Statistisk sentralbyrå
Statistics Norway

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

TALL SOM FORTELLER

Kristine M. Grimsrud, Cathrine Hagem, Arne Lind, and Henrik Lindhjem

DISCUSSION PAPERS

938

Discussion Papers No. 938, August 2020
Statistics Norway, Research Department

Kristine M. Grimsrud, Cathrine Hagem, Arne Lind, and Henrik Lindhjem

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

Abstract:
Negative environmental externalities associated with wind power plants depend on the physical characteristics of turbine installations and associated power lines and the geographical siting. We derive analytically an environmental taxation scheme for achieving the efficient spatial distribution of new wind power production, taking account of both production and environmental costs. Further, we illustrate the analytical results by means of a detailed numerical energy system model for Norway. We 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. We also show that the environmental costs associated with both turbines and power lines were crucial to the efficient spatial allocation of wind power plants.

Keywords: Wind power, wind power plant, renewable energy, environmental externalities, environmental taxes, energy system model

JEL classification: H23, Q42, Q48, Q51

Acknowledgements: The authors would like to thank Bente Halvorsen and Linda Nøstbakken for valuable comments on the manuscript. The research was funded by The Research Council of Norway, grant number 267909 WINDLAND.

Address: Kristine Grimsrud, Statistics Norway. E-mail: kristine.grimsrud@ssb.no

Cathrine Hagem, Statistics Norway. E-mail: cathrine.hagem@ssb.no

Arne Lind, IFE, Institute for Energy Technology, E-mail: arne.lind@ife.no

Henrik Lindhjem, Menon Economics, E-mail: henrik@menon.no

Discussion Papers comprise research papers intended for international journals or books. A preprint of a Discussion Paper may be longer and more elaborate than a standard journal article, as it may include intermediate calculations and background material etc.

Abstracts with downloadable Discussion Papers
in PDF are available on the Internet:
http://www.ssb.no/en/forskning/discussion-papers
http://ideas.repec.org/s/ssb/dispap.html

ISSN 1892-753X (electronic)

Sammendrag

Miljøkostnadene som følger av nye vindkraftverk avhenger av grad av fysiske inngrep i landskapet som følge installasjoner av vindturbiner, nye kraftledninger samt den geografiske plasseringen av kraftverket. I dette paperet utleder vi analytisk en miljøskatteordning som gir en effektiv geografisk fordeling av vindkraftproduksjon i Norge når en tar hensyn til både produksjons- og miljøkostnader. Videre illustrerer vi de analytiske resultatene ved hjelp av en detaljert numerisk energisystemmodell, TIMES, for Norge. Vi viser at et gitt mål for vindkraftproduksjon kan oppnås til en betydelig lavere samfunnsøkonomisk kostnad dersom en innfører en miljøskatteordning sammenlignet med dagens situasjon uten en slik skatteordning. Vi finner også at miljøkostnadene forbundet med vindturbiner og kraftledninger er avgjørende for effektiv geografisk fordeling av vindkraftverk.

1. Introduction

Decarbonization of the electricity markets is expected to result in a large increase in 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 wildlife impacts (see e.g. reviews by Saidur et al. 2011; Mattmann et al. 2016; Zerrahn 2017). These negative external effects of WPPs 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 a 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 negative visual impacts on the landscape and noise 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 starting point of this paper is a potential national target for wind power production. We follow Drechsler et al. (2017) and define efficiency such a way that a given target for wind power production is achieved at minimum social costs. These social costs comprise the private costs borne by private investors as well as the external environmental costs. This study analyzes how these environmental costs influence the efficient spatial allocation of WPPs across Norway. The environmental costs of a potential WPP is 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 consideration is how the local versus 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 costs related to installation costs, civil work, assembly and installation, etc.

This paper contributes by: i) deriving, analytically, an environmental taxation scheme to achieve an efficient spatial allocation of WPPs for a given wind power production target when both production and environmental costs, as discussed above, are included in the analysis, and ii) illustrating 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 illustrates how efficient taxation of externalities affects the social costs and spatial allocation of WPPs compared to the present situation with no environmental taxes.

In Norway, investors can to a certain degree choose the site of their WPP but must obtain a production license by the Norwegian Water Resources and Energy Directorate (NVE). The publicly available database of license applications for WPPs from the NVE contains detailed information on all the proposed WPP projects in Norway (NVE 2018a). 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 2019). The total potential annual production from approved WPPs and WPPs under the licensing process is about twice the assumed target of 20 TWh (NVE 2019). Hence, the authorities must determine the future spatial distribution of WPPs across the country. The licensing database provides information on the geographical site of potential WPPs, installed production capacities, investment costs for turbines and required new reginal powerlines, wind capacity factor, and estimated production. After incorporating this information into the TIMES-Norway model, the model can determine for each potential new WPP, the upgrades required in the regional and transmission grid as well as the need for new power lines. The TIMES-Norway model can therefore be used to identify the subset of potential new WPPs that can achieve the assumed national target of 20 TWh at the lowest possible private production cost. By assigning monetary values to the environmental externalities caused by the turbines and associated new power lines of each potential WPP the TIMES-Norway can find the subset of WPPs that minimize the social costs of achieving the proposed production target. The estimates of environmental costs are transferred from relevant Norwegian studies of willingness to pay (WTP) to avoid or willingness to accept (WTA) compensation.

This paper contributes to the relatively limited literature analyzing potential spatial trade-offs between the economic and environmental aspects of siting WPPs, especially in combination with energy system modelling. Some studies have used multi-objective linear programming to minimize production costs or emission levels (Arnette and Zobel 2012) or various forms of multicriteria analysis (Sánchez-Lozano et al. 2014; Watson and Hudson 2015; Hanssen et al. 2018; Eichhorn et al. 2019).

The only economic studies we are aware of that attempt to monetize some aspects of environmental costs in spatial trade-off analyses of renewable energy production are Drechsler et al. (2011) for West Saxony in Germany and Drechsler et al. (2017) generalized for the whole of Germany. However, these studies included only a limited part of the environmental costs of wind power (local WTP to increase 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.

To our knowledge, this study is therefore the first to analyze 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 siting of WPPs in Norway by employing detailed information from the WPP licence applications. The environmental taxation scheme proposed 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.

We find that if introducing efficient taxation of environmental externalities, Norway could produce 20 TWh of new wind power at a 25 percent lower social cost per kWh compared with a scenario without taxing environmental externalities. The environmental costs decrease significantly, while we find a slight increase in production costs, as it is not exclusively the WPP projects with the lowest production costs that will be implemented. Another important finding is that if taxing only one type of externality, for example only turbines, this would significantly alter the allocation of wind power production across the country compared to the socially efficient allocation, considering externalities from both turbines and all power lines. Furthermore, if only taxing the environmental costs of new turbines and regional powerlines, and not the transmission lines, the social costs will be about the same as without taxation.

