Meteorologische Zeitschrift, Vol. **22**, No. 2, 111–115 (April 2013)

Open Access Article

Application of footprint models for wind turbine locations

THOMAS FOKEN[1,2,*]

[1]Department of Micrometeorology, University of Bayreuth, Bayreuth, Germany
[2]Member of Bayreuth Center of Ecology and Environmental Research (BayCEER)

(Manuscript received August 30, 2012; in revised form October 24, 2012; accepted December 3, 2012)

Abstract

The possibility to use footprint models, which are well established in micrometeorology and ecology, is discussed also for the fine-tuning of the location of wind turbines. A selection of possible models is given. In an example it is shown that differences in the wind power of two nearby located wind turbines can be explained by the presence of forested areas within the footprint.

Keywords: footprint, wind power.

1. Introduction

The influence of the roughness of the underlying surface is a key parameter for the prediction of the wind energy potential at a possible wind power location. This was taken into account with a special scheme to calculate an effective roughness length in the European Wind Atlas (TROEN and PETERSON, 1989). This scheme does not allow the calculation of a weighted influence of the surface dependent on the distance to the wind power location, the wind speed and the stratification. To overcome this weakness, the application of footprint models is proposed. Footprint models have been well established in micrometeorology and ecology for about 20 years for the determination of the source areas of concentration and flux measurements (VESALA et al., 2008). They offer the possibility of selecting specific measuring locations for flux measurements, as was done by GÖCKEDE et al. (2008) for European carbon dioxide flux measuring sites. Most of these models are of the analytical type – comparable with Gaussian air pollution models – or of the Lagrangian type. On the other hand, there are only a few wind power studies where the term *footprint* was used in the micrometeorological sense (HASAGER et al., 2006) and not related to land use or carbon emission. FOKEN (2012) – based on earlier investigations (HIERTEIS et al., 2000; WICHURA et al., 2001) – proposed the application of footprint models for the final tuning of wind power locations in inland areas. Even when the hub height is – as is the case nowadays – about 100–150 m, the influence of the surface roughness is not negligible (TROEN and PETERSON, 1989) and any influence on the wind profile due to the dependence of the wind power on the cube of the wind velocity is highly relevant. Footprint models were developed for energy and matter fluxes but not for the analysis of the wind field. Therefore two issues must be regarded: Firstly, it can be assumed that the underlying surface has a similar influence on the reduction of the wind speed due to roughness or displacement height, as such influences were found for scalar fluxes. This was in principle shown by FOKEN and LECLERC, 2004 in their proposal to use surface heterogeneities for the validation of footprint models. But due to the physics of the footprint model a direct calculation of the wind energy potential is impossible. Secondly, the influence of the footprint on wind power can only be shown in a more or less qualitative way, because the owners of wind turbines are very restrictive in making data available for research. Hopefully, with a higher acceptance of wind power, this problem can be overcome.

2. Theoretical basis

Over flat terrain the ground level of the models or wind power calculations is nearly identical with the physical surface, but for high vegetation such as forests, this is displaced by the so-called zero-plane displacement height d. Therefore, for the wind profile near the surface for the neutral case, which is here used for simplification (because high wind conditions are more important for wind power applications this does not represent a restriction),

$$u(z) = \frac{u_*}{\kappa} \ln \frac{z-d}{z_0}, \tag{1}$$

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 (see e.g. FOKEN, 2008). Models use as the ground level the aerodynamical height, which

---

[*] Corresponding author: Thomas Foken, Department of Micrometeorology, University of Bayreuth, Universitätsstrasse 30, 95440 Bayreuth, Germany, e-mail: thomas.foken@uni-bayreuth.de

DOI 10.1127/0941-2948/2012/0390

0941-2948/2012/0390 $ 2.25

is z – d, where d is often assumed as being two thirds of the canopy height. For example, a wind turbine 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 be applied for the power calculation. Without discussion of the special effect of the roughness sublayer (mixing layer theory, Garratt, 1978; Raupach et al., 1996), the power law

$$\frac{u_1}{u_2} = \left(\frac{z_1}{z_2}\right)^p \tag{2}$$

in the version by Sedefian (1980) with

$$p = \frac{\varphi_m\left(\frac{z-d}{L}\right)}{\left[\ln\left(\frac{z-d}{z_0}\right) - \psi_m\left(\frac{z-d}{L}\right)\right]} \tag{3}$$

is often applied for the lowest 100-200 m of the atmospheric boundary layer and also used in the analytical footprint model by Kormann and Meixner (2001). In Eq. (3), L is the Obuchov length and φ_m the universal function for momentum, with ψ_m its integrated form. It can easily be seen that the wind velocity, even in larger heights, depends on the roughness length and the zero-plane displacement.

