Time Series Model for Wind Turbine Losses: Assessing Regional and Temporal Variability, Loss Interactions, and Market Values

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Abstract. National assessments of wind power losses typically rely on static loss factors and focus on annual energy production (AEP), implicitly assuming a one-to-one correspondence between energetic losses and their economic significance. This paper challenges this assumption by applying a time-resolved, national-scale loss modeling framework to the German onshore wind fleet for the year 2024, simulating all turbines at 10-minute resolution to quantify losses due to wake, noise-related curtailment, and bat protection measures, including their interactions. We find that wake losses dominate energetically, while those from noise and bat curtailment are smaller in magnitude. Accounting for interactions demonstrates that the combined loss differs from the sum of individual contributions. By weighting losses with hourly day-ahead electricity prices, we introduce the loss market value (LMV) as a metric to assess their economic relevance. The results show that energetic magnitude and economic relevance are largely decoupled: wake losses exhibit an LMV close to unity (≈ 1.1), whereas bat curtailment shows a substantially higher LMV (≈ 1.5). Noise-related losses are concentrated in low-price night hours, resulting in an LMV below unity (≈ 0.8).

1. Introduction

Loss estimation plays an important role in estimating the annual energy production (AEP) and, thus, for the economical assessment of wind energy projects. Losses in energy yield can result from various sources, including wakes, curtailments for the reduction of noise and shadow immissions, and the protection of endangered species, icing, degradation and technical non-availability. Depending on when those losses occur, their equivalent in revenue can vary significantly due to the dynamics of energy market prices, which also correlate with the amount of wind power feed-in. Furthermore, the regional and timely occurrence of yields and losses is critical for both the planning and operation of the energy system as well as individual wind farms - for instance to strategically plan maintenance during periods of lower yields. Thus, time series-based loss models, which depend on weather conditions and time of day, are crucial for evaluating energy

yields and the economic implications of various loss types. Current literature primarily focuses on one of two aspects.

(1) Assessments of wind energy potential conducted on large scale, such as at regional or national level, that mostly provide estimates of energy yield, often strongly simplifying energy losses. Some directly use the gross AEP [1], while others apply a flat-rate reduction in yield, such as 10-15 % overall as in [2, 3]. Although some studies differentiate those losses into various sources as in [4], they still rely on flat loss assumptions.

(2) On the other hand, yields and losses are usually considered in more detail on the level of individual wind farms. An overview of academic and industrial studies along with considered loss sources and uncertainties can be found in [4]. Important time-dependent loss sources are losses due to wake, regulations for noise immission reduction and bat protection. Among those, *wake* losses are the most commonly analyzed due to their magnitude and dependence on the farm layout (see e.g. [5]) and therefore are a driving factor for a wind farms design and profitability. Several programming libraries, such as the open-source software PyWake [6] exist to model wakes at the wind-farm level. *Noise* emissions from turbines are mostly analyzed in terms of received immission and environmental impact, see e.g. [7]. There are different strategies for noise emission reduction. Usually, manufacturers provide operational modes to reduce noise emission by reducing rotor tip speeds [8]. Yield losses resulting from shutdown strategies, utilizing bat activity and collision models for *bat* protection, have been analyzed in [9] based on data from 70 turbines in Germany through modeling time intervals of curtailments. While this method effectively calculates yield losses, it is not applicable on a national scale due to the lack of operational data.

Considerable efforts have been directed towards modeling energy production and losses at different scales. However, consistent evaluations of the combined, time- and region-dependent yield losses of wakes and regulatory measures on a national scale - including their interactions and economical impacts - have been neglected so far.

