Wind power density loss for wind turbines due to upstream hills

BODO RUCK & MANUEL GRUBER
Laboratory of Building- and Environmental Aerodynamics
Institute for Hydromechanics
Karlsruhe Institute of Technology (KIT)
Kaiserstr. 12, 76131 Karlsruhe
GERMANY
ruck@kit.edu http://www.gebaeudeaerodynamik.de

Abstract: The installation of wind turbines in hilly terrain is not straightforward. For the planning, an accurate and reliable estimation of the annual energy production has to be performed. The local wind potential is a crucial quantity within this assessment, however, it is unknown in most cases. In order to obtain more reliable data about wind potential in hilly terrain, an investigation in an atmospheric boundary layer tunnel is presented, delivering detailed information on the interaction of upstream hills and wind power potential for wind turbines. The investigations were performed for the case, when wind turbine height and hill height are at least in the same order of magnitude. Specific exposure coefficients are given depending on the distance of the upstream hill, the surface roughness of the terrain and the ratio of turbine height to hill height.

Key-Words: wind turbine power, wind power density, upstream hill, orographically structured terrain

1 Introduction

Wind turbines are installed increasingly in hilly terrain. To assess the efficiency of a wind turbine and to estimate the annual energy production, the wind climatology at the turbine location must be known. Unfortunately, the site-specific wind data are not known in most cases, so that wind data from remote weather stations are taken and 'extrapolated' by flow models to the wind turbine site ('micro-siting'). For this purpose, flow models of different type are used. Linear flow models [1,2] compute the wind climatology by parameterizing relevant factors of influence (surface roughness, site-near obstacle dimensions, height contour lines of terrain). However, the incorporated orographic flow model [3] can be applied only to neutrally stable wind flows over gently sloping terrain and low hills. In rugged or complex terrain, linear flow models show well-known limitations e.g. overestimating wind speed-up [4,5,6]. In contrast to linear models, 3-D nonlinear flow models [7] compute the 3-D wind field with input data from a digital terrain model, a roughnesss map and from wind climatology data derived from at least one met station within the modeled area. The wind field computation is based on the solution of the time-averaged Navier-Stokes equations (RANS = Reynolds-averaged Navier-Stokes equations). To close the system of equations, the k-ε turbulence model is used in most of these non-linear flow models. However, it is known from various fields of fluid research that RANS models tend to overestimate turbulent kinetic energy and to underestimate mean flow recirculation zones and often lead to uncertainties when large-scale turbulent transport phenomena and sharp bends in the flow field are present [8,9]. More sophisticated or even time-resolved flow computations with Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS) are either not practical for industrial use because of their costs or not feasible because of their physical limitation (transition not predictable, Reynolds numbers too high).

As reported in literature, 3-D nonlinear flow models show better agreement with mast measurements than results obtained with linear models. However, independent studies on this subject [10] are rare and indicate that terrain complexity can generate substantial modeling uncertainties obviously with both model types. Thus, the question how accurate the wind energy resources can be estimated for a specific location cannot easily be answered by existing commercial wind resource assessment programs

As a consequence of the shortcomings of software-based models, it seems that physical modeling in an atmospheric boundary layer wind tunnel can deliver more detailed and realistic data on wind power density loss in hilly terrain where wind field conditions are characterized by specific orographically generated turbulence and wind profile shapes.

2 Experimental details

There is no doubt that orography exerts a great influence on instant, time-averaged or climatologic wind speed at a given site. Thus, in mountainous regions, the energy production of wind turbines is in most cases smaller than in the plane countryside. Additionally, surface roughness and atmospheric stability influence the wind power density [11,12]. In many cases, even a doubling of the hub height cannot compensate the loss induced by a fully rough or forested surface when compared to a smooth surface. Keeping in mind that a wind reduction of 20 % results in a wind energy loss of about 50%, it is worthwhile to investigate in detail the wind conditions at projected turbine sites in hilly terrain as sketched in Fig. 1.

Fig. 1: Erection of wind turbines in hilly terrain

In this context, it is most interesting how an upstream hill alters the wind power density for a wind turbine, see Fig. 2.

Thus, in order to contribute to the fluid mechanical understanding of wind potential in orographically structured terrain, the influence of upstream hills on wind power density has been investigated in an atmospheric boundary layer wind tunnel. The use of such wind tunnels to investigate wind flows over complex and forested terrain is well established in building- and environmental aerodynamics [13-15].

