



## Insights on the use of wind speed vertical extrapolation methods

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**Abstract.** The present work aims to study the influence of using different methods for wind speed extrapolation in energy production calculations. A dataset of 21 meteorological masts from several landscape characteristics and locations, with at least one year of 10-minute wind speed/direction data, was used as the basis for calculations. Both the power law through estimation of wind shear coefficients, and the logarithmic-based profile using WAsP, were used as mathematical models for predicting wind shear. Wind speed extrapolation was performed either from the top-most height, using a distance method that incorporated all measurement heights, or using the function for wind shear coefficient prediction. It was found that using the logarithmic-based profile was the less reliable of all studied methods. The study showed that the most accurate method was the power law with wind shear coefficients estimated from the two upper heights closest to the extrapolation height, by wind direction sector of 30°, and the wind speeds extrapolation from the top-most height of the two. It is suggested that the use of this method reduces uncertainty in AEP estimates.

**Key words.** wind shear, power law, logarithmic-based profile, vertical wind speed extrapolation, energy production

### 1. Introduction

The evaluation of wind shear is a fundamental part in wind resource assessment. Although the existing measurement mast technology is improving the feasibility of measuring wind speed and wind direction at higher heights, it is still more economical to perform wind measurements at lower heights and extrapolate to the hub height. This extrapolation is based on estimates of the vertical wind profile through measurements at different heights.

Wind shear characterization is often complex, as it is dependent on many factors, namely of thermal and dynamic nature [1]. Thermal factors influence atmospheric stability and may cause wind shear to vary hourly, by

month/season of the year, and from one year to the other [2]. A measure of thermal stability is the Obukhov length  $L$ , which estimates the influence of buoyancy over mechanical forces [3].

Three main atmospheric thermal stability classes are usually defined [4], which can be characterized by the Obukhov length: *unstable* conditions ( $-500 < L < 0$ ) occur when there is a lot of vertical mixing between a heated surface and a cooled upper atmosphere, leading to low wind shear; *stable* conditions ( $0 < L < 500$ ) correspond to a large wind shear and near laminar flow, provided by a cooler surface than the air above it; finally, *neutral* conditions ( $L < -500$  or  $L > 500$ ) take place when air is in thermal equilibrium with its surroundings, causing only a moderate wind shear, usually due to turbulence [5].

Dynamic factors that predominate in thermally neutral conditions include wind speed, surface roughness, and height interval [2]. Sharp slopes can cause acceleration trends that govern the wind profile. Similarly, surface roughness caused by irregularities in the land cover increases friction between land and air causing a disturbance in wind shear due to wind speed decrease near the soil [5, 6].

Both thermal and dynamic factors contribute to a high variability of wind shear, which causes high uncertainties in speed extrapolation. It was reported that differences between predicted and observed wind energy production, when using extrapolation procedures, can reach 40% [7].

The two most common mathematical models used to describe wind shear are the logarithmic-based profile and the power law [7, 8]. The logarithmic-based profile used in the most common software for wind resource assessment, WAsP by DTU [9], is based on the European Wind Atlas (EWA) method, which calculates “*stability-induced deviations from the logarithmic wind profile*, by

applying perturbation theory to both the Monin-Obukhov form for the wind profile and to the geostrophic drag law” [10]. The mean wind profile is applied as a function of land cover, more specifically, the surface roughness lengths, [8, 11], and is expressed by the equation:

$$u(z) = \frac{u_r}{k} \left[ \ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right) \right] \quad (1)$$

Where  $u(z)$  is the mean wind speed at height  $z$  above the surface,  $z_0$  is the surface roughness length, and  $\psi_m$  is the correction function of the logarithmic profile for stability, which depends on  $L$ .

The power law, also called Hellman’s exponential law, is often the simplest way to perform wind speed extrapolation, and generally the most effective. It is a simple exponential relationship between wind speed and height, characterized by the wind shear coefficient,  $\alpha$ :

$$\left(\frac{u}{u_r}\right) = \left(\frac{h}{h_r}\right)^\alpha \quad (2)$$

Where  $u$  is the wind speed at height  $h$  and  $u_r$  is the wind speed at reference height  $h_r$ .

