The Strict Relationship between Surface Turbulence Intensity and Wind Shear Coefficient Daily Courses: A Novel Method to Extrapolate Wind Resource to the Turbine Hub Height

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Abstract– Based on power law, a novel method is proposed to extrapolate surface wind speed (*v*) to the wind turbine (WT) hub height, via prediction of the wind shear coefficient (WSC) daily course, by only using the surface turbulence intensity (*I*) daily course. Work's main outcome is a strict (almost 1:1) relationship between WSC and *I* daily courses which was found after applying a linear regression analysis. Practical usefulness of this finding for wind energy applications is straightforward, as merely using *I* values routinely collected at surface heights a WSC predicting model may be used to fairly estimate energy yield at WT hub height.

A 2–year (2012–2013) dataset from the meteorological mast of Cabauw (Netherlands) was used, including 10–min records collected at heights of 10, 20, 40, and 80 m. Methods were trained over a 1–year period (2012) and then validated over an independent 1–year period (2013). WT hub heights of 40 and 80 m have been targeted for the extrapolation, being accomplished based on *I* observations at two surface levels: 10 and 20 m.

As a result, good scores were returned by the proposed method over the most challenging height intervals: between 10 and 80 m, a 5% mean bias was achieved in extrapolated *v* values and at worst a 11.51% in calculated energy yield; between 20 and 80 m, extrapolated *v* values were biased by 2%, while energy output at worst by 6.62%.

Keywords– Wind resource extrapolation; Power law; Wind shear coefficient; Turbulence intensity; Daily course; Wind energy yield.

1. Introduction

The frequent lack of wind speed measurements at heights relevant to wind energy exploitation often makes it necessary to extrapolate observed wind speeds from lower available heights to the upper wind turbine (WT) hub heights [1]. Unfortunately, wind speed extrapolation is probably one of the most critical uncertainty factors affecting the assessment of a site wind power potential during the feasibility studies. To date, this has become more and more challenging if considering the increasing size of modern multi–MW WTs, and thus of their hub height. In such a rapidly growing scenario, chasing the wind at steadily increasing WT hub heights by using the classical meteorological masts appears as a more and more expensive solution [2]. The use of wind profilers such as LIDAR or SODAR is certainly more appropriate [3], yet it would largely increase the costs of the wind power project, often making it economically not viable. Therefore, to increase the knowledge on wind speed extrapolation methods appears preferable, as not only allowing a wider application spectrum to predict wind resource at different WT hub heights, but also offering the advantage of merely using wind measurements routinely collected at surface heights (10 or 20 m above ground level, AGL) [2].

Various methods exist in the literature addressing extrapolation of wind speed to the WT hub height. Among these methods, power law (PL) is the most widely used in wind energy studies [4]. Ultimately, PL–based wind speed extrapolation is performed once a proper value is set to wind shear coefficient (WSC), which may be either achieved from an earlier measurement or, where this is not possible, *a priori* assigned through a default value. To this goal, in the present work three PL–based methods of extrapolating available observations of surface wind speed are analysed and compared, and their impact on predicted power output from commonly used WTs assessed. This was accomplished by considering the following options in setting WSC: (i) the typical 0.143 (1/7) *a priori* default value; (ii) site's previously measured overall yearly mean value; (iii) site's previously measured daily course. Option (i) is generally chosen when no wind speed observations at a second upper height are available, thus being quite a common practice in many wind energy applications. However, several works worldwide have demonstrated that this simplification may lead to dramatic wind speed extrapolation errors, and thus to appreciably biased predicted energy output. For example, with respect to the observed value, Firtin et al. [4] reported a difference of up to 28% in annual energy yield obtained using between 10 and 50 m extrapolated wind speed values based on the 0.143 WSC value. Therefore, in the current work option (i) is treated as a base case to which options (ii) and (iii) are compared against so as to realistically improve extrapolation accuracy. Unfortunately, the latter have the disadvantage or requiring availability of wind speed observations at a second upper height, which may be of great concern – as discussed above – when this is a modern WT hub height. To this aim, as far as option (iii) is concerned, a novel method is proposed herein to predict the WSC daily course by only using the surface turbulence intensity daily course. Turbulence intensity is commonly regarded as a critical parameter in wind energy studies [5–8]. Conversely, following up the issue addressed in [2], it has been treated as a "positive" factor here by investigating the existence of a reasonable relationship with WSC in order to be used as a predictor of the latter. Practical usefulness of this finding for wind energy applications will be highlighted.

Observations from the 213–m tall meteorological mast of Cabauw (Netherlands) were used, including 10–min records collected at heights of 10, 20, 40, and 80 m AGL. Data from 01/01/2012 to 31/12/2013 (2 full years) were processed: data from the year 2012 (analysis period) were used to assess site's wind characteristics and train the extrapolation methods, which were later validated over the year 2013 (testing period). Turbulence intensity observations collected at two surface levels, 10 and 20 m, were used. Two WT hub heights, 40 and 80 m, have been targeted, since observations to test the methods were available at those heights.

2. Methods

2.1 Weibull Wind Speed Distribution

Determination of wind speed characteristics can be achieved through several wind speed probability density functions, such as Weibull, Rayleigh, Gamma, Lognormal, etc. [9]. A broad classical (e.g., [10]) as well as recent literature (e.g., [11]) indicate the two–parameter Weibull probability density function *f(v)* to be the best fitting model for wind speed data analysis, which constitutes, also for its simplicity, the most widely accepted and commonly used distribution for wind energy studies [9]:

$$f(v)=\frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (1)$$

where c [m/s] is the scale parameter, k the shape parameter, and v [m/s] is wind speed.

Site's available wind power density $P(v)$ [W/m^2] is defined as the wind power per unit area A [m^2] swept by the WT rotor [12]:

$$P(v)=\frac{1}{2}\rho v^3 \quad (2)$$

where ρ [kg/m^3] is the air density, which may be calculated as [13]:

$$\rho=\frac{P_a}{R\times T} \quad (3)$$

P_a being the air pressure [mbar], R the specific gas constant for air [287.053 J/kg K], and T the air temperature [K].

2.2 Wind Energy Output

After combining, for each v bin, site's wind speed frequency distribution *f(v)* and the WT electric power curve $P_e(v)$ as provided by the manufacturer, it is possible to calculate the actual energy production of a WT (E_A) over a given duration t, or its Annual Energy Yield (AEY) [kWh/y] when commonly assuming $\bar{t}$ =8760 hours [14]:

$$AEY = E_A = \bar{t}\int_{v_i}^{v_o} P_e(v)\,f(v)\,dv \quad (4)$$

where v is integrated between WT's cut–in (v_i) and cut–off (v_o) wind speeds.

Capacity factor (CF) [%] is a crucial index for assessing the WT's performance at a site. It is defined as the ratio of AEY to the energy (E_r) that the WT could have been produced if operated at its rated power (P_r) through the same period [14]:

$$CF=\frac{E_A}{E_r} \quad (5)$$

The knowledge of *CF* enables Full–Load Hours (*FLH*) [h/y] to be calculated after multiplying *CF* by the number of hours in one year ($\bar{t}$ =8760) [15]:

$$FLH = CF * \bar{t} = CF * 8760 \quad (6)$$

A further crucial parameter to assess WT's performance at a site, availability factor (*AF*) [%] accounts for the time percentage a WT is operating between its v_i and v_o values at a site, and can be calculated using the following equation [16]:

$$AF = \int_{v_i}^{v_o} \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] dv \quad (7)$$

2.3 Wind Shear Coefficient

The PL equation is given as [16]:

$$v_2 = v_1 \left(\frac{z_2}{z_1}\right)^{\alpha} \quad (8)$$

where v_1 and v_2 are simultaneous wind speeds at elevations z_1 and z_2, respectively. The exponent α [–], also known as WSC, is highly site– and time–dependent [17], as well as a function of the considered height interval. In particular, WSC depends on *v*, roughness length (z_0), nature of terrain, and atmospheric stability [16–21], often changing from less than 1/7 during the day to more than 1/2 at night [16]. Observed WSCs typically range from 0.40 in urban areas with high buildings to 0.10 over smooth, hard ground, lakes or ocean [1, 13, 16, 18, 19, 22]. Indeed, Eq. (8) is an engineering, empirical formula, essentially amalgamating the stability correction and z_0 features into one single factor (i.e., α) [16, 23], but has no physical basis. Its validity is generally limited to the lower atmosphere, up to 150–200 m [16].

