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Internalizing negative environmental impacts from wind power production: Coasian bargaining, offsetting schemes and environmental taxes

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Abstract:
On the one hand, wind power production is necessary for decarbonizing the electricity sector. On the other hand, we risk replacing one environmental problem with other environmental problems, that is, stopping climate change in exchange with increased loss of pristine land and biodiversity. The present paper provides a novel contribution to the literature on how to regulate the development of wind power plants (WPPs). Current regulation is largely based on a concession system, where both environmental taxes and offset schemes are left unexplored. We develop a theoretical model of WPP development with offsets and environmental taxes. We show that if additional loss of pristine nature and biodiversity is acceptable at some monetary price, establishing an offset market for WPP development and combining it with an environmental tax will be socially desirable. In fact, this solution is preferable to both only having an environmental tax or only having a compulsory offset market. However, if no more loss of pristine land and biodiversity can be tolerated, compulsory and complete offsetting should be the norm. We look at two restoration projects in Norway and evaluate to what extent they could have been used as offsets for a recent WPP development in Norway. We conclude that they can, but an offset scheme demands good measurement methods and regulations to ensure equivalence in the values of ecosystem services lost and gained

Keywords: Wind power, Offsetting schemes, Environmental taxes, Resource Equivalency Analysis, Habitat Equivalency Analysis.

JEL classification: D62, Q24, Q26, Q42, Q48, Q51, Q56, Q57,Q58

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Sammendrag

På den ene siden er vindkraftproduksjon nødvendig for å nå målene om et lavutslippssamfunn. På den andre side risikerer vi å erstatte ett miljøproblem med et annet: Vi reduserer utslipp av klimagasser, men øker tapet av uberørt natur og naturmangfold. Denne studien bidrar til litteraturen om hvordan man kan regulere fremveksten av vindkraftverk for å ta hensyn til andre miljøeffekter enn klimagassutslipp. Dagens regulering er i hovedsak basert på et konsesjonssystem, der det ikke er påkrevd verken naturavgift eller at utbygger skal kompensere for naturødeleggelsen gjennom restaurering av andre ødelagte naturområder («offsets»). Vi presenterer en analytisk modell for vindkraftutvikling hvor vi inkluderer både miljøavgift og offsets. Der viser vi at det er samfunnsøkonomisk lønnsomt å kombinere en naturavgift med et system for offsets, så lenge det er akseptabelt å måle naturødeleggelser i penger. En slik kombinasjon av virkemidler vil være å foretrekke fremfor å kreve at alle investeringer i vindkraft skulle kompenseres gjennom offsets. Dersom det derimot ikke akseptabelt med noe mere (netto) tap av naturmangfold og uberørt natur, bør alle nye inngrep i naturen kompenseres gjennom offsets. Vi ser på to restaureringsprosjekter i Norge og vurderer hvorvidt de kunne ha vært brukt som restaureringsprosjekter for et vindkraftverk som nylig har blitt bygget. Vi konkluderer med at det kan de, men et offset-system krever gode målemetoder og reguleringer for å sikre at naturmangfoldet som går tapt blir tilstrekkelig kompensert.

1. Introduction

Wind power production is likely to play an important part in the decarbonization of the electricity sector and thus contribute to combatting global warming (IEA 2021). However, there are also environmental concerns associated with wind power plants (WPPs), such as noise, impaired landscape aesthetics, loss of biodiversity, and wildlife impacts (see e.g., reviews by Saidur et al. 2011; Mattmann et al. 2016; Zerrahn 2017). There is thus a growing opposition to large-scale, land-based wind energy developments in many countries (Ladenburg et al., 2020). Monetary compensation to the affected local communities has been suggested as means to ease the opposition to WPPs. As suggested in Coase (1960), it might be possible for the WPP developer and the local municipality to reach a mutually beneficial agreement. In Norway there are already one example of Coasian bargaining between a municipality and a WPP developer which resulted in compensation being paid to the municipality as a fixed yearly monetary transfer over the lifetime of the WPP.[1] Furthermore, a system for special taxes on WPPs, where the revenues accrue to the municipalities hosting the WPPs, was implemented 2022.[2] The tax was set to € 0.001 per kWh, and later increased to € 0.002 per kWh.

Local compensation does not, however, internalize the national environmental costs connected to WPP development. Among the most important national environmental problems is the loss of untouched nature. For many people, untouched nature has an intrinsic value, even though they may not intend to spend time in the areas, so called non-use values. Furthermore, the loss of untouched nature is also often accompanied with a decline in biodiversity. According to economic theory, unless all the negative environmental impacts of WPPs are properly priced, we may observe excessive environmental degradation from WPPs.

Until the special tax was introduced in 2022 (see above), the Norwegian government had not chosen to tax neither the local nor the national environmental externalities from WPPs. Instead, the government has managed the development of WPPs by a concession system, which still applies. For every WPP project the Norwegian Water Resources and Energy Directorate (NVE)

[1] See https://www.nationen.no/motkultur/kronikk/det-store-kraftranet/ (in Norwegian).

[2] Prop. 1 LS (2021–2022) For budsjettåret 2022 — Skatter, avgifter og toll 2022, 7.2 https://www.regjeringen.no/no/dokumenter/prop.-1-ls-20212022/id2875345/ (in Norwegian). https://www.regjeringen.no/no/aktuelt/avgift-pa-landbasert-vindkraft/id2919971/

weights the environmental costs of the WPP against the expected profitability of the WPP, but without assigning pecuniary values to the environmental costs. Only projects with a perceived positive benefit-cost calculus will go through.

The task of setting the right price on the environmental degradation from WPPs is obviously difficult. It is therefore not surprising that the Norwegian regulator NVE has not used such prices. Moreover, some will argue that environmental degradation cannot and should not be priced at all (Muradian and Gomez-Baggethun, 2021). Grimsrud et al. (2022) consider a system for spatial allocation of WPPs where development of areas of specifically high scores on biodiversity and wilderness indicators are ruled out. Another approach to address the negative environmental impacts of WPPs is for the government to demand environmental restoration of formerly degraded natural landscapes and habitats to compensate for the adverse impact of WPPs, so called offsets. This is widely used in many countries in connection with degrading of wetland as results of for example road construction or housing development, see for instance Vaissiére and Levrel (2015).

In this paper, we pose the following three research questions: I) Should governments introduce offsetting schemes for WPPs? II) Should complete offsetting be compulsory, or should offsetting be voluntary and used together with environmental taxes and/or concession system? And how could an offset-scheme be designed, and is it practically feasible?

To answer the first two research questions, we develop a theoretical model of WPP development, which we use to compare a concession system with offsets and emission taxes. Our main finding is that if the regulator can put a price on the environmental degradation from WPPs plants, complete offsetting should not be compulsory, but used together with environmental taxes. However, if no more loss of pristine land and biodiversity can be tolerated, compulsory and complete offsetting should be the norm. To answer the third question, we look at two restoration projects in Norway and evaluate to what extent they could have been used as offsets for a recent WPP development in Norway. Furthermore, we propose a metric for comparing the environmental loss from the WPP in question with the environmental gain from the chosen offset projects. We conclude that restoration projects could offset the nationwide negative environmental effects of WPPs along some dimensions, but not all. Moreover, offsetting the local environmental cost may not be possible.