Based on a definition by Horst and Weil (1992) follows the mathematical formulation of the footprint, where the footprint function *f* – comparable with the distribution function in air pollution modelling as in Gryning et al. (1987) – combines the source area Q_η of a measuring signal η (scalar or flux) in relation to its spatial extent and its distribution of intensity, as illustrated in Fig. 1, and is given by

$$\eta(x_m, y_m, z_m) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} Q_\eta(x', y', z' = z_0) \cdot f(x_m - x', y_m - y', z_m - z_0)\,dx'dy', \tag{4}$$

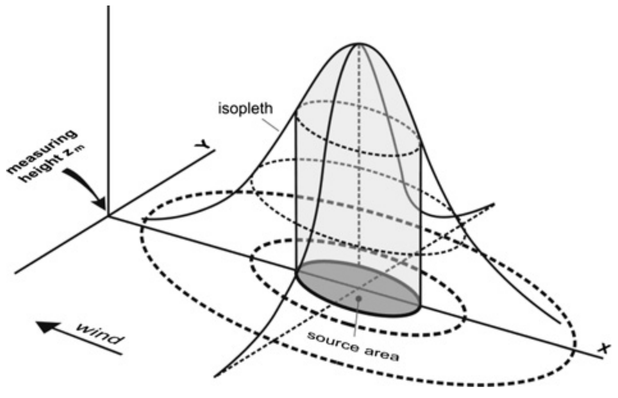

Figure 1: Schematic view of the footprint function for a given measuring height, with the strongest influence in the centre of the source area and lower influences in the outer parts characterized by effect levels (Schmid, 1994, modified).

where the source area is at the height $z' = z_0$ and the footprint is calculated for the sensor or wind turbine height z_m. These models are defined for concentrations and scalar fluxes but not for wind velocity and friction, because for both a source area function cannot be defined. Therefore, the model can only be applied to determine a footprint weighted roughness length which can be used – as usual in wind energy application – in power laws (Eqs. (2)-(3). Because the roughness length is more related to the gradient of the wind velocity the flux footprint approach is used, which also agrees well for gradients (Horst, 1999).

According to Schmid (1994) effect levels can be formulated as shown in Fig. 1. In the inner column is the highest influence, because the cycle is small in comparison to the outer cycles with the same footprint but distributed over larger areas. An area of a selected underlying surface A_i has a weighted influence on the whole footprint dependent on these effect level footprint functions f^P

$$\overline{A} = \sum f_i^P A_i. \tag{5}$$

This can be used for the proposed application, to detect the influence e.g. of a forest on the whole footprint.

An overview of the numerous footprint models is given by Foken (2008) and Vesala et al., 2008. Because analytical models are only valid in the surface layer of the atmosphere (following Eq. 1, i.e. in the lowest 10 – 30 m, and are limited to homogeneous surfaces), these models will not be discussed in detail. Footprint models based on power laws (Eq. 2) can also be applied for the lower part of the boundary layer. From the scientific point of view the best for the wind power application is the Lagrangian backward model by Kljun et al. (2002), which is – from the physics – not limited to the surface layer, takes into account the influence of the Coriolis force, and 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 (Kljun et al., 2003; Markkanen et al., 2009). While the model itself needs a lot of computer time, a simplified parameterized version is available online (Kljun et al. (2004), http://footprint.kljun.net/). The only disadvantages are that this model is based on homogeneous surfaces – in most cases this has no significant influence on the final results – and it is crosswind integrated (1-dimensional). For the latter, extensions for a 2-dimensional footprint are available (Metzger et al., 2012). Only one of the analytical models by Kormann and Meixner (2001), using a power law for the vertical wind profile, can also be applied in the lower boundary layer. An overview is given in Table 1.

3. Application of footprint models

The application of footprint models for the selection of the optimal position of a wind turbine follows the general

Table 1: Proposed footprint models for wind power applications (Foken, 2012); for application in the atmospheric boundary layer see text.