This leaves a gap in understanding the implications of losses at regional and national scales, which are highly relevant for informed regulation, system planning, and operational strategies. This study aims to fill this gap by performing detailed simulations of energy production and energy losses on wind turbine level and subsequently aggregating the results to regional and national levels, building on the work of [10]. In a second step, simulated losses are correlated to day-ahead electricity prices to assess the economic implications of different loss types. Using these simulations, this paper addresses the following questions: 1.) How important are different sources of yield losses in Germany, namely due to wakes and regulations for bat protection and noise immission? 2.) What regional differences exist in the magnitude of these losses across federal states in Germany? 3.) When do those losses occur, and do they occur simultaneously? 4.) How do energetic loss magnitudes differ from their economic relevance under consideration of time-resolved electricity prices? Only physical-operational losses that can be influenced by turbine layout, permitting, or operational strategies are considered; systemic constraints such as redispatch, which operators cannot control, are excluded.

2. Methodology

2.1. Data

The *turbine data* is based on the official register of energy facilities in Germany, known as Core Energy Market Data Register (MaStR) [11]. It includes coordinates of the wind turbines as well as meta information like rated power, hub height and rotor diameter. As data in the MaStR is known to have inaccuracies and data gaps [12, 13], two methods for corrections were

combined and applied to the MaStR data to produce the turbine dataset used for this paper, namely the corrections described in [12] and the remote sensing and deep learning approach to correct turbine coordinates from [13]. For this paper, both approaches are used in the following hierarchy. Meta information is used from the dataset described in [12] when available. Coordinates are taken from [13]. Remaining gaps are first filled using [12] and then from the original MaStR.

If one or more of the parameters hub height, rotor diameter, rated power are missing, they are filled with median values based on the commissioning year and available parameters, prioritizing existing data to fill gaps, and using the median for the commissioning year if all are missing. Finally, turbines with a total height below 50 m are discarded. If two turbines are within half a rotor diameter of each other (i.e., they are touching), the coordinates are assumed to be incorrect, and only the turbine with the newest commissioning date, highest rated power or highest serial number is retained. The resulting dataset consists of $27,751$ onshore turbines.

The parameters wind speed, wind direction and temperature used for calculating power production are sourced from ERA5 [14] with a horizontal resolution of 31 km and a temporal resolution of 60 minutes. Reanalysis data is commonly used for modelling power generation from wind turbines due to its high coverage and resolution. While reanalysis data is known to have regional biases, ERA5 was shown to have good performance in simulating power generation on a national scale in Europe and Germany [3, 15] and to capture diurnal [3] and seasonal [16] patterns well. Wind speed and wind direction are interpolated to hub height using the power law and linear interpolation respectively.

High resolution precipitation data needed for the bat model is sourced from DWD [17] with a horizontal resolution of 1 km and a temporal resolution of 5 minutes. All meteorological time series are linearly interpolated/averaged to 10 minute intervals.

The turbine portfolio and the energy market in Germany have strongly evolved over the last decade. The year 2024 was therefore chosen to provide the most recent complete dataset of both meteorological and turbine data.

To account for spatial distances in three dimensions within the wake and noise models, terrain heights are required. They are sourced from the digital elevation model [18] with a resolution of 25m x 25m. Land-use information of forest cover is needed for the bat model, and residential information is required for the noise model. Both are taken from [18].

2.2. Power calculation

To simulate energy yield and losses for each turbine in Germany, we use a modular framework that builds on [10]. The methodology for the models for wake and bats was recently published in [10], and has since been upgraded with a noise model. Each sub-module either defines an operating mode (bat and noise losses) or computes a wind speed deficit (wake losses) for each time step. The operating mode is linked to the power curve which is used to compute the power production under consideration of that loss source.

Full load power curves are produced for each turbine from rated power and rotor diameter using the generic power curve generator from PyWake [6]. The turbine portfolio is handled in batches, which are buffered with a distance of 8 km to account for wake and noise effects from turbines next to the batch.

2.2.1. Gross energy production The gross energy production time series is computed using the power curve associated with full load operation and the meteorological time series.

2.2.2. Bat The German Federal Nature Conservation Act (BNatSchG) [19] mandates the protection of all bat species that are native to Germany. To reduce the collision risk with wind turbines, shutdown strategies are employed that target periods of high bat activity. Generalized

Table 1. Bat curtailment parameters for federal states. Nighttime refers to the hours before sunset and after sunrise during which the rules apply, indicated as [-xh, +yh], meaning the rule is in effect from x hours before sunset to y hours after sunrise. Further, T refers to the temperature, WS to the wind speed and P to the precipitation.

