path (base), presented in appendix B we find that:

$$
\begin{aligned}
&CE_{iF} = 37.33 \cdot (BMA_i + BMB_i) \cdot F_i, \\
&CE_{iM} = 5.15 \cdot M_i, \quad CS_{iF} = 0.07 \cdot F_i, \quad CS_{iM} = 0.03 \cdot M_i
\end{aligned} \quad , \tag{7}
$$

where M_i and F_i are the area (m^2) of mires and forests, respectively, in the concession area of WPP$_i$, and BMA_i and BMB_i are tons of biomass stored per m^2 forests, above and below ground, respectively. As the average outcome of $(BMA_i + BMB_i)$ is around 0.007, we see that loss of mires has a significantly larger impact on the carbon costs than a loss of forest area per m^2. Furthermore, the loss in future carbon sequestration due to the loss of forest area and mires

(CS_{iF} and CS_{iM}) is of significantly less importance for the carbon costs than the immediate emissions during the construction phase (CE_{iF} and CE_{iM}).[9] For already existing WPPs, that are reinvested, the carbon emissions from land use change is assumed to be sunk costs and are therefore set to zero.

3.2.3. Loss of land important for wilderness and biodiversity

Wind farms can negatively affect wildlife and habitats either through direct impacts, such as bird collisions with wind turbine rotors or loss of habitat for infrastructure construction, or indirectly, for example by acting as migration barriers (Arnett et al. 2016; Kuvlensky et al. 2007). We use Nowell et al. (2020) as a starting point to account for the impacts on biodiversity and wilderness as a result of land-use change from each WPP construction. Two criteria were assessed, namely the potential loss of wilderness areas and the potential loss of biodiversity. Wilderness is defined as areas free from

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[9] Note that life cycle impacts of the production and transportation of turbines to Norway are not included in the carbon costs used here. Carbon content of fuel used for transport on Norwegian territory is priced higher than EU ETS carbon prices.

infrastructure where flora and fauna can exist undisturbed. A loss of wilderness can result in fragmentation, increased potential for environmental barriers and/or habitat loss (Di Marco et al. 2019). Since the exact area or location of construction was not available for all WPPs, we assessed the potential impact by how much of each WPP was classified as wilderness. Instead of using the simple INON[10] indicator to identify wilderness areas as Nowell et al. (2020) did, we used the so-called Infrastructure Index (Bakkestuen et al. 2022). The INON indicator has been criticised for being too simplistic (e.g., not distinguishing between the intensity and extent of infrastructure impact in an area). The Infrastructure Index measures the frequency of infrastructure within a 500m circle for each pixel. It takes a value of 0 (min) if the area is completely void of human infrastructure and 13.23 (max) if the area is completely covered in human construction (e.g., a densely constructed urban area) (Jacobsson et al. 2020)[11]. The advantage of using this indicator over the INON maps is that the intensity of infrastructure can be accounted for, and undisturbed areas are mapped at a finer spatial resolution. In this study, an area-weighted sum of the infrastructure index was calculated for each area of the WPP. This approach gave more insight into the distribution of different intensities of infrastructure in each wind farm area while controlling for the size of the wind farm. All WPPs with a score below 1.8 were considered to be wilderness areas according to Erikstad et al. (2013) and any construction would therefore impact wilderness areas.

To assess the second criteria for the impact on biodiversity, several spatial indicators were used based on guidance from the Norwegian Environment Agency (NEA), namely: 1) overlap with functional areas (NEA 2019), 2) nationally and locally important nature types for biodiversity (NEA 2001), 3) protected areas NEA 2022), and 4) the ranges of wild reindeer, a species that Norway has a special responsibility for managing (NEA 2018). Furthermore, each WPP was also evaluated to see if it overlapped threatened species hotspots for insects and arachnids, bryophytes, fungi, lichens, and vascular plants (Olsen et al. 2018, Olsen et al. 2020). Wind farms have been found to have the greatest influence on birds and bats, but also influence how other wildlife use areas near wind turbines and

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[10] Norwegian authorities maintain an indicator called “INON”, which measures the size of natural and unfragmented areas less than 1 km, 1-3 km or more than 5 km, respectively, from the nearest technical installation such as roads, power lines, houses, etc.

[11] The index is calculated as the frequency of key characteristics (in this context different types of infrastructure that involve intervention and fragmentation of areas), measured in a circle with a radius of 500 m around each pixel (focus point) and calculated for the whole country. The infrastructure index consists of two components that are summed up: a building component and a constructed mainland component (which indicates the occurrence of constructed fixed land area, the result of interventions, which gives the landscape a 'human landscape character'). The infrastructure index is 2-logarithmic in each component, which means in principle that each doubling of the frequency of buildings and constructed fixed land, respectively, increases the value of the respective component by a constant number of units. two components are considered not to be equally important for the landscape's character of utilisation; the occurrence of buildings is considered to leave a stronger mark (2/3) on the landscape than the occurrence of constructed land areas (1/3).

other infrastructure associated with WPPs (Arnett et al. 2016; Kuvlensky et al. 2007). While cohesive national-scale datasets are not yet available for migration routes, mapped functional areas were used as an indicator of the impact on breeding, nesting and grazing areas for priority, red list species and other game species.

Important nature types were included as an indicator of the impact on ecosystems. Next, overlap with protected areas was used as an additional indicator of important habitats and the species associated with them. Wild reindeer breeding, calving, migration, and grazing areas were also included as an indicator. Wild reindeer have been shown to avoid WPPs and the construction of wind farms alters migration routes and corridors, which are already severely restricted in Norway because of infrastructure (Skarin et al. 2015; Skarin et al. 2018). Finally, hotspots for insects and arachnids, bryophytes, fungi, lichen, and vascular plants were used as an indicator of threatened species. These hotspots are based on the top 10% probability of finding threatened species at a given location.

Spatial overlap with one or more of these indicators meant that a WPP would have a potential impact on biodiversity. Nowell et al. (2020) classified WPPs as to whether the concession area overlapped indicators by more than 5%[12]. Since Nowell et al. (2020) had used a 1 km buffer around the boundaries of WPP that was not used in this analysis, the threshold for overlap was reevaluated and increased to 1%. A sensitivity analysis revealed that a loss of 1% of the area could in some cases exceed 1km^2 of important habitat, which is a significant impact on biodiversity. Of the cases with less than 1% overlap, the greatest loss of important habitats was 0.05 km^2 which is considerably less. An increase to 2% resulted in almost triple the area being impacted (i.e., - 2.7 km^2). Therefore, 1% was chosen as the threshold, meaning that if the overlap with one or more indicators was greater than 1% of the WPP area, then the WPP was flagged as having a potential impact on biodiversity.

We do not attach a specific monetary value to the *loss of wilderness* and *loss of land that is important for biodiversity and wildlife,* but instead investigate the social cost of providing a certain amount of wind power if all WPPs that do not meet the criteria are excluded from the potential set of WPPs. Hence, these concerns are implemented in the model analysis as sustainability constraints, i.e., constraints that are activated whenever a corresponding 0-1 variable is equal to 1.

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[12] 5% was used to account for geometric error in the data that may cause some overlap in the GIS analysis where in reality there may not be any or very insignificant overlap. With national scale spatial data, there is always some geometric error, but the benefit of using this data (namely being able to evaluate all WPPs equally) outweighs the error.