Once concurrent records of v_1 and v_2 are available at a site, from Eq. (8) α can be measured as:

$$\alpha = \frac{ln(v_2 / v_1)}{ln(z_2 / z_1)} \quad (9)$$

Conversely, when observed values are not available, as reported earlier, a rule of thumb is to take α as approximately 0.143 (or 1/7, known as the $1/7^{th}$ PL), although in principle this value is only appropriate for a smooth terrain (z_0 in the order of a few centimetres) to describe wind profiles up to the first 100 m during near–neutral (adiabatic) conditions [23, 24].

2.4 Turbulence Intensity

Wind turbulence is a critical parameter in wind energy owing to various aspects, as it increases: (i) the load levels onto WTs, thus reducing WTs operational life [5]; (ii) the energy yield uncertainty, mostly as a result of WT power curve uncertainty [6, 7]; (iii) energy losses, thus reducing the WT power output [5, 7, 8]. It is mainly generated from two causes: (i) friction with terrain surface (e.g., trees and buildings) and topographical features (such as hills and mountains), and (ii) thermal effects due to convective variations of temperature, and hence of air density, causing air masses to move vertically. Turbulence intensity (*I*), commonly expressed in [%], is one of the most widespread turbulence indicators used in wind energy studies, and is defined as the standard deviation of *v* fluctuations from 10–min averaged mean *v* ($\bar{v}$) [8]:

$$I = \frac{\sigma_u}{\bar{v}} \quad (10)$$

where σ_u (the standard deviation of longitudinal *v* fluctuation) and $\bar{v}$ are calculated over 10–min bins. Actually, *I* as defined in Eq. (10) is more properly intended as ambient turbulence intensity, i.e., dependent on site conditions only and thus as distinct from turbulence generated by neighbouring turbines (wake interferences), which should be regarded as an added value [16, 25]. *I* was experimentally found to vary with the same parameters as WSC, i.e., z_0, *v*, *z*, atmospheric stability, and topographic features [18]. In particular, *I* increases with z_0 [5, 18, 25–27], while decreases with *v* and *z* [12, 13, 26–28].

3. Study Area and Data

Starting from 1972, the Royal Netherlands Meteorological Institute (KNMI) operates a 213–m tall meteorological mast near Cabauw (the Netherlands), a village about 50 km SE from the North Sea [29]. The tower (51.971° N, 4.926° E) is located in a polder 0.7 m below average sea level (ASL). The site, topographically flat within a radius of 20 km, is in open pasture for at least 400 m in all directions [22]. Mast data, maintained by the Cabauw Experimental Site for Atmospheric Research (CESAR), are available as 10–min averages over several years, and can be freely downloaded from the related website (http://www.cesar–database.nl).

In the present work, 10–min averaged observations of wind speed and direction, standard deviation of wind speed, air temperature and pressure were collected at heights of 10, 20, 40, and 80 m AGL. Data from 01/01/2012 to 31/12/2013 (2 full years) were processed, where those from the year 2012 (analysis period) were used to assess site's meteorological characteristics and train the extrapolation methods, which were later validated over the year 2013 (testing period). Since the work is focused on actual wind energy applications, the following assumptions have been made in the training and testing phases: (i) both predicted and observed *v* values (v_{40} and v_{80}) are greater or equal to 3 m/s, since this is the typical cut–in v value of modern 40–m and 80–m hub height WTs; (ii) observed surface v values (v_{10} and v_{20}) are greater than 1.5 m/s, i.e., after applying a reasonable downscaling factor to v=3 m/s. Based on a number of studies (e.g., [22, 29]), the Cabauw site z_0 is supposed to be about 2 cm.

4. Data Analysis

4.1 Overall Meteorological Statistics

The overall annual statistics of main meteorological variables measured at 10, 20, 40, and 80 m from 10–min records during the analysis period (2012) are summarised in Table 1. After applying work's general assumptions (see § 3), a data sample of 85.46% was processed. As expected, mean values of v (4.42–7.19 m/s) and P (99.2–332.5 W/m^2) increase with height, while those of I decrease (14.55–8.55%). Conversely, σ_u, T and ρ are quite constant with height.

Table 2 reports the overall annual statistics of WSC, calculated through Eq. (9) from 10–min v pairs measured at various height intervals between 10 and 80 m. As shown, mean WSCs range from 0.241 (α_{10-40}) to 0.263 (α_{20-80}).

Table 1. Overall annual mean and standard deviation of 10–min records observed between 10 and 80 m at the Cabauw site (2012)[a]

Variable	Height AGL (m)			
	10	20	40	80
v (m/s)	4.42 ± 2.15	5.10 ± 2.29	5.97 ± 2.40	7.19 ± 2.67
σ_u (m/s)	0.64 ± 0.34	0.66 ± 0.35	0.65 ± 0.36	0.60 ± 0.35
I (%)	14.55 ± 4.63	12.97 ± 4.60	10.93 ± 4.62	8.55 ± 4.41
T (°C)	10.39 ± 6.62	10.37 ± 6.64	10.40 ± 6.58	10.30 ± 6.62
ρ (kg/m^3)	1.246 ± 0.034	1.245 ± 0.034	1.242 ± 0.034	1.236 ± 0.034
P (W/m^2)	99.2 ± 180.8	140.8 ± 241.9	205.2 ± 315.9	332.5 ± 438.2

[a] Statistics for 52,704 records (01/01/2012–31/12/2012). Sample size: 85.46%.

Table 2. Overall annual mean and standard deviation of 10–min WSC observed between 10 and 80 m at the Cabauw site (2012)[a]

Variable	Height interval AGL (m)		
	10–40	10–80	20–80
α	0.241 ± 0.137	0.252 ± 0.131	0.263 ± 0.145

[a] Statistics for 52,704 records (01/01/2012–31/12/2012). Sample size: 85.46%.

4.2 Wind Shear Coefficient

Agreeing with several findings (e.g., [4, 7, 13, 23, 30]), daily variation of observed WSCs (Fig. 1a) is a clear function of the diurnal heating/cooling cycle of air above the ground, and thus of atmospheric stability. Indeed, a very slight difference affects WSCs observed at various height intervals, particularly in the daytime unstable hours. Overall, hourly WSCs spread from a nighttime (h. 22–23) top value in the range of 0.330–0.353 to a noon bottom value close to 0.130, globally exhibiting a 150–170% difference between the extremes.

