



# Evaluation of the Impact of Environmentally Driven Curtailment Regulations on Wind Farm Energy Production

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## Abstract

Environmentally driven curtailment strategies—based on increasing wind turbine cut-in speeds during high bat activity—are increasingly adopted in wind energy regulations worldwide. These measures, typically enforced during summer nights, aim to reduce bat mortality but lead to energy losses that can compromise the economic performance of wind farms. This study assesses the impact of such regulations by analyzing three key variables that influence curtailed energy: mean wind speed, wind variability, and turbine design, characterized through specific power (the ratio of rated power to rotor swept area). A combined approach is proposed, integrating a theoretical energy model with real performance data from 130 commercial wind turbines, enabling a comprehensive evaluation across a wide range of wind regimes and turbine configurations. The results show that curtailed energy increases significantly at low-wind sites and for turbines with lower specific power. Wind variability also has a notable influence, with contrasting effects depending on the wind class. Although the study is based on the regulatory framework under development in Spain, the methodology is generalizable to other regions. The findings provide valuable insights for developers and policymakers, supporting the design of strategies that balance biodiversity conservation with the economic sustainability of wind energy deployment.

**Keywords** Bat mortality mitigation · Energy curtailment · Environmental regulation · Wind energy · Wind turbines

## 1 Introduction

Wind energy is a form of renewable generation that is gaining increasing prominence on a global scale. However, its expansion sometimes presents challenges that must be considered in relation to wildlife conservation, including bat populations [1, 2]. Bats are essential to ecosystems due to their role in insect control and pollination. Nevertheless, wind turbines pose a significant threat to these species, resulting in fatal collisions [3–5].

Among the existing measures to mitigate bat mortality associated with wind energy developments, production

curtailment during specific periods stands out. In practical terms, curtailment involves adjusting the turbines' cut-in speed—that is, the wind speed at which turbines begin generating power—during periods of high bat activity. This adjusted threshold is typically set at 5–6 m/s, as bats are less active above these wind speeds. This technique has been the subject of numerous studies that have demonstrated its effectiveness and provided data on its optimal implementation [6–8]. In fact, it is even being implemented as a mandatory measure in some regulatory frameworks such as in Spain [9], where it is proposed to stop wind turbines during the nights from July to October when the wind speed is less than 6 m/s, unless operators can prove that there is no effect on bats populations. However, this measure entails a reduction in energy output, as turbines are prevented from operating during certain low-wind conditions, which—although typically moderate—lead to a reduction in the revenues initially expected by wind farm operators. While there are several studies that analyze the implications of curtailment due to other technical [10–12] or environmental reasons, such as noise mitigation [13, 14], to the best of the authors'

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knowledge, there is no work that examines the overall and widespread impact of curtailment regulations aimed at bat protection.

Environmentally driven curtailment is carried out by increasing the cut-in speed of wind turbines (which typically ranges from 2 to 3 m/s by default) to levels above which bats tend to be less active. In the literature, cut-in speeds between 4.0 m/s and 6.9 m/s have been proposed, resulting in bat mortality reductions ranging from 42.5% to 93%. The implementation of this strategy is mainly focused on the summer and autumn seasons, from dusk until dawn, coinciding with the periods of peak bat activity and migration.

A literature review has been conducted to synthesize the most relevant scientific studies addressing the impact of curtailment strategies on wind farm energy production. The review focuses on research analyzing bat mortality reductions associated with increased turbine cut-in speeds in operational wind farms across a range of geographic regions.

Arnett et al. [15] presented the results obtained at the Caselman Wind Project in Pennsylvania (United States). The authors concluded that increasing the turbine cut-in speed from 3.5 m/s to 5.0 m/s or 6.5 m/s significantly reduces bat mortality. Their analysis found that implementing curtailment strategies decreased nocturnal bat fatalities by 44% to 93%, with an annual energy loss of less than 1% (specifically, 1% for curtailment at wind speeds below 6.5 m/s and 0.3% for curtailment at wind speeds below 5 m/s).

Hayes et al. [16] reported results following the implementation of a smart curtailment strategy based on real-time bat activity detection. The application of this approach led to a significant reduction in bat fatalities compared to control turbines. Specifically, bat mortality was reduced by 84.5%. Additionally, the authors noted that curtailment time was reduced by 48% compared to standard curtailment rules (i.e., without the use of bat activity sensors), with an associated annual energy and revenue loss of 3.2%. Although this annual energy loss is relatively high, it is important to note that the study proposed a cut-in speed of 8 m/s, which is substantially higher than that used in most other studies.

Adams et al. [17] conducted a meta-analysis of 36 studies. The results of this analysis indicated an average reduction in bat fatalities of 63%.

Maclaurin et al. [18] presented a study analyzing 18 curtailment scenarios, including cut-in speeds of 5.0, 6.0, and 6.9 m/s and curtailment periods ranging from mid-July to late October, as well as from April to October. The study focused on assessing energy losses, concluding that annual production losses would be 0.5%, 1.3%, and 3.8% for cut-in speeds of 5.0 m/s, 6.0 m/s, and 6.9 m/s, respectively.

Good et al. [19] presented a study analyzing how the combination of curtailment strategies and the use of acoustic

deterrents can reduce bat mortality. The study concluded that implementing curtailment alone at wind speeds below 5.0 m/s reduced bat fatalities by 42.5%, whereas combining curtailment with acoustic deterrents increased this reduction to 66.9%. The results reported by Bennet et al. [20] indicated that increasing the cut-in speed from 3.0 to 4.5 m/s during periods of peak bat activity reduced mortality by 54%.

The study conducted by Hayes et al. [21] introduced a simulation-based approach to estimate generation losses across several wind farms in the United States. Specifically, the authors compared the performance of standard and smart curtailment strategies (the latter based on real-time detection of bat activity). In the analyzed scenarios cut-in speeds ranging from 5 to 7 m/s were considered, resulting in energy losses between 0.148% (5 m/s) and 1.130% (7 m/s) under standard curtailment, and between 0.034% (5 m/s) and 0.222% (7 m/s) under smart curtailment.

The study presented by Thurber et al. [22] examined the economic implications of applying curtailment measures in wind farms located in the province of Ontario, Canada. The results showed that implementing curtailment strategies across the province's wind farms would reduce annual energy production from 12.09 to 12.04 TWh, corresponding to a decrease of 0.42% in generated energy.

Table 1 provides a summary of the main characteristics and findings from the studies reviewed in this literature analysis. As shown, most studies assess the effectiveness of curtailment strategies in reducing bat mortality. The reported reductions in mortality vary considerably across studies, largely depending on the cut-in speed applied in the curtailment strategy and the local conditions of each project. Reported reductions range from 42% (observed in [19] with a cut-in speed of 5 m/s) to 84.5% (reported in [16] with a cut-in speed of 8 m/s).

Regarding previous studies focused on analyzing the energy associated with curtailment strategies, two articles have been identified within the reviewed literature [15, 16]. In addition to field investigations estimating bat mortality reduction, these studies also evaluated the associated energy losses, which ranged from 0.3% (reported in [15] for a cut-in speed of 5 m/s) to 3.2% (reported in [16] for a cut-in speed of 8 m/s) of annual energy production. Additionally, three studies [18, 21, 22] were identified in which the primary objective was to assess energy losses through simulation. The estimated annual losses in these studies ranged from 0.148% (in [21] for a cut-in speed of 4.5 m/s) to 3.8% (reported in [18] for a cut-in speed of 6.9 m/s).

