

## Wind energy availability above gaps in a forest

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*Published in:*  
EWEC 2009 Proceedings

*Publication date:*  
2009

*Document Version*  
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*  
Sogachev, A., Mann, J., Dellwik, E., Bingöl, F., Rathmann, O., Ejsing Jørgensen, H., & Panferov, O. (2009). Wind energy availability above gaps in a forest. In EWEC 2009 Proceedings (Vol. 6, pp. 4198-4206). EWEC.

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## **WIND ENERGY AVAILABILITY ABOVE GAPS IN A FOREST**

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### **Summary**

There is a lack of data on availability of wind energy above a forest disturbed by clear-cuts, where a wind energy developer may find an opportunity to install a wind farm. Computational fluid dynamics (CFD) models can provide spatial patterns of wind and turbulence, and help to develop optimal installation strategies. The canopy-planetary boundary-layer model SCADIS is used to investigate the effect of forest gap size (within the diameter range of 3 - 75 tree heights,  $h$ ) on wind energy related variables. A wind turbine was assumed with following features: the hub height and rotor diameter of  $3.5h$  and  $3h$ , respectively; this provides the clearance between the rotor and ground of  $2h$  which is similar to the value obtained by the rule of thumb. Spatial variations of wind energy production, the average wind speed shear and cumulative TKE inside the layer of  $2h$  -  $5h$  above the ground around the gaps were estimated from modelled data. The results show that the effect of the forest gaps with diameters smaller than  $55h$  on wind energy captured by the assumed wind turbine and located in the centre of round low-roughness gap is practically insignificant. The high level of spatial variation of considered characteristics within the clear-cut indicates that a joint influence of wind turbine properties and turbine's location within the gap can result in both win and loss of the wind energy capture. Therefore, for any particular land-use situation and wind turbine properties this combined effect should be considered carefully before a placement of turbine.

### **1. Introduction**

There are a few investigations of wind flow over complex terrain aimed on wind power production. Forest is one of elements of such complex terrain that affects the airflow in a way that is not very well understood. Even on a flat terrain the heterogeneities in forest density caused e.g. by gaps, by uneven aged trees or by mixed species composition might create a complex airflow. In the recent wind availability studies it is usual to neglect the influence of forest composition. However, the neglect of such landscape elements as forest gaps can result in wrong assessment of available wind power [1, 2]. Forest gaps are often considered as suitable places for installation of wind turbines because wind speed should be higher there. Yet when planning the location of wind turbine the effect of forest on turbulence should not be forgotten. Full real scale investigation of effects of forest gaps on flow statistics (especially in the layer which is of interest for wind energy industry namely: within the 100 m above surface) would be very expensive. Instead of that a windflow model can be implemented which provides the information needed for further analysis and helps to find an optimal location for the turbine. The goal of present work is to quantify the effect of a round forest clearing on power production potential.

## 2. Numerical experiment

### 2.1 Windflow model

The canopy-planetary boundary-layer model SCADIS with the closure scheme based on transport equations for turbulent kinetic energy (TKE) and specific dissipation [3, 4] is used in the present study. Model equations and detailed description of numerical schemes and boundary conditions can be found in [5, 6, and 7]. The model was extensively tested against the results of field and wind tunnel experiments [3]. It has shown rather good agreement with measured data and, moreover, demonstrated the universality of applied parameterisation. The reader is invited to refer to cited papers for details about the model equations and numerical aspects. Yet, it should be emphasized here that the model takes into account the Coriolis and pressure force effects.