As far as we know, the present paper is the first paper to model and discuss offset markets used in connection with WPP developments. One premise of the paper is that the environmental externalities from WPPs can be divided into local environmental effects and national environmental effects. On the one hand, people living close to WPPs are typically more strongly affected than the rest of the population, see Meyerhoff et al. (2010), Jensen et al. (2013), Brennan and Van Rensburg (2016) and Krekel and Zerrahn (2017). The reason being that adjacent households face daily noise pollution, and deterioration of local recreational areas and the visual aesthetics of the local landscape. On the other hand, there will be both use and non-use values of the nature affected by a WPP, see e.g., Garcia et al. (2016) and Mattmann et al. (2016). For instance, to the extent that a WPP reduces biodiversity, degrades areas of pristine nature and/or cultural heritage sites, there are clearly national negative environmental externalities of a WPP, see Navrud (2005) and Navrud et al. (2008). It is the national effects that in our opinion have the largest potential to be offset. We will return to a more elaborate discussion of the environmental effects of WPPs in the next section.

Our literature review of the environmental costs of WPPs shows that it is very difficult to put a common price on the environmental damages from WPP development. Local effects will obviously vary from location to location. Grimsrud et al. (2021) suggest site-specific taxes as functions of inter alia the number of people living near the installations. National environmental externalities, such as biodiversity loss is inherently difficult to put a price on (Bateman et al., 2013). Thus, we propose a solution in which the local environmental effects are internalized in Coasian bargaining between the municipalities and the WPP developers. This implies that the affected municipalities must have a veto right towards the WPP developers. We discuss the weaknesses of this assumption in the concluding remarks. For the national environmental effects, there are advantages of having a nationally set common environmental tax based on the area demand of the WPP, as this will ensure that only the WPP locations with the highest net benefits will be developed. Clearly, it is difficult to set the size of this tax, and a reverse process may be the only option. That is, the parliament sets an upper limit of WPP development nationally, and the proper tax ensures that this upper limit is not breached.

The rest of the paper is laid out as follows. In the next section, we look at the literature on regulating WPP development. This section will cover both the environmental effects of WPPs and the efforts to put a price on WPP development. Section 3 then presents the theoretical model and draws some general conclusions. In Section 4, we present the metrics to compare the environmental cost of WPPs with the environmental gains from restoration projects. In section 5, we introduce our two case restoration projects, and a recently built WPP. Section 6 compares the cost of offsets with estimated environmental costs from stated preference studies. Finally, Section 6 concludes and discusses some weaknesses.

2. Instruments for regulating the development of wind power plants

2.1. Concession system

This is the system used in Norway. To develop a WPP, the firm must be granted a production license by the authorities. The Norwegian Water Resources and Energy Directorate (NVE) is responsible for processing license applications. All applications for licenses must come with a sufficient description of the projects impact on the environment. This is often done through an environmental impact assessment conducted by private consultants. The impacts are graded both by the license applicants (private consultants) and (partly) by public administrative agencies, like the Norwegian Environment Agency.

There are five main non-monetary environmental impacts assessed by NVE:

i. *Landscape:* The visuality of the turbines and the impact of the esthetical value of the land-scape
ii. *Culture environment*: The impact on buildings and construction of cultural importance (cul-tural heritage).
iii. *Natural environment*: Impacts on biodiversity, habitats, animal life, endangered species, and the consequences for “areas without major infrastructure development” and protected ar-eas.
iv. *Reindeer husbandry*: Degree of conflicts between WPPs and reindeer husbandry. Note that reindeer husbandry is seen as culturally essential for the laps which is an indigenous people in Norway with special protection in the constitution and international law.

v. *Outdoor life*: Conflict between the use of land for wind power production and recreational purposes: hiking, fishing, hunting etc.

All categories i. to v. can be characterized as ecosystem services. Most categories, e.g., i., ii. & v., fall in under the heading *cultural/recreational services*, while category iii. is partly a *supporting service* and category iv. is partly a *provisioning service*.

The literature concludes that negative visual impacts on the landscape are found to be a central externality of WPPs, and a main trigger of opposition to WPPs, see, e.g., Mattmann et al. (2016) and Zerrahn (2017). Moreover, in empirical study of the Norwegian concession process, Grimsrud et al. (2020) find that a high degree of harmfulness on *Natural environment*, *Outdoor life* and *Reindeer husbandry* reduced the likelihood of a successful license application.

In Norway, once a license is granted, there is no environmental taxation of the externalities, except from the modest tax of € 0.002 per kWh produced. [3, 4]

2.2. Environmental taxes

Environmental taxes levied on firms being responsible for WPP developments may serve at least three purposes. First, they should limit the total number of WPPs within a country to avoid excessive biodiversity loss and degradation of un-spoilt nature and/or cultural heritage sites on a country level. Second, the environmental tax should ensure that exactly the WPPs with the highest net benefits are built where we by net benefits imply economic profits subtracted environmental costs. As elaborated on in the next section, a tax on WPPs could accomplish these two purposes. Finally, an environmental tax could have a local component ensuring that the size and architecture of the WPP at a given location balances economic efficiency and environmental impact. We will not venture into the third purpose in this paper but assume that this issue can be sorted out by Coasian bargaining between the local authorities and the WPP developer.

The major challenge for the government with respect to the first two purposes is to put a monetary value on the five categories of damages listed above. Several techniques can be

[3] Most recently, the Government has proposed to introduce a resource rent tax on wind power production.
[4] The investors may be required to implement mitigation measures within the area they develop.

applied to determine the monetary value of these damages. With respect to WPP development, the methods must be based on non-market evaluations such as revealed preferences and stated preferences, including various types of survey techniques, see Champ et at. (2017). The revealed preference method may use property values or the travel cost method, while the stated preference method uses data generated from surveys eliciting people's contingent preferences in constructed (hypothetical) market scenarios (Kling et al., 2012; Haab et al., 2012; Mariel et al., 2021). There are several challenges of using these methods, and it has been argued that environmental degradation cannot be measured in monetary terms and substituted by man-made capital (Edwards-Jones et al. 2009; Hanley and Barbier, 2009).

There are several studies trying to estimate the willingness to pay (WTP) to avoid negative impacts on ecosystem services from WPPs. These generally find that both use- and non-use values will be reduced by the environmental impacts from WPPs, see for instance Dugstad et al. (2020). Hence, a significant number of people outside the local area of the WPP will experience welfare effects even if they do not visit or use these areas. As we already have argued, this implies that wind power expansion should be considered on a national scale. We find two papers that address this issue for Norway; Navrud (2005), and Lindhjem et al. (2022).

Navrud (2005) estimates WTP to avoid environmental externalities from a wind power expansion of 6.7 TWh. He finds a mean WTP of € 140 (2021 prices) per household per year.[5] As the number of households has increased by 30 percent since then, this translates into € 0.05 per kWh.

Lindhjem et al. (2022) conducted a national choice experiment study of willingness to pay to avoid new turbines on land in Norway. Both positive (lower GHG-emissions, increased employment, value added) and negative impacts (loss of biodiversity, impaired landscape aesthetic, noise etc.) of wind power development were emphasised. Although there was a preference for new renewable energy, the net impact on welfare of wind power on land was negative. The WTP to avoid 700 wind turbines was on average € 192. A doubling and tripling of the number of avoided turbines increased the WTP estimate to € 333 and € 408, respectively. This indicates diminishing marginal utility loss of additional turbines (see a discussion on scope

[5] We have set 1 euro equal to 10 Norwegian kroner.

elasticities in Dugstad et al., 2021). On a national scale we would generally conjecture that the marginal utility loss was increasing. That is, the less pristine nature you have left, the higher payment would you demand before accepting additional loss of pristine nature, see for instance NVE (2017). This suggests that the respondents in Lindhjem et al. (2022) may have had local effects in mind, e.g., if a local area is destroyed by a few turbines, it does not matter if you add more turbines as the area is lost anyway. On average, the WTP per household per avoided turbine per year was € 0.24, corresponding to € 0.042 per kWh (assuming an annual average production of 14 GWh per turbine).