The main contribution of the present work lies in the estimation of the impact of curtailment measures (taking as a reference the regulatory framework currently under development in Spain) on the energy production and economic

**Table 1** Summary of the main findings from the studies analyzed in the literature review

Work	Year	Proposed cut-in speed	Mortality reduction	Curtailment periods	Quantified energy loss
[15]	2010	5.0 m/s and 6.5 m/s	44% to 93% reduction	July 27 – October 9 (2008), July 26 – October 8 (2009), nighttime	0.3% (5.0 m/s), 1.0% (6.5 m/s)
[16]	2019	8.0 m/s	84.5% reduction	July 15 – October 31, nighttime	3.2% of annual production
[17]	2021	4.0 m/s to 7.0 m/s	Average reduction of 63%	Not specified, generally nighttime	Not addressed
[18]	2022	5.0 m/s, 6.0 m/s, 6.9 m/s	Not addressed	July 15 – October 15, nighttime	0.5% (5.0 m/s), 1.3% (6.0 m/s), 3.8% (6.9 m/s)
[19]	2022	5.0 m/s	42.5% (curtailment only), 66.9% (curtailment + deterrents)	August 1 – October 15, nighttime	Not addressed
[20]	2022	4.5 m/s	54% reduction	December 31 – May 1, nighttime	Not addressed
[21]	2022	5.0–7.0 m/s (increments of 0.5 m/s)	Not addressed	August 1 – October 15, nighttime	Standard curtailment: 0.148%–1.130%
[22]	2023	5.5 m/s	Not addressed	July 15 – September 30, nighttime	0.42%

performance of wind farms, through the modeling of wind energy output—following a similar approach to that of previous studies such as [18, 21] and [22]. However, those studies focus on specific case studies, based on the environmental and wind conditions of particular sites. In contrast, this paper adopts a broader, site-independent approach, aiming at characterizing the impact of curtailment measures as a function of typical wind conditions across different locations.

As such, the findings of this study may be of interest to researchers working on the mitigation of wind energy impacts on bat populations, as well as to those involved in environmental assessment and wind farm planning. In addition, the outputs presented here may be of practical use to project developers and regulatory authorities by providing

estimates of the expected curtailment impact depending on the wind resource profile of a given site.

The remainder of the paper is organized as follows. Section 2 describes the analytical framework used to estimate wind energy production and curtailed energy losses, introducing the wind behavior model, the theoretical turbine power curve, and the energy calculation methodology. Section 3 presents a theoretical approach to quantify curtailment losses as a function of wind class and turbine design, using a generic power curve parametrized by specific power. Section 4 complements this with a data-driven analysis based on real wind turbine models, providing a more detailed assessment of curtailment impacts under realistic conditions. This section also includes a sensitivity analysis with respect to mean wind speed and culminates in the evaluation of two real-world case studies. Finally, Sect. 5 discusses the main conclusions of the study.

## 2 Energy Curtailment Calculation Model

### 2.1 Wind Behavior Model

To estimate the wind potential at a given site and subsequently evaluate the energy produced by a wind farm—as well as the generation losses associated with curtailment measures—it is essential to have sufficient information about wind behavior in terms of speed, frequency, and direction (the latter being relevant when considering wake losses). The analysis of wind speed time series allows to determine the shape parameter  $k > 0$  and scale parameter  $C > 0$  of the Weibull statistical distribution, which can then be used to estimate the probability or frequency of occurrence of a given wind speed  $v \geq 0$  [23, 24]:

$$p(v) = \frac{K}{C} \cdot \left(\frac{v}{C}\right)^{K-1} \cdot e^{-\left(\frac{v}{C}\right)^K}. \quad (1)$$

The scale parameter  $C$  defines the horizontal stretching of the Weibull curve and is directly related to the mean wind speed. For a given shape parameter  $k$ , higher values of  $C$  correspond to higher average wind speeds at the site. In contrast, the shape parameter  $k$  affects the form of the distribution: as  $k$  increases, the curve becomes narrower and more peaked, with wind speeds increasingly concentrated around the scale parameter  $C$ .

This study proposes an analysis of the impact of curtailment under different typical wind conditions. To this end, the classification of wind turbines defined in the IEC 61,400 standard, published by the International Electrotechnical Commission, is used as a reference. This standard establishes the wind conditions that turbines must withstand to

be certified under a given class. While the IEC 61,400 standard defines wind classes for turbine design purposes, these classes are widely used as a practical reference to characterize the wind resource at a given site, which is the approach adopted in this study.

Therefore, high-, medium-, and low-wind sites are defined in this work as those with average wind speeds of 10.0 m/s, 8.5 m/s, and 7.5 m/s, respectively. However, as previously introduced, wind behavior is better described by the shape and scale parameters of the Weibull distribution. For this reason, it is necessary to assume a typical variability range for the Weibull shape factor,  $k$ , within the interval [1.6–2.4], which allows the scale parameter of the Weibull distribution to be determined using Eq. (2):

$$C = \frac{v_m}{\Gamma(1 + \frac{1}{k})}, \tag{2}$$

where  $v_m$  is the mean wind speed and  $\Gamma(\cdot)$  is the Gamma function.

This approach enables the analysis of a set of representative wind resource conditions that can be used to illustrate curtailment-related energy losses in a given wind project, depending on the local wind characteristics at the site.

### 2.2 Wind Turbine Power Curve

In order to evaluate the energy produced by a wind turbine, it is necessary not only to consider the wind conditions at the site, but also the technical characteristics of the turbine itself. This requires knowledge of the power curve, which describes the relationship between the wind speed and the electrical power output of the turbine. In practice, the power curve is provided by the manufacturer and determined based on a set of standardized tests. The power curve of a wind turbine is defined by key parameters such as the cut-in speed  $v_{ci}$ , cut-out speed  $v_{co}$ , rated wind speed  $v_{rated}$ , and rated power,  $P_{rated}$ . A typical wind turbine power curve begins generating power at the cut-in speed. From that point, the output increases approximately cubically with wind speed until the rated power is reached. From that speed onward, the power output typically remains constant up to the cut-out speed (although some turbine models may limit power output slightly before cut-out, leading to a gradual decrease).

Since the actual power curve of a modern wind turbine is often proprietary and not always publicly available, many studies rely on an idealized representation to estimate energy production. In the absence of the manufacturer-provided curve, the theoretical power curve  $P(v) \geq 0$  is commonly defined as a piecewise function of wind speed  $v$ , divided into three characteristic regions.:

$$P(v) = \begin{cases} 0 & v < v_{cut-in} \\ \frac{1}{2} \rho A C_p(v) v^3 & v_{cut-in} \leq v < v_{rated} \\ P_{rated} & v_{rated} \leq v < v_{cut-out} \\ 0 & v \geq v_{cut-out} \end{cases}, \tag{3}$$

where  $\rho$  is the air density (typically 1.225 kg/m<sup>3</sup>),  $C_p$  is the power coefficient and  $A$  is the area swept by the rotor.

### 2.3 Energy Calculation

Once the wind behavior has been characterized, the energy produced by the wind turbines can be evaluated. Considering a wind farm composed of a set of  $N_i$  turbines and assuming no wake interference between them, the total energy produced is given by:

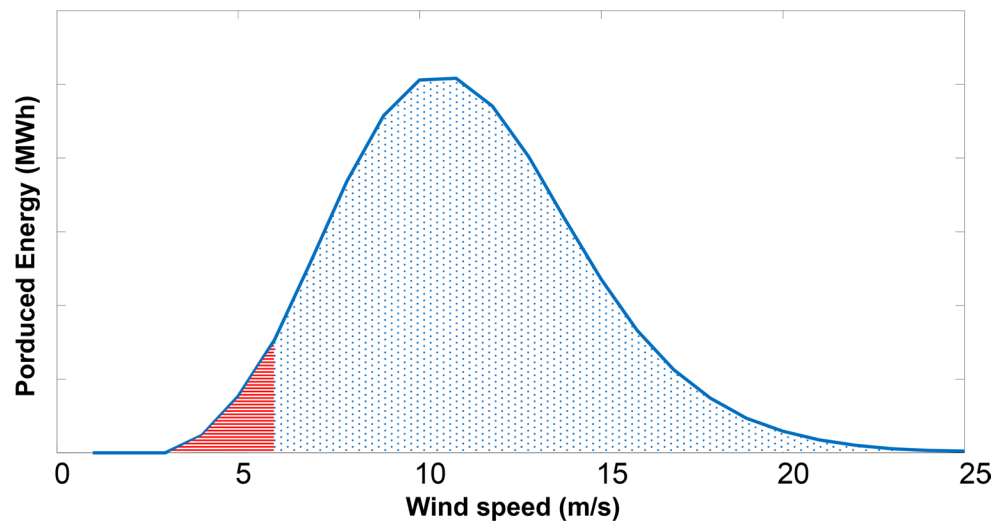
$$E_{WF} = T \sum_{i=1}^{N_{WT}} \int_{v_{cut-in}}^{v_{cut-out}} P(v_i) p(v_i) dv, \tag{4}$$

where  $E_{WF}$  is the total annual energy produced by the wind farm (WF = wind farm),  $N_{WTS}$  is the number of turbines,  $P(v_i)$  is the power curve of the turbine,  $p(v)$  is the wind-speed PDF, and  $T$  is the number of hours in a year (8760 h). The integration is taken over  $v \in [0, \infty)$  (equivalently up to  $v_{co}$  since  $P(v) = 0$  beyond cut-out).