### 2.2 Setup

A forest stand with an average tree height,  $h$ , of 15 m, total leaf area index, LAI, of  $5 \text{ m}^2 \text{ m}^{-2}$  and the vertical distribution of leaf area density, (LAD or  $A$ ) described by the beta-function with  $\beta$  parameter of 3 and  $\alpha$  - parameter of 7 (for the shape of the distribution see Fig. 1) located at  $55^\circ\text{N}$  is modelled. The drag coefficient  $c_d$  is set as 0.2 ignoring its dependence on flow velocity (see Discussion). The stand with such parameters was assumed to approximate a typical boreal forest [8, 5]. To avoid the additional complications caused by corner effects in rectangular openings (clear-cuts), gaps with round shape ranged in diameter  $D$ , from  $3h$  to  $75h$  (3, 6, 10, 15, 20, 25, 30, 40, 55 and 75) are considered as in [9] (Fig. 2). Therefore, the “lateral” borders of round gap mean henceforth, the left and right edges of a gap relatively to a wind direction. The velocity of geostrophic wind at the upper boundary is taken as  $10 \text{ m s}^{-1}$  (except some cases indicated in the text with  $U_g = 20 \text{ m s}^{-1}$ ). It is assumed that the roughness length at gap surface is the same as at the forest floor:  $z_0 = 0.03 \text{ m}$ . The model is run with horizontal resolution of  $1h$  for all gap diameters except for  $3h$ . To check for the effect of horizontal resolution on model results, the spatial resolution is changed to  $0.5h$  and the experiments are repeated for gap diameters  $6h < D < 30h$  and additionally carried out for a gap with  $D = 3h$ . To provide close approximation of gaps to a circle shape on rectangular grid the total LAI in cells crossed by a circle is weighted according to the ratio between area of full grid cell and that falling outside the circle. The vertical grid consists of 50 nodes with variable size (0.2 m near ground and 200 m near upper border of modelling domain that is set as 2 km).

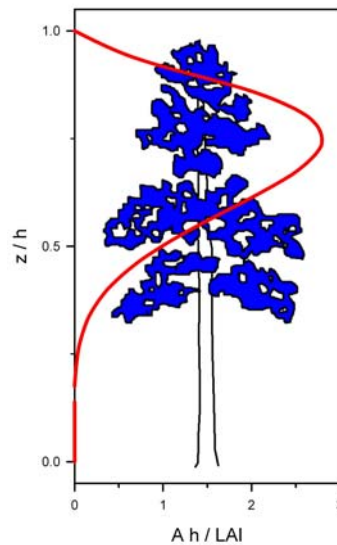


Fig. 1. Vertical profile of normalized leaf area density,  $Ah / LAI$  (dimensionless).