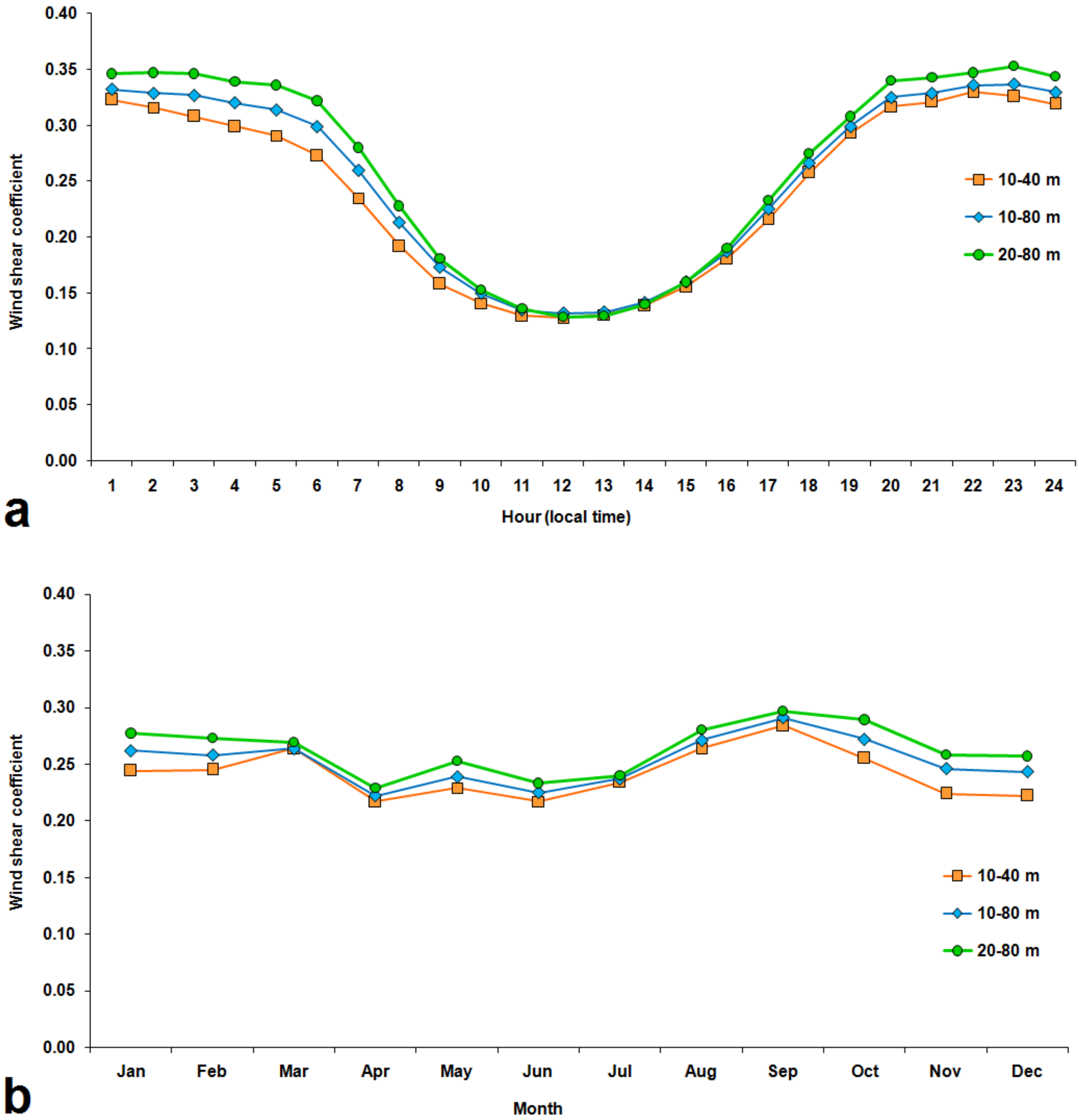


Figure 1. Variation of 10–min WSC observed between 10 and 80 m at the Cabauw site (2012) by: (a) hour of day; (b) month of year.

Monthly variation of observed WSCs (Fig. 1b) shows the extreme values occurring during the transition seasons, with the highest markedly in Sep. (0.284–0.297), and the lowest in April (0.217–0.229). However, this monthly course is far less pronounced than the daily one (relative difference at maximum of 31%). It should be noted that the pattern among WSCs at different height intervals during the warmer (more unstable) months is basically the same, which definitely agrees with the one affecting the WSC daily course during the warmer (more unstable) hours (Fig. 1a).

4.3 Turbulence Intensity

Similarly to WSC, daily I variation (Fig. 2a) is a straight function of atmospheric stability. Consistently with several findings (e.g., [7, 13, 27, 30]), I hourly mean values are lower during stable nighttime conditions (bottom values around midnight), whereas they start to increase after sunrise, i.e., as the air above the ground warms up, becoming buoyant enough to rise up and form a pattern of convection cells [8]. This phenomenon reaches a peak around noon, then drops down till sunset. As shown, this daily course is smoother at lower heights (I_{10} ranging 12.60–17.00%, 35% difference) and sharper at upper heights (I_{80} ranging 6.30–12.00%, 90% difference). Also, the comparison between Figs. 1a and 2a highlights an appreciable different pattern between I at various heights vs. WSCs at various height intervals.

The I variation by month (Fig. 2b) also depends on stability conditions, as lower values occur during the colder (and more stable) months (Nov to Feb), and higher during the warmer (and more unstable) ones (May to July). However, this monthly I variation is smoother than the daily one, as the difference between the extremes spans from 27% (I_{10}) to 32% (I_{80}).

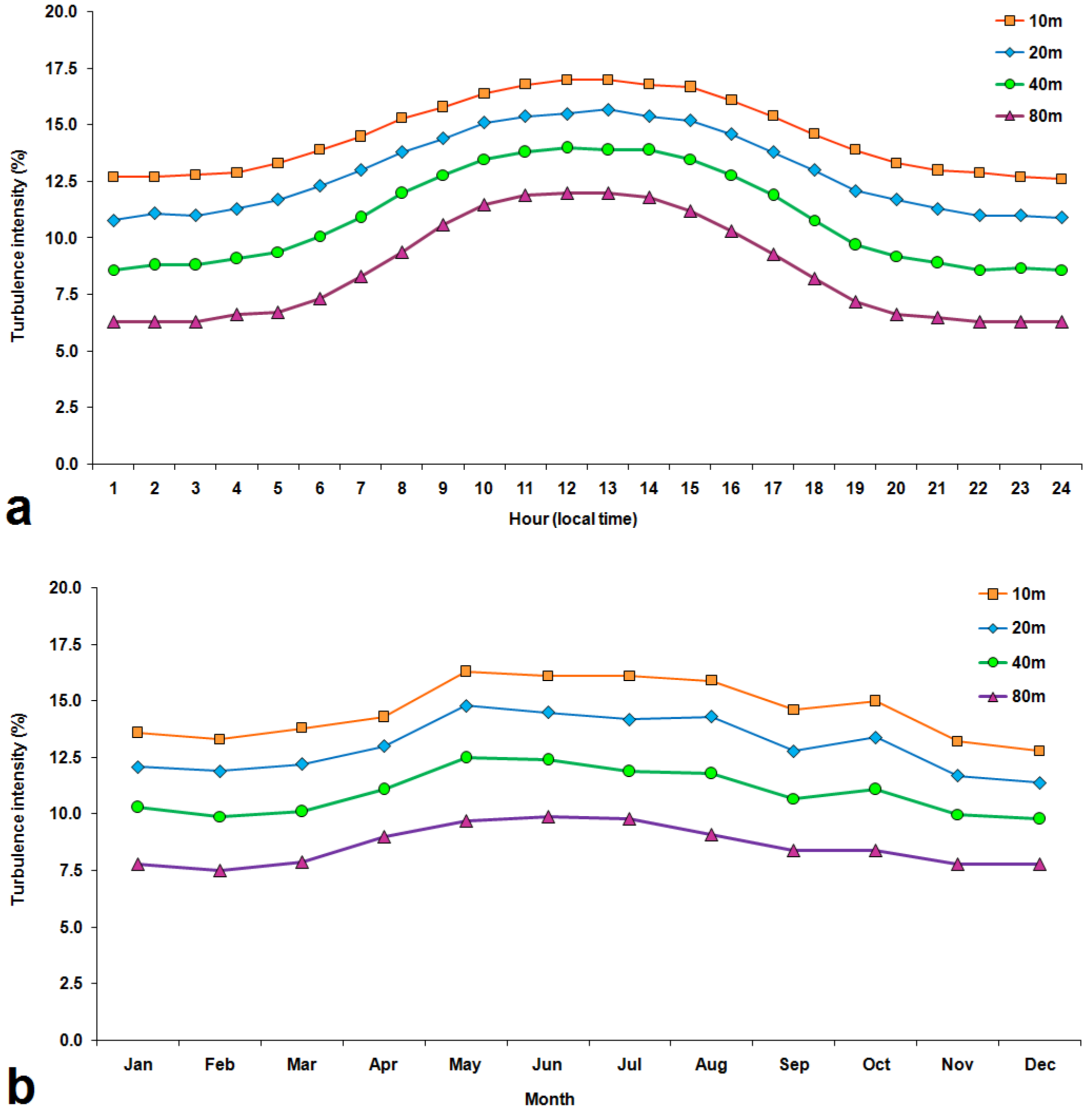


Figure 2. Variation of 10–min turbulence intensity observed between 10 and 80 m at the Cabauw site (2012) by: (a) hour of day; (b) month of year.