It is important to note that wake losses have not been considered in this study, as their estimation requires detailed knowledge of the exact location of each wind turbine in the project, as well as accurate orographic data of the site, among other factors. Nevertheless, neglecting wake effects results in a potential bias in the estimation of the energy not generated due to curtailment when this loss is expressed relative to the wind-farm annual energy production. This is because wake losses are more pronounced at low wind speeds [25, 26], meaning their relative impact is greater within the range between the turbine’s cut-in speed and the wind speed threshold used for curtailment due to bat activity. Therefore, within the scope of this work, this simplification is considered acceptable, as the proposed approach provides an upper bound for curtailment-related energy losses.

Figure 1 graphically illustrates an example of the calculation process for the energy produced by a wind turbine. The blue curve represents the product of the power curve and the probability of occurrence of a given wind speed—i.e., the integrand in Eq. (4). Accordingly, the annual energy produced by the turbine corresponds to the area under this curve, shown in blue. Similarly, the annual energy not supplied due to curtailment requirements at wind speeds above the turbine’s cut-in speed can also be determined. This curtailed energy corresponds to the area under the blue curve between the turbine’s cut-in speed and the wind speed threshold defined by the curtailment criterion, as shown

**Fig. 1** Illustration of the annual energy calculation and curtailed energy estimation based on the wind speed distribution and the turbine's power curve



in red in Fig. 1. However, since curtailment is typically applied only at night during certain months of the year, the calculation of curtailed energy must consider the fraction of total annual hours during which the curtailment constraint is active—in this case, from July 1 to October 31, during nighttime.

### 3 Theoretical Approach To Evaluating Curtailment Requirements Related to Bat Activity

As can be deduced from (3), the power curve depends on several key design characteristics: (i) the power coefficient, which varies with wind speed and depends on the operational conditions and the aerodynamic design of the blades; (ii) the swept area of the rotor, which is determined by the rotor radius,  $R > 0$ ; and (iii) the rated power,  $P_{rated} > 0$ , which is defined by the technical specifications of the electrical generator. The latter two parameters are combined in the so-called specific power,  $P_{spec}$  (spec=*specific*), defined as the ratio between the rated power and the rotor's swept area:

$$P_{spec} = \frac{P_{rated}}{A} = \frac{P_{rated}}{\pi R^2}. \quad (5)$$

In this context, it is important to highlight that wind turbine design choice vary depending on the wind resource characteristics at the site. The higher the wind speeds, the general trend is to use turbines with higher specific power, which implies shorter blades for the same rated power. This is mainly because, in high-wind locations, turbines operate more hours at rated power, making it less necessary to maximize energy capture at sub-nominal wind speeds—thus allowing for a cost-effective balance between turbine cost and energy output. Conversely, in low-wind locations,

the tendency is to reduce the specific power (by installing longer blades), which increases energy production at wind speeds below the rated value. In this case, the turbine is more expensive, but it enables greater overall energy generation.

The considerations discussed in the previous paragraph are highly relevant to the present study, as the energy not supplied due to curtailment strategies is directly influenced by the turbine design and the wind conditions at the site. Specifically, energy losses are expected to be greater for low specific-power turbines (typically installed in low-wind locations) than for high specific-power turbines (used in high-wind sites). In other words, the amount of curtailed energy increases as wind conditions worsen (i.e., lower scale parameters), and this effect is further amplified by the design characteristics of turbines tailored to low-wind environments. Therefore, this study proposes an energy evaluation that considers different types of wind turbines according to their suitability for each typical wind condition (as introduced previously in Table 2).

#### 3.1 Distribution of Specific Power in Operational Wind Turbines by Wind Class

In order to identify patterns between turbine design and site-specific wind characteristics, an analysis has been conducted on the distribution of specific power values across

**Table 2** Annual wind speed for the different wind turbine classes according to IEC 61,400

Wind turbine class	I (high wind)	II (medium wind)	III (low wind)	IV (very low wind)
Mean wind speed (m/s)	10.0	8.5	7.5	6.0
50 years extreme gust	70.0	59.5	52.5	42
Turbulence class (%) A:	18	18	18	18
B:	16	16	16	16

wind turbines installed in operational wind farms, categorized according to standard wind classes: Class I (high wind), Class II (medium wind), and Class III (low wind). The analysis is based on a data collected from several datasets [27–29] where each specific power value is weighted according to the number of turbines installed at each site. Although the database is not exhaustive, it can be taken as a reference, as each specific power value is weighted according to the number of turbines installed at each site, ensuring that, as far as possible, the aggregated distributions reflect real-world deployment intensity.

The boxplot shown in Fig. 2 illustrates the distribution of specific power values (in W/m<sup>2</sup>) across wind turbine classes I, II, and III, with each observation weighted according to the number of turbines per installation. The boxes represent the interquartile range (IQR), bounded by the 25th and 75th percentiles, while the central line indicates the median (50th percentile). Whiskers extend up to 1.5 times the IQR, and data beyond are considered outliers.

As expected, turbines designed for high-wind sites exhibit higher specific power values than those intended for low-wind locations. Class I turbines exhibit higher specific power overall, with a median of 400.2 W/m<sup>2</sup> and an interquartile range of 393.0–451.7 W/m<sup>2</sup>. This reflects their design for high-wind environments. Class II turbines show a lower central tendency, with a median of 322.1 W/m<sup>2</sup> and an IQR of 318.3–345.3 W/m<sup>2</sup>. Class III turbines, intended for low-wind sites, display the lowest values, with a median of 284.0 W/m<sup>2</sup> and IQR of 277.9–314.4 W/m<sup>2</sup>.

### 3.2 Theoretical Analysis of Curtailed Energy as a Function of Wind Class

The analysis of power density and wind turbine characteristics by wind class presented in the previous section is particularly relevant for the characterization of curtailment

losses associated with bat activity, as it provides a basis for the preliminary estimation of the share of energy production potentially affected by such curtailment, relying solely on the wind regime at the site under assessment (i.e., high-, medium-, or low-wind conditions).

For this analysis, a generic power curve is defined as a function of the turbine’s specific power, derived from the theoretical formulation introduced in Eq. (3). This approach is well suited for general-purpose analyses aimed at capturing performance trends across different wind classes and turbine configurations, without relying on proprietary manufacturer data. The model is based on fundamental physical principles and is fully parameterized through the turbine’s specific power, which serves as the key design variable.

The model is based on assuming a constant power coefficient,  $C_p$ , (a typical value of 0.42 has been assumed for this analysis) up to the rated wind speed. The rotor-swept area  $A$  is derived from the turbine’s rated power  $P_{rated}$  and its specific power  $P_{spec}$  based on the definition previously introduced in Eq. (5):

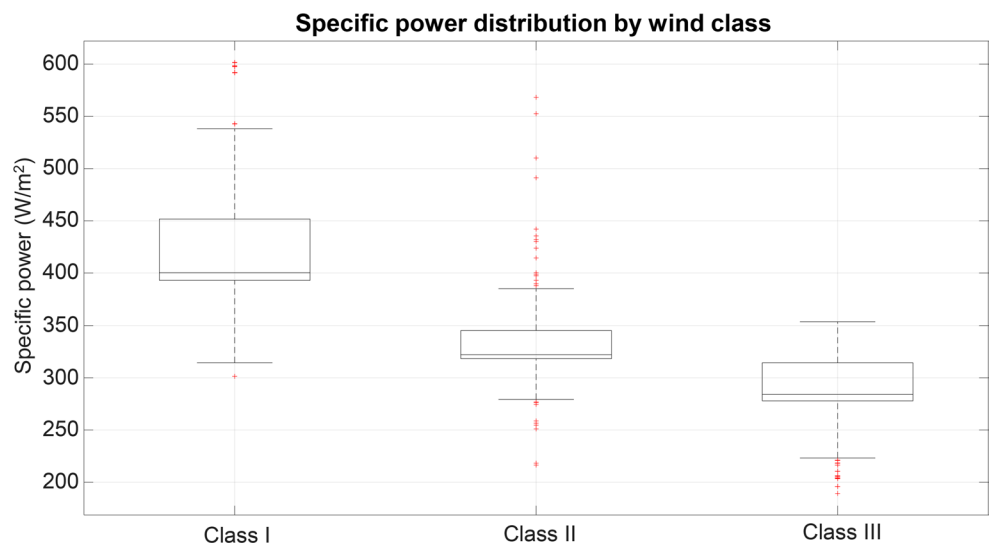
$$R = \sqrt{\frac{P_{rated}}{\pi P_{spec}}}, \tag{6}$$