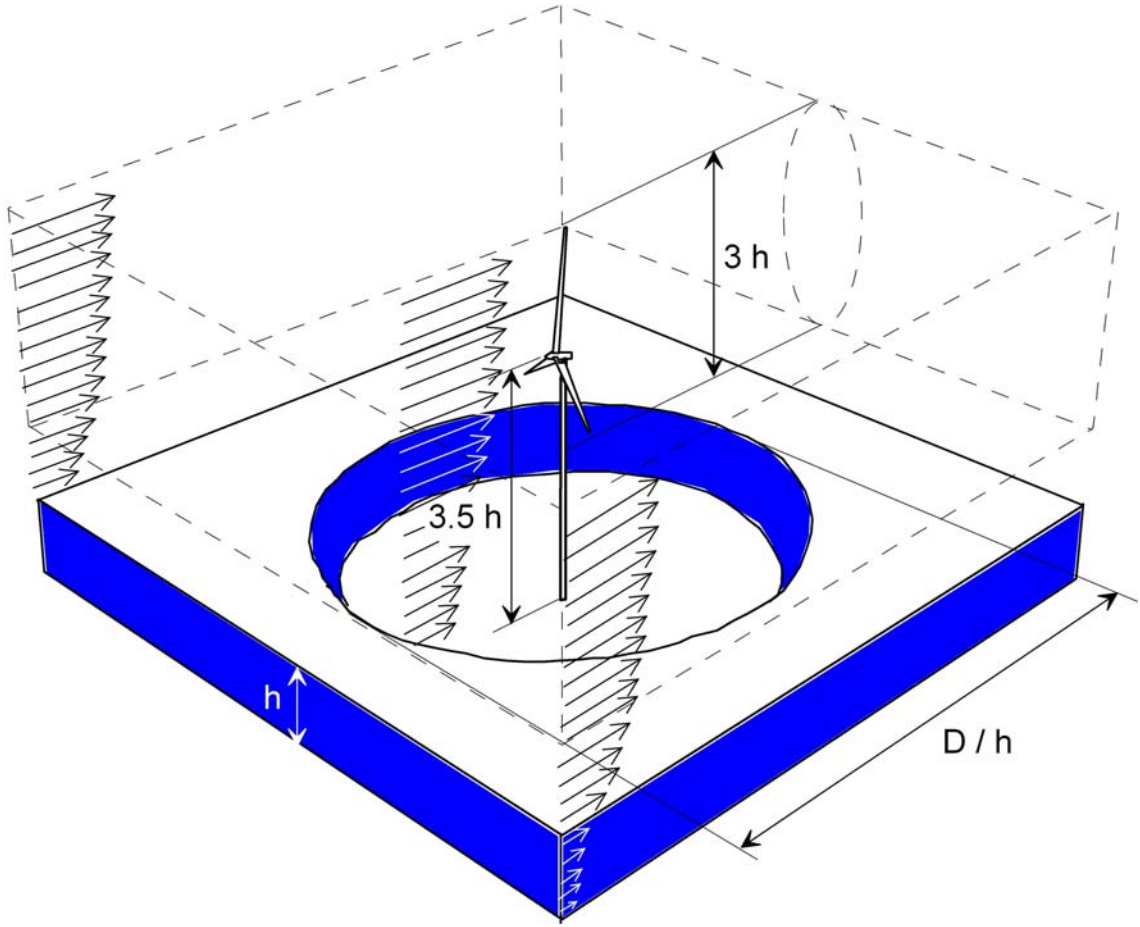


Fig 2. Sketch of numerical experiments for estimation of wind energy availability above gaps of different relative sizes ( $D/h$ ) in a forest of the height,  $h$ , for wind turbine having hub height and rotor diameter  $3.5h$  and  $3h$ , respectively.

### 3. Results

#### 3.1. Pattern of wind energy related variables

A wind turbine was assumed with following features: the hub height and rotor diameter of  $3.5h$  and  $3h$ , respectively; this provides the clearance between the rotor and ground of  $2h$  which is similar to the value obtained by the rule of thumb. Spatial variations of wind energy production  $E$ , the average speed shear,  $S$ , and cumulative turbulent kinetic energy,  $cTKE$ , inside the layer of  $2h - 5h$  above the ground around the gaps were estimated from modelled data (see Fig. 2) as follows:

$$E = \int_{2h}^{5h} c_1 U^3(z) dz ,$$

$$S = \frac{U(5h) - U(2h)}{3h} ,$$

$$cTKE = \int_{2h}^{5h} TKE(z) dz .$$

In the expression for  $E$ ,  $c_1$  is the dimensional factor incorporating different efficiencies of a wind turbine. As a first approximation cumulative TKE characterizes fluctuations of wind around its mean value. Fig. 3 illustrates how spatial distributions of considered variables are affected by a gap size. The fields in  $x$  -  $y$  plane of  $E$ ,  $S$  and  $cTKE$  are presented for three gap diameters (10h, 25h and 55h).