2. Analytical Model

Let $i = \{1,2,\ldots,J\}$ denote potential WPPs, where WPP_i is characterized by the geographical site (Municipality, M_i), number of wind turbines, (V_i), wind capacity factor, η_i , production costs, c_i , length K_i (km) of new regional power lines, and length T_i (km) of new transmission lines entailed by building WPP_i. For sites where the capacity of the existing transmission grid is sufficient to bring the new production into the wider power system, $T_i = 0$.

The wind capacity factor measures average, annual energy production per wind turbine $(\eta_i = q_i / year / V_i)$, where q_i (kWh) is the total production of WPP$_i$. The production cost c_i captures annual production costs and charges, as well as annualized investments costs for the wind turbines and grids per unit of annual production ($/kWh). We consider a competitive electricity market with profit-maximizing producers and utility-maximizing consumers where p_i ($/kWh) is the price of electricity (equal to the marginal utility of consumption) in the area where WPP$_i$ is established. In the absence of policy interventions, the annual profit from WPP$_i$, if implemented, is:

(1) $$\Pi_i^0 = (p_i - c_i)\cdot(V_i \cdot \eta_i).$$

Investment in renewable energy production has been stimulated by a variety of policy instruments, see Kitzing et al. (2012). The focus of this analysis is the spatial allocation of WPPs. We, therefore, assume that the regulator has a target for average annual wind energy production.[1]

We define an annual environmental cost function for WPP$_i$ where the environmental costs of wind power production are expressed by additive cost functions of *V*, *K*, and *T*:

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

where $\alpha_i(V_i)$, $\beta_i(K_i)$ and $\varphi_i(T_i)$ represents the environmental cost functions of the turbines, the new regional power lines and new transmission lines, respectively. If $T_i = 0$, then $\varphi(T_i) = 0$. We define the net social costs of WPP$_i$ as:

(3) $$\Omega_i = (c_i - p_i)\cdot(V_i \cdot \eta_i) + \left[\alpha_i(V_i) + \beta_i(K_i) + \varphi_i(T_i)\right].$$

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

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

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

[1] Marcantonini and Ellerman (2015) discuss the implicit carbon price of renewable energy.

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 (4), are implemented. Let $S \in J$ denote the subset of WPPs for which the target is met at lowest possible net social costs:

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

and that the total net social cost ($T\Omega_s$) of meeting the target at lowest possible cost is given by:

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

2.2 Profit Maximization with Subsidy, but without Environmental Taxes

Consider a private investor investing in profitable WPP projects. At the outset we assume that investors pay the full costs of new production, including the new regional power lines and the required investment in the transmission lines[2] (c_i). We assume that the government subsidizes private producers per unit energy produced by *R* to make sure the renewable target is met. *R* may take the form of a certificate price or feed-in premium.[3] If the producer faces no transfers or taxes other than *R*, the profit function is given by:

$$\Pi_i = (p_i - c_i + R) \cdot (V_i \cdot \eta_i). \quad (7)$$

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

$$Q_F = \sum_{f \in F} V_f \cdot \eta_f \quad . \quad (8)$$

As none of the environmental costs enter 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:

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

[3] *R* will be negative if wind energy production needs to be taxed so as not to exceed the national target.

(9) $$T\Omega_F = \sum_{f \in F} \Omega_f > T\Omega_S .$$

2.3. Environmental Tax Scheme

To achieve Q_s, the general production subsidy *R* must be complemented with environmental taxes. Note that the level of the general subsidy per unit kWh will have to be adjusted upwards to meet the 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.

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 can only be obtained if the investors internalize all the costs, including the environmental costs of WPP_i (see Eqn. (3)).

The environmental costs may differ substantially across WPPs, due not only to the differences in turbine numbers and the lengths of new power lines, but also to the evaluation of these externalities across WPPs. It is generally too costly a task to estimate the environmental cost of each WPP when all the characteristics of the sites are taken into account. We have made some simplifications in order to construct an operational tax scheme. The simplifications are discussed 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 expansions of the distribution and transmission grid (Navrud et al. 2008; Magnussen et al. 2009). It is well-documented in the economic literature that both use and non-use values will be reduced by environmental impacts from WPPs. 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. Garcia et al. 2016; Mattmann et al. 2016). We therefore assume that the environmental costs of WPPs for the national population as a whole (*N*) increase in *V*, *K*, and *T*. People living close to WPPs are typically more strongly affected (Meyerhoff et al. 2010; Jensen et al. 2013; Brennan and Van Rensburg 2016; Krekel and Zerrahn 2017) than the rest of the population. We let M_i^V, M_i^K and M_i^T denote the number of households living in the vicinity of turbines, regional power lines and transmission lines, respectively, in the local community where the potential WPP_i is sited.

Furthermore, we assume constant marginal environmental costs. Let a^M and a^N denote the environmental cost per household per turbine for the local population (*M*) and national population (*N*), respectively. b^M and b^N are the environmental costs per household per km distribution line for the local and national populations, respectively. The environmental costs per household per km transmission line for the local and national populations are denoted d^M and d^N, respectively. Hence, we define the terms in the environmental cost function in Eqn. (2) as:

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

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

Let $t_\alpha(M^V)$, $t_\beta(M^K)$ and $t_\varphi(M^T)$ denote the tax per turbine, per km regional power line and per km transmission line, as follows:

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

Given that our stylized model of environmental costs in Eqn. (10) captures the correct environmental costs, the taxes given by Eqn. (11) internalize 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.

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 Eqn. (11). The various scenarios are described in more detail in Section 4.

3. Numerical Methods

The numerical energy system model TIMES-Norway is used to illustrate the socially efficient siting of WPPs in Norway and the social costs of a potentially inefficient spatial distribution of wind power production, given a target of 20 TWh wind power production. Based on model simulations, the NVE's database of applications for WPPs, the values of the environmental costs of 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) and (10). One advantage of using an energy system model like TIMES-Norway to identify the socially efficient siting of new WPPs is the simultaneous optimization of sites for new power plants and necessary grid investment achieved by minimizing energy system costs, including the costs of necessary investment in the 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 price area to price area are captured. By considering various environmental taxation scenarios in the TIMES model, this study explores the implications of environmental taxes for the social costs of meeting a production target, and the subsequent spatial allocation of WPPs.