Finally, the rated wind speed  $v_{rated}$  is computed from the wind power equation:

$$v_{rated} = \left(\frac{2P_{rated}}{\rho AC_P}\right)^{1/3}, \tag{7}$$

These expressions enable the construction of a theoretical power curve for any given  $P_{spec}$ , facilitating a consistent and flexible framework for comparative analysis across a wide range of turbine designs and wind regimes. Additionally, standard values are adopted for the cut-in and cut-out wind

Fig. 2 Boxplot of specific power by wind turbine class



speeds ( $v_{cut-in}=3$  m/s and  $v_{cut-out}=25$  m/s), consistent with typical commercial turbines. While simplified, this formulation captures the essential physics of turbine behavior and allows for representative energy production assessments without relying on manufacturer-specific performance data.

Following this approach, the energy curtailed due to bat activity restrictions during summer (understood hereinafter as July to October in the northern hemisphere) nights is estimated. The calculation is carried out using the methodology described in Section 2, along with the theoretical power curve parameterized by specific power, as defined in Eqs. (4)–(7). Typical specific power values for each wind class—identified in the analysis shown in Fig. 2—are used as a reference, and the corresponding standard mean wind speed for each class is considered.

Additionally, the shape parameter,  $k$ , of the Weibull distribution is assumed to vary between 1.6 and 2.4, allowing for the representation of typical wind variability at the site. Based on this, the scale parameter,  $C$ , of the Weibull distribution is determined using Eq. (2), which enables the estimation of both the annual energy production and the curtailed energy due to environmental curtailment requirements.

Figures 3 and 4 present the results of the theoretical analysis conducted for curtailment restrictions applied at wind speeds below 5 m/s and 6 m/s, respectively. These figures illustrate the dependence of curtailed energy losses on typical wind conditions, represented by three wind classes: high wind (mean speed of 10 m/s, shown in blue), medium wind (8.5 m/s, red), and low wind (7.5 m/s, yellow). The curves reflect the influence of both specific power and the Weibull shape parameter  $k$ , which is varied between 1.6 and 2.4 to account for site-level wind variability. For illustrative purposes, vertical lines indicating the 25th, 50th, and 75th percentiles of specific power are included, based on the distributions identified in Section 3.1. These percentile markers

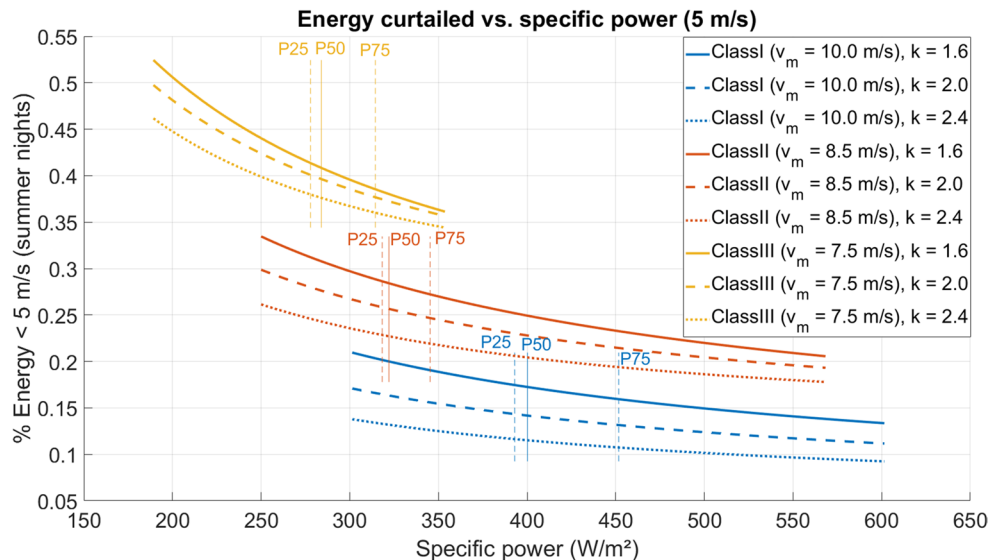
are not intended as limits, but rather as a reference to help interpret the range of turbine designs typically deployed in each wind class.

The results are expressed as the percentage of curtailed energy relative to the total annual energy production. Several trends emerge from the analysis. First, the relative curtailed energy increases as mean wind speed decreases, with low-wind sites (Class III) experiencing significantly higher relative losses. Second, turbines with lower specific power exhibit greater curtailed losses under the same wind conditions, due to their enhanced energy capture at low wind speeds, which increases the proportion of energy affected by curtailment.

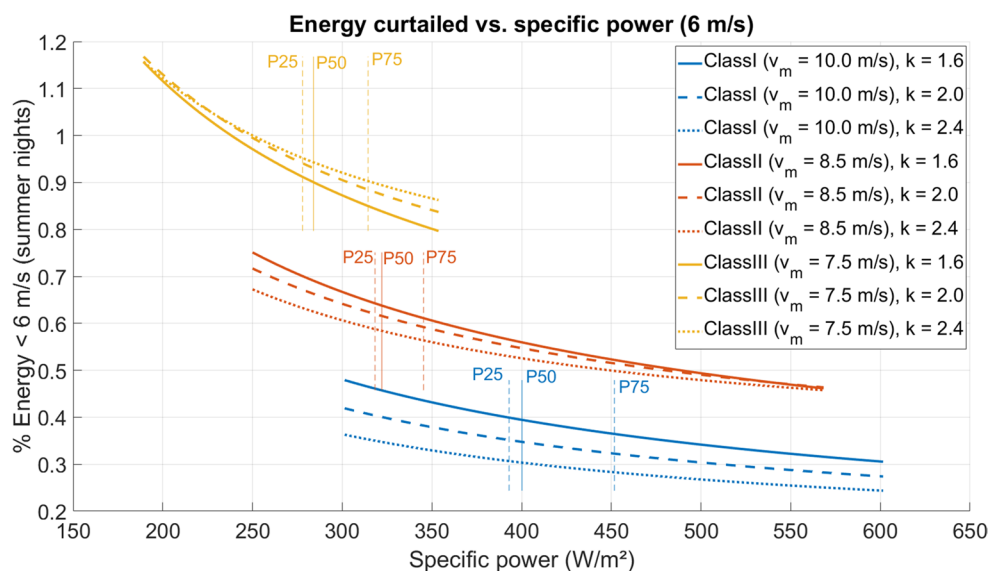
A third important trend is related to wind variability, represented by the Weibull shape factor  $k$ . In general, curtailed energy tends to increase as  $k$  decreases (that is, as wind becomes more variable) since a wider wind speed distribution implies a greater probability of wind speeds falling below the curtailment threshold. This pattern is observed for both 5 and 6 m/s thresholds across all wind classes, with one exception: in Class III under a 6 m/s curtailment threshold, the trend reverses. In this particular case, higher  $k$  values (lower variability) lead to greater curtailed losses. This occurs because, at low wind sites with high  $k$ , the wind speeds are more tightly concentrated around the mean. When the mean is close to the curtailment threshold, a large portion of the wind resource falls within the curtailed range, intensifying the impact of the restriction. Conversely, in high-wind sites, lower  $k$  values result in a broader distribution, increasing the likelihood of wind speeds occasionally dropping below the curtailment threshold and therefore increasing curtailed energy.