Author	Model type	Remarks
Kljun et al. (2002)	Lagrangian backward model	Only for specialists
Kljun et al. (2004)	Parameterized version of Kljun et al. (2002)	Available online: http://footprint.kljun.net/
Kormann and Meixner (2001)	Analytical power law model	Easily to apply
Göckede et al. (2006)	Includes tool to combine land use characteristics and footprint	Similar tool should be used

schema for such investigations (Troen and Peterson, 1989), to which is added some special features for the footprint (Foken, 2012). 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, such data should be applied. Because the OBUCHOV length for the stability calculation is in most cases not available, Foken (2012) proposed the application of PASQUILL classes from the air pollution networks. The footprint model should be calculated for different wind and stability classes as look-up tables instead of calculations for each single case. 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. Finally, the effect levels of the footprint model must be compared with the land use map, which is divided into grid elements. The properties of each grid (roughness length) element should be weighted with the footprint function and averaged over the footprint according to Eq. (5). 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 a nonlinear aggregation schema (Hasager and Jensen, 1999) as it was proposed by Göckede et al. (2006).

For finding the optimal location of a wind turbine 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 (Foken, 2008). If these also represent 10 % or more of the weighted footprint, this value can be assumed as the mean zero-plane displacement

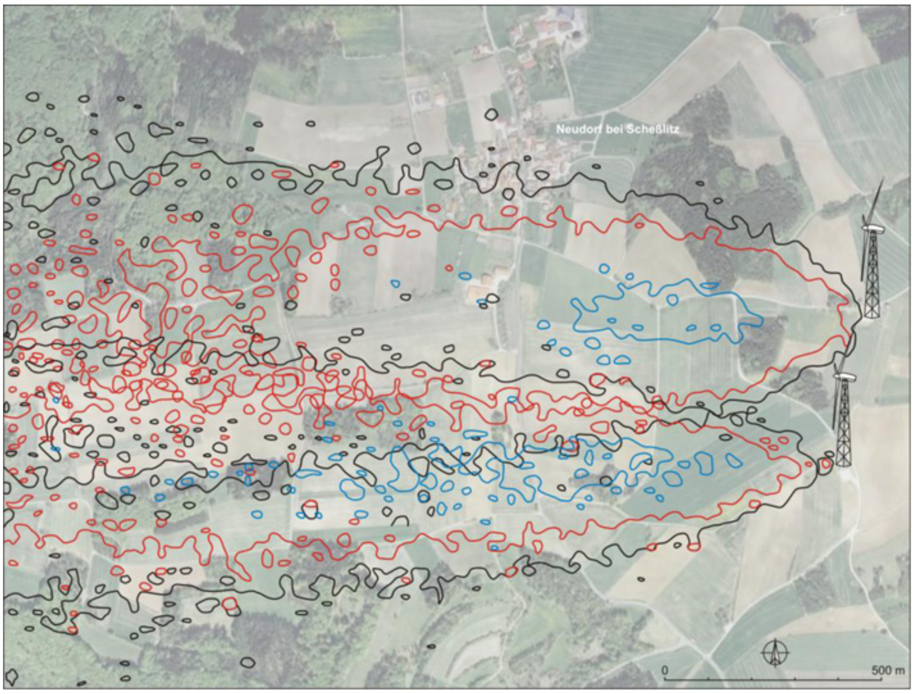

Figure 2: Locations of two REpower MD77 wind turbines with 96 m hub height near Litzendorf region Bamberg with footprint areas for slightly unstable ($L \sim -70$) stratification and moderate westerly winds ($u_* \sim 0.3$ ms^{-1}). The roughness length was assumed to be 1.0 m for the northerly and 0.15 m for the southerly wind turbine. The difference of the roughness length is already footprint weighted, but slightly increased to see the roughness effect on the footprint better. The effect levels are 90% (blue), 50% (red) and 10% (black). For the calculation the Lagrangian backward footprint model according to Kljun et al. (2002) was used.

Table 2: Number of the grid points (50 x 50 m^2) affected by forest for different effect levels and their contribution to the whole footprint for slightly unstable ($L \sim -70$) stratification and moderate westerly winds ($u_* \sim 0.3\ ms^{-1}$). The roughness length was assumed to be 1.0 m for the northerly and 0.15 m for the southerly wind turbine.

	≥ 90%		50-90%		10-50%		
Effect level	No.	Sum in %	No.	Sum in %	No.	Sum in %	Sum in %
Northerly station	1	2	5	7	10	6	14
Southerly station	0	0	2	3	1	<1	3

and roughness length for the area. This pragmatic classification is based on long-term experimental experience.

