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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 by land-based wind power is expected to play a crucial role in the decarbonisation of the economy. However, with the looming biodiversity and nature crises, spatial allocation of wind power can no 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 renewable energy transition. We suggest a modelling system for selecting among a pool of potential wind power plants (WPPs) by combining an energy system model with a GIS analysis of WPP sites and surrounding viewscapes. The modelling approach integrates monetised local disamenity and carbon sequestration costs and places constraints on areas of importance for wilderness and biodiversity (W&B). 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 local disamenity costs (and to a lesser extent carbon costs) and W&B constraints are added successively to the scenarios, it becomes increasingly beneficial to site WPPs in the northern part of Norway. We find that the W&B constraints have the largest impact on the spatial distribution of WPPs, while the monetised costs of satisfying these constraints are relatively small. Overall, our results show that there is a trade-off between local disamenities and loss of W&B. Siting wind power plants outside the visual proximity of households has a negative impact on W&B.

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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1 Introduction

Energy generated by 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 wind conditions and necessary investments in turbines, infrastructure, and associated grids. Differences in expected prices across a 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 (W&B) (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 and sequestration through land-use changes, especially through the conversion of mires and forests.

From the regulator's point of view, when a spatial deployment plan for the economic profitability of WPPs is being chosen, 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 for WPPs.

Research on spatial trade-offs in wind power deployment has to date focused primarily on the negative effects for nearby residents (Zerrahn 2017; Mattmann et al. 2016; Wen et al. 2018; Weinand et al. 2022), and only a few such studies have, to our knowledge, incorporated some measure of (primarily local) environmental and disamenity costs in energy system models (e.g., Lehmann et al. 2021a, b; 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 and that the two effects are mutually reinforcing. Hence, the impacts of land use on W&B must also be thoroughly assessed and considered in order 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 at national level in Norway. The paper also contributes to a wider and more heterogeneous literature on trade-offs in renewable energy deployment that investigates a range of different impacts (such as on land use and landscapes, scenics, biodiversity, equality, etc.) on different geographical levels by means of different methods (such as multicriteria analysis) (e.g.,Lehman et al. 2021b; Mckenna et al. 2021, 2022; Sasse and Trutnevyte 2020; Tafarte and Lehman 2021; Weinand et al. 2022).

The main contribution of the present paper is to provide a framework and an analysis of the evaluation and inclusion of various kinds of environmental impacts, more comprehensively assessed than previously, for the regulator's decisions on the domestic siting of wind power production on land. We analyse the optimal siting of new potential wind power production capacity until 2050 based on concession applications obtained from the Norwegian Water Resources and Energy Directorate (NVE). As such, the potential analysed in this study is pre-selected by investors, while the true technical potential would be larger. From the total production capacity of 11 TWh, we apply a maximum target of 4 TWh from new land-based wind power in order to assess which WPPs are most favourable for investment. The selection of WPPs is subject to local nuisance and disamenity costs and the cost of carbon emissions due to land-use change, as well as constraints to prevent the loss of W&B. Hence, this type of analysis follows

the approach by Bateman and Mace (2020), for example, arguing that a monetary value should not be placed on biodiversity impacts but rather constraints on the loss of critical natural capital for which there is limited substitutability.

By employing a fit-for-purpose, modified and updated energy system model for Norway (IFE-TIMES-Norway) (Loulou 2008; Loulou and Labriet 2008; Danebergs et al. 2021; Seljom et al. 2020), we explicitly derive the socially optimal selection of WPPs, taking into consideration both energy system revenues and costs, local disamenity costs, and the impacts of WPPs on W&B.

We also derive the energy system surplus of new wind power for different scenarios, with and without externality costs and the W&B constraints that have been included. The scenario analyses demonstrate spatial trade-offs and the explicit costs of accounting for W&B impacts. Although we conduct the analysis on Norwegian data, the analytical framework for optimal spatial selection 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 (1) the energy system model, IFE-TIMES-Norway, (2) how local disamenity impacts and carbon emissions are estimated and monetised, and (3) the derivation of W&B constraints. In section four, we first present the most important and illustrative scenarios for the spatial distribution of WPPs where we successively introduce more comprehensive environmental costs and constraints. Second, we present the most important numerical results from model simulations and a sensitivity analysis. Concluding remarks are given in section five.

2 Analytical Framework

While an elaborated dynamic numerical model is described in Sect. 3.1, Sect. 2 introduces a simplified analytical framework explaining the basic concept of the optimisation 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. We then modify this model to include the monetised environmental costs. Finally, we add constraints, as proposed by Bateman and Mace (2020), on the construction of new WPPs on land areas important for wilderness and biodiversity (W&B). We chose this approach as it is often considered both controversial and methodologically challenging to place a value on impacts on biodiversity and to determine the "extent of the market" of affected households where substantial non-use values are likely to be present. Hence, such impacts are sometimes included as constraints instead (e.g., Bateman et al. 2013). The implementation of these constraints is further described in Sect. 3.2.3.

Let $i = \{1, 2, \ldots, J\}$ denote all new potential WPPs, where WPP_i is characterised by its average annual electricity production (q_i), its production and investment costs and its location.[1, 2, 3] We assume a target, Q, for new wind energy production, where $Q \leq \sum_{i \in J} q_i$. We

[1] Note that the symbol J has a double interpretation as it denotes the total number of WPPs as well as the ultimate WPP of the WPPs.

[2] Electricity production, q_i, will be a function of the installed capacity and the capacity factor at WPP_i. The capacity factor describes the ratio of the actual power output of the WPP to its maximum power output in any given hour and is influenced by different parameters including the wind speed at the location of the WPP.

[3] Note that in the empirical analyses in later sections, the set of new potential WPPs considered is limited to WPPs for which a concession has either been granted or for which an application is under consideration by the authorities (c.f. discussion in Sect. 2.4).

compare three different optimisation problems, each increasing the wind energy production by Q. First, we derive the selection of WPPs which maximise the energy system surplus, but without taking account of environmental costs (see Sect. 2.1). Second, we derive the selection of WPPs which maximise the energy system surplus, while also including monetised environmental costs (see Sect. 2.2). In the third optimisation problem, we exclude from the set of new potential WPPs those power plants that overlap (by more than a certain percentage) with valuable areas in terms of wilderness and biodiversity richness, i.e., we add W&B constraints. From the remaining WPPs, we select those which maximise the energy system surplus after monetised environmental costs have been taken into account (see Sect. 2.3).

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 is 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 siting/location since we are considering 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 from the cost of producing Q units of new wind power. As discussed above, *ESS* will depend on the choice of 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 WPP selection will also affect the total environmental costs, as the impact on the environment differs across WPPs. For each WPP_i, we assign a monetised environmental cost associated with the location of the WPP. The environmental cost is denoted by $e_i = TD_i + TC_i$, where TD_i is the total disamenity cost for affected households when the WPP is in operation, and TC_i is the total carbon cost caused by land-use change from constructing the 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 wilderness and biodiversity richness. The W&B 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 including the monetised environmental costs and the additional requirements to prevent impacts on wilderness and biodiversity-rich areas.

