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Surface turbulence intensity as a predictor of extrapolated wind resource to the turbine hub height: method's test at a mountain site

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ABSTRACT

Following testing at the Cabauw (Netherlands) flat and inland site, and at the FINO3 offshore platform in the North Sea (Germany), the α–I wind resource extrapolating method was tested at the Boulder (CO, USA) mountain site (1855 m), another substantially different location in terms of surface characteristics, stability conditions, and wind energy pattern. Data from local 82-m M2 met mast between 10 and 80 m were used, with extrapolations to 50-m and 80-m turbine hub heights performed based on 10-m and 20-m turbulence intensity observations. Trained over a 2-year period (1997–1998), the method was validated on the year 1999.

Slightly better results than those at both Cabauw and FINO3 were achieved in 50-m and 80-m wind speed extrapolations, with bias within 5%, NRMSE = 0.17–0.23, and r = 0.96–0.98. In predicting the annual energy yield, a bias within 1% was achieved at 50 m, which at worst increased to 6.44% at 80 m. The method was less stability-sensitive than at Cabauw and particularly FINO3. It proved to be reliable even over a mountain site affected by fairly complex terrain, which is noteworthy if considering the power law the method is based upon was actually developed for flat and homogeneous terrain.

1. Introduction

Wind data are generally measured significantly below the WT hub height, thus requiring lower wind measurements to be adjusted to the WT hub height by using a reliable wind speed extrapolation model [1]. Modern multi-MW WTs operate at heights well above the surface layer, thus becoming necessary that such an extrapolation model be valid up to at least 150–200 m [2]. In wind energy studies, PL and LogL are the most widely used wind speed extrapolation models [3]. Although LogL is quite accurate near the surface, its accuracy proved to decrease as the height grows [4], which becomes an issue when dealing with modern multi-MW WTs. Since further from the surface evidences suggested that the wind speed vertical profile has a PL form [4], the use of PL is generally preferred. However, careful estimation of the PL exponent α (or WSC) is crucial for applying this model, as a rough α assessment may result in inaccurate energy yield predictions (e.g. Refs. [5,6]). With this in mind, a method making use of surface turbulence intensity I as a predictor of α, and thus of extrapolated wind resource to the WT hub height via application of the PL, has been recently proposed [7,8]. Originally developed and validated at Cabauw (Netherlands), a flat and sea-level inland site, based on data collected between 10 and 80 m from the KNMI 213-m tall met mast [7], this α–I method was then tested at the FINO3 offshore platform in the North Sea (Germany) based on records collected between 30 and 100 m from the BSH 120-m tall met tower [8]. The goal of this work is thus to provide further insight into its application field by testing the method over an elevated mountain site, significantly different from the other two in terms of surface characteristics, stability conditions, and wind energy pattern.

Winds associated with mountainous terrain are generally of two types: (i) terrain-forced flows, produced when large-scale winds are modified or channelled by the underlying complex terrain; (ii) thermally-driven circulations, produced by temperature contrasts that form within the mountains or between the mountains and the surrounding plains [9]. Wind speed is generally increased on hill and mountain locations: this results from altitude, as hill tops and mountain peaks extend high into the atmosphere where wind speeds are higher, as well as from wind flow acceleration over and around hills and mountains, and funnelling through passes or along valleys aligned with the flow [10]. However, valleys, basins, and lee slopes within a mountain area are often sheltered from the generally stronger winds at high altitudes by the surrounding

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Nomenclature

Abbreviations

AGL	above ground level
ASL	above sea level
BSH	Bundesamt fuer Seeschifffahrt und Hydrographie
KNMI	Royal Netherlands Meteorological Institute
LogL	logarithmic law
NWTC	National Wind Technology Center
PL	power law
WSC	wind shear coefficient
WT	wind turbine

Variables

α	wind shear exponent [−]
AEY	annual energy yield [MWh/y]: WT net energy production over a 1-year period
AF	availability factor [%]: time percentage a WT operates between its cut-in and cut-off wind speeds
c	Weibull scale factor [m/s]
CF	capacity factor [%]: ratio of *AEY* to the energy that the WT could have produced if operated at its rated power through the same period
FLH	full-load hours [h/y]: number of hours in one year corresponding to *CF*
I	turbulence intensity [%]
k	Weibull shape factor [−]
P	wind power density [W/m^2]
P_a	pressure [mbar]
ρ	air density [kg/m^3]
σ_θ	standard deviation of wind direction [deg]
σ_u	standard deviation of longitudinal wind speed fluctuation [m/s]
T	temperature [°C]
v	wind speed [m/s]
z	height AGL [m]
z_o	roughness length [m]