Early work by Frost (1947) proposed a value of 1/7 for the wind shear coefficient  $\alpha$  in open land and atmospheric neutral conditions, however, this is an oversimplification since the  $\alpha$  exponent can vary with the topography of the site and the atmospheric stability [12], as well as with the other factors which influence wind shear [13]. Still, according to Gualtieri et al. [2], most authors agree that the power law gives a better and more accurate representation of wind speed profiles than the logarithmic-based profile, especially under unstable and stable atmospheric conditions. In fact, through the determination of  $\alpha$ , the wind vertical profiles can also be categorized according to atmospheric stability: unstable conditions correspond to  $\alpha < 0.1$ , while the typical logarithmic neutral profile is established with a wind shear coefficient between 0.1 and 0.2, and the stable atmosphere is described by  $\alpha > 0.2$  [14]. Although wind shear coefficients can be correlated to surface roughness lengths [12], extrapolation using each mathematical model can lead to different results, resulting in the aforementioned uncertainty in wind resource assessment. Bañuelos-Ruedas et al. [12] recommend the use and comparison of those different equations and methodologies to minimize errors in wind speed extrapolation, but this is hardly feasible to carry out in every wind resource assessment procedure. In this sense, other researchers such as Durisic et al. [9] have compared different methodologies for energy production estimation using wind speed extrapolation in a few distinct landscape scenarios, aiming to draw more general conclusions to improve the precision of energy production estimates.

The aim of this work is to extend this study of comparison between wind speed extrapolation methodologies for wind turbine hub height energy production estimates to a larger database of characteristic sites. It is expected that by studying a wider range of scenarios, more definite conclusions can be drawn about the advantages and disadvantages of each methodology according to the orography, roughness and wind characteristics of the site. These conclusions can then be used as recommendations for reducing uncertainty in wind resource assessment.

## 2. Methodology

With a selected set of data from wind measurement stations, two distinct main approaches were studied for predicting wind climate at hub height, namely:

- Use of the power law and the estimation of wind shear coefficients, working with data from different heights;
- Use of logarithmic-based profile modelling by WAsP employing a single wind data series at a top-most measurement height.

### A. Site database

21 met. masts were used for this study, to cover, as much as possible, a wide variety of landscape characteristics and different wind regimes. The site database includes masts from 13 countries across 3 continents.

Met masts were installed and instrumented according to typical guidelines and practices. Wind measurements were acquired using adequate data loggers and stored as data series of 10-min statistics.

For each mast, pluriannual data periods were selected, with over 90% availability for every measurement level. All data was subjected to quality control validation before analysis, according to best procedures.

The studied locations were classified according to their orography characteristics in different degrees of surface complexity, using as reference the site Ruggedness Indicator (RIX). This parameter is an objective measure of the extent of steep slopes in the area [15]. Similarly, they were characterized according to their land cover. Table I presents a summary of the studied masts, with the respective locations, orography and roughness characteristics and measurement levels.

**Table I** Site database and respective measurement levels and orography and roughness characteristics.

| # Site | Generic Location | Orography     | RIX [%] | Roughness               | Meas. levels [m] |       |       |       |
|--------|------------------|---------------|---------|-------------------------|------------------|-------|-------|-------|
|        |                  |               |         |                         | $h_1$            | $h_2$ | $h_3$ | $h_4$ |
| 1      | Macedonia        | Quite complex | 4.8     | Low vegetation          | 30               | 50    | 70    | 90    |
| 2      | Bulgaria         | Flat land     | 0.0     | Agricultural fields     | 38               | 57    | 76    | 93    |
| 3      | Poland           | Flat land     | 0.0     | Agricultural fields     | 41               | 61    | 81    | 98    |
| 4      | Egypt            | Flat land     | 0.0     | Sand/near sea           | 25               | 50    | 70    | 80    |
| 5      | South Africa     | Quite complex | 2.5     | Low vegetation          | 36               | 51    | 66    | 81    |
| 6      | South Africa     | Complex       | 5.1     | Forested                | 36               | 51    | 66    | 81    |
| 7      | Brazil           | Flat land     | 0.2     | Forested                | 40               | 80    | 100   | 122   |
| 8      | Brazil           | Flat land     | 0.0     | Forested/near sea       | 30               | 70    | 85    | 100   |
| 9      | Brazil           | Flat land     | 0.0     | Low vegetation          | 60               | 80    | 90    | 100   |
| 10     | Poland           | Flat land     | 0.0     | Agricultural fields     | 43               | 61    | 79    |       |
| 11     | Portugal         | Complex       | 6.1     | Forested                | 40               | 60    | 81    |       |
| 12     | Portugal         | Complex       | 9.1     | Forested                | 40               | 60    | 81    |       |
| 13     | Croatia          | Complex       | 6.2     | Low vegetation          | 30               | 50    | 79    |       |
| 14     | Serbia           | Flat land     | 0.0     | Agricultural fields     | 60               | 90    | 120   |       |
| 15     | Israel           | Flat land     | 0.0     | Sand                    | 20               | 40    | 60    |       |
| 16     | Morocco          | Quite complex | 4.5     | Low vegetation          | 20               | 50    | 80    |       |
| 17     | Mozambique       | Flat land     | 0.2     | Low vegetation/near sea | 43               | 62    | 82    |       |
| 18     | Brazil           | Flat land     | 0.0     | Low vegetation/near sea | 20               | 52    | 78    |       |
| 19     | Brazil           | Flat land     | 0.0     | Low vegetation/near sea | 30               | 50    | 70    |       |
| 20     | Brazil           | Flat land     | 0.0     | Agricultural fields     | 20               | 50    | 78    |       |
| 21     | Argentina        | Flat land     | 0.0     | Low vegetation          | 40               | 60    | 82    |       |