2.1 Cost-Effective Solution: Maximising Energy System Surplus Excluding 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 included in the optimisation. The net energy system revenue (ESS^B), total monetised environmental costs (E^B), total production, and monetised welfare (MW^B) for this distribution are expressed as follows:

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

2.2 Maximising the Energy System Surplus Including Monetised Environmental Costs But Excluding Wilderness and Biodiversity Constraints

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

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

2.3 Socially Optimal Solution: Maximising the Energy System Surplus Including Monetised Environmental Costs and Wilderness and Biodiversity Constraints

Let Ω_S be the subset of WPPs that maximises the energy system surplus of Q including monetised environmental costs and that satisfies the W&B constraints. Under the condition of a binding W&B constraint, the net energy system revenue (ESS^S), total monetised environmental costs (E^S), total production, and monetised welfare (MW^S) of this distribution are expressed as:

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

2.4 Anticipated Results of 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 in turn 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 model in Sect. 2.2 includes the environmental costs in the optimisation problem, as opposed to the cost-effective solution, it is expected that:

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

Both the model in Sect. 2.2 and in Sect. 2.3 include the monetised environmental costs, but the latter also has the W&B constraints. 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 W&B constraints.

In the cost-effective solution, the energy system costs will be the determining factor for the selection of WPPs. The monetised environmental costs include inter alia the 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 located near residential areas and thus shift WPP development into land areas that are valuable in terms of their W&B (nature areas). Adding the W&B constraints, on the other hand, will 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 $E^S - E^B$.

In the numerical modelling we refer to the solution of the optimisation problem given by Eq. (3) as the *socially optimal selection* of WPPs, although, as noted in the introduction, the new *potential* WPPs ($i = \{1, 2, \ldots, J\}$) analysed in this study only cover WPPs that have applied for production concessions. The true technical potential would be larger, as licence applications are based on investors' assessment of profitable locations. Similarly, there may be additional potential that entails a lower environmental impact. Furthermore, there may be costs and benefits of WPPs other than energy system costs and environmental impacts that will not be taken into account in our numerical modelling. Hence, *socially optimal*

selection must be interpreted as the selection of WPPs from among the pre-selected locations that will maximise the energy system surplus by producing Q units of new wind power when the monetised environmental costs are included, and the W&B constraints are satisfied. As all WPPs have a defined geographical location, all potential selections of WPPs lead to a well-defined spatial distribution of WPPs across the country. We therefore use the phrase "selection of WPPs" and "spatial distribution" of WPPs interchangeably in the paper.

3 Empirical Methods

Given the analytical model above, we explain first the empirical modelling framework (the IFE-TIMES-Norway model), and second, how the monetised impacts and W&B 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 (Loulou 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 for meeting the demand for energy services for the specified 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 exports to and the costs of electricity imports 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, construction, and transport. The demand may be met by both existing and new technologies, using energy carriers such as electricity, bioenergy, 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 their respective existing wind power capacities and potentials. The model provides operational and investment decisions from the initial year, 2018, up to 2050. To capture operational variations in energy generation and end-use, each year is divided into 96 time slices where each of the four seasons (spring, summer, fall, winter) is represented by a 24-h day.

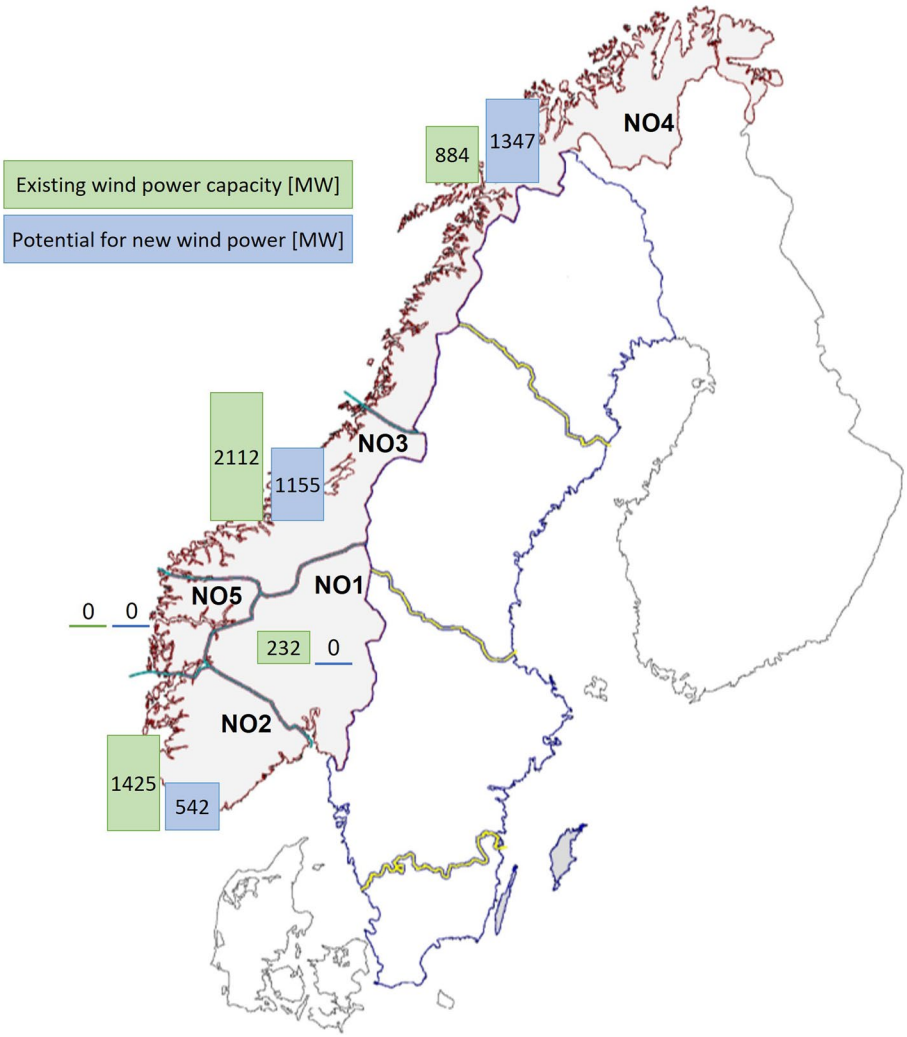

Fig. 1 Illustration of spot price zones in Norway together with existing and potential wind power capacity (MW) as based on concession applications

3.1.2 Assumptions and Methods for Incorporating WPPs in TIMES

To investigate the most efficient geographical selection 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", "concession granted" and "under assessment". The latter category includes WPPs for which there is a concession application or for which plans have been announced. Applications that have been rejected, therefore, do not form part of potential investment in new wind power. The same applies to applications

that have been put on hold, as most of these are quite old and will require new applications that would also have to be granted. Lastly, applications that were submitted before 2010 and for which no updates have been reported, have been excluded. In total, 4.6 GW capacity is already in operation with the first WPP installed in 1998. As regards the potential for new wind power capacity, 26 WPPs have been included in the analysis, with concessions granted for 1.2 GW and 1.9 GW still under assessment. This corresponds to approximately 15.5 TWh of existing wind power production and 11 TWh from potential new WPPs. WPPs that are already in operation are included in the model as existing capacity (15.5 TWh). However, we allow for the possibility of reinvestment in these plants (i.e., renewals of any expiring production concessions at current sites). Reinvestment in existing capacity is allowed at a 20% lower cost than the initial investment due to reduced costs for new infrastructure and wind turbines.[4] The possible capacity of reinvested WPPs is restricted by regulations on existing WPP capacity.