State	Period	Nighttime	T [°C]	WS [m/s]	P [mm/h]
BW	01/04 - 31/10	[-(1-3)h,+0h][c]	≥ 10	< 6	n.s.
BY	01/04 - 15/11	[-(0-1)h,+0h][c]	≥ 10	< 6	< 0.2
BB	01/04 - 31/10	[-1h,+0h]	≥ 10	≤ 6	≤ 0.2
HE	01/04 - 31/10[a]	[-0.5h,+0h]	≥ 10	< 6	≤ 0.2
MV	01/05 - 30/09[a]	[-1h,+0h]	n.s.	< 6.5	< 2
NI	01/04 - 31/10	[-0h,+0h]	> 10	< 6	0
NW	01/04 - 31/10	[-0h,+0h]	> 10	< 6	n.s.
RP	01/04 - 31/10	[-(1-3)h,+0h]	≥ 10	< 6	n.s.
SL	01/04 - 31/10	[-0h,+0h][c]	≥ 10	< 6.5[b]	0
SN	15/04 - 15/11	[-(1-3)h,+0h][c]	≥ 10	$< (5-7)$[c]	< 2
ST	01/04 - 31/10	[-1h,+0h]	≥ 10	< 6.5	< 0.5
SH	10/05 - 30/09[a]	[-1h,+1h]	> 10	< 7[d]	< 0.5
TH	15/03 - 31/10	[-1h,+1h]	≥ 10	≤ 6	n.s.

[a]period varies depending on bat habitat. [b]WS varies depending on bat habitat; the mean is shown. [c]varies depending on the month. [d]WS varies depending on rotor passage; the mean is shown.

shutdown algorithms for the first two years after commissioning are determined at the federal state level, leading to variations in implementation across the country. In this analysis, we use these generalized shutdown algorithms mandated by the federal states also as a proxi for later stages in the turbine operation when curtailment can be based on the results of local bat monitoring, as the results of bat monitoring are usually not publicly available. It should also be noted that authorities may deviate from these algorithms when granting permits and not all turbines are subject to these regulations - in contrast to the assumptions in this study. Moreover, hysteresis effects and effects of reduced wind speeds by turbine wakes are not considered, likely resulting in an underestimation of losses.

In general, shutdowns are required during periods of low wind speeds, no precipitation, and mild temperatures from April to October. A simplified overview of the generalized shutdown algorithms is provided in Table 1. The bat model applies the shutdown algorithm relevant to the state in which each turbine is located. The turbine is modeled to be completely shutdown for that time step, if all conditions are met at the same time.

2.2.3. Noise The german TA Lärm [20] stipulates that wind turbines must be curtailed to reduce noise immisions if certain noise thresholds at buildings are exceeded. These thresholds vary based on the type of residential area and differ between daytime and nighttime (10 PM to 6 AM), during which the thresholds are lower. The noise model operates through adjusting the turbines mode, and thus, the power curve, when the permissible noise thresholds are exceeded. The residential areas are applied within the model as immission points along with their thresholds. In order to model the adjusted operating modes, different operating modes with varying noise levels and modified power curves are computed generically. Power curves and noise level for reduced operating modes are computed through scaling the original power curve with factors depending on wind speed and rated power that were calibrated using existing power

curves. The noise model computes the total noise immission received by each immission point and iteratively reduces the operating mode of the turbine with the highest noise contribution until compliance with all thresholds is achieved. The resulting modes along with their power curves are subsequently used for computing the energy production.

2.2.4. Wake Wake losses describe the effect of the wind speed deficit behind a wind turbine caused by the extraction of energy from the wind and the resulting power deficit of the turbine behind it. Here, PyWake [6] in combination with the analytical Park2 model [21] was used for the wake computation. A wake decay constant of $k = 0.09$, recommended for onshore sites [21], was chosen. For each time step, the wind speed deficit and the resulting power loss is calculated for each turbine. The wake effect is considered in the simulations through buffering to a distance of 8 km.