4.4 Temporal Course Relationship between WSC and Surface Turbulence Intensity

The existence of a possible linear relationship between WSC and I, suggested in the past literature [18, 28], has been recently clearly demonstrated [2]. In this work it has been analysed with a specific focus of their temporal pattern. In particular, the values of both daily and monthly courses reconstructed through the year 2012 and plotted in Figs. 1a (α) and 2a (I), and Figs. 1b (α) and 2b (I), have been used to perform an α vs. I crosscorrelation. As a result, while WSC and I are not significantly correlated in the monthly course, a strict relationship was found in the daily course, where WSC and I exhibit a strong anti–correlation, being very close to the 1:1 ratio (Table 3).

Table 3. Correlation coefficients (*r*) by height interval and temporal course between WSC and *I* observed between 10 and 80 m at the Cabauw site (2012)

Temporal course	Height interval AGL (m)		
	10–40	10–80	20–80
	Correlation		
	I_{10} vs. α_{10-40}	I_{10} vs. α_{10-80}	I_{20} vs. α_{20-80}
Daily	–0.985	–0.991	–0.990
Monthly	0.024	–0.159	–0.270

Owing to their importance for the scope of the present work, the hourly averaged values of WSC and *I* through the year 2012, plotted in Figs. 1a (α) and 2a (*I*), have been also explicitly reported (Table 4).

The daily course α vs. *I* strict relationship has been further investigated by applying a linear regression analysis in the form:

$$\alpha = a * I + b \quad (11)$$

where α is the predicted variable, *I* the independent variable or regressor, and *a* and *b* the regression coefficients. Note that in Eq. (11) *I* has been expressed in decimal rather than in percent values. The results of this linear regression analysis by height interval are summarised in Table 5, showing a remarkable r^2 value ranging 0.971–0.982, and indicating the α prediction at worst to be affected by a 0.013 SE. Overall, it should be noted that the numerical values of *a* and *b* regression coefficients are quite similar from one height interval to the other. Summarising, the10–80 m α estimation proved to be the finest, while the 10–40 m one is (by a very small amount, actually) the least accurate.

Table 4. Variation by hour of the day of 10–min WSC and *I* observed between 10 and 80 m at the Cabauw site (2012)

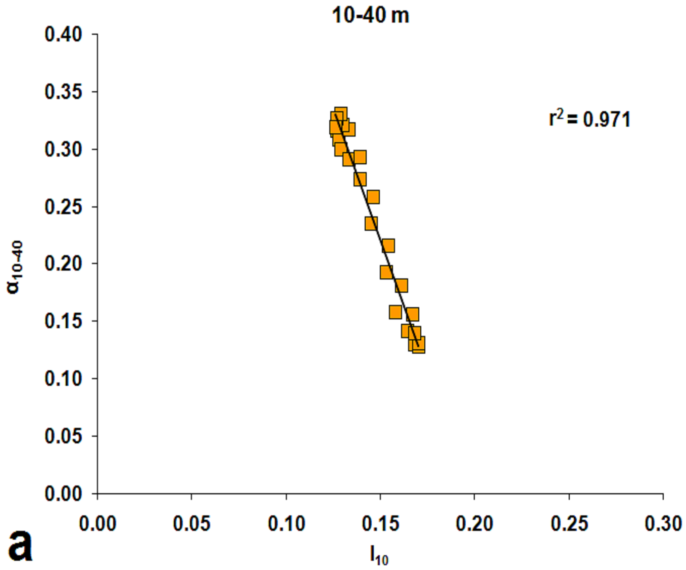
Hour	Turbulence intensity		WSC		
	Height AGL (m)		Height interval AGL (m)		
	10	20	10–40	10–80	20–80
1	0.127	0.108	0.323	0.332	0.346
2	0.127	0.111	0.316	0.329	0.347
3	0.128	0.110	0.308	0.327	0.346
4	0.129	0.113	0.299	0.320	0.339
5	0.133	0.117	0.291	0.314	0.336
6	0.139	0.123	0.273	0.299	0.322
7	0.145	0.130	0.235	0.260	0.280
8	0.153	0.138	0.192	0.213	0.228
9	0.158	0.144	0.158	0.173	0.181
10	0.164	0.151	0.141	0.150	0.153
11	0.168	0.154	0.130	0.135	0.136
12	0.170	0.155	0.128	0.132	0.129
13	0.170	0.157	0.131	0.133	0.130
14	0.168	0.154	0.139	0.142	0.140
15	0.167	0.152	0.156	0.160	0.160
16	0.161	0.146	0.181	0.187	0.190
17	0.154	0.138	0.216	0.225	0.233
18	0.146	0.130	0.258	0.266	0.275
19	0.139	0.121	0.293	0.299	0.308
20	0.133	0.117	0.317	0.325	0.340
21	0.130	0.113	0.321	0.329	0.343
22	0.129	0.110	0.330	0.336	0.347
23	0.127	0.110	0.326	0.337	0.353
24	0.126	0.109	0.319	0.330	0.344

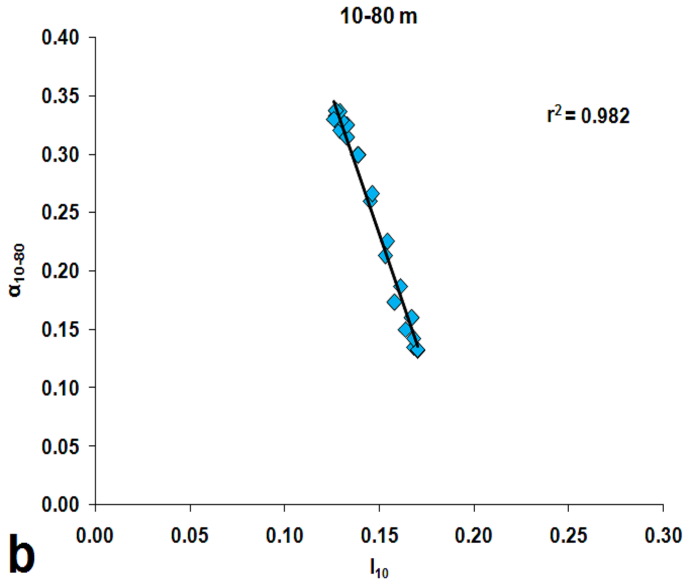
Table 5. Statistical results of linear regression analysis by height interval between WSC and I daily courses performed between 10 and 80 m at the Cabauw site (2012)

Height interval AGL (m)	Regression	Coefficients		Statistical indicators		
		a	b	SE	r^2	F–$stat$
10–40	$\alpha_{10-40} = a * I_{10} + b$	–4.57	0.91	0.013	0.971	741
10–80	$\alpha_{10-80} = a * I_{10} + b$	–4.76	0.94	0.011	0.982	1183
20–80	$\alpha_{20-80} = a * I_{20} + b$	–4.78	0.88	0.013	0.980	1097

SE standard error, *F–stat* statistic of the F test.