Based on the concession applications included in this analysis, only WPPs in areas NO2, NO3 and NO4 have been assessed. In other words, no new wind capacity is assumed to be built in NO1 and NO5. The former regions will henceforth be referred to as South (NO2), Central (NO3), and North (NO4).

An overview of the existing and new WPPs included in this analysis, along with specifications, can be found in "Appendix A", Tables 4 and 5. Model input data include investment costs, operation and maintenance (O&M) costs, 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 O&M costs are assumed to be equal for all plants at 10 €/MWh (IRENA 2020; NVE 2019).[5] The year of investment for new WPPs is fixed as 2025, with a technology learning pace of 16% from the starting year of 2018 to 2025 (IRENA 2019). Moreover, as investment costs tend to be estimated at the time of the submission of the concession application, and these often go back many years, an annual cost reduction of 3% from the cost year to 2018 is applied to wind turbines that are not yet in operation. These technology learning rates are based on projections from IRENA (2019). Lastly, all cost inputs to the model are in 2020 prices. The WPPs have a lifetime of 25 years, and reinvested plants 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 selection of new wind power, we assume that only a portion of the total potential of 11 TWh for which concessions have been applied will be implemented. Considering the strong opposition to land-based wind power development in Norway and the 3-year-long hold in the concession 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 annual wind power production from new WPPs is constrained to 4 TWh in all years following 2025. Note that production from existing WPPs and reinvested WPPs are not included in this constraint, meaning that wind power production by 2050 could potentially reach 19.5 TWh (i.e., 15.5 + 4 TWh) if there is reinvestment in all existing plants. This is considered a

[4] The assumption is based on a review of the cost breakdown from different concession applications in NVE's database.

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

reasonable assumption as reinvested WPPs will not require new land-use change and are likely to face less opposition than new installations.

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 particular, the electricity price in Norway follows, to a large degree, market prices in Europe. Given higher CO_2 prices and stronger penetration of variable renewable energy, prices are expected to increase and become more volatile (Statnett 2020). The impact is uncertain, however, and will depend on several factors such as gas prices, the 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 is therefore uses two different price sets for neighbouring countries with transmission cables to Norway.[6] A baseline scenario is used for the initial analysis, while a sensitivity analysis is performed with a high electricity price scenario. The electricity price profiles for European countries are consistent with the carbon price pathways used for the carbon emission cost calculaton (3.2.2) and presented in Table 6, "Appendix B". Average electricity price developments for the two scenarios for some selected countries are presented in Fig. 8, Appendix B.

3.2 Monetised Local Disamenity and Carbon Costs and the Wilderness and Biodiversity Constraints

A WPP affects the environment in several ways. We distinguish between disamenity impacts affecting households in the vicinity of WPPs and more general environmental impacts affecting society as a whole (wider environmental costs). The latter category includes (1) monetised values of carbon emissions from land-use change due to the establishment of the WPPs, and (2) impacts on land areas important for wildlife and biodiversity included as constraints in the model. In addition to the cost of direct emissions from WPPs, the model also captures the indirect emission reductions from substituting brown with green electricity consumption in Norway (e.g., EVs instead of fossil fuel cars). The benefit of indirect emission reductions will, however, not be affected by the spatial selection of the individual WPPs, only the total production volume. On this subject, there will be no differences between the scenarios as the same production target is defined for all.

3.2.1 Local Disamenity Costs

Neighbouring 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 in an attempt to capture this "bundle" of impacts.[7] 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:

[6] The European power prices used in this analysis do not represent the current price levels resulting from the energy crisis.

[7] For the sake of simplicity and to avoid any issues of double counting, we do not include externalities related to the construction or upgrade of power lines, locally, regionally or nationwide. 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.

$$TD_i = C_d h_i, \tag{4}$$

where C_d is the disamenity cost. We assume that the affected households are *all* located at a distance of less than 4 km from the WPP_i as well as households within 4 to 30 km of WPP_i if it is in the viewscape of the household.

To capture the disamenity costs of households in the vicinity of existing and potential new WPPs, GIS analysis combined with land registry data was used to identify the number of households in each affected residential building. Vacation homes may also be in the vicinity of WPPs. A vacation home is typically occupied by one household for a certain percentage of the year. GIS analysis was used to identify residential buildings and vacation homes with a WPP, existing or potential new, in their viewscape. For existing WPPs, the viewscape analysis relied on information from NVE on the height of turbines and the siting in the landscape of each WPP. For potential new WPPs, the viewscape analysis is more challenging, as information on the number of turbines, their height and their placement is not available. Information on the total capacity (MW) applied for in the concession application for each new potential WPP is however provided by NVE. We therefore used data for WPPs that came into operation in 2021 to estimate the number of turbines for each potential WPP development. For the WPPs that came into operation in 2021, the average capacity of each turbine is 5 MW[8]and the average turbine height is 171 m. For the viewscape analysis for new potential WPPs, we assumed that the estimated number of turbines would have a height of 171 m and that these would be distributed evenly across the area indicated in the concession application for the WPP.

While households in residential buildings are assumed to be affected all year round, households in vacation homes are assumed to be affected in proportion to the share of the year they use their vacation home. 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 vacation homes (Prognosis Centre 2021).[9]

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) to avoid one turbine of €23 per household 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 (García et al. 2016, WTP estimate used in Grimsrud et al. 2021) and one from a proposed WPP in the municipality of Aurskog-Høland in eastern Norway (Dugstad et al. 2022). Because of 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 vacation homeowners in the viewscape of each WPP.

[8] WPP concession applications only indicate the total MW to be produced. To estimate the number of turbines, we divided the total MW to be produced by the average capacity per turbine in 2021, which was 5 MW.