For sensitivity, we added a third, highly relevant, but principally different, type of constraint from a recent high court verdict on indigenous rights of the Sami people to conduct their traditional reindeer husbandry unaffected by land-based wind power. Herding reindeer is an important cultural and economic activity for the Sami people, particularly in Northern Norway but also in many other parts of the country.[13] In late 2021, the court sided with reindeer owners against the wind power company in a case regarding the largest WPP in Norway (and Europe) in Fosen in Mid Norway. It was concluded that the WPP is violating their indigenous rights. The consequence of this verdict for Fosen and other existing or new WPPs is not yet decided. It could be, that future WPPs have to completely stay out of reindeer herding areas. We performed a spatial analysis to determine the area of overlap between areas used for reindeer husbandry and WPPs. This criterion consisted of 7 indicators representing the four seasonal grazing areas[14], movement corridors[15], staging areas[16], and administrative areas[17]. As with the other indicators, if there was more than a 1% overlap for one or more of the reindeer indicators, the WPP was flagged as having an impact on reindeer husbandry.[18]

National scale, freely available spatial datasets were used in the spatial analysis such that each WPP could be assessed equally. These datasets may have some geometric error because of the scale of mapping. The spatial analysis was performed in ArcMap 10.8 using the Spatial Analyst extension (ESRI). Table D1 in Appendix D shows for each WPP which criterion is activated.

4. Results from model simulations

4.1. Land-based wind power deployment scenarios

We run five different land-based wind power development scenarios, se Table 1.

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[13] Note that wild reindeer (ca. 25 000 individuals in total) is included as part of the biodiversity constraint above, while tame reindeer (ca. ten times as many) are included in this separate constraint.

[14] Seasonal grazing areas consist of zones where the reindeer graze during spring, summer, autumn and winter.

[15] Movement corridors are routes that the reindeer either migrate or are driven along between seasonal grazing areas.

[16] Staging areas are areas where reindeer are gathered for relocation, calving or slaughter.

[17] Administrative areas («siidaområde») are managed by a family for the various reindeer activities during the year. https://register.geonorge.no/register/versjoner/produktark/landbruksdirektoratet/reindrift-siidaomrade

[18] A sensitivity analysis revealed that there was no difference in the number of WPPs that had < 40% overlap (i.e- 48% of WPPs). A total of 37% of WPP included in the analysis had < 75% overlap and 33% had 100% overlap with reindeer areas.

Table 1 Wind power deployment scenarios as basis for main results

Scenario number	**Scenario name**	**Description**
S1	Base	Cost-effective spatial distribution of WPPs when excluding all environmental impacts and costs
S2	Carbon costs (*CC*)	Like S1, but including the carbon cost of land-use change (cf. 3.2.2)
S3	Local disamenity costs (*DISAM*)	Like S1, but including local disamenity costs for neighbouring households and recreational homeowners (cf. 3.2.1)
S4	Carbon costs and sustainability constraints *(CC+WILD+BIO)*	Like S2, but excluding WPPs with impact on land important for wilderness and biodiversity (cf. 3.2.3)
S5	All environmental costs and sustainability constraints *(CC+DISAM+WILD+BIO)*	Including all negative externalities associated with WPPs that are considered in S2-S4.

In all the scenarios, the annual production from new wind power plants is restricted to 4 TWh, as explained in section 3.1. Reinvestments in existing capacity is not included in this target and are limited by the initial capacity of the plant. Moreover, reinvestments will not cause emission costs from land-use change or be disabled by their impact on wildlife and undisturbed land areas, as these costs/losses are considered sunk. This is based on the assumption that reinvestments do not occupy any additional land area. Local disamenity costs for reinvestments are included with the assumption that the new wind turbine height remains the same as for the initial turbines.

In scenarios 2-4 we consider the impact of only one or two types of environmental externalities at the time, whereas in scenario 5 we include all the environmental externalities simultaneously (except the impact on reindeer husbandry). This scenario can be considered to give the socially optimal spatial distribution of new wind power capacity, if the goals of limiting impacts on undisturbed land, wildlife and biodiversity should be fulfilled. We start in the next section by presenting results from the spatial distribution of WPPs, followed by the derived energy system surplus, environmental costs and welfare impacts. We end with some sensitivity considerations, including results from imposing a third constraint: impacts on reindeer husbandry.

4.2. Spatial distribution of WPPs across scenarios

Figure 0-1 illustrates the spatial distribution of new wind power capacity in Norway from the TIMES model simulations for the five main wind power deployment scenarios. The base scenario represents the optimal, cost-effective distribution when no environmental impacts are considered. From an energy system perspective, the South is the most favourable region for wind power investments, reaching its maximum potential of 542 MW. The optimal distribution of the WPPs derives both from the levelised cost of electricity, i.e., the difference in investment costs and capacity factors, but also (largely) from the difference in electricity price for each of the regions. While the South obtains the highest electricity price from the model results, the North is consistently the region with the lowest electricity price across all scenarios, making it the least optimal region for wind investments. Moreover, the South is more closely connected to the European energy system, allowing the export of wind power production without the need for large domestic grid investments. A total of 16 wind power plants are chosen in the cost-effective scenario, out of 26 possible.

Figure 0-1: Spatial distribution of WPP's for each of the five scenarios (S1-S5). Values are given in MW

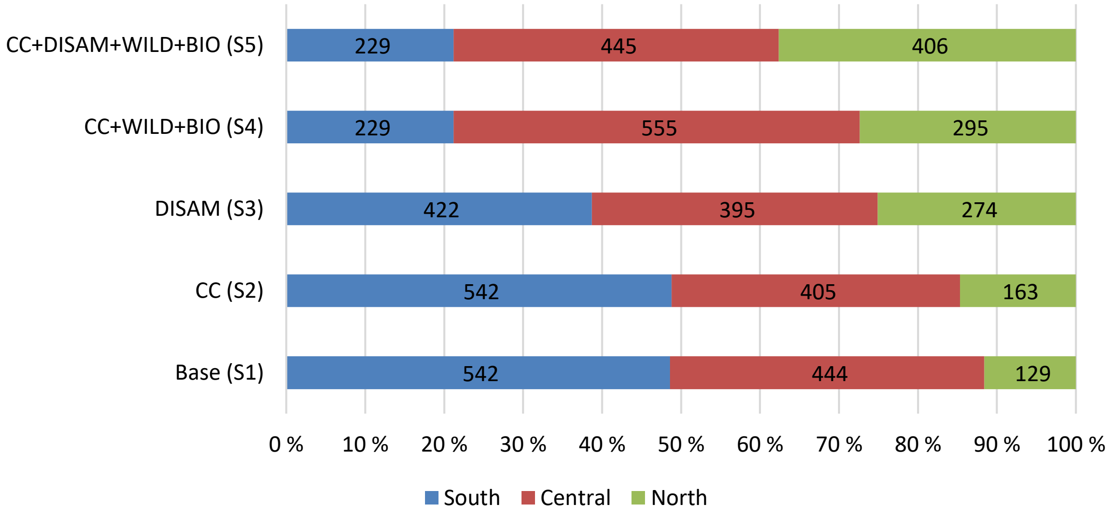

Table 2: Change in the selection of power plants relative to scenario S1 and total number of wind power plants.

