Application of Footprint Models for the Fine-Tuning of Wind Power Locations on Inland Areas

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Introduction

In the last years the contribution of newly installed wind power on inland areas is up to 50-60 % of all newly installed wind power in Germany [1]. Most of this is in flat lands, but due to the replacement of atomic energy by renewable energy, an increasing interest in wind power can also be recognized for hilly regions in Southern Germany, especially for smaller wind parks. Because the ratio of usable energy to installed energy on the inland areas is much lower than at the coast or at sea, the requirements for finding optimal locations are very high. Normal tools to find optimal locations, like wind atlases or even the program WAsP based on the European wind atlas [2], cannot fulfill all aspects for the application of all relevant factors. In this paper the influence of forest and small forested areas will be discussed by application of the footprint methodology, which is well established in air pollution and ecological science [3] but almost not at all in wind power application [4,5]. The method should not be confused with the physical footprint of a wind power station, which is the land use for the installation of all facilities related to the station of approx. 0.5 ha MW^{-1} [6], or the carbon footprint of a station.

Theoretical Background

In the following, some micrometeorological basics [7, see also for further details] will be briefly explained for a better understanding of the presented concept. For wind atlases or other calculations of the wind velocity in a certain level above the ground, meso-scale numerical models are applied. At sea and in flat terrain the ground level of the model is nearly identical with the physical surface, but for high vegetation such as forests, both are displaced by the so-called zero-plane displacement height d. Therefore, for the wind profile near the surface, it follows for the neutral case, which is here used for simplification,

$$u(z) = \frac{u_*}{\kappa} ln \frac{z-d}{z_0}$$

with the wind velocity u, the height above the ground z, the friction velocity u_*, the von-Kármán-constant κ, and the roughness length z_0. Models use as the ground level the aerodynamical height, which is z – d, where d is often assumed as being two thirds of the forest height (Fig. 1). For example, a wind power station installed in a 30 m high forest and with a hub height of 150 m has a height of 130 m above zero plane displacement and the wind model for 130 m must

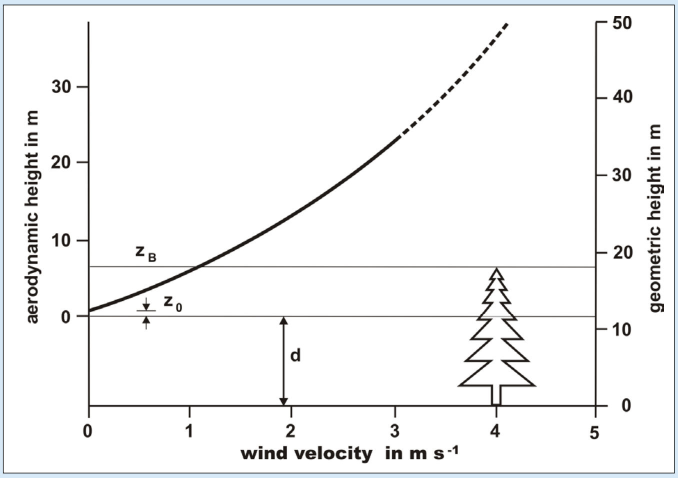

Fig. 1: Schematic wind profile above a canopy with the height z_B, the roughness length z_0, and the zero-plane displacement d and the definition of the aerodynamic height (left) in comparison to the geometric height (right), beginning at the physical ground (from [7], modified)

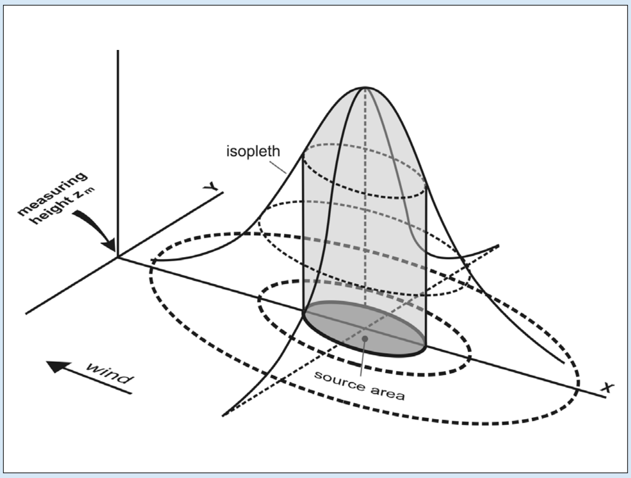

Fig. 2: Schematic view of the footprint function for a certain measuring height, with the strongest influence in the centre of the source area and lower influences in the outer parts characterized by effect levels (from [9], modified)

be applied for the power calculation. The change of the wind velocity with the height in this level is not very much and the calculation often contains errors [2], but because of the dependence of the power on the cube of the wind velocity and the low performance rate on inland areas, these facts should be taken into account. In addition, it should be noted that over forest and areas with high roughness, the wind profile up to about three times of the forest height is reduced due to the so-called roughness sublayer (mixing layer), which also generates, additional to the random turbulence, coherent turbulent structures. More complicated are landscapes with a patchy structure of forested and agricultural areas.

