

Article



# Wind Energy Assessment during High-Impact Winter Storms in Southwestern Europe

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Abstract: The electricity produced through renewable resources is dependent on the variability of weather conditions and, thus, on the availability of the resource, as is the case with wind energy. This study aims to assess the wind resource available and the wind energy potential (WEP) during the December months for the three years 2017, 2018, and 2019, in southwestern Europe, when several high-impact storms affected the region. Additionally, a comparison of Prandtl's logarithmic law and Power-law equations for extrapolation of the vertical wind profile is performed for onshore conditions, to evaluate the differences in terms of energy production, with the use of different equations. To assess the effect of the strong winds associated with the storms, 10 m wind components are used, with a 6-hourly temporal resolution, for the December months over the southwestern Europe region ( $30^{\circ}$ N-65° N; 40° W-25° E). Results are compared to the climatology (1981-2010) and show an increase of wind intensity of  $1.86 \text{ m} \cdot \text{s}^{-1}$  in southwestern Europe during December 2019, and a decrease up to  $2.72 \text{ m} \cdot \text{s}^{-1}$  in December 2018. WEP is calculated for the selected wind turbine, 4 MW E-126 EP3—ENERCON, as well as the values following the wind resource record, that is, (i) higher values in December 2019 in the offshore and onshore regions, reaching 35 MWh and 20 MWh per day, respectively, and (ii) lower values in December 2018, with 35 MWh and 15 MWh per day for offshore and onshore. Differences in WEP when using the two equations for extrapolation of wind vertical profile reached 60% (40%) in offshore (onshore) regions, except for the Alps, where differences of up to 80% were reached. An additional analysis was made to understand the influence of the coefficients of soil roughness and friction used in each equation (Prandtl's logarithmic law and Power-law), for the different conditions of onshore and offshore. Finally, it is notable that the highest values of wind energy production occurred on the stormy days affecting southwestern Europe. Therefore, we conclude that these high-impact storms had a positive effect on the wind energy production in this region.

Keywords: renewable energy; wind energy potential (WEP); wind vertical profile; extreme events; windstorms; Northeast Atlantic

## 1. Introduction

In recent decades, the continuing demand for renewable and clean energy has increased, which has allowed a significant reduction in greenhouse gas emissions [1,2], and in this sense, the decarbonization of the electricity sector represents one of the main measures to slow the step of climate change [3].

The renewable energy sector (such as hydroelectric, wind, and solar energy) is heavily impacted by atmospheric variability: energy demand and supply are dependent on atmospheric conditions at several time scales ranging from small-scale turbulence through day-ahead weather or seasonal anomalies and up to climate change impacts [4]. Therefore, it is important to understand the availability of the resources and their vulnerability



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to weather and climate conditions [1,2]. Wind has proven to be a renewable, efficient, and clean energy source, with a high potential for reducing greenhouse gas emissions [5,6]. In general, wind energy resources can be divided into two types: onshore wind and offshore wind, and as a result, wind power generation is composed of onshore and offshore wind farms. Until then, most of the wind power has been generated by onshore wind farms, where the technique for the usage of onshore wind power is well proven. Nevertheless, offshore wind power is getting more attractive for its stable wind resources, generally less environmental impact, and fewer constraints on wind turbine size [6,7]. Wind energy is one of the fastest-growing technologies to produce renewable energy and it has become increasingly attractive, presenting a successful economic development [5,8]. In Europe, the wind energy capacity was 205 GW at the end of 2019, where 15.4 GW of capacity was installed during 2019. Three-quarters of the new wind installations in 2019 were onshore, and Spain installed the most capacity, with 2.2 GW of new onshore wind farms. Onshore wind continues to be the main technology and still makes up 89% of all capacity. This value of new wind power capacity is 27% higher than in 2018, but less than the record in 2017. In 2019, wind energy represented 15% of the electricity consumed by EU-28 countries. In terms of the share of wind in its electricity demand in 2019, Denmark had the highest share (48%), followed by Ireland (33%) and Portugal (27%) [9]. This energy has a high potential of expansion, with capacity scenarios to 2030 that range from 251 to 392 GW production. Thus, by 2030, it could reach 350 GW, supplying up to 24% of electricity demand in Europe [10,11].

Wind energy potential (WEP) is sensitive and strongly dependent upon the strength of near-surface winds which are determined by synoptic-scale variability and local processes, such as those related to orography, which can change the available wind resources [2,12,13].

The vertical gradients of the mean wind speed and wind direction must be known, as well as the turbulence intensity above the surface layer [14], since the wind speed increases as we move away from the ground. This variation in wind speed is essentially due to the irregularity of the soil, vegetation, buildings, and other types of obstacles. The effect of the frictional force fades until it is practically cancelled at a height of approximately 200 m. This area of the atmosphere characterized by the variation of the wind speed with the height is called the atmospheric boundary layer, and above this zone, it is said that the atmosphere is free. Thus, the wind speed, at the presumed average hub height of the installed wind turbines, needs to be corrected [15] and the measured wind speed needs to be extrapolated to hub-height. Several mathematical expressions describe the vertical wind profiles in the surface layer, which allow for reliable vertical interpolations and extrapolations for flat and homogeneous terrain [14], among which are the logarithmic law and the power-law [16].

Thus, the influence of the terrain topography and the soil roughness in the wind speeds profile can be adequately represented by Prandtl's logarithmic law (LogL) [8,17,18], and this law has been used in many studies of wind energy analyses [19–24] with different applications. The Power-law (PL) mathematical relation was normally used to extrapolate the wind speeds at higher heights [6]. This law characterizes the impact of the roughness of the earth's surface on wind speed and it is recognized as a reasonable approximation of the wind vertical profile in the surface layer characterized by neutral conditions and smooth areas [8]. Several studies [5,6,13,16,25–27] used the PL as reference.

Several authors [19,28–31] presented a review of wind resource extrapolation models applied on wind energy, where they highlighted the differences between the various models and equations used in the calculation of wind extrapolation. However, there is no uniform analytic expression for wind speed variation with height, which could be valid for all stability conditions [28] and the formulations only provide a first approximation to the variation of wind speed with elevation; nothing is better than real site measurements [32]. According to these studies, the LogL and the PL equations are the two main approaches to achieving wind speed extrapolation. PL was found to give a reasonably accurate and better representation of wind speed profiles than LogL, at least under unstable and neutral

conditions [19,29]. Thus, PL is identified as a reasonable approximation of the wind vertical profile in the surface layer characterized by neutral conditions and smooth areas [8].

The PL indicates the increment of surface wind speed concerning height z. The PL neither satisfies the upper boundary nor the lower boundary conditions [31]. However, the log law model fits well for the wind speed profile at a larger height, which is one of the critical reasons for its preference. Thus, it has been found that the power-law does not fit well at the higher height ranger (typically more than 150 m), and the LogL produces better results at a higher level [31].

The operation of wind turbines is determined by weather, and thus, strongly depends on the regional atmospheric conditions; it could be potentially affected by climate change [33,34]. Modifications, for example, in the intensity and frequency of intense extratropical cyclones, with the origin being in the North Atlantic, that reach Europe and affect the near-surface wind conditions, as the weather is controlled by the passage of these systems and their associated fronts [35], can lead to changing frequencies of calm or strong wind periods. Consequently, this would imply stronger fluctuations of generated electric power [12,34,36,37].

Moreover, the variability and uncertainty in the renewable resource (as wind energy) availability must be properly accounted for in the complex decision-making processes required to balance supply and demand in the power system. Thus, it is becoming increasingly evident that forecasting is a key solution to efficiently handle renewable energy in power grid operations [38]. The variability and uncertainty in renewable resources such as wind power present new challenges from a long-term planning perspective; however, the system reliability must be maintained while trying to minimize the total cost of meeting the electricity demand [39]. This factor is especially important in the long-term planning of new windfarms given the need for the timing of power generation to match the timing of demand, due to the lack of largescale energy storage [2,12]. In this context, ref [3] analyzed the impacts of energy storage systems and the variability and uncertainty of variable renewable energy on power system decarbonization in 2050. On the other hand, the increasing offshore wind deployments will further elevate the concerns that are emerging regarding the challenges of grid integration and system reliability with the rise of variable renewables [40]. These concerns vary from system to system; however, one mechanism to mitigate any issues related to variability and uncertainty is energy storage. Advanced energy storage technologies, such as batteries, can provide the grid with a variety of system-level services, which includes the added flexibility needed to reliably accommodate much higher levels of variable renewable generation [40,41].

The increase in electricity production through renewable energy sources, such as onshore and offshore wind energy, makes energy systems more sensitive to weather and climatic conditions and their variability [42,43]. Extreme weather conditions, such as extreme winds, are a challenge to the normal and safe operation of wind turbines, and because of the entire European electrical system, considering the weight of wind energy in the energy mix [44,45]. In the study of Cutululis et al. [44], the impact of critical weather periods, with very high wind speeds, on the stable operation of the power system was assessed. The wind turbine has a storm control system to protect itself and to stop when the wind speed exceeds a certain value, which leads to the sudden loss of wind power due to the way the wind turbines operate. The obtained results show that, with the present storm controller, during critical weather conditions periods, significant amounts of wind power production will be lost in periods ranging from 10 min to over an hour. Those amounts, in the worst case, can go up to 50% of installed capacity in 30 min and around 70% in an hour. That means that losses in production are highly significant [44]. In this way, it is important to consider the spatial and temporal variations in production and demand of energy and the design and operation of power systems of renewable sources [42], to guarantee a continuous and secure energy supply in the future [46].

High-impact storms (storms associated with extreme precipitation and strong winds) are an example of these extreme weather events, which, when they are intense and persist

for several days, cause serious impacts on the sector of production and consumption of electricity. These situations are considered a serious risk for the power production sector of electricity and its facilities, which can provoke disruption, supply cuts, and affect other infrastructures depending on the energy supply [42,43,47–49].

In the three December months (2017, 2018, 2019), southwestern Europe was affected by several high-impact storms that caused major adverse impacts [50–52]: in December 2017, three high-impact named storms (Ana, Bruno, and Carmen storms [50–52]); in December 2018, another three storms affected these regions (Etienne, Flora [50,51] and Oswalde [53] or Deirdre [54]); and in the last considered December month (2019), three additional storms (Daniel, Elsa, and Fabien storms [50,51]) affected southwestern Europe, which had strong winds.

This study has the objective of providing a first assessment of the available wind resource and wind energy potential (WEP) during the considered months of December 2017, 2018, and 2019, and understanding the influence of high-impact storms in the production of electricity through wind energy technology in this region.

For this assessment, an analysis comparing two different equations of extrapolation of the vertical wind profile (Prandtl's logarithmic law and Power-law) for onshore conditions is done, to evaluate the differences in terms of WEP. An additional analysis is made to understand the influence of the coefficients of soil roughness and friction used in each equation (Prandtl's logarithmic law and Power-law), for the different onshore and offshore conditions, and in WEP values posteriorly obtained.

# 2. Materials and Methods

#### 2.1. Meteorological Data

The analysis of wind resource and the availability of the WEP during the three months of December of 2017, 2018, and 2019 was performed through the use of ERA5 Reanalysis 10 m wind components (10-m U and V wind components) retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF) [55]. The fields were extracted at 00, 06, 12, and 18 UTC (6-hourly data), over a geographical sector that covers the Northeast Atlantic and southwestern Europe region (30° N–65° N; 40° W–25° E) and compared to the climatological average of 6-hourly values for the December months for the 1981–2010 period. Anomaly composites, namely the departures of arithmetic mean over each month of the considered fields from the respective grand means computed over December 1981–2010, are analyzed. The availability of wind resources is assessed for each of the three months separately.

# 2.2. Methodologies for Calculating the Wind Potential

For WEP calculations, ERA5 10 m wind velocities (V10) are extrapolated to 135 m, which is the height of the onshore wind turbine considered in this study [55–57]. The wind speed must be corrected [15] and extrapolate measured wind speed to hub-height of the installed wind turbines. For that, the LogL and the PL [16] were used to describe the vertical wind profiles in the surface layer, which allow for reliable vertical interpolations and extrapolations in flat and homogeneous terrain [14]. Wind speed variation is essentially due to the irregularity of the soil, vegetation, buildings, and other types of obstacles. Prandtl's logarithmic law can adequately represent the influence of the terrain topography and the soil roughness in the wind speeds profile [8,17,18], and it is expressed in Equation (1):

$$\overline{v}(z) = \frac{v_r}{k} \ln\left(\frac{z}{z_0}\right) \tag{1}$$

where  $\overline{v}(z)$  is the average wind speed at height H,  $v_r$  is the friction speed, k is the Von Karman constant (with value 0.4), and  $z_0$  (m) is defined by the characteristic length of the roughness of the soil [15,32]. It is usual to use Equation (1) for the extrapolation of the wind speeds to different heights [18,19]. Wind extrapolation is carried out using a logarithmic wind profile that assumes a neutrally stratified atmosphere [15]. In this study, a value

of 0.03 m is considered for the coefficient of soil roughness,  $z_0$ , considering a type of soil with "open areas with a few windbreaks"; this value was obtained from Table 6.4 in [32]. Moreover, the LogL is more complicated to use than the PL because the latter is simpler to apply in this type of studies [58].

The PL is the only method without a physical basis, and it seems to give a better fit to most of the data over a greater height range and for higher wind conditions [16]. In general, it is customary to adopt a height ( $H_0$ ) of 10 m above the ground as a reference and for this height also a reference speed ( $v_r$ ). Therefore, it is necessary to estimate the harvested wind energy at wind speeds magnitude at greater heights, with appropriate equations that predict the wind speeds at one height in terms of the measured speed at another height. PL characterizes the impact of the roughness of the earth's surface on wind speed [8] and it can be expressed by Equation (2):

$$v_h = v_r \left(\frac{H}{H_0}\right)^{\alpha} \tag{2}$$

where  $\alpha$  is the power-law exponent, which depends on such factors as the nature of the terrain (surface roughness), typically 0.20 for onshore areas [13,32,58,59], considering a terrain with "high crops, hedges and shrubs"; this value was obtained from Table 6.3 in [32]. However, to understand the influence of the type of soil in the extrapolation of the vertical wind profile, the various coefficients mentioned in [32] were used in the calculation of the WEP, and the results are shown in Figures S1 and S2 (see Supplementary Materials).

The wind energy density (WED), wind potential (WP), or power output of a wind turbine measures the energy contained in the winds, i.e., the kinetic energy flux associated with the winds, which is proportional to the third power of wind speed [8]. The wind potential (WP) depends on air density (the standard near-surface value of 1.225 kg·m<sup>-3</sup>), turbine radius, *R* (m), wind speed, *V* (m·s<sup>-1</sup>), and rotor power coefficient, *Cp*, i.e., the Betz limit (*Cp* = 16/27), which describes the maximum amount of energy a turbine can theoretically extract from the wind. Moreover, that is the ratio of the rotor power density (mechanical power at the turbine shaft per unit of swept area) to the wind power density [19,60]. However, the real-world values of *Cp* are well below the Betz limit with typical values in the order of 0.35–0.50 [61–63].

Between the turbine specific cut-in and rated wind velocity, the WP is proportional to the cubic power of wind speed:

$$WP = (1/2) \times C_p \rho \pi R^2 V^3 \tag{3}$$

Hence, the sensitivity of WP to wind speed is particularly high and depends on the power coefficients of a given turbine model [13]. The wind energy potential (WEP), or gross energy output (*E*), for a period (*t*) is calculated as follows:

$$WEP = WP \times t \tag{4}$$

In 2019, in Europe (EU-28), the average power rating of new onshore wind turbines was 3.1 MW, and it was 7.2 MW for new offshore turbines. The largest turbine in the world is GE's Haliade-X, the industry's first 12-MW onshore turbine. The first prototype was installed at the Port of Rotterdam in 2019 for testing and its commercialization is expected in 2021 [9].

For this study, the turbine ENERCON of the model 4MW E-126 EP3 is used, and the characteristics are presented in Figure 1 and Table 1 [56,57].



**Figure 1.** The power curve (in kW) of the selected wind turbine (4 MW E-126 EP3, ENERCON) for wind speeds ranging from 0 to over the cut-out velocity ( $25 \text{ m} \cdot \text{s}^{-1}$ ). Note a rated (maximum) power of 4000 kW, wind-rated speed of 13 m·s<sup>-1</sup>, rotor diameter of 127 m, and cut-in velocity of 3 m·s<sup>-1</sup>. Adapted from [56,57].

**Table 1.** Characteristic of the selected wind turbine (4 MW E-126 EP3, ENERCON). Adapted from [56,57].

Turbine Characteristics	
Rated power	4000 kW
Wind rated speed	$13 \mathrm{m} \cdot \mathrm{s}^{-1}$
Rotor diameter	127 m
Cut-in velocity	$3 \text{ m} \cdot \text{s}^{-1}$
Cut-out velocity	$25 \mathrm{m} \cdot \mathrm{s}^{-1}$
Cut-out velocity storm	$28-34 \text{ m} \cdot \text{s}^{-1}$

#### 2.3. Energy Data

To confirm and to compare the obtained results, the European reports of renewable energies—wind energy—are used for the years of 2017 to 2019 [9–11,64–74]. These reports present the production of wind energy in the countries of Europe (EU-28) as well as the installed capacity of wind energy, for the years and months under study.

# 3. Results

The wind resource and wind energy potential (WEP) analysis for the considered December months of 2017, 2018, and 2019 are presented in Figures 2–4.

#### 3.1. The Wind Resource

To evaluate the wind resource availability in the December months of 2017, 2018, and 2019 and to understand how the wind resource varies spatially and temporally, the climatological average of the 10 m wind speeds for the month of December for the period 1981 to 2010 was calculated (Figure 2A). The mean wind speeds at 10 m over southwestern Europe ranged from 1 to 5 m·s<sup>-1</sup>. Then, respective anomalies (departures from year nto the climatological average) were calculated for each considered year (Figure 2B-D). In December 2017 (Figure 2B), the obtained results showed an increase of wind intensity of up to 0.7 m·s<sup>-1</sup> over southwestern Europe in onshore areas, except for the west coast of the British Isles and the Nordic countries (Sweden and Norway). In offshore areas, in the Atlantic Ocean on the north of the Iberian Peninsula (IP), Mediterranean Sea, in the North Sea, and Baltic Ocean, it reached up to  $1.43 \text{ m} \cdot \text{s}^{-1}$ . North of the Azores Archipelago, there is a region with positive anomalies that also reached up to  $1.43 \text{ m} \cdot \text{s}^{-1}$ . On the other hand, to the west and south of the Azores Archipelago, a strong negative anomaly was observed, reaching  $-2.16 \text{ m} \cdot \text{s}^{-1}$ . On the west coasts of the Iberian Peninsula and the British Isles, the values of negative anomalies ranged from 0 to  $-2.16 \text{ m} \cdot \text{s}^{-1}$ . In December 2018, it was verified that there was a decrease in wind speed overall southwestern Europe, with a special impact on Iberia, where the negative anomalies reached  $-1.4 \text{ m}\cdot\text{s}^{-1}$  and were even larger on the Mediterranean Sea and southwest coast of Portugal, where the difference reached  $-2.72 \text{ m}\cdot\text{s}^{-1}$  when compared with the respective climatology for the 1981–2010 period (Figure 2A). However, in the region of northern France, Germany, and Poland, an increase of  $0.7 \text{ m}\cdot\text{s}^{-1}$  was verified. On the Atlantic Ocean, on the north of Azores Archipelago, there was a well-marked positive anomaly, with values reaching  $1.76 \text{ m}\cdot\text{s}^{-1}$ , as well as on the west coast of Norway, over the Norwegian Sea. Concerning December 2019, from Figure 2C, the increase in resource availability was obvious, showing the map positive anomalies across southwestern Europe and over the Atlantic Ocean. In some regions, positive values reached up to  $1.86 \text{ m}\cdot\text{s}^{-1}$ , as is the case of the Atlantic Ocean and the Mediterranean Sea, with the exception on the Balearic Sea region that presents negative anomalies ( $-1.78 \text{ m}\cdot\text{s}^{-1}$ ). It can be concluded from Figure 2 that, in general, December 2019 presented an increase in available wind resource, while December 2018 presented a clear decrease, highlighted in the Iberian Peninsula region.



**Figure 2.** (**A**) Climatological average of ERA5 wind speed at 10 m ( $m \cdot s^{-1}$ ), for the December months of 1981 to 2010. (**B–D**) Anomalies of wind speed at 10 m ( $m \cdot s^{-1}$ ) for the December months of 2017, 2018, and 2019, respectively.



**Figure 3.** Wind Energy Potential (WEP) (MWh·day<sup>-1</sup>): December 2017 (**A**,**B**); December 2018 (**D**,**E**); December 2019 (**G**,**H**); (**A**,**D**,**G**) calculations made using Equation (1) (LogL,  $z_0 = 0.03$  m); (**B**,**E**,**H**) calculations made using Equation (2) (PL,  $\alpha = 0.20$ ); (**C**,**F**,**I**) percentage difference of WEP between the use of Equations (1) and (2), for the respective months of each year.





**Figure 4.** (**A**,**E**) Climatological average of the Wind Energy Potential (WEP) (MWh·day<sup>-1</sup>) for the December months of 1981 to 2010. Anomalies of WEP (MWh·day<sup>-1</sup>) for the December months of (**B**) and (**F**) 2017; (**C**,**G**) 2018; (**D**,**H**) 2019. (**A**–**D**) calculations made using Equation (1) (the LogL,  $z_0 = 0.03$  m); (**E**–**H**) calculations made using Equation (2) (the PL,  $\alpha = 0.20$ ).

#### 3.2. The Wind Energy Potential (WEP)

The Wind Energy Potential (WEP) was calculated using two different equations (Equations (1) and (2)) for the extrapolation of the vertical wind profile, by Equation (1), which uses the LogL (with  $z_0 = 0.03$  m), and Equation (2), which uses the PL (with  $\alpha = 0.20$ ), with coefficients to onshore conditions. Figure 3 illustrates the WEP for the months of December in 2017, 2018, and 2019. The first column shows the results calculated with Equation (1); the second column shows the results obtained with Equation (2). The third column shows the difference (in percent) between the results of WEP obtained by both equations (Equations (1) and (2)), to understand the influence of the vertical wind profiles on the surface layer and the roughness of the terrain. Equation (1), Prandtl's logarithmic law, was used as a reference.

In December 2017 (Figure 3A,B), the WEP values in onshore regions varied between 5 and 20 MWh·day<sup>-1</sup>. The northern coast of Europe (France, Germany, the Netherlands, Denmark, Poland, and countries in the east), as well as the British islands, had the highest values, while in offshore regions, it ranged from 15 to 40 MWh·day<sup>-1</sup>. These values were higher (up to 35 MWh·day<sup>-1</sup>) on the North Sea and Baltic Ocean and on the Atlantic Ocean on the north of the Azores archipelago. The direct differences of the WEP for December 2017 in percentage (Figure 3C) verified that the differences reach -80% of energy production on onshore areas, as in Alpes and Norway, and over up to -50% in all Europe. On the other hand, an increase in energy production occurred in the north region of the Atlantic Ocean, north of the Azores Archipelago, north of the Iberian Peninsula, and the entire west coast of France and the British islands, with up to 20% more energy and in the region of the Mediterranean Sea.

In December 2018, a decrease in wind production occurred (Figure 3D,E), especially in the Iberian Peninsula, south of France, and the British Isles. The highest WEP values were reached in the region north and west of Europe, reaching 35 MWh·day<sup>-1</sup> on offshore regions and 15 MWh·day<sup>-1</sup> on onshore regions. The differences of the WEP for December 2018 (Figure 3F) were more visible between the onshore and offshore regions as in 2017 (Figure 3C), but with higher values of WEP in the offshore regions for 2018, which reach up to 50% more, over the Atlantic Ocean (at northern latitudes of Azores Archipelago) and the west coast of the British Islands.

On the other hand, in the onshore regions, as in the case of the Iberian Peninsula, the Pyrenees, and the Alps region, there were differences in WEP varying between -40%and -80%. Concerning December 2019, there was a particular increase in onshore production compared with the previous years. The WEP values in the onshore regions reached 25 MWh·day<sup>-1</sup>, while the WEP values in the offshore regions was 35 MWh·day<sup>-1</sup>. Areas on the northern coast of Europe (such as the British Isles, Denmark), France, Germany, the Netherlands, and Poland recorded the highest WEP values, in the order of 15 MWh·day<sup>-1</sup> (Figure 3G) and up to 25 MWh·day<sup>-1</sup> (Figure 3H). In the offshore regions, the values reached 35 MWh $\cdot$ day<sup>-1</sup> over the northern region of the Atlantic Ocean, in the Baltic Ocean and the North Sea (Figure 3G,H). Additionally, in the offshore regions, the differences between the application of wind extrapolation equations are notable. On the Atlantic Ocean, in the North Sea, the Baltic Ocean, and the Mediterranean Sea, differences between 10% and 60% more than WEP were verified, using the LogL. On the other hand, using LogL as a reference, the differences in onshore regions reached -80% WEP in the Alps (Figure 3I). However, there was a difference between -20% to -60% in all onshore regions (Figure 3I).

Thus, considering the results obtained, using Equation (1) (Prandtl's logarithmic law) in the calculation of the extrapolation of the vertical wind profile, showed the highest values of WEP for offshore regions. Nevertheless, when Equation (2) (the PL) was used, the WEP values were higher in the onshore regions. This pattern was consistent and similar in the three December months under study. Moreover, the differences in the values of WEP obtained were observed in the same regions, even considering the roughness and fiction factors of the soil for onshore conditions.

#### 3.3. The Anomalies of Wind Energy Potential (WEP)

The anomalies of the WEP values for December 2017, 2018, and 2019 were calculated and compared with the climatological WEP values for all December months of the 30-year period from 1981 to 2010 (Figure 4), using, respectively, Prandtl's logarithmic law (Equation (1), with  $z_0 = 0.03$  m; Figure 4A) and the PL (Equation (2), with  $\alpha = 0.20$ ; Figure 4E) in the extrapolation of the wind profile.

Analyzing the climatological average of WEP (Figure 4A,B), there are differences in the production of WEP in several offshore and onshore regions in concordance with the analysis performed in Section 3.2. Figure 4A shows high average values, on offshore areas, over the Atlantic Ocean and on the west coast of the British Isles, in the order of 35 MWh·day<sup>-1</sup>. For the onshore regions, the highest average values (15 MWh·day<sup>-1</sup>) are found in the British Isles and the north of the countries of France, Germany, Poland, Denmark, and Sweden. When the power-law equation is applied (Figure 4E), higher WEP values were found in the onshore regions (up to 20 MWh·day<sup>-1</sup>), except for the Baltic Ocean, which presented higher values (reaching 35 MWh·day<sup>-1</sup>) than in Figure 4A.

In the Iberian Peninsula and over the north countries (France, Germany, and British Isles) (Figure 4E), the highest WEP values are very noticeable when compared to Figure 4A. Thus, it is possible to conclude that the PL (Equation (2)) allows obtaining higher values of WEP in onshore regions.

The anomalies show how the WEP availability varies (Figure 4B,F). In December 2017, the values of WEP presented an increase of around to 3 MWh·day<sup>-1</sup> on onshore areas, except for the British Isles and Scandinavia Peninsula that have experienced a reduction in WEP of up to -3 MWh·day<sup>-1</sup>. Moreover, in the west region of IP, there was also a reduction of WEP of up to about -3 MWh·day<sup>-1</sup>. These values are valid for both approaches, that is, for the values obtained through the two different wind extrapolation formulas (Figure 4B,F). On offshore areas, it is possible to observe an increase and a decrease in WEP. Thus, an increase was verified that ranges from 6.80 MWh·day<sup>-1</sup> (Figure 4B) to 8.14 MWh·day<sup>-1</sup> (Figure 4F) on the Mediterranean Sea and Baltic Ocean, north and east of the British Islands, and north of Azores Archipelago region. On the other hand, the reduction in WEP is more pronounced on the west coast of Portugal and in the region of the Gulf of Biscay and in the English Channel, where the values varied between -7.53 and -8.51 MWh·day<sup>-1</sup>, Figure 4B,F, respectively.

Concerning December 2018, this month showed the lowest values of WEP when compared with the other two. The reduction in WEP is more pronounced in onshore areas (Figure 4C,G), where practically the whole of Europe presents negative anomalies, with values ranging from -6 to -3 MWh·day<sup>-1</sup>, considering the two equations for extrapolating the wind. However, in onshore regions, there was an increase in the production of WEP in the north of France, Germany, and the Netherlands, where the values are up to 3 MWh $\cdot$ day<sup>-1</sup> higher than the climatology. Moreover, the highest values of positive anomalies are present in offshore regions and the values range from 6.85 to 7.70 MWh·day<sup>-1</sup> (Figure 4C,G, respectively). Concerning negative anomalies, the highest negative values were obtained for the offshore regions and the values vary between -10.64and -11.01 MWh day<sup>-1</sup> (Figure 4C,G, respectively), over the Balearic Islands and on the west and southwest coast of Iberia. Along the coast of the British Isles and in the Baltic Ocean, there is also a slight decrease in WEP  $(-6 \text{ MWh} \cdot \text{day}^{-1})$ . Additionally, in the Atlantic Ocean, the region south of the Azores Archipelago and the Macaronesia islands, as well as on the Italian and Greek coast, there are negative anomalies with values ranging between -3 and -9 MWh·day<sup>-1</sup>, for the two approaches.

Finally, the month of December 2019 showed a general increase in energy production (WEP) compared with the climatology. This increase is in line with the greater availability of wind resources, shown in Figures 2D and 3G,H. The highest values of positive anomalies obtained for the two situations plotted in Figure 4D,H, are 8.10 MWh·day<sup>-1</sup> and 8.30 MWh·day<sup>-1</sup>, respectively, and these are observed for offshore regions (the North Sea, the Baltic Ocean, and in the Mediterranean Sea). For the onshore regions, this in-

crease in WEP is most noticed in the Iberian Peninsula and France, where the values reach  $6 \text{ MWh} \cdot \text{day}^{-1}$ . It should be noted that although in the Iberian Peninsula and France there is an increase in WEP, the west and north offshore coast of both regions present negative anomalies that range from -6 to  $-3 \text{ MWh} \cdot \text{day}^{-1}$  (Figure 4D,H). In the Atlantic Ocean, the region of the Azores Archipelago presents negative anomalies over the islands (in the order of  $-3 \text{ MWh} \cdot \text{day}^{-1}$ ) and positive anomalies in the region surrounding it, and around the Madeira Islands. The highest values of negative anomalies are shown in offshore regions over the Norwegian Sea and in the northern region of the Atlantic Ocean, where the values are up to -6.36 and  $-9.13 \text{ MWh} \cdot \text{day}^{-1}$  (Figure 4D,H, respectively).

When the PL is considered for the extrapolation of the wind (Equation (2)), there are more pronounced positive and negative anomalies, so the values are higher than those calculated using LogL. However, it is also shown that LogL (first column) presented higher values of WEP in the offshore regions, and on the other hand, the PL (second column) presents higher values of WEP in the onshore regions.

Thus, considering the results obtained (in Figure 3), it appears that, when we use Equation (1) (LogL) in the calculation of the extrapolation of the vertical wind profile, the highest values of WEP correspond to offshore regions. Nevertheless, when we use Equation (2) (the PL), WEP values are higher in onshore regions. This pattern is consistent and similar in the three months of December under study. Moreover, the differences in the values of WEP obtained are observed in the same regions, for the different studied months.

In the analysis of anomalies of the WEP (Figure 4), when the PL is considered for the extrapolation of the wind (Equation (2)), there are more pronounced positive and negative anomalies, and the values are higher than those calculated when LogL is used. Furthermore, it is also shown that LogL (first column) presented higher values of WEP in the offshore regions, and on the other hand, the PL (second column) presented higher values of WEP in the onshore regions.

Although in this analysis only the coefficients of roughness and soil fiction for onshore conditions were used, the values obtained in Figures 3 and 4 show that if we consider the onshore regions for the study, it is better to use Equation (2) (the PL). On the other hand, if the objective is to study the WEP in the offshore regions, Equation (1) (Prandtl's logarithmic law) presents better results.

To understand the effect of the coefficients of soil roughness and friction used in each equation (LogL ( $z_0$ ) and PL( $\alpha$ )), an additional analysis was done and the WEP values were then calculated. The values of the coefficient used follow the tabled values of Tables S1 and S2, and the results are presented in Figures S1 and S2 (see Supplementary Materials).

When we analyze the obtained results with the different coefficients, we identify the same pattern in the two figures, that is, when we increase the value of  $z_0$  (Figure S1) or  $\alpha$  (Figure S2), the roughness of the land or the friction of the terrain, respectively, is devalued allowing the increase of WEP in the onshore regions. On the other hand, a decrease is observed in WEP values in the offshore regions. This pattern is similar for the 3 months under study. The low WEP values in the mountainous regions of the Pyrenees and Alps should be highlighted, with this pattern being maintained in all figures (Figure S1 and S2).

## 4. Discussion

To compare and validate these results calculated using ERA5 wind values, we used the electricity production reports available for the December months in the study. When these reports are analyzed, the values obtained for Europe, using the EU-28 statistics, allow confirming and understanding the results presented in Figures 2–4. The reports show high values of wind energy produced in the months under study, with emphasis on December 2017 and 2019, where there was a greater production of wind energy, and a comparative decrease in the December 2018. This fact is confirmed with the values obtained in this study, in which the availability of wind resources and the WEP show the same pattern—an increase in the months of December 2017 and 2019 and a decrease in December 2018. In 2017, wind energy generated enough electricity to meet 11.6% of the EU-28's total elec-

tricity demand. Denmark was the EU country with the highest penetration rate (44%), followed by Portugal (24%) and Ireland (24%). Germany registered the highest increase from the previous year, now covering over 20% of its annual demand. Ten out of the twenty-eight Member States had a wind penetration rate of more than 10%. Thus, the total EU electricity consumption was 2906 TWh, of a total wind energy production of 336 TWh, of which 292 TWh was onshore wind energy production and 43 TWh was offshore wind energy production [64].

In 2018, wind energy generated enough electricity to meet 14% of the EU's electricity demand. This is a 2% share higher than in 2017 levels, in part due to the lower electricity demand registered. Denmark had the highest share of wind (41%) in Europe, followed by Ireland (28%) and Portugal (24%). Germany, Spain, and the UK followed with 21%, 19%, and 18%, respectively. Nine Member States had a wind share of 10% or more. Throughout 2018, wind power plants produced a stable output, with peak production (98 GW of average output during the day) on 8 December. On that day, wind energy supplied one-third of Europe's electricity needs. The year 2018 was a less windy year than 2017. This is reflected in a decrease of the capacity factors both for onshore (22%) and offshore energy production (36%). Thus, the total of EU Electricity consumption was 2645 TWh, of a total wind energy production of 362 TWh, of which 309 TWh was onshore wind energy production and 53 TWh was offshore wind energy production. In 2018, wind energy represented 14% of the EU's electricity demand. According to data on wind energy production (onshore and offshore) from the EU member states, the months of January, February, March, November, and December had the highest energy production, with the remaining months having a very low wind energy production. It is worth mentioning that the month of December showed high values of wind production, with a record value of almost 100 GW (onshore) and almost 90 GW offshore on 8 December [65]. The strong winds recorded since 7 December caused hundreds of flight delays and cancellations on 8 December at the Amsterdam airport. Wind speeds were 32–40 km $\cdot$ h<sup>-1</sup> (8.9–11.1 m $\cdot$ s<sup>-1</sup>) and the highest gusts were forecast for the Amsterdam region by the end of the day [66]. Figure 5 shows a wind speed at 10 m for 8 December 2018, and by analyzing the figure, it is possible to confirm the strong winds that affected the northern region of Europe, with the coast of the British Isles, France, Germany, Netherlands, and the entire North Sea region showing values between 10 and 20 m  $\cdot$  s<sup>-1</sup>. The pattern of wind speed suggests that strong gusts of wind affected those areas; despite these strong winds, the wind turbines were not forced to be stopped.



**Figure 5.** Wind speed at 10 m (m  $\cdot$  s<sup>-1</sup>) on 8 December 2018.

Figure 6A,B allow us to confirm the high WEP on December 8, with values varying from 50 to  $175 \text{ MWh} \cdot \text{day}^{-1}$  on the northern coast of Europe, in countries such as the British Isles, the north of France and Germany, the Netherlands, and the entire North Sea region. Figure 6 also presents the results obtained with the two equations (Equations (1) and (2)) for extrapolating the vertical wind profile. The results are shown in Figures 3 and 4, that is, showing higher WEP values in offshore regions (Figure 6A, Equation (1)) and higher WEP values in onshore regions (Figure 6B, Equation (2)).



**Figure 6.** Wind energy potential (WEP) (MWh·day<sup>-1</sup>) on 8 December 2018. (**A**) Calculations made using Equation (1) (the LogL,  $z_0 = 0.03$  m); (**B**) calculations made using Equation (2) (the PL,  $\alpha = 0.20$ ).

The obtained results shown in Figures 5 and 6 permit us to understand the values mentioned in the reports for 8 December 2018, which was a record day for wind production (both onshore and offshore). In other words, according to our calculations and the data obtained, 8 December had a high wind potential. This wind potential was captured by the wind turbines, which suggests that the wind speed values were not as destructive for the wind turbines as to be necessary to force the cut-off of the turbines, and thus, it was possible to take advantage of the wind resource and the production of electricity.

In 2019, wind energy generated enough electricity to meet 15% of the EU's electricity demand. This is one percentage point higher than in 2018, and results from the new installations as well as windy conditions around Europe throughout 2019. Denmark had the highest share of wind in its electricity mix (48%), followed by Ireland (33%), Portugal (27%), and Germany (26%). Twelve Member States had a wind share above 10%.

In 2019, Europe's wind farms produced a stable output throughout the year with daily peak production of 102 GW registered on 13 March. March was the month with the highest average hourly generation. In March, wind energy generated more than 34 GW of electricity an hour 90% of the time in the EU. From June to August, the amount of electricity produced by wind energy generation peaked in the winter months, although in winter, the variation in the hourly generation is higher than in summer. Although March was the month with the highest wind production, there were high values of wind production throughout the month of December, ranging from 40 to 80 GW [9].

During the three December months assessed in this study, southwestern Europe was affected by many severe storms, which caused serious impacts on the population. In December 2017, two storms first reached the Iberian Peninsula and then the rest of Europe, namely, the Ana storm on 9–11 December and the Bruno storm on 25–27 December.

The passage of these two storms represented an increase in wind energy production in the IP [67,68]. In December 2018, more than two high-impact storms affected, simultaneously, the IP and the other countries of southwestern Europe. Storm Flora on 13 December and storm Oswalde on 16 December hit the southwestern European countries with strong winds, which caused high values of wind energy production during the days when the storms passed. However, a reduction was verified in the monthly wind productivity in December 2018, when compared to the previous months and the values of the previous year [69,70]. Although 8 December is considered a record day for wind energy production, there is no record that the favorable conditions (high wind speeds) for this increase in production were related to the passage of a low-pressure system or a high-impact storm that affected southwestern Europe.

In December 2019, three consecutive storms (Daniel, Elsa, and Fabien) affected southwestern Europe, but firstly the IP, where it caused strong impacts due to extreme winds and heavy precipitation. From 12 December until 23 December, renewable production (wind and hydroelectric energy) reached a new historic record. This corresponded to a consecutive period of 5 and a half days (uninterrupted period of 131 h), between 18 and 23 December, when the production of renewable electricity was enough to satisfy consumption needs in mainland Portugal. In total, 331 h of 100% renewable consumption were recorded in December 2019 [71,72]. The values obtained for Spain show a new historic maximum of wind power was reached in the peninsular electricity system on 12 December and the maximum daily wind energy on 13 December [63].

Thus, the reports of energy production for the IP and European Union countries, EU-28, confirm the trends of the obtained values with theoretical values of wind speed, and they can demonstrate that the high-impact storms influenced the electricity production favorably in the southwestern Europe region. The values of wind energy production for Europe, EU-28, also reflect the values obtained in this work for WEP, and therefore, in December 2017 and 2019, an increase in electricity production by wind energy was registered (more wind resource available), and in December 2018, there was a decrease (less wind resource available) [9,64,65].

Additionally, our results show that for a comprehensive study, it is necessary to consider the different types of soil and terrain, as well as the type of equation of extrapolation of vertical wind profile when the WEP values are calculated for a wind farm. Indeed, these factors have a great influence on the energy results both for onshore and offshore conditions (see Figures S1 and S2, Supplementary Materials). However, when the objective is to assess the wind energy production in a specific period and region, these differences obtained with the different coefficient values are irrelevant because the most important is to compare the WEP obtained in each month under the same conditions.

Nonetheless, and to the best of our knowledge, there are no previous studies on this question. Therefore, it is necessary to deepen this study and the results obtained here, to understand how the type of terrain and soil can influence the use of wind energy, as well as what is the best equation to use in the prediction of the WEP value obtained in wind farms. This issue is important since wind energy remains one of the biggest bets for the decarbonization of the electricity sector.

## 5. Conclusions

Wind energy has been extensively utilized to meet the great demands of industrial production and ease the energy crisis in sustainable development [7] and is a key solution to cope with climate change. However, climate change will be more likely to result in the high frequency and intensity of extreme weather events (such as windstorms and high-impact storms), which may have negative effects on wind power generation [45].

Wind energy has an important role in the renewable energy mix of Europe, EU-28, [74]. The installed capacity and the annual participation of wind energy in the energetic system of each country is high, and this is important, because these countries are betting and continuing to bet on wind energy to produce clean energy and reduce  $CO_2$  emissions.

As previously discussed in Section 3.2, the results in Figure 4 illustrate that the use of the two equations for the vertical extrapolation of the wind at the height of the turbine, and later the calculation of the WEP, show that the WEP is sensitive to the variability of wind patterns. Moreover, the effect of the characteristics of the orography is quite remarkable in the transitions between onshore and offshore [8]. The differences between the WEP calculated by the two equations are observed in Figure 3, where it is possible to verify that LogL allows more WEP production in offshore regions and the PL allows greater WEP values in onshore regions, with differences reaching 80%. The values obtained in Figures 3 and 4 also revealed that for onshore regions it is better to use Equation (2) (the PL) and, if the objective is to study the WEP in the offshore regions, Equation (1) (LogL) presents better results, even if, in a first analysis, only the coefficients of roughness and fiction of the soil for onshore conditions were considered.

Although several authors [30,31,75,76] studied the different methods to extrapolate the vertical wind-speed profile, there is no obvious conclusion about which equation is best suited for the onshore and offshore regions. Thus, it is possible to declare that both LogL and the PL are suitable and commonly utilized to calculate the vertical variation of mean wind speeds in the atmospheric boundary layer. However, most authors agree with the fact that the PL is widely used due to its simplicity, and it seems to give a better fit to most of the data over a greater height range and for higher wind conditions, compared to LogL [28,58,77]. Thus, to the best of our knowledge, this is the first time that this pattern is highlighted—further research should be performed in the future to confirm these results for a larger dataset and diverse conditions.

The obtained results for WEP can be confirmed and compared with other studies. For example, Santos et al. [13] performed a study on the potential of wind energy of the Iberian Peninsula, in which the values obtained for WEP and for the mean annual patterns and the mean patterns for the winter months (December, January and February), where the highest values ranged from 8 to 16 MWh per day on the northwest and north of the IP region, on the southeast region of the IP and the Gibraltar strait region. Moreover, while onshore daily WEP varies between 2 and 16 MWh per day, in winter, offshore values are never below 16 MWh per day [13].

Regarding the results obtained with the theoretical values, these were followed by the real reported values of the production of electricity from wind energy in the countries, that is, an increase in production in the months of December of the year 2017 and 2019, and a decrease in December 2018. Moreover, it was also verified that the occurrence of high-impact storms with associated strong winds influences the available wind resource for energy production in the studied months, due to the high WEP values observed during the days of the storm's passage.

The event of 8 December 2018 (Figures 5 and 6) is classified as a record day in terms of onshore and offshore wind production in Europe. The remaining high-impact storms that hit Europe with strong winds during the months of December, studied here, have become a positive factor to produce renewable energy. In other words, this study suggests that high-impact storms and events with strong associated winds have a positive impact on the renewable energy sector, thus allowing an increase in electricity production through wind energy. Nowadays, wind energy technology is so evolved (more resistant and efficient materials) that storms and extreme wind events can contribute to a greater wind potential, considering that the wind turbines do not need to be shut down and maintain energy production during these periods.

Nevertheless, the kind of data available to perform this study, without information from wind energy plants, did not allow us to verify whether the passage of these highimpact storms caused the cut-off in the wind turbines, due to the high values of the wind speed and strong gusts with different directions. This can be discussed in future work. **Supplementary Materials:** The following are available online at https://www.mdpi.com/article/10 .3390/atmos12040509/s1, Figure S1: Wind Energy Potential (WEP) (MWh.day<sup>-1</sup>): December 2017 (A), (B), (C), (D) and (E); December 2018 (F), (G), (H), (I) and (J); December 2019 (K), (L), (M), (N) and (O); Calculations made using equation 1 (LogL); (A), (F) and (K) calculations made using 0.0002 m as  $z_0$  coefficient; (B), (G) and (L) calculations made using 0.003 m as  $z_0$  coefficient; (C), (H) and (M) calculations made using 0.1 m as  $z_0$  coefficient; (D), (I) and (N) calculations made using 0.4 m as  $z_0$ coefficient; (E), (J) and (O) calculations made using 1.6 m as  $z_0$  coefficient, for the respective months of each year, Figure S2: Wind Energy Potential (WEP) (MWh·day<sup>-1</sup>): December 2017 (A), (B), (C), (D), (E) and (F); December 2018 (G), (H), (I), (J), (K) and (L); December 2019 (M), (N), (O), (P), (Q) and (R); Calculations made using equation 2 (PL); (A), (G) and (M) calculations made using 0.10 as  $\alpha$ coefficient; (B), (H) and (N) calculations made using 0.15 as  $\alpha$  coefficient; (C), (I) and (O) calculations made using 0.20 as  $\alpha$  coefficient; (D), (J) and (P) calculations made using 0.25 m as  $\alpha$  coefficient; (E), (K) and (Q) calculations made using 0.30 m as  $\alpha$  coefficient; (F), (L) and (R) calculations made using 0.40 m as  $\alpha$  coefficient, for the respective months of each year, Table S1: Roughness coefficient ( $z_0$ ). Adapted from [32], Table S2: Friction coefficient ( $\alpha$ ). Adapted from [32].

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