	CC (S2)	DISAM (S3)	CC+WILD+BIO (S4)	CC+DISAM+ WILD+BIO (S5)
Number of WPP's included compared to S1	0	0	2	1
Number of WPP's excluded compared to S1	0	3	10	10
Total number of WPP's	16	13	8	7

The second scenario, CC (S2), includes the emission cost of land-use change, resulting from mires excavation and loss of biomass. As illustrated by Figure 0-1, incorporating these costs have a minor impact on new wind power plant investments, even though excavation of mires has a large impact on CO_2 emissions (per m^2). In fact, the same 16 wind power plants are chosen, but there is a slightly higher-capacity investment for the single WPP in the North, in favour of WPP’s in the Central. The reason for this small impact is that very few WPPs have large areas of mires within the concession area, and even more importantly, it is only a small part (4 %) of the concession area that is assumed to be affected by the establishment of a WPP. Internalising the welfare loss of neighbouring households and recreational homeowners (S3) leads to a 10 percent lower investment share in the South. This is due to the higher population compared to the northern parts of Norway. Correspondingly, new power plants in the North will generally have lower local disamenity costs than those located further south, making investments more favourable in this region.

The same tendency can be observed when incorporating the impact on wilderness and biodiversity in the analysis (S4 and S5). In general, when gradually including more of the monetized environmental costs and sustainability constraints associated with WPPs, the more beneficial WPPs in the northern part of Norway become. For the wilderness constraint (WILD), in which WPPs in areas with low human infrastructure impact are excluded, results show that this constraint alone leads to a 5% shift in investment share from the South to the Central. In total, 5 of the 7 wind power plants violating this constraint are initially part of the optimal investment solution from S1, indicating that most of the wind parks in violation of the wilderness constraint are considered cost-optimal. However, the impact on the spatial distribution is minor as these 5 WPPs only constitute 7% of the new wind power capacity in Base (S1). Incorporating the biodiversity constraint has the largest impact on the spatial distribution, disabling largely WPPs in the South that otherwise would be considered cost-optimal (the results for the two sustainability criteria have not been shown separately in Figure 2). Together with the wilderness constraint, a total of 10 wind parks are disabled out of the invested 16 in the Base scenario (S1). Of these, 8 are located in the South. To compensate for the loss in production, two new, but less profitable, wind parks are selected in Central. This is somewhat surprising considering our anticipations described in Section 2.4, in which the sustainability constraints were expected to shift WPP siting out of pristine nature areas and nearer the more populated areas. From the results, we can see that such pristine nature areas also to a large extent exist in southern parts of Norway. Nevertheless, the choice of WPPs within each of the regions indicate that our hypothesis is supported, as will be discussed in the following section. Lastly, the inclusion of local environmental costs (S5) further enhances the social profitability of WPPs in North, reducing investments in the Central by 10%.

4.3. Energy system surplus, environmental costs and welfare impacts of increased wind power production – comparison across scenarios.

In the numerical illustrations above, we considered the optimal spatial distribution of WPPs under different environmental impact constraints and given an annual production increase of 4 TWh (S1-S5). Here we explore the impact of increased wind power production on the energy system costs and environmental costs. In Figure 3 and Table 3, we present the additional energy system surplus, local disamenity and carbon costs of increasing the production of wind energy by 4 TWh/year over 25 years, across the different scenarios. Figure 3 illustrates the costs and benefits in k€, whereas Table 3 presents the numerical values in c€/kWh.

Figure 0-1: Net monetised welfare gains of new wind power, measured by the difference in energy system surplus and environmental costs (in k€)

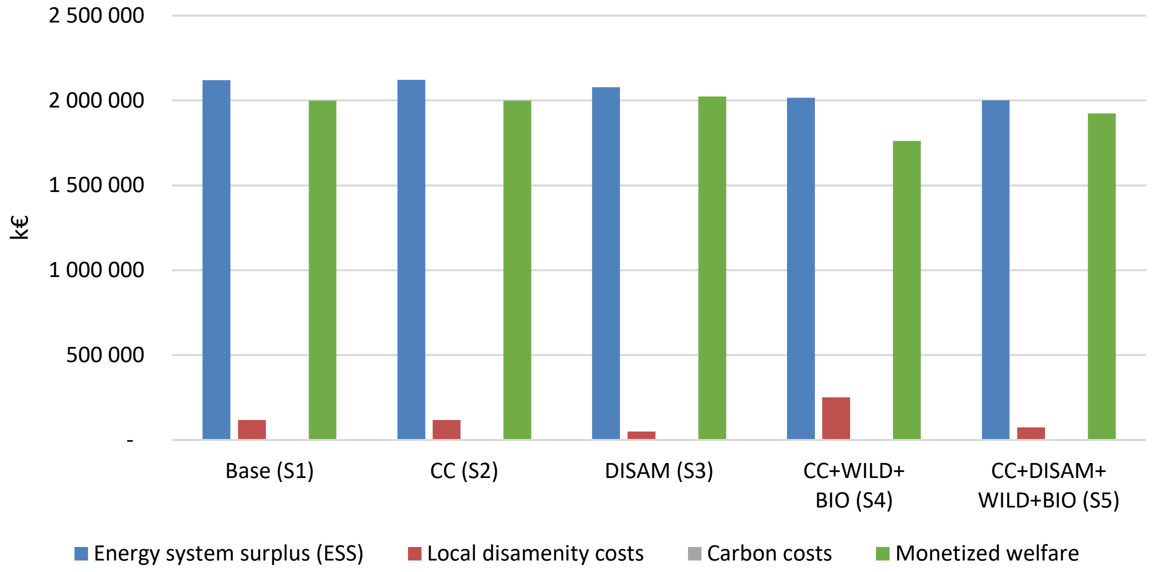

Table 3: Net monetised welfare gains of new wind power, measured by the difference in added revenues and costs (in c€/kWh).

c€/kWh	**Base (S1)**	**CC (S2)**	**DISAM (S3)**	**CC+WILD+ BIO (S4)**	**CC+DISAM+ WILD+BIO (S5)**
Energy system surplus (ESS)	3.39	3.39	3.33	3.23	3.20
Local disamenity costs	0.19	0.19	0.08	0.40	0.12
Carbon costs	0.01	0.01	0.01	0.01	0.01
Monetized welfare	**3.20**	**3.20**	**3.24**	**2.82**	**3.08**

The energy system surplus (ESS) represents the additional surplus (i.e., revenues minus costs) for the energy system of installing 4 TWh new wind power. ESS includes the total lifetime revenues of the new WPPs, the cost of increased wind energy production, as well as the additional grid investment costs triggered by new wind power capacity. Moreover, the spatial distribution of wind power also impacts the income of other power producers, in particularly hydropower. For example, the income of hydropower producers in 2040 in the North decreases by 14% in S5 compared to S1, as the shift in wind investments lead to lower electricity price in the region[19]. Hence, the net energy system revenue includes the overall system benefits and not only the private profitability of the wind producers. By subtracting the local disamenity and carbon costs from the energy system surplus, we find the increase in pecuniary social welfare (*Welfare*) of increased wind power production. Note that *Welfare* does not

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[19] Results on the average regional electricity price in Norway for the different scenarios are presented in Appendix B, Figure B2.

include the welfare loss due to loss of land of especially high nature value (land areas that are excluded from development by the WILD and BIO constraints).