Both for Navrud (2005) and Lindhjem (2022), it is hard to split the figures into a local and a national environmental cost. Moreover, it is up to discussion whether it is possible to evaluate such complicated environmental damages as biodiversity loss by stated preference methods.

2.3. Offset schemes

Offsets is a way to compensate for the negative impacts on the environment. The basic idea is that the loss of ecosystem services at one place can be compensated by increased ecosystem services at another place. Offsets is extensively used in connection with loss of wetlands. For instance, in the State of Florida regulation defines *service areas*, which are between 255 to 3544 square kilometers. Inside a service area, no loss of wetland is tolerated, and all developments implying loss of wetland must buy *wetland offsets* from a wetland developer. To sell wetland offsets, the wetland developer must have restored a formerly degraded area to wetland within the same service area.[6] Clearly, all categories of impacts of WPPs have both a local and a national dimension. Moreover, since a WPP likely will affect an area of a considerable size, offsets may have to be provided some distance away from the location of the WPP. Hence, the local dimension will naturally be challenging, or next to impossible, to offset. In the present paper, we assume that the local loss of ecosystem services from a WPP can be compensated by a monetary transfer, and we only consider offsets for national loss of ecosystem services. Furthermore, we do not discuss the proper *service area* for a national WPP offset. One reason is that, in Norway there is a general concern that so-called interference-free nature, defined as areas located more than one kilometer from major infrastructure developments, is steadily declining over time.

[6] There are also different classifications of wetland, and the offset must be of the correct type, se Vaissiére and Levrel (2015).

WPPs in Norway tend to contribute significantly to the loss of interference-free nature as they most often are built in remote locations. Moreover, WPPs have proven to be especially threatening to bird populations as birds may collide with the rotating wings. Thus, we consider the most important externality on a national level is the deterioration of the value of landscapes and the loss of birds.

To find the most suitable metrics for these environmental externalities, we draw on the literature on habitat (or resource) equivalent analysis (HEA/REA). Below is a table of types of externalities, proposed metrics, and estimation method:

Table 1: Metrics and methods for measuring environmental costs

Externality	Metric	Methods
Loss in wildlife (Birds)	Weighted number of birds	Resource Equivalency Analysis (REA) (NOAA,2000).
Loss of interference-free area	**Three categories of interference-free areas:** **Type 1:** Wilderness areas (lying at least 5 km from significant human construction (such as roads, railways and hydropower infrastructure) **Type 2:** Interference-free area zone 1 is area that lies between 3 and 5 km from nearest significant human construction **Type 3:** Interference-free area zone 2 is area that lies between 1 and 3 km from nearest significant human construction.	Habitat equivalence analysis (HEA)

The categorization of interference-free nature presented in Table 1 is deployed by The Norwegian Environment Agency, a government agency under the Ministry of Climate and Energy.[7] The content of the externalities listed in the first column can be partly overlapping. Loss of pristine nature may also lead to loss in wildlife and endangered species.

HEA was originally developed by the American Oceanic and Atmospheric Administration (NOAA) in 1995 as a tool to provide compensation for the ecosystem services lost through pollution

[7] https://www.miljodirektoratet.no/ansvarsomrader/overvaking-arealplanlegging/naturkartlegging/Inngrepsfrie-naturom-rader/ (In Norwegian)

accidents (oil spills or hazardous-substance releases), NOAA (2000). The amount of money the polluter is required to pay is based on the cost of restoration actions which achieve biophysical equivalence in ecosystem service units. A key feature of the HEA and REA is that ecological value of lost services (habitat) can be estimated without assigning a monetary value to the services. The methods are widely used for scaling compensatory restoration requirements, see REMEDE (2008).

Although the methods do not rely on monetary values of the environment, it relies on metrics to compare the services lost at one site to services gained through compensatory restoration. The choice of metrics is one of the most crucial aspects of the HEA and REA methods. Desvousges et al. (2018) provide a critical assessment of the expended use of HEA. They argue that although the computation required is relatively simple, the theoretical underpinnings are complex and include many assumptions that are not always considered in the applications of the methods. It is argued in the literature that it is hard to compare the quality of land areas at different locations – so-called ecological equivalence (see Dunford et al. (2004), Quétier and Lavorel, 2011). Bezombes et.al. (2017) discuss the trade-offs between operationality, scientific basis, and comprehensiveness. We discuss our approach further in Section 0.

To sum up: Ensuring socially efficient entry of WPPs may be accomplished by a concessions system, by environmental taxes, by an offsetting scheme, or by a combination of the two latter. In the next section, we analyze these four alternatives with point of departure in a theoretical model.

3. Regulation of WPP development

3.1. Preliminaries

We look at WPPs established in areas that can be characterized as interference-free nature of Type 3 as described in Table 1[8]. We also assume that the biodiversity loss from a WPP is proportional to its size, e.g., the number of square kilometers occupied by windmills and access roads.

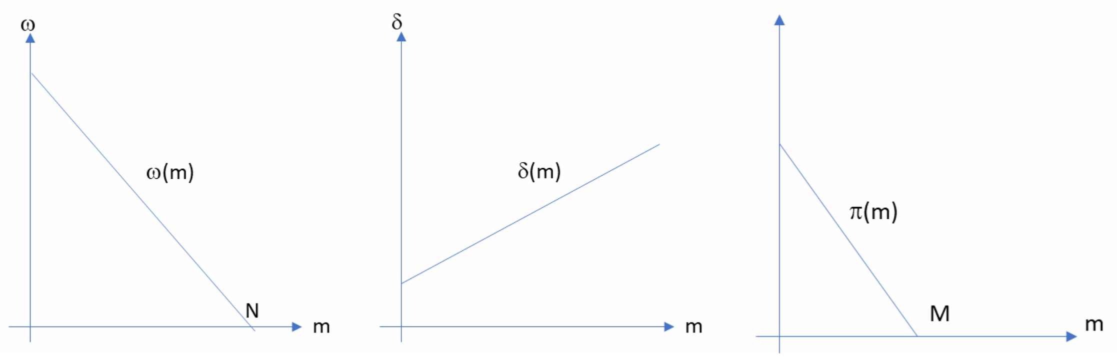
[8] No WPPs in Norway have so far been located in areas formerly characterized as Type 1 and very few WPP areas have had significant overlap (more than 5%) with Type 2 (Nowell et al., 2020).

The private cost of electricity from a WPP is almost entirely made up by capital costs. Some of the investment costs like grid connection and road construction depend on the location. Moreover, the expected output of electricity from the standard WPP is also dependent on the location, see for instance NVE (2017). Thus, the private profit from the standard WPP is location dependent.

In the country we are looking at, let there be *N* potential square kilometers that can be used for WPPs. WPPs placed in this area will generate a private profit ω per square kilometer of area. For simplicity, we assume that ω is uniformly distributed according to $\omega \sim [0, \overline{\omega}]$ with mass *N*. Hence, the best location will generate a profit $\overline{\omega}$ per square kilometer. Furthermore, let the local external costs be equal to δ per square kilometer covered. We assume that δ is uniformly distributed according to $\delta \sim [\underline{\delta}, \bar{\delta}]$, and that δ is uncorrelated with ω .