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

There is uncertainty regarding the local disamenity cost specification. Both theoretical and empirical studies generally show ambiguous results for distance decay effects, which determine boundaries for affected populations (e.g., Glenk et al. 2020) and the 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 Mattmann et al. (2016). Some studies apply a distance decay function (e.g., Lehmann et al. 2021a, b and Ruhnau et al. 2022) and/or use a close boundary around each WPP (e.g., Krekel and Zerrahn 2017).[10] We therefore use three alternative specifications for sensitivity. First, we base our distance decay function on Lehmann et al. (2021a; b), [11]

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

and translate their distance decay function, which calculates per month disamenity costs measured in € from German studies as a function of a household's distance d_h (m) from a wind turbine, into an annual disamenity cost depending on distance to a WPP. We assume, as do Lehmann et al. (2021a; b), that the per turbine cost is linear in the number of turbines (located as part of the same WPP or adjacent ones). The disamenity cost used in the sensitivity analysis that assumes distance decay is higher than the cost in our base case if the distance of the household to the WPP is less than 3822 m, but lower than the base case cost for distances beyond 3833 m. For households at a distance greater 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 at 4 km and double the cost for the full viewscape. 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 vacation 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 concession area (Nowell et al. 2020). For all WPPs, we assume that a share of 4% of all types of land in the concession area is converted into 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 of carbon

[10] This study has used a subjective wellbeing valuation approach to show that the negative effect of wind power drops substantially beyond 4 km from the WPP in Germany.

[11] In the equation from Lehman et al. (2021a, b), 90 is a constant measured in €, and 1054 and 543 are constants measured in metres.

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} represents emissions costs from loss of stored carbon in forests (measured in tons of biomass above and below ground), during the construction year, CE_{iM} is the carbon cost of emissions from loss of mires, also in the construction year, and CS_{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 the scenarios for EU-ETS prices presented in "Appendix B". The base case prices are used for the initial analysis, while a sensitivity analysis is performed for 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 depth at 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 metre depth, we use the same average factor as in the official report to the UNFCCC, which is set as 0.1683 tons of CO_2 (Norwegian Environment Agency, 2022). In calculating 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:

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

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 of forest, 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 carbon costs than a loss of forest area per m^2. Furthermore, the loss of 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}).[12] For existing WPPs where there is reinvestment, the carbon emissions from land-use change are assumed to be sunk costs and are therefore set at zero.

3.2.3 Loss of Land of Importance 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 to infrastructure construction, or indirectly, for example by acting as migration barriers (Arnett and May 2016; Kuvlesky et al. 2007). We use Nowell et al. (2020) as a starting point to take account of the impacts on biodiversity and wilderness as a result of land-use change for 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 infrastructure where flora and

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

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 according to how much of each WPP was classified as wilderness. Instead of using the simple INON[13] 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 500 m circle around each pixel. It takes a value of 0 (min) if the area is completely devoid of human infrastructure and 13.23 (max) if the area is completely covered in human construction (e.g., a dense urban area) (Jakobsson et al. 2020).[14] The advantage of using this indicator rather than the INON maps is that the intensity of infrastructure can be taken into account, 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 criterion for 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 nature types of importance 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 with threatened species hotspots for insects and arachnids, bryophytes, fungi, lichens, and vascular plants (Olsen et al. 2018, 2020). Wind farms have been found to have the greatest impact on birds and bats, but also influence how other types of wildlife use areas near wind turbines and other associated infrastructure (Arnett and May 2016; Kuvlesky et al. 2007). While comprehensive national 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-listed species and other species of wildlife.

Important nature types were included as an indicator of the impact on ecosystems. 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

[13] Norwegian authorities maintain an indicator called "INON", which measures the size of natural and unfragmented areas of less than 1 km, 1–3 km or more than 5 km from the nearest technical installations such as roads, power lines, houses, etc.

[14] 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 (focal point) and calculated for the whole country. The infrastructure index consists of two components that are added together: a building component and a constructed mainland component. The latter 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, 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 utilisation character; the presence of buildings is considered to leave a stronger mark (2/3) on the landscape than the presence of land areas with infrastructure (1/3).

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, 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 according to whether the concession area overlapped indicators by more than 5%.[15] Since Nowell et al. (2020) used a 1 km buffer around WPP boundaries that was not used in the present analysis, the overlap threshold was reevaluated and set to 1% in this study. A sensitivity analysis revealed that a loss of 1% of the area could in some cases exceed 1 km^2 of important habitat, which implies 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 a considerable reduction. An increase to 2% resulted in almost a tripling of the area 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 on–off constraints, i.e., constraints that are activated whenever a wind farm violates the abovementioned indicators.

For sensitivity, we added a third, highly relevant, but principally different, type of constraint from a recent Supreme Court verdict on the indigenous right 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.[16] In late 2021, the court sided with reindeer owners against a wind power company in a case regarding the largest WPP in Norway (and Europe) in Fosen in central Norway. It was concluded that the WPP violates their indigenous rights. The consequence of this verdict for Fosen and other existing or new WPPs is not yet clear. It could be that future WPPs must remain completely outside 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,[17] movement corridors,[18] staging areas,[19] and administrative

[15] 5% was used to account for geometric error in the data that may cause some overlap in the GIS analysis, whereas in reality there may no overlap or none of any significance. With national scale spatial data, there is always some geometric error, but the benefit of using these data (i.e., being able to evaluate all WPPs equally) outweighs the error.

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

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

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

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

Table 1 Wind power deployment scenarios as a basis for main results

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

areas.[20] 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.[21]

National scale, freely available spatial datasets were used in the spatial analysis such that each WPP could be assessed according to the same criteria. These datasets may have some geometric error due to the mapping scale. The spatial analysis was performed in ArcMap 10.8 using the Spatial Analyst extension (ESRI). Table 8 in "Appendix D" shows which criterion is activated for each WPP.

4 Results of Model Simulations

4.1 Land-Based Wind Power Deployment Scenarios

Five different land-based wind power development scenarios were analysed, see Table 1.

In all the scenarios, the annual production from new WPPs is restricted to 4 TWh, as explained in Sect. 3.1.2. Reinvestment in existing capacity is not included in this target and are limited by the initial capacity of the plant. Moreover, reinvestment in already established WPPs is assumed to not cause further land use change. Therefore, such reinvestment is assumed to be emission-free as related to land use change. Emission costs from land-use change and the loss of wildlife and undisturbed land areas from reinvestment are therefore considered sunk costs, and not included in the analysis. However, local disamenity costs for reinvested WPPs are included, with the assumption that the new wind turbine height remains the same as for the initial turbines.

[20] 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-siida omrade

[21] 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 WPPs included in the analysis had < 75% overlap and 33% had 100% overlap with reindeer areas.

In scenarios S2-S4, we consider the impact of only one or two types of environmental externalities at a time, whereas scenario S5 includes all the environmental externalities simultaneously (except the impact on reindeer husbandry). This scenario can be considered to yield the socially optimal siting of new wind power capacity if the goal of limiting impacts on undisturbed land, wildlife and biodiversity is to be fulfilled. We start in the next section by presenting results for the spatial distribution of WPPs followed by the derived energy system surplus, environmental costs and welfare impacts. We conclude with some sensitivity considerations, including the results of imposing a third constraint: the impact on reindeer husbandry.