Statistical skill scores

IA	index of agreement = $1-[N\cdot RMSE^2/\sum_{i=1}^{N}(\lvert P_i-\overline{O_i}\rvert+\lvert O_i-\overline{O_i}\rvert)^2]$
$\mu_O=\overline{O_i}$	mean observations $=\frac{1}{N}\sum_{i=1}^{N}O_i$
$\mu_P=\overline{P_i}$	mean predictions $=\frac{1}{N}\sum_{i=1}^{N}P_i$
N	number of observations
NB	normalized bias $=\frac{1}{N}\sum_{i=1}^{N}(O_i-P_i)/\sqrt{\overline{O_i}\cdot\overline{P_i}}$
NE	normalized error $=(O_i-P_i)/O_i$
NRMSE	normalized root mean square error $=RMSE/\sqrt{\overline{O_i}\cdot\overline{P_i}}$
O_i	observations
P_i	predictions
r	correlation coefficient $=\frac{1}{N}\sum_{i=1}^{N}(O_i-\overline{O_i})\cdot(P_i-\overline{P_i})/\sigma_O\cdot\sigma_P$
RMSE	root mean square error $=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i-P_i)^2}$
σ_O	standard deviation of observations $=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(O_i-\overline{O_i})^2}$
σ_P	standard deviation of predictions $=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(P_i-\overline{P_i})^2}$

topography [9]. Also thermal effects may be caused by differences in altitude: cold air from high mountains can sink down to the plains below, causing quite strong and highly stratified downslope winds [10].

Mountainous locations generally exhibit a complex terrain, i.e. great variety of features such as hills, ridges, high passes, plateaus, large escarpments, valleys, and canyons. Since elevations and depressions occur in a random fashion, flow conditions over these features are the most complex to be addressed [11]. As shown within several works (e.g. Refs. [12–16]), numerical meteorological models are unable to resolve the considerable wind speed variability over short distances caused by local terrain features [3], resulting in a certain (up to 13.2% [14]) or even substantial (50% [12], or up to 83.3% [15]) average wind speed over-estimation. Accordingly, the available wind resource over such complex areas depicted by wind maps or atlases is affected by the highest uncertainty degree [13]. Actually, both PL and LogL were developed for flat and homogeneous terrain [3,11], so that any surface irregularities will modify the wind flow through velocity deficits, unusual wind shear, and wind acceleration. This raises serious concerns on applicability of these vertical laws over areas subject to important terrain effects [11], thus making a particularly challenging issue to apply the α–I extrapolating method – which is actually a modified PL – over a mountain site affected by a complex terrain. To this goal, observations from an 82-m tall met tower located at the NWTC elevated site near Boulder (CO, USA) were used, including 10-min records collected between 10 and 80 m. Two WT hub heights, 50 and 80 m, were considered for wind resource extrapolation. A linear regression analysis by stability condition through a 2-year period (1997–1998) was performed to train the method, which was later validated over an independent 1-year period (1999) and its accuracy assessed in extrapolating annual mean wind speed, Weibull distribution, and wind energy yield.

With respect to current Boulder application, two general comparisons have been performed throughout the paper: (i) scores of the α–I method's application achieved over the other two locations of Cabauw and FINO3 (Table 1); (ii) wind characteristics observed at other elevated sites worldwide, and wind resource extrapolating scores achieved at some of those sites (Table 2).

2. Background

From the PL equation, the exponent α_{12} between heights z_1 and z_2 can be determined once concurrent wind speeds v_1 and v_2 at corresponding heights are available [5]:

$$\alpha_{12} = \frac{\ln(v_2/v_1)}{\ln(z_2/z_1)} \tag{1}$$

Wind turbulence intensity I is defined as the ratio between wind speed standard deviation (σ_u) and wind speed average ($\overline{v}$) [11]:

$$I = \frac{\sigma_u}{\overline{v}} \tag{2}$$

with both σ_u and $\overline{v}$ calculated – by convention in wind energy engineering – over 10-min bins.

The existence of a possible relationship between I and α was suggested in the past literature [33,34], although with some restrictions applying, including: (i) wind speeds above 10 m/s [34]; (ii) flat and quite smooth terrain ($z_0 \leq 10$ cm) [33]; (iii) near-neutral stability conditions [33,34]; (iv) height of 15 m [34] or 30 m [33].

Within two previous studies [7,8], the exponent α_{12} between z_1