2.1 Boundary layer simulation

The simulation of an atmospheric boundary layer in the wind tunnel was realized according to the criteria given in Tab. 1. For a detailed description of the simulation of atmospheric boundary layers see also [16,17]. The simulation and measurement of the flow field were carried out in the atmospheric boundary layer wind tunnel (length 29 m) of the Laboratory of Building- and Environmental Aerodynamics at KIT. This constant pressure wind tunnel has a closed recirculation and an octagonal cross-section with a width of 1.5 m. The test section is divided into a 4 m long fetch needed for the formation of the boundary layer and a 4 m long measuring section in which the boundary layer with a height of about 0:55 m is almost constant. The velocity field at the entrance of the measuring section corresponds to a roughness height of category suburbs/forests according to DIN EN 1991-1-4:2010-12. Using the logarithmic wall law, the roughness length for the model amounts to z_0 = 1,1 mm. The shear stress velocity is u_* = 0.327 m/sec with a wall shear stress of τ_0 = 0.131 N/m.

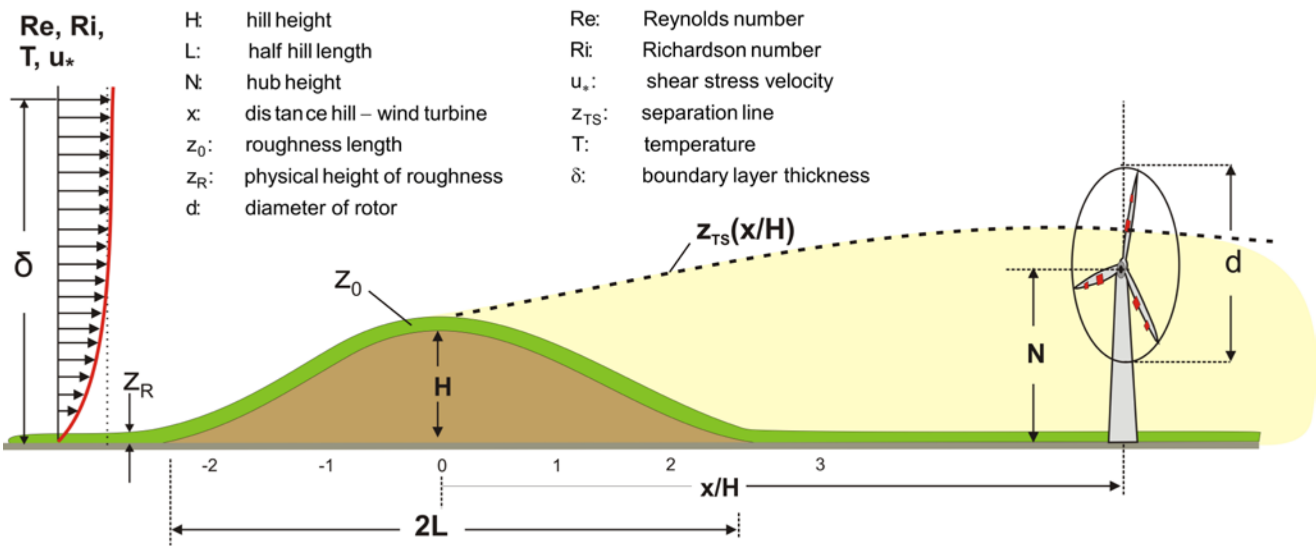

Fig. 2: Upstream hill changes the wind profile and the wind power density

Tab. 1: Similarity criteria for the model investigation in an atmospheric boundary layer wind tunnel:

- wind profil exponent

$$\alpha_{\text{model}} = \alpha_{\text{full scale}} \tag{1}$$

- geometry

$$\frac{z_{0,\text{model}}}{z_{0,\text{full scale}}} = M \tag{2}$$

- turbulence intensity

$$I_{u,\text{model}}(z) = I_{u,\text{full scale}}(z) \tag{3}$$

- turbulent spectrum

$$\left(\frac{f \cdot S_{uu}(f)}{\sigma_u^2}\right)_{\text{model}} = \left(\frac{f \cdot S_{uu}(f)}{\sigma_u^2}\right)_{\text{full scale}} \tag{4}$$

- turbulent length scale

$$\frac{L_{u,\text{model}}(z)}{L_{u,\text{full scale}}(z)} = M \tag{5}$$

- roughness Reynolds number

$$Re_{R,\text{model}} = \frac{u_* \cdot z_{0,\text{model}}}{\nu} > 5 \tag{6}$$

2.2 Measuring technique

For the flow measurements, a two-dimensional LDA system was used, whose properties are listed in Table 2. It uses an argon-ion laser with a power of 4 watts (Manufacturer: Coherent, model Innova 90) as light source. The system operates in dual-beam mode. Fig. 3 shows a photo of the 2D-LDA system used during the measurement process.