### B. Wind shear coefficient estimation

Several methods were used to determine the wind shear coefficient ( $\alpha$ ). Three measurement levels were used for this purpose ( $h_1$  to  $h_3$ ) which correspond to all

measurement levels for 3-level masts (sites 10 to 21), and the lower ones for the 4-level masts (sites 1 to 9). For  $\alpha$  determination, a linearization of Eq. (2) was used and considering a reference height of 1m a linear regression is obtained in which  $\alpha$  is the slope:

$$\ln(u) = \alpha \ln(h) + \ln(u_r) \quad (3)$$

The determination of  $\alpha$  was carried out by either direct fitting or least squares regression plotting  $\ln(u)$  vs.  $\ln(h)$ . Three different methods were used throughout the study, from different combinations of the three heights information used for calculations: lowest and highest height ( $h_1$ - $h_3$ , resulting in  $\alpha_{13}$ ), two highest heights ( $h_2$ - $h_3$ , resulting in  $\alpha_{23}$ ), and finally, all three heights using linear regression ( $h_1$ ,  $h_2$ ,  $h_3$ , resulting in  $\alpha_{123}$ ).

#### C. Detail in wind shear coefficient determination

Wind shear coefficients can be estimated through average wind speed or on a record-by-record basis.

It is known that wind shear varies with wind direction [2] and speed [13]. Therefore, a table of average wind shear coefficients according to bins of wind direction and speed (from the top-most height) can be generated for each site.

Wind shear coefficients with different level of detail can be obtained using four methods:

- *By 10-minute record* (10-min): using each combination of 10-minute wind speed values at different heights. This method may lead to some incongruent values, especially when wind speeds are low;
- *Average wind shear coefficient by wind direction* (DIR): Only values over 4 m s<sup>-1</sup> wind speed were considered, to avoid the influence of incongruent wind shear coefficient values due to low speeds on the final average;
- *Average wind shear coefficient by wind speed* (SPD).
- *Average wind shear coefficient by wind direction and speed* (DIR+SPD).

#### D. Wind speed extrapolation using power law

For each given  $\alpha$ , calculated with one of the tested methods, three different approaches to extrapolate wind speed to a higher height were tested. The simplest and most straightforward one was using Eq. (2) with reference height  $h_3$ . Another combines the extrapolations using each of the heights  $h_1$ ,  $h_2$  and  $h_3$  using a weighted mean inversely proportional to the squared distance to the height. Finally, another method used was the linearized function of Eq. (3) obtained with linear regression from all three heights to predict the speed at a higher height.

#### E. WASP wind speed extrapolation

For wind speed extrapolation using the logarithmic-based profile we resorted to WASP software (DTU Wind Energy).

WASP uses stability-induced deviations from the logarithmic profile for vertical extrapolation of wind speed and climate. It considers that the atmosphere is neutral and height above ground, roughness length and friction velocity as parameters for wind profile modelling [16]. Calculations are based on the wind rose and Weibull distribution observed at the meteorological mast location

and height. These data are converted into a generalized wind climate or wind atlas, by subtracting the effect of orography, roughness, and obstacles at the measurement point. It then estimates the wind climate at any point with the inverse calculation [17].

Therefore, in WASP calculations, the software was provided with wind climate data and orography and roughness maps. Finally, a virtual wind turbine was simulated to be placed at the mast location with a hub height  $h_4$ .

### 3. Results and discussion

#### A. Average wind speed variability study

The average wind speeds at heights  $h_1$  to  $h_3$  were used to determine average wind shear coefficients ( $\bar{\alpha}$ ) through the different extrapolation methodologies previously exposed. The extrapolated average annual wind speed at an extrapolation height  $h_5$  (corresponding to 1.5  $h_3$ , defined as the maximum height for which predictions are recommended) was determined using combinations of those average shear coefficients ( $\bar{\alpha}$ ) and different extrapolation methods for all studied sites.