The α vs. I daily course strict relationship has been also graphically displayed through the scatter–plots (Fig. 3), where the equations of linear best–fits are given by Eq. (11) after applying, for each height interval, the coefficients reported in Table 5.





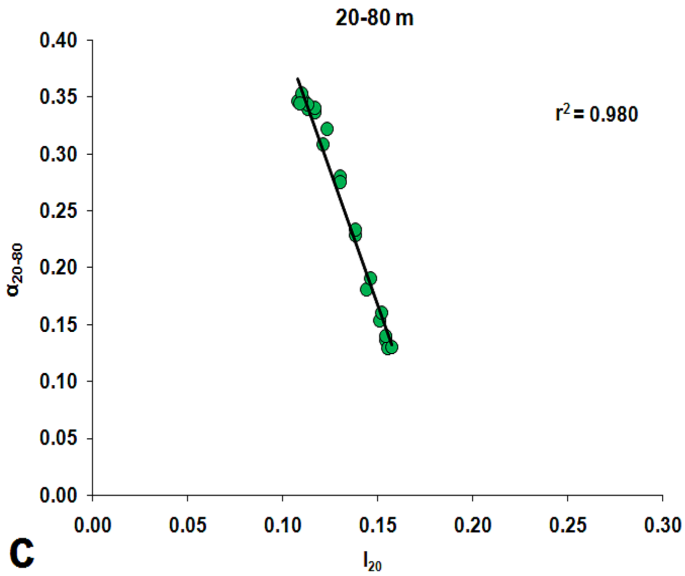


Figure 3. Daily course scatter-plot and linear best fit between WSC and I observed 10 to 80 m at the Cabauw site (2012): (a) I_{10} vs. α_{10-40}; (b) I_{10} vs. α_{10-80}; (c) I_{20} vs. α_{20-80}.

5. Wind Resource Extrapolation to the WT Hub Height: Results and Discussion

5.1 Extrapolation Details

During the testing period (year 2013), observed 10–min records of surface v_1 values at height z_1 have been extrapolated to predict v_2 at height z_2 by applying the PL (Eq. 8) after using the α values calculated during the analysis period (year 2012). In detail, the following v extrapolations have been performed: (i) 10–40 m (v_{10} to v_{40}) by using α_{10-40}; (ii) 10–80 m (v_{10} to v_{80}) by using α_{10-80}; (iii) 20–80 m (v_{20} to v_{80}) by using α_{20-80}. Thus, observed surface v values (v_{10} and v_{20}) were used to predict extrapolated v values (v_{40} and v_{80}). For each v extrapolation, three options have been implemented in calculating the α values: (i) α=0.143 (the 1/7 default value); (ii) $\alpha=\overline{\alpha}$ (the overall yearly mean values, see Table 2); (iii) α daily course (the α hourly averages, see Table 4).

5.2 Wind resource extrapolation

The statistical scores of the 10–40 m, 10–80 m, and 20–80 m v extrapolations are presented, respectively, in Tables 6, 7 and 8.

Table 6. Statistical values of 10–min wind speed at 40 m observed and extrapolated from 10 m at Cabauw during the testing period (2013)[a]

Parameter	Wind speed at 40 m			
	Observed	Extrapolated from 10 m using		
		α=0.143	$\overline{\alpha}$ =0.241	α daily course
Observations				
μ_O (m/s)	6.23			
σ_O (m/s)	2.35			
Predictions				
μ_P (m/s)		5.68	6.65	6.47
σ_P (m/s)		2.71	3.17	3.02
NB		0.09	–0.07	–0.04
NRMSE		0.17	0.19	0.17
IA		0.96	0.95	0.96
r		0.96	0.96	0.95

[a] Statistics for 52,560 records (01/01/2013–31/12/2013). Sample size: 79.31%.

Table 7. Statistical values of 10–min wind speed at 80 m observed and extrapolated from 10 m at Cabauw during the testing period (2013)[a]

Parameter	Wind speed at 80 m			
	Observed	Extrapolated from 10 m using		
		α=0.143	$\overline{\alpha}$ =0.252	α daily course
Observations				
μ_O (m/s)	7.47			
σ_O (m/s)	2.56			
Predictions				
μ_P (m/s)		6.27	8.06	7.84
σ_P (m/s)		2.99	3.84	3.72
NB		0.18	–0.08	–0.05
NRMSE		0.27	0.27	0.25
IA		0.89	0.89	0.91
R		0.88	0.88	0.89

[a] Statistics for 52,560 records (01/01/2013–31/12/2013). Sample size: 79.31%.

Table 8. Statistical values of 10–min wind speed at 80 m observed and extrapolated from 20 m at Cabauw during the testing period (2013)[a]

Parameter	Wind speed at 80 m			
	Observed	Extrapolated from 20 m using		
		α=0.143	$\overline{\alpha}$ =0.263	α daily course
Observations				
μ_O (m/s)	7.47			
σ_O (m/s)	2.56			
Predictions				
μ_P (m/s)		6.49	7.76	7.65
σ_P (m/s)		2.82	3.38	3.29
NB		0.14	–0.04	–0.02
NRMSE		0.22	0.20	0.18
IA		0.92	0.93	0.95
r		0.91	0.91	0.92

[a] Statistics for 52,560 records (01/01/2013–31/12/2013). Sample size: 79.31%.

Overall, the 10–40 m *v* extrapolation (Table 6) returns quite fine scores, as indicated by the remarkably high values of both IA and *r* (0.95–0.96) and relatively low of NRMSE (0.17–0.19). As expected, since 0.143 is lower than $\overline{\alpha}$, the use of the 1/7 method results in a v_{40} underestimation, which is affected by a 9% NB value. Conversely, if applying the α previously measured overall yearly or daily course mean values, this error is reduced to 7 and 4%, respectively, although resulting in a *v* overestimation. Currently achieved 10–40 m results are better, for example, than those reported by Pneumatikos [24], who performed a similar PL–based *v* extrapolation methods comparison between 8 and 32 m over a rural site in Greece (495 m AGL, z_0=34 cm), where he found the 1/7 and $\overline{\alpha}$ methods returning NB values of 32 and 18%, respectively. Conversely, if only considering the $\overline{\alpha}$ method, scores at Cabauw are comparable to those (NB=4.54%) observed 10 to 50 m at a coastal and rough site in Southern Italy [21].

As expected, the 10–80 m *v* extrapolation (Table 7) proves to be more challenging for the applied methods than the 10–40 m one, as showed by the lower IA (0.89–0.91) and *r* (0.88–0.89) values, as well as higher NRMSE (0.25–0.27). In this case, the extrapolation performed by using the 1/7 method returns a 18% (underestimation) mean bias, which is appreciably reduced, instead, if using the α pre–calculated overall yearly (8%) and particularly daily course (5%) mean values. If focusing on the 1/7 method, 10–80 m *v* extrapolation scores at Cabauw are finer than those (NB=26.3%, NRMSE=51%) returned by Kubik et al. [23] from a flat near-coastal site in Scotland between 20.8 and 60 m.

Overall, the 20–80 m *v* extrapolation (Table 8) exhibits a (slightly) higher accuracy than the 10–80 m one, as showed by all statistical indicators. Scores are generally worse than in the 10–40 m *v* extrapolation, vice versa, yet by a small amount. The 14% NB value achieved if using the 0.143 α value is significantly reduced to 4% if using $\overline{\alpha}$, and even to 2% if using the α hourly averaged values.