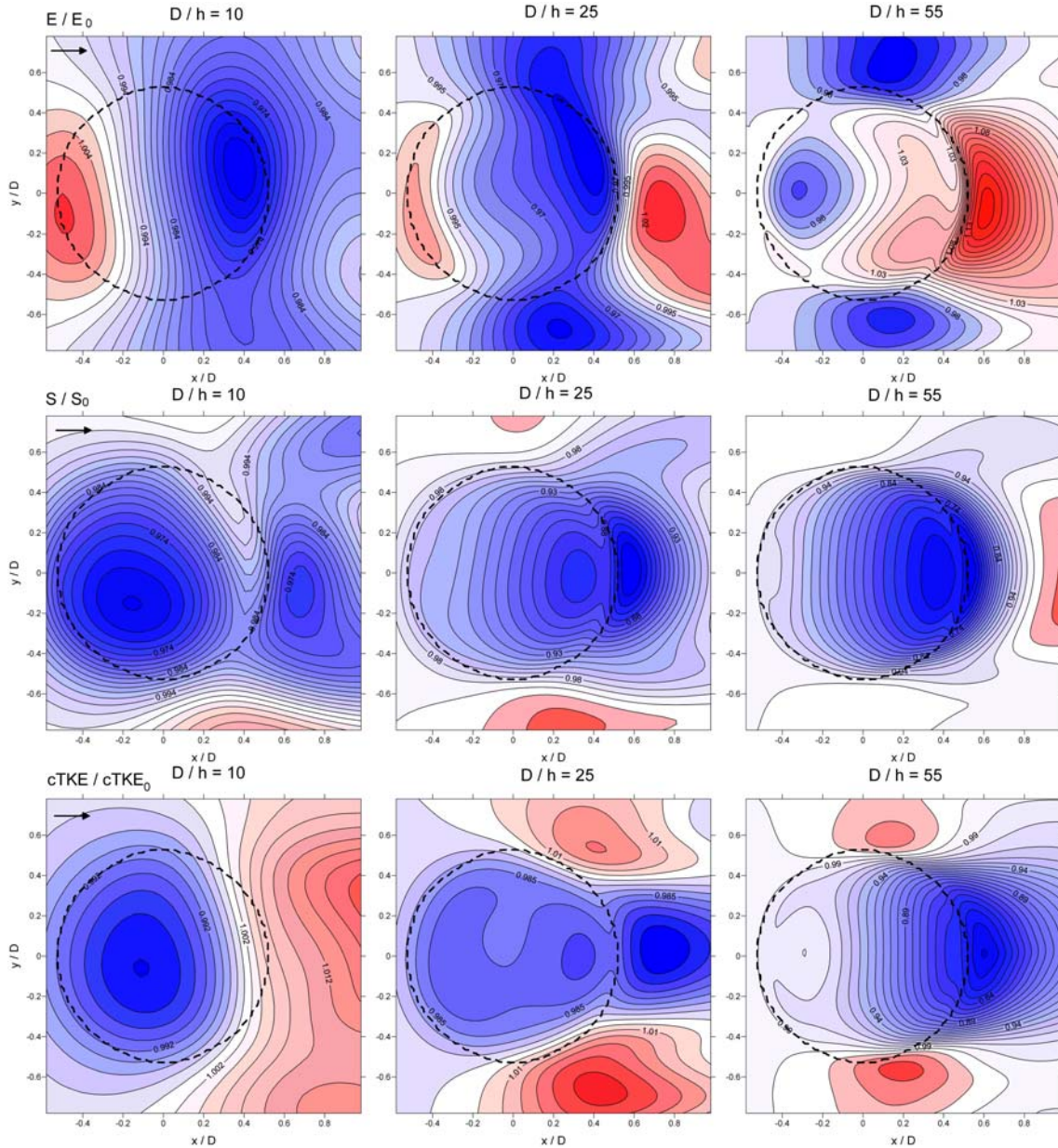


Fig. 3. Spatial distribution of normalized wind energy related variables in the layer 2h-5h above the ground for the gaps of different diameters: 10h, 25h and 55h. The upper panel shows available energy, the middle panel shows the mean wind shear and the lower panel shows the cumulative TKE. Dashed line indicates the vegetation border. Prevailing wind direction over the gaps is from the left to the right.

