The sound of high winds
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VI STRONG WINDS BLOW UPON TALL TURBINES: wind statistics below 200 m altitude

VI.1 Atmospheric stability in wind energy research
In the European Wind Atlas model (‘Wind Atlas Analysis and Application Program’ or WAsP) [Troen et al 1989] wind energy available at hub height is calculated from wind velocities at lower heights. The Atlas states that “modifications of the logarithmic wind profile are often neglected in connection with wind energy, the justification being the relative unimportance of the low wind velocity range. The present model treats stability modifications as small perturbations to a basic neutral state.” With the increase of wind turbine heights this quote is now an understatement. In recent years atmospheric stability is receiving gradually more attention as a determinant in wind energy potential, as demonstrated by a growing number of articles on stability related wind profiles in different types of environments such as Danish offshore sites [Motta et al 2005], the Baltic Sea [Smedman et al 1996], a Spanish plateau [Pérez et al 2005] or the American Midwest [Smith et al 2002]. Recently Archer and Jakobsen [2003] showed that wind energy potential at 80 m altitude in the contiguous US ‘may be substantially greater than previously estimated’ because atmospheric stability was not taken into account: on average 80-m wind velocities appear to be 1.3 – 1.7 m/s higher than assumed from 10-m extrapolated wind velocities in a neutral atmosphere.

VI.2 The Cabauw site and available data
To investigate the effect of atmospheric stability on wind, and thence on energy and sound production, data from the meteorological research station of the KNMI (Royal Netherlands Meteorological Institute) at Cabauw in the western part of the Netherlands were kindly provided by dr Bosveld of the KNMI. The site is in open pasture for at least 400 m in all directions. Farther to the west the landscape is open, to the distant east are trees and low houses. More site information is given in [KNMI 2005, Van Ulden et al 1996]. The site is considered representative for the flat western and
northern parts of the Netherlands. These in turn are part of the low-lying plain stretching from France to Sweden. Meteorological data are available as half hour averages over several years. Here data of the year 1987 are used. Wind velocity and direction are measured at 10, 20, 40, 80, 140 and 200 m altitude. Cabauw data are related to Greenwich Mean Time (GMT); in the Netherlands the highest elevation of the sun is at approximately 12:40 Dutch winter time, which is 20 minutes before 12:00 GMT.

An indirect measure for stability is Pasquill class, derived from cloud cover, wind velocity and position of sun (above or below horizon). Classes range from A (very unstable: less than 50% clouding, weak or moderate wind, sun up) to F (moderately to very stable: less than 75% clouding, weak or moderate wind, sun down). Pasquill class values have been estimated routinely at Dutch meteorological stations [KNMI 1972].

**VI.3 Reference conditions**

To relate the meteorological situation to wind turbine performance, an 80 m hub height wind turbine with three 40 m long blades will be used as reference for a modern 2 to 3 MW, variable speed wind turbine. To calculate electrical power and sound power level, specifications of the 78 m tall Vestas V80 – 2MW wind turbine will be used. For this turbine cut-in
(hub height) wind velocity is 4 m/s, and highest operational wind velocity 25 m/s.

Most data presented here will refer to wind velocity at the usual observation height of 10 m and at 80 m hub height. Wind shear will be presented for this height range as well as the range 40 to 140 m where the rotor is. The meteorological situation is as measured in Cabauw in 1987, with a roughness height of 2 cm. The year will be divided in meteorological seasons, with spring, summer, autumn and winter beginning on the first day of April, July, October and January, respectively.

We will consider four classes of wind velocity derived from Pasquill classes A to F and shown in table 1: unstable, neutral, stable and very stable. In table VI.1 (the same as table III.1, but written slightly different to show boundaries between stability classes in terms of m) this is also given in terms of the shear exponent, but this is tentative as there is no fixed relation between Pasquill classification and shear exponent or stability function $\Psi$. This classification is in agreement with that in chapter III, though there typical mid-class values of $m$ were given, not values at the boundaries between classes. In our reference situation ‘very stable’ ($m > 0.4$) corresponds to a Monin-Obukhov length $0 < L < 100$ m, ‘stable’ ($0.25 < m < 0.4$) refers to $100 m < L < 400$ m, near neutral to $|L| > 400$ m. This is somewhat different from the Monin-Obukhov length based classification used by Motta et al [2005] for a coastal/marine environment. Motta et al qualified $0 < L < 200$ m as very stable, $200 m < L < 1000$ m as stable and $|L| > 1000$ m as near-neutral, so they considered a wider range of conditions as (very) stable when compared to table 1.