4.2 Spatial Distribution of WPPs Across Scenarios

Figure 2 illustrates the spatial distribution of new wind power capacity in Norway resulting 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 investment, with a maximum potential of 542 MW. The optimal distribution of the WPPs is determined by differences in both investment costs and wind conditions, but also, to a large extent, by differences in electricity prices in the different regions. While the South has the highest electricity price in the model results, the North is consistently the region with the lowest electricity price across all scenarios making it the least appropriate region for wind power investment. Moreover, the South is more closely connected to the European energy system, which makes the export of wind power energy possible without the need for large domestic grid investments. A total of 16 WPPs, of 26 possible, are chosen in the cost-effective scenario.

The second scenario, CC (S2), includes the emission cost of land-use change resulting from mire excavations and loss of biomass. As illustrated by Fig. 2, incorporating these costs has only a minor impact on the number of new WPP even though excavation of mires has a large impact on CO_2 emissions (per m^2). In fact, the same 16 WPPs are chosen, but there is a slightly higher capacity investment for the single WPP in the North accompanied with a slightly reduced investment of WPP's in the Central region. The reason for

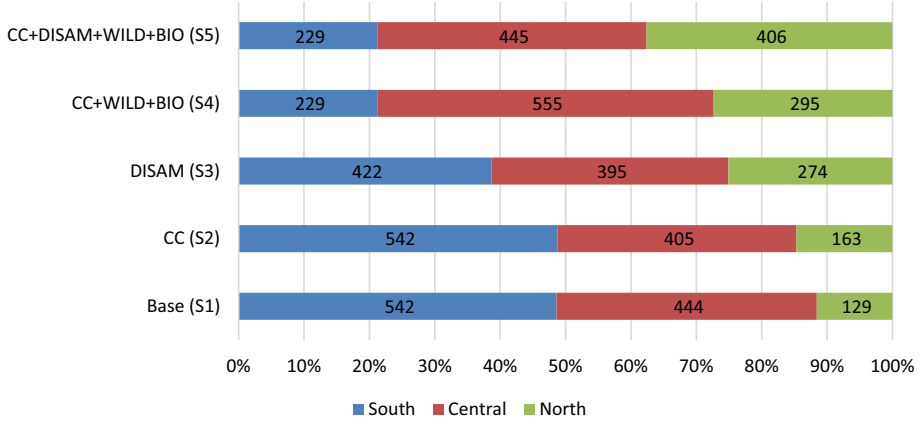

Fig. 2 Spatial distribution of WPP's for each of the five scenarios (S1–S5). Values are in MW

the impact being small is that few WPPs have large areas of mires within the concession area and, more importantly, only a small part (4%) of the concession area is assumed to be affected by the establishment of a WPP. Internalising the welfare loss for neighbouring households and vacation homeowners (S3) leads to a 10% lower investment share in the South. This is due to the higher population compared to the northern parts of Norway. Similarly, new power plants in the North will generally have lower local disamenity costs than those located further south.

The same tendency can be observed when the impact on W&B is incorporated in the analysis (S4 and S5). In general, the more of the monetised environmental costs and W&B constraints that are incorporated, the more beneficial WPPs become in the northern part of Norway. For the wilderness constraint (WILD), whereby 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 region. In total, 5 of the 7 WPPs violating this constraint are initially part of the optimal investment solution from S1, indicating that most of the WPPs in violation of the wilderness constraint are considered cost-optimal. The impact on the spatial distribution, is minor, however, as these 5 WPPs only constitute 7% of the new wind power capacity in the baseline scenario (S1). Incorporating the biodiversity constraint (BIO) 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 constraints are not shown separately in Fig. 2). When the biodiversity constraint is applied together with the wilderness constraint, a total of 10 wind parks are disabled out of the invested 16 in the base scenario (S1), as seen in Table 2. Of these, 8 are located in the South. To compensate for the production loss, two new, but less profitable wind parks are selected in the Central region. This is somewhat surprising considering our anticipation, in Sect. 2.4, that the wilderness and biodiversity constraints would shift WPP siting out of pristine nature areas and closer to more populated areas. The results indicate that that large pristine nature areas of importance for wilderness and biodiversity are also found in the southern parts of Norway. Nevertheless, the choice of WPPs within each of the regions indicate support for the assumption that there is a trade-off between pristine wilderness and local disamenity costs. Lastly, compared to S4, including also local disamenity costs (S5) further enhances the social profitability of WPPs in North, reducing investment in the Central region by 10%.

Table 2 Change in the selection of WPPs relative to scenario S1 and total number of WPPs

	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

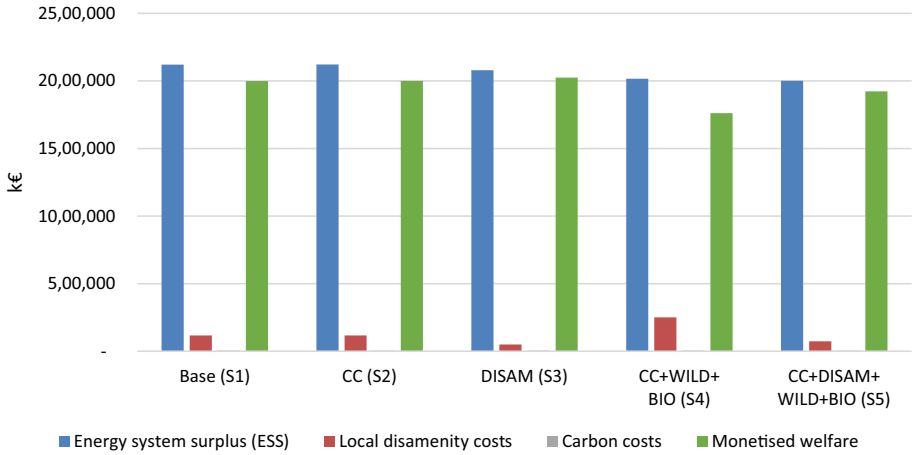

Fig. 3 Net monetised welfare gains of new wind power measured by the differences in energy system surplus and environmental costs (in k€)

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)	2.12	2.12	2.08	2.02	2.00
Local disamenity costs	0.12	0.12	0.05	0.25	0.07
Carbon costs	0.005	0.004	0.005	0.005	0.004
Monetised welfare	2.00	2.00	2.02	1.76	1.92

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, given an annual production increase of 4 TWh (S1-S5). Here we explore the impact of increased wind power production on the energy system and environmental costs. In Fig. 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 and across the different scenarios. Figure 3 illustrates the costs and benefits in thousands of euro (k€), whereas Table 3 presents the numerical values in eurocents per kWh (c€/kWh).

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 producers of other types of power, in particular hydropower. For example, the income of hydropower producers in the North in 2040 is 14% less in S5 compared to S1, as the shift in wind power investment leads to lower electricity prices in the region.[22] 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 include the welfare loss due to loss of land with an especially high nature value (areas that are excluded from development by the W&B constraints).