Summarising, the use of the 1/7 method may be a fair approximation in the 10–40 m *v* extrapolation, not only as returning a slight bias, but also because a conservative approach since the actual *v* value is underestimated. This outcome confirms validity of recommendations reported earlier (§ 2.3), that this default extrapolation method may be applied with fair confidence over a basically flat and quite smooth (z_0=2 cm) site. However, this is true provided that the height interval is limited to 10–40 m or so. Conversely, when considering either the 10–80 m or 20–80 m height intervals, both previously measured overall yearly and particularly hourly averaged α values result in a much finer estimation of extrapolated *v* values. In any case, the improvement achieved when using the α daily course vs. overall yearly mean value is slight.

A further assessment of methods' capability in extrapolating wind resource may be derived by comparing the annual Weibull probability density function of observed vs. predicted *v* distributions (Fig. 4). Actually, it should be borne in mind that, owing to the above assumptions (§ 3), the one presented here does not reflect the actual *v* Weibull distribution affecting the Cabauw site.

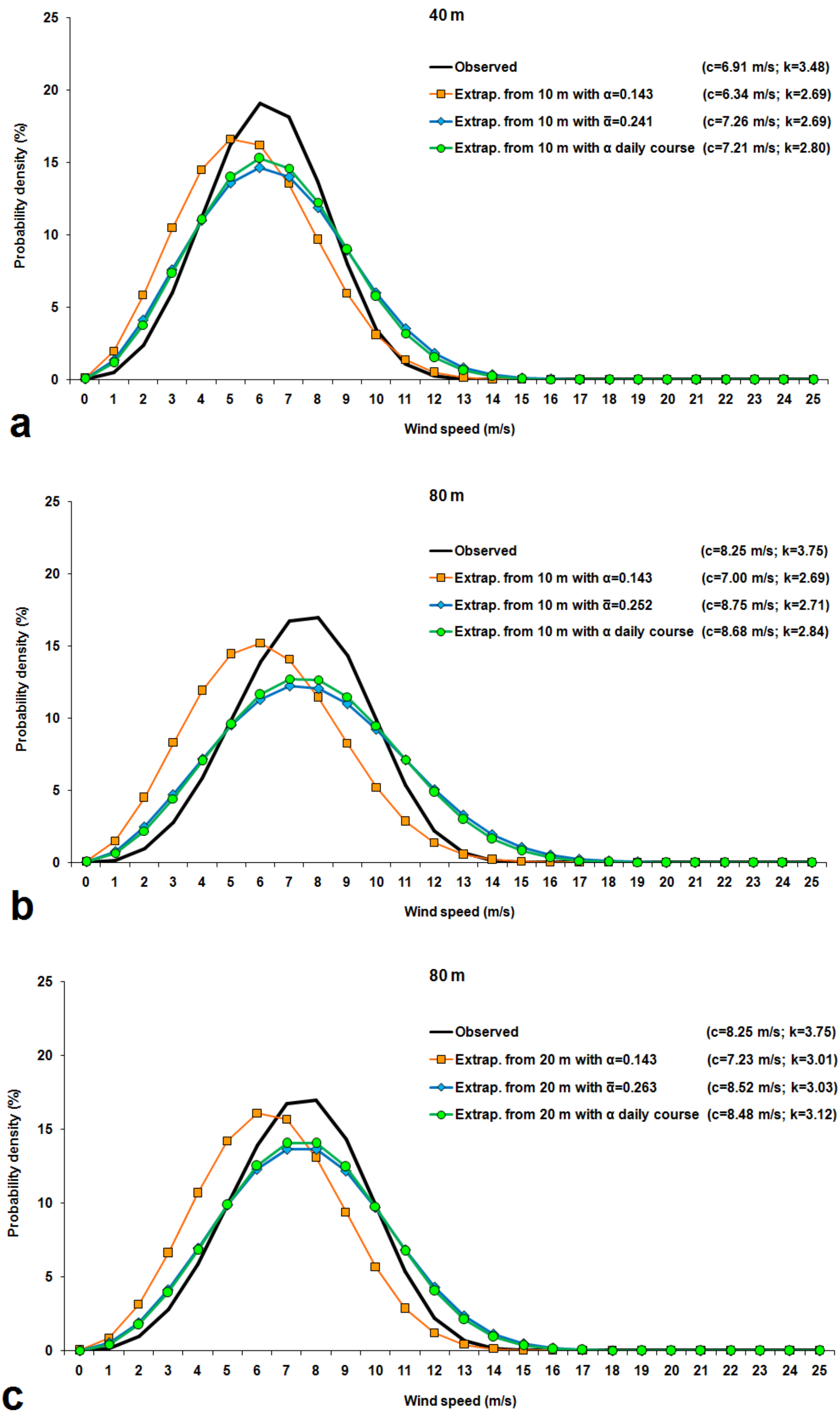


Figure 4. Annual wind speed Weibull distribution observed and predicted at the Cabauw site during the testing period (2013): (a) 40–m observed vs. extrapolated from 10 m; (b) 80–m observed vs. extrapolated from 10 m; (c) 80–m observed vs. extrapolated from 20 m.

At 40 m (Fig. 4a), observed v_{40} Weibull distribution is reproduced quite well by all extrapolation methods, although a 20–23% underestimation affects the k parameter. Also, the c parameter is underestimated by 8.2% if using α=0.143, while overestimated by 5 and 4.3% if using $\overline{\alpha}$ and the α daily course, respectively. Similarly to the v extrapolation, also in the Weibull distribution 10–80 m wind resource extrapolation (Fig. 4b) is less accurate than the 10–40 m one (e.g., k biased by 24–28%). Again, the c prediction error is reduced from 15% (underestimation) if using α=0.143, to 6 and 5.2% (overestimation) if using $\overline{\alpha}$ and the α daily course, respectively. Quite similar results to 10–80 m, yet a bit finer, are achieved in the 20–80 m v extrapolation (Fig. 4c): k is underestimated by 17–20%, while c is underestimated by 12.4% if using α=0.143, though overestimated by 3.3 and 2.8% if using $\overline{\alpha}$ and the α daily course, respectively.

In all three extrapolations, application of both $\overline{\alpha}$ and α daily course methods appreciably increases the accuracy of median v estimation than using the 1/7 method: this error is respectively reduced from 11 to 1.4–2% (10–40 m), 21 to 0.4–1.5% (10–80 m), and 18 to 2.6–3% (20–80 m). Again, the improvement resulting from using the hourly averaged vs. overall yearly α values is confirmed to be marginal. In any case, the use of the α daily course method proves to result in the finest overall scores, both in c and k parameters estimation, and thus in the predicted wind resource Weibull distribution.

5.3 Wind energy yield estimation

Skills of extrapolation methods have been also assessed and compared in calculating the annual wind energy yield over the year 2013. To this aim, two different groups of worldwide commercially available WTs have been selected, regardless of rated power, with hub height approximately in the order of 40 and 80 m, respectively. In Table 9 the main characteristics of the WT models used are summarised. Note that, consistently with § 3, their cut–in v values are confirmed to be greater or equal to 3 m/s. In particular, the 40–m energy yield assessment involved 3 among the most commonly used WT models, overall featuring a hub height ranging from 40 to 44 m and rated power between 330 and 850 kW. At 80 m, wind energy output has been assessed after considering 3 WTs with hub height of 80 m and rated power from 2000 to 2500 kW. All wind energy yield computations and comparisons among WTs have been performed by using the wind resource assessment tool described in [15].