Results indicate that Base (S1) and CC (S2) obtain the highest net ESS, as these scenarios are less restricted in terms of where wind power plants can be located. The scenario which includes all environmental costs and sustainability constraints (S5) obtains the lowest net ESS, caused by less profitable wind power plants and a deployment which is forced to regions with lower electricity prices. This confirms our anticipated results discussed in section 2.4. The ESS is reduced by 6% (from 3.39 to 3.20 c€/kWh). S5 induces less local environmental cost than S1. Including the monetary costs of local environmental degradation and carbon costs, we find that the welfare of new wind power development is only reduced by 4% (0.12 c€/kWh). Another environmental benefit of S5 compared to S1 is that S5 preserves more land areas with valuable nature than S1, as 10 of the WPPs included in S1 is excluded in S5 due to the biodiversity and wilderness criteria. By comparing S5 with S3, we find that imposing the sustainability constraints (and carbon costs) in addition to local disamenity costs, induces an extra cost of 0.16 c€/kWh (101 M€), which we can refer to as the monetised welfare cost of the sustainability constraints, as discussed in section 2.4[20]. We see from Table 3 that the selected WPPs differ substantially between S3 and S5. For S5 to be socially preferred to S3, the value of protecting the valuable nature, developed in S3 must be perceived as higher than 0.16 c€/kWh (101 M€).

Incorporating only local disamenity costs (S3) has a significant impact on the outcomes for neighbouring households. In comparison to Base (S1), the local disamenity costs are more than halved. This emphasises the importance of internalising such costs in the selection process of WPPs. Furthermore, we see from Table 3 that neighbouring households face considerably higher local disamenity costs when only the sustainability constraints are accounted for (S4), than if no disamenity costs are accounted for (S1). The local disamenity costs more than doubles when moving from S1 to S4. Even though the sustainability constraints lead to lower investments in southern parts of Norway, the large increase in local disamenity costs indicates that concerns for loss of wilderness and biodiversity (S4) shifts wind power production to areas with higher population density within these regions. Consequently, the WPPs that are selected within the South region in S4 are located in areas with more people in the viewscape than those selected in S1. This indicates that there is a trade-off between concerns for the welfare loss of affected people locally and the loss of wilderness and biodiversity. However, we see that the differences in the monetised environmental costs between S5

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[20] We have ignored the impact of the minor effect of also including carbon costs in S5.

and S3 are relatively modest (0.04 c€/kWh or 24 M€). Thus, it can be argued that the benefit to society overall of preserving hotspots for biodiversity and wilderness more than outweigh the increased local disamenity costs of affected people locally, as long as these costs are included in the optimisation problem, that is moving from S3 to S5.

4.4 Sensitivity analysis

4.4.1. Effects of alternative local disamenity cost specifications

The disamenity costs faced by people affected locally differ depending on the methodology used and the cost assumed per turbine. This section therefore addresses the impact of varying costs and distance to the turbines. In the *DISAM < 4km* scenario, we only consider the cost of turbines for households within a 4 km radius, excluding the cost of WPPs within the viewscape further away. In this scenario, the difference in distribution of wind power plants to the base scenario (S1) is minor, indicating that very few WPPs are planned within this distance. Hence, the largest impact of the local environmental cost arises from the visual disamenities further away than 4 km.

In the *DISAM decay* scenario, the cost that neighbouring households incur depends on their distance from the wind power plant (cf. function in section 3.2.1 above). Households closest to the WPP incur the highest cost, while the cost diminishes as the distance increase up until 4km. In such a distance decay scenario, wind power plants in the Central region are preferred in favour of those in the South. From these results, it follows that wind power plants in the South are planned in closer proximity to households compared to other regions.[21]

Lastly, the *DISAM double* scenario assumes a doubling in the local environmental cost for each of the WPPs. As presented in

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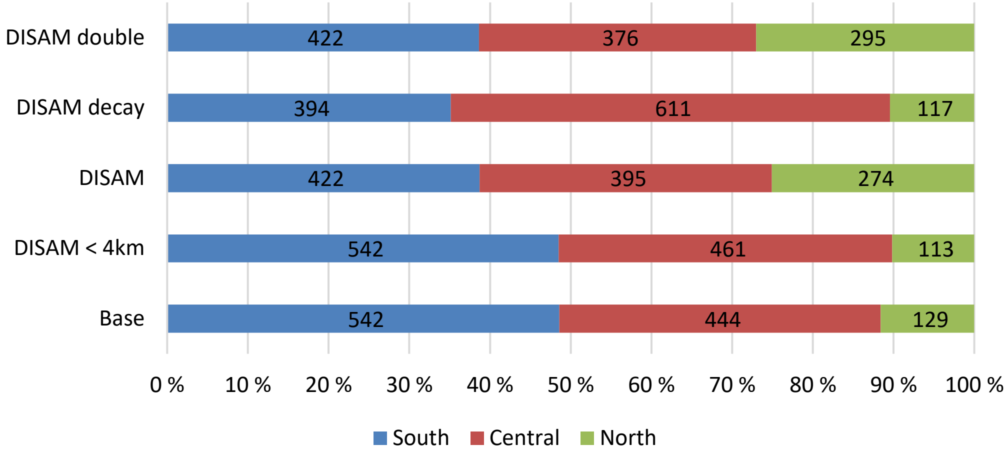
[21] We also conducted a sensitivity analysis where the WTP per turbine was decreasing in the number of turbines at a site, based on a transferred estimate of scope elasticity from Dugstad et al.'s (2021) choice experiment study of a national wind power development plan with number of turbines as an attribute. Results (left out for sake of brevity) showed marginal impacts on the spatial distribution of WPPs compared to the base case.

Figure *0-1*, the distribution is almost unaffected by the increase, compared to S3. The spatial distribution of WPPs is therefore more sensitive to variations in cost with distance, rather than a uniform increase in cost.

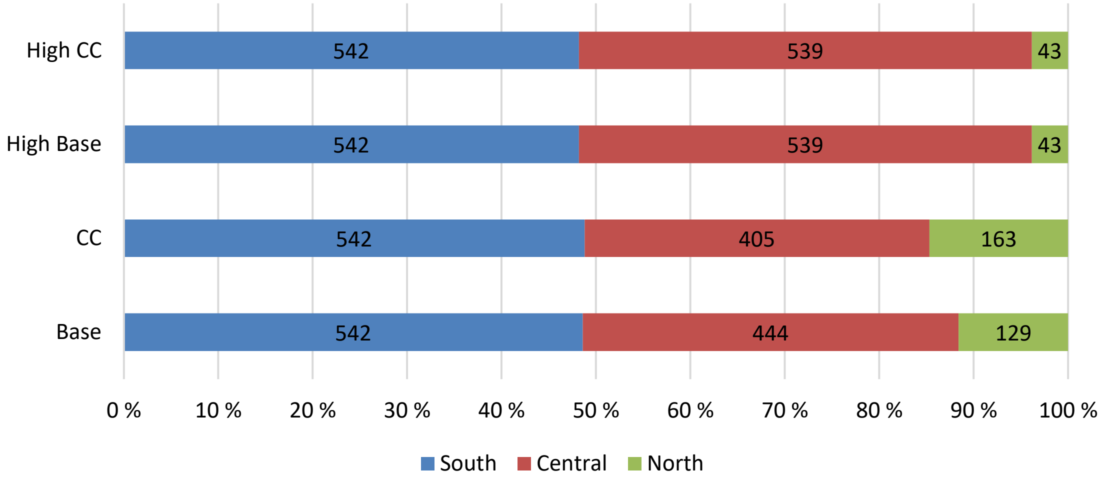
Figure 0-1: Spatial distribution of WPP's for different local environmental cost scenarios. Values given in MW



4.4.2. *Effects of a higher carbon price path*

Due to the highly uncertain development of carbon prices, a sensitivity analysis is conducted to evaluate the impact of a higher carbon price on new wind power investments. The increase in carbon price is applied both to the emission cost calculations, but also on the European energy system. Hence, a higher electricity price for countries with transmission capacity to Norway is included in the model.

