

## The Influence of Meteorological Parameters on the Operational Behavior of Multi-Megawatt WEC

Kevin Bleibler, Theo Kramkowski, Deutsches Windenergie-Institut GmbH,  
Ebertstr. 96, D-26382 Wilhelmshaven, Germany,  
phone: +49-4421-4808-98, fax: +49-4421-4808-43, [k.bleibler@dewi.de](mailto:k.bleibler@dewi.de)

Nicolai Cosack, Institut für Flugzeugbau, Stiftungslehrstuhl Windenergie (SWE), Universität Stuttgart  
Allmandring 5B, D- 70550 Stuttgart, Germany

Kurt Braun, Institut für Aerodynamik und Gasdynamik (IAG), Universität Stuttgart  
Pfaffenwaldring 2, D - 70550 Stuttgart, Germany

*This thesis evaluates the influence of meteorological parameters on the operational behavior on multi-megawatt wind turbines. Based on measurement data, the changes in operational behavior for different turbulence intensities, wind gradients and atmospheric stratification are discussed. The data indicate that higher turbulence intensities and higher wind gradients lead to improved power performance, but also to increased loads on the wind turbine. The turbulence intensity and the wind gradient are linked by the stratification. In instable atmospheric conditions the turbulence intensity is high and the wind gradient low, while in stable atmospheric conditions the wind gradient is high and the turbulence intensity low. In the analyzed data, the turbulence intensity is the most significant parameter. The changes in the power performance and loads of the wind turbine are considerable. The relevance of these operational behavior changes is discussed. The meteorological conditions offshore are completely different compared to the onshore conditions. The turbulence intensity and the wind gradient are lower offshore than onshore, which implies lower power performance and loads onshore for than the same wind turbine on an onshore site has*

### 1 Introduction

Wind Energy has developed very fast in the last decade. Modern wind turbines size and power output were hardly imaginable only a few years ago. The next step in wind turbine development is large scale offshore installation. It is known that at sea very different meteorological conditions can be expected, compared to onshore. However, the exact influence of meteorological parameters on the wind turbine is not clear. This essay shows the influences of the most important meteorological parameters based on measured data of a North German onshore site /1/.

All figures shown are based on measured data. The measured 10 Minutes mean values of the campaign have been bin averaged for this essay.

### 2 Metrological Parameters

#### 2.1 Turbulence

In wind energy, the turbulence is evaluated by the turbulence intensity. The turbulence intensity is calculated by dividing the standard deviation of a 10 minute wind speed measurement by the mean wind speed:

$$tu = \frac{\sigma_0 \text{ (standard deviation)}}{v_0 \text{ (mean wind speed)}} \quad \text{Formula 1}$$

#### 2.2 Wind gradient

In this essay, a (relative) wind gradient is defined to classify the wind profile. The wind gradient describes the increase of the wind speed with height according to the following formula:

$$v_g = \frac{v_1 - v_2}{h_1 - h_2} \cdot \frac{1}{2} * (v_1 + v_2) \quad \text{Formula 2}$$

with:  $v_1$  = upper wind speed  
 $v_2$  = lower wind speed  
 $h_1$  = height of  $v_1$  above ground  
 $h_2$  = height of  $v_2$  above ground

Figure 1 demonstrates the change in the wind gradient with a changing wind profile:

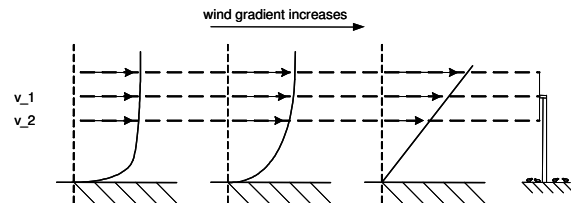


Fig. 1 Different wind gradient

#### 2.3 Atmospheric stratification

Solar irradiation heats air near the ground more than air in upper layers, so the air begins to ascend. But with increasing height the air pressure decreases, so that the air cools down again. This causes, that the air only ascends until the temperature difference is equalized by the decreasing air pressure and the resulting temperature decrease. A distinctive parameter to classify the current atmospheric stratification is the potential temperature difference of two heights. The potential temperature is defined according to the following formula /2/:

$$\Theta = (273,15 \text{ K} + T) * \left( \frac{p_n}{p} \right)^{\left( \frac{R}{c_p} \right)} \quad \text{Formula 3}$$

with:  $T$  = temperature (in K)  
 $p_n$  = reference air pressure (= 1013hPa)  
 $p$  = air pressure (in hPa)  
 $R$  = specific gas constant of air  
 (=287,05 J/kgK)  
 $c_b$  = specific thermal coefficient of air  
 (=105 J/K)

At a constant potential temperature constant versus height, there is no vertical wind flow without excitation. The atmospheric stratification is neutral. When the potential temperature at ground level is higher than in upper layers, the air near the ground ascends and the air in upper layers descends. The atmospheric stratification is instable: vertical wind flows like turbulences are intensified. A stable atmospheric stratification is inverse: the potential temperature is higher in upper layers than near the ground, vertical wind flow is jammed. For this essay the atmospheric stratification is classified as follows (derived from temperature sensors in hub height and near the ground):

- Instable atmospheric stratification:*  $\Delta\Theta < -0,5K$
- Neutral atmospheric stratification:*  $-0,5K < \Delta\Theta < 0,5K$
- Stable atmospheric stratification:*  $0,5K < \Delta\Theta < 2,5K$
- Very stable atmospheric stratification:*  $\Delta\Theta > 2,5K$

2.4 Dependence of the metrological parameters  
 As described before, with increasing stability of the atmospheric stratification turbulence is more and more inhibited and the turbulence intensity decreases. Figure 2 shows this with the turbulence intensity in three heights plotted versus the potential temperature difference.

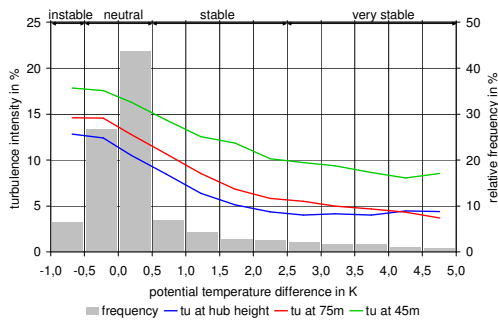


Fig. 2 Turbulence intensity over potential temperature difference

The wind gradient on the other hand increases with higher stability of the stratification (see figure 3 and 4). In a stable stratification with no vertical flow a nearly linear wind profile develops. In very stable stratifications the wind gradient decreases again. Figure 3 shows the relative wind profile based on wind speed at 45m, figure 4 shows three wind gradients over the potential temperature difference.

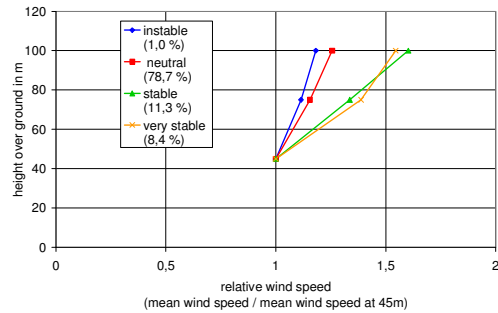


Fig. 3 Wind profile at different stratifications

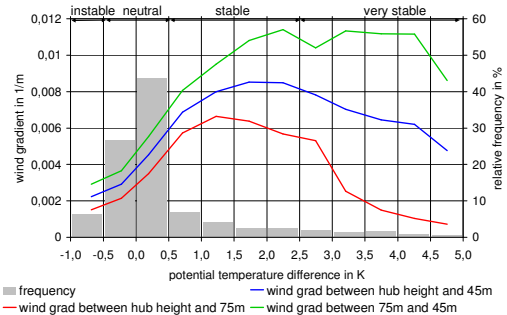


Fig. 4 Wind gradient over potential temperature difference

From this it follows, that a high turbulence comes along with a low wind gradient and in a stable stratification a high wind gradient comes along with low turbulence. In a very stable stratification a low turbulence and a low wind gradient can be found (see figure 5).