Below, in Figure 1, we have drawn three diagrams. Along the X-axis in each diagram, we measure the square kilometers covered by windmills denoted by m. In the first figure to the left, we have ranked each available square kilometers according to the private profit from a WPP per square kilometer. The ranking is given by the ranking function $\omega(m)$. Note that there are precisely *N* square kilometers that have a private profit ω larger than zero.

Figure 1 "Ranking of WPPs"



The figure in the middle then shows the local external costs per square kilometer of the *N* potential available square kilometers for WPPs. By the assumption of no correlation between private profits and local external costs, the ranking function $\delta(m)$ in this figure implies a totally different sorting of areas than in the figure to the left. Finally, in the figure to the right, we have subtracted the local external costs from the private profits for each square kilometer. We then obtain a new ranking $\pi(m)$ which sorts the available areas for WPP development according to their net benefits per square kilometer, e.g., the difference $\omega(m) - \delta(m)$. As shown by the figure, there are now only *M* square kilometer of area that yield a positive net benefit.[9] Clearly, we must have *M* < *N*.

As mentioned, our point of departure is that the local external costs will be internalized by Coasian bargaining between the local authorities and the WPP developer. Hence, for the rest of this section only the ranking $\pi(m)$ will be relevant. The total profit from *m* square kilometers covered by WPPs is then given by:

$$\Pi(m) = \int_0^m \pi(s)ds$$

3.2. Concessions versus environmental taxes

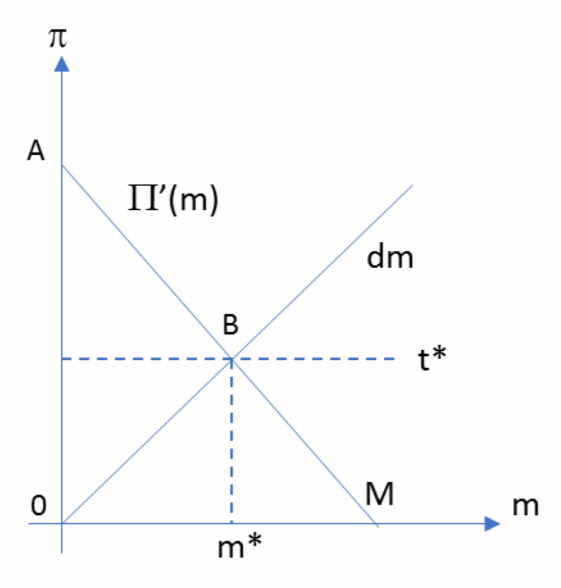
The local external costs do not depend on the total number of square kilometers covered by windmills. This is not reasonable for the national external costs; the more WPPs you develop, the less undisturbed nature is left, and the valuation of the remaining undisturbed nature then increases (NVE, 2017). We therefore assume that the national external costs can be represented by the following quadratic environmental damage function $D(m) = (d/2)m^2$, where $m \leq M$ is defined above as the total number of square kilometers covered by windmills. To find the optimal amount of land (nationwide) to set aside for windmills, the government then solves:

$$\max_m \left\{\Pi(m) - \frac{d}{2}m^2\right\}$$

The optimal solution can be illustrated in the following figure:

[9] The sum of two independent, uniformly distributed variables is not necessarily uniformly distributed. For the sake of illustration, we have however drawn the $\pi(m)$ curve linear.

Figure 2. Land set aside for windmills without off-sets



On the x-axis we measure the square kilometers covered by windmills *m*, while on the Y-axis we measure potential profit subtracted local external costs. The downward sloping line marked $\Pi'(m)$ denotes the marginal benefit of wind power production (the profit subtracted the local external costs of the m'th square kilometer that is developed). Total benefit from the developed land is then the area under this curve.

The upward sloping line denoted *dm* is the marginal *national* environmental costs of WPP development. The optimal amount of land set aside for windmills is then m*. If there is no taxation of the national environmental externality, the owners of the WPPs will earn a regulation rent. The rent is equal to the trapezoid 0ABm*. This may create a political pressure to develop more WPPs.

Even if a regulator had set the total number of WPPs correctly, equal to m*, the actual solution may depart from the optimal solution. As long as an approval to develop a plant is made on a first-come, first-serve basis, land with a potential benefit in the interval $[\pi(m^*), \pi(M)]$ may be developed before more desirable land in the interval $[\pi(0), \pi(m^*)]$. That is, an area will be developed for windmills if the potential profit is higher than the local external costs and the total area set aside for windmills is below m*. Clearly, this is inefficient from the point of view of the country.

How would this change with an environmental tax aiming to internalize the national external costs? We see from Figure 2 that in equilibrium the marginal national environmental damage is equal to t^*. If the environmental tax per square kilometer is set to t^*, no land will be developed with a potential net benefit smaller than t^* (per square kilometer), which will ensure that only the most profitable land areas within the set [0,M] is developed. However, the problem of fixing t^* remains. First, it must be possible to separate the national environmental costs and the local environmental costs of WPPs which will vary from place to place. Second, alternatively, the Norwegian parliament could set the limit m^*, and then the correct tax t^* would be the tax that realized m*. We conclude this section with the following observation: An environmental tax could potentially yield a socially more efficient set of WPPs than a concession system based on first come – first serve basis.

3.3. Compulsory offsetting

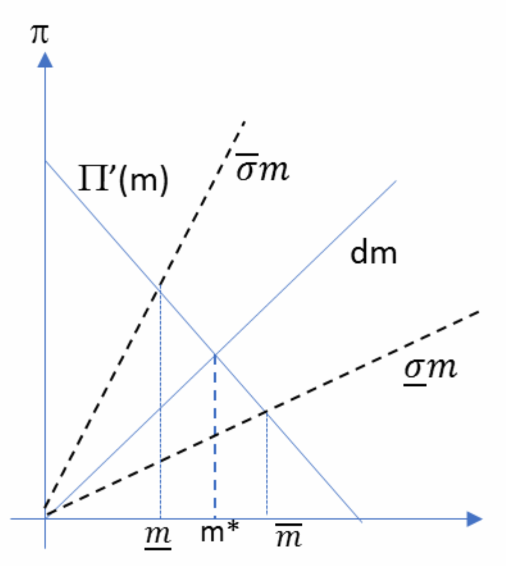
Instead of setting a monetary value on the national external costs, one can try to eliminate them. This is exactly the aim of an offsetting scheme. Then how does the environmental tax compare with a requirement to off-set the national external costs of windmills through a market for offsets? Clearly, this depends on the supply of offsets. This supply will depend on the availability of land restoration projects, that is, human influenced land that can be converted into un-fragmented land of either of the three types in Table 1. We will later describe a large land restoration project in Norway in which a large mountain area formerly used a military training ground was converted into a national park. There are obviously more potential projects: removal of old grid connection lines that runs through pristine nature, removal of roads with little usage, establishment of new national parks etc.

