Time Dependent Energy Calculations

Authored by Mr Paul van Lieshout
Wind Power Development Manager
Sinclair Knight Merz (Europe) Ltd
Email: pvanlieshout@skm.co.uk
Web site: www.skmconsulting.com

This paper has been presented at the 'Wind flow and Trees' workshop organised by the British Wind Energy Association 17/3/2004 Glasgow, UK

Every wind power project has to be financially viable throughout its project life, from an accounting as well as from an investor's point of view. As such it is important to have a thorough and detailed understanding of the future energy output of proposed wind farms.

Over the years several different methodologies have been developed to forecast the future energy production of a proposed wind farm. Most are based on the tested Measure-Correlate-Predict methodology, however differences in the execution and output of this methodology are important to note, particularly when the energy calculations are made for wind power projects situated in complex or forested terrain.

Keywords: wind shear, boundary layer stability, energy forecasting

Introduction

The Measure-Correlate-Predict methodology (MCP) is usually implemented in order to calculate the expected energy output of a proposed wind farm. For this, wind measurements taken at a proposed wind farm site are correlated with a short-term data set from a nearby meteorological station. A relationship between the wind farm site and the meteorological station is then established, and the so-called long-term wind speed is then calculated using a long-term data set from the meteorological station. This wind speed will then be used, in combination with wind flow programs, to extrapolate the long-term correlated data set, valid for the location of the anemometer tower site in the wind farm, to all locations in the proposed wind farm area where wind turbines are to be installed. The wind speed at each of the turbine locations is then combined with the wind turbine power curve after which the energy production for the whole wind farm is calculated. Inefficiencies like wake effects, turbine availabilities, electrical losses and a myriad of others are then incorporated to produce the net expected Annual Energy Production.

This has been rather straightforward for small wind farm projects. However when using this methodology in forested/wooded areas (or other complex terrain areas), large discrepancies have been found between forecasted wind speeds and measured wind speeds thus making the Annual Energy Production calculations unreliable. This unreliability is due to several issues of which this paper only describes those associated with wind shear and 'average value' calculations. It will show that time domain calculations will alleviate many of the weaknesses associated with calculations that use 'average values' and generic wind shear characteristics.

Wind shear

The energy output of a wind turbine is a function of the air mass that is flowing through the rotor surface of a wind turbine. This is depicted by the power curve of the turbine, which describes the relationship between the power output of the wind turbine and the undisturbed wind speed as seen by the wind turbine. Such power curves are normally measured/calculated as a function of the 10-minute averaged undisturbed hub height wind speed, however they are also a function of the wind shear profiles.

The wind shear profile is most important for future energy calculations for several reasons:

- The profile is used to calculate the hub height wind speed if measurements have been taken at heights different from the turbine's hub height.
- It is further used to adjust the turbine's power curve, as these curves are only valid for a single wind shear profile.
- It is used in algorithms that extrapolate wind data from a measurement tower to nearby proposed wind turbine locations, as such it is used in wind flow models like WAsP.

The wind shear profile is not a static profile but changes with time, and space:

- The profile is a function of surrounding area (grass, trees, houses, hills, crags etc). As such it is location dependent.
- The profile further depends on the wind direction as the profile is dependent on the area over which the wind is blowing.
- The profile is a function of the stability of the boundary layer.

As such the wind shear profile is a function of time. The whole dependency of the wind shear profile on time would result in the introduction of errors if a 'fixed' or 'averaged' wind shear profile is used for energy calculations. To undertake accurate energy calculations as required by developers and financial institutions it is of utmost importance to undertake Annual Energy Production calculations in the time domain.