Overall, curtailed energy remains limited in high- and medium-wind sites, the impact becoming more pronounced under low-wind conditions. For a curtailment threshold

**Fig. 3** Percentage of curtailed energy for each wind class as a function of specific power. Curtailment restriction for  $v < 5$  m/s



**Fig. 4** Percentage of curtailed energy for each wind class as a function of specific power. Curtailment restriction for  $v < 6$  m/s



of 5 m/s, the estimated losses are below 0.21% for Class I, 0.34% for Class II, and 0.53% for Class III. When the threshold is increased to 6 m/s, these values rise to approximately 0.48%, 0.76%, and 1.17%, respectively.

These results should be regarded as preliminary, as they stem from a theoretical analysis based on simplified assumptions. In the following sections, more realistic scenarios will be explored using empirical data and site-specific configurations. Nevertheless, as will be shown later, the results presented here can be interpreted as an estimate of curtailed energy losses and may serve as a useful reference for initial assessments.

#### 4 Curtailed Energy Analysis Based on Real Turbine Data

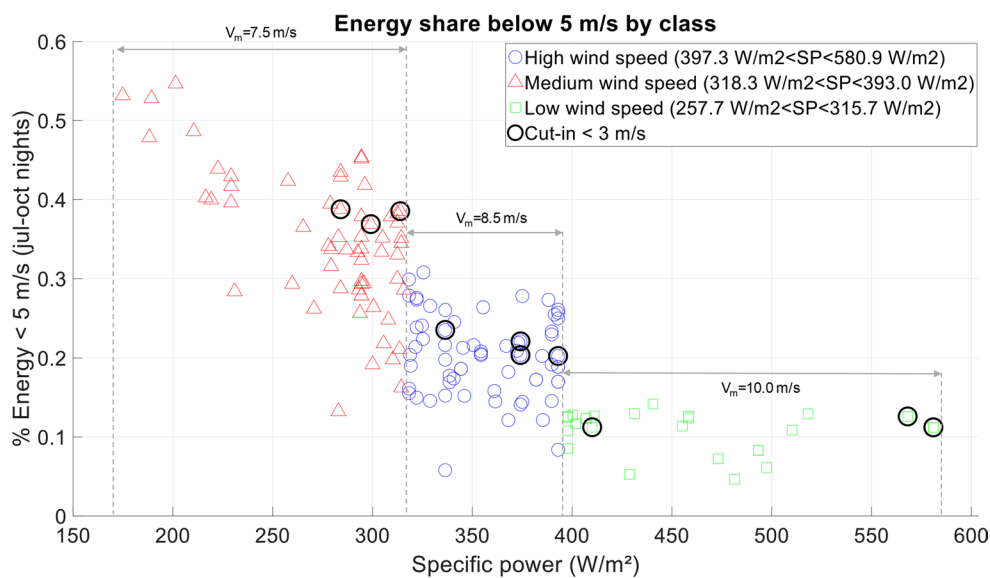
This analysis evaluates energy losses due to environmentally-constrained curtailment based on real wind turbine power curves obtained from [28] and the EMD WindPro database. From these databases, the following turbine-model information was extracted: the discrete manufacturer power curve (tabulated electrical power values across wind-speed bins), the rated power, the swept area and cut-in/cut-out wind speeds. The processed dataset includes 130 turbine models, all with nominal power ratings between 1 and 7.6 MW. Turbines have been classified according to their specific power to assign them to a particular wind class. This classification is an assumption, as the database lacks information on the certified wind class for some turbines. It is also important to highlight that, in practice, there is an overlap between the specific powers of different classes (as shown in Fig. 2). However, for the purposes of this study, this information is not critical, as it is mainly used to define typical wind regimes based on turbine-specific power — which,

as previously highlighted, is a turbine characteristic that strongly influences environmental curtailment losses.

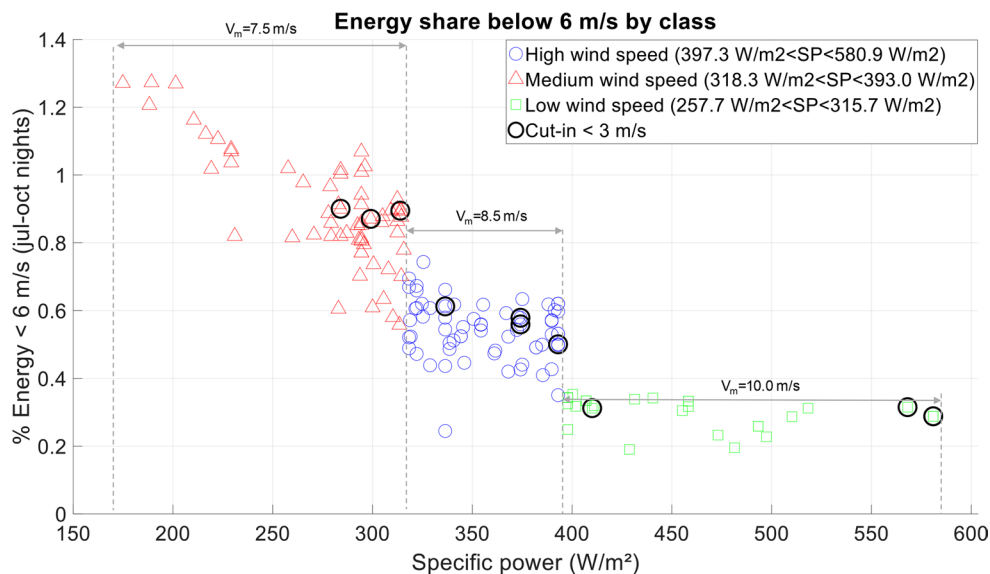
Following this approach, the dataset comprises 26 turbines with specific power values typical of high-wind conditions (Class I), 59 turbines classified as medium-wind (Class II), and 45 turbines associated with low-wind conditions (Class III). Thus, the approach consisted of assuming standard wind conditions for each case, with a mean wind speed of 10.0 m/s for turbines with specific power values ranging from 397.9 to 580.9 W/m² (typical of Class I turbines), a mean speed of 8.5 m/s for specific powers from 318.3 to 393.0 W/m² (typical of Class II turbines), and a mean speed of 7.5 m/s for turbines with specific power between 174.9 and 315.7 W/m² (characteristic of Class III turbines). The extracted power curves are used directly to compute annual energy produced and curtailed energy within the target wind-speed range, whereas rated power and swept area are combined to compute the specific power  $P_{\text{spec}}$ , which is used as a proxy to assign turbines to representative wind classes when certified wind-class information is unavailable. In all cases, wind speed distributions have been modeled using a Weibull function with a shape parameter of  $k=2$ , representing moderately variable wind regimes.

Figures 5 and 6 present the distribution of the percentage of energy curtailed below 5 m/s and 6 m/s, respectively, during summer nights for wind turbines classified according to their specific power. As observed, for high-wind conditions, the fraction of curtailed energy remains constrained between 0.05% and 0.15% for an increase in cut-in speed to 5 m/s, and between 0.2% and 0.35% for 6 m/s across all analyzed wind turbine models (blue markers) in this category. For medium-wind conditions, the analyzed turbine models (green markers) exhibit curtailed energy percentages ranging from 0.05% to 0.31% and 0.24% to 0.74% for an increase in cut-in speed

**Fig. 5** Distribution of energy generation (%) below 5 m/s during summer nights for real wind turbines classified by specific power



**Fig. 6** Distribution of energy generation (%) below 6 m/s during summer nights for wind turbines classified by specific power