The cost of a restoration projects is twofold; you have the actual restoration cost, and you have the alternative use of the land, in particular, if the land has to be made into a national park which prohibits many provisioning services like forestry. Hence, it seems reasonable to assume that restoration projects are a scarce resource, and that the more land you set aside for windmills, the higher the cost of the next restoration project. Assume then that the cost for offsetting each square kilometer of land with windmills is given by $c(m) = (\sigma/2)m^2$, in which m is defined above. The regulator then solves the following maximization problem:

$$\max_m \left\{\Pi(m) - \frac{\sigma}{2}m^2\right\}$$

For the optimal level of land set aside for windmills, given that all land use must be offset, we then have $\Pi'(m) = \sigma m$. With perfect competition between restoration suppliers, the price of offsets per square kilometer will be equal to marginal costs σm in equilibrium. Hence, only WPPs for which $\pi(m) \geq \sigma m$ will be realized. As with the environmental tax, this is an advantage of offset over a first-come, first-served concession system. The market equilibrium level of WPP developments will then depend on the steepness of the off-set supply curve as depicted in Figure 3:

Figure 3 "Offsetting"



In the figure we draw two potential equilibriums; one with a high σ and one with a low σ; $\overline{\sigma}, \underline{\sigma}$. In the former case, less land than m* will be developed due to a steeply increasing offset supply curve, while in the latter case more land than m* will be developed due to a flat offset supply curve. Note that the *dm* curve in the figure is for illustrating purpose only. If all national environmental damages from WPPs are offset, there will be no (net) national environmental damages associated with wind power development. However, this comes at cost. The areas below the σm curves represent the cost of offsetting the environmental damage from having windmills on *m* square kilometers of land.

This also means that the optimal target for land development in the absence of offsets (*m**) differ from the optimal target of development if offsets are compulsory. Thus, knowledge on the profit function and the environmental costs, *d(m),* is not sufficient to determine the optimal level of land development for WPPs if the costs of offsets are uncertain. On the other hand, since offsets imply that there are no residual national environmental damages, establishing a compulsory offset market for WPPs clearly has merits in a situation in which additional loss of pristine nature and biodiversity is not acceptable.

3.4. Environmental taxes in combination with offset schemes

Lastly, we discuss a combination of the nature tax and the off-set scheme. Let *x* be the land area with windmills that are completely off-set (measured in square kilometers as m). National environmental damages are then given by $D(m) = (d/2)(m - x)^2$. Consequently, we have that the government solves:

$$\max_{m,x}\left\{\Pi(m) - \frac{d}{2}(m - x)^2 - \frac{\sigma}{2}x^2\right\}$$

The first order conditions are:

$$\Pi'(m) = d(m - x)$$
$$d(m - x) = \sigma x$$

Hence, the land area with windmills that is offset *x* is given by:

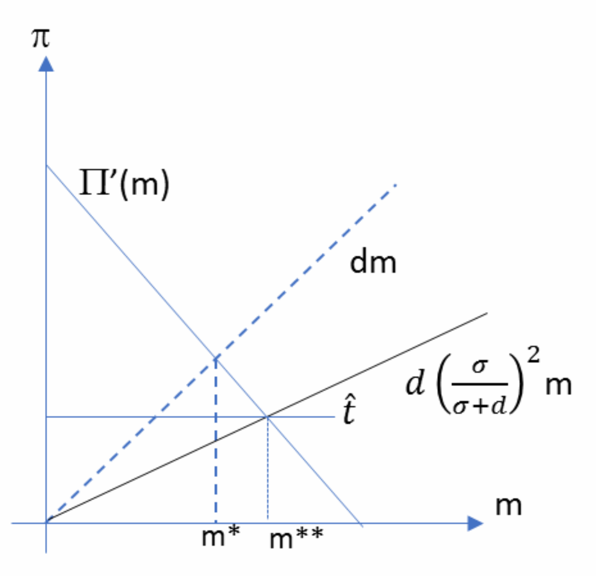
$$x^{**} = \frac{m^{**}}{1 + \sigma/d}$$

Here x^{**} is the optimal amount of land to offset, while m^{**} is the optimal amount of land used for WPP development. Note that as long as $\sigma > 0$, only a fraction of the land set aside for windmills will be offset, e.g., $x^{**} < m^{**}$. By inserting for x^{**} in the new environmental damage function we have:

$$\hat{d}(m) = \frac{d}{2}\left(\frac{\sigma}{\sigma + d}\right)^2 (m)^2$$

Since $\sigma/(\sigma + d)$ is less than unity, the availability offsets shift the environmental damage function downwards as depicted in the figure below.

Figure 4 "Offsetting in combination with a tax"



The figure also depicts the new optimal environmental tax $\hat{t}$, which is lower than t*. Note that the optimal m becomes higher due to the offsets (see the Appendix B for a formal proof).

The optimal amount of land used for windmills m** will be realized with an emission tax $\hat{t}$ in a decentralized market equilibrium with a price of offsets equal to σ (per km2). Each WPP developer will buy an offset if the tax $\hat{t}$ is higher or equal to the offset price σ. As the use of offset increases, the marginal cost of offset increases, while the marginal damage decreases, and thus the tax decreases. In equilibrium, the offset price and the tax are equal. This determines the supply *x* of offsets in equilibrium. Moreover, since *x* < m**, there still will be WPPs with profit potential larger than the tax. These WPPs will also be realized such that we get $\Pi'(m^{**}) = \hat{t}$ in equilibrium. Lastly, note that the WPP owners will be indifferent between buying an offset or paying the tax as the price of offsets is equal to the tax in equilibrium. In the Appendix B we also show that the loss of interference-free land in this solution is lower than the loss in interference-free land with a tax alone, e.g., $m^{**} - x^{**} < m^{*}$.

Adding an offset market (in addition to the tax) improves efficiency because it is cheaper to produce offsets than the marginal environmental costs of land developed for WPP (in the case of only tax scenario).

When there is only the offset market (which implies high marginal cost of offsets), adding the tax improves efficiency because the marginal environmental costs of developed land for WPP (equal to the tax) is lower than the cost of producing offsets.

We can hence conclude: If additional loss of pristine nature and biodiversity is acceptable at some monetary price, establishing an offset market for WPP development and combining it with an environmental tax will be socially desirable. In fact, this solution is preferable to both only having an environmental tax or only having a compulsory offset market.

The lower marginal costs of offsets (the smaller σ), and the larger environmental marginal costs of land devolped for WPP (the larger *d*), the larger share of the developed land will be offset.

4. The offset metrics

As already discussed, WPPs will likely lead to loss of interference-free nature with associated biodiversity loss. In HEA, restoration credits to be used as offsets are expressed in terms of *discounted service acre years* (DSAYs) for a specific habitat which is lost and gained. Moreover, injury and restoration of animals lost and gained are expressed in terms of discounted species years (DSYs), see for instance Baker et al. (2020). DSAYs and DSYs have no real monetary value and are only used to compare alternative actions. The HEA approach thus identifies alternative restoration actions that provide resource services that are "equally desirable" to society as the services lost.

We define the following basic equations for a loss in the *DSAYs* provided by each of the types of interference-free landscape Li, (i=1,2,3) ($DSAYs_{G,Li}$) by development of a potential WPP at location *G*.

(1) $$DSAYs_{G,Li} = \sum_{t=0}^{T_G} \frac{A_{G,Li} \cdot (ES_{G,Li}^{B} - ES_{G,Li}^{I})}{(1+r)^t},$$

where $A_{G,Li}$ is the km2 of landscape of type L*i* i=1,2,3 at location G developed for wind power, *r* is the discount rate, $ES_{G,Li}^{B}$ represents the baseline ecological services (as a percentage) provided by the landscape *i* in the absence of intervention, and $ES^{I}_{G,Li}$ is the ecological services (as a percentage) provided by the landscape *I* after it has been injured. In the following we assume that the baseline services in the absence of intervention and the ecological service after the intervention is constant over time during the project period.