In energy calculations often two different wind shear profiles are used, namely the exponential wind shear profile;

1a)

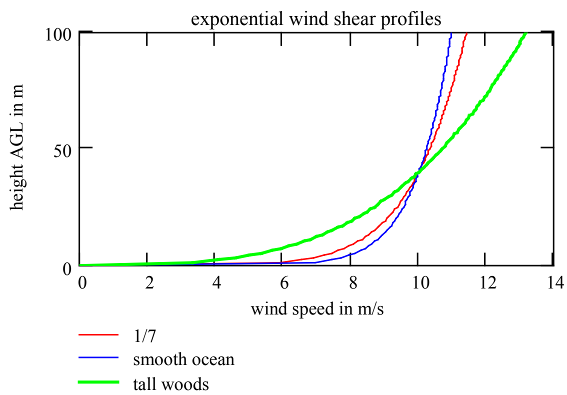
$$v_{hub} := wind_{meas} \cdot \left(\frac{h_{hub}}{h_{meas}} \right)^{\alpha}$$

or the surface roughness wind shear profile

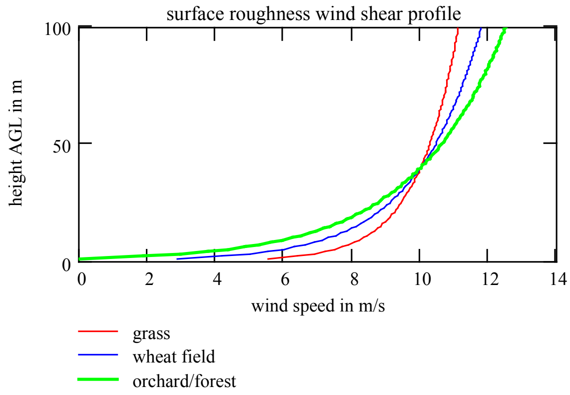
1b)

$$v_{hub} := v_{ref} \frac{\ln\left(\frac{z_{hub}}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)}$$

Formula 1a) changes into the well known 1/7th power law when the exponential value α equals 1/7. This wind shear profile is often used for UK's rolling country site. For tall wooded areas with many trees, suburbs or small towns, this value can be as high as 0.3, whereas smooth seas see values closer to 0.1. The following graph shows the exponential wind shear profile for these three values of α. It is assumed that the wind speed at 40mAGL (measurement height) is 10 m/s.



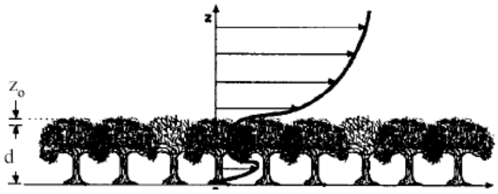
The next graph shows the surface roughness dependent wind shear profile for surface roughness values of z_0=0.1 for grass lands, for z_0=1.0 which is valid for some orchards and a value between z_0=0.3 and z_0=4.0 used for coniferous forests. Note the large uncertainty as to what value represent the forests. As a guide a roughness length of 1/30 of the obstruction height can be used (but this is only a very rough guide!).



It is obvious from these graphs that the way the atmospheric boundary layer acts is sensitive to the values chosen to represent the surface roughness of the surrounding area.

Displacement height

The above wind shear profiles follow exponential curves all the way to ground level. In forested areas this is not valid. A generic forest profile is depicted in the following figure.



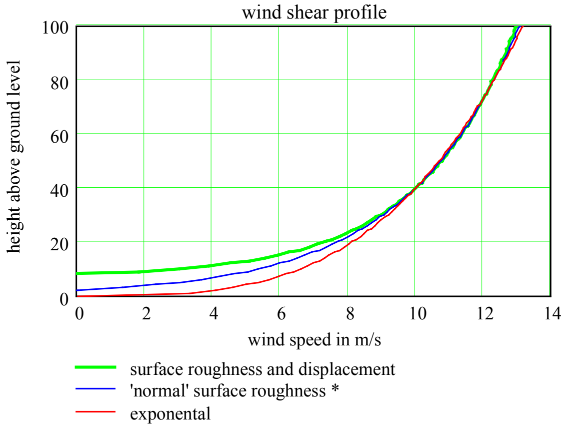
This curve shows a distinct deviation from the above exponential graphs. Effectively, the wind shear profile is 'displaced in height'. (It is further noted that the porosity of the tree will have a distinct effect on the wind flow, and as such a dependency of the wind shear on seasonality can be expected.) This has led to the development of wind shear profiles that take into account displacement heights. In effect, it raises the actual ground level to a new 'virtual ground level'. The following formula shows this phenomena;