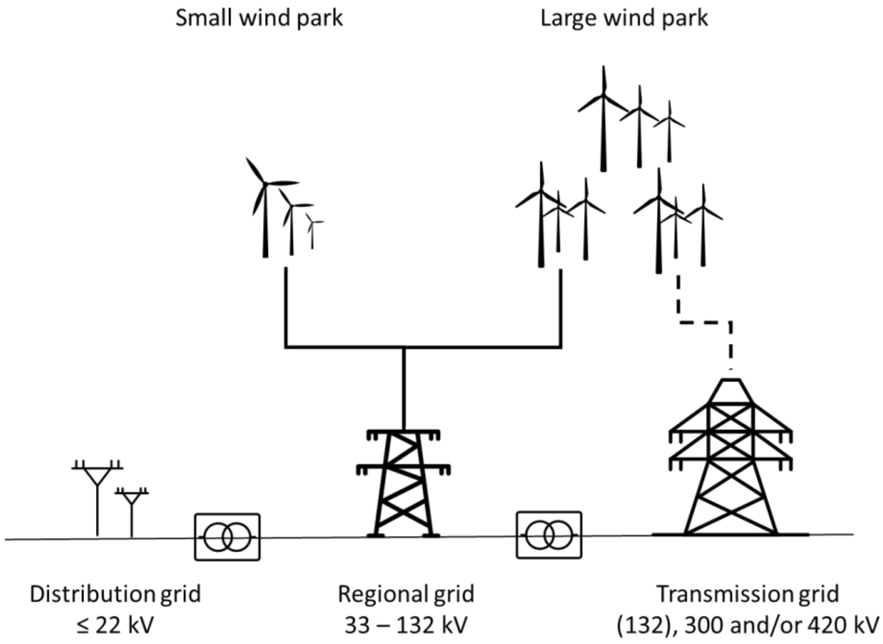
3.1. Numerical Model – TIMES

TIMES-Norway is a bottom-up optimization model of the Norwegian energy system. The model is generated by the TIMES modelling framework (see Loulou et al. 2008), which combines a technical engineering approach 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 minimize the total discounted cost of a given energy system to meet the demand for energy services for the model regions over the period analyzed.

A version of the TIMES model modified for Norway, TIMES-Norway (see Lind et al. 2013; Rosenberg et al. 2014; Seljom et al. 2020) uses various environmental cost estimates to analyze the efficient geographical siting 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 licenses for the production of wind power,[4] 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[5] 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. Figure 1 provides an illustration of the Norwegian electricity grid. As seen, the system is divided into three levels: the transmission grid, the regional grid and the distribution grid. 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).[6] A more thorough description of transmission grid modelling in TIMES-Norway is provided by Bjørnebye et al. (2018).

Figure 1. The Norwegian electricity grid



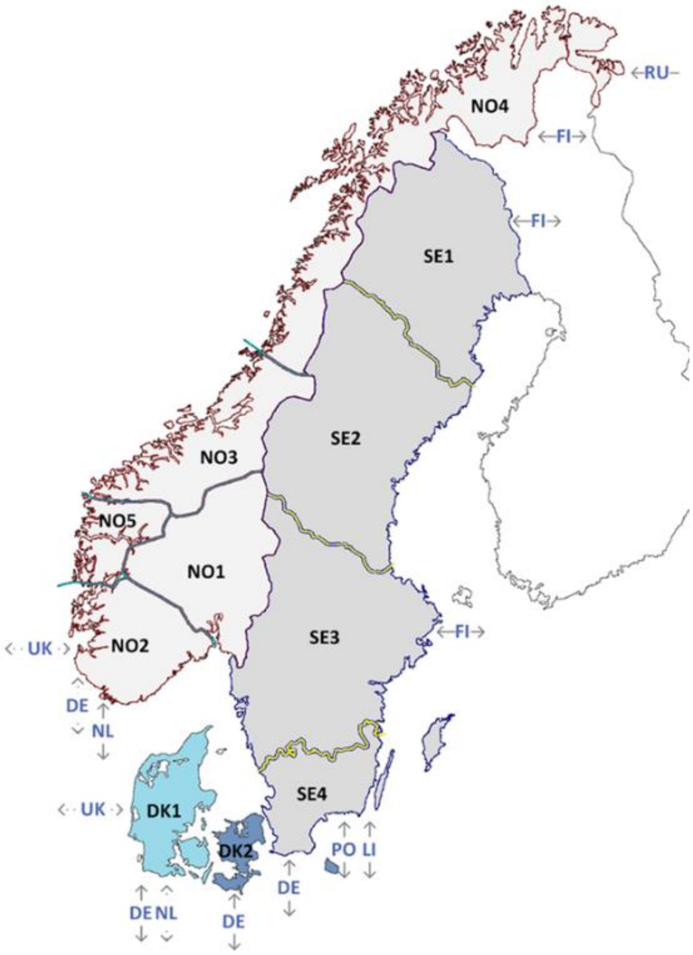
[4] Typical processes involved in granting wind power licenses include environmental impact assessments and may require mitigating measures, but do not involve any compensation scheme for environmental degradation (see e.g. Lindhjem et al. 2019).

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

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

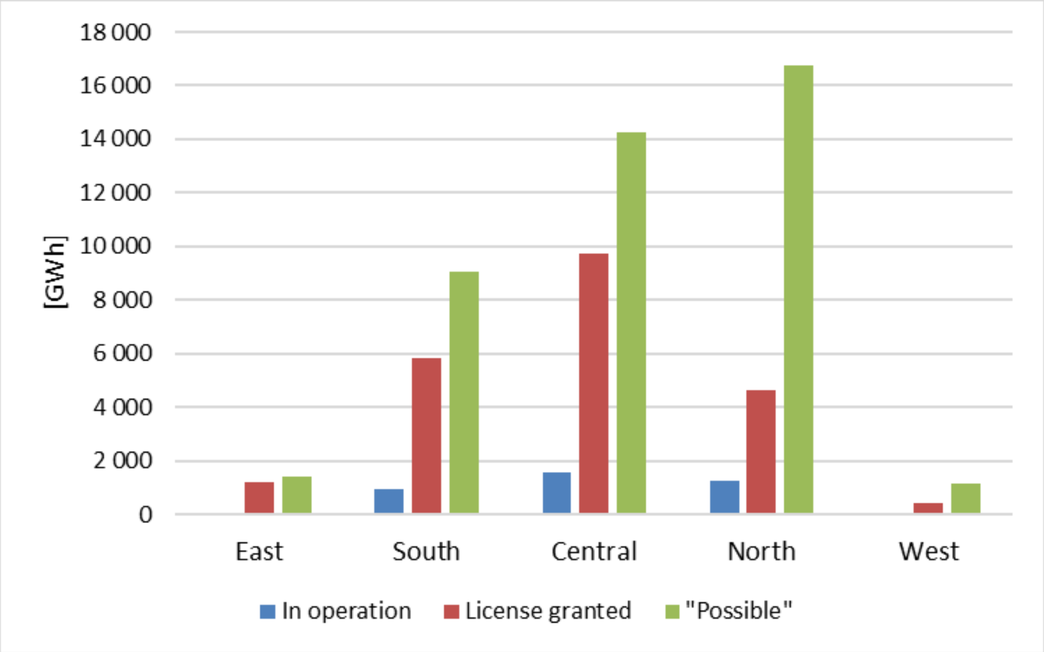
Spatially, the TIMES-Norway model covers the Norwegian land-based energy system, which is divided into five geographical regions corresponding to the current electricity spot market price areas (see Figure 2.). In the following, the regions depicted will be referred to as: "East" (NO1), "South" (NO2), "Central" (NO3), "North" (NO4) and "West" (NO5).