In the following, the application of so-called footprint models is proposed. Hereby the footprint [8] for a certain point, like the hub height of a wind power station, is the influence of the properties of the upwind source area weighted with the footprint function, which is very similar to distribution functions used in air pollution models. A schematic view of the footprint function for a certain measuring height is given in Fig. 2. The strongest influence comes from the centre of the source area, with lower influences from the outer parts. Typically this can be characterized by effect levels with a certain percentage of influence on the measuring point. By combining a land use map with the effect levels of the footprint, the influence of each patchy structure can be determined. Because the roughness of a landscape is characterized by the highest roughness elements, probably by the 10 % of the highest roughness elements [7, see there for more references], these roughness elements also determine the displacement height for the area. The footprint model is able to weight the effect of each patchy structure.

Application of Footprint Modeling

The application of footprint models for the selection of the optimal position of a wind power station follows the general schema for such investigations [2], to which are added some special features for the footprint (Fig. 3). Besides the wind climatology, a land use map with roughness lengths and zero-plane displacement should be available. Because footprint is strongly dependent on the wind velocity and the stratification wind, such data should be applied. The most difficult part is the selection according to the stability. If such information is not available, five typical stratification classes should be used (Tab. 1). The frequency of the Obukhov length or the Pasquill class is available from flux measuring stations or air pollution networks. The Pasquill class can also easily be determined dependent on wind velocity and an irradiation class [7, 10]. The footprint model should be calculated for different wind and stability classes. The number of classes depends on the frequency of the classes and the differences of the footprint between the classes, about 15-20 runs for 5 stability and 3-4 wind classes should be enough, but must be repeated for different wind sectors.

Most important is the selection of one of the numerous footprint models [3, 7]. The simplest are analytical models, which are comparable to air pollution models. More sophisticated are Lagrangian models, which also can be applied in the atmospheric boundary layer, or even Large-Eddy-Simulations (LES). Because analytical models are only valid in the surface layer of the atmosphere, i.e. in the lowest 10 – 30 m, and are limited to homogeneous surfaces, these models will not be discussed in detail. From the scientific point of view the best for the wind power application is the Lagrangian backward model by Kljun et al. [11], which can also be applied in heterogeneous terrain. This model is well applicable in the lower part of the boundary layer up to about 200-300 m height [12], which is used by wind power stations. While the model itself needs a lot of computer time, a simplified parameterized version is available online [13], which can easily be calculated for the given wind and stability classes. The only disadvantage is that this model is based on homogeneous surfaces, but in most cases this has no significant influence on the final results. Only one of the analytical models, using a power low for the vertical wind profile, can also be applied in the lower boundary layer [14]. Some more details are given in Tab. 2. Footprint models are available for concentrations (scalar) and for fluxes, where the concentration footprint is significantly larger. Because for wind power purposes the wind gradient over the blade is important the flux footprint must be applied [16]. Finally, the footprint must be compared with the land use map [15, Fig. 3]. Fig. 4 shows

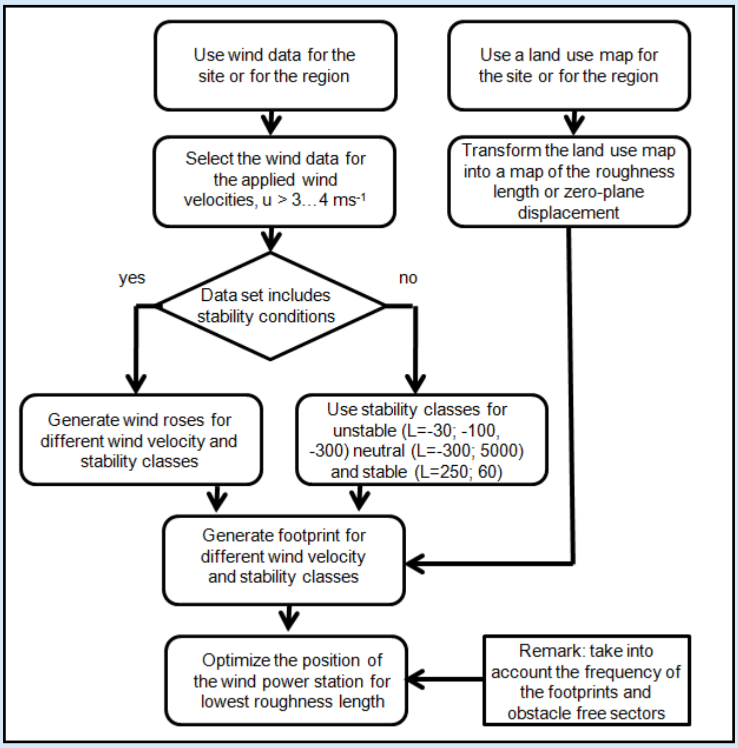

Fig. 3: Schema to find the best position for wind power stations based on wind roses, stability selections and footprint analysis. Finally the roughness length and zero-plane displacement height in the most frequent footprint sector must be minimized.