Construction of WPP will typically affect the population of different species of birds. One could argue that an offset scheme should measure all species of birds individually, and that individuals lost of one species must be compensated by an increase in the population of the same kind of species. A fundamental assumption in our estimates of DSYs of birds is that we can define metrics that captures the aggregated birdlife provided by the injured WPP area and the potential offset area. (See Appendix A for the measure of birdlife). We define the following basic equations for a loss in the *DSYs* by development of a potential WPP at location *G (* $DSYs_G$).

(2) $$DSYs_G = \sum_{t=0}^{T_G} \frac{(N^B_G - N^I_G)}{(1+r)^t},$$

where N^B_G represents the measure of birdlife provided by the potential WPP area before development at time *t*, and N^I_G is the measure of birdlife provided by the area after it has been injured (developed) at time *t*. The lifetime of the project is given by T . We assume immediately recovery of the birdlife after the project has been completed (see further discussion in Appendix A)

The environmental impact of the development of a WPP at location G can be fully compensated/offset by implementing a restoration project which provide an equal amount of DSAYs and DSYs that are lost due to the WPP (see eqs. (1) and (2) above), that is:

(3) $$DSAYs_{H,L_i} = DSAYs_{G,L_i} \quad i = 1,2,3, \text{ and}$$

(4) $$DSYs_S = DSYs_G, \text{ where}$$

(5) $$DSAYs_{H,Li} = \sum_{t=0}^{T_H} \frac{A_{H,Li} \cdot (ES^B_{H,Li} - ES^I_{H,Li})}{(1+r)^t}$$

(6) $$DSYs_S = \sum_{t=0}^{T_S} \frac{(N_S^B - N_S^I)}{(1+r)^t}$$

and where $A_{H,Li}$ is the km2 of landscape of type Li i=1,2,3 at the location for restoration , *H*. $ES_{H,Li}^B$ and $ES_{H,Li}^I$ represent the baseline ecological service (as a percentage) from landscape *Li* before and after restoration, respectively. N_S^B and N_S^I are metrics for birdlife before and after the area has been restored, respectively. The lifetime of the project is given by T_S.

5. The case study

5.1. About the cases

In this section we will present Norwegian examples of restoration of landscapes (*Hjerkinn*) and wetland area (*Skottvatnet*) and elaborate how these projects could have compensated for the environmental external impact of a specific area developed for a WPP (*Geitefjellet*). We distinguish between two losses of ecosystem services from the development of *Geitefjellet* WPP: interference-free landscape and birdlife. Habitat Equivalence Analysis (HEA) will be used to quantify the loss in interference-free landscape, while Resource Equivalence Analysis (REA) could be used to quantify the damage to bird populations.

Geitfjellet WPP is located at a mountain plateau in the municipality of Snillfjord and is covering a total area of approximately 25 km2. The power plant will have 43 turbines with a total capacity of 180,6 megawatts (MW) and an expected yearly production of 548 gigawatt hours (GWh). They were granted a license to operate for 25 years from the day operation starts.

The potential offset areas we consider is *Hjerkinn*, a mountain area of 163 km2 which has been restored from military use, and *Skottvatnet,* a wetland area for birds, that had been degraded over years, but was significantly restored in 2009-11. The restoration procedure and its effects on bird life are summed up in Høitomt (2013).

Hjerkinn is a small place located in the Dovre Mountains of Norway. Until the year 2002, a large area around Hjerkinn, in total 165 km3, was set aside as a military training ground, but have now successfully been restored, see Hagen et al (2022). The military started using the area already in

1923 just after the railway between Oslo and Trondheim across the Dovre Mountains was built. Military use was restricted before the Second World War, and the area became an important tourist destination. Some of Norway's highest mountains are located there, and these mountains have an important cultural meaning to many Norwegians figuring in old Norse mythology, fairy tales and literature. However, during the cold war years after the Second World War, both the use and the size of land set aside land increased, and the Norwegian Hiking Association had to close one of its most popular huts.

In 1999 the Norwegian Parliament decided to close the area for military use and move all the activities of the military to an already existing training ground located in Rena. Rena has lower elevation and a more robust ecology compared to the fragile mountain landscape at Hjerkinn. The military had then left a significant mark on the Hjerkinn area; 90 km of various roads, a 0,24 km2 leveled area for artillery training, numerous landfills with various content, and finally, potentially a large number of undetonated grenades. Partly to compensate for the increased demand on the new training area in Rena, the parliament decided to restore completely the Hjerkinn area. The restoration is now completed, and the closed mountain hut has reopened. All landfills, undetonated grenades and roads, except the 14 km road to the mountain hut, has been removed. A threatened species of fox, the mountain fox (*Vulpes lagopus*), is reintroduced. Moreover, the area of the nearby national park protecting the Dovre wild reindeer population could be increased by about 10%. The total restoration budget was 60 million euros (Hagen et al. 2022). The budget was provided by the Norwegian Parliament, and hence, by the taxpayers.

Skottvatnet was established as a nature conservation area in 1990. It is an important wetland area for animal life, especially for birds either nesting or resting during migration. It was originally a part of a bigger wetland area. In the years leading up to 2009 it was observed that the water level had decreased significantly, due to human impacts (mass filling during floods). During the fall there would only be small areas covered with water and mud banks would be showing. The changes to the area have caused noticeable negative changes to the bird life (Høitomt and Hoff 2009). Its function as location for nesting and stopover site during migration for waterbirds would have been further reduced if the overgrowing and mass filling had continued.
In 2009 there was conducted a report suggesting several actions to counteract the human impacts such as dredging to clear more of the water surface from vegetation and increasing the

water levels. The activities took place in 2009-2011. The restoration procedure and its effects are summed up in Høitomt (2013). The total cost of the restorations was 274 700 euros (2021-prices). There was conducted bird registrations during the summer of 2011 and 2012. The registrations show that the objectives of the restoration were partially achieved in 2011 and fully achieved in 2012. Both the number of individuals and the number of species is reported to have increased after the intervention.

5.2. Loss of interference-free landscape- calculating DSAYs

WPP at Geitefjellet reduces the amount of interference-free landscape (INON) in Norway. Geitfjellet WPP is located at the mountain plateau of Geitfjellet in the municipality of Snillfjord and is covering a total area of approximately 25 km2. 17,2 km2 of the area is free from other significant human impacts and is characterized as a so-called interference-free nature Type 3, which implies that it lies between 1 and 3 km from nearest significant human construction (Melby, 2010)

The lifetime of the project is 28 years. 3 years of construction and 25 years in operation, according to license.[10] The baseline km2 (A_G) of interference-free Landscape Type 3 is set to 17 km2). We only consider the operational phase and, as stated above, we assume that the landscape will be restored to interference-free nature Type 3 when the operation phase is completed. The ecological service from the interference-free landscape type 3, prior to development of WPP at Geitefjellet (ES_G^B) is set to 100 percent. With development of a WPP, there will be no interference-free nature type 3 left, during the operational phase, such that (ES_G^I) is set to zero. This leads to the following calculation of loss in DSAYs from land development at Geitfjellet

$$DSAYs = \sum_{t=0}^{t=25} \frac{A_G \cdot (ES_G^B - ES_G^I)}{(1+r)^t} = \sum_{t=0}^{t=27} \frac{17}{(1+r)^t} \qquad (7)$$

[10] Construction phase: 32 month https://www.produktfakta.no/geitfjellet-vindpark-snillfjord/prosjekt.html, that is approx. 3 years.