Figure 0-2: Spatial distribution of WPPs for different carbon price pathways



As described above, higher CO_2 prices affects the results both directly through higher carbon costs of land use changes, and indirectly through higher international electricity prices. From Figure 5, we can observe that the change in spatial distribution is mainly caused by higher electricity prices in Europe, favourising production and export of wind power from the southern parts of Norway. This is clear from the comparison of High Base and High CC, in which no differences occur in wind power deployment. The reason for the increase in deployment share in Central for the high price scenarios is due to shorter distances to export cables compared to North. In the Base and CC scenario, the new wind power potential is already reached in the South, making Central the region with the lowest additional cost for grid expansion. This is further confirmed by the transmission flow results, in which net export from Central to southern parts of Norway is increased by 5.8 TWh in the CC scenario with high CO_2 prices compared to the CC scenario with medium CO_2 prices. Hence, the impact of emission cost of land use on the spatial distribution seems to be limited or close to zero, regardless of the CO_2 price assumptions.

4.4.3. Effects of hard constraint on indigenous rights to reindeer husbandry

The spatial distribution of WPPs has also been assessed according to their interference with reindeer husbandry, cf. 3.2.3. This criterion is activated for WPPs with more than 1 percent overlap for one or several of the reindeer indicators, which disables a total of 12 WPPs out of 26. By adding this to the wilderness and biodiversity criteria, we are left with only three wind power plants as possible investment alternatives. Consequently, the production levels from new land-based wind power would reach only 1.3 TWh/year, substantially lower than the maximum target of 4 TWh/year (top bar in Figure 6). The production would be distributed between the South and the Central, with no new wind capacity in the North, where reindeer husbandry is most prevalent. Hence, this constraint would have substantial and wide-reaching implications for new (and potentially some existing) WPPs if interpreted as a hard constraint, as we have done here[22].

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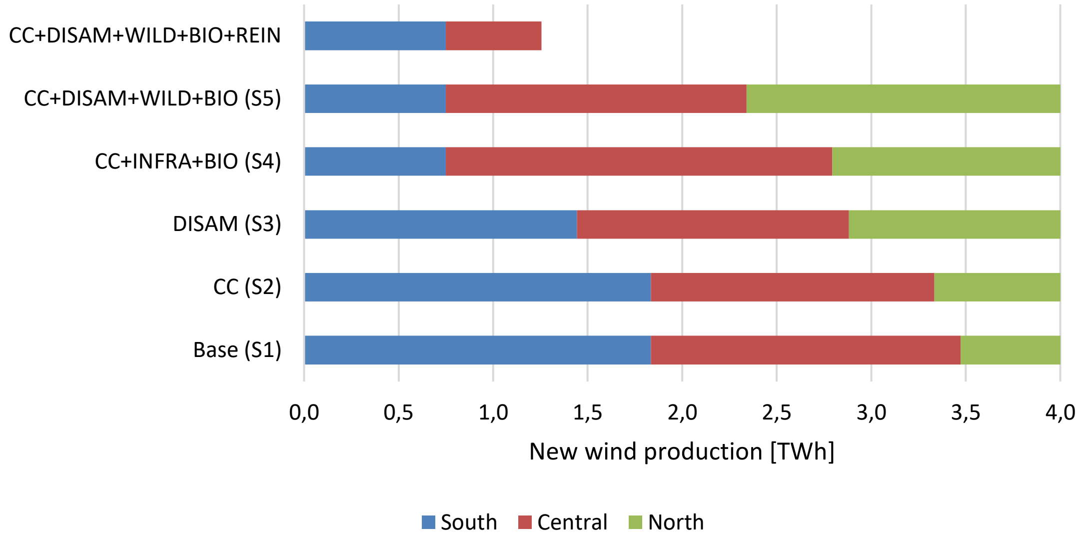
[22] At the time of writing, the consequences of the high court verdict mentioned in 3.2.3 is unclear, both in terms of whether the Fosen WPP (and any other existing WPPs in violation of similar indigenous rights) must remove their turbines and restore the area or not and whether new WPPs has to avoid all similar reindeer areas.

Figure 0-3: New wind power production across scenarios with respective regional distribution.



5. Concluding remarks

We have presented a system for taking into account various environmental concerns when deciding on the spatial distribution of new wind power production. An energy system model (IFE-TIMES-Norway) has been deployed to find the distribution which maximises the social welfare under various constraints in Norway. For the local disamenity costs, faced by people in the viewscapes, and carbon emissions cost, we included the estimated externality costs directly into the model. Impacts on wilderness and biodiversity were implemented in the model analysis as strong sustainability constraints. We used the database over proposed WPP projects in Norway (NVE 2022) as the pool of potential WPPs contributing to reaching a target of 4 TWh annual production from new wind power.

Our numerical simulations show that the environmental concerns had significant impact on the optimal geographical distribution of WPPs across the country. In the Base scenario (S1) we did not take into account any environmental impacts. From a purely energy system perspective, the South is the most favourable region for wind investments, reaching its maximum potential in the Base scenario. In the scenario where all environmental concerns were accounted for (S5), the production in the South was only 40 percent of its maximum potential, and the production in North was three times higher than under S1.

The impact on the energy system surplus of increased wind power production did not deviate substantially across the scenarios, at the most 6% (between S1 and S5). Hence, replacing some WPPs with others did not have a very large impact on the surplus. This implies that taking all the environmental concerns into account when selecting WPPs to be constructed, is not very costly. Following the framework of Bateman and Mace (2020), regarding biodiversity as a strong sustainability concern, we do not attempt to estimate of the value impacts on wilderness and biodiversity, but rather impose those as sustainability constraints on the model. The numerical illustration shows, somewhat surprisingly, that if the benefit of avoiding the development of 10 WPPs, in violation of these constraints, exceeds 0.16 c€/kWh, the S5 (all environmental costs and constraints included) is welfare superior to S3 (only local disamenity costs included). In total, this amounts to 101 million (M) Euro. Dividing this on the number of households in Norway (ca 2.5 M), if considered a national responsibility to preserve biodiversity and wilderness, this amounts to around 40 Euro per household as a one-time amount. While it is not straightforward to compare this with results from Norwegian non-market valuation studies, there are some indications that this amount is modest. Lindhjem et al. (2015) found, for example, an annual WTP per household of NOK 1040-1300 (2007) in a contingent valuation study of the preservation of forest biodiversity on the national level in Norway. This amount is around four times higher in real terms than what would be required to satisfy the sustainability constraints considered here. A recent studies of national wind power externalities conducted in two regions in Norway, though likely covering a mix of different types of impacts, also showed substantial WTP among households in areas affected and unaffected of wind power to avoid a broad set of externalities (Dugstad et al. 2020).