<table>
<thead>
<tr>
<th>Pasquill class</th>
<th>name</th>
<th>shear exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>A – B</td>
<td>(very – moderately) unstable</td>
<td>$m \leq 0.21$</td>
</tr>
<tr>
<td>C</td>
<td>near neutral</td>
<td>$0.21 &lt; m \leq 0.25$</td>
</tr>
<tr>
<td>D – E</td>
<td>(slightly – moderately) stable</td>
<td>$0.25 &lt; m \leq 0.4$</td>
</tr>
<tr>
<td>F</td>
<td>very stable</td>
<td>$0.4 &lt; m$</td>
</tr>
</tbody>
</table>

Table VI. 1: stability classes and shear exponent m
VI.4 Results: wind shear and stability

VI.4.1 Wind velocity shear

In figure VI.2 the average wind velocities at altitudes of 10 m to 200 m are plotted versus time of day. Plotted are averages per half hour of all appropriate half hours in 1987. As figure VI.2 shows, the wind velocity at 10 m follows the popular notion that wind picks up after sunrise and abates after sundown. This is obviously a ‘near-ground’ notion as the reverse is true at altitudes above 80 m. Figure VI.2 helps to explain why this is so: after sunrise low altitude winds are coupled to high altitude winds due to the vertical air movements caused by the developing thermal turbulence. As a result low altitude winds are accelerated by high altitude winds that in turn are slowed down. At sunset this process is reversed. In figure VI.2 also the wind velocity \( V_{80} \) is plotted as calculated from the measured wind velocity \( V_{10} \) with equation III.3 \((z_o = 2\, \text{cm}, \text{equivalent to equation III.1 with } m = 0.14)\), as well as the shear exponent \( m \) calculated with equation III.4. The logarithmically extrapolated \( V_{80} \) approximates actual \( V_{80} \) in daytime when the shear exponent has values close to 0.14. However, the prediction is very poor at night time, when \( m \) rises to a value of 0.3, indicating a stable atmosphere.

Figure VI.2: solid lines, bottom to top: 1987 wind velocity per clock hour at heights 10 to 200 m; dotted line: logarithmically extrapolated \( V_{80} \); \(+\): shear exponent \( m_{10,80} \)
For the hourly progress of wind velocities large deviations from the average wind profile occur. This is illustrated in figure VI.3 for a week in winter and a week in summer with measured \( V_{10} \) values and measured as well as logarithmically extrapolated \( V_{80} \) values. In the winter week in January 1987 ground and air were cold for a long time (below freezing point) with very little insolation. Temperature varied from night to day (diurnal minimum to maximum) with 7 °C on the first day and 5 °C or less on the next days, and the atmosphere was close to neutral with measured \( V_{80} \) more or less equal to the extrapolated \( V_{80} \). In the summer week in July 1987 there was little clouding after the first two days; insolation was strong in daytime, and nights were 10 to 14 °C cooler than days, resulting in a stable to very stable night time atmosphere. Here, night time wind velocity was rather higher than predicted with the logarithmic wind profile.

In figure VI.4 wind velocities per half hour are again plotted for different heights, as in figure VI.2, but now averaged per clock half hour and per meteorological season. In spring and summer differences between night
and day seem more pronounced than in autumn or winter. In fall and winter wind velocities are on average higher.

Figure VI.4: wind velocity per hour GMT at heights of 10, 20, 40, 80, 140 and 200 m (bottom to top; 80 m is bold) in the meteorological seasons in 1987
In figure VI.5 the frequency distribution is plotted of the half-hourly wind velocities at five different heights. Also plotted is the distribution of wind velocity at 80 m as calculated from the 10-m wind velocity with the logarithmic wind profile (equation III.3, \( m = 0.14 \)). Wind velocity at 80 m has a value of \( 7 \pm 2 \) m/s for 50% of the time. For the logarithmically extrapolated wind velocity at 80 m this is \( 4.5 \pm 2 \) m/s.