5.3. Loss in Birdlife – calculating DSYs

A fundamental assumption in our estimates of DSYs of birds is that we can define one common metric that captures the birdlife provided by the injured WPP area and the potential offset area. We follow Skulstad (2019) and aggregate the observed species adjusted according to their redlist status, observed frequency, and usage of the area. See Appendix A for the calculation methods. Furthermore, we assume that the deterioration of birdlife happens immediately after the WPP is built and will recover as soon as the WPPs is no longer in operation. The measure of birdlife at Geitfjellet ex post of the development of WPPs, the baseline, N_G^B is set to 6,17. (See Appendix A). Furthermore, Larsen and Gaarder (2010) state that impact on the fauna and flora during the operational phase was considered to be between medium negative and greatly negative.[11] Based on this we assume a 50 percent reduction in birdlife. Thus, the numeric value of birdlife during the operational phase is 50 percent of the baseline value. The calculated DSYs loss from the WPPs at Geitefjellet is given by

$$DSYs_G = \sum_{t=0}^{t=27} \frac{(N_G^B - N_G^I)}{(1+r)^t} = \sum_{t=0}^{t=27} \frac{6.17 - 0.50 \cdot 6.17}{(1+r)^t} \quad (8)$$

5.4. Potential compensating scheme -interference-free landscape

At that time the potential offset area Hjerkinn was decided to be closed for military use, the area had significant infrastructure developments. Approximately 70 percent of the area could be characterised as "close to interventions", and the remaining 30 per cent was characterised as interference-free area Type 3 (see Table 1). The restoration process increased the interference-free area (A_H) by 63 km2. Furthermore, 7 percent (8 km2) of the interference-free area could be characterised as Type 1 (Wilderness) and 35 percent (40 km2) was Type 2, see Hagen et al. (2022).

We find the following *increase* in DSAYs of interference-free nature (of all three types) from the Hjerkinn project ($DSAYs_H$)

[11] Larsen and Gaarder (2010) consider the impact to be more severe in the construction phase. In the present paper we do not distinguish between the construction phase and the operational phase.

(9) $$DSAYs_H = \sum_{t=0}^{t=\infty} \frac{A_H \cdot (ES_H^B - ES_H^I)}{(1+r)^t} = \sum_{t=0}^{t=\infty} \frac{63 \cdot 1}{(1+r)^t} \approx \frac{63}{r}$$

As we see from the equations above, the DSAYs are dependent on the choice of discount rent. In **Table 1**, we present the outcomes of DSAYs for three different discount rates. Furthermore, the fourth column show the share of the DSAYs from the Hjerkinn restoration that offset the loss of DSAYs from the Geitefjellet WPP ($DSAYs_G / DSAYs_H$). The fifth column show the increase in production cost per unit kWh produced at Geitefjellet should the DSAYs loss be fully compensated by corresponding DSAYs increase at Hjerkinn (assuming the Hjerkinn restoration project cost is 65 million euros). [12]

Table 1. DSAYs and compensation costs Hjerkinn

r	$DSAYs_G$	$DSAYs_H$	$DSAYs_G / DSAYs_H$	€ per kWh	Share of investment costs
0.02	378	3100	0.12	0.00058	0.04
0.04	308	1550	0.20	0.00094	0.07
0.06	256	1033	0.25	0.00117	0.09

The cost of compensating the lost DSAYs from the development of Geitfjellet by a corresponding increase in DSAYs from the restoration of Hjerkinn is small relative to the investment costs at Geitfjellet (4 - 8 percent depending on the choice of choice of discount rent). With a discount rent of 4 per cent, the compensating cost amounts to € 0.0009 per kWh. For comparison, the average spot price in 2018-2020 was € 0.031 per kWh.

5.5. Potential compensating scheme -Birdlife at Skottevatnet

We find the following *increase* in DSYs of birdlife from the Skottevatnet project ($DSYs_S$), (see Appendix A)

(10) $$DSYs_S = \sum_{t=0}^{t=\infty} \frac{(N_S^B - N_S^I)}{(1+r)^t} = \sum_{t=0}^{t=\infty} \frac{1.64}{(1+r)^t} \approx \frac{1.64}{r} ,$$

which equals 82, 41, 27 for r=0.2, 0.04, and 0.06, respectively. The cost of Skottevatnet restoration is 0.26 million euros (adjusted to 2018 prices).

[12] Geitefjellet's estimated production is 548 GWh per year in 25 years.

Table 2 DSYs and compensation costs. Birdlife

r	$DSYs_G$	$DSYs_S$	$DSYs_G / DSYs_S$	€ per kwh	Share of investment cost
0.02	69	82	0.8	0.000017	0.0012
0.04	56	41	1.4	0.000027	0.0020
0.06	46	27	1.7	0.000032	0.0025

The cost of compensating the loss in DSYs from Geitfjellet by increased DSYs from the restoration of Skottevatnet is very small relative to the investment costs of Geitfjellet (0.1 – 0.3 percent depending on the choice of choice of discount rent). With a discount rent of 4 per cent, the compensating cost amounts to € 0.00003 per kWh.

In section below, we compare the cost of compensating schemes with the estimated welfare loss of degraded environmental amenities measured by WTP/WTA estimates.

6. Offsets versus environmental taxes.

In section 0 we presented some recent estimates on the WTA for new wind power installations and WTP for increased renewable energy (Lindhjem et al., 2022). Summing up the willingness to pay for increased renewable energy production and the environmental damage (measured by WTA) from the wind turbines, the net environmental cost of WPP can be estimated to € 0.04 per kWh produced. This can be used as an estimate of an environmental tax, correcting for environmental impacts (at the present level of wind power production). However, as discussed previously, these estimates likely also include parts of the environmental costs faced by the local communities, which cannot be compensated by offsets. Hence, we could deduct the costs related to local environmental impact to make the environmental cost estimates comparable to the costs of the offsets. Garcia et al. (2016) estimates local WTA compensation in a community in Norway by choice experiment. The average cost estimate is 15 euros per turbine per household per year. With around 450 household living in the municipality hosting Geitfjellet WPP, we can very roughly estimate the local environmental cost to € 0.0005 per kWh which is too small to have a significant impact on the environmental costs of € 0.04 per kWh, estimated by Lindhjem et al. (2022).

If we sum up the costs of offsetting loss of birdlife and loss of interference-free land from the section above, we find the offsetting amounts to be € 0.0005 – 0.0017 per kWh (depending on the discount rate). This clearly indicate that there is scope for allowing offsets as an alternative to – or in combination with – environmental taxes. The cost of offsetting the environmental damage of Geitfjellet is between 1 - 4 percent of the environmental costs measured by WTP/WTA of the WPP (in the absence offsetting).

This numerical exercise can only provide a point estimate on the cost of offsets versus the environmental costs, measured by WTA and WTP. As we have illustrated in section 0, the steepness of the cost function of offsets and the damage function will determine the optimal combination of two policies over time (with increasing number of WPP).

7. Concluding remarks and discussion of possible weaknesses of the methods

We concluded in the theoretical model that offsets in combination with environmental taxes are superior to only relying on environmental taxes or a concession system. Certain conditions must be satisfied for this conclusion to be practically relevant. First, it must be developed metrics which makes the environmental degradation following from WPPs comparable to the environmental improvement from restoration projects. Second, there must be restoration projects available. Third, the cost of the restoration projects cannot be too high.