Overall, results show that there is a trade-off between local disamenties and loss of biodiversity and wilderness. Siting wind power plants outside the visual proximity of households yield negative consequences for biodiversity and wilderness. We conducted a comprehensive sensitivity analysis. Due to uncertainty and discussion in the literature about the local disamenity cost function (Lehman et al. 2021; Grimsrud et al. 2021), we devoted some consideration to that point. The sensitivity analysis explored the consequences of increasing the disamenity costs, the carbon costs, and adding a constraint to prevent new WPPs that violate indigenous rights to reindeer husbandry.

The sensitivity analysis shows that our main results are relatively robust. The sensitivity analysis with increased local disamenity costs had very little effect on the results, although there was a small change in where the WPPs were located for the case with distance decay within 4 km. In that case, some wind power production moved from the South where WPPs, in general, are located closer to residential areas and to the Central. Increased carbon costs lead to more demand for wind power by importing countries and therefore more WPPs were sited in locations closer to the export cables. The increased carbon cost did not cause fewer WPPs to be built on mires. The sensitivity analysis showed that if adding a constraint for indigenous rights to reindeer husbandry while also having constraints on wilderness and biodiversity, it is no longer possible to realise the target of 4 TWh – instead only 1.3 TWh can be produced.

There are, however, some issues we are aware of that could have some impact on the results of the modelling that we have not yet fully investigated. First, regarding the local disamenity costs, we admit that it may be hard to differentiate fully the local disamenity impacts from impacts on biodiversity and wilderness more generally, as people in the viewscape may also be aware of and consider such impacts as part of the "bundle" of disamenities they experience. However, we do believe that other impacts (such as noise, flickering, landscape aesthetics and reduced quality of recreation), may be the most important locally. The more fundamental importance of biodiversity (as a fundamental building block for other services), and the reason why such impacts are considered a hard sustainability constraint, may not be fully appreciated, and thus the problem of "double counting" is likely relatively small. Further, in the modelling, we make some simplifying assumptions and do not include any form of stochasticity or uncertainty. For example, we assume that all WPPs are invested in 2025, while some are likely to be installed earlier and some later. We have not differentiated between those which already have obtained a concession (and likely will soon be built) and those which are in the process (and that have a higher probability of not being built). In future work, such points may be refined.

Further, as the whole energy system will undergo a transition, it will be important also to consider the environmental impacts of other renewable energy sources, for example, offshore wind power and solar power, which both are scheduled for large expansions in Norway during the next decades. Finally, while we have investigated how to factor in both local and wider environmental impacts and derive more optimal spatial configurations of wind power production, it will be important to work towards regulatory instruments to internalise the environmental impacts in developer and regulator decisions.

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Appendix A: Specifications of new and existing wind power plants

Table A1: Parameters for new wind power plants. Operational cost equal for all plants at 8.4 €/MWh (from 2025). Lifetime of 25 years and investment year fixed to 2025.

ID	**Name of WPP**	**Spot region**	**Capacity**	**Production**	**Investment cost €/kW (2025)**
38	Dønnesfjord	NO4	14	58	956
51	Faurefjellet	NO2	67	219	978
54	Skorveheia	NO2	45	156	825
55	Gilja	NO2	135	469	936
58	Friestad	NO2	2.4	10	925
62	Kvinesheia	NO2	90	328	686
66	Nordkyn	NO4	750	3063	771
73	Remmafjellet	NO3	130	505	870
80	Bremangerlandet	NO3	86	293	1041
109	Grøndalsfjellet	NO3	200	722	855
110	Mariafjellet	NO3	150	541	855
172	Bjørnevatn	NO4	60	185	1195
178	Andmyran	NO4	160	503	953
200	Innvordfjellet	NO3	115	363	877
214	Eggjafjellet/Åsfjellet	NO3	184	686	977
217	Dalbygda	NO2	42	136	679
227	Vikna	NO3	9	34	722
230	Oddeheia og Bjelkebjerget	NO2	97	287	916
231	Hyllfjellet, Sognavola og Markavola	NO3	281	1052	1053
233	Borealis	NO4	200	638	1045
241	Kroken	NO4	60	193	1003
256	Moldalsknuten	NO2	30	98	708
157	Utsira II	NO2	11	51	1014
261	Lillesand	NO2	12	45	784
5017	Larvik	NO2	10	36	887
5119	Raggovidda trinn 3	NO4	103	366	834

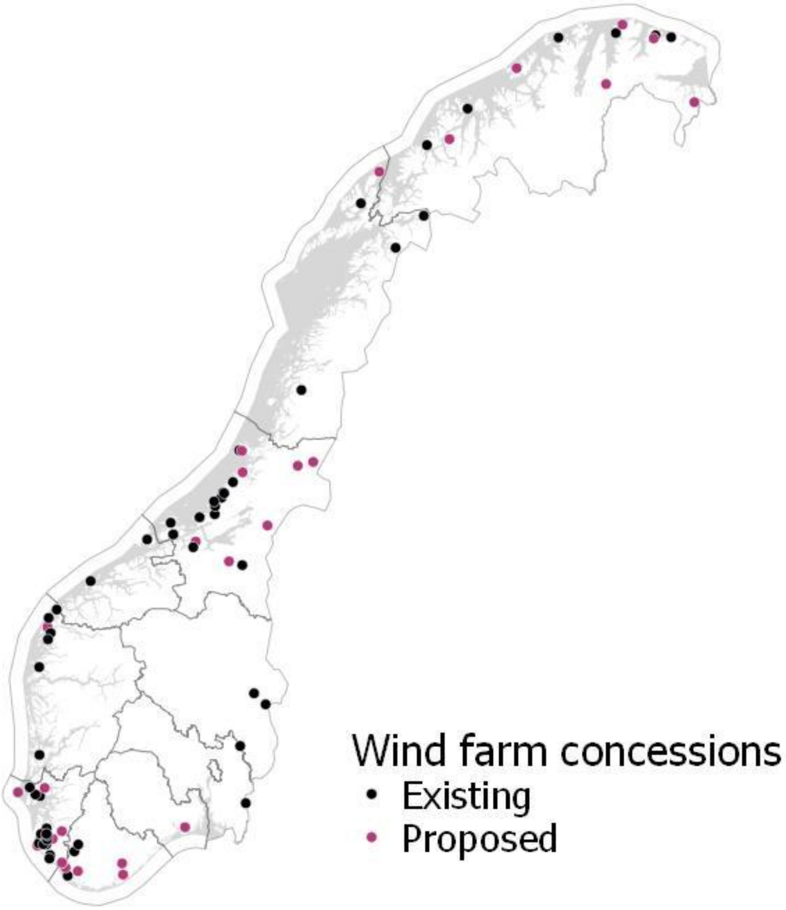
Table A2: Parameters for existing wind power plants. Operational cost equal for all plants at 10 €/MWh (from 2025). Lifetime of 25 years and possible reinvestments at decommissioning.