Table 9. Technical characteristics of WTs used in 40–m and 80–m annual wind energy yield calculation at the Cabauw site (2013)

Wind turbine	Ref.[a]	P_r (kW)	D (m)	A (m^2)	H_{hub} (m)	v_i (m/s)	v_r (m/s)	v_o (m/s)
40–m converted energy								
Enercon E33	[31]	330	33.4	876	44	3	13	28
AWE 52–750	[32]	750	52	2082	40	3	15	25
Gamesa G58–850	[33]	850	58	2642	44	3	16	21
80–m converted energy								
Vestas V90–2.0	[34]	2000	90	6362	80	3	13	25
Suzlon S88–2.1	[35]	2100	88	6082	80	4	14	25
Nordex N100–2500	[36]	2500	100	7854	80	3	13	20

[a] WTs technical characteristics and power curves derived from cited references.
P_r rated power, D rotor, A swept area, H_{hub} hub height, v_i cut–in wind speed, v_r rated wind speed, v_o cut–off wind speed.

First, applying the 2012 previously measured ρ mean value and accounting for a total energy losses of 10.86%, the 2013–observed 40–m v values were used. Then, observed wind energy output from the three 40–m WTs detailed in Table 9 has been assessed (Table 10), resulting in AF values ranging 94.69–98.68%, and CF values comprised between 21.40 and 22.70% (corresponding to FLH=1876–1990 h/y). Accordingly, using the same ρ value and total energy losses, predicted wind energy output by using 10–40 m extrapolated v values based on the three α methods was calculated. As a result, the AF–related NE score overall ranged from a minimum of 1.41 to a maximum of 7.65%. In particular, the bias resulting from using α=0.143 is basically halved if applying the α overall yearly mean value, while a further (slight) reduction is (again) achieved when using the α daily course. Conversely, if focusing on the *CF* parameter (and thus on *AEY*), the magnitude of related NE is much larger, with underestimations up to 16.52% (α=0.143) and overestimations up to 19.25% (overall yearly and hourly α mean values). If focusing on the 1/7 method, after extrapolating wind resource 10 to 50 m by using two (800– and 900–kW) WTs over a roughly complex and 230 m ASL site in the Marmara region (Turkey), Fırtın et al. [4] found a *CF*–related NE score in the order of 25–28%, which is higher than the one (16.52%) achieved at Cabauw by using the comparable 850–kW Gamesa G58 WT.

By using the 2012 pre–calculated ρ mean value and considering a 11.31% total energy losses, the employment of 2013–observed 80–m v values returned an energy production from the three selected 80–m WTs (Table 9) featuring a 93.58–98.87% *AF* and a 32.76–36.82% *CF* overall range (corresponding to *FLH*=2872–3228 h/y, Table 11). With respect to the 10–40 m v extrapolation (Table 10), in the 10–80 m one the improvement in assessing *AF* by using $\overline{\alpha}$ and α daily course rather than α=0.143 is increased, markedly by a factor of 3 when applying the hourly α mean values. A similar improvement is found in the *CF*–related NE score, whose magnitude is reduced from 32.05–33.21% (α=0.143) to 9.02–11.51% (α daily course), although the latter method provides a *CF* overprediction. The *CF* estimating bias at Cabauw by applying 10 to 80 m the 1/7 method to the 2000–kW Vestas V90 WT (32.47%) is similar to the corresponding one (29.7%) observed by using between 10 and 60 m a comparable 2000–kW WT over the afore–mentioned site in Scotland [23].

Methods predicting skills in assessing wind energy output between 20 and 80 m (Table 12) from the three selected 80–m WTs (Table 9) definitely prove to be finer than between 10 and 80 m. In the *AF* estimation, apart from the 9.66% NE score returned after applying the 1/7 method to the Suzlon S88–2.1 WT, the overall bias is within 4.69%, with the α daily course method again increasing the accuracy vs. the 1/7 method by a factor of 3. Furthermore, the improvement rate in predicting *CF* is higher than in the 10–80 m v extrapolation (Table 11), as its related NE score is reduced from (underestimated) 27.38–28.66% (α=0.143) to (overestimated) 5.16–6.62% (α daily course).

Summarising, since conservative over a site such as Cabauw, for the 10–40 m v extrapolation the 1/7 method appears preferable with respect to the other two (excessively optimistic) methods, although exhibiting a relevant bias (15.93–16.52%) in wind energy output assessment. On the contrary, in 10–80 and particularly 20–80 m v extrapolations, application of both $\overline{\alpha}$ and α daily course methods is preferable, although they provide a certain *CF* (and thus *AEY*) overprediction. In particular, although only slightly improving the $\overline{\alpha}$ method, the α daily course method is the finest, as returning *CF* values at worst biased by 11.51% (10–80 m) and 6.62% (20–80 m). This outcome is in agreement with the one by Ðurisic and Mikulovic [20] in extrapolating wind resource 10 to 60 m by applying a 500–kW WT over three locations in Serbia, as they pointed out the *AEY* estimating error being significantly lower if vertical extrapolation is carried out by means of the time–varying (by hour of the day) than fixed (overall year) α values.

This conclusion is of particular concern if recalling the strict (almost 1:1) relationship between α daily course and surface *I* daily course (§ 4.4). As a matter of fact, provided that site's v records are available at 10–min bins (to properly calculate *I*), by applying to the *I* values routinely collected at surface heights (10 or 20 m AGL) the regression coefficients reported in Table 5, it is possible to reconstruct site–specific α daily course, and thus provide a fairly confident energy yield estimation at WT hub height. Therefore, Eq. (11) may be used to define a WSC predicting model capable of fully coping with upper WT hub height v observations unavailability.

Table 10. Annual wind energy yield parameters calculated at 40 m at the Cabauw site using a single WT and relative difference of 10–m extrapolations compared to observations (2013)[a,b,c]. WTs used: 330–kW Enercon E33 [31], 750–kW AWE 52–750 [32], and 850–kW Gamesa G58–850 [33]

Wind turbine	Parameter	40–m converted energy			
		AF (%)	*CF* (%)	*FLH* (h/y)	*AEY* (MWh/y)
Enercon E33 (330 kW)	Observed				
	μ_O	94.69	21.91	1921	770.8
	Extrapolated from 10 m using α=0.143				
	μ_P	87.45	18.34	1608	530.6
	NE (%)	7.65	16.29		
	Extrapolated from 10 m using $\overline{\alpha}$ =0.241				
	μ_P	91.13	26.10	2288	755.1
	NE (%)	3.76	–19.12		
	Extrapolated from 10 m using α daily course				
	μ_P	91.79	25.47	2232	736.7
	NE (%)	3.06	–16.25		
AWE 52–750 (750 kW)	Observed				
	μ_O	98.68	21.40	1876	773.8
	Extrapolated from 10 m using α=0.143				
	μ_P	95.59	17.99	1577	1182.8
	NE (%)	3.13	15.93		
	Extrapolated from 10 m using $\overline{\alpha}$ =0.241				
	μ_P	96.93	25.47	2233	1674.7
	NE (%)	1.77	–19.02		
	Extrapolated from 10 m using α daily course				
	μ_P	97.29	24.85	2178	1633.7
	NE (%)	1.41	–16.12		
Gamesa G58–850 (850 kW)	Observed				
	μ_O	94.69	22.70	1990	774.8
	Extrapolated from 10 m using α=0.143				
	μ_P	87.45	18.95	1661	1412.0
	NE (%)	7.65	16.52		
	Extrapolated from 10 m using $\overline{\alpha}$ =0.241				
	μ_P	91.13	27.07	2373	2016.9
	NE (%)	3.76	–19.25		
	Extrapolated from 10 m using α daily course				
	μ_P	91.79	26.42	2316	1968.9
	NE (%)	3.06	–16.39		

[a] Statistics for 52,560 records (01/01/2013–31/12/2013). Sample size: 79.31%.

[b] 2012 observed ρ mean value (1.242 kg/m^3) used for energy predictions.

[c] Total energy losses accounted for energy yield are 10.86%, resulting from the following: –1.14% (air density), 2.00% (control system), 3.00% (unavailability and maintenance), 2.00% (electric losses), 4.00% (ice), 1.00% (other losses).