Figure 2. Price-areas in the electricity spot markets in Norway



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 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. Other data input include fuel prices, renewable resource potential and technology characteristics such as costs, efficiencies, lifetime and learning curves.

Figure 3. Wind power potential per region



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*", "*license granted*" and "*possible*", see Figure 3. *"Possible"* consists of WPPs that have either applied for a license, announced plans, or are the subject of public inquiries and appeals. Rejected license applications are therefore not a part of the "*possible*" category. The assumed 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 license before 2030, the analysis includes all WPPs in this category.

The data on the required new regional power lines for each of the potential new WPP is provided by the NVE application database (NVE 2018a). Data on the number of households in affected municipalities is obtained from population statistics. Table 1 sums up the average and median lengths of regional power lines in the application database and the populations of affected municipalities, across regions. The North is more sparsely populated but requires longer power lines than in the other price areas. Of the regions where most new WPPs are likely to be sited - the South, the Central and the North - the South is the most densely populated but would require shorter power lines.

Table 1. Length (km) of new regional power lines in WPP projects in the license 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	9 950	5 518	3 587	2 626	8 536	5 780
Median	3 502	2 279	1 789	1 038	2 124	2 119

As discussed in Section 2, new power production may trigger the need for new transmission lines. This 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 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 required, the lines may pass through several municipalities.[7] In that case, the average number of households in the municipalities that the power lines transect is used to calculate M_i^T. For the remainder of the national population it is assumed a (low) environmental cost per turbine and of transmission line length (km).

Even if the international literature quantifying and valuing environmental costs of WPP per household is quite extensive (e.g. Mattmann et al. 2016; Zerrahn 2017), it is not straightforward to synthesize or transfer such estimates to Norway due to different environmental conditions and the inherent uncertainty (errors) in such transfers (Lindhjem and Navrud 2009; 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

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

study has instead based the environmental cost estimates on available Norwegian studies. The values of the environmental costs per household used in the analysis are presented in Table 2.

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 local power lines for local population	15.42
b^N	$/km local 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 Jan. 01, 2020–Apr.28 2020, which was USD 1 = NOK 9.73

The source of the estimate of WTA of USD 15.42 (a^M) per household per year to avoid one additional wind turbine is the choice experiment (CE) study by Garcia et al. (2016). They investigate 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: 72 000)[8]. 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 to 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 on 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

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

conservative cost estimate of NOK 0.21 per household per avoided km of local grid is chosen, again based on Navrud et al. (2008).

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 natural areas (e.g. mountainous areas). We therefore chose an estimate of WTP equal to 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, it is assumed a WTP of USD 0.41 per household per year to avoid one km of high voltage power line (d^N). This estimate is chosen because it may be reasonable to assume that the relative difference in magnitude of 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 variation in unit costs (i.e. per household costs per turbine). We return to a discussion of these assumptions in the final section.

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* (*FB*). WPP investors incur the full social costs through the appropriate taxes as described in Eqn. (11). This scenario corresponds to the socially efficient outcome.
2. *Regional Power Lines & Turbines* (*RPL&TB*). WPP investors incur the environmental costs of the local distribution grid and turbines, $t_\alpha(M^V)$, $t_\beta(M^K)$, but not of regional transmission lines.
3. *Regional Power Lines* (*RPL*). WPP investors incur the environmental costs of local grids only, $t_\beta(M^K)$.
4. *Turbines* (*TB*). WPP investors incur the environmental costs of turbines only, $t_\alpha(M^V)$
5. *No Environmental Costs (NEC).* WPP investors assume no environmental costs.

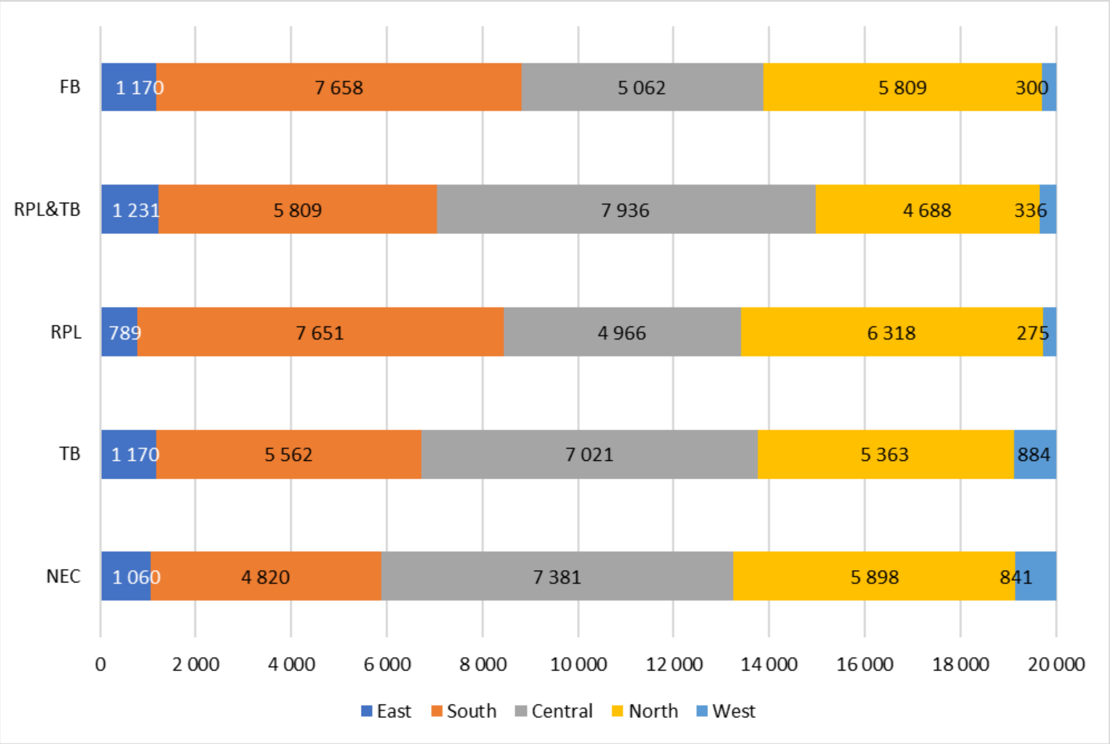
All scenarios assume that *R* is set such that total new wind power production will be identical (or close) to the political target of 20 TWh. As environmental taxes differ across the scenarios, the level of *R* will also have to differ across the scenarios to ensure the target is achieved. The scenarios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

5. Results

5.1. Base Case – Geographical Distribution

Figure 4 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 internalization of environmental costs.