In this paper, we suggested the concept of Habitat Equivalence Analysis (HEA) and Resource Equivalence Analysis (REA) to quantify ecosystem service losses and calculating the scale of compensatory restoration required to offset those service losses. We considered two types of ecosystem losses: loss of undeveloped landscape and loss of birdlife. We presented two restoration projects *Hjerkinn* and *Skottvatn* and a recently developed WPP (*Geitfjellet*). We showed that the cost of compensating environmental degradation from *Geitfjellet* by financing (a share) of these two projects was small relative to the investment cost of the WPP, and also measured by the cost per kWh. We also showed that the costs of offsets were considerably lower than estimates of marginal environmental damage from WTP/WTA studies (Navrud, 2005 and Lindhjem et al. 2022). All in all, this indicates that an offset system for WPPs is promising and should be further explored.

Clearly, one should consider developing a multidimensional offset scheme for WPPs. As already mentioned, there are 3 classifications of untouched landscapes and a fully developed offsetting schemes should take this into account. Moreover, there are different classifications of landscapes: coastal, inland forest, mountains etc. Preferably, offsetting a WPP should happen within the same type of landscape.

Another challenge with the offset scheme is how to compensate the loss of wildlife. In the present paper we only considered compensating the loss of birdlife as birds are the main species threatened by development of wind power. We suggested to weigh the observation of species by their observed frequency, use of the area, and the Redlist categorization. Other metrics may be considered. One could for example only focus on the loss of endangered species, and demand that the loss of each endangered species is fully compensated. Baker et al. (2020) suggest a restoration system where, for all the main species affected, the loss of individuals within a specie cannot be compensated by an increase in individuals of another species. In general, an offset scheme demands good measurement methods and regulations to ensure equivalence in the values of ecosystem services lost and gained.

A crucial question is whether there are more suitable projects for restoration, beyond the two considered in this paper. Recent development indicates that there is. For the first time since 1990 larger areas have been restored. According to the State agency *Environment Norway*, around 144 km2 of land was restored from developed to interference-free land during the period 2012-2018.[13] This is mainly due to removal of transmission grids and roads. So far, these restoration projects are financed by public spending. As discussed by Scemama and Levrel (2015) offset-requirements can develop into a system where a number of bodies, such as private investors or NGOs could assume responsibility for restoration projects. For instance, in Italy, degraded grassland was restored to compensate for a WPP at another location (Madsen et al., 2010). In countries in which offsets are used, private investors will have incentives to set up so-called offset-banking. Then, degraded land is restored for sale to some developer emerging later (see Froger et al. (2015) for a critical discussion). This may create a market for tradable permits to ecosystem conservation, see Wissel and Wätzold (2010) and Drechsler and Wätzold (2009). To facilitate the development of such system, the regulator could identify potential restoration projects.

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[13] https://miljostatus.miljodirektoratet.no/tema/naturomrader-pa-land/inngrepsfri-natur/

In this paper, we assumed that environmental impacts on the local community could be solved by Coase bargaining. This is obviously a simplification. History tells us that there have been severe local conflicts around new WPPs, even though the establishment has been endorsed by the local councils. Last year, the Supreme Court of Norway stated in their decision that Norway violated the rights of the Sámi people by permitting the construction of two specific WPPs.[14] This calls for a national framework, making restrictions for investment in WPPs in areas of specific value to certain group within the communities (Bateman and Mace, 2020; Grimsrud et al., 2022). Furthermore, a municipality considering whether to host a WPP may not take fully into account the negative impacts on the population of the neighboring municipality, who may also face a degradation of their recreational area.

[14] https://www.saamicouncil.net/news-archive/smi-victory-in-supreme-court-illegal-wind-farm-on-smi-land

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Appendix A: Calculating the DSYs of birdlife

Based on Larsen and Gaarder (2010), Høitomt and Hoff (2009) and Høitomt (2013), Skulestad (2019) finds that there were 41 species observed at Geitfjellet ex ante of the WWP construction, there were 91 species at Skottvatnet ex ante of the recovery and 120 species ex post. Obviously, it is not only the number of observed species that matters for the ecosystem services from birdlife. Skulestad (2019) calculates a metric for the aggregate value of birdlife where each observed species is given weight based on its **regularity**, **its use of the area**, and by its R**ed List status**. The regularity of each species is divided in three categories, characterized by the frequency of observations, and assigned values from 1 to 0.33: frequent (1); frequent, but small population (0.66); rare (0.33).

The use of the area is divided in five categories, with assigned values from 1 to 0.6: permanent, or approximately permanent, nesting bird (1); probable nesting bird (0.8); roaming, no sign of nesting (0.6); molting (ducks) (0.6); and observed only during migration (0.6).

Each species is characterized by its Red list status as defined by the international union for conservation, IUCN. The IUCN Red List of Ecosystems includes eight categories: Collapsed (CO), Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC), Data Deficient (DD), and Not Evaluated (NE). Each of the observed species from CR to LC is assigned numerical value to reflect the rank (from 1 to 0.2, with an interval of 0.2). RE and NE are not found in the dataset. DD is found and is given the same value as LC, i.e., 0.2.

This calculation gives the following values for birdlife used in the calculations of DSYs; $N_G^B = 6.17,\ N_S^B = 10.88,\ N_S^A = 12.52$.

Appendix B Proof

In the tax solution we have the following first order condition:

$$\Pi'(m^*) = dm^*$$

While in the solution with both a tax and an offsetting scheme we have the following two first order conditions:

$$\Pi'(m^{**}) = d(m^{**} - x^{**})$$
$$d(m^{**} - x^{**}) = \sigma x^{**}$$

Here m^* denotes the area that is used for windmills in the tax solution, while in the solution with both tax and offsets, $m^{**} - x^{**}$, gives the area that is covered by windmills and not offset by creating new pristine areas in other places.

We can solve for x^{**}:

$$x^{**} = \frac{m^{**}}{1 + \sigma/d}$$

Hence, we have for the area that is not offset:

$$m^{**} - x^{**} = \frac{\sigma}{\sigma + d} m^{**}$$

By combining the equations from the first order conditions, we must then have:

$$\Pi'(m^{**}) = \frac{d\sigma}{\sigma + d} m^{**}$$

Assume then that $m^{**} \leq m^*$. We must then have $\Pi'(m^{**}) \geq \Pi'(m^*)$ since π is a declining function. This implies that:

$$\frac{d\sigma}{\sigma + d} m^{**} \geq dm^*$$

Which must be false. Hence, $m^{**} > m^*$, which implies that more area is used for windmills in the solution with both tax and offsets.

Assume then that:

$$\frac{\sigma}{\sigma + d} m^{**} \geq m^*$$

That is, the area that is not offset in the offset-tax solution is larger or equal to the area that is developed in the tax-only solution. Multiplying with d, we get the equation above:

$$\frac{d\sigma}{\sigma + d} m^{**} \geq dm^{*}$$

This cannot be true since it implies $\Pi'(m^{**}) \geq \Pi'(m^{*})$, and we have already shown that $m^{**} > m^{*}$ such that $\Pi'(m^{**}) < \Pi'(m^{*})$. Consequently, we must have:

$$\frac{\sigma}{\sigma + d} m^{**} < m^{*}$$

That is, the area that is *not offset* in the offset-tax solution is smaller than the area that is developed in the tax-only solution.