That such an approach is useful is shown for two REpower MD77 wind turbines with 96 m hub height near Litzendorf, region Bamberg, at about 550 m a.s.l. The location is approximately 250–300 m above the Main-Regnitz valley near Bamberg. For two wind turbines at a distance of approximately 300 m (Fig. 2) it is known that the wind power of the northerly is lower and of the southerly higher than projected, with a difference between both of about 10%. The footprint calculation was made for slightly unstable ($L \sim -70$ m) stratification and moderate westerly winds ($u_* \sim 0.3\ ms^{-1}$). The roughness length was assumed to be 1.0 m for the northerly and 0.15 m for the southerly wind turbine. The strongest influence of the surface at hub height can be found within a distance of about 500 m and significant influences are still found up to 3 km distance. With increasing surface roughness the influence of surface is shifted in the direction of the wind turbine. It can be seen that for the northerly wind turbine larger areas of forest with a canopy height of about 20 m are in the footprint area. Table 2 gives for this example the number of grid elements ($50 \times 50\ m^2$) within the different footprint effect levels. Finally, it follows that for the northerly station 14% of the footprint is affected by the forest. Due to the non-availability of wind velocity and power output data, an applicable relationship between the power output and influencing factors in the footprint area is still impossible.

4. Conclusions

The proposed method has not, up to now, been applied in the wind power application to find the best position for a wind turbine. 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) come, or from which wind sector fluxes are erroneous due to different influencing factors like different land use types or obstacles (GÖCKEDE et al. 2008). 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 turbines in inland areas. Such an approach can overcome the simple determination of the surface characteristics in the European Wind Atlas (TROEN and PETERSON, 1989). Because heterogeneities and obstacles in the footprint also have a significant influence on the turbulence intensity (FOKEN and LECLERC, 2004), which was also found in the energy output of wind turbines (ZELENÝ and FOKEN, 1995), such a tool may also be applied for minimizing the influence of turbulence. More exact would be a LES simulation, but such calculations are still at an early stage of development (PORTE-AGEL et al., 2011) and are too cost-intensive for single wind turbines or small parks. But to make the method applicable it is urgently necessary to obtain access to data for wind turbines from the owners.

Acknowledgements

The author is grateful to Ms. Doojdao CHARUCHITTIPAN for calculating the footprints and to Dr. Natasha KLJUN for making her Langrangian footprint model available.

References

FOKEN, T., 2008: Micrometeorology. – Springer, Berlin, Heidelberg, 308 pp.

FOKEN, T., 2012: Application of footprint models for the fine-tuning of wind power locations on inland areas. – DEWI Mag.. **40**, 51–54.

FOKEN, T., M.Y. LECLERC, 2004: Methods and limitations in validation of footprint models. – Agric. Forest. Meteor. **127**, 223–234.

GARRATT, J.R., 1978: Flux profile relations above tall vegetation. – Quart. J. Roy. Meteor. Soc. **104**, 199–211.

GÖCKEDE, M., T. MARKKANEN, C.B. HASAGER, T. FOKEN, 2006: Update of a footprint-based approach for the characterisation of complex measuring sites. – Bound.-Layer Meteor. **118**, 635–655.

GÖCKEDE, M., T. FOKEN, M. AUBINET, M. AURELA, J. BANZA, C. BERNHOFER, J.-M. BONNEFOND, Y. BRUNET, A. CARRARA, R. CLEMENT, E. DELLWIK, J.A. ELBERS, W. EUGSTER, J. FUHRER, A. GRANIER, T. GRÜNWALD, B. HEINESCH, I.A. JANSSENS, A. KNOHL, R. KOEBLE, T. LAURILA, B. LONGDOZ, G. MANCA, M. MAREK, T. MARKKANEN, J. MATEUS, G. MATTEUCCI, M. MAUDER, M. MIGLIAVACCA, S. MINERBI, J.B. MONCRIEFF, L. MONTAGNANI, E. MOORS, J.-M. OURCIVAL, D. PAPALE, J. PEREIRA, K. PILEGAARD, G. PITA, S. RAMBAL, C. REBMANN, A. RODRIGUES, E. ROTENBERG, M.J. SANZ, P. SEDLAK, G. SEUFERT, L. SIEBICKE, J.F. SOUSSANA, R. VALENTINI, T. VESALA, H. VERBEECK, D. YAKIR, 2008: Quality control of CarboEurope flux data – Part 1:

Coupling footprint analyses with flux data quality assessment to evaluate sites in forest ecosystems. – Biogeosci. **5**, 433–450.