Table 11. Annual wind energy yield parameters calculated at 80 m at the Cabauw site using a single WT and relative difference of 10–m extrapolations compared to observations (2013)[a,b,c]. WTs used: 2000–kW Vestas V90–2.0 [34], 2100–kW Suzlon S88–2.1 [35], and 2500–kW Nordex N100–2500 [36]

Wind turbine	Parameter	80–m converted energy			
		AF (%)	*CF* (%)	*FLH* (h/y)	*AEY* (MWh/y)
Vestas V90–2.0 (2000 kW)	Observed				
	μ_O	98.87	35.63	3123	6409.7
	Extrapolated from 10 m using α=0.143				
	μ_P	93.91	24.06	2109	4218.3
	NE (%)	5.02	32.47		
	Extrapolated from 10 m using $\overline{\alpha}$ =0.252				
	μ_P	96.70	39.54	3466	6932.5
	NE (%)	2.19	–11.01		
	Extrapolated from 10 m using α daily course				
	μ_P	97.11	39.17	3434	6867.2
	NE (%)	1.78	–9.94		
Suzlon S88–2.1 (2100 kW)	Observed				
	μ_O	93.58	32.76	2872	6411.7
	Extrapolated from 10 m using α=0.143				
	μ_P	80.06	21.88	1918	4027.6
	NE (%)	14.45	33.21		
	Extrapolated from 10 m using $\overline{\alpha}$ =0.252				
	μ_P	88.70	36.96	3240	6803.8
	NE (%)	5.21	–12.85		
	Extrapolated from 10 m using α daily course				
	μ_P	89.49	36.53	3202	6724.6
	NE (%)	4.37	–11.51		
Nordex N100–2500 (2500 kW)	Observed				
	μ_O	97.77	36.82	3228	6413.7
	Extrapolated from 10 m using α=0.143				
	μ_P	90.24	25.02	2193	5483.3
	NE (%)	7.70	32.05		
	Extrapolated from 10 m using $\overline{\alpha}$ =0.252				
	μ_P	94.64	40.47	3548	8869.9
	NE (%)	3.20	–9.94		
	Extrapolated from 10 m using α daily course				
	μ_P	95.20	40.14	3519	8796.3
	NE (%)	2.63	–9.02		

[a] Statistics for 52,560 records (01/01/2013–31/12/2013). Sample size: 79.31%.

[b] 2012 observed ρ mean value (1.236 kg/m^3) used for energy predictions.

[c] Total energy losses accounted for energy yield are 11.31%, resulting from the following: –0.69% (air density), 2.00% (control system), 3.00% (unavailability and maintenance), 2.00% (electric losses), 4.00% (ice), 1.00% (other losses).

Table 12. Annual wind energy yield parameters calculated at 80 m at the Cabauw site using a single WT and relative difference of 20–m extrapolations compared to observations (2013)[a,b,c]. WTs used: 2000–kW Vestas V90–2.0 [34], 2100–kW Suzlon S88–2.1 [35], and 2500–kW Nordex N100–2500 [36]

Wind turbine	Parameter	80–m converted energy			
		AF (%)	*CF* (%)	*FLH* (h/y)	*AEY* (MWh/y)
Vestas V90–2.0 (2000 kW)	Observed				
	μ_O	98.87	35.63	3123	6409.7
	Extrapolated from 20 m using α=0.143				
	μ_P	96.00	25.70	2253	4505.5
	NE (%)	2.90	27.87		
	Extrapolated from 20 m using $\overline{\alpha}$ =0.263				
	μ_P	97.59	37.91	3323	6646.9
	NE (%)	1.29	–6.43		
	Extrapolated from 20 m using α daily course				
	μ_P	97.81	37.67	3302	6604.9
	NE (%)	1.07	–5.73		
Suzlon S88–2.1 (2100 kW)	Observed				
	μ_O	93.58	32.76	2872	6411.7
	Extrapolated from 20 m using α=0.143				
	μ_P	84.54	23.37	2049	4302.7
	NE (%)	9.66	28.66		
	Extrapolated from 20 m using $\overline{\alpha}$ =0.263				
	μ_P	90.37	35.2	3086	6480.7
	NE (%)	3.43	–7.48		
	Extrapolated from 20 m using α daily course				
	μ_P	90.87	34.93	3062	6430.4
	NE (%)	2.90	–6.62		
Nordex N100–2500 (2500 kW)	Observed				
	μ_O	97.77	36.82	3228	6413.7
	Extrapolated from 20 m using α=0.143				
	μ_P	93.18	26.74	2344	5859.2
	NE (%)	4.69	27.38		
	Extrapolated from 20 m using $\overline{\alpha}$ =0.263				
	μ_P	95.85	38.94	3413	8533.1
	NE (%)	1.96	–5.79		
	Extrapolated from 20 m using α daily course				
	μ_P	96.17	38.72	3394	8485.7
	NE (%)	1.64	–5.16		

[a] Statistics for 52,560 records (01/01/2013–31/12/2013). Sample size: 79.31%.

[b] 2012 observed ρ mean value (1.236 kg/m^3) used for energy predictions.

[c] Total energy losses accounted for energy yield are 11.31%, resulting from the following: –0.69% (air density), 2.00% (control system), 3.00% (unavailability and maintenance), 2.00% (electric losses), 4.00% (ice), 1.00% (other losses).

6. Conclusions

Over a basically topographically flat and quite smooth site, provided that the height interval is limited to 10–40 m or so, the commonly used 1/7 default *v* extrapolation method may be a fair approximation, particularly in those cases where it is conservative since α=1/7 is lower than the overall yearly mean value ($\overline{\alpha}$). However, although quite reasonable (9%) in extrapolated *v* values, method's error is relevant (15.93–16.52%) in extrapolated wind energy output. Conversely, when addressing larger height intervals, consistently with several works worldwide the 1/7 method is confirmed to be a misleading extrapolation simplification, as in the best case *CF* is underpredicted by 32.05% (10–80 m), and 27.28% (20–80 m). Instead, application of those methods based on site's previously measured α mean values (overall yearly or hourly averaged α values) is preferable, as they return much finer scores: between10 and 80 m, a 5–8% mean bias resulted in predicting *v* values and 9.02–12.85% in calculating *CF*, while between 20 and 80 m, a 2–4% mean bias in predicting *v* values and 5.16–7.48% in calculating *CF*. In particular, although bringing about a slight improvement with respect to the $\overline{\alpha}$ method, the α daily course method is the finest, as returning *CF* values at worst biased by 11.51% (10–80 m) and 6.62% (20–80 m).

Unfortunately, these methods based on site's previously measured α mean values have the disadvantage or requiring availability of *v* observations at a second upper height, which may be of great concern when this is a modern WT hub height. To cope with this frequent problem, a novel method is proposed herein to predict the α daily course (i.e., the finest extrapolation method) by only using the surface *I* daily course, as a strict (almost 1:1) relationship between these two patterns was found after applying a linear regression analysis. In other words, provided that site's *v* records are available at 10–min bins (to properly calculate *I*), by merely using *I* values routinely collected at surface heights (10 or 20 m AGL), a WSC predicting model may be used which is fairly capable of estimating energy yield at WT hub height. The proposed method has a further number of advantages: (i) it is able to capture the site–specific time–varying (by hour of the day) variation of WSC; (ii) since z_0–independent, all (often complex) investigations on terrain topography and roughness features are not necessary; (iii) since stability–independent, no need for implementation of all routines to calculate stability conditions is required. Apparently, its main drawback is a general tendency of (slightly) overestimating WT energy output, vice versa.

This work represents a first attempt of training and testing the proposed method, which in the future could be applied for as many sites as possible and other WT hub heights to obtain the empirical correlations for a more realistic output.

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