In figure VI.6 the prevalence of the shear exponent in the four meteorological seasons is plotted, determined from the half-hourly 10-m and 80-m wind velocities. It shows that, relative to autumn and winter, a neutral or mildly stable atmosphere occurs less often in spring and summer, whereas an unstable as well as --in summer- a very stable atmosphere occurs more often. As summer nights are short this means that a relatively high percentage of summer night hours has a stable atmosphere.

\[\begin{align*}
\text{Figure VI.5: distribution of measured wind velocities at 10, 40, 80, 140 and 200 m; dashed line: } V_{80} \text{ extrapolated from } V_{10} \\
\text{Figure VI.6: distribution of shear exponent per meteorological season, determined from } V_{80}/V_{10}
\end{align*}\]
VI.4.2 Shear and ground heat flux

Figure VI.7 shows how the shear exponent depends on the total heat flow to the ground for two different height ranges: 10 – 80 m in the left panel, 40 – 140 m in the right panel. The shear exponent is calculated from the wind velocity ratio with equation III.1. The heat flow at Cabauw is determined from temperature measurements at different heights, independent of wind velocity. Total heat flow is the sum of net radiation, latent and sensible heat flow, and positive when incoming flow dominates. For heat flows above approximately 200 W/m² the shear exponent m is between 0 and 0.21, corresponding to an unstable atmosphere, as expected. For low or negative (ground cooling) heat flows the range for m increases, extending from -1 up to +1.7. These values include conditions with very low wind velocities. If low wind velocities at 80 m height ($V_{80} < 4$ m/s, occurring for 19.7% of the time) are excluded, $m_{10,80}$ varies (with very few exceptions) between 0 and 0.6, and $m_{40,140}$ varies between -0.1 and +0.8. A negative exponent means wind velocity decreases with height. The data show that below 80 m this occurs in situations with little wind ($V_{80} < 4$ m/s), but at greater heights also at higher wind velocities. In fact, $V_{140}$ was lower than $V_{80}$ for 7.5% of all hours in 1987, of which almost half (3.1%)

![Figure VI.7: shear exponent m from wind velocity gradient between 10 and 80 m (left), and 40 and 140 m (right) vs. total ground heat flow; grey circles: all data, black dots: $V_{80} > 4$ m/s](image)
when $V_{80}$ was over 4 m/s. Such a decrease of wind velocity with height occurs at the top of a ‘low level jet’ or nocturnal maximum; it occurs at night when kinetic energy of low altitude air is transferred to higher altitudes.

For $V_{80} > 4$ m/s both shear exponents ($m_{10,80}$ and $m_{40,140}$) are fairly strongly correlated (correlation coefficient 0.85), showing that generally there is no appreciable change between both altitude ranges. For low wind velocities ($V_{80} < 4$ m/s) both shear exponents are less highly correlated (correlation coefficient 0.62).

VI.4.3 Wind direction shear

When stability sets in the decoupling of layers of air also affects wind direction. The higher altitude wind more readily follows geostrophic wind and therefore can change direction when stability sets in, while lower altitude winds are still influenced by the surface following the earth’s rotation. In the left panel of figure VI.8 the change in wind direction at 80 m relative to 10 m is plotted as a function of the shear exponent as a measure of stability. A positive change means a clockwise change (veering wind) at increasing altitude. The right panel shows the wind direction change from 40 to 140 m as a function of the shear exponent determined from the wind velocities at these heights. In both cases the prevailing change from $m = 0$ to $m = 0.5$ is 30°, but with considerable variation.

![Figure VI.8: wind direction change between 10 and 80 m (left) and 40 and 140 m (right) vs. shear exponent $m$ between same heights for $V_{80} > 4$ m/s](image)
VI.4.4 Prevalence of stability

In figure VI.9 the percentages are given that the atmosphere is very stable, stable, neutral and unstable respectively (as defined in table VI.1) for 1987 as a whole and per meteorological season. Prevalence is given for heights from 10 and 80 m (upper panel figure VI.9) and for heights from 40 to 140 m (lower panel). The upper panel is in fact a summation over the four ranges of the shear exponent indicated in figure VI.6. It appears that in autumn the atmosphere is most often stable, and least often unstable. In spring the opposite is true: instability occurs more often than stability. Overall the atmosphere up to 80 m is unstable ($m < 0.21$) for 47% of the time and stable ($m > 0.25$) for 43% of the time. At higher altitudes (40 to 140 m) percentages are almost the same: 44% and 47%, respectively. This means that for most of the daytime hours the atmosphere is unstable, and for most of the night time hours stable. For the rest (9 to 10%) of the time the atmosphere is near neutral.