Figure 3 shows that the presence of a gap in a forest not always provides a win in available wind power. With increasing of gap size the area with potentially high rate of available wind energy shifts from downwind side to upwind side of gap. For gap diameters less than 50h, however, a large part of the gap does not provide any increase in energy supply (see also the Fig. 6 below). On the contrary - wind shear and cumulative TKE above the gaps provide more favourable situation for wind turbine exploitation. Practically, on the largest part of gaps the values of S and cTKE are lower than above uniform forest with exceptions of small gaps ( $D/h < 15$ ), where at some locations these values can be higher than above forest. Common for all variables is their asymmetric distribution relatively to prevailing wind direction. This is specially emphasized for small gaps where the Coriolis force (changing wind direction in roughness layer) and the locally formed pressure field affect wind flow notably. Distribution of variables become more symmetric with increasing of gap size (see Fig. 3 for  $D = 55h$ ) when the wind flow adapts to surface conditions.

### 3.2 Wind energy related variables in the centre of a gap

Besides the spatial distribution the magnitudes of U and TKE also depend directly on gap size. Figs 4 and 5 show respectively the vertical profiles of U and TKE, taken in the middle of a gap. This position is a logical choice for siting of a wind turbine in order to minimize the dependence on wind direction. The information on changes of TKE should complement the description of U changes with increasing of gap size as TKE characterizes the wind gust magnitude. Two reference vertical profiles both for U and TKE are also shown, namely: "Forest" – profile in an undisturbed homogeneous forest with the same structural characteristics as the forest surrounding the modelled gaps, and "Open place" - the profile at some "ideal" open place without any vegetation. The results show that the wind turbine located inside homogeneous forest will gain about 30% of energy of that located at the open place (in layer 2h-5h). The cTKE value and the speed shear above forest will be higher in 2.3 and 1.8 times, respectively then above open place.

The very first and obvious result in Fig. 4 is that even in the gaps with diameter of 75h the value of wind speed is not fully restored after disturbance. It means inter alia that implementing the wind speed value measured at some (even large) clear cut or gap within a forest as an open place value, one should take into account its possible underestimation and consider such values only as "quasi open place" approximations. The dependence of turbulent energy profiles on gap size presented for the same point (Fig. 5) is more complicated than that of U. Above the undisturbed forest the local maximum in the vertical profile of TKE is formed near the trees tops (curve "Forest" in Fig. 5). The maximum starts to dissolve rather quickly as the gap diameter increases – it shifts upwards and within the vertical layer of 2h no maximum could be observed for gaps larger than 6h. In the crown space and above the canopy TKE is higher than at open place and does not reduce to the open place value even above the large gaps.

The results show that the effect of the forest gaps smaller than 55h on wind energy captured by the wind turbine with mentioned characteristics and located in the centre of a round low-roughness gap is practically insignificant. For example the wind energy captured by turbine located in a forest gap with the size of 25h is even 5% lower comparing with a turbine placed above homogeneous forest. Only when gap size exceeds 55h the wind energy becomes slightly higher than that for homogeneous forest reaching 4% increment for the gap size of 75h (Fig. 6). The average speed shear in the centre of a gap decreases monotonically with increasing gap size and is reduced by 30% for the gap size of 75h (Fig. 7). cTKE levels above gaps are almost the same as above homogeneous forest up to the gap size of 30h and then decrease gradually with increasing gap size. The reduction reaches 10% for the gap size of 75h (see Fig. 8).