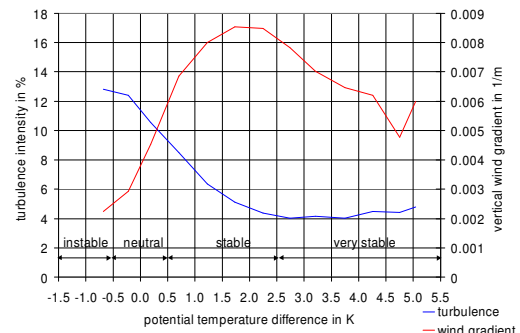


Fig. 5 Turbulence and wind gradient over potential temperature difference

### 3 Influence of the meteorological parameter on the operational behavior

#### 3.1 Influence of the turbulence on power performance

With increasing turbulence an increased power performance up to rated power can be expected (see figure 6 and 7). As long as the slope of the power curve is increasing, higher turbulence always leads to a better power performance. Near rated power, when the slope of the power curve decreases this behavior is inverted. The reason for this

behavior can be seen in the formula to calculate the electrical power P:

$$P = \frac{1}{2} \rho A c_p v^3 \quad \text{Formula 4}$$

with:  $\rho$  = air density  
 $A$  = rotor plane  
 $c_p$  = power coefficients  
 $v$  = wind speed

The electrical power depends on the wind speed cubed. Because of this non linear connection, a positive wind fluctuation around the mean value of the 10 min measurement period leads to a higher power increase, as an equal sized negative wind fluctuation leads to a decrease of power (see figure 8) /3/.

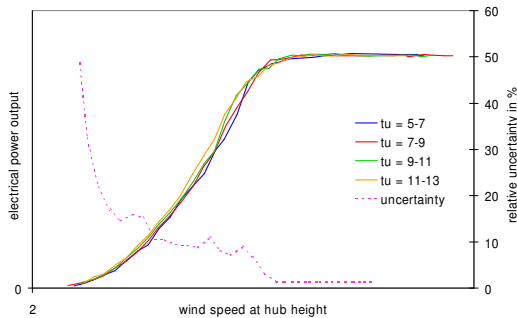


Fig. 6 Power performance at different turbulence intensities

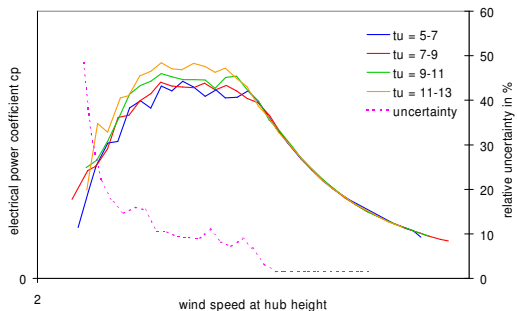


Fig. 7 Power coefficient at different turbulence intensities

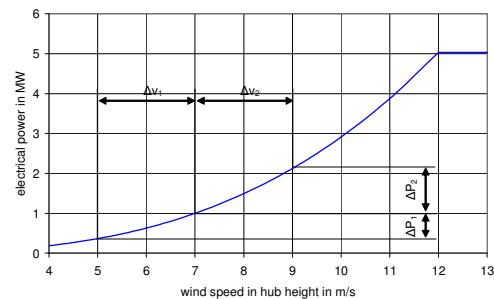


Fig. 8 Wind speed fluctuations and corresponding power fluctuations (theoretical power curve)