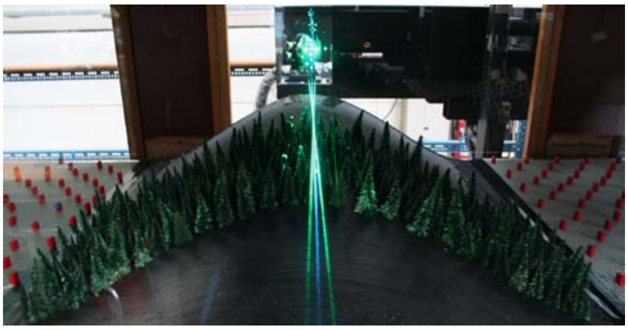

Fig. 3: 2D-LDA system for flow measurements

LDA-system properties	u-component (green)	v- component (blue)
wave length λ	515 nm	488 nm
max. light power	3 W	3 W
frequency shift	0.60 MHz	0.75 MHz
focal length	1.5 m	1.5 m
half angle φ of crossing beams	0.955°	0.955°
fringe spacing Δx	14.64 µm	15.42 µm
number n of fringes	51	52

Tab. 2: Properties of LDA-system

Two double Bragg cells (TSI ColorBurst) were used for the frequency shift of the partial beams. The scattered light was detected in forward direction by a photomultiplier unit (TSI; Color Link). The data processing was performed with two TSI signal processors (Model IFA 550).

2.3 Hill modeling

The two-dimensional model hill (scale 1:300) was made of plywood and has a cosine shape according to:

$$z_h(x) = H \cdot \cos^2\left(\frac{\pi \cdot x}{2 \cdot L}\right) \quad -L < x < L \tag{7}$$

with H = 0.2 m and L = 0.5 m. The length L is defined as the distance between the foot and the top of the hill. After the wooden construction was completed, the surface of the hill was covered with a layer of styrofoam.

2.4 Calculation of wind power and power coefficient

The wind power computed with the mean horizontal wind velocity u, which falls onto the rotor swept area is obtained via the solution of the intergral (8), see Fig. 4 for notation, characterizes the wind energy content.

$$P(N,r) = \frac{1}{2} \cdot \int_{z=(N-r)}^{z=(N+r)} \rho \cdot u^3(z) \cdot s(z) \cdot dz = \int_{z=(N-r)}^{z=(N+r)} \rho \cdot u^3(z) \cdot \sqrt{r^2 - (N-z)^2} \cdot dz \tag{8}$$

The maximum energy content available for wind turbines can be computed by multiplying equation

(8) with the Betz constant of 0.59. If the velocity field is disturbed by an upstream hill, the wind energy content depends on the streamwise position x behind the hill, the hill height H, the hub height N and the rotor swept area diameter r.

$$P(N,r,x,H) = \frac{1}{2} \cdot \int_{z_0=(N-r)}^{z_1=(N+r)} \rho \cdot u^3(x,z) \cdot s(z) \cdot dz \qquad (9)$$

Referring the wind power for a given hub height and swept area diameter behind an upstream hill to the corresponding wind power in the undisturbed approach flow before the hill delivers an exposure coefficient, which quantifies the decrease or increase of wind power due to the hill.

$$\varepsilon_H(N,r,x,H) = \frac{P_{after}(N,r,x,H)}{P_{before}(N,r)} \qquad (10)$$