Results indicate that the baseline scenario (S1) and CC (S2) obtain the highest net ESS as these scenarios are less restrictive in terms of where WPPs can be located. The scenario which includes all environmental costs and W&B constraints (S5) has the lowest net ESS, due to less profitable WPPs and a deployment which is relegated to regions with lower electricity prices. This confirms our anticipated results as discussed in Sect. 2.4. The ESS is reduced by 6% (from 2.12 to 2.00 c€/kWh). Scenario S5 results in a lower local environmental cost than S1. Including the monetary costs of local environmental degradation and carbon costs, we find that welfare as a result of new wind power developments is only reduced by 4% (0.08 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 are excluded in S5 due to the W&B constraints. By comparing S5 with S3, we find that imposing the W&B constraints (and carbon costs) in addition to local disamenity costs, results in an extra cost of 0.10 c€/kWh [101 million euro (M€)], which we can refer to as the monetised welfare cost of the W&B constraints, as discussed in Sect. 2.4.[23] We see from Table 3 that the selected WPPs differ substantially between S3 and S5. For S5 to be socially preferable to S3, the value of protecting the valuable nature in the S3 scenario must be perceived as higher than 0.10 c€/kWh (101 M€).

Incorporating only local disamenity costs (S3) has a significant impact on the outcomes for neighbouring households. The local disamenity costs are more than halved compared to the baseline (S1). This emphasises the importance of including such costs in the WPP selection process. Furthermore, we see from Table 3 that neighbouring households face considerably higher local disamenity costs when only the W&B constraints are taken into account (S4) than if no disamenity costs are taken into account (S1). The local disamenity costs more than double when moving from S1 to S4. Although the W&B constraints lead to lower investment 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 a higher population density within these regions. Consequently, the WPPs that are selected within the South region in S4 are located in areas with more households 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 between S5 and S3 in monetised environmental costs are relatively modest (0.024 c€/kWh or 24 M€). Thus, it can be

[22] The results for average regional electricity prices in Norway for the different scenarios are presented in "Appendix B", Figure B2.

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

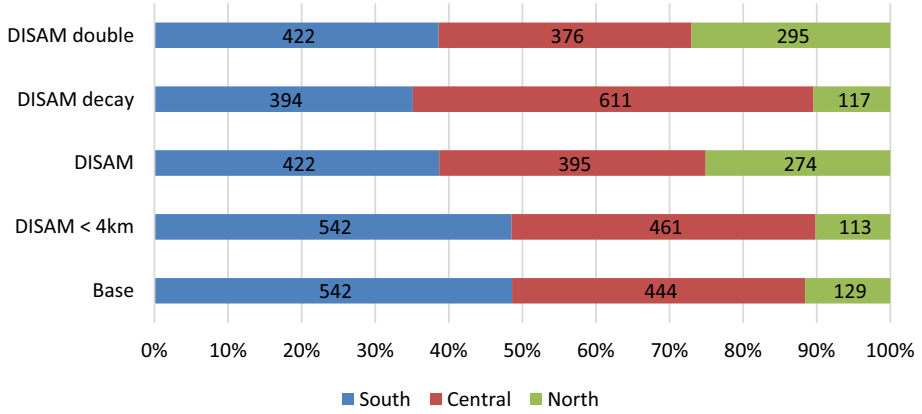

Fig. 4 Spatial distribution of WPP's for different local environmental cost scenarios. Values in MW

argued that the benefit to society as a whole of preserving biodiversity hotspots 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, i.e., 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 assumed cost per turbine. This section therefore addresses the impact of varying the costs of and distance from the turbines. In the *DISAM* < 4 km 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 WPPs from 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 WPP, cf. Eq. (5). Households closest to the WPP incur the highest cost, while the cost diminishes as the distance increase up to 4 km. In such a distance decay scenario, WPPs in the Central region are preferred to those in the South. From these results, it follows that WPPs in the South are planned in closer proximity to households than in other regions.[24]

Lastly, the *DISAM double* scenario assumes a doubling in the local environmental cost of each of the WPPs. As presented in Fig. 4, the distribution is almost unaffected by the

[24] We also conducted a sensitivity analysis where the WTP per turbine decreased with 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 the sake of brevity) showed marginal impacts on the spatial distribution of WPPs compared to the base case.

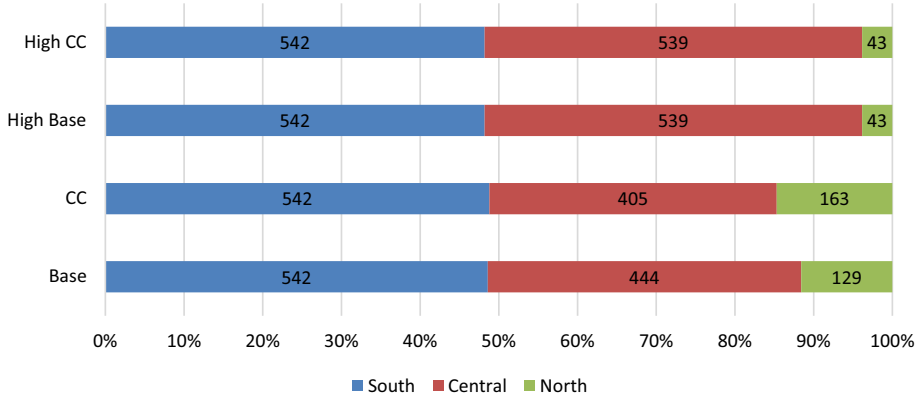

Fig. 5 Spatial distribution of WPPs for different carbon price pathways

increase compared to S3. The spatial distribution of WPPs is therefore more sensitive to variations in cost with distance [Eq. (5)] than a uniform increase in cost [Eq. (4)].

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 to the emission cost calculations and to the European energy system. Hence, a higher electricity price for countries with transmission capacity to Norway is included in the model. To differentiate between the impact from the carbon cost of land use and the impact from changes in the European energy system, we designed two high scenarios, High CC and High Base. The High Base only includes the high carbon price path in Europe and not for the WPP emission cost calculation.

As described above, higher CO_2 prices affect the results both directly through the higher carbon costs of land use changes, and indirectly through higher international electricity prices. In Fig. 5, we can observe that the change in spatial distribution is mainly caused by higher electricity prices in Europe, favourising the 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 there are no differences in wind power deployment. The reason for the increase in the deployment share in the Central region for the high price scenarios is due to shorter distances to export cables compared to the North. In the Baseline and CC scenarios, the new wind power potential has already been realised 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 exports from the Central region to the South are 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 the emission cost of land use on the spatial distribution seems to be limited or close to zero, regardless of the CO_2 price assumptions.