2)

$$v_{hub}(z1, z1_0) := v_{ref} \frac{\ln\left(\frac{z1 - d}{z1_0}\right)}{\ln\left(\frac{z_{ref} - d}{z1_0}\right)}$$

where d is the displacement height, z1 the height above ground level and $z1_0$ the new surface roughness. It is noted that the displacement height is NOT the same as the height of the trees and $z1_0$ is NOT the same as z_0.

The following graph shows the comparison of the above three formulae, namely the exponential and surface roughness wind shear profiles for forested areas without displacement height and the surface roughness wind shear profile taking the displacement height into account.



It is noted that there is a small discrepancy between the three curves, it is further noted that slight changes in surface roughness or displacement values would result in different profiles, likely showing larger differences. This is not satisfactory for the Annual Energy Production calculations, particularly because the power output of the turbine does not have a linear relationship with the wind speed.

Stability of the boundary layer

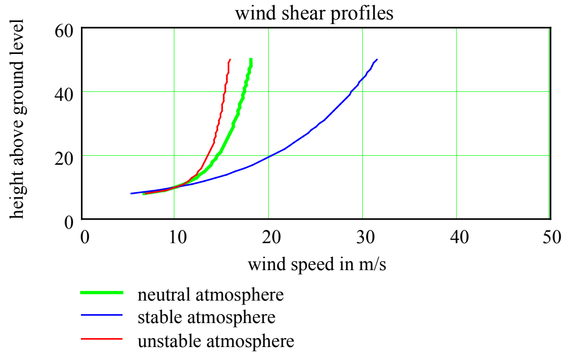
To further complicate the issue, it is noted that the above relationships (1a, 1b and 2) are only valid for a neutral atmosphere, whereas it actually has a diurnal profile starting the day generally as a stable boundary layer, to unstable, to neutral and then back to stable again. The boundary stability has a profound influence on wind shear profiles. The stability of the boundary layer can be described by the Atmospheric Stability Function which is defined by the Monin-Obukhov stability length. The wind shear profile function taking the boundary layer stability into account is then described as follows;

3)

$$U(z, \Psi, \Psi_r) := U_r \frac{\ln\left(\frac{z-d}{z_0}\right) + \Psi}{\ln\left(\frac{z_r-d}{z_0}\right) + \Psi_r}$$

where Ψ depicts the atmospheric stability function.

Using the same surface roughness but depicting the wind shear profile for the different periods of the day (boundary layer stability periods) we find the following graphical relationships between wind speed and height above ground level.



The above graph shows large differences for the wind shear profile, depending on the boundary layer stability. These widely different profiles will have a distinct effect on the Annual Energy Production. Choosing to ignore such diurnal effects would surely result in unreliable energy forecasts. This is particularly true for forested areas, where a more intense heat transfer occurs between the forest and the boundary layer. It is noted however that under actual circumstances the boundary layer stability is further complicated as the boundary layer tends to become more neutral when the wind speed increases.

The above identifies that when the provided models are used in a generic ‘average value’ calculation that the output is largely dependent on the assumptions made to define the wind shear profiles.