Climatological observations can put the Cabauw data in national perspective. In figure VI.10 the prevalence of Pasquill classes E and F (corresponding to approximately $m > 0.33$) are given as observed at 12 meteorological stations all over the Netherlands over the period 1940 - 1970 [KNMI 1972], ordered according to yearly prevalence. Three of the
dunes on the North Sea coast, Vlissingen is at the Westerschelde estuary and Den Helder is on a peninsula between the North Sea and the Wadden Sea. At Den Helder a stable atmosphere occurs for only 8% of the time per year, whereas at both other coastal stations this is 13% to 16% and at the other landward stations 15% to 20% of the time. At Cabauw a value of $m > 0.33$ occurs for 27% of the time.

![Figure VI.10: prevalence of observed stability (Pasquill classes E and F) per season and per year at 12 different Dutch stations over 30 years (data from KNMI)](image)

**VI.5. Results: effects on wind turbine performance**

**VI.5.1 Effect on power production**

The effect of atmospheric stability can be investigated by applying the Cabauw data to a reference wind turbine, the Vestas V80-2MW [Vestas 2003, Jorgensen 2002]. This turbine has an ‘Optispeed’ sound reduction possibility to reduce sound power level (by adapting the speed of the rotor and generator). We will present data for the highest (‘105.1dB(A)’) and lowest (‘101.0dB(A)’) sound power curve. To calculate the electric power $P_{80}$ as a function of wind velocity $V_h$ at hub height the factory ‘105.1dB(A)’ highest power (‘hp’) curve is approximated with a fourth power polynome:
\[ P_{h, hp} = 0.0885 \cdot V_h^4 - 8.35 \cdot V_h^3 + 186 \cdot V_h^2 - 1273 \cdot V_h + 2897 \text{ kW} \quad (VI.1a) \]

which is valid for \( 4 < V_h < 14.3 \text{ m/s} \). In figure VI.11 this fitted curve is plotted as diamonds on top of the manufacturer’s specification [Vestas 2003]. For higher wind velocities (>14.3 m/s; 2\% of time at Cabauw) electric power is constant at 2000 kW, for lower wind velocities (< 4 m/s; 20\% of time) electric power is set to zero.

A fourth power relation is used as this is convenient to fit the power curve at 12 m/s where maximum power is approached. For lower wind velocities \( (V_h < 11 \text{ m/s}) \) the power curve can be fitted with a third power \( (P_h = 1.3 \cdot V_h^3) \) in agreement with the physical relation between wind power and wind velocity.

Electric power can thus be calculated from real wind velocities as measured each half hour at 80 m height, or from 80-m wind velocities logarithmically extrapolated from wind velocity at 10 m height. The result is plotted in figure VI.12 as an average power versus time of day \( P_{80, hp} \) (the power averages are over all hours in 1987 at each clock hour). Actual power production appears to be more constant than estimated with extrapolations from 10-m wind velocities. When using a logarithmic extrapolation, daytime power production is overestimated, while night time power production is underestimated. The all year average is plotted with large symbols at the right side of the graph in figure VI.12: 598 kW when based on measured wind velocity or a 30\% annual load factor, 495 kW
when based on extrapolated wind velocity or a 25% load factor. In figure VI.12 also the wind power is plotted when the turbine operates in the lowest ‘101.0dB(A)’ power curve (‘lp’) where the best fit is:

\[ P_{h,lp} = 0.089 \cdot V_h^4 + 0.265 \cdot V_h^3 + 43 \cdot V_h^2 - 326 \cdot V_h + 749 \text{ kW} \quad \text{(VI.1b)} \]

The year average is now 569 kW, corresponding to a 28% annual load factor. The 4 dB lower sound level setting thus means that yearly power production has decreased to a factor 0.94.