2.2.5. Total For the total loss computation, bat, noise and wake model are applied in that order such that turbines that are shutdown do not exhibit further losses and the wake computation is based on the selected operation mode given by the noise model.

2.3. Economic evaluation

The economic evaluation is based on the hourly day-ahead market prices taken from from [22]. For a loss model m, wind turbine t, and a time step i with energy production $e_{i,t,m}$ and price p_i, we define the weighted annual electricity price for 2024 as

$$\mathrm{WEP}_m \coloneqq \sum_{i=1}^{8760} e_{i,t,m} \cdot p_i.$$

The loss of a model m is computed with respect to the the gross AEP, denoted by AEP_{gross}. Hence, relative losses in AEP and WEP are computed as the ratios

$$\frac{\Delta\mathrm{AEP}_m}{\mathrm{AEP}_{gross}} \coloneqq \frac{\mathrm{AEP}_{gross} - \mathrm{AEP}_m}{\mathrm{AEP}_{gross}}, \frac{\Delta\mathrm{WEP}_m}{\mathrm{WEP}_{gross}} = \frac{\mathrm{WEP}_{gross} - \mathrm{WEP}_m}{\mathrm{WEP}_{gross}}$$

respectively. The loss market value (LMV) is defined as the ratio of loss in WEP and in AEP:

$$\mathrm{LMV}_m \coloneqq \frac{\frac{\Delta\mathrm{WEP}_m}{\mathrm{WEP}_{gross}}}{\frac{\Delta\mathrm{AEP}_m}{\mathrm{AEP}_{gross}}}.$$

Hence, this value is a measure of how valuable the specific loss source is in terms of electricity prices compared to its mere energetic value.

3. Results

3.1. Importance of different energy loss types

The importance of the evaluated loss sources across Germany with respect to the AEP for the year 2024 is shown in Table 2. Among the evaluated loss sources, wake losses are the most significant with a value of 13.1 % across Germany. This deviates slightly from the value of 14.5 % found in [10] where the same framework was used with different meteorological time series. The difference highlights the dependency on the underlying time series. Both values fit well with the range of 5 to 15 % indicated in [15] for onshore wind farms up to 20 turbines. Nationwide, noise losses rank second with a

Table 2. Simulated energy yield losses across Germany for 2024.

Loss model	AEP Loss [%]
Wake	13.1
Noise	4.0
Bats	2.2
Total	17.7

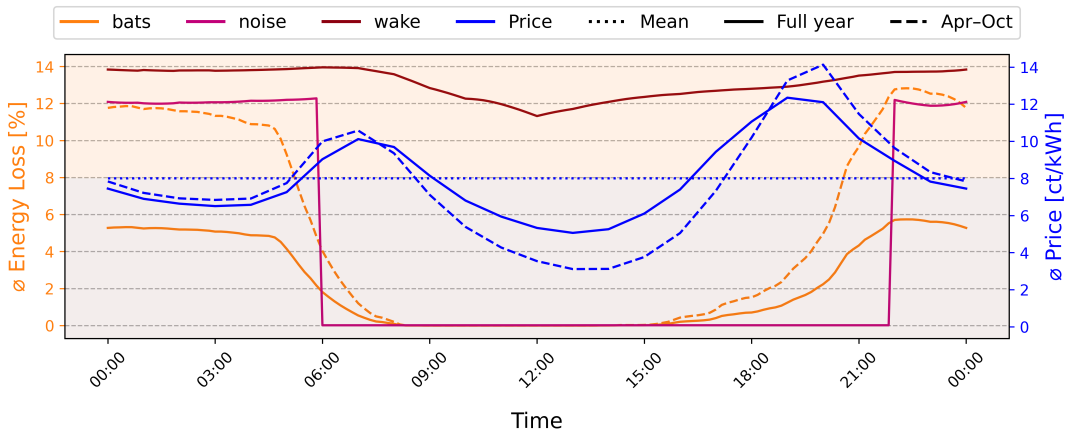


Figure 1. Diurnal cycles of simulated losses, normalized by the mean gross AEP, and mean day-ahead prices per time step across Germany. The dashed lines only take into account the period between April and October, i.e. the period of active bat protection measures. The background color reflects the mean price over all time steps. Time stamps are in CET.