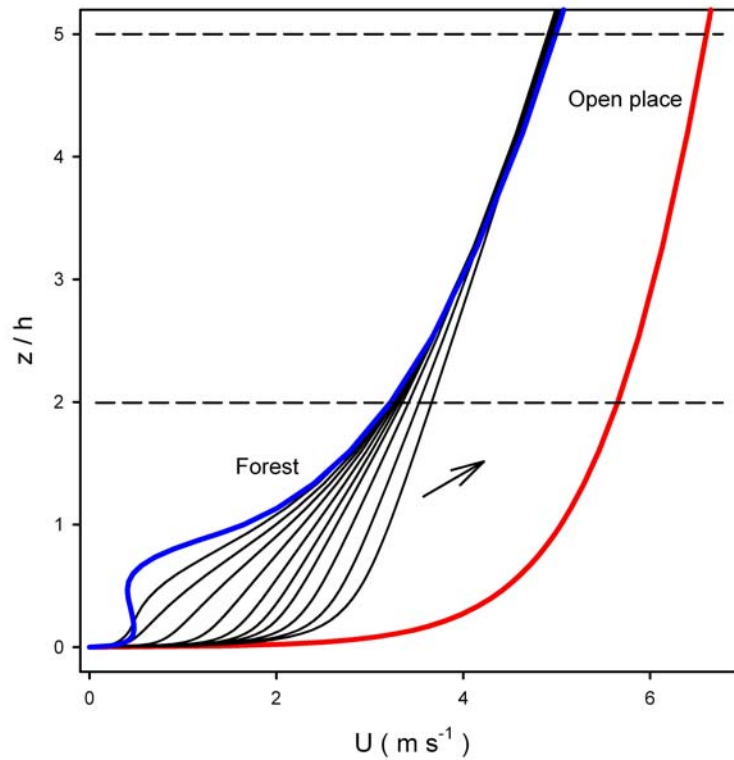


Fig 4. Vertical profiles of the mean wind speed,  $U$ , in the middle of gaps of different diameters  $3h \leq D \leq 75h$  ( $D$ -increasing is shown by arrow). Two reference vertical profiles of  $U$  (heavy solid lines) are also shown: 1) "Forest" - for undisturbed homogeneous forest with the same structural characteristics as the forest surrounding the modelled gaps and 2) "Open place" - for an "ideal" open place without any vegetation.

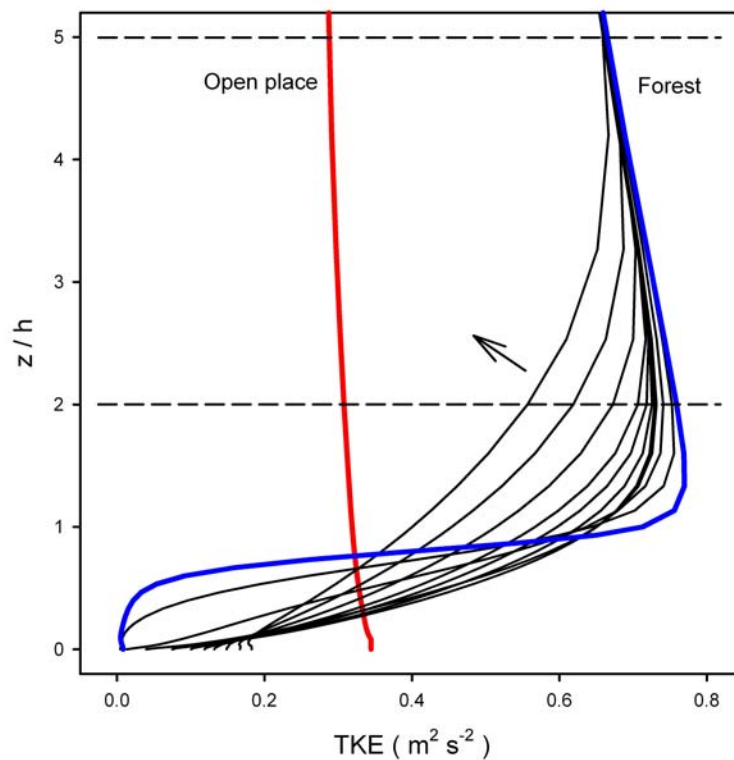


Fig 5. The same as in Fig.4 except for turbulent kinetic energy.