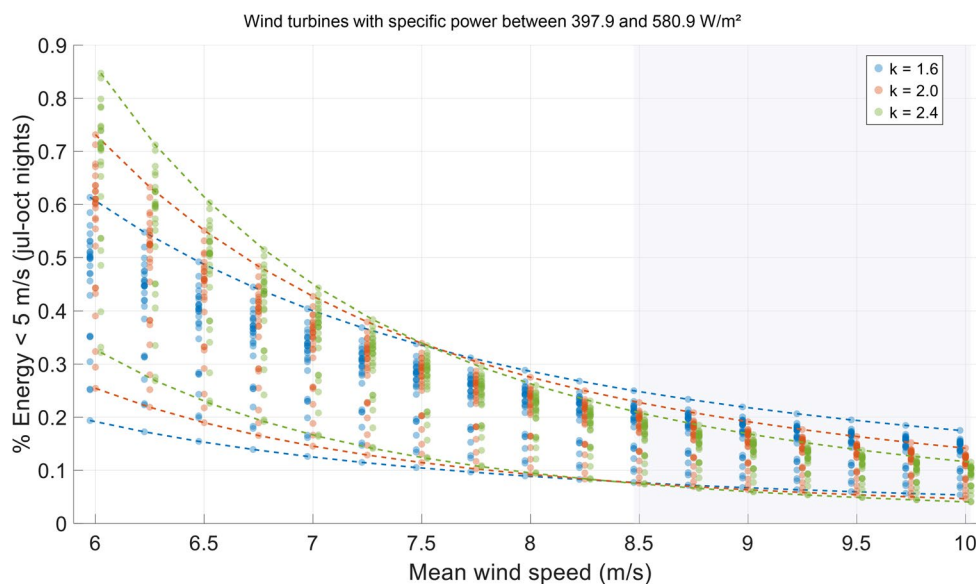
to 5 and 6 m/s, respectively. In contrast, for turbines designed for low-wind conditions (red markers), these percentages reach 0.13–0.55% for 5 m/s and 0.55–1.27% for 6 m/s.

It is also noteworthy that, as expected from the theoretical analysis presented in the previous section, there is a general trend of increasing curtailed energy as the specific power of wind turbines decreases. However, there are appreciable differences in curtailed energy among models with similar specific power. In contrast to the theoretical analysis in Section 3.2 (which assumes a constant power coefficient below rated conditions), the present results are based on manufacturer power curves. Therefore, the implied efficiency is not constant: it varies both across turbine models and with wind speed, reflecting differences in aerodynamic design as well as control and drivetrain behavior near cut-in and in the partial-load region. These performance differences become

even more pronounced when turbines operate at relatively low wind speeds, close to the cut-in threshold. In this regime, turbines often operate under operational constraints (e.g., minimum rotor speed and start-up/control requirements), which prevent operation at the optimal tip-speed ratio; consequently, the effective energy-conversion efficiency is reduced and may differ substantially between models.

Additionally, the figures highlight turbines with cut-in wind speeds below 3 m/s as, theoretically, the ability to start generating at lower wind speeds could imply a higher fraction of curtailed energy. However, as shown in the figures, there are no significant differences compared to turbines with cut-in speeds of 3 m/s or higher. This is attributed to the limited energy content in airflow at wind speeds between 2 and 3 m/s, as well as the reduced aerodynamic efficiency of wind turbines at speeds near their cut-in threshold.

**Fig. 7** Sensitivity analysis of curtailed energy for turbines with specific power between 397.9 and 580.9 W/m<sup>2</sup> (typical for Class I), under a curtailment threshold of 5 m/s

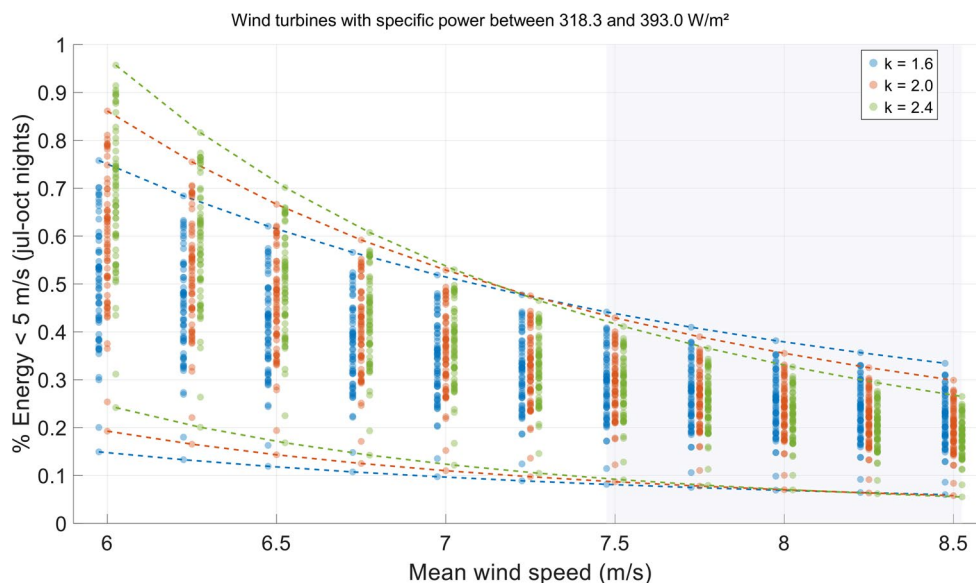


#### 4.1 Curtailed Energy Sensitivity To Mean Wind Speed with Real Turbine Models

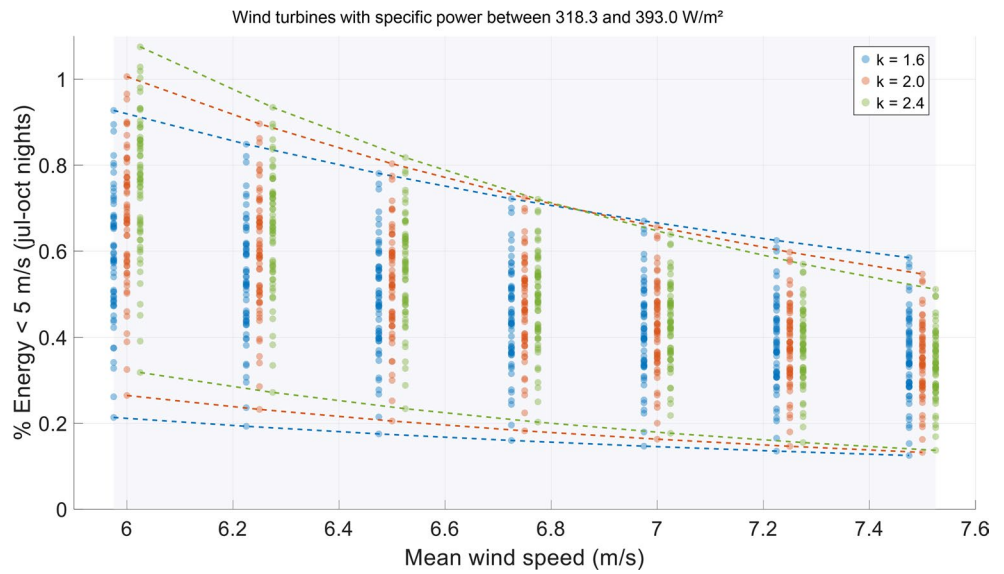
This section presents a sensitivity analysis aimed at evaluating the percentage of curtailed energy as a function of the mean wind speed, using real wind turbine data. The analysis is based on a dataset of commercial turbines categorized by their specific power, grouped into three standard wind classes (Class I, II, and III). For each class, the mean wind speed is progressively reduced to 6 m/s, which is generally considered the lower limit for economically viable wind farm deployment. By simulating each turbine’s energy production and curtailment losses under varying wind regimes, the analysis provides insight into how the interaction between wind conditions and turbine design affects curtailment performance in practical scenarios.