value of 4.0 %. Comparable investigations of yield losses due to noise immission regulations are not known to the authors. Losses due to bat protection rank last with a value of 2.2 %. This aligns well with values of $1 - 3$ % that were found in [23], [24]. It should be emphasized that taking into account wake deficits and hysteresis effects for the bat model will likely increase the estimated losses. Values reported here for bat protection yield losses are expected to be slightly too low. The combined loss for wakes and curtailment due to noise and bat protection was simulated to be 17.7 % across Germany. Simply adding up the individual losses would result in a combined loss of 19.3 %, resulting in a relative overestimation of ≈ 9 %. Consequently, loss interactions influence the estimation of net yields and should be accounted for.

3.2. Temporal variations in energy losses

Figure 1 shows the diurnal cycles of losses normalized by mean gross AEP across all turbines and time steps as well as mean electricity prices over the whole year 2024. Additionally, in dashed lines, the averages taken between April and October are shown in order to assess the active period of bat protection measures.

Several aspects are noteworthy. First, electricity prices show a huge variation throughout the day. The diurnal averages are relatively low during the night. They begin to rise between 3 AM from around 6.5 ct/kWh to 10 ct/kWh at 7 AM. Afterwards, the average electricity prices decline, reaching their lowest point with 5 ct/kWh around noon. Afterwards, they rise again until they reach their highest point of 12 ct/kWh in the late afternoon. The normalized wake losses are slightly lower around noon. Note that simulations were done with a constant wake decay constant. Therefore, variations in wake recovery introduced by stability conditions are not accounted for. The reductions in normalized wake losses around noon purely stem from normalization effects, because the energy production at that time is below the daily average. Apart from this effect, they show no systematic variation with time of day. However, both losses due to noise and bats occur only during night time, the latter also in the early morning/late evening. Losses due to bat shutdowns start earlier in the evening as shutdowns start around dawn, whereas losses due to noise regulations only apply from 10 PM onwards. Consequently, losses due to noise regulations mostly occur at times of low electricity prices, whereas losses due

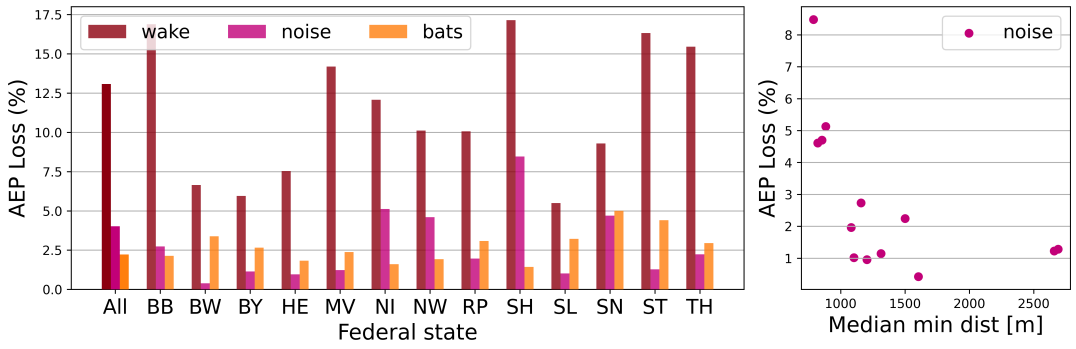


Figure 2. Left: Cumulated losses in AEP in percent for the year 2024 per federal state in Germany, showing great regional variations. City states Bremen, Hamburg and Berlin are omitted here for lack of bat protection regulations. Right: The cumulated AEP loss per federal state against the median of the minimal distance of a turbine to a residential area, where lower distances show a relation with higher losses.

to bat protection regulations also fall within the period of high energy prices in the afternoons and partially in the mornings. Moreover, the price effects are even more prominent in the period between April and October when bat protection measures are active. Another aspect of losses due to bat protection is that they occur at times of low wind speed, thus, low power feed-in from wind energy, and hence, higher prices. This aspect will be further discussed in Sect. 3.4.