Figure 4. Wind power production [GWh] by region for scenarios



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

Table 3. Number of distinct WPPs per scenario

	NEC	***TB***	***RPL***	***RPL&TB***	***FB***
Number of WPP's	67	61	70	58	70

The *NEC* scenario in Figure 4 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 to export the produced electricity out of the region. There is also a considerable production increase in South, which is closely connected to Europe through power cables.

In the *TB* scenario, where the environmental costs of the turbines are internalized, production drops slightly in Central, North and West, compared with the *NEC* scenario, directly reflecting the number of households in the affected communities in these regions. Production increases by almost 1 TWh in South for 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 results from the *TB* scenario confirm this.

In the *RPL* scenario, which includes the environmental costs of regional power lines, wind power production increases significantly in South and drops in Central, compared with the *NEC* scenario. The average length of new regional power lines is high for the latter region (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 the *NEC* scenario.

Including the environmental costs of only wind turbines yields a different spatial distribution of wind power production than including only the environmental costs of regional power lines. This can be seen by comparing the *TB* scenario with the *RPL* scenario as explained above: the increase in production in South for the *RPL* scenario 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 *RPL&TB* 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 not affected as much as the other four.

For the *FB* scenario, the analysis identifies the combination of new WPP sites and grid investment that minimizes social costs by minimizing the 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 reduction in Central is high environmental costs for the transmission grid in this region. The *FB* scenario is equivalent to including the environmental costs through the appropriate taxes, given by Eqn. (11) in the analytical model.

Figure 5 presents the maximum and minimum production following from the five scenarios across the three main regions for production. South is most affect by an implementation of an efficient taxing policy, compared with the present situation (*NEC* scenario). As seen, the *FB* scenario leads to maximum production for this region, almost 50 percent higher than the minimum production in the *NEC* scenario. This clearly demonstrates the need for an environmental taxation scheme to achieve an efficient spatial distribution of new wind power production.

Figure 5. Minimum and maximum production for each of the environmental cost scenarios

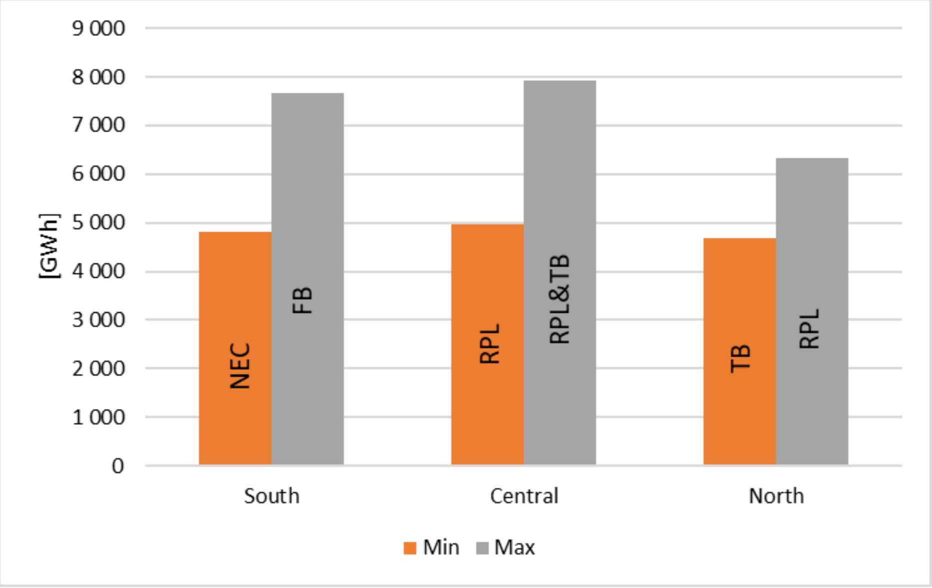


Figure 5 also shows that production in Central and North is strongly affected by the environmental taxation policy. The difference between minimum and maximum production in these regions is around 3 TWh for Central and 2 TWh for North. The *RPL* scenario leads to minimum production in Central and maximum production in North. The *RPL&TB* scenario places maximum production in Central. For North, minimum production occurs in the *TB* scenario.

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 the *NEC* scenario. Overall, the introduction of efficient, national taxation of WPPs reduces the net social costs of wind energy production by 25 percent.

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

	NEC	***TB***	***RPL***	***RPL&TB***	***FB***
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**

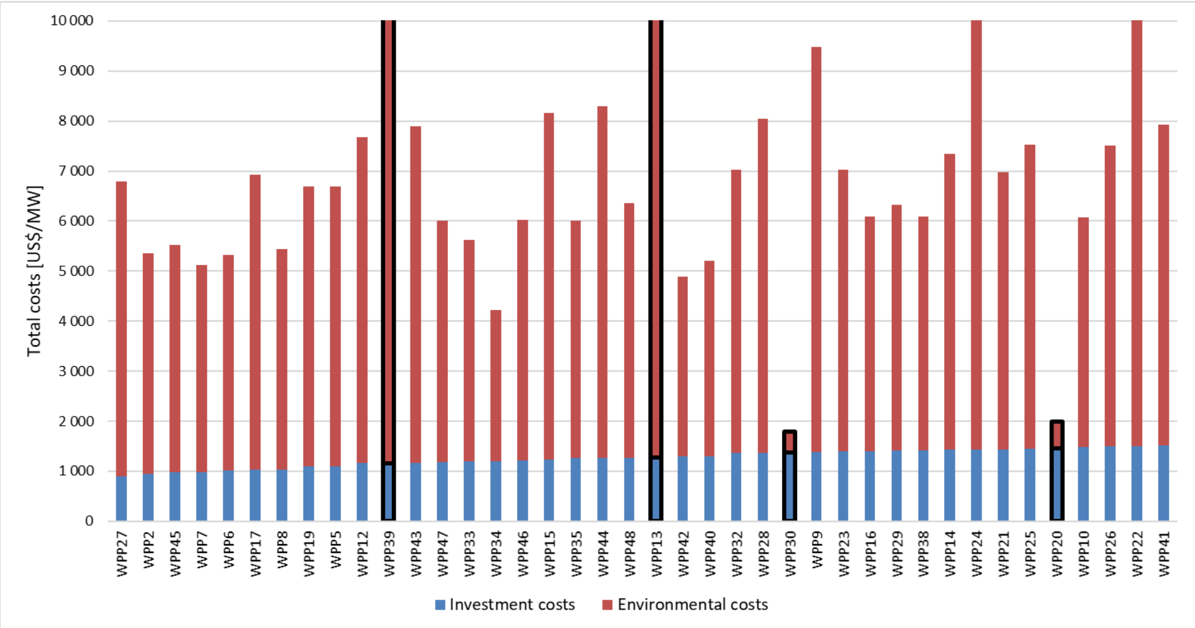
As seen, the differences in production costs across subsets of WPPs and price differences across price zones are of minor importance. What matters is the variation in environmental costs following from the diverse spatial allocations under the different scenarios. We also see that the environmental costs are (more than) twice the electricity prices in all scenarios. This means that that the environmental taxes must be accompanied by a large general production subsidy to make the investments privately profitable, see discussion of *R* in Section 2.3.