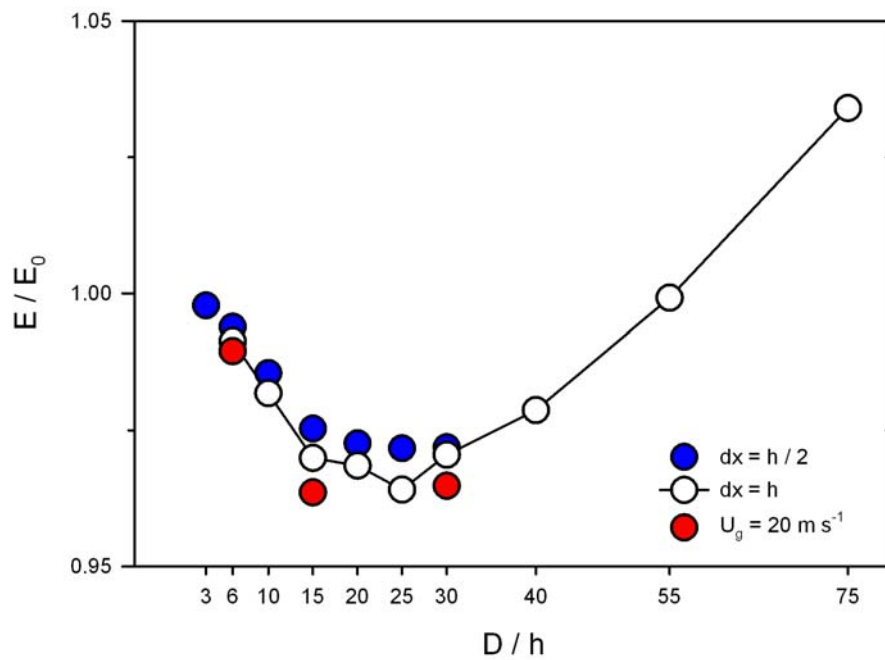


Fig. 6. Normalized values of available energy,  $E$ , as a function of the gap size.  $E$  in the layer  $2h$ - $5h$  above the middle of a forest gap normalized with its value above homogeneous forest stand,  $E_0$ . Blue circles indicate the results of modelling with  $0.5h$  spatial resolution and the white circles with spatial resolution of  $1h$ . Red circles indicate the results of modelling with  $U_g = 20 \text{ m s}^{-1}$  and spatial resolution of  $1h$ .

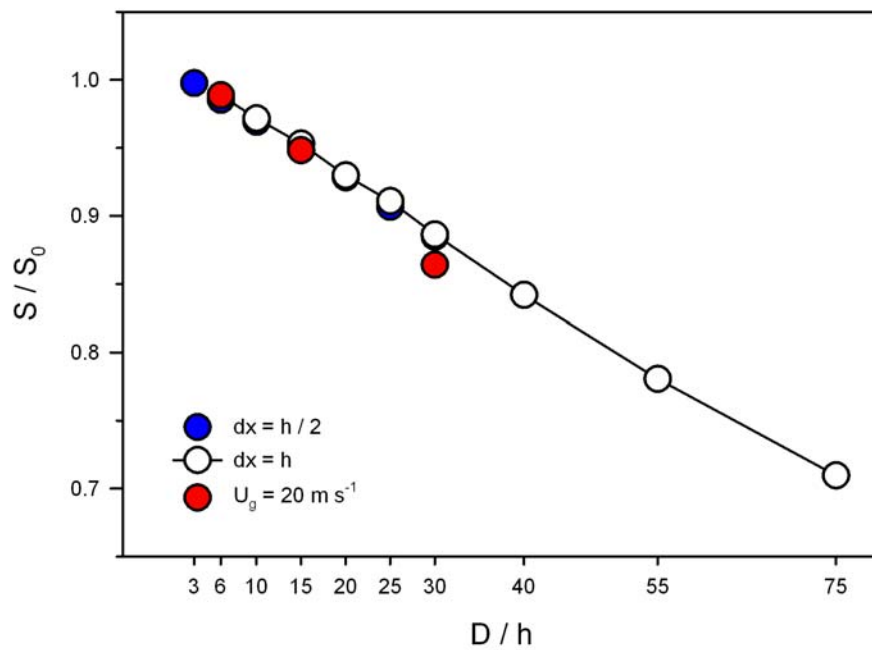


Fig. 7. The same as in Fig. 6 except for wind shear.