Time dependency

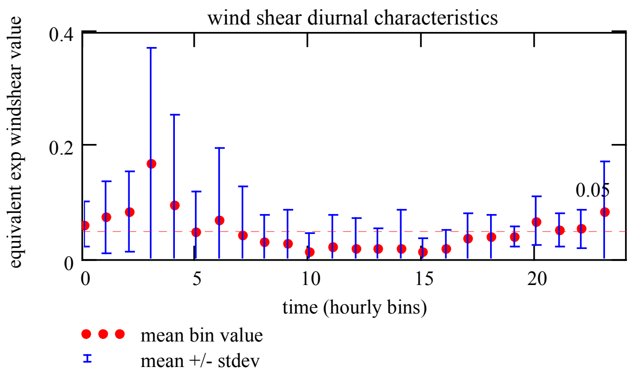
It is noted again that the wind shear assumptions are time dependent. Static wind shear profiles introduce errors in the Annual Energy Production (AEP) calculations.

- Displacement heights change throughout the decades as trees grow or are harvested.
- Surface roughness lengths (above the changing displacement heights) change with the seasons and also as the foliage of the tree changes.
- Wind shear profiles are dependent on the wind direction as surrounding areas are normally not uniform, particularly when wind turbines are located near the edge of forests or lakes.
- Wind shear profiles show distinct diurnal variations due to the changing boundary layer stability.

Due to the changing diurnal, seasonal and long-term statistics including directional wind shear profiles, it is much preferred to undertake energy calculations in the time domain and calculate wind shear for each distinct time period. Wind shear characterisation should be undertaken when appropriate wind speed measurements are taken at different heights above ground level, either at 10-minute or hourly intervals. Dynamic wind shear calculations based on actual wind measurements should be undertaken for each of these time periods and should not be averaged out over the whole period over which the measurements have been taken.

Such dynamic wind shear calculations are undertaken in SKM's WindToolBox™. This software automatically extrapolates multiple measurements taken at different heights on an anemometer tower to the hub height of a wind turbine (normally every 10 or 60 minutes). This will allow dynamic adjustment for all the above mentioned time dependent diurnal and seasonal effects on wind shear over the period which the measurements have been taken. In addition SKM's WindToolBox™ adjusts dynamically the wind turbine's power curve to allow for accurate mass flow through the rotor surface of the proposed wind turbines. The combination of this software package and wind flow programs result in accurate Annual Energy Production calculations which has eliminated the uncertainty associated with the generic 'averaged value' wind shear

The following curve shows measured and dynamically extrapolated hub height wind speeds displayed in a diurnal graph. The graph clearly depicts the different wind shear profiles for the different parts of the day.



Besides confirming the time dependent variability of wind shear throughout the day (as discussed above), the graph also shows the average equivalent exponential wind shear value ($\alpha = 0.05$), which would be used in conventional Annual Energy Production calculations and wind flow analysis programs. Due to the non linear relationship between wind speed and energy production, the AEP based upon the 'average value' contains a large uncertainty. Please note the actual spread in wind shear values within each bin (+/- standard deviation).

Summary

The paper has introduced several wind shear profiles used in the wind industry. As these profiles are valid for neutral boundary layer conditions, these have to be adjusted for stable and unstable conditions by incorporating the Monin-Obukhov stability length.

It is noted that wind shear profiles are not static but that they change with time and space. Both in short time frames (diurnal effects) as well as seasonal (i.e. summer and winter foliage) and longer time frames (growth of trees and harvesting). Furthermore, the wind direction plays a role as wind shear is defined by the surface roughness over which the wind flows (turbines installed near forest edges). The time dependency thus has to be incorporated in the Annual Energy Production as the energy production depends on the hub height wind speed and the wind shear profile of the air mass flowing through the turbine's rotor surface.

It is further noted that the popular wind flow programs use distribution curves of wind speed data and generic wind shear profiles (valid only for neutral boundary layer conditions) and do not address these dynamic time dependent issues.

Dynamic wind shear calculations, as undertaken in SKM's WindToolBox™ in combination with wind flow models, address both wind shear and turbine power curve time dependent issues. This methodology provides the Annual Energy Production calculations with an associated statistically higher degree of confidence, particularly in complex terrain, which include wind farm areas which are planned in forested regions.