Stratification	Pasquill class	Obukhov length [m]	Remark
Very unstable	A	-30	
Unstable	B	-100	
Neutral to light unstable	C	-300	
Neutral (to light stable)	D	5000	
Stable	E	250	
Very stable	F	60	No practical relevance

Tab. 1: Typical stability classes for application of footprint models (from [7], modified)

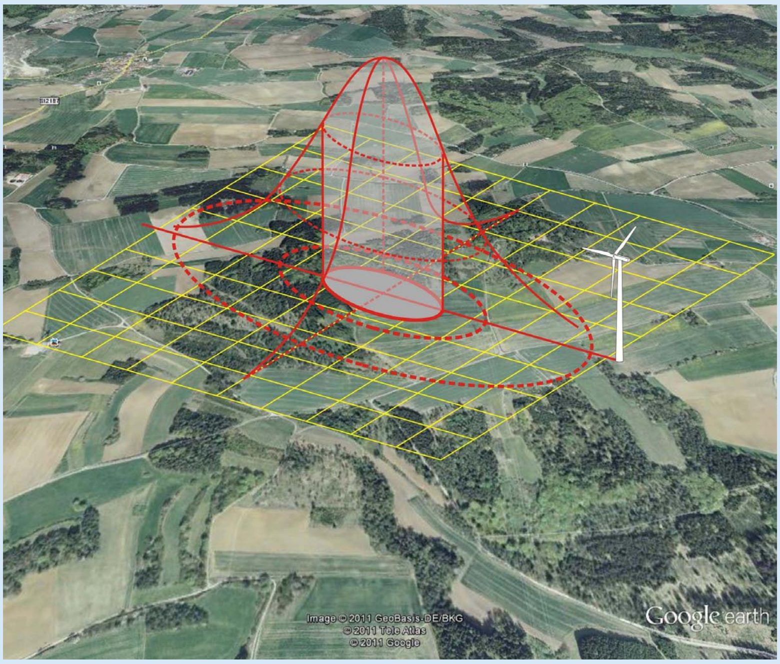

Fig. 4: Combination of a land use map, divided into different grid elements, and combined with the effect levels of the footprint model. The position of the wind power station is on the right (image from Google).

Author	Model type	Remarks
Kljun et al. [11]	Lagrangian backward model	Only for specialists
Kljun et al. [13]	Parameterized version of [11]	Available online: http://footprint.kljun.net
Kormann and Meixner [14]	Analytical power law model	Easily to apply
Göckede et al. [15]	Includes tool to combine land use characteristics and footprint	Similar tool should be used

Tab. 2: Proposed footprint models for wind power applications

such a map divided into grid elements, which must be combined with the effect levels of the footprint model. The properties of each grid element should be weighted with the footprint function and averaged over the footprint. Because there is a nonlinear relation between the roughness length and the wind velocity or friction, this must be taken into account by the application of an effective roughness length [15, 17]. This method should be applied to calculate exact footprints. It is recommended to repeat this footprint calculation in an iterative schema with a starting roughness length and in the next step with an updated roughness length according to the relevant footprint.

In order to find the exact location of a wind power station in a patchy landscape a simplified method is proposed. Highly relevant are the largest roughness elements, which also determine the zero-plane displacement of an area. To determine the zero-plane displacement of the area the 10 % of the largest roughness elements (patches of forest) should be indicated. If these also represent 10 % of the weighted footprint, the mean zero-plane displacement can be assumed for the area. If this is more than 10 % then probably the highest elements determine the zero-plane displacement of the area, if this is lower than 10 % then a lower zero-plane displacement can also be assumed. This pragmatic classification is based on experience and can hardly be controlled for a certain place, due to the measuring technique: because the installation of towers is impossible, remote sensing technique is widely applied. But the often-used mono-static Doppler-sodar measures the wind vector with three beams in different directions, so the wind vector and also its dispersion is measured from components which are measured at different points. This makes it impossible to select small differences because the difference between remote sensing data with displaced beams and in-situ measurements is not negligible [18]. But the effect of a changing footprint due to variations of the wind velocity and the stratification can be easily indicated.

Conclusions

The proposed method has not, up to now, been applied in the wind power application to find the best position for a wind power station. But the methodology itself is well established for ecological flux measurements, mainly for determining the areas from where the fluxes (e.g. carbon dioxide flux) comes, or from which wind sector fluxes are erroneous due to different influencing factors like different land use types or obstacles [19]. On the basis of this long-term experience in footprint modeling, the fine-tuning of positions of wind power stations was done by the author in a more phenomenological way. More objective is the model application. Therefore the models applied in ecology should be transferred to wind power applications and should be made into a tool for finding the best positions for wind power station on inland areas. Because heterogeneities and obstacles in the footprint also have a significant influence on the turbulence intensity [20], which was also found in the energy output of wind power stations [21], such a tool should also be applied for minimizing the influence of turbulence. More exact would be a LES simulation, but such calculations are still in the beginning of development [22].

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