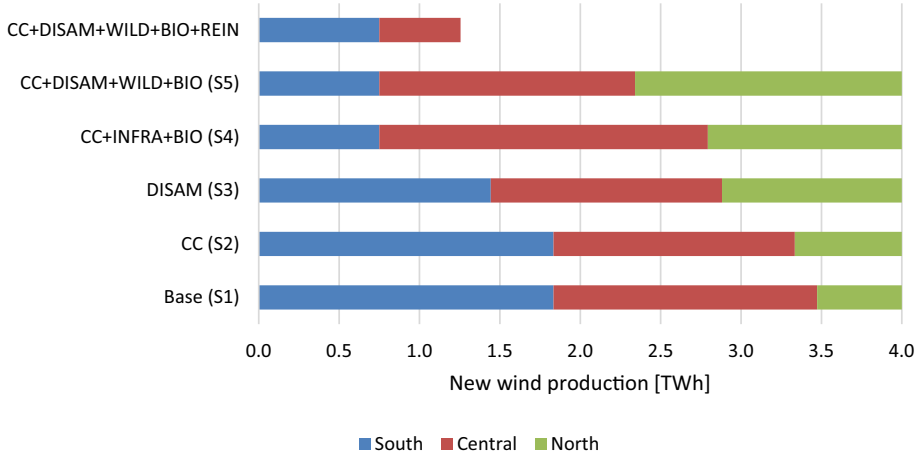

Fig. 6 New wind power production across scenarios with regional distribution

4.4.3 Effects of Hard Constraint in the Form of Indigenous Reindeer Husbandry Rights

The spatial distribution of WPPs has also been assessed with respect to their interference with reindeer husbandry, see Sect. 3.2.3. This criterion is activated for WPPs with more than 1% overlap for one or more of the reindeer criteria, which disables a total of 12 WPPs out of 26. Adding this to the W&B constraints leaves us with only three WPPs 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 Fig. 6). Production would be distributed between the South and the Central regions, 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.[25]

5 Concluding Remarks

We have presented a modelling framework for taking into account various environmental concerns when selecting new wind power production plants using a pool of potential new WPPs as our starting point. An energy system model (IFE-TIMES-Norway) was used to select WPPs which maximise social welfare under various constraints in Norway. We incorporated directly into the model the estimated externality costs in the form of carbon emission costs and the local disamenity costs faced by households with WPPs in their viewscape. Impacts on wilderness and biodiversity were implemented in the model

[25] At the time of writing, the consequences of the Supreme Court verdict mentioned in 3.2.3 is unclear, with respect to both 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 have to avoid all similar reindeer areas.

analysis as strong wilderness and biodiversity (W&B) constraints. We used the database of proposed WPP projects in Norway (NVE 2022) as the pool of potential WPPs for reaching a target of 4 TWh annual production from new wind power.

Our numerical simulations show that the environmental concerns had a significant impact on the optimal selection of WPPs across the country. In the base scenario (S1) we did not take into account any environmental impacts. Purely from an energy system perspective, the South is the most favourable region for wind power investment, showing its maximum potential in the base scenario. In the scenario where all environmental concerns were taken into account (S5), production in the South was only 40 percent of its maximum potential, and production in the North was three times higher than in scenario S1.

The impact of increased wind power production on the energy system surplus does not differ substantially across the scenarios, being 6% at the most (between S1 and S5). Hence, replacing some WPPs with others does 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. While not directly comparable, a recent analysis from the UK in a similar vein shows that removing 10% of the most scenic areas for onshore wind power implies about an about 18% lower generation potential and 8–26% higher costs (McKenna et al. 2022).

Following the lines of Bateman and Mace (2020) regarding biodiversity as critical natural capital with limited substitutability, we did not attempt to estimate the value of impacts on wilderness and biodiversity, but rather imposed those as constraints on the model. The numerical illustration shows, somewhat surprisingly, that if the benefit to society of avoiding the development of the 10 WPPs which violate the W&B constraints exceeds 0.10 c€/kWh, the S5 scenario (all environmental costs and constraints included) is superior in terms of welfare to S3 (only local disamenity costs included). In total, this amounts to 101 million (M) €. Dividing this by the number of households in Norway (approximately 2.5 million), if preserving biodiversity and wilderness is considered a national responsibility, this amounts to around EUR 40 per household as a one-time amount. While it is not straightforward to compare this with the results of Norwegian non-market valuation studies, there are some indications that this amount is modest. For example, Lindhjem et al. (2015) found an *annual* WTP per household of NOK 1040-1300 (in 2007) in a contingent valuation study of the preservation of forest biodiversity at national level in Norway. This is substantially higher than the amount that would be required to satisfy the W&B constraints considered here, which are strict for the areas included in the analysis. Hence, in future analyses it may be justified to include further criteria and areas to account for stronger concerns about W&B. A recent study in two regions of Norway also showed substantial WTP among households in areas affected and unaffected by wind power to avoid a broad set of externalities (Dugstad et al. 2020).

Overall, our 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 yields negative consequences for biodiversity and wilderness. We conducted a comprehensive sensitivity analysis. In view of uncertainty and discussion in the literature about the local disamenity cost function (Lehman et al. 2021a; b; Grimsrud et al. 2021; Ruhnau et al. 2022), 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 reindeer husbandry rights.

The sensitivity analyses show that our main results are relatively robust. Increasing the local disamenity costs has only a minor impact on results, although there is a small change in terms of where the WPPs were located for the case with distance decay within 4 km. In that case, some wind power production moves from the South, where WPPs are generally located closer to residential areas, to the Central region. Increased carbon costs lead to more demand for wind power by importing countries and therefore more WPPs are 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 also shows that if a constraint relating to indigenous reindeer husbandry rights is added in addition to 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.

However, we are aware of some caveats and potential weaknesses that may be important for our results and that we have not yet fully investigated. First, it is clear that limiting the allowable WPPs to the existing pool of concession applications is a practical decision, but a potential weakness. There may be other sites that could both increase the total generation capacity and have better profiles in terms of environmental impact. In the modelling, we also make some simplifying assumptions and do not include any form of stochasticity. 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 that have already obtained a concession (and are likely to be built soon) and those that are in the application process (and that have a higher probability of not being built). In future work, such points may be refined.

Second, with regard to the local disamenity costs, we admit that it may be difficult to fully differentiate between local disamenity impacts and impacts on biodiversity and wilderness more generally, as people in the viewscape may also be aware of and consider such impacts to be part of the "bundle" of disamenities they experience. However, we do believe that other impacts (such as noise, flickering lights, landscape aesthetics and reduced recreation quality), may be the most important locally (cf. e.g., Dugstad et al. 2022; Handberg et al. 2020). The more fundamental importance of biodiversity (as a building block for other services), and the reason why such impacts are considered an important constraint, may not be fully appreciated, and thus the problem of "double counting" is probably relatively small. Our assumptions regarding the local disamenitiy costs of future WPPs, based on the average specifications of turbine capacity and height in 2021, along with the assumption of uniform placement of turbines in the WPP plan area, also add uncertainties to our results.

Lastly, this analysis was performed before the energy crisis in Europe, and thus the results do not represent the current electricity price situation. With higher prices in Europe, we would expect an even larger North–South price difference, resulting in even more favourable conditions for onshore wind power in the South. The cost of including environmental concerns, i.e., moving investment in wind power to the North, would therefore likely be higher. It is also expected that households would be less reluctant to accept new wind turbines, as new, cheap power is one of the main contributors to reducing electricity prices and ensuring security of supply. Despite electricity prices reaching an all-time high, it is, however, expected that prices will ease as economies slow and markets rebalance (IEA 2022).

As the whole energy system will undergo a transition, it will also be important to consider the environmental impacts of other renewable energy sources, for example, offshore wind power and solar power, which are both scheduled for major expansions in Norway during the next decades. Replacing onshore with offshore wind power, for example, will reduce land requirements (Tröndle 2020). 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 environmental impact in developer and regulator decisions. It is clear that in doing so it will also be important to balance efficiency and equity considerations (Weinand et al. 2022), as our results show that there may be relatively large and unequal effects across the different scenarios, especially between North and South.

Appendix A: Parameters for New and Existing Wind Power Plants

See Tables 4 and 5.

Table 4 Parameters for new wind power plants. Operation and maintenance (O&M) costs equal for all plants at 8.4 €/MWh (from 2025)[a]

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

[a]O&M costs for new wind power plants assumed to be 16% lower than for existing plants. Based on technology development from 2018–2025 (IRENA 2019).

Lifetime of 25 years and investment year fixed as 2025

Table 5 Parameters for existing wind power plants. Operation and maintenance (O&M) costs are equal for all plants at 10 €/MWh (from 2025) (IRENA 2020; NVE 2019). Lifetime of 25 years and possible reinvestment on decommissioning[a]

ID	Name of WPP	Spot region	Capacity	Production	Reinvestment cost NOK 1000/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

Table 5 (continued)

ID	Name of WPP	Spot region	Capacity	Production	Reinvestment cost NOK 1000/MW (2025)
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

[a]Reinvestment cost assumed to be 80% of initial investment cost

Appendix B: Assumptions Regarding carbon price paths

See Table 6 and Figs. 7 and 8.

Table 6 Two alternative carbon price pathways (base case and high case) in €/ton

Annual 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 onwards

Appendix C: Carbon Emission Calculations

The present values of the carbon cost components of equations in (7) are calculated as:

$$CE_{iF} = 0.04 \cdot q_0 \cdot \delta_1 \cdot (BMA_i + BMB_i) \cdot F_i,$$
$$CE_{iM} = 0.04 \cdot q_0 \cdot \delta_2 \cdot M_i,$$
$$CS_{iF} = 0.04 \cdot \left[\sum_{t=1}^{75} q_t \cdot \frac{1}{(1+r)^t} + q_{75} \frac{\left(\frac{1}{1+r}\right)^{75}}{\left(1 - \frac{1}{1+r}\right)} \right] \cdot (\delta_3 + \delta_4) \cdot F_i,$$
$$CS_{iM} = 0.04 \cdot \left[\sum_{t=1}^{75} q_t \cdot \frac{1}{(1+r)^t} + q_{75} \frac{\left(\frac{1}{1+r}\right)^{75}}{\left(1 - \frac{1}{1+r}\right)} \right] \cdot \delta_5 \cdot M_i.$$

We assume that carbon prices will increase until 2100 and remain constant thereafter (see "Appendix B"). See Table 7 for the description of symbols, units and assigned values.

Table 7 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 felling trees	EUR	
CE_M	Emission cost from excavating 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[a]
TC	Total carbon costs	EUR	
q_t	Carbon costs year t	EUR per ton CO_2	See "Appendix B"
δ_1	Emission factor for lost forest biomass above and below ground	Tons of CO_2 per ton of biomass stored in forests	1.83[b]
δ_2	Emissions factor for lost mires	Tons CO_2 per m^2 mires	0.25245 (0.1683 *1,5)[c]
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)

[a]The recommendation of 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 of 4 per cent. They assume a risk-free interest rate of 2.5 per cent and risk adjustment of 1.5 per cent

[b]We have set 1 ton of biomass equal to 0.5 ton of carbon (see Petersson et al., 2012) and used the conversion factor 44/12 to convert from carbon to CO_2

[c]We have set the depth for all marshes as 1.5 m. The CO_2 emission factor per m^2 per metre depth is taken from Norwegian Environment Agency (2022)

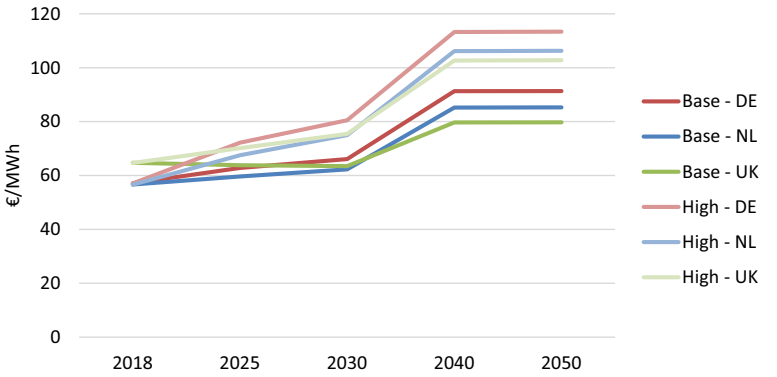

Fig. 7 Two alternative European power price pathways (base case and high case) for some selected countries (Germany, the Netherlands, and the UK) in €/MWh

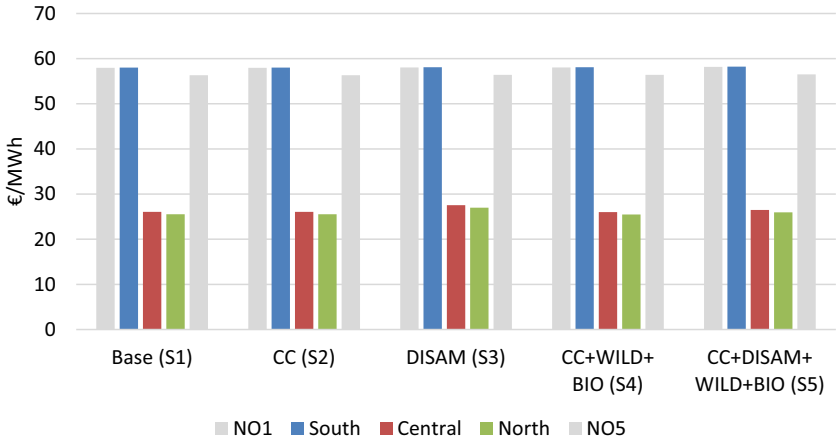

Fig. 8 Model results for average regional electricity prices in 2025 (year of investment) for the five scenarios S1–S5. All 5 spot regions are included, but no wind power investment is made in NO1 and NO5

Appendix D: Wilderness and Biodiversity Constraints

See Table 8.

Table 8 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			

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