3.3. Regional variations of energy losses

Factors such as wind availability, wind farm configurations, and federal regulations are important inputs for the loss models and vary significantly among federal states. Simulation results in $\frac{\Delta \mathrm{AEP}_m}{\mathrm{AEP}_{gross}}$ per federal state in Germany are presented in Figure 2.

All loss types exhibit strong regional differences. As expected, wakes are the main source of energy loss across all states. Nevertheless, variations in their extent are evident. They range from 6 % to 17 % across the federal states. For instance, northern states like Schleswig-Holstein (SH) and Mecklenburg–Western Pomerania (MV) experience higher losses compared to southern states like Bavaria (BY) and Baden-Württemberg (BW). Those effects are likely correlated with wind farm sizes. Northern federal states have a much higher capacity density [25] than southern federal states.

While noise losses rank second overall, their magnitude ranges from below 1 % in Baden-Württemberg (BW) to around 8 % in Schleswig-Holstein (SH). Noise losses are primarily dependent on the distance between turbines and residential areas as well as density of turbine placing. The former can be seen in the right panel, where the noise loss per federal state is depicted against the median of the minimal distance between turbines and residential areas, showing a relationship of lower losses with increasing minimal distance. Differences of this distance between the federal states stem from varying approaches concerning the distance of residential areas and wind energy areas - for example, Hesse stipulates a distance of at least 1000m, whereas Lower Saxony (NI) allows for distances as low as 2 times the turbines total height [26]. Varying data quality for the categorization of residential areas among federal states is also likely to have some influence on the results. Finally, higher capacity densities naturally lead to more noise emissions, and thus, higher yield losses.

Losses due to bat protection regulations are subject to state-specific regulations as shown in

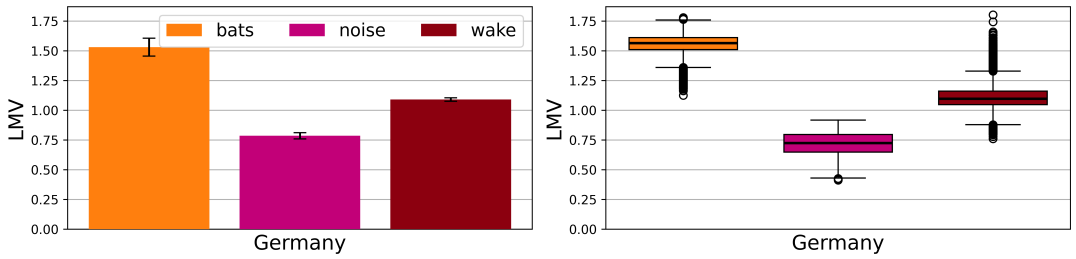


Figure 3. Left: The loss market values for the entire country of Germany. The black lines illustrate their spread across all federal states. While being the largest energy loss source, wake effects exhibit only marginally elevated LMV, whereas bat curtailment have a small energetic impact that is economically much higher. Right: The spread of the loss market values across all turbines in Germany.

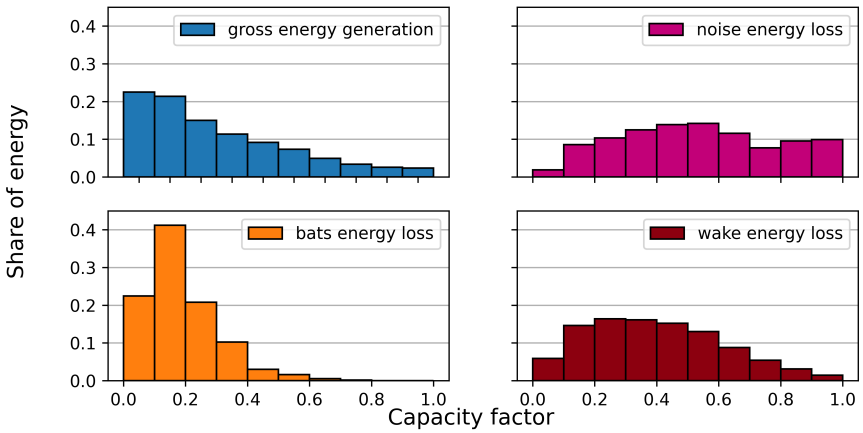


Figure 4. The share of energy production (top left) and energy loss (top right to bottom right) with respect to the capacity factor per time step.