GRYNING, S.E., A.A.M. HOLTSLAG, J.S. IRVIN, B. SIVERTSEN, 1987: Applied dispersion modelling based on meteorological scaling parameters. – Atmos. Environm. **21**, 79–89.

HASAGER, C.B., N.O. JENSEN, 1999: Surface-flux aggregation in heterogeneous terrain. – Quart. J. Roy. Meteor. Soc. **125**, 2075–2102.

HASAGER, C.B., R.J. BARTELMIE, M.B. CHRISTIANSEN, M. NIELSON, S.C. PRYOR, 2006: Quantifying offshore wind resources from satellite wind maps: Study area the North Sea. – Wind. Energ. **9**, 63–74.

HIERTEIS, M., J. SVOBODA, T. FOKEN, 2000: Einfluss der Topographie auf das Windfeld und die Leistung von Windkraftanlagen. DEWEK 2000, Wilhelmshaven, 07.–08.06.2000 2000. – Deutsches Windenergie-Institut, 272–276.

HORST, T.W., 1999: The footprint for estimation of atmosphere-surface exchange fluxes by profile techniques. – Bound.-Layer Meteor. **90**, 171–188.

HORST, T.W., J.C. WEIL, 1992: Footprint estimation for scalar flux measurements in the atmospheric surface layer. – Bound.-Layer Meteor. **59**, 279–296.

KLJUN, N., M.W. ROTACH, H.P. SCHMID, 2002: A three-dimensional backward Lagrangian footprint model for a wide range of boundary layer stratification. – Bound.-Layer Meteor. **103**, 205–226.

KLJUN, N., R. KORMANN, M. ROTACH, F.X. MEIXNER, 2003: Comparison of the Lagrangian footprint model LPDM-B with an analytical footprint model. – Bound.-Layer Meteor. **106**, 349–355.

KLJUN, N., P. CALANCA, M. ROTACH, H.P. SCHMID, 2004: A simple parameterization for flux footprint predictions. – Bound.-Layer Meteor. **112**, 503–523.

KORMANN, R., F.X. MEIXNER, 2001: An analytical footprint model for non-neutral stratification. – Bound.-Layer Meteor. **99**, 207–224.

MARKKANEN, T., G. STEINFELD, N. KLJUN, S. RAASCH, T. FOKEN, 2009: Comparison of conventional Lagrangian stochastic footprint models against LES driven footprint estimates. – Atmos. Chem. Phys. **9**, 5575–5586.

METZGER, S., W. JUNKERMANN, M. MAUDER, F. BEYRICH, K. BUTTERBACH-BAHL, H.P. SCHMID, T. FOKEN, 2012: Eddy-covariance flux measurements with a weight-shift microlight aircraft. – Atmos. Meas. Tech. **5**, 1699–1717.

PORTE-AGEL, F., Y.T. WU, H. LU, R.J. CONZEMIUS, 2011: Large-eddy simulation of atmospheric boundary layer flow through wind turbines and wind farms. – J. Wind Engineer. Industr. Aerodynam. **99**, 154–168.

RAUPACH, M.R., J.J. FINNIGAN, Y. BRUNET, 1996: Coherent eddies and turbulence in vegetation canopies: the mixing-layer analogy. – Bound.-Layer Meteor. **78**, 351–382.

SCHMID, H.P., 1994: Source areas for scalars and scalar fluxes. – Bound.-Layer Meteor. **67**, 293–318.

SEDEFIAN, L., 1980: On the vertical extrapolation of mean wind power density. – J. Climate Appl. Meteor. **19**, 488–493.

TROEN, I., E.W. PETERSON, 1989: European Wind Atlas. – Risø National Laboratory, Roskilde, 656 pp.

VESALA, T., N. KLJUN, U. RANNIK, J. RINNE, A. SOGACHEV, T. MARKKANEN, K. SABELFELD, T. FOKEN, M.Y. LECLERC, 2008: Flux and concentration footprint modelling: State of the art. – Environ. Poll. **152**, 653–666.

WICHURA, B., U. BEHRENS, M. GÖCKEDE, T. FOKEN, 2001: Einfluss der Rauhigkeitsparametrisierung auf die Windenergiepotentialbestimmung. – Österr. Beitr. Meteorol. Geophys. **27** (Extended Abstract), 266.

ZELENÝ, J., T. FOKEN, 1995: Leistungsuntersuchungen an einer Windkraftanlage im Gebirge. – DEWI Mag. **7**, 46–51.