Figures 7, 8 and 9 show the results of the curtailed energy sensitivity analysis as a function of the average wind speed, for a curtailment threshold of 5 m/s, corresponding to wind classes I, II, and III, respectively. In these figures, the percentage of energy generated below 5 m/s during summer nights is computed for a wide range of real wind turbine models operating under different mean wind speeds and Weibull shape parameters. Figures 10, 11 and 12 present the same analysis but for a curtailment threshold of 6 m/s, again disaggregated by wind class. The horizontal axis represents the mean wind speed at the site, varied within the typical range for each wind class. Each data point represents the curtailed energy percentage calculated for a specific real-world wind turbine model, under a given combination of mean wind speed and Weibull shape parameter  $k$ . The points are color-coded according to the value of  $k$  (blue for  $k = 1.6$ ,

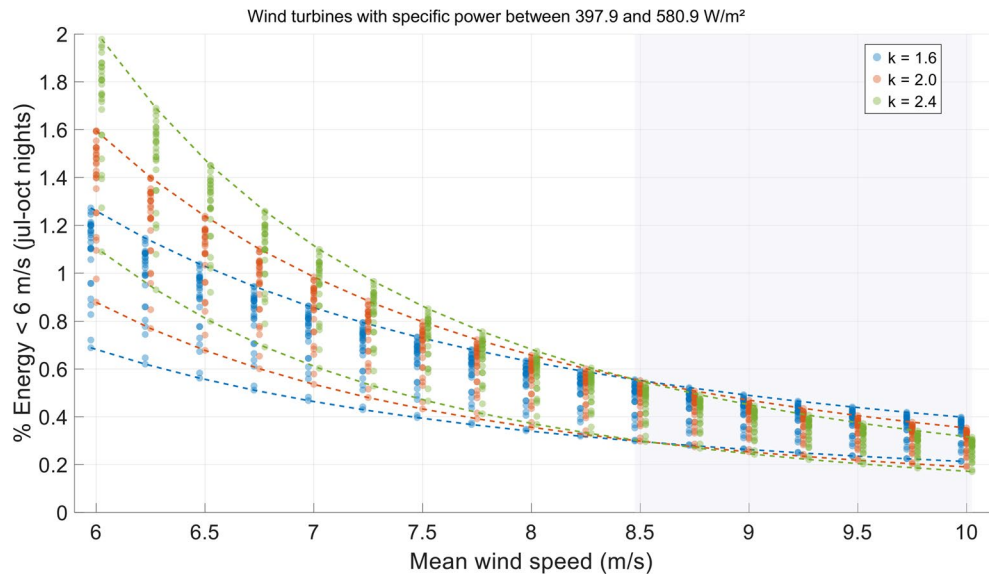
**Fig. 8** Sensitivity analysis of curtailed energy for turbines with specific power between 318.3 and 393.0 W/m<sup>2</sup> (typical for Class II), under a curtailment threshold of 5 m/s



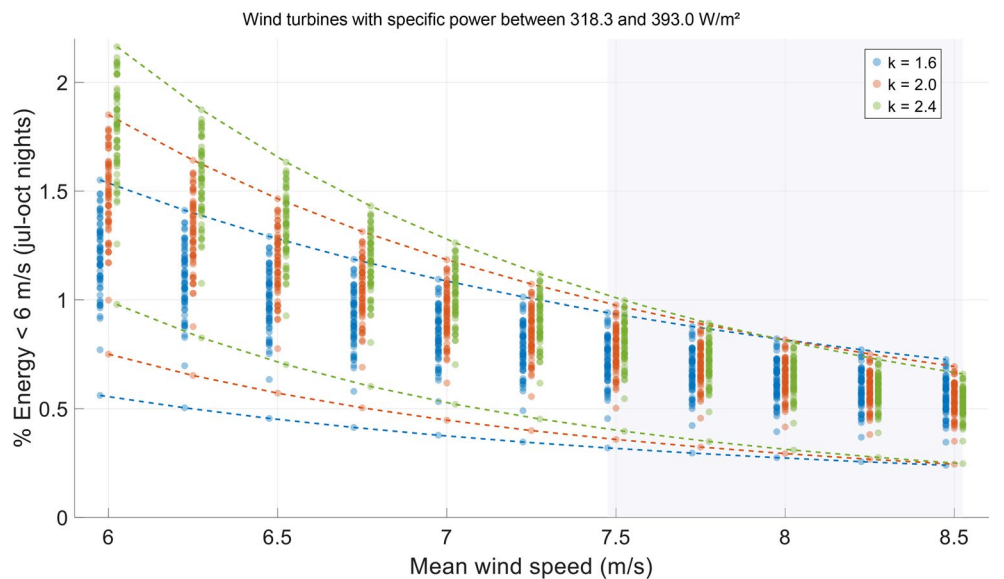
**Fig. 9** Sensitivity analysis of curtailed energy for turbines with specific power between 174.9 and 315.7 W/m<sup>2</sup> (typical for Class III), under a curtailment threshold of 5 m/s



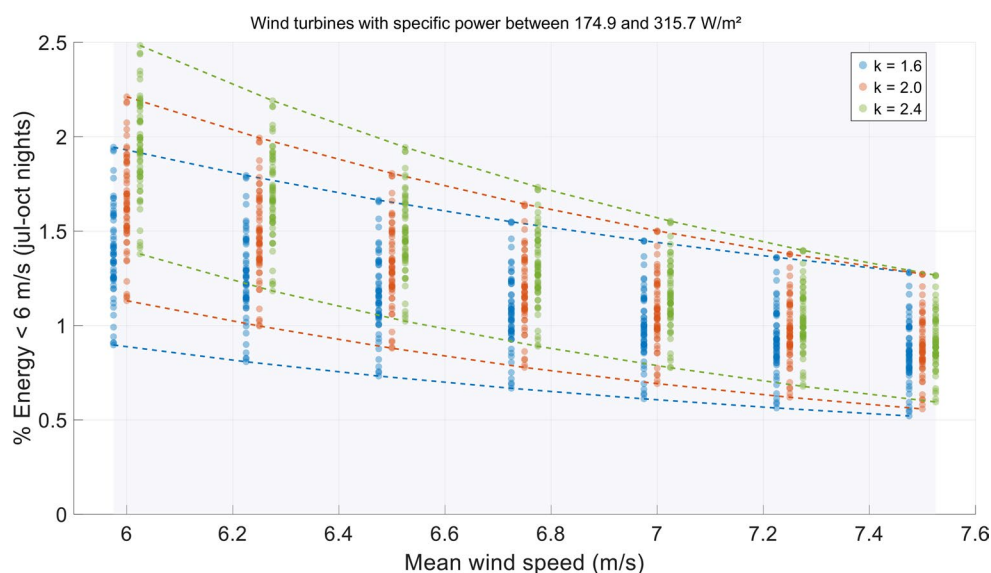
**Fig. 10** Sensitivity analysis of curtailed energy for turbines with specific power between 397.9 and 580.9 W/m<sup>2</sup> (typical for Class I), under a curtailment threshold of 6 m/s



**Fig. 11** Sensitivity analysis of curtailed energy for turbines with specific power between 318.3 and 393.0 W/m<sup>2</sup> (typical for Class II), under a curtailment threshold of 6 m/s



**Fig. 12** Sensitivity analysis of curtailed energy for turbines with specific power between 174.9 and 315.7 W/m<sup>2</sup> (typical for Class III), under a curtailment threshold of 6 m/s



red for  $k=2.0$ , and green for  $k=2.4$ ) to reflect different levels of wind variability typically encountered at wind farm sites. In addition to the individual turbine results, dashed lines indicate the minimum and maximum curtailed energy values observed at each mean wind speed. These envelopes help visualize the range of curtailment impacts due to differences in turbine design within the same wind class. Additionally, shaded areas represent the typical range of mean wind speeds at which turbines certified for a given wind class are commonly deployed. This reflects standard industry practice, where turbines are usually selected for wind conditions close to their design class to optimize economic performance and reduce equipment costs.

As illustrated in the figures, for high wind speed sites (Class I), curtailed energy losses remain relatively low and are consistently concentrated around a narrow range, regardless of the Weibull shape parameter  $k$ . This is evidenced by the limited dispersion in the results. For mean wind speeds equal to or above 8.5 m/s, curtailed energy losses remain below 0.28% for a curtailment threshold of 5 m/s, and below 0.59% for a threshold of 6 m/s, across all  $k$  values. These results suggest that in high-wind environments, curtailment due to environmental constraints—such as those imposed to mitigate bat activity—has a limited impact on overall energy production.

In contrast, for medium (Class II) and especially low wind speed sites (Class III), curtailed energy losses increase significantly and show a much wider range of variation. This increase is more pronounced for turbines with lower specific power, which are commonly installed in such environments to enhance energy capture at sub-nominal wind speeds. As seen in the figures, the lower the wind speed and the specific power, the steeper the rise in curtailed energy, particularly at thresholds close to the turbine's cut-in speed. As the mean wind speed decreases, the influence of the Weibull shape

parameter  $k$  becomes increasingly significant. For higher values of  $k$ , the wind speed distribution becomes more sharply peaked around the mean, which can intensify curtailment losses when the average wind speed is close to the curtailment threshold. This effect is especially noticeable in low-wind sites (Class III), where curtailed energy can be close to 2.5% under a 6 m/s curtailment threshold.

#### 4.2 Assessment of Environmentally Curtailed Energy in Real Wind Farms

This section proposes an evaluation of curtailed energy under the assumption that wind turbines are required to cease operation at wind speeds below 5–6 m/s during summer nights. The analysis focuses on two real wind farms where bat-related mortality issues have been reported [30, 31]. The first wind farm (WF1) is located in the region of Navarra, while the second (WF2) is situated in Castilla y León. The main characteristics of these wind farms are summarized in Table 3. For each case, the energy evaluation was carried out using historical wind data (2005–2023) from the EMD-WRF Europe+ dataset [32], processed in WindPro software and extrapolated to hub height at the geographical coordinates of each site.

The wind conditions at the two wind farms analyzed correspond to medium wind environments, with average wind speeds of 7.16 m/s at WF1 and 6.64 m/s at WF2, typical of IEC Class II sites. Furthermore, the specific power values of the turbines installed—322.1 W/m<sup>2</sup> for WF1 (GE 1.5sle) and 336.4 W/m<sup>2</sup> for WF2 (Gamesa G87/2000)—are consistent with turbines commonly used in Class II wind conditions.

As shown by the results in Table 4, curtailment at a wind speed threshold of 5 m/s during summer nights results in a loss of 0.22% of the annual energy production for WF1.

**Table 3** Key technical characteristics of the wind farms included in the analysis

Wind farm	Long	Lat	C (m/s)	k	V <sub>m</sub> (m/s)	Turbine Model	WT Number	Specific Power (W/m <sup>2</sup> )
WF1	-5.32	42.3196	8.08	2.41	7.16	GE 1.5sle	33	322.1
WF2	-2.47	41.3892	7.5	2.04	6.64	Gamesa G87/2000	25	336.4

**Table 4** Summary of curtailed energy results for the analyzed wind farms

Wind farm	Total Annual Energy (MWh)	Curt. <5 m/s (MWh)	Curt. <6 m/s (MWh)	Curt. <5 m/s (%)	Curt. <6 m/s (%)
WF1	160657.15	357.48	1233.20	0.22	0.77
WF2	142365.28	607.40	1614.70	0.43	1.13

When the curtailment threshold is increased to 6 m/s, the curtailed energy rises to 0.77%. Similarly, for WF2, curtailment at 5 m/s leads to a loss of 0.43%, increasing to 1.13% when the threshold is set at 6 m/s. These values are notably higher than those observed for WF1, mainly due to less favorable wind conditions at the WF2 site, despite both turbines having relatively similar specific power values. It is also worth noting that these case study results are consistent with the trends observed in Figs. 8 and 11.

## 5 Conclusion and Policy Implications

This study has presented an analysis of the impact of the regulatory framework—aimed at mitigating bat mortality in wind farms—currently under development in Spain on wind energy production (although the results obtained are directly applicable to other similar regulatory frameworks and different geographical contexts). This regulatory framework mandates that all wind turbines, unless the operator can demonstrate no significant impact on bat activity, must cease operation during the nights from July to October when wind speeds are below 6 m/s. However, the Spanish framework is not unique, as these strategies are increasingly being incorporated into regulatory frameworks across the globe. In many countries, operators are required to halt turbine operation at wind speeds below 5–6 m/s during summer nights, typically for a four-month period—July to October in the Northern Hemisphere or January to April in the Southern Hemisphere. While such measures have proven effective in reducing bat fatalities, they also result in a measurable loss of energy production, which can negatively affect the economic performance of wind farms.

It is important to highlight that the impact of these curtailment measures varies significantly across projects, depending on local wind conditions and turbine characteristics—most notably, the specific power. For this reason, the objective of this study is to identify and quantify the key factors that influence curtailed energy due to such environmental constraints.

To that end, a generalized analysis has been proposed focusing on three main variables: the mean wind speed at the site, the wind variability characterized by the Weibull shape parameter, and the wind turbine design, expressed through the ratio of rated power to rotor swept area—known as specific power. Each of these factors was studied through both a theoretical model and a dataset of 130 real commercial turbines, enabling a robust evaluation across a wide range of scenarios.

The results clearly show that curtailed energy increases in relative terms as the mean wind speed decreases. Sites with lower average wind speeds present a larger proportion of time within the curtailed range, and therefore suffer more significant energy losses. Likewise, turbines with lower specific power—commonly used in low-wind environments to optimize energy capture—are more susceptible to curtailment losses, as their energy production is more concentrated in the range of wind speeds typically affected by curtailment restrictions. With respect to wind variability, the effect is more nuanced. At low-wind sites, curtailed energy losses increase as the wind becomes more constant, that is, when the Weibull shape parameter is higher and the distribution is more sharply peaked around the mean. In these cases, if the mean wind speed is close to the curtailment threshold, a significant portion of the energy yield may be lost. In contrast, for high-wind sites, curtailed energy increases with greater variability. A broader wind speed distribution leads to more frequent occurrences within the curtailed range, even though the average wind speed remains high.

These relationships were assessed through theoretical modeling and then applied to real-world turbine data and site-specific simulations. Case studies on two operational wind farms in Spain confirmed the trends observed in the general analysis. Despite both sites featuring turbines with similar specific power values and classified as medium-wind environments, curtailed energy varied significantly depending on the local wind regime.

Regarding the energy policy implications that can be drawn from this work, the following points are worth highlighting:

- The impact of these measures varies significantly depending on local wind conditions and the turbine technology employed. Sites with lower wind resources are disproportionately affected, with environmentally driven curtailment potentially leading to energy losses of up to 2%, which may substantially affect project profitability.

In contrast, high-wind sites typically experience a much smaller impact, with annual production losses generally below 0.5%. This disparity could lead to compensation claims if such measures are applied retroactively to existing wind farms, and any compensation should be calculated based on the specific characteristics of each site.

- The introduction of environmental curtailment requirements may also discourage the development of new wind projects, particularly as prime wind sites are increasingly occupied and developers turn to lower-wind locations. To mitigate this disincentive, regulatory measures could be introduced. For example, in renewable energy auctions, the bid price—commonly used as the main selection criterion—could be adjusted to account for the estimated energy losses associated with environmental curtailment. Such adjustments would help ensure a level playing field among projects competing in these schemes.
- In schemes where wind projects are awarded through regulated remuneration mechanisms, such as Contracts for Difference (CfD), environmentally driven curtailment could be explicitly factored into the calculation of the strike price. This would help ensure that projects subject to such operational constraints remain financially viable and can compete on equal terms with less-affected developments.

Future work should explore ways to refine these estimations by incorporating real-time bat activity monitoring, high-resolution wind measurements, and dynamic curtailment strategies. Additional efforts could focus on modeling the seasonal and hourly variability of wind patterns, which may significantly affect curtailment performance depending on the time of day and period of the year. Furthermore, curtailment scenarios could be extended to partial stop requirements, limited to specific hours of the night—particularly at dusk and dawn, when bat activity tends to peak—rather than full-night restrictions. Finally, incorporating the hourly variability of market electricity prices would allow for a more accurate estimation of the opportunity cost or foregone revenue associated with environmental curtailment, providing a clearer picture of its economic implications for wind farm operators.

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**Author Contributions** J.S.G. conceived the study, led the development of the analytical framework, performed the main data analysis, and wrote the first draft of the manuscript. A.G.G.R. contributed to the methodology, supported the implementation of the simulations, and assisted in manuscript preparation. A.G.E. supervised the research, contributed to the theoretical formulation, and provided critical revisions

to improve the manuscript. J.M.R.S. curated the dataset of wind turbine models, prepared the figures, and contributed to the interpretation of results. All authors reviewed and approved the final version of the manuscript.

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**Data Availability** Data sets generated during the current study are available from the corresponding author on reasonable request. The wind turbine technical data used in this study were obtained from thewindpower.net (publicly available at <https://www.thewindpower.net>) and from the EMD WindPro turbine database, which is not publicly available and requires a valid license from EMD International A/S. Wind resource data were obtained from the Global Wind Atlas (publicly available at <https://globalwindatlas.info>).

## Declarations

**Competing interests** The authors declare no competing interests.

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