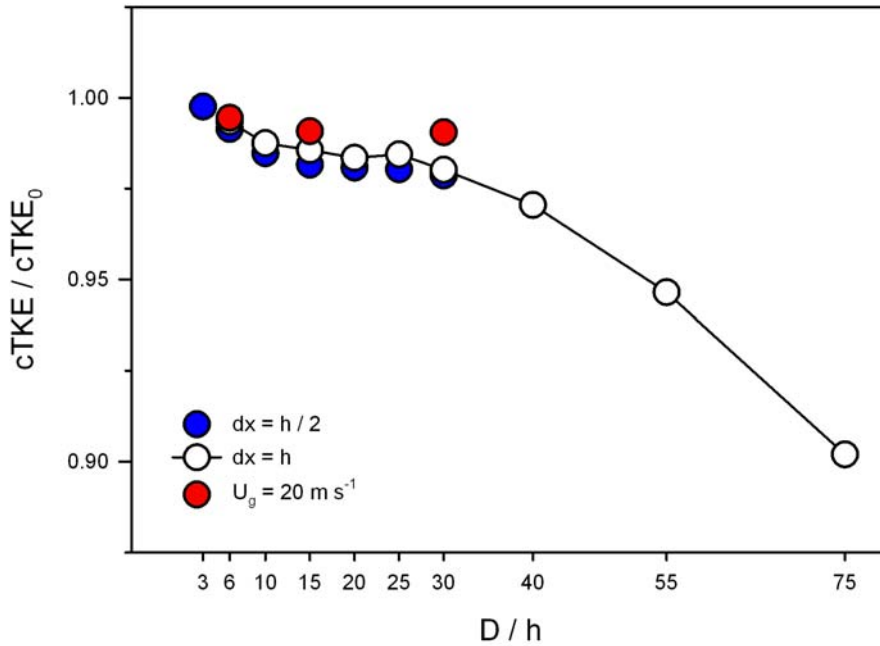


Fig. 8. The same as in Fig. 6 except for cumulative TKE.

Figs. 6 and 8 demonstrate also that the wind energy related variables obtained with model horizontal resolutions of 0.5h and 1h are almost identical. This means that the model accuracy for dynamical characteristics does not depend on spatial resolution within the range of 1h for the gaps with  $D \geq 6h$ . Therefore, coarser resolution could be used for many applied tasks being computationally more economical. The normalized wind energy related variables estimated for  $U_g = 20 \text{ m s}^{-1}$  and shown in Figs. 6 - 8 demonstrate small difference from those for  $U_g = 10 \text{ m s}^{-1}$  but similar dependency of them on gap size.

#### 4. Discussion and Conclusions

We explored the potential of wind energy production over gaps in a forest using ABL model SCADIS. In addition, the parameters affecting the work of turbine such as wind shear and turbulent kinetic energy were estimated. The study has been carried out under several assumptions and simplifications. First, the thermal effects of gaps are ignored. We consider the thermal effects as negligible under the high wind velocities which are favourable for wind energy production. This assumption simplifies the model which in turn considerably reduces the computing time. Nevertheless, the thermal effects can affect the production of TKE (especially for large gaps) and, thus, cause high gustiness. Therefore, the assumption should be avoided further on when estimating the wind energy availability over gaps in a forest. Second, it is assumed in our calculation gaps surrounding by uniform forest (the same height, LAI and LAD shape) with constant aerodynamic properties. The drag coefficient,  $c_d$ , does not depend on the speed of incoming air flow, although there is experimental data evidence that such dependence exists and is different for various tree species (e.g. [10]). We do not think that introducing  $c_d$  dependent on wind velocity will considerably change our results, but it should be mentioned for impartial analysis of results.

The high level of spatial variation of considered characteristics within the clear-cut indicates that a joint influence of wind turbine properties and turbine's location within the gap can result in both win and loss of the wind energy capture. Therefore, for any particular land-use situation and wind turbine properties this combined effect should be considered carefully before a placement of turbine. The additional uncertainties of the not ideally round representation of a gap in this study raise a question about the influence of gap form on the magnitude and spatial distribution of different components of wind load on surrounding trees which will be discussed in a next study.

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