Table 1. Moreover, they are affected by varying meteorological conditions at the sites. Indeed, we observe higher losses for states like Saxony (SN) and Saxony-Anhalt (ST) with higher cut in wind speeds, i.e. stricter shutdown algorithms, and for states like Baden-Württemberg (BW) with lower wind speeds. On the other hand, states with less stringent rules and higher wind speeds like Schleswig-Holstein (SH), where the time period for which the rules hold only ranges from mid May to the end of September, exhibit less losses.

Overall, all sources of energy loss show great regional variations that provide valuable insights for project developers and policymakers.

3.4. Market value of losses

Interestingly, while the loss values themselves vary greatly between states, a general trend can be observed regarding their relative loss market value. The left panel of Figure 3 displays the loss market values (LMV) for Germany, with the spread across all federal states illustrated by the black lines. Notably, the loss market values remain relatively stable across states for a given loss type, but show great differences between the different loss types. The LMV was found to be 1.5 for the bat model, 1.1 for wake losses, and 0.8 for the noise model. Thus, across Germany,

wake losses are economically similarly relevant as energetically. This can be different for a single turbine as shown in the left panel of Figure 3. While the loss in AEP is significantly lower for losses due to bat protection than for losses due to noise, their economic equivalent, the loss in WEP, is slightly higher. The right panel of Figure 3 illustrates the spread of the loss market values between the turbines. There is a noteworthy variation across the turbines for all three loss market values. However, the overall tendency (below/above 1) is stable across the models for noise and bats.

In addition to the diurnal effects shown in Figure 1, the respective meteorological conditions play an important role for this effect. Figure 4 shows the share of generated energy and energy losses with respect to capacity factors. Notably, noise losses occur during periods of both low and high energy production, but their share is disproportionately high in times of high energy production. Contrarily, over 80 % of power losses due to bat protection occur at time of capacity factors below 0.3. Low energy production from wind energy is often correlated with high electricity prices. Wake losses are underrepresented in the very low energy production range with capacity factors below 0.2, and slightly higher share in the factors 0.2 - 0.5.

4. Conclusion

By simulating wind power losses for wakes, bat protection and noise immission for the German onshore wind fleet and evaluating their market value, this paper highlights the importance of regional and time dependent loss evaluations. Energetically, wake losses are the dominant source of loss, followed by losses due to noise, and finally bat protection regulations. All sources of loss exhibit substantial regional variations, resulting from varying meteorological conditions, farm layouts and regulatory measures. We found that assessing losses by AEP alone is not sufficient - their timing is crucial. Wake losses were shown to only marginally vary across the day, whereas losses due to noise regulations and bat protection measures occur only around nighttime. The latter further occurs at dawn and low wind speeds and high electricity prices, whereas noise-related losses mostly occur during times of low electricity prices. Nevertheless, different sources of loss occur simultaneously, and their interactions prove to be non-negligible. The total energetic loss accounting for interactions was 17.7%, compared to 19.3% from simply summing up the individual losses.

Electricity price effects were captured through the introduction of the loss market value that provides a transparent and easily computable metric. Results showed that the LMV of losses due to bat protection shutdowns is the largest with a value of 1.5, followed by the value for wakes of 1.1 and the value of 0.8 for noise regulations. Consequently, energetic losses do not translate one-to-one into economic losses. As the share of wind energy in the energy system increases, the relevance of the LMV is likely to increase due to an increased impact of wind power feed-in on the electricity price. Thus, time-resolved loss modeling combined with market-based evaluations is essential for informed regulation, system planning, and operational strategies.

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