In the calculations it was implicitly assumed that the wind velocity gradient over the rotor was the same as at the time the power production was determined as a function of hub height wind velocity. In stable conditions however, the higher wind gradient causes a non-optimal angle of attack at the blade tips when the tips travel far below and above the hub. This will involve some loss, which is not determined here.

**VI.5.2 Effect on sound production**

Figure VI.13 shows ‘theoretical’ sound power levels for the Vestas turbine [Vestas 2003, Jorgensen 2002]; in fact for \( V_h < 8 \text{ m/s} \) measured levels are somewhat lower, for \( V_h > 8 \text{ m/s} \) somewhat higher [Jorgensen 2002]. To calculate the sound power level \( L_W \) as a function of hub height wind velocity \( V_h \) the factory ‘105.1dB(A)’ high power curve is approximated with a fourth power polynome:

\[ L_{W,hp} = -0.0023 \cdot V_h^4 + 0.146 \cdot V_h^3 - 2.82 \cdot V_h^2 + 22.6 \cdot V_h + 39.5 \text{ dB(A)} \quad \text{(VI.2a)} \]
for $4 < V_h < 12$ m/s and $L_{W, hp} = 107$ dB(A) for $V_h > 12$ m/s. In figure VI.14 the result per clock hour is plotted when using actual and extrapolated (from 10 m) wind velocities. Averaged over all 1987 the sound power level in daytime is overestimated by 0.5 dB, but at night underestimated by 2 dB. In the ‘101.0dB(A)’ low power curve setting the best fourth power polynomial fit is (in figure VI.13 plotted as diamonds over the Vestas curve):

$$L_{W, lp} = -0.022 \cdot V_h^4 + 0.78 \cdot V_h^3 - 10 \cdot V_h^2 + 55.3 \cdot V_h - 12.3 \quad \text{dB(A)} \quad (VI.2b)$$

for $4 < V_h < 12$ m/s and $L_{W, hp} = 105$ dB(A) for $V_h > 12$ m/s. The sound power levels in this setting are, for $6 < V_h < 12$ m/s, on average 3 dB lower than in the high power setting.
The differences between actual and logarithmically predicted sound power levels can be bigger than the over one year hourly averaged values in figure VI.14 show. This is illustrated in figure VI.15 for two days each in January and July 1987 (also shown in figure VI.3) where actual and predicted half-hour sound power levels are plotted as a function of 10-m wind velocity. On both winter days actual sound power agrees within 1 dB with the predicted sound power for wind velocities $V_{10} > 5.5$ m/s; at lower 10-m wind velocities actual levels are rather higher for most of the time. On both summer days the 10-m wind velocities are lower than in winter, and sound power level now is more often higher than predicted and can reach near maximum levels even at very low (2.5 m/s) 10-m wind velocities (when at ground level people will probably feel no wind at all). In these conditions residents in a quiet area will perceive the highest contrast: hardly or no wind induced sound in vegetation, while the turbine(s) are rotating at almost top speed. In these conditions also an increased fluctuation strength of the turbine sound will occur (see chapter V), making the sound more conspicuous.

![Figure VI.15: half-hourly progress of actual (grey diamonds) and logarithmically predicted (black dots) sound power level plotted vs. 10-m wind speed over 48 hours; left: January 13-14; right: July 2-3](image-url)
VI.6 Other onshore results

Values of wind shear have been reported by various authors, showing similar results. Pérez et al [2005] measured wind velocities up to 500 m above an 840 m altitude plateau north of Valladolid, Spain, for every hour over sixteen months. The shear exponent, calculated from the wind velocity at 40 m and 220 m, varied from 0.05 to 0.95, but was more usual between 0.1 and 0.7. High shear exponents occurred more often than in Cabauw: m > 0.48 for 50% of the time. This is likely the result of the more southern position: insolation is higher, causing bigger temperature differences between day and night, and the atmosphere above the plateau is probably drier causing less reflection of outward infrared radiation at night. There was a distinct seasonal pattern, with little day-night differences in January, and very pronounced differences in July.