The minimum and maximum values were then taken to calculate the variability of the wind speed extrapolation using the different proposed methods. This variability was expressed in percentage of the average value of extrapolated wind speed from all methodologies for each site. The results are presented in Table II, along with  $\bar{\alpha}_{123}$ , the wind shear coefficient calculated using the linear regression with the three heights.

**Table II** Average results for all sites of  $\bar{\alpha}_{123}$  and extrapolated wind speed variability.

| # Site | Extrapolation height ( $h_5$ ) [m] | $\bar{\alpha}_{123}$ | Wind Speed Variability [%] |
|--------|------------------------------------|----------------------|----------------------------|
| 1      | 105                                | 0.103                | 3.3%                       |
| 2      | 114                                | 0.180                | 0.6%                       |
| 3      | 120                                | 0.233                | 2.7%                       |
| 4      | 104                                | 0.112                | 3.4%                       |
| 5      | 99                                 | 0.093                | 4.6%                       |
| 6      | 99                                 | 0.139                | 3.7%                       |
| 7      | 150                                | 0.179                | 2.0%                       |
| 8      | 127                                | 0.236                | 1.7%                       |
| 9      | 135                                | 0.213                | 3.6%                       |
| 10     | 119                                | 0.311                | 3.4%                       |
| 11     | 121                                | 0.190                | 2.8%                       |
| 12     | 121                                | 0.082                | 2.2%                       |
| 13     | 118                                | 0.162                | 4.0%                       |
| 14     | 180                                | 0.171                | 2.9%                       |
| 15     | 90                                 | 0.101                | 6.1%                       |
| 16     | 120                                | 0.227                | 4.8%                       |
| 17     | 123                                | 0.233                | 1.6%                       |
| 18     | 117                                | 0.130                | 4.2%                       |
| 19     | 105                                | 0.197                | 3.4%                       |
| 20     | 117                                | 0.370                | 4.8%                       |
| 21     | 123                                | 0.201                | 0.5%                       |

Extrapolated wind speed variability is not dependent on any factor, as it cannot be easily correlated, from these values, with closed or open wind profiles (low or high  $\alpha$ ), or to orography and roughness features. The lowest wind speed variability was found at a flat land site with low vegetation with a slightly open wind profile ( $\bar{\alpha}_{123} =$

0.201), while the highest extrapolation method variability was found to be also a flat land site but with sandy land cover and a more closed wind profile ( $\bar{\alpha}_{123} = 0.101$ ). In terms of atmospheric stability, eleven sites (52%) have estimated  $\bar{\alpha}_{123}$  between 0.1 and 0.2, indicating a neutral thermal profile, the optimal conditions for the application of the logarithmic-based profile for wind shear estimation. In eight sites (38%),  $\bar{\alpha}_{123}$  exceeds 0.2, indicating a stable atmosphere, while the remaining two sites have  $\bar{\alpha}_{123}$  below 0.1; however, for the latter it is very close to 0.1 so conditions are near neutral. The maximum value for the extrapolated speed variability was 6.1%. This is not a very high value itself but having into consideration that the power density varies to the cube of the wind speed, this represents a variability of  $\approx 20\%$ .

### B. Detail of wind shear coefficient estimation study

To establish the influence of the detail in wind shear coefficient estimation, only the information of 4-level sites was considered (sites 1 to 9). The extrapolated wind speed data series at an extrapolation height  $h_4$  were determined from height  $h_3$  using Eq. (2) and wind shear coefficients estimated from heights  $h_2$  and  $h_3$  by wind direction, wind speed, or wind direction and speed, taken from a generated matrix for each site. The obtained extrapolated wind speed data series using the 4 different methods were initially compared to the measured data series using the ANOVA and Anderson-Darling tests, the latter being of relevance in the context of Weibull distributions, which is the case [18]. Initially, all extrapolated and measured wind speed data series were considered, and the ANOVA test was applied to check for significant differences among them. The results revealed no significant differences ( $p^* > 0.001$ ) between the extrapolated wind speed data series obtained using the four methods and the measured data series for five of the sites. On the contrary, in the remaining sites significant differences ( $p^* < 0.001$ ) were observed among the four extrapolated wind speed data series and the corresponding measured data series.