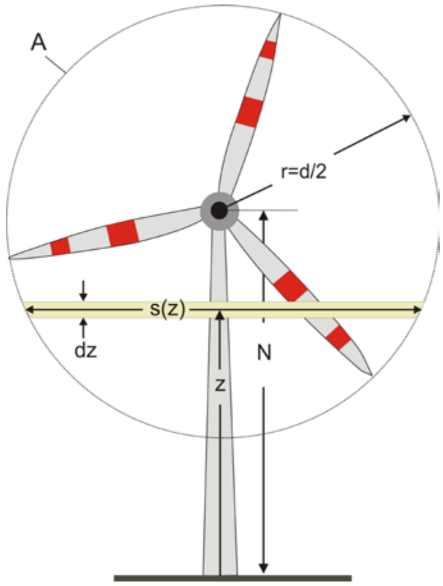

Fig. 4: Notation for wind power computation

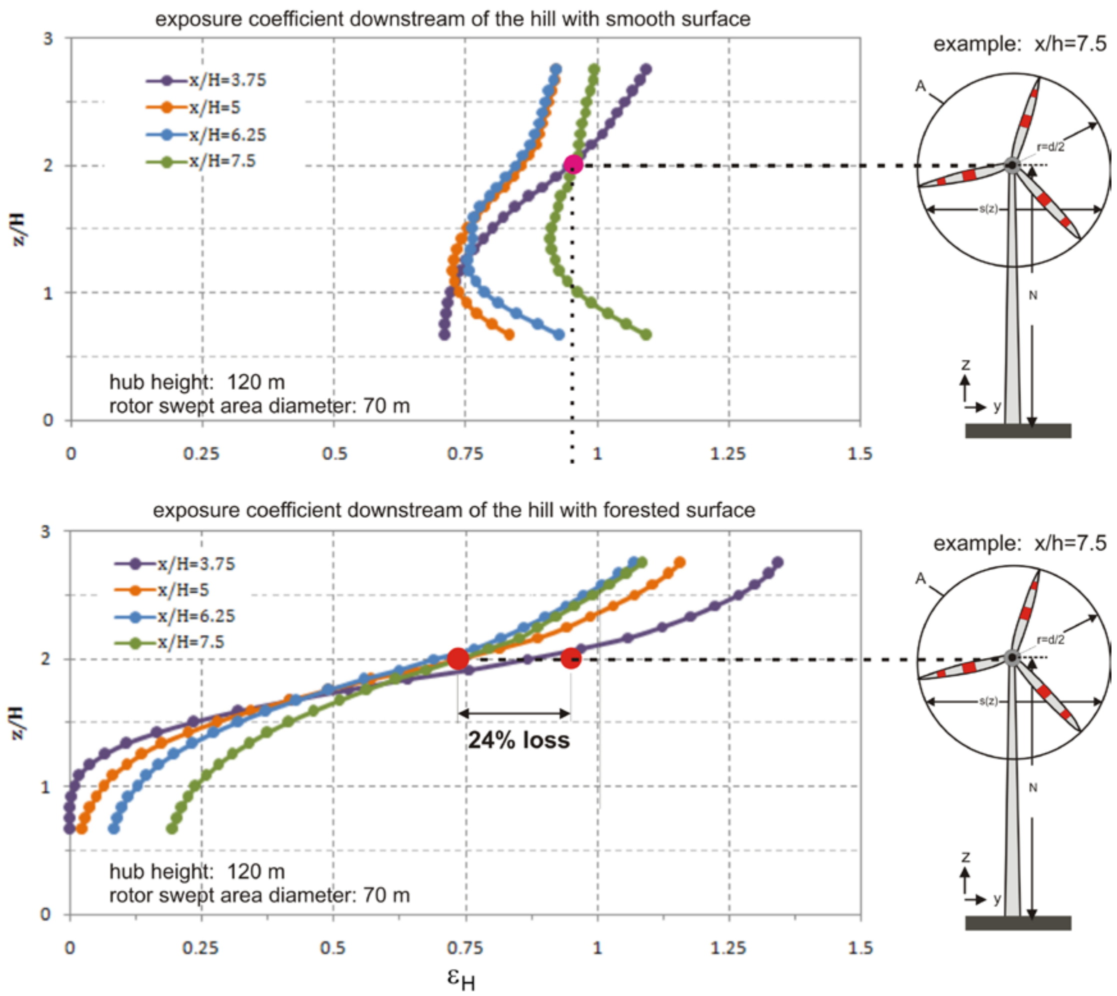

Fig. 5: Exposure coefficient for different turbine positions downstream of the hill;
top: smooth hill; bottom: forested hill with tree density 600 tree/ha, tree height 16.5 m, permeability 0.7 m^{-1}

3 Results

Figure 5 shows the exposure coefficient for a wind turbine with rotor swept area diameter of 70 m. As can be inferred from Fig. 5, the distance from the wind turbine to the upstream hill plays an important role for the available wind power. Additionally, comparing Fig. 5 top with Fig. 5 bottom reveals that the fully rough forested hill surface induces a significant loss of wind power when compared to the smooth hill surface. For a wind turbine with hub height of 120 m and rotor swept area diameter of 70 m, the loss amounts to 24%.