Figure 6 illustrates the effect of adding environmental costs to the various WPPs. The figure shows the selected WPPs for the *NEC* and *FB* scenarios for South, illustrating the total production costs (including environmental costs) per WPP for the two scenarios.[9] 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

[9] The total costs of WPP39, WPP13, WPP24 and WPP22, are 9023 $/MW, 11182 $/MW, 20068 $/MW and 19012 $/MW, respectively.

environmental costs excluded. The sum of the blue and red bars represents *FB*. A total of 40 different plants are installed in the two scenarios combined, with 25 WPPs in *NEC* and 34 WPPs in *FB*. WPP39 and WPP13, highlighted in the figure, are clearly among the 25 cheapest plants when the 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 *FB* solution. Similar figures as Figure 6 may be used for each model region and for each scenario to study the impacts of various model assumptions.

Figure 6. Total investment costs for turbines and grid. *NEC* (blue) and *FB* (blue + red) scenarios



As discussed in Section 2.2, the scenario in which all externalities are taken into account (*FB*) leads to lower net social costs than the scenario with no environmental taxes (*NEC*), see Eqn. (9). The numerical analyses show that efficient taxation (*FB* scenario) of the externalities implies that 20 TWh new wind power production in Norway can be achieved at a 25 percent lower net social costs per kWh compared with the *NEC* scenario; see Table 4. For the socially efficient siting of WPPs, the environmental costs are lower than in the *NEC* scenario, but the production cost is slightly higher. When it comes to partial implementation of taxes (*TB*, *RPL*, *RPL&TB*), the analytical model cannot generate any general results, except that the social costs of achieving the production target must be higher than under *FB*. The numerical analysis shows that if the environmental costs of new turbines and regional power lines only are taxed, and not the environmental costs of the transmission lines, the social costs are about the same as a no-taxation scenario. In the *RPL&TB* scenario there is less investment in regional power lines, but investment in the transmission grid is too high compared with the *FB* scenario.

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. Additionally, the cost per household for the rest of the Norwegian population of avoiding externalities from one additional turbine was increased to USD 0.41 (‘high’) per year.

Figure 7. Sensitivity analysis of *TB* and *RPL&TB* scenarios with high environmental costs per turbine

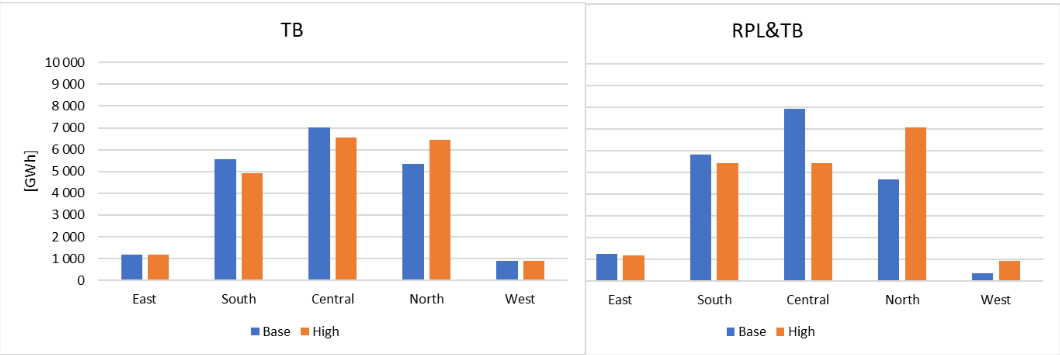
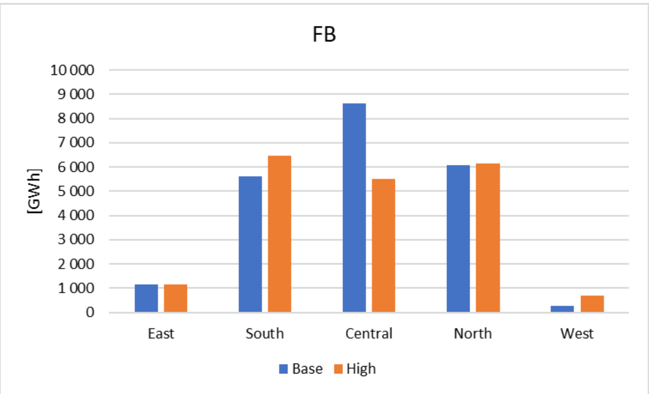


Figure 8. Sensitivity analysis of the *FB* scenario with high environmental costs per turbine



Sensitivity analyses were performed for three of the scenarios, and Figure 7 illustrates the results for the *TB* and *RPL&TB* scenarios. The results are compared to the base case results from Figure 4 (referred to as “Base” in Figure 7). As seen, a higher environmental cost per turbine leads to lower electricity production in South and Central, especially for the *RPL&TB* scenario. Production also increases significantly in North, with an increase of over 2 TWh in the *RPL&TB* scenario. In both cases, production becomes highest in region North.

Figure 8 illustrates changes to the *FB* 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.

6. Conclusion, Discussion, and Policy Implications

This study analyzed 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 a simple site-specific environmental taxation scheme, where each of the externalities (turbines, regional power lines and transmission lines) is taxed in proportion to the number of affected people. 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.

In order to produce wind energy in Norway, investors in WPPs must be granted a production license by the authorities (NVE). The goal of NVE's processing of license 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 siting is assessed as "too harmful" for the environment, the license is not granted. However, once a license 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 WPP applications. The environmental taxation scheme proposed in this paper is a remedy for this inefficiency.