Smith et al [2002] used data from wind turbine sites in the US Midwest over periods of 1.5 to 2.5 years and calculated shear exponents for wind velocities between a low altitude of 25 - 40 m and a high altitude of 40 – 123 m. At four sites the hourly averaged night time (22:00 – 6:00) shear exponent ranged from 0.26 to 0.44, in daytime from 0.09 to 0.19. The fifth station (Ft. Davis, Texas) was exceptional with a day and night time wind shear below 0.17 and a very low day time wind shear (m = 0.05).

Archer et al [2003] investigated wind velocities at 10 m and 80 m from over 1300 meteorological stations in the continental USA. No shear statistics are given, but for 10 stations the ratio V_{80}/V_{10} is plotted versus time of day. At all these stations the ratio is 1.4 ± 0.2 in most of the daytime and 2.1 ± 0.3 in most of the night time. Using equation III.4, it follows that the shear exponent has a value of 0.15 ± 0.07 and 0.35 ± 0.07, respectively.

At the 2005 Berlin Conference on Wind Turbine Noise two presentations added to these wind shear data, now (also) from a noise perspective. Harders et al [2005] showed hourly wind velocity averaged over the year 2000 at altitudes between 10 and 98 m from the Lindenberg Observatory near Berlin. The results are very much like those in figure VI.2, with a wind velocity ratio V_{80}/V_{10} = 1.3 at noon, increasing to 1.9 in night time.
hours. This corresponds to an average shear exponent of 0.13 and 0.3, respectively.

Botha [2005] presented results from 8 to 12 months measurements at sites in two flat Australian areas and two sites in more complex (non flat) New Zealand terrain. On the Australian sites the average day time wind velocity ratio $V_{80}/V_{10}$ was 1.5, in night time 1.7 and 1.8. This corresponds to shear exponents of to 0.19 and 0.26 to 0.28, respectively. In the hilly New Zealand areas the average wind velocity ratio was between 1.2 and 1.25 in day as well as night time, from which the shear exponent can be calculated as 0.1.

From the measurements at the Rhede wind farm the shear exponent could be calculated from the 10-m and 100-m wind velocity, the latter determined from the sound level and the relation between sound power level and hub height (100 m) wind velocity. This was done for all (892) five minute periods when wind turbine sound was dominant between 23:00 and 04:00 hours within the measurement period (May and June; location A in figure IV.2). From the Cabauw data the same period and time was selected and all values of the half-hour shear exponent $m_{10,80}$ were determined. For both locations the resulting frequency distributions of the shear exponent are plotted in figure VI.16. The distributions are rather similar and show that a stable atmosphere ($m > 0.25$) occurred for over 95% of the time in night time hours (23 – 4 o’clock) in spring (May – June) at Cabauw as well as at Rhede.

![Figure VI.16: frequency distribution of the shear exponent at Cabauw and in the measurement period near the Rhede wind farm in the same period of time](image)
VI.7 Conclusion

Results from various landward areas show that the shear exponent in the lower atmospheric boundary layer (< 200 m) in daytime is 0.1 to 0.2, corresponding to a wind velocity ratio $V_{80}/V_{10}$ of 1.25 to 1.5. The associated wind profile is comparable to the profile predicted by the well-known logarithmic wind profile for low roughness lengths (low vegetation).

At night the situation is quite different and in various landward areas the shear exponent has a much wider range with values up to 1, but more usually between 0.25 and 0.7. Near the Rhede wind farm the same range of wind shear occurred, showing that the site indeed was suitable to study the effect of atmospheric stability on wind turbine performance and representative for many other locations.

A shear exponent $0.25 < m < 0.7$ means that the ratio $V_{80}/V_{10}$ varies between 1.7 and 4.3. High altitude wind velocities are thus (much) higher than expected from logarithmic extrapolation of 10-m wind velocities.

A high wind shear at night is very common and must be regarded a standard feature of the night time atmosphere in the temperate zone and over land. In fact the atmosphere is neutral for only a small part (approximately 10%) of the time. For the rest it is either stable (sun down) or unstable (sun up).

As far as wind power concerns, the underestimate of high altitude night time wind velocity has been compensated somewhat by the overestimate of high altitude daytime wind velocity. This may partly explain why, until recently, atmospheric stability was not recognized as an important determinant for wind power.

To assess wind turbine electrical and sound power production the use of a neutral wind profile should be abandoned as it yields data that are not consistent with reality.