In a second phase, the Anderson-Darling test was applied for two samples at a time. This test allowed the identification of differences between the results from each of the methods and between each method and measured data. The results were analysed using a significance factor of 0.05 to reject the null hypothesis that the data series under comparison come from the same distribution. Interpretation of the differences is especially relevant between extrapolated and measured (OBS) data, as these relate to the accuracy of each method in predicting the

wind speed data series at a higher height. The obtained results were inconclusive. For shear estimation methods by direction or 10-minute, five of the sites showed significant differences between predictions and observations. Predictions were only slightly better using estimation by wind speed or wind speed and direction, with only four of the sites showing significant differences between measured and predicted data. Except for site 8, there are no significant differences between estimating the wind speed coefficient according to wind speed or wind speed and direction simultaneously, and it can be concluded that these two methods produce similar results. In sites 2, 3 and 8, for most of the considered pairs significant differences were observed. These three sites correspond to flat land with agricultural fields or forest. Still, sites 7 and 9 have similar characteristics, and were well predicted using most or all methods, so we cannot establish correlation between prediction difficulty and these topography and land use features.

The residuals behaviour (differences between extrapolated data series and observed values) was studied and the ANOVA test results revealed significant differences ( $p^{***} < 0.001$ ) among all four methods.

Each method performance was also analysed through the computation of the mean, standard deviation (STD) and mean squared error (MSE) of the residuals (Table III-a). From the results presented in Table III it seems that in terms of MSE of the residuals, the 10-min method performs better in a larger number of sites. For the other three methods, values of MSE in the same order of magnitude were obtained. However, the asymmetry coefficients for the residual distributions were computed and a large variability of the results of the 10-min method was verified (Table III-b). The results also show that method DIR presents lower asymmetry coefficients than DIR+SPD in five of the sites.

Taking all the performed statistical tests, it is difficult to single out one level of detail of wind shear coefficient estimation as the best method. Results obtained with the ANOVA test were inconclusive.

The Anderson-Darling test indicated that wind speed or wind speed and direction combined should be the most adequate levels of detail, but its performance was only slightly better than other methods. The analysis of the residuals and the calculation of their asymmetry coefficients aimed to confirm this result, but here, the direction method performed better in terms of asymmetry, with lower asymmetry coefficients in most sites.

**Table III a) Residuals (Mean, STD and MSE) – lowest presented in bold**

| # | DIR    |       |              | SPD    |       |              | DIR+SPD |       |              | 10-min |       |              |
|---|--------|-------|--------------|--------|-------|--------------|---------|-------|--------------|--------|-------|--------------|
|   | Mean   | STD   | MSE          | Mean   | STD   | MSE          | Mean    | STD   | MSE          | Mean   | STD   | MSE          |
| 1 | 0.006  | 0.352 | 0.124        | -0.009 | 0.357 | 0.128        | -0.009  | 0.353 | 0.125        | 0.000  | 0.263 | <b>0.069</b> |
| 2 | -0.016 | 0.310 | <b>0.096</b> | -0.029 | 0.310 | 0.097        | -0.029  | 0.308 | 0.097        | -0.141 | 0.322 | 0.123        |
| 3 | -0.077 | 0.450 | 0.209        | -0.081 | 0.448 | 0.208        | -0.081  | 0.437 | <b>0.198</b> | -0.184 | 0.491 | 0.275        |
| 4 | -0.008 | 0.171 | 0.029        | -0.014 | 0.190 | 0.036        | -0.013  | 0.166 | 0.028        | -0.007 | 0.089 | <b>0.008</b> |
| 5 | 0.011  | 0.263 | 0.070        | 0.062  | 0.249 | 0.062        | 0.004   | 0.240 | 0.058        | 0.008  | 0.188 | <b>0.032</b> |
| 6 | -0.001 | 0.292 | 0.085        | -0.011 | 0.307 | 0.095        | -0.009  | 0.289 | <b>0.084</b> | -0.214 | 0.325 | 0.150        |
| 7 | -0.038 | 0.268 | 0.073        | -0.026 | 0.262 | <b>0.070</b> | -0.026  | 0.264 | <b>0.070</b> | -0.022 | 0.031 | 0.177        |
| 8 | 0.074  | 0.260 | <b>0.073</b> | 0.077  | 0.271 | 0.080        | 0.077   | 0.276 | 0.082        | 0.101  | 0.667 | 0.456        |
| 9 | 0.010  | 0.117 | 0.014        | 0.012  | 0.121 | 0.015        | 0.012   | 0.117 | 0.014        | 0.005  | 0.069 | <b>0.005</b> |