The interpretation of the curves in Figure 5 is easy, because each curve refers to a fixed and specified distance from the hill. The rotor swept area diameter is specified with 70 m in Fig. 5. Going upwardly along a curve means that at the same x-position the hub height is pushed upwards, which usually increases the exposure coefficient.

As can be seen, the exposure coefficient can obtain values greater than 1 or less than 1 denoting turbine positions and/or hub heights, where an increase or decrease of wind power is introduced by the hill. Thus, for a fixed rotor swept area diameter, there are many possible positions behind a hill, in both, horizontal and vertical directions.

On the basis of the wind tunnel measurements, one can calculate the exposure coefficient for all possible positions and display these values in an isoplot, see Fig. 6. Each point in the colored area denotes an exposure coefficient for the chosen swept area diameter.

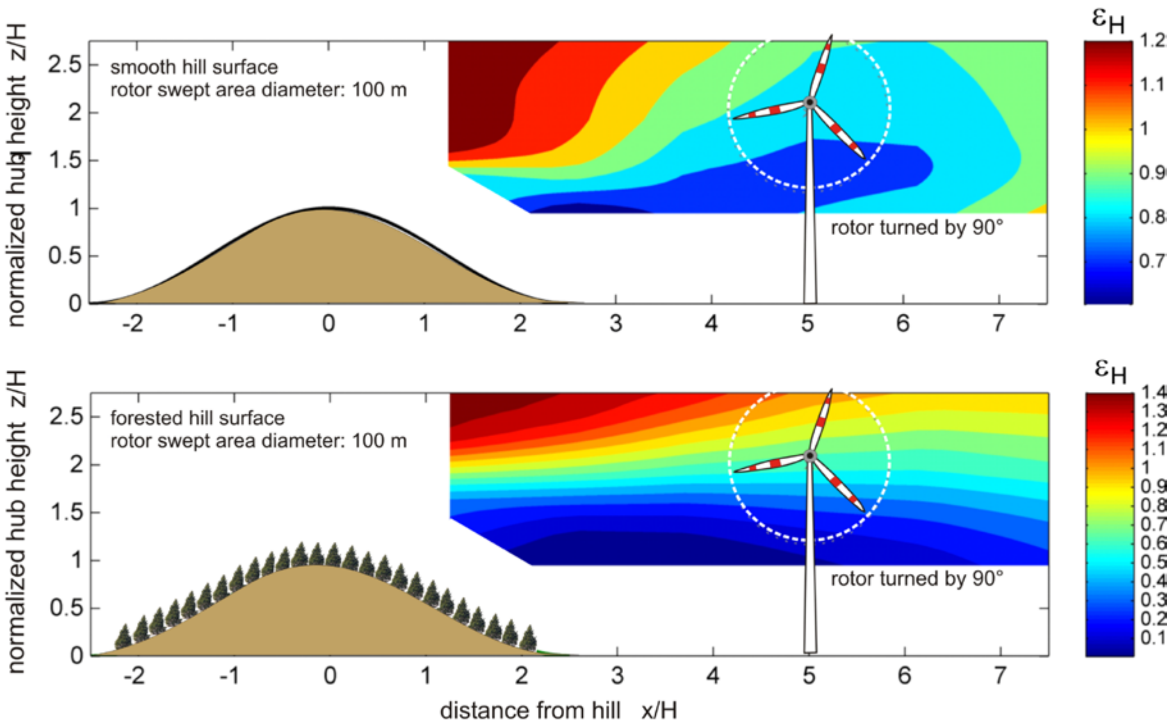

Fig. 6: Isoplots of exposure coefficients for different turbine positions downstream of the hill
top: smooth hill; bottom: forested hill with tree density 600 tree/ha, tree height 16.5 m, permeability 0.7 m^{-1}

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