ID	**Name of WPP**	**Spot region**	**Capacity**	**Production**	**Reinvestment cost kNOK/MW (2025)**
1	Sandøy	NO3	4	10	817
3	Smøla	NO3	150	356	830
4	Utsira	NO2	1	4	1100
5	Lindesnes	NO2	7	26	833
9	Valsneset	NO3	12	35	1173
10	Hitra	NO3	55	138	1100
12	Lista	NO2	71	220	1212
13	Nygårdsfjellet	NO4	32	104	1100
14	Tysvær	NO2	47	150	923
15	Fakken	NO4	54	139	1335
17	Midtfjellet	NO2	150	434	990
21	Kjøllefjord	NO4	39	119	910
22	Bessakerfjellet	NO3	58	175	710
23	Kvitfjell	NO4	197	541	1427
24	Høg-Jæren	NO2	74	222	977
25	Haram	NO3	34	127	916
31	Egersund	NO2	112	370	1270
32	Bjerkreim	NO2	155	558	1214
34	Hitra 2	NO3	94	290	1267
42	Sørfjord	NO4	99	380	819
43	Storheia	NO3	288	973	1100
59	Røyrmyra	NO2	2	8	1251
63	Skinansfjellet	NO2	139	543	1176
65	Tellenes	NO2	160	550	1038
69	Okla	NO3	21	75	987
81	Hennøy	NO3	50	171	1125
87	Guleslettene	NO3	197	712	962

89	Ytre Vikna	NO3	39	103	1069
90	Raudfjell	NO4	84	227	910
91_1	Raggovidda trinn 1	NO4	45	189	1088
91_2	Raggovidda trinn 2	NO4	17	72	739
93	Hamnefjell	NO4	52	186	1277
94	Kvenndalsfjellet	NO3	113	405	903
95	Roan	NO3	256	900	939
96	Valsneset teststasjon 3	NO3	13	45	1100
103	Svåheia	NO2	25	96	1195
122	Frøya	NO3	59	197	1107
147	Vardafjellet	NO2	30	85	1112
148	Ånstadblåheia	NO4	50	154	780
170	Gismarvik	NO2	13	43	1229
175	Hundhammerfjellet	NO3	55	211	940
176	Lutelandet	NO3	51	149	1068
177	Harbaksfjellet	NO3	126	474	1100
183	Geitfjellet	NO3	181	546	870
185	Tonstad	NO2	208	670	993
187	Åsen II	NO2	2	5	1191
207	Måkaknuten	NO2	95	363	1121
208	Stigafjellet	NO2	30	117	1154
215	Raskiftet	NO1	112	369	1185
218	Øyfjellet	NO4	174	554	1028
221	Stokkfjellet	NO3	88	311	1144
225	Marker	NO1	54	192	931
226	Buheii	NO2	80	312	942
228	Odal	NO1	10	31	986
240	Kjølberget	NO1	56	195	797
245	Storøy	NO2	6	25	792
249	Mehuken 3	NO3	25	74	869
250	Tindafjellet	NO2	10	36	858
251	Skurvenuten	NO2	7	23	910
259	Skomakerfjellet	NO3	13	36	1020

262	Sørmarkfjellet	NO3	130	485	1579
4959	Havøygavlen	NO4	41	137	1169

Figure A1: Geographical location of existing and potentially new WPPs in the dataset



Appendix B: Assumptions of carbon price paths

Table B1: Two alternative carbon price pathways (base case and high case) in €/ton.

Yearly price	Base	High
2020	40	40
2021	42	45
2022	44	51
2023	47	56
2024	49	62
2025	51	67
2026	54	74
2027	57	80
2028	59	87
2029	62	93
2030	65	100
2031	68	107
2032	71	113
2033	73	120
2034	76	127
2035	79	134
2036	82	140
2037	85	147
2038	87	154
2039	90	160
2040	93	167
2041	96	174
2042	99	180
2043	101	187
2044	104	193
2045	107	200
2046	110	207
2047	113	213
2048	115	220
2049	118	226
2050	121	233

We assume constant present value prices from 2050 and onwards.

Figure B1: Two alternative European power price pathways (base case and high case) for some selected countries (Germany, the Netherlands, and the UK) in €/MWh.

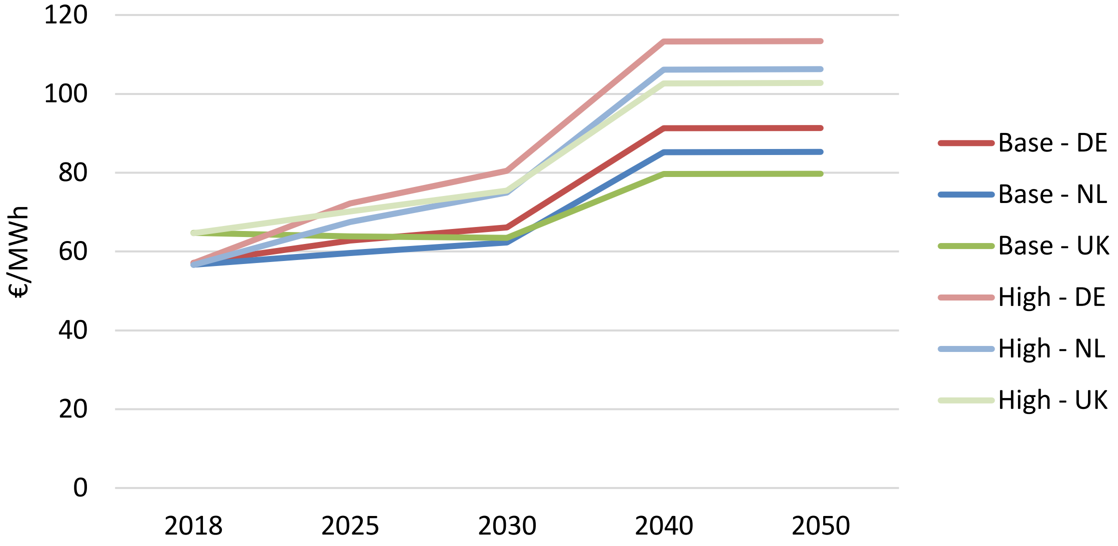
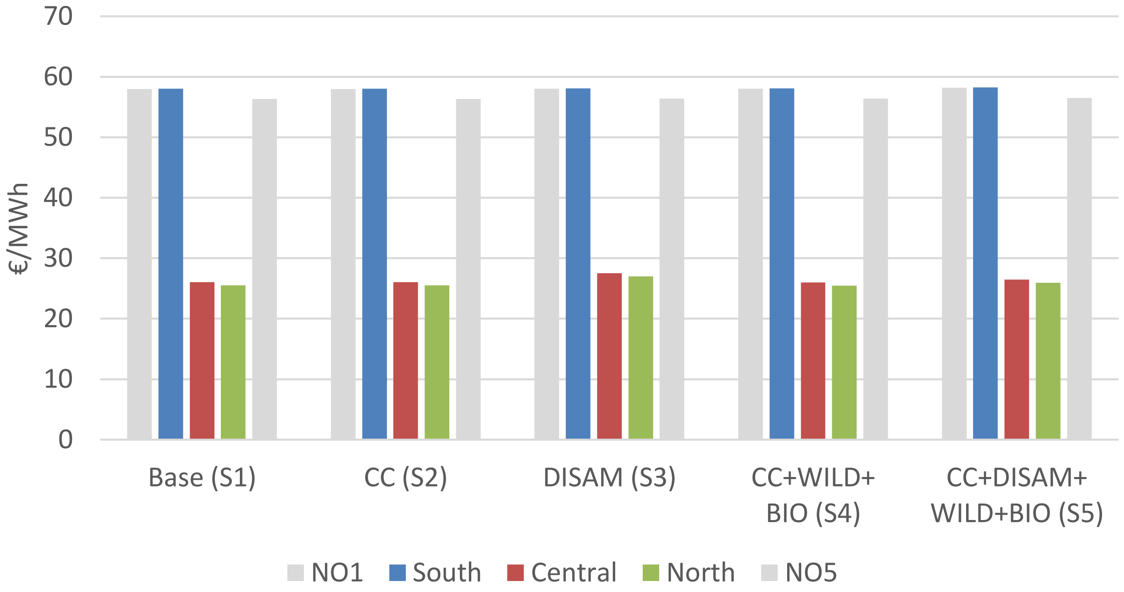


Figure B2: Model results on the average regional electricity price in 2025 (year of investment) for the five scenarios S1-S5. All 5 spot regions are included, but no wind investments are made in NO1 and NO5.