3.2 Influence of the turbulence on loads  
 With increasing turbulence, the fatigue loads of the turbine increase severe. At high turbulence the wind speed and the related thrust T change permanently causing increased fatigue loads of the wind turbine components (see figure 9).

$$T = \frac{1}{2} \rho c_t A v^2 \quad \text{Formula 5}$$

with:  $\rho$  = air density  
 $A$  = rotor plane  
 $c_t$  = thrust coefficient  
 $v$  = wind speed

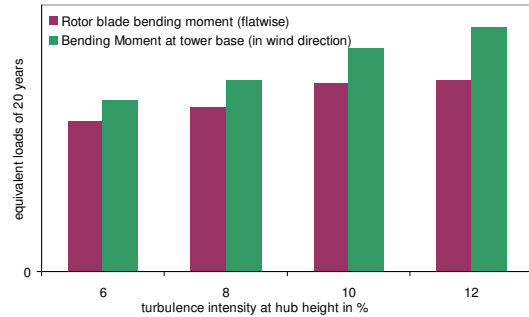


Fig. 9 Fatigue loads for different turbulence intensities (wind gradient = 0.0025 – 0.0035<sup>1</sup>/m)

3.3 Influence of the wind gradient on power performance

For increasing wind gradients, also a better power performance will be achieved (see figure 10). Currently the wind speed is measured at hub height only, but with higher wind gradients the wind profile becomes more linear resulting in a higher wind speed averaged ( $v_{eff}$ ) over the rotor plane (see figure 11). Additional, high wind gradients also increase power performance because of  $P \sim v^3$ .

*Note: Database for wind gradient evaluation has been small.*

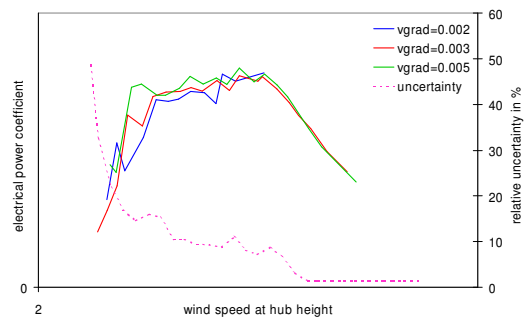


Fig. 10 Power coefficient at different wind gradients (turbulence intensity = 7 – 9%)

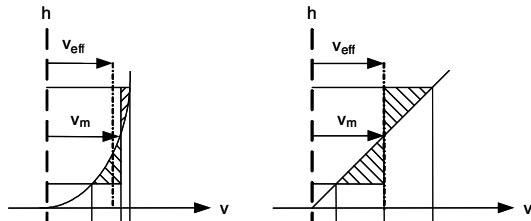


Fig. 11 Wind speeds on wind turbine with different wind gradients

**3.4 Influence of the wind gradient on loads**  
 With higher wind gradients the wind speed differences and the resulting blade bendings during one rotation increase resulting in higher fatigue loads (see figure 11 - it's not clear why the fatigue loads decrease at the highest wind gradient). The wind gradient has no effect on the fatigue loads of the tower (they even decrease, because of the lower turbulence).

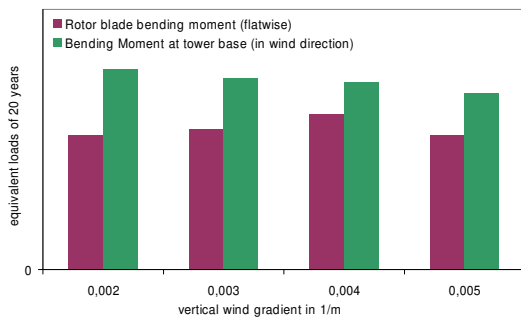


Fig. 12 Fatigue loads for different wind gradients (turbulence intensity = 7 – 9%)

**3.5 Influence of the stratification on power performance**  
 As expected the influences of the turbulence and the wind gradient crosstalk in neutral and stable stratifications. So there is no clear influence. But in very stable conