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Efficient spatial distribution of wind power plants given environmental externalities due to turbines and grids

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ABSTRACT

Negative environmental externalities associated with wind power plants are due to the physical characteristics of turbine installations and associated power lines and the geographical siting. This paper presents an environmental taxation scheme for achieving efficient spatial distribution of new wind power production, taking account of both production and environmental costs. Further, the paper illustrates the impact of environmental taxation by means of a detailed numerical energy system model for Norway. The analyses show that a given target for wind power production can be achieved at a significantly lower social cost by implementing a tax scheme, compared to the current situation with no environmental taxes. The analyses also show that the environmental costs associated with both turbines and power lines were crucial to the efficient spatial allocation of wind power plants.

1. Introduction

Decarbonisation of the electricity markets is expected to result in a large increase in land-based wind power production (IEA, 2019). Although there are CO_2 emissions associated with the construction of wind power plants (WPPs) (Bonou et al., 2016), the conversion of wind energy into electricity generates no CO_2 emissions. However, there are other environmental concerns associated with WPPs, such as noise, impaired landscape aesthetics, and impact on wildlife (see e.g., reviews by Saidur et al., 2011; Mattmann et al., 2016; Zerrahn, 2017). These negative external effects are attributable to both the WPP itself and the associated investment in power lines.

For private investors, wind conditions, investment costs and expected electricity prices determine the profitability of their WPP. The net social costs of a WPP also include the environmental costs, however. Unless the negative environmental impacts are properly priced, these concerns will not be included in the private investors' profit function. There is growing opposition to large-scale, land-based wind energy developments in many countries (Ladenburg et al., 2020). In a review of the broad social science literature, Devine-Wright (2005) concludes that noise and negative visual impacts on the landscape are the most frequent reasons for public opposition. These findings were confirmed in more recent reviews focused on the environmental economics literature (Mattmann et al., 2016; Zerrahn, 2017). The environmental cost of a WPP typically increases with the number of directly and indirectly affected people.

The promotion of renewable energy production is typically motivated by a desire to reduce carbon emissions, stimulate technological development and innovation, and ensure energy supply security; see for instance EU (2009). In the present paper we do not discuss the different reasons for supporting wind power but take as our starting point a national target for land-based wind power. We follow Drechsler et al. (2017) and define efficiency as attaining a specific wind power production target at the lowest possible social costs. These social costs comprise the private costs borne by private investors as well as the external environmental costs. This study analyses how these environmental costs influence the efficient spatial allocation of WPPs across Norway. The environmental costs of a potential WPP are modelled as a function of plant size, associated requirements for new or upgraded power lines, and number of people directly and indirectly affected. The environmental costs of wind power production will therefore typically differ across WPP sites. In this simplified set-up, the most important

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consideration is how the local as opposed to the national population assesses the environmental externalities due to turbines and the associated power lines. The private production costs will also differ spatially, depending on the wind conditions and the required investments, which vary across sites due to differences in the costs of installation, civil works, assembly and installation, etc. Private investors will internalise the environmental costs and choose an optimal spatial allocation of WPP if the external effects are properly taxed (Pigouvian taxes). A tax scheme that internalises the costs of degradation of nature has recently been recommended for further analysis by a public expert committee on Green Taxation in Norway (NOU, 2015), though little is still known of how it should be designed or its potential effects.

This paper contributes by: i) presenting a simple environmental taxation scheme that captures the main sources of the environmental costs of WPPs, and ii) illustrating the impact on social benefit of employing the environmental taxation scheme by means of a detailed numerical energy system model, TIMES-Norway. The numerical model simulations assume a set target for increased wind power production in Norway and illustrate how efficient taxation of externalities affects the social costs and spatial allocation of WPPs compared to the present situation with no environmental taxes. We also demonstrate the social cost of inefficient taxation.

This paper contributes to the relatively limited literature by analysing potential spatial trade-offs between the economic and environmental aspects of WPP siting, especially in combination with energy system modelling. Some studies have used multi-objective linear programming to minimise production costs or emission levels (Arnette and Zobel, 2012), various forms of multicriteria analysis (Sánchez-Lozano et al., 2014; Latinopolous and Kechagia, 2015; Watson and Hudson, 2015; Hanssen et al., 2018; Harper et al., 2019) or sustainability assessments (Eichhorn et al., 2017; Eichhorn et al., 2019). The only economic studies we are aware of that attempt to monetise some aspects of environmental costs explicitly in spatial trade-off analyses of renewable energy production are Drechsler et al. (2011) and Salomon et al. (2020) for Saxony in Germany, and Drechsler et al. (2017) generalised for the whole of Germany. However, these studies covered only a limited part of the environmental costs of wind power (local willingness to pay (WTP) to increase the minimum distance to turbines) and did not include environmental costs associated with grid expansions, and only Drechsler et al. (2017) included the financial cost of grid expansion. There are also few economic studies that assess the implicit costs of imposing constraints on cost-optimising models, e.g., related to the landscape visual impact of wind power systems in Great Britain (Price et al., 2020), or the opportunity costs of undisturbed landscapes, when wind power is compared to the best feasible alternative, solar photovoltaics, in Austria (Wehrle and Schmidt, 2020).

To our knowledge, this study is therefore the first to analyse the efficient spatial distribution of wind power production by incorporating the more complete environmental costs of both wind turbines and associated power line expansions in a detailed numerical energy system model.

This paper provides a realistic and policy-relevant numerical illustration of efficient distribution of WPPs in Norway by employing detailed information from the WPP licence applications.[1] The proposed environmental taxation scheme contributes to a more socially efficient expansion of wind power production, as investors in new WPPs must take into account the environmental costs of turbines and power lines when deciding whether or not to carry out their proposed WPP project.

This analysis sets the target for Norwegian wind power production at 20 TWh, approximately four times the present production level. This target is in line with expected wind power production in 2030 of 19–29 TWh (NVE, 2019a). We find that if efficient taxation of environmental externalities was introduced, Norway could produce 20 TWh of new wind power at a 25% lower social cost per kWh than in a scenario without such taxation. The environmental costs decrease significantly, while we find a slight increase in production costs, as it is not solely the WPP projects with the lowest production costs that will be implemented. Another important finding is that if only one type of externality were taxed, for example only turbines, this would significantly alter the allocation of wind power production across the country compared to the socially efficient allocation, when externalities due to both turbines and all power lines are considered. Furthermore, if only the externalities from new turbines and regional powerlines are taxed, and not those from the transmission lines, the social costs will be about the same as they would be without taxation.

Section 2 presents an analytical model that extends the private profit function of WPPs to include the social costs of wind power production and describes the socially optimal solution before deriving an environmental tax scheme designed to achieve the socially optimal solution. Section 3 discusses the numerical model and methods used to analyse the empirical implications for optimal WPP siting of introducing the environmental tax scheme derived in Section 2. Section 4 sets out environmental tax scenarios, which are analysed numerically, and Section 5 presents the results of these analyses. Section 6 contains a discussion and a conclusion as well as some policy implications.

2. Analytical model

In this section we present an analytical model of the private profit on a potential new WPP, and the profit on this WPP with the external environmental costs of turbines and power lines internalised. We then show the difference between the private and socially optimal geographical siting of all new WPPs. Finally, we suggest specifications of the environmental cost functions and present an environmental taxation scheme that internalises the environmental costs of all new WPPs, enabling socially optimal choice of new WPP sites.

Let $i = \{1, 2, \ldots, J\}$ denote potential WPPs, where WPP$_i$ is characterised by its number of wind turbines, (V_i), the length K_i (km) of new regional power lines required, the length T_i (km) of new transmission lines required, the average annual energy production per wind turbine (η_i), and the production cost c_i (\$/kWh) per unit of average annual production. The production cost, $c_{i,}$ captures annual production costs and charges, as well as annualised investments costs for the wind turbines and grids per unit of average annual production.

We consider a competitive electricity market with profit-maximising producers and utility-maximising consumers where p_i (\$/kWh) is the market price of electricity in the area where WPP$_i$ is established. In the absence of policy interventions, the average annual profit from WPP$_i$, if implemented, is:

$$\Pi_i^0 = (p_i - c_i)\cdot(V_i\cdot\eta_i) \tag{1}$$

We define an annual environmental cost function for WPP$_i$ where the environmental costs of wind power production are expressed by the additive cost functions of V_i, K_i and T_i:

$$C_i = \alpha_i(V_i) + \beta_i(K_i) + \varphi_i(T_i), \tag{2}$$

where $\alpha_i(V_i)$, $\beta_i(K_i)$ and $\varphi_i(T_i)$represent the environmental cost functions of the turbines, new regional power lines and new transmission lines, respectively. In principle, these functions capture reductions in both the use and the non-use values of a composite or index of a diverse set of environmental impacts associated with turbines and grid expansion. For sites where the capacity of the existing transmission grid is sufficient to

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[1] In Norway, WPP investors must obtain a production licence from the Norwegian Water Resources and Energy Directorate (NVE). The publicly available NVE database of WPP licence applications contains detailed information on all the proposed WPP projects in Norway (NVE, 2018a). See Section 3.

bring the new production into the wider power system, $T_i = 0$ and $\varphi_i(T_i) = 0$.

We define the net social costs of WPP$_i$ as[2]:

$$\Omega_i = (c_i - p_i)\cdot(V_i\cdot\eta_i) + [\alpha_i(V_i) + \beta_i(K_i\,,) + \varphi_i(T_i)]. \tag{3}$$

The WPPs differ with respect to the net social costs per kWh produced (ω):

$$\omega_i = c_i - p_i + \frac{\alpha_i(V_i)}{V_i\cdot\eta_i} + \frac{\beta_i(K_i)}{V_i\cdot\eta_i} + \frac{\varphi_i(T_i)}{V_i\cdot\eta_i}, \tag{4}$$

where the terms on the right-hand side represent the production cost minus the electricity price, and the environmental costs of turbines, regional power lines, and transmission lines, respectively. All costs are measured per kWh produced from WPP$_i$.

2.1. Socially optimal solution

Let Q_s denote the wind power production target, which will be achieved if the WPPs with the lowest costs, as measured by Eq. (4), are implemented. Let $S \in J$ denote the subset of WPPs for which the target is met at the lowest possible net social cost:

$$Q_s = \sum_{s\in S} V_s\cdot\eta_s, \tag{5}$$

and let the total net social cost ($T\Omega_S$) of meeting the target at the lowest possible cost be given by:

$$T\Omega_s = \sum_{s\in S}\Omega_s. \tag{6}$$

2.2. Profit-maximising behaviour with output subsidy, but without internalising environmental costs

Consider a private investor investing in profitable WPP projects. At the outset we assume that investors pay the full costs of new production (c_i), including the new regional power lines and the required investment in transmission lines.[3] We assume that the government subsidises private producers per unit energy produced by an amount R (\$/kWh) to ensure that the renewable target is met. R may take the form of a certificate price or feed-in premium.[4] If the producer faces no transfers or taxes other than R, the profit function is given by:

$$\Pi_i = (p_i - c_i + R)\cdot(V_i\cdot\eta_i) \tag{7}$$

We assume that all investments with a positive profit are implemented. For a given R, let $F \in J$ denote the subset of WPP for which $\prod_i > 0$, with total production, Q_F, given by:

$$Q_F = \sum_{f\in F} V_f\cdot\eta_f. \tag{8}$$

As none of the environmental costs are taken into account in the producer's profit function, these costs will not affect the producers' investment decisions. R can be set such that Q_F is equal (close) to Q_S, but the subset of WPPs included in F may differ substantially from the subset of WPPs included in S, leading to:

$$T\Omega_F = \sum_{f\in F}\Omega_f \geq T\Omega_S. \tag{9}$$

2.3. Specification of the environmental cost functions

We have identified three sources of environmental costs that may result in inefficient spatial distribution of WPPs: turbines, regional power lines and transmission lines. The optimal WPP siting will be arrived at if the investors internalise all the costs, including the environmental costs of WPP$_i$ (see Eq. (3)).

Environmental costs may differ substantially across WPPs due to differences in turbine numbers and the lengths of new power lines, as well as differences in the evaluation of these externalities across WPPs. We do not have a sufficient basis to differentiate environmental costs according to the detailed characteristics of each site. We have therefore made some simplifications in order to construct an operational scheme. These are discussed further in Section 6.

First, we distinguish strictly between adjacent households that are "local" and more distant households that are "national". It is reasonable to assume that all households in a country are affected in some way by the environmental degradation following from the establishment of WPPs (Navrud, 2005) and the associated expansion of the distribution and transmission grid (Navrud et al., 2008; Magnussen and Navrud, 2009). It is well-documented in the economic literature that both use and non-use values will be reduced by environmental impacts from WPPs (Dugstad et al., 2020). Hence a significant number of people outside the local area of a WPP will experience welfare effects even if they do not visit or use these areas, especially when wind power expansion is considered on a national scale, as it is here (see e.g., García et al., 2016; Mattmann et al., 2016). We therefore assume that the environmental costs of WPP$_i$ for the national population as a whole (N) increase in V_i, K_i and T_i. People living close to WPPs are typically more strongly affected than the rest of the population (Meyerhoff et al., 2010; Jensen et al., 2014; Brennan and Van Rensburg, 2016; Krekel and Zerrahn, 2017). The number of local households in the vicinity of WPP$_i$ affected by environmental externalities due to turbines, regional power lines and transmission are denoted M_i^V, M_i^K and M_i^T, respectively.

Furthermore, we assume constant marginal environmental costs per household per turbine and per km grid. We return to this assumption in Section 6. Let a^M and a^N denote the environmental cost per household per turbine for the local and national populations, respectively. b^M and b^N are the environmental costs per household per km of distribution line for the local and national populations. The environmental costs per household per km of transmission line for the local and national populations are denoted d^M and d^N.

Hence, the functional forms of the environmental cost functions related to turbines, new regional power lines and new transmission lines are identical for all WPPs, and are given by:

$$\begin{aligned}
\alpha_i(V_i) &= \widetilde{\alpha}\left(V_i, M_i^V\right) = V_i\cdot\left[a^M M_i^V + a^N\left(N - M_i^V\right)\right] \\
\beta_i(K_i) &= \widetilde{\beta}\left(K_i, M_i^K\right) = K_i\cdot\left[b^M M_i^K + b^N\left(N - M_i^K\right)\right] \\
\varphi_i(T_i) &= \widetilde{\varphi}\left(T_i, M_i^T\right) = T_i\cdot\left[d^M M_i^T + d^N\left(N - M_i^T\right)\right]
\end{aligned} \tag{10}$$

The environmental cost of WPP$_i$ will be a function of the number of turbines, lengths of regional power and transmission lines and number of people living in the vicinity of these installations.

2.4. Internalising environmental costs through an environmental tax scheme

To achieve the wind power production target, Q_s, the general production subsidy R must be complemented with a regulatory instrument that internalises environmental costs. In the following we derive a taxation scheme to serve this purpose. Note that the level of the general subsidy per unit kWh will have to be adjusted upwards to meet the

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[2] Note that we only consider local environmental costs here, as we are looking at the optimal geographical location for a given wind power production, and not the production target per se. We therefore ignore the possibility that the impact on other externalities, such as carbon emissions or technological innovations, is affected by the geographical locations of the WPPs.

[3] For a discussion of the inefficiencies following from shallow versus deep connection charges, see Turvey (2006), Bjørnebye et al. (2018) and Wagner (2019).

[4] Investment in renewable energy production has been stimulated by a variety of policy instruments, see Kitzing et al. (2012).

production target if environmental taxes are introduced. The environmental taxes ensure an efficient spatial distribution (subset of J), whereas R ensures that the target is met.

Efficient spatial allocation can be achieved by means of environmental taxes on the externalities that capture the environmental costs identified by Eq. (10).

We can write the optimal environmental taxes per turbine, per km regional power line and per km transmission line as functions of the number of people living in the vicinity of the specific installations at WPP$_i$.

$$\begin{aligned} t_\alpha\left(M_i^V\right) &= \left[a^M \cdot M_i^V + a^N \cdot \left(N - M_i^V\right)\right] \\ t_\beta\left(M_i^K\right) &= \left[b^M \cdot M_i^K + b^N \cdot \left(N - M_i^K\right)\right] \\ t_\varphi\left(M_i^T\right) &= \left[d^M \cdot M_i^T + d^N \cdot \left(N - M_i^T\right)\right] \end{aligned} \tag{11}$$

Given that our stylised model of environmental costs in Eq. (10) captures the correct environmental costs, the site specific taxes given by Eq.(11) internalise the environmental costs and hence, in combination with a general production subsidy R, result in socially efficient geographical distribution of WPPs for any total production target.

As the environmental cost per household is higher for the local population than for the national population, the optimal taxes increase linearly with the number of households living in the vicinity of the installations.

In the following sections we explore numerically the implications for the social costs of wind power production and the spatial distribution of WPPs of introducing, partly or fully, the taxation scheme represented by Eq. (11). The various scenarios are described in more detail in Section 4.

3. Numerical methods

In Norway, WPP investors must obtain a production licence from the Norwegian Water Resources and Energy Directorate (NVE). The publicly available NVE database of WPP licence applications contains detailed information on all the proposed WPP projects in Norway (NVE, 2018a). The database provides information on the geographical sites of WPPs, installed production capacities, number of turbines, investment costs for turbines and required new regional powerlines, wind capacity factors, and estimated production.[5] The total potential average annual production from approved WPPs and WPPs in the licensing process is about twice the assumed target of 20 TWh (NVE, 2019b). Hence, a socially efficient spatial allocation of WPPs implies choosing the WPPs with the lowest social cost with aggregate production of up to about half of the total production capacity applied for.

The numerical energy system model TIMES-Norway is used to illustrate the socially efficient siting of WPPs in Norway compared with the social costs of a potentially inefficient spatial distribution of wind power production, given a target of 20 TWh wind power production. Using model simulations, the NVE database of WPP applications, the environmental costs based on willingness to pay (WTP) or willingness to accept compensation (WTA) estimates from the literature, and data on current energy transmission capacities, we can construct social cost estimates per kWh for all potential WPPs in the application database; see Eqns. (3,10). One advantage of using an energy system model like TIMES-Norway to identify the socially efficient siting of new WPPs is the optimisation of both siting for new power plants and grid investment that is achieved by minimising energy system costs, including the costs of necessary investment in regional and transmission grids. The spatial resolution of the model also improves the representation of local characteristics such as resource availability and wind conditions. Another strength of using an energy system model with regional characteristics is that variations in the electricity price (p_i) from one price area to the next are captured. By considering various environmental taxation scenarios in the TIMES model, this study explores the implications of environmental taxes for the social cost of meeting a production target, and the subsequent spatial allocation of WPPs. An additional advantage of using a TIMES energy system model is that it covers conventional generation technologies, renewable generation technologies, energy storage technologies, transmission grids, multiple energy carriers, several end-use sectors, possibility for elastic demand, and other capabilities as well (see e.g., Ringkjøb et al., 2018).

3.1. Numerical model – TIMES

TIMES-Norway is a bottom-up optimisation model of the Norwegian energy system. The model is generated by the TIMES modelling framework (see Loulou, 2008; Loulou and Labriet, 2008), which combines a technical engineering and an economic approach. A TIMES model provides a detailed description of the entire energy system including all resources, energy production technologies, energy carriers, demand devices, and sectoral demand for energy services. A two-step method is used, in which demand for energy services is calculated first. This is used as input to the energy system model, which in turn calculates energy consumption. More information regarding calculation of energy service demand can be found in Rosenberg et al. (2013). TIMES models minimise the total discounted cost of a given energy system to meet the demand for energy services of the model regions over the period analysed.

A version of the TIMES model modified for Norway, TIMES-Norway (see Lind et al., 2013, Rosenberg and Lind, 2014; Seljom et al., 2020) uses various environmental cost estimates to analyse the efficient geographical distribution of new WPPs. The potential for new land-based WPPs in the TIMES-Norway model is based on data from NVE (NVE, 2018a). NVE is responsible for processing applications and granting licences for the production of wind power,[6] and reports the results. The investment and operating costs of each WPP, obtained from NVE data, are included in the model, along with associated capacity factors. Investment costs also include the contribution to new radial[7] grids.

Investment in new WPPs may necessitate grid reinforcement. Indeed, several of the potential new WPPs in Norway will require investment in the transmission or regional grid. Fig. 1 provides an illustration of the Norwegian electricity grid. As seen, the system is divided into three levels: the transmission, regional and distribution grids. A new WPP will typically be connected to the regional grid. However, if the WPP is large, around 300 MW or above, the plant may be connected directly to the transmission grid. WPP investors must pay a connection charge to cover the cost of connecting new customers to the grid or of reinforcing the grid for existing customers. This applies to the cost of investment on all grid levels (NVE, 2018b).[8]

In this paper, the TIMES model is used solely to determine the efficient distribution of new wind power plants, given environmental externalities due to the physical characteristics of turbine installations and associated power lines. This means that any measures on the supply side of the energy system are not covered here. As mentioned above, most investment in new wind power production capacity entails reinforcing the grid. As introduced and described in Bjørnebye et al. (2018), the current model version also utilises integer variables to describe whether grid investment takes place. This is demonstrated schematically in Fig. 2

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[5] For the vast majority of the applications, the installed capacity per turbine was between 2 and 3 MW.

[6] Typical processes involved in granting wind power licences include environmental impact assessments and may require mitigating measures, but do not involve any compensation scheme for environmental degradation (see e.g., Lindhjem et al., 2019).

[7] Connection between WPP and a connection point (e.g., transformation station) in the grid.

[8] http://publikasjoner.nve.no/faktaark/2018/faktaark2018_03.pdf

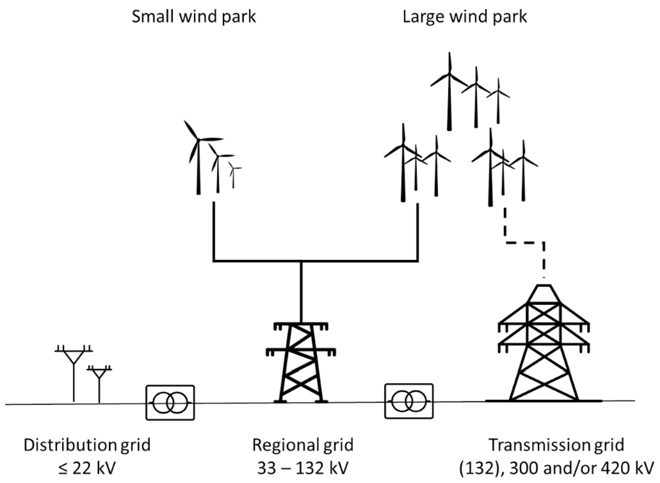

Fig. 1. The Norwegian electricity grid.

below and is an extension of the work of Bjørnebye et al. (2018). In the current paper, environmental cost estimates are added to the optimisation problem, capturing externalities related to wind turbines and regional and transmission grid lines. As seen in Fig. 2, some wind power projects can use the same transmission line if they are built, whereas none of the projects can be completed if the opposite happens. If, for example, the uppermost transmission line is constructed in some of the scenarios, it is most likely that the majority of the wind power projects connected to this line will be built before another transmission line is constructed. The same argument applies to the regional grid lines. Moreover, some wind power projects do not require grid reinforcement and can be connected directly to the existing grid. Fig. 2 also illustrates schematically that the various wind power projects have different investments costs (Inv_i) and environmental costs ($\alpha_i(V_i)$), and the same applies to the power lines ($Inv\_f(T_i)/Inv\_f(K_i)$ and $(\varphi_i(T_i)/\beta_i(K_i))$.

Spatially, the TIMES-Norway model covers the Norwegian land-based energy system, which is divided into five geographical regions corresponding to the current electricity spot market price areas (see Fig. 3.). In the following, the regions depicted will be referred to as: "East" (NO1), "South" (NO2), "Central" (NO3), "North" (NO4) and "West" (NO5).

The model provides operational and investment decisions from the base year, 2015, up to 2050. To capture operational variations in energy generation and end-use, each model period is divided into 260 sub-annual time slices. This corresponds to five weekly time slices. The number of time slices in TIMES models usually ranges from 4 to 48 (Gaur et al., 2019), but more detailed models exist. However, increasing the temporal resolution of a TIMES model beyond this may lead to non-solvable models (see e.g., Ringkjøb et al., 2020). The model has a detailed description of the end-uses of energy, and demand for energy services is divided into 400 end-use categories. The price of electricity exports/imports to/from countries with transmission capacity is exogenous to the model. It is assumed that the electricity prices in the neighbouring countries are independent of the quantities that are traded from and to Norway. Projected energy prices for biomass and fossil fuels are based on the New Policy Scenario in World Energy Outlook 2017 (IEA, 2017). Electricity trade prices for neighbouring countries are based on information from NVE (NVE, 2018c), where the various price profiles for each of the individual time slices are calculated from historical prices. The annual discount rate is set at 4%. The characterization of energy technologies, such as cost data and the efficiencies of various technologies, are input to the model, and can be found in Seljom and Tomasgard (2017). One major difference compared to the latter is that all costs related to the various WPPs are taken from NVE (NVE, 2018a). National generation capacities, electricity, and district heat generation as well as cross-border interconnection capacity and trade have been calibrated against statistics for the base year of the model. Generation or interconnection capacity that is under construction is also included in the model but fixed at the value in its actual start-up year.

Electricity production in Norway is mainly based on hydropower, but the share of wind power is increasing gradually. In 2019, total production was 146.8 TWh (NVE, 2019b), with renewables accounting for almost 98%.

3.2. *Information on potential new wind power plants*

The WPP applications (NVE, 2018a) and the associated wind power production potential can be divided into three categories: "*in operation*", "*licence granted*" and "*possible*", see Fig. 4. In the "*possible*" category are WPPs that have either applied for a licence, announced plans, or are the subject of public inquiries and appeals. Rejected licence applications are therefore not included in the "*possible*" category. The assumed

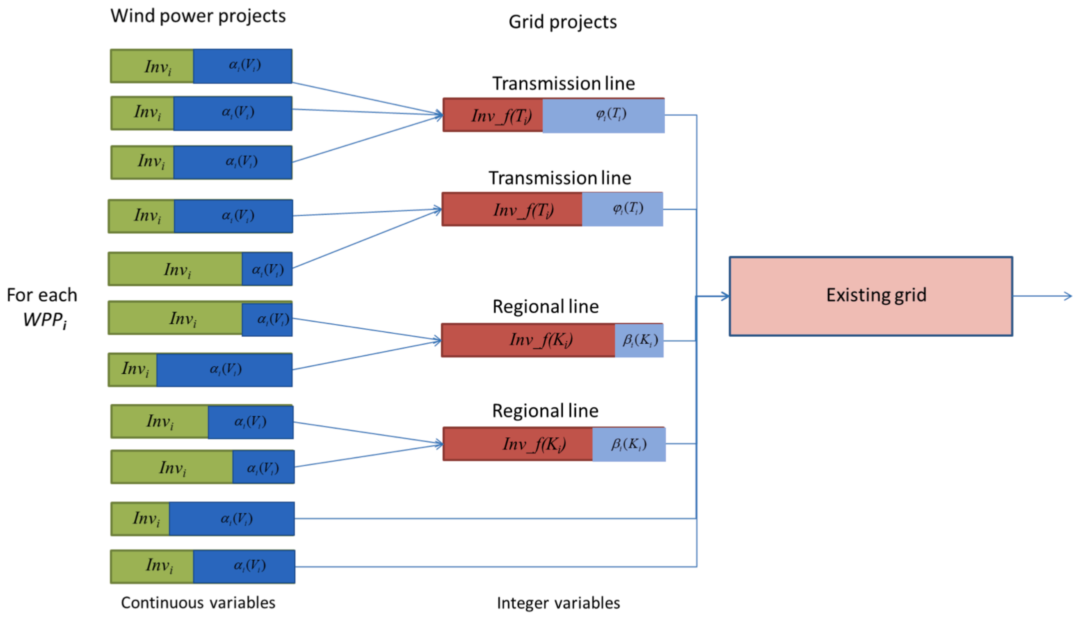

Fig. 2. Intersection between wind power and transmission grid projects.

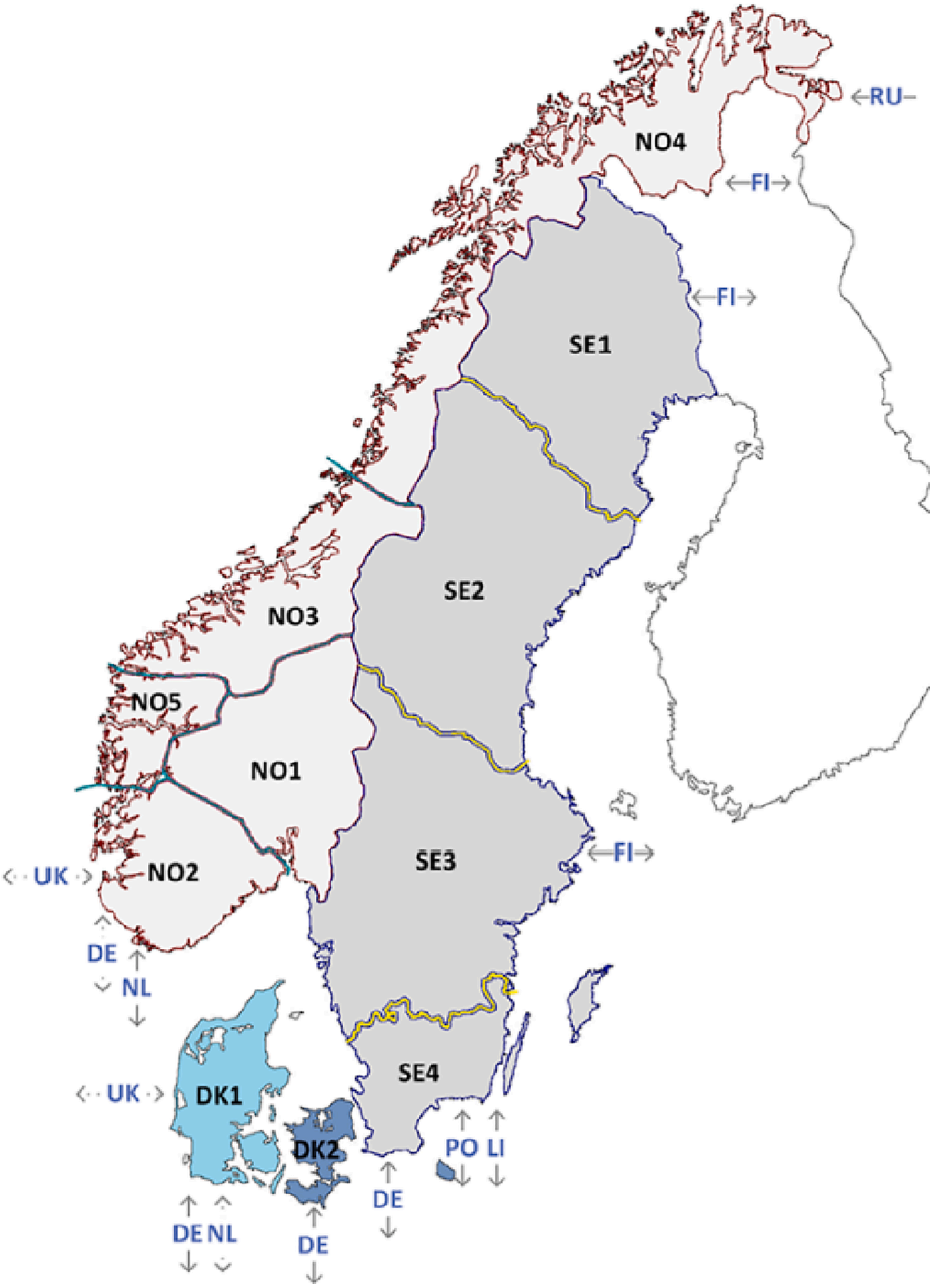

Fig. 3. Price areas in the electricity spot market in Norway.

renewable target is included in the TIMES model by adding the restriction that 20 TWh of new wind power production is required in Norway by 2030 (see more information below). Since it is likely that some of the *"possible"* WPPs will be granted a licence before 2030, the analysis includes all WPPs in this category.

The data on the new regional power lines required for each of the potential new WPPs are provided by the NVE application database (NVE, 2018a). Data on the number of households in potentially affected municipalities are obtained from population statistics. Table 1 sums up information about population and length of regional power lines across regions. North is more sparsely populated but, on average, requires longer power lines than in the other price areas. Of the regions where most new WPPs are likely to be sited - South, Central and North - South is the most densely populated but WPPs established there would generally require shorter power lines. Note that the numbers in Table 1 are taken from the application database. In the numerical simulations by the TIMES model, we find the number of people affected and power line investment for the specific WPPs chosen by the model.

As discussed in Section 2, new power production may trigger the need for new transmission lines. These data cannot be found explicitly in the NVE database, but by running the TIMES-Norway model it is possible to determine how each WPP affects the need for new transmission lines.

3.3. *Environmental cost estimates*

The number of households living near WPP$_i$ and the new associated regional power lines, M_i^V and M_i^K, respectively, are for simplicity defined by administrative boundaries, and set equal to the number of households in the municipality in which the WPP is to be established. See discussion of this simplification in Section 6.

If new regional power lines and/or transmission lines are also

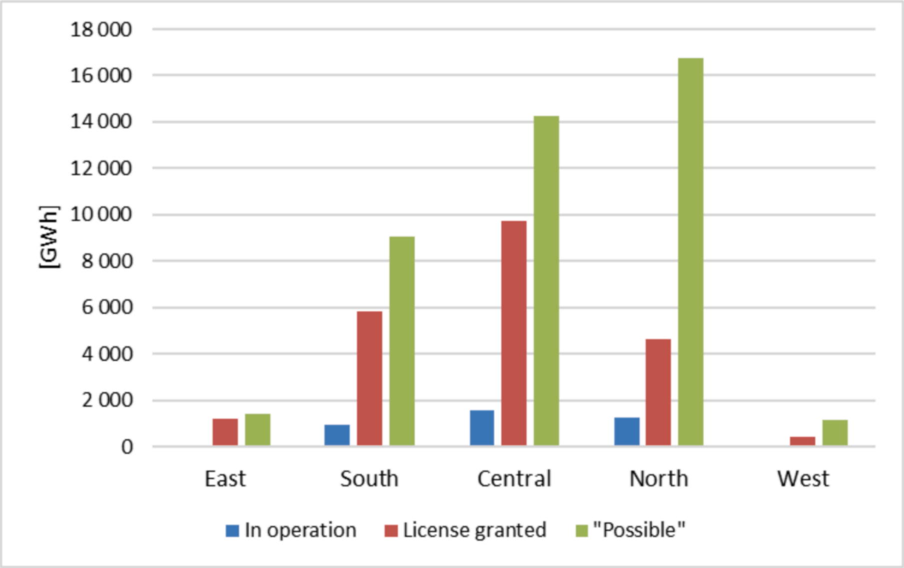

Fig. 4. Wind power potential per region.

Table 1
Length (km) of new regional power lines in WPP projects in the licence application database and number of households in the municipalities for which WPPs have been applied.

Regional power lines (km)	East	South	Central	North	West	Total
Average	7	5	15	22	6	13
Median	6	3	9	10	4	6
Households	East	South	Central	North	West	Total
Average	9950	5518	3587	2626	8536	5780
Median	3502	2279	1789	1038	2124	2119

required, the lines may pass through several municipalities.[9] In that case, the average number of households in the municipalities that the power lines transect is used to calculateM_i^T. For the remainder of the national population a (low) environmental cost per turbine and transmission line length (km) are assumed.

Although the international literature quantifying and valuing the environmental costs of WPP per household is quite extensive and contains both revealed and stated preference studies (e.g., Mattmann et al., 2016; Zerrahn, 2017), it is not straightforward to synthesise or transfer such estimates to Norway because of different environmental conditions and the inherent uncertainty (errors) in such transfers (Lindhjem and Navrud, 2008; Johnston et al., 2015). Moreover, studies of the full externality costs of grids, beyond the limited effects on house prices, are relatively scarce in the international literature (Giaccaria et al., 2016; Brinkley and Leach, 2019). Therefore, this study has instead based the environmental cost estimates on available Norwegian stated preference studies capturing both use and non-use values for the local and national populations.[10] The values of the environmental costs per household used in the analysis are presented in Table 2.

The source of the WTA estimate of USD 15.42 (a^M) per household per year to avoid one additional wind turbine is the choice experiment (CE) study by García et al. (2016). This study investigates local WTA compensation for the construction of wind turbines (from 9 to 18) in the municipality of Sandnes, in Rogaland county on the west coast of Norway (size: 286 km^2, inhabitants: 72000).[11] They find different WTA estimates ranging from USD 5.24 to USD 24.05 per household per year, depending on whether people live close to or far away from the site and whether they are users of the areas or not. We chose an estimate in the middle of this range to represent the typical municipal household.

For the remainder of the Norwegian population, the source of the estimate of USD 0.21 (a^N) in WTP to avoid environmental externalities from one turbine is the national contingent valuation (CV) study by Navrud (2005). In the second valuation scenario of a wind power expansion of 6.7 TWh, Navrud (2005) finds a mean WTP of USD 103.70 per household per year, which translates into USD 0.24 per turbine. We set this conservatively at USD 0.21 per turbine.

The estimate of the externality costs of distribution lines is based on the local cost estimate (b^M) of USD 15.42 per household per year per km from the study by Navrud et al. (2008), as discussed by Lindhjem et al. (2018). Estimates lie in the range USD 14.80–38.54 for people within 1 km of the power line. We conservatively select an estimate in the lower part of this interval to represent the average environmental costs experienced by a typical household locally. For the national population, a conservative cost estimate of NOK 0.21 per household per avoided km of regional grid is chosen, again based on Navrud et al. (2008). Note that since the estimates for both regional and transmission lines and turbines

Table 2
Environmental costs in USD ($) per household per year used in the analysis.

Parameter	Environmental costs per household	Value USD
a^M	$/turbine local population	15.42
a^N	$/turbine national population	0.21
b^M	$/km regional power lines for local population	15.42
b^N	$/km regional power lines for national population	0.21
d^M	$/km transmission lines for local population	30.83
d^N	$/km transmission lines for national population	0.41

Note: We use the average exchange rate for 1 January 2020–28 April 2020, which was USD 1 = NOK 9.73.

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[9] This could of course also be the case for distribution grid expansion. However, our data suggest that this is rarely the case. We have therefore ignored this possibility.

[10] Revealed preference studies cover only use values, so we chose to base our estimates on stated preference studies. To our knowledge there is also very limited revealed preference evidence from Norway: only one travel cost study from the south-west of Norway (Kipperberg et al., 2019).

[11] In this study, 9 turbines were assumed to have a total capacity of about 30 MW, based on recently built WPPs.

are uncertain and roughly in the same range, they were harmonised and rounded (yielding USD 15.42 and USD 0.21).

Transmission lines are high voltage lines that have a bigger impact on the landscape than distribution lines (e.g. wider track, taller pylons) and typically pass through more uncultivated areas (e.g. mountainous areas). We therefore chose a WTP estimate of USD 30.83 per household per year to avoid one km of high-voltage power line for the local population (d^M), based on the range of values from Navrud et al. (2008) above. Finally, for the national population, a WTP of USD 0.41 per household per year to avoid one km of high voltage power line (d^N) is assumed. This estimate was chosen because it may be reasonable to assume that the relative difference in WTP between local and national populations remains constant across all environmental cost estimates. Finally, an assumption is then made that the environmental cost estimates per household per year can be transferred to other municipalities and areas of the country. Note that the spatial variation in total externality costs in this simple set-up is driven by population densities in different areas of the country, rather than by variations in unit costs (i.e., per household costs per turbine). We return to a discussion of these assumptions in the final section. With the cost estimates presented above, we are able to calculate the optimal taxes per turbine, per km regional power line and per km transmission line for each potential WPP, as given by Eq. (11).

4. Scenarios

The TIMES-Norway model is used to compare the outcomes in terms of social costs and spatial distribution of WPPs under the following environmental taxation policy scenarios:

1. *First Best* (*FstBst*). WPP investors internalise the full social costs through the appropriate taxes as described in Eq. (11). This scenario corresponds to the socially efficient outcome.
2. *Regional Power Lines & Turbines* (*RgPwLn&Turb*). WPP investors internalise the environmental costs of the turbines and regional power lines, see $t_\alpha(M_i^V)$and $t_\beta(M_i^K)$ in Eq. (11), but not of transmission lines.
3. *Regional Power Lines* (*RgPwLn*). WPP investors internalise the environmental costs of regional power lines only, see $t_\beta(M_i^K)$in Eq. (11).
4. *Turbines* (*Turb*). WPP investors internalise the environmental costs of turbines only, see $t_\alpha(M_i^V)$in Eq. (11).
5. *No Environmental Costs (NEC)*. WPP investors internalise no environmental costs.

All scenarios assume that R is set such that total new wind power production will be identical (or close) to the political target of 20 TWh. As environmental taxes differ across the scenarios, the level of R will also have to differ across the scenarios to ensure the target is achieved. The scenarios are compared with respect to wind power production sites and to the production, environmental and total social costs of achieving the production target.

5. Results

5.1. Base case – geographical distribution

Fig. 5 illustrates how production is distributed across the different regions for the five scenarios listed above. As shown, the model results vary considerably for most regions, depending on the assumptions regarding the internalisation of environmental costs.

A total of 100 different WPPs were chosen out of a possible 149 in the different model runs. Table 3 shows the number of WPPs per scenario. The *RgPwLn&Turb* scenario results in the fewest number of new WPPs but the highest average production, as the total production target is fixed.

The *NEC* scenario in Fig. 5 illustrates the siting of new WPPs when all necessary investment costs related to production and power lines are included, but environmental costs are excluded. Production is clearly highest in Central for this scenario. This region is currently a net importer of energy, so increasing local production will decrease dependence on imports from other regions. It is also a region with a very high wind power production potential. The production increase is second largest in North. This is largely due to high-capacity factors, but WPPs here will require significant grid investment in order to be able to export the produced electricity out of the region. There is also a

Table 3
Number of distinct WPPs per scenario.

	NEC	*Turb*	*RgPwLn*	*RgPwLn&Turb*	*FstBst*
Number of WPP's	67	61	70	58	70

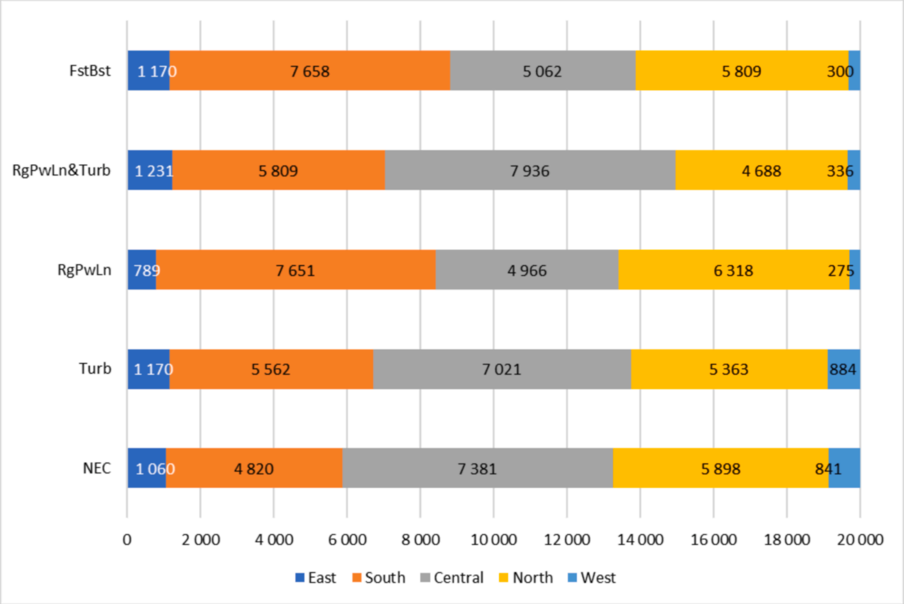

Fig. 5. Wind power production [GWh] by region for the different scenarios.

considerable production increase in South, which is closely connected to Europe through power cables.

In the *Turb* scenario, where the environmental costs of the turbines are internalised, production drops slightly in Central, North and West, compared with in the *NEC* scenario, directly reflecting the number of households in the affected communities in these regions. Production increases by almost 1 TWh in South in this scenario. New plants in North will generally have lower environmental costs than plants in South when the local population is considered, see Table 1. However, there are some potential WPPs in communities in North with a high population and only medium capacity factors. The *Turb* scenario results confirm this.

In the *RgPwLn* scenario, which includes the environmental costs of regional power lines, wind power production increases significantly in South and drops in Central compared with *NEC*. The average length of new regional power lines is high for Central (see Table 1), which directly increases the environmental costs. At the same time, the average length of new regional power lines in South is lowest, resulting in an increase of approximately 1.8 TWh compared with *NEC*.

Including the environmental costs of wind turbines alone yields a different spatial distribution of wind power production compared with including only the environmental costs of regional power lines. This can be seen by comparing the *Turb* scenario with *RgPwLn* as explained above: the increase in production in South in *RgPwLn* is directly related to the length of new power lines. As seen, there is actually a small increase in North as well. One reason for this is that half of the increase is attributable to two very large WPPs. Both have low environmental costs for the regional grid.

In the *RgPwLn&Turb* scenario, the environmental costs of both regional power lines and turbines are included. Here the strongest effects are found in South, Central, North and West. Compared with the *NEC* scenario, wind power production is almost 1.3 TWh higher in South and 0.5 TWh in Central, while production drops by 0.56 TWh in West and 1.3 TWh in North. East is less affected than the other four.

For the *FstBst* scenario, the analysis identifies the combination of new WPP sites and grid investment that minimises social costs by minimising total energy system costs, including the costs of necessary investment in the transmission and regional grids and the accompanying environmental costs for wind turbines, regional power lines and transmission lines. Compared with the *NEC* scenario, the biggest changes take place in South and Central. South experiences an increase of 2.8 TWh whereas production drops by 2.3 TWh in Central. The main reason for the reduction in Central is high environmental costs for the transmission grid in this region. The *FstBst* scenario represents the inclusion of environmental costs through the appropriate taxes, given by Eq. (11) in the analytical model.

Fig. 6 presents the maximum and minimum production following from the five scenarios across the three main production regions. South is most affected by the implementation of an efficient taxation policy compared with the present situation (*NEC* scenario). As seen, the *FstBst* scenario leads to maximum production for this region, almost 50% higher than the minimum production in *NEC*. This clearly demonstrates the need for an environmental taxation scheme to achieve an efficient spatial distribution of new wind power production.

Fig. 6 also shows that production in Central and North is strongly affected by the environmental taxation policy. The difference between minimum and maximum production in these regions is around 3 TWh for Central and 2 TWh for North. The *RgPwLn* scenario leads to minimum production in Central and maximum production in North. The *RgPwLn&Turb* scenario places maximum production in Central. For North, minimum production occurs in *Turb*.

Table 4 presents the net social costs (per kWh) of producing 20 TWh under the different environmental taxation scenarios. As seen, the net social costs are highest for *NEC*. Overall, the introduction of efficient, national taxation of WPPs reduces the net social costs of wind energy production by 25%.

As seen, the differences in production costs across subsets of WPPs and price differences across price zones are of minor importance. What matters is the variation in environmental costs following from the various spatial allocations in the different scenarios. We also see that the environmental costs are (more than) twice the electricity prices[12] in all scenarios. This means that that the environmental taxes must be accompanied by a large general production subsidy to make investments privately profitable; see discussion of *R* in Section 2.2.

Fig. 7 illustrates the effect of adding environmental costs to the various WPPs. The figure shows the selected WPPs for the *NEC* and *FstBst* scenarios for South, illustrating total production costs (including environmental costs) per WPP for the two scenarios.[13] The bars are plotted in order of increasing investment cost. For *NEC*, only the blue bars are relevant, i.e., the investment costs with all environmental costs are excluded. The sum of the blue and red bars represents *FstBst*. A total of 40 different plants are installed in the two scenarios combined, with 25 WPPs in *NEC* and 34 in *FstBst*. WPP39 and WPP13, highlighted in the figure, are clearly among the 25 cheapest plants when environmental costs are excluded. These WPPs are therefore a part of the solution for the *NEC* scenario. On the other hand, WPP20 and WPP30 are among the most expensive WPPs when investment costs only are considered and are therefore not a part of the *NEC* solution. But these two WPPs are cheapest when total costs are considered, and therefore a part of the *FstBst* solution. Similar figures may be used for each model region and for each scenario to study the impacts of various model assumptions.

As discussed in Section 2.2, the scenario in which all externalities are taken into account (*FstBst*) leads to lower net social costs than the scenario with no environmental taxes (*NEC*), see Eq. (10). The numerical analyses show that effective taxation (*FstBst* scenario) of the externalities implies that 20 TWh new wind power production in Norway can be achieved at a 25% lower net social cost per kWh compared with the *NEC* scenario; see Table 4. The environmental costs of socially efficient WPP siting are lower than in *NEC*, but the production cost is slightly higher. When it comes to partial implementation of taxes (*Turb*, *RgPwLn*, *RgPwLn&Turb*), the analytical model cannot generate any general results, except that the social costs of achieving the production target must be higher than under *FstBst*. The numerical analysis shows that if the environmental costs of new turbines and regional power lines, but not of transmission lines, are taxed, the social costs are about the same as a no-taxation scenario. In *RgPwLn&Turb* there is less investment in regional power lines, but investment in the transmission grid is higher than in *FstBst*.

5.2. Sensitivity analysis – Increased environmental costs per turbine

A sensitivity analysis was performed with higher environmental costs per turbine. The cost per household per turbine for the local population was increased to USD 30.83 ('high') per year to avoid one additional wind turbine. In addition, the cost per household for the rest of the Norwegian population of avoiding externalities due to one additional turbine was increased to USD 0.41 ('high') per year. Sensitivity analyses were performed for three of the scenarios, and Fig. 8 illustrates the results for the *Turb* and *RgPwLn&Turb* scenarios. The results are compared to the base case results from Fig. 5 (referred to as "Base" in

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[12] Even though Norwegian power production is close to 100% renewable, the transmission capacity and coupling makes Norway part of a broader European power market covering large parts of Europe. This means that power from non-renewable sources also enters the Norwegian grid. As a consequence, the price of electricity is influenced by power prices on the European continent, including a carbon price contribution. More information on this topic can be found in Marcantonini and Denny Ellerman (2015), which discusses the implicit carbon price of renewable energy.

[13] The total costs of WPP39, WPP13, WPP24 and WPP22, are USD 9023 per MW, USD 11182 per MW, USD 20068 per MW and USD 19012 per MW, respectively.

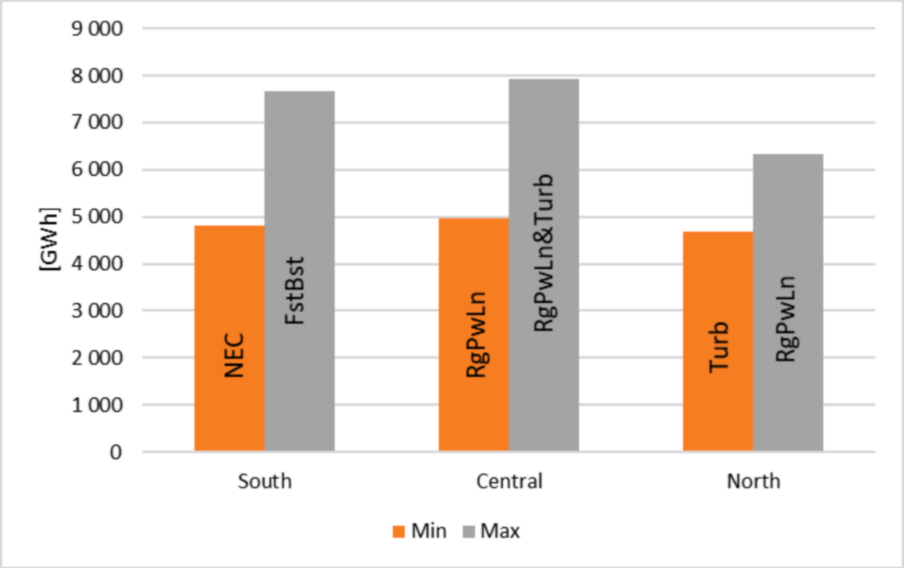

Fig. 6. Minimum and maximum production for each of the environmental cost scenarios.

Table 4
Net social costs per kWh across scenarios ($/kWh).

	NEC	*Turb*	*RgPwLn*	*RgPwLn&Turb*	*FstBst*
Production costs	0.035	0.036	0.036	0.036	0.036
Price of electricity	0.032	0.032	0.031	0.033	0.033
Environmental costs turbines	0.068	0.052	0.071	0.054	0.057
Environmental costs regional grid	0.015	0.013	0.006	0.007	0.008
Environmental costs transmission grid		0.007		0.020	
Total	0.086	0.076	0.082	0.083	0.068

Fig. 8). As seen, a higher environmental cost per turbine leads to lower electricity production in South and Central, especially in the *RgPwLn&Turb* scenario. Production also increases significantly in North, with an increase of over 2 TWh in *RgPwLn&Turb*. In both cases, production becomes highest in region North.

Fig. 9 illustrates changes to the *FstBst* scenario, with high environmental costs for wind turbines. As seen, production drops in Central and increases in South and West. Otherwise, there are minor changes compared to the base case.

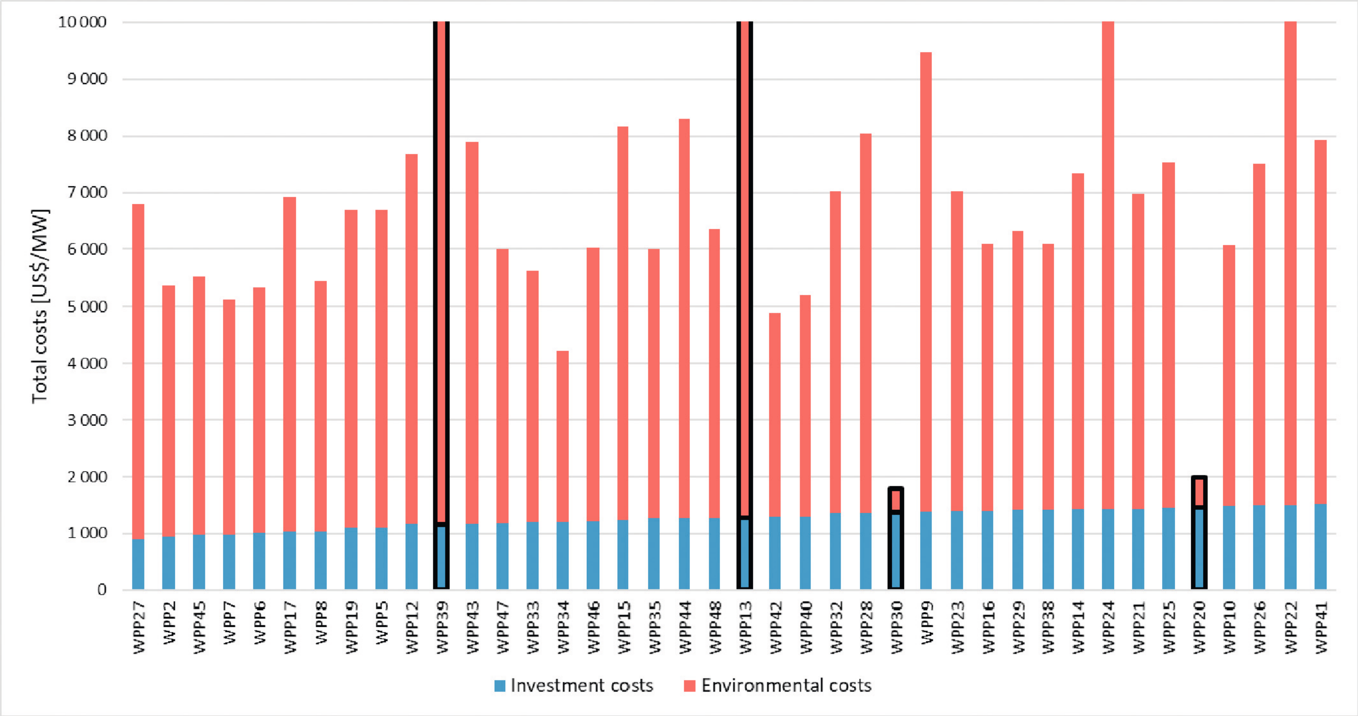

Fig. 7. Total investment costs for turbines and grid. *NEC* (blue) and *FstBst* (blue + red) scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

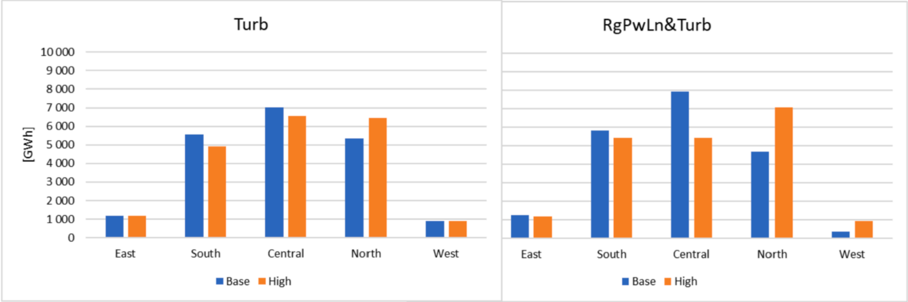

Fig. 8. Sensitivity analysis of *Turb* and *RgPwLn&Turb* scenarios with high environmental costs per turbine.

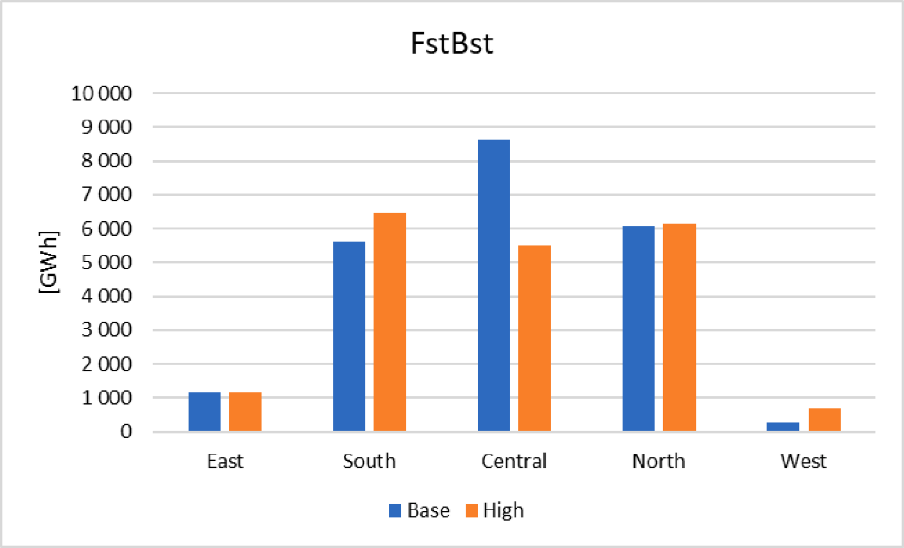

Fig. 9. Sensitivity analysis of the *FstBst* scenario with high environmental costs per turbine.

6. Conclusion, discussion, and policy implications

This study has analysed the efficient spatial allocation of wind power production by incorporating the environmental costs of both wind turbines and the associated power line expansions in a detailed numerical energy system model.

The paper proposes internalising the environmental costs through a simple site-specific environmental taxation scheme, whereby each of the externalities (turbines, regional power lines and transmission lines) is taxed in proportion to the number of people affected. With this scheme, a specific target for new wind power production in Norway can be met at a significantly lower social cost than the current situation without environmental taxation. The general framework for environmental taxation of WPPs derived in this paper is applicable to all countries with an emerging wind power industry.

In order to produce wind energy in Norway, investors in WPPs must be granted a production licence by the authorities (NVE). The goal of NVE's processing of licence applications is to ensure that the benefits of a proposed project are greater than the ensuing disadvantages. Environmental concerns are considered in the sense that if a site is assessed as “too harmful” for the environment, the licence is not granted. However, once a licence is granted, there is no environmental taxation of the externalities. Therefore, there is no policy to ensure that WPP investors take sufficient account of the externalities when they decide which of the licensed wind power plants to develop or, in the future, which sites they choose for WPPs. The environmental taxation scheme proposed in this paper is a remedy for this inefficiency. With full information about production costs, the regulator could achieve the same outcome by direct regulation. However, such information is likely to be private information confined to the investors. In such case, the optimal siting would only be achieved by letting the investors internalising the environmental costs through environmental pricing.

The numerical results are based on a least-cost model, assuming perfect competition and perfect foresight. Generally, the projected energy demand is supplied to the TIMES model exogenously. This means that there is no mechanism for capturing the price elasticity to the quantity in demand. As an alternative, endogenous demand can be included by hard-linking different models, for example as described by Helgesen et al. (2018). Other approaches, including elastic demand, are discussed by Ringkjøb et al. (2018). The model does not cover the human behaviour aspect, either. The perfect foresight assumption is also a simplification. This means the model results could be too optimistic with regard to investment levels. The difference between the cost-effective solutions for the various model regions does not necessary imply that individual actors in the real market consider the investment profitable, for example because of different rates or payback times.

The environmental cost framework that this study adds to the TIMES model is admittedly simple and does not, for example, take account of the fact that the marginal local (and national) environmental cost of wind turbines may decrease or increase for some people at a given WPP site. Our cost function represents a composite of a diverse set of impacts, each of which may decrease or increase on the margin. Some, for example, may view a natural area developed for wind power as to some extent permanently degraded, so that the 8th or 10th turbine in the same area may not add much extra damage. However, other impacts, such as noise, flickering and impaired landscape views, may increase with the number of turbines on the margin. Moreover, increasing marginal costs is the more standard assumption in environmental economics. The same applies, for example, to air pollution.[14] In the absence of clear evidence from the literature and local studies in this respect (Mattmann et al., 2016), this paper uses a linear function. Further, since there is no firm evidence as to how marginal costs can be differentiated across geographical regions, the same unit costs were used across the country (see discussion in Dugstad et al., 2020). Ideally, environmental costs should have been differentiated on the basis of factors such as landscape aesthetics, biological features and other qualities of different sites (Zerrahn, 2017; Price, 2017; Hedblom et al., 2020). Other WPP sites nearby and any available substitutes for recreational areas, for instance, may also be important. In that case, the environmental cost (and optimal taxes) per turbine and km grids would not be functions of the number of local households alone but would also have to take account of other site-specific attributes. Even so, the unit cost estimates are less important for the total environmental cost estimates than the number of people assumed to be affected, so this may not seriously influence the overall results (Johnston et al., 2017). The wind power externality literature does demonstrate that local impacts (use values) decrease with distance to sites; in Germany, for example, such impacts are most pronounced within a 4 km radius (Krekel and Zerrahn, 2017). However, such effects depend very much on visibility distance and are not easy to generalise.

The more general literature on non-market valuation using stated preference methods is not clear with respect to how use values, and more especially non-use values, vary with geographical distance from an environmental impact (so called “distance decay”) (Glenk et al., 2020). One must often resort to defining the affected households (“extent of the market”) with the aid of administrative boundaries (Johnston et al., 2017), e.g., municipal boundaries, as in this study. Finally, there is some evidence that people may adapt to impacts over time (e.g., Krekel and Zerrahn, 2017) or, conversely, that after turbines have been built, impacts may be more serious than anticipated (Dugstad et al., 2020). In the absence of clear evidence on this point, this study assumes a relatively conservative environmental cost per household and year that is constant and permanent. A pilot choice experiment study of WTA compensation for a national plan for increasing wind power production in Norway conducted in two regions shows preliminary mean annual environmental cost estimates around USD 0.3 per household per turbine, or NOK 1 per kWh (Lindhjem et al., 2019; Dugstad et al., 2020). These estimates are comparable to the estimate per turbine used in the present study for a national population. The above discussion about the environmental costs of turbines also applies to electricity grids. In fact, less is known about externalities attributable to this infrastructure than to the wind turbines themselves (Giaccaria et al., 2016; Brinkley and Leach, 2019).

There are relatively few similar studies to compare our overall results with. One of the conclusions in Drechsler et al. (2017), for example, was that, for the most part, a socially efficient allocation of WPPs in Germany matched the most favourable wind locations. Thus, the considerable external effects did not alter the socially efficient solution. This contrasts with our study, which finds that the socially efficient allocation of wind power production across regions (*FstBst* scenario) differs substantially from the cost-minimising allocation when all external costs are ignored (*NEC* scenario). Our study also shows that the social costs can be significantly reduced by efficient taxation, compared to the current situation with no environmental taxes. One reason for the different results may be that our study, in contrast to Drechsler et al. (2017), includes the environmental costs of the transmission lines. As Table 4 shows, it is only in the scenario that includes all environmental costs (*FstBst* scenario) that the social costs are significantly reduced compared to the no environmental taxes scenario. Another possible reason is that our analysis only considered WPP locations for which a licence has already been applied. Thus, all the potential WPPs in our study are likely to have good wind conditions. Where they differ is in the environmental costs.

In addition to working towards more precise estimation of the local and national environmental costs of wind power, a better understanding of the curvature of the marginal environmental cost function, the geographical differences in the environmental effects across sites and populations, and an understanding of the permanence or otherwise of such effects over time, there may also be other fruitful avenues for future research. For example, it may be possible to impose constraints on the TIMES model to reflect the wish to exclude certain areas with specific natural or landscape qualities from wind power development. Such an analysis would yield implicit (shadow) prices for the environmental constraints imposed. It would also be interesting to investigate not just the geographic distribution of a given wind power development target, as we have done here, but to try to determine the optimal level of wind power development when the environmental costs of alternative energy sources are also included. Finally, in order to achieve more efficient environmental taxation in practice, for example by including even more location-specific taxes than were investigated here, more research is clearly required to provide a better understanding of factors that limit policy acceptability. An example is social equity concerns that may be particularly important for siting renewable energy installations (Grimsrud et al., 2019; Lehmann et al., 2020). In Norway, a recent Green Tax Commission report recommends a geographically differentiated nature tax which would internalise the environmental damage of various land uses, including wind power (NOU, 2015). Further, the energy regulator NVE recently drew up a national plan that indicates areas of Norway that are suitable for wind power, and which takes account of technical, environmental, and other concerns (NVE, 2019a). However, explicit trade-offs were not assessed using economic methods. Both this direct spatial targeting plan and the proposed tax scheme have so far run aground in the political process, illustrating both the importance of designing acceptable policy instruments and the need for more knowledge of how best to site energy infrastructure.

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[14] Note also that we have let the environmental cost of turbines be a function only of the number of turbines, and not of their size; see Section 2.3. This is a simplification that can be justified as long as the turbines do not differ “too much” in size across the WPPs. If there is a large size difference across WPPs, the installed capacity or height of the wind turbines could be included in the environmental cost function associated with the turbines. In the numerical illustration of our model in Section 3, the wind turbines did not vary very much in capacity across the licence applicants. The more recently planned wind turbines are taller than the older ones. Higher turbines cause higher environmental costs (especially as they can be seen from a greater distance), but they also produce more electricity, and fewer turbines are required for the same output.

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