Appendix C: Carbon emission calculations

The calculation of the present values of the carbon costs components of equations in (7) is given by:

$$CE_{iF} = 0.04 \cdot q_0 \cdot \delta_1 \cdot (BMA_i + BMB_i) \cdot F_i,$$

$$CE_{iM} = 0.04 \cdot q_0 \cdot \delta_2 \cdot M_i,$$

$$CS_{iF} = 0.04 \cdot \left[\sum_{t=1}^{75} q_t \cdot \frac{1}{(1+r)^t} + q_{75} \frac{\left(\frac{1}{1+r}\right)^{75}}{\left(1 - \frac{1}{1+r}\right)} \right] \cdot (\delta_3 + \delta_4) \cdot F_i,$$

$$CS_{iM} = 0.04 \cdot \left[\sum_{t=1}^{75} q_t \cdot \frac{1}{(1+r)^t} + q_{75} \frac{\left(\frac{1}{1+r}\right)^{75}}{\left(1 - \frac{1}{1+r}\right)} \right] \cdot \delta_5 \cdot M_i \ .$$

We assume an increase in the carbon prices until 2100, and constant thereafter (see appendix B). See Table C1 for the description of symbols, units and assigned values.

Table C1: Symbols and values (the subscript *i* is omitted).

Symbol	Definition	Units	Values/reference
BMA	Biomass stored in forests above ground	Tons per m^2 forest	
BMB	Biomass stored in forests below ground	Tons per m^2 forest	
M	Mires	m^2	
F	Forest	m^2	
CE_F	Emission cost from cutting trees	EUR	
CE_M	Emission cost from excavated mires	EUR	
CS_F	Emission costs from lost carbon sink in trees	EUR	
CS_M	Emission costs from lost carbon sink in mires	EUR	
r	Discount rate	unitless	0.04[23]
TC	Total carbon costs	EUR	
q_t	Carbon costs year *t*	EUR per ton CO_2	See appendix B

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[23] The recommendation in the Ministry of Finance (2012) for public projects with normal risk and a horizon of less than 40 years is to use a discount rate equal to 4 per cent. They assume a risk-free interest rate of 2.5 per cent and a risk adjustment of 1.5 per cent.

δ_1	Emission factor for removed biomass in forests above and below ground	Tons of CO_2 per ton of biomass stored in forests	1.83[24]
δ_2	Emissions factor for mires removed	Tons CO_2 per m^2 mires	0.25245 (0.1683 *1,5)[25]
δ_3	Emission factor for lost sequestration due to forest loss	Tons CO_2 per m^2 forest	0.00004 (de Wit et al., 2015)
δ_4	Emission factor for lost sequestration in forest soil	Tons CO_2 per m^2 forest	0.0000088 (de Wit et al., 2015)
δ_5	Emission factor for lost sequestration from lost mires	Tons of CO_2 per m2 mires	0.000019 (de Wit et al., 2015)

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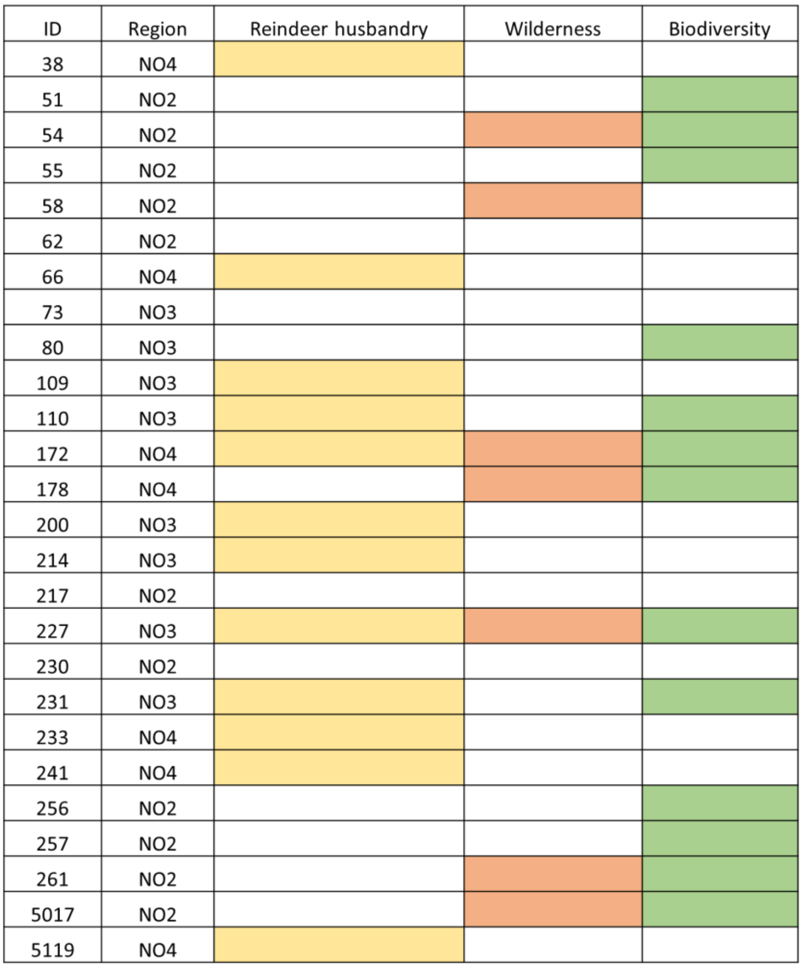
[24] We have set one ton of biomass equal to 0.5 ton of carbon (see Peterson et al., 2012) and used the conversion factor 44/12 to convert from carbon to CO_2.

[25] We have set the dept for all mires to 1.5 meters. The CO_2 emission factor per m^2 per meter depth is from Stokland et al. 2022.

Appendix D: Strong sustainability constraints

Figure D1: results of the GIS analysis of overlaps between a specific WPP and either Reindeer husbandry, Wilderness or Biodiversity



ID	Region	Reindeer husbandry	Wilderness	Biodiversity
38	NO4	🟨		
51	NO2			🟩
54	NO2		🟧	🟩
55	NO2			🟩
58	NO2		🟧	
62	NO2			
66	NO4	🟨		
73	NO3			
80	NO3			🟩
109	NO3	🟨		
110	NO3	🟨		🟩
172	NO4	🟨	🟧	🟩
178	NO4		🟧	🟩
200	NO3	🟨		
214	NO3	🟨		
217	NO2			
227	NO3	🟨	🟧	🟩
230	NO2			
231	NO3	🟨		🟩
233	NO4	🟨		
241	NO4	🟨		
256	NO2			🟩
257	NO2			🟩
261	NO2		🟧	🟩
5017	NO2		🟧	🟩
5119	NO4	🟨		