The environmental cost framework that this study adds to the TIMES model is admittedly simple and does, for example, not take account of the fact that the marginal local (and national) environmental cost of wind turbines may decrease for some people at a given WPP site. However, a more standard assumption in environmental economics is an increasing marginal environmental damage costs curve.[10] In the absence of clear evidence from the literature and local studies in this respect, this paper

[10] Note also that the more recently planned wind turbines are taller than the older ones. We do not differentiate between them. 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.

uses a linear function. Further, since there is no firm evidence on 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 based on factors such as landscape aesthetics, biological features and other qualities of different sites (Zerrahn 2017; Price 2017; Hedblom et al. 2020). Even so, the unit cost estimates are less important for the total environmental costs estimates than the number of people assumed to be affected, so this may not seriously affect 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 4km radius (Krekel and Zerrahn 2017). However, such effects depend very much on visibility distance and are not easy to generalize. The more general literature on non-market valuation using stated preference methods is not clear on how use values, and especially non-use values, vary with geographical distance from an environmental impact (so called "distance decay") (Glenk et al. 2019). One must often resort to defining the affected people ("extent of the market") with the aid of administrative boundaries, e.g. municipality boundaries, as done in this study (Johnston et al. 2017). 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. The above 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). Although, as noted above, it is difficult to compare environmental cost estimates across countries, our estimates per turbine do not seem to be unrealistically high. For example, Krekel and Zerrahn (2017), using real data on wind power sites, combined with a 12- year time series of life satisfaction data and household income, find an annual environmental cost of roughly USD 300 per household per turbine as a permanent disamenity for households within a 4 km radius of a wind turbine. An additional hedonic analysis confirms the level of this valuation. This estimate per household per turbine in the very local area around a WPP plant is more than 10 times higher than our estimate for people in a municipality where a WPP is located. The estimates used in this study also seem conservative but are comparable to ongoing research work in Norway on quantifying the environmental costs of wind power more precisely. A pilot choice experiment study in two regions of WTA compensation for a national plan for increasing wind power production in Norway shows preliminary annual environmental cost estimates in the range of USD 0.38-0.56 per household per turbine, or NOK 0.12-0.17 per kWh (Lindhjem et al. 2019; Dugstad et al.

2020). These estimates are comparable to the estimate per turbine use in this study for a national population.

One of the conclusions in Drechsler et al. (2017) was that a socially efficient allocation of WPP in Germany for the most part matched the most favorable wind locations. Thus, the considerable external effects did not alter the socially efficient solution. This is in contrast to our study which finds that the socially efficient allocation of wind power production across regions (*FB* scenario) differs substantially from the cost-minimizing 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), have included the environmental costs of the transmission lines. As Table 5 shows, it is only in the scenario that includes all environmental costs (*FB* 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 that have already been applied for. Hence, all the potential WPPs in our study are likely to have good wind conditions. What distinguishes them is the environmental costs.

In addition to working towards a 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, as well as 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 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 investigated here, more research is clearly required to better understand factors that limit policy acceptability, for example social equity concerns that may be particularly important for siting renewable energy installations (Grimsrud et al. 2019; Lehman et al. 2020).

References:

Arnette, Andrew, and Christopher W. Zobel. (2012). "An optimization model for regional renewable energy development." *Renewable and Sustainable Energy Reviews* 16(7): 4606-4615.

Bjørnebye Henrik, Cathrine Hagem, and Arne Lind. (2018) "Optimal location of renewable power" *Energy* 147: 1203 – 1215.

Bonou, Alexandra, Alexis Laurent, and Stig I. Olsen. (2016). "Life cycle assessment of onshore and offshore wind energy-from theory to application." *Applied Energy* 180: 327-337.

Brennan, Noreen, and Thomas M. Van Rensburg. (2016). "Wind farm externalities and public preferences for community consultation in Ireland: A discrete choice experiments approach." *Energy Policy* 94: 355-365.

Brinkley, Catherine, and Andrew Leach. (2019). "Energy next door: A meta-analysis of energy infrastructure impact on housing value." *Energy Research & Social Science* 50: 51-65.

Devine-Wright, Patrick. (2005). "Beyond NIMBYism: towards an integrated framework for understanding public perceptions of wind energy." *Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology* 8(2): 125-139.

Drechsler, Martin, Cornelia Ohl, Jürgen Meyerhoff, Marcus Eichhorn, Jan Monsees. (2011) "Combining spatial modeling and choice experiments for the optimal spatial allocation of wind Turbines." *Energy Policy* 39(6): 3845-3854.

Drechsler, Martin, Jonas Egerer, Martin Lange, Frank Masurowski, Jürgen Meyerhoff, Malte Oehlmann. (2017). Efficient and equitable spatial allocation of renewable power plants at the country scale. *Nature Energy, 2*(9) article number 17124.

Dugstad, Anders, Kristine Grimsrud, Gorm Kipperberg, Henrik Lindhjem, Ståle Navrud. (2020). "Acceptance of national wind power development and exposure: A case-control choice experiment approach". Statistics Norway Discussion Paper no. 933.

Eichhorn, Marcus, Frank Masurowski, Raik Becker, and Daniela Thrän. (2019). "Wind energy expansion scenarios–A spatial sustainability assessment." *Energy* 180: 367-375.

García, Jorge H., Todd L. Cherry, Steffen Kallbekken, and Asbjørn Torvanger. (2016). "Willingness to accept local wind energy development: Does the compensation mechanism matter?" *Energy Policy* 99 (2016): 165-173.

Giaccaria, Sergio, Vito Frontuto, and Silvana Dalmazzone. (2016). "Valuing externalities from energy infrastructures through stated preferences: a geographically stratified sampling approach." *Applied Economics* 48(56): 5497-5512.

Glenk, Klaus, Robert J. Johnston, Jürgen Meyerhoff, and Julian Sagebiel. (2020). "Spatial dimensions of stated preference valuation in environmental and resource economics: methods, trends and challenges." *Environmental and Resource Economics* 75 (2): 215-242.

Grimsrud, Kristine M., Henrik Lindhjem, Ingvild Vestre Sem, and Knut Einar Rosendahl. (2019). "Public acceptance and willingness to pay cost-effective taxes on red meat and city traffic in Norway." *Journal of Environmental Economics and Policy* 1-18.

Hanssen, Frank, Roel May, Jiska van Dijk, and Jan Ketil Rød. (2018). "Spatial Multi-Criteria Decision Analysis Tool Suite for Consensus-Based Siting of Renewable Energy Structures." *Journal of Environmental Assessment Policy and Management* 20(3): 1840003.

Hedblom, Marcus, Henrik Hedenås, M. Blicharska, S. Adler, Igor Knez, G. Mikusiński, J. Svensson, S. Sandström, P. Sandström, and D. A. Wardle. (2020). "Landscape perception: linking physical monitoring data to perceived landscape properties." *Landscape research* 45(2): 179-192.

IEA (2019). World Energy Outlook 2019. Flagship report - November 2019. International Energy Agency.

Jensen, Cathrine Ulla, Toke Emil Panduro, and Thomas Hedemark Lundhede. (2014). "The vindication of Don Quixote: The impact of noise and visual pollution from wind Turbines." *Land Economics* 90(4): 668-682.

Johnston, Robert J., John Rolfe, Randall S. Rosenberger, and Roy Brouwer. (2015). *Benefit transfer of environmental and resource values*. Vol. 14. New York: Springer.

Johnston, Robert J., Kevin J. Boyle, Wiktor Adamowicz, Jeff Bennett, Roy Brouwer, Trudy Ann Cameron, W. Michael Hanemann et al. (2017). "Contemporary guidance for stated preference studies." *Journal of the Association of Environmental and Resource Economists* 4(2): 319-405.

Kitzing, Lena, Catherine Mitchell, and Poul Erik Morthorst. (2012). "Renewable energy policies in Europe: Converging or diverging?" *Energy policy* 51: 192-201.

Krekel, Christian, and Alexander Zerrahn. (2017). "Does the presence of wind turbines have negative externalities for people in their surroundings? Evidence from well-being data." *Journal of Environmental Economics and Management* 82: 221-238.

Lind, Arne, Eva Rosenberg, Pernille Seljom, Kari Espegren, Audun Fidje, and Karen Lindberg. (2013). "Analysis of the EU renewable energy directive by a techno-economic optimisation model." *Energy Policy* 60: 364-377.

Ladenburg, Jacob, Pablo Hevia-Koch, Stefan Petrović, and Lauren Knapp. (2020). "The offshore-onshore conundrum: Preferences for wind energy considering spatial data in Denmark." *Renewable and Sustainable Energy Reviews* 121: 109711.

Lehmann, Paul, Kathrin Ammermann, Erik Gawel, Charlotte Geiger, Jennifer Hauck, Jörg Heilmann, Jan-Niklas Meier et al. (2020). *Managing spatial sustainability trade-offs: The case of wind power*. No. 4/2020. UFZ Discussion Papers.

Lindhjem, Henrik, Anders Dugstad, Kristine Grimsrud, Øyvind N. Handberg, Gorm Kipperberg, Eirik Kløw, and Ståle Navrud (2019). Wind power against the wind – The environmental costs should not be ignored" (In Norwegian: Vindkraft i motvind – Miljøkostnadene er ikke til å blåse av). Aktuell kommentar. *Samfunnsøkonomen* 4: 6-17.

Lindhjem, Henrik, Ståle Navrud, Kristin Magnussen, Nina B. Westberg, Ingeborg Rasmussen, Frank Hanssen, and Jiska van Dijk. (2018). Investments in the electricity grid network and impacts on ecosystem services in cost benefit analysis (In Norwegian, «Tiltak i strømnettet og påvirkning på økosystemtjenester i samfunnsøkonomiske analyser»). Vista Analyse and Menon Economics report.

Lindhjem, Henrik, and Ståle Navrud. (2008). How Reliable are Meta-Analyses for International Benefit Transfers? *Ecological Economics* 66(2-3): 425-435.

Loulou, Richard, and Maryse Labriet. (2008). "ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure." *Computational Management Science* 5 (1-2): 7-40.

Loulou, Richard. (2008). "ETSAP-TIAM: the TIMES integrated assessment model. part II: mathematical formulation." *Computational Management Science* 5(1-2): 41-66.

Marcantonini, Claudio, and A. Denny Ellerman. (2015). "The implicit carbon price of renewable energy incentives in Germany." *The Energy Journal* 36 (4).

Magnussen, Kristin, and Ståle Navrud. (2009). Verdsetting av estetiske konsekvenser ved nettinvesteringer. [in Norwegian]. Sweco-rapport 141341-101-A01 (04.02.2009), 106 s.

Mattmann, Matteo, Ivana Logar, and Roy Brouwer. (2016). "Wind power externalities: A meta-analysis." *Ecological Economics* 127: 23-36.

Meyerhoff, Jürgen, Cornelia Ohl, and Volkmar Hartje. (2010). "Landscape externalities from onshore wind power." *Energy Policy* 38(1): 82-92.

Mirasgedis, S., C. Tourkolias, E. Tzovla, and D. Diakoulaki. (2014). "Valuing the visual impact of wind farms: An application in South Evia, Greece." *Renewable and Sustainable Energy Reviews* 39: 296-311.

Navrud, Ståle. (2005). Miljøkostnader av vindkraft i Norge. [in Norwegian]. Notat. Institutt for Økonomi og ressursforvaltning, Universitetet for Miljø og Biovitenskap (UMB). Notat Sept. 2004. Revidert Aug. 2005.

Navrud, Ståle, Richard C. Ready, Kristin Magnussen, and Olvar Bergland. (2008). "Valuing the social benefits of avoiding landscape degradation from overhead power transmission lines: Do underground cables pass the benefit–cost test?" *Landscape research* 33(3): 281-296.

NVE (2018a). Licensing [in Norwegian], https://www.nve.no/konsesjonssaker.

NVE (2018b). Oppsummeringsrapport: Forslag til endringer i forskrift om kontroll av nettvirksomhet. Forslag til endringer i regelverket om anleggsbidrag. NVE Rapport 67/2018.

NVE (2019). Forslag til nasjonal ramme for vindkraft. [in Norwegian] Rapport 12/2019

Price, Colin. *Landscape economics*. Springer, 2017.

Rosenberg, Eva, Arne Lind, and Kari A. Espegren (2013). "The impact of future energy demand on renewable energy production–Case of Norway." *Energy* 61: 419-431.

Rosenberg, Eva, and Arne Lind. (2014). "TIMES-Norway - Oppdateringer 2013/2014". Institute for Energy Technology.

Saidur, Rahman, N. A. Rahim, M. R. Islam, and K. H. Solangi (2011). "Environmental impact of wind energy." *Renewable and sustainable energy reviews* 15(5): 2423-2430.

Sánchez-Lozano, Juan Miguel, M. S. García-Cascales, and M. T. Lamata (2014). "Identification and selection of potential sites for onshore wind farms development in Region of Murcia, Spain." *Energy* 73: 311-324.

Seljom, Pernille, Eva Rosenberg, Linn E. Schäffer, Marte Fodstad (2020) "Bidirectional linkage between a long-term energy system and a short-term power market model" *Energy* 198: 117311.

Turvey, Ralph. (2006). "Short & long run transmission incentives for generation location." MIT-CEEPR (Series) 06-004WP. MIT Center for Energy and Environmental Policy Research.

Van Rensburg, Thomas M., Hugh Kelley, and Nadine Jeserich. (2015). "What influences the probability of wind farm planning approval: Evidence from Ireland." *Ecological Economics* 111: 12-22.

Wagner, Johannes. (2019). "Grid investment and support schemes for renewable electricity generation." *The Energy Journal* 40(2): 195-220.

Watson, Joss JW, and Malcolm D. Hudson. (2015). "Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation." *Landscape and Urban Planning* 138: 20-31.

Zerrahn, Alexander. (2017). "Wind power and externalities." *Ecological Economics* 141: 245-260.