**b) Asymmetry coefficients for residuals distributions (lowest in bold).**

| # Site | DIR           | SPD           | DIR+SPD       | 10-min        |
|--------|---------------|---------------|---------------|---------------|
| 1      | 0.085         | 0.113         | 0.107         | <b>-0.056</b> |
| 2      | <b>-0.025</b> | 0.100         | 0.126         | 1.051         |
| 3      | -1.771        | -1.816        | <b>-1.592</b> | -2.120        |
| 4      | -1.410        | <b>-1.218</b> | -1.593        | -5.945        |
| 5      | <b>-0.790</b> | -1.145        | -0.976        | -0.797        |
| 6      | <b>-0.876</b> | -1.158        | -0.917        | -1.123        |
| 7      | -0.623        | -0.721        | <b>-0.393</b> | 1.033         |
| 8      | -0.494        | -0.244        | <b>0.038</b>  | 3.563         |
| 9      | -0.192        | <b>-0.070</b> | -0.110        | -0.408        |

The only significant conclusion that could be drawn was that the 10-minute method presents the worst performance, due to the high asymmetry coefficients. As suggested, the estimation of  $\alpha$  for each 10-minute record may lead to incongruent values when wind speeds are low, and extrapolation of wind speed leads to propagation of these inconsistencies, leading to less accurate results.

However, if mean values of  $\bar{\alpha}$  are used, it was shown here that the level of detail does not influence very strongly the result in terms of average annual wind speed. Although the level of detail in  $\bar{\alpha}$  estimation is increased from estimation by wind direction, to estimation by wind speed, to estimation by wind speed and direction, this does not lead to increased accuracy in wind speed extrapolation. Therefore, it may not be necessary to use higher levels of detail, as they only lead to increased difficulty in performing calculations.

Overall, the estimation of  $\bar{\alpha}_{23}$  by wind direction is a method which yields good results in terms of wind speed extrapolation from  $h_3$ . In those sites in which it does not yield the best results, it does not present very significant deviation, being close to the best performing method. Therefore, it was selected as the level of detail to use in the remaining study when estimating wind shear coefficients.

### C. Study of wind speed extrapolation from data

To study the different combined methodologies of wind shear coefficient estimation/wind speed extrapolation when applied to wind data series (as opposed to average values as was presented in section 3A), for all 4-level sites (sites 1 to 9), an extrapolated wind speed at an extrapolation height  $h_4$  was generated by using the combination of methodologies. However, in this case the wind shear coefficients were estimated by wind direction sector (best level of detail as concluded in section 3.B.) and the extrapolation was carried out by 10-minute records, using the wind data series from heights  $h_1$  to  $h_3$ . The extrapolated data series were compared with the measured wind speeds at height  $h_4$  and the accuracy of each methodology was measured through the statistical parameter Root Mean Squared Error (RMSE) presented in Table IV. The RMSE represents the sample standard deviation of the differences between predicted values ( $v_e$ ) and observed values ( $v_m$ ), being a measure of accuracy.

**Table IV** RMSE values for wind speed data series prediction for all 4-level sites and different methodologies (lowest in bold).

| #<br>Site | RMSE, m/s                     |                           |                               |                           |                                |                            |
|-----------|-------------------------------|---------------------------|-------------------------------|---------------------------|--------------------------------|----------------------------|
|           | $\bar{\alpha}_{13},$<br>$h_3$ | $\bar{\alpha}_{13},$<br>d | $\bar{\alpha}_{23},$<br>$h_3$ | $\bar{\alpha}_{23},$<br>d | $\bar{\alpha}_{123},$<br>$h_3$ | $\bar{\alpha}_{123},$<br>d |
| 1         | 0.367                         | 0.454                     | <b>0.352</b>                  | 0.431                     | 0.368                          | 0.457                      |
| 2         | 0.310                         | 0.400                     | <b>0.310</b>                  | 0.400                     | 0.310                          | 0.401                      |
| 3         | 0.452                         | 0.508                     | <b>0.451</b>                  | 0.507                     | 0.452                          | 0.508                      |
| 4         | 0.172                         | 0.224                     | <b>0.171</b>                  | 0.224                     | 0.172                          | 0.224                      |
| 5         | <b>0.260</b>                  | 0.335                     | 0.264                         | 0.340                     | <b>0.260</b>                   | 0.335                      |
| 6         | <b>0.288</b>                  | 0.364                     | 0.292                         | 0.369                     | <b>0.288</b>                   | 0.364                      |
| 7         | <b>0.264</b>                  | 0.347                     | 0.271                         | 0.355                     | 0.272                          | 0.358                      |
| 8         | <b>0.258</b>                  | 0.340                     | 0.270                         | 0.355                     | <b>0.258</b>                   | 0.339                      |
| 9         | 0.128                         | 0.166                     | <b>0.118</b>                  | 0.155                     | 0.129                          | 0.167                      |

The calculated RMSE shows that for five sites the best approach was using  $\bar{\alpha}_{23}$  with reference height  $h_3$ . In four of the sites, the method using  $\bar{\alpha}_{13}$  with reference height  $h_3$  shows a better accuracy while for three of them the same results for RMSE were obtained using  $\bar{\alpha}_{123}$  with reference height  $h_3$ . In general, the distance method seems to be worse in predicting wind speed at extrapolated height.

The average wind speed was then calculated for each extrapolated data series and for the measured data series at height  $h_4$ . The results in average wind speed values and standard deviation for wind speed extrapolation using different methodologies are presented for each 4-level site and extrapolation methodology in Table V.

**Table V** Mean wind speed obtained at  $h_4$  and standard deviation (*Std*) for each extrapolation procedure, including measured values (OBS).

| #<br>Site | Average wind speed at $h_4$ , m/s and ( <i>Std</i> ) |                              |                           |                               |                           |                                |                            |
|-----------|------------------------------------------------------|------------------------------|---------------------------|-------------------------------|---------------------------|--------------------------------|----------------------------|
|           | OBS<br>( $h_4$ )                                     | $\bar{\alpha}_{13}$<br>$h_3$ | $\bar{\alpha}_{13},$<br>d | $\bar{\alpha}_{23},$<br>$h_3$ | $\bar{\alpha}_{23},$<br>d | $\bar{\alpha}_{123},$<br>$h_3$ | $\bar{\alpha}_{123},$<br>d |
| 1         | 6.24<br>(4.27)                                       | 6.31<br>(4.33)               | 6.34<br>(4.34)            | 6.25<br>(4.30)                | 6.24<br>(4.29)            | 6.32<br>(4.34)                 | 6.35<br>(4.34)             |
| 2         | 6.61<br>(3.17)                                       | 6.60<br>(3.16)               | 6.62<br>(3.14)            | 6.59<br>(3.15)                | 6.60<br>(3.14)            | 6.60<br>(3.16)                 | 6.62<br>(3.15)             |
| 3         | 6.77<br>(3.18)                                       | 6.69<br>(3.04)               | 6.70<br>(3.03)            | 6.71<br>(3.05)                | 6.72<br>(3.03)            | 6.69<br>(3.04)                 | 6.70<br>(3.02)             |
| 4         | 8.77<br>(3.54)                                       | 8.75<br>(3.52)               | 8.75<br>(3.51)            | 8.76<br>(3.52)                | 8.76<br>(3.52)            | 8.75<br>(3.52)                 | 8.75<br>(3.51)             |
| 5         | 7.63<br>(3.98)                                       | 7.65<br>(4.06)               | 7.66<br>(4.09)            | 7.64<br>(4.07)                | 7.65<br>(4.10)            | 7.65<br>(4.06)                 | 7.66<br>(4.09)             |
| 6         | 7.93<br>(3.80)                                       | 7.96<br>(3.81)               | 7.97<br>(3.83)            | 7.93<br>(3.80)                | 7.94<br>(3.82)            | 7.96<br>(3.81)                 | 7.97<br>(3.83)             |
| 7         | 8.56<br>(2.46)                                       | 8.56<br>(2.40)               | 8.57<br>(2.38)            | 8.52<br>(2.39)                | 8.51<br>(2.36)            | 8.53<br>(2.40)                 | 8.52<br>(2.38)             |
| 8         | 8.53<br>(2.22)                                       | 8.59<br>(2.26)               | 8.60<br>(2.25)            | 8.60<br>(2.26)                | 8.62<br>(2.26)            | 8.59<br>(2.26)                 | 8.60<br>(2.25)             |
| 9         | 7.84<br>(2.88)                                       | 7.89<br>(2.90)               | 7.90<br>(2.89)            | 7.85<br>(2.88)                | 7.85<br>(2.87)            | 7.89<br>(2.90)                 | 7.90<br>(2.90)             |

Comparing the average extrapolated wind speed values at  $h_4$  (Table V) with those measured at the same height, no large differences between averages were observed, but applying a Z-test mean differences to those results, some significant differences were verified (Table VI).

In Table VI the values marked as bold are those which reveal significant differences between average extrapolated and measured wind speed values at  $h_4$ , using the different methods.

Results show that for sites 1, 2, 4, 5, 6 and 9, methods using  $\bar{\alpha}_{23}$  with reference height  $h_3$  or the distance method were a good methodology. For sites 2, 4, 5, 6 and 7, the method using  $\bar{\alpha}_{13}$  or  $\bar{\alpha}_{123}$  with reference height  $h_3$  also show good accuracy. Using  $\bar{\alpha}_{13}$  or  $\bar{\alpha}_{123}$  with the distance method only showed good accuracy in sites 2, 4, 5 and 7. In site 3 and 8 all methods revealed bad performance with very significant differences ( $p = 0.000$ ).

It can be observed that lower errors are obtained when estimating  $\alpha$  using the two higher heights,  $h_2$  and  $h_3$ . This may be because these heights are closer to the topmost height ( $h_4$ ) used as observed measurement reference. Regardless of the extrapolation methodology, estimating the wind shear coefficient as  $\bar{\alpha}_{23}$  leads to a good estimate

of average wind speed in six of the nine sites (67%). In this case, varying the extrapolation methodology does not lead to a great difference in wind speed estimates but it can be concluded that, on average, best results were obtained with method using  $\bar{u}_{23}$  with reference height  $h_3$ .

**Table VI** Z-test differences. (Significant differences ( $p < 0.05$ ) are presented in bold)

| #Site | Observed value Z-test and ( $p_{value}$ ) |                         |                         |                         |                         |                         |
|-------|-------------------------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
|       | $\bar{u}_{13}, h_3$                       | $\bar{u}_{13}, d$       | $\bar{u}_{23}, h_3$     | $\bar{u}_{23}, d$       | $\bar{u}_{123}, h_3$    | $\bar{u}_{123}, d$      |
| 1     | <b>2.83</b><br>(0.002)                    | <b>3.92</b><br>(0.000)  | 0.23<br>(0.409)         | -0.05<br>(0.520)        | <b>2.97</b><br>(0.001)  | <b>4.13</b><br>(0.000)  |
| 2     | -0.49<br>(0.690)                          | 0.55<br>(0.290)         | -1.13<br>(0.870)        | -0.39<br>(0.653)        | -0.40<br>(0.655)        | 0.70<br>(0.243)         |
| 3     | <b>-6.81</b><br>(0.000)                   | <b>-6.27</b><br>(0.000) | <b>-5.79</b><br>(0.000) | <b>-4.76</b><br>(0.000) | <b>-6.94</b><br>(0.000) | <b>-6.47</b><br>(0.000) |
| 4     | -0.66<br>(0.746)                          | -0.55<br>(0.710)        | -0.38<br>(0.648)        | -0.14<br>(0.555)        | -0.69<br>(0.755)        | -0.60<br>(0.725)        |
| 5     | 0.56<br>(0.287)                           | 0.88<br>(0.189)         | 0.40<br>(0.345)         | 0.64<br>(0.260)         | 0.59<br>(0.278)         | 0.92<br>(0.179)         |
| 6     | 1.22<br>(0.111)                           | <b>1.97</b><br>(0.025)  | -0.03<br>(0.513)        | 0.13<br>(0.449)         | 1.27<br>(0.101)         | <b>2.04</b><br>(0.021)  |
| 7     | 0.31<br>(0.379)                           | 0.83<br>(0.202)         | -2.53<br>(0.994)        | -3.36<br>(1.000)        | -1.91<br>(0.972)        | -2.43<br>(0.993)        |
| 8     | <b>8.73</b><br>(0.000)                    | <b>4.88</b><br>(0.000)  | <b>5.32</b><br>(0.000)  | <b>6.25</b><br>(0.000)  | <b>4.31</b><br>(0.000)  | <b>4.79</b><br>(0.000)  |
| 9     | <b>2.60</b><br>(0.005)                    | <b>3.04</b><br>(0.001)  | 0.58<br>(0.280)         | 0.21<br>(0.417)         | <b>2.76</b><br>(0.003)  | <b>3.25</b><br>(0.001)  |

## 4. Conclusion

The characterization of wind shear and wind speed vertical extrapolation is a challenge that leads to increased uncertainty in wind resource assessment and energy production estimates.

It was confirmed that, through a wide variety of landscapes and land covers, the power law is a more accurate method for wind shear prediction and speed extrapolation than the logarithmic-based profile, with WAsP default settings. For this reason, if measurements at several heights are available, the power law should be applied. However, the generalization of this conclusion requires its validation with a bigger sample of sites.

Moreover, if more than two heights of measurement data are accessible, the two heights closer to the extrapolation height should be used to estimate wind shear coefficients. It was also found that estimating an average wind shear coefficient by 30° wind direction sectors, by 1 m/s wind speed bin, or the combination of both did not influence the accuracy strongly, therefore estimation by wind direction sector was used to minimize calculation complexity.

As far as the wind speed extrapolation method is concerned, direct extrapolation using the power law from the top-most height is recommended.

The proposed power law method for wind data series extrapolation was found to be efficient and reliable in a variety of conditions. It is suggested that opting for its use instead of other less reliable methods may contribute to reduce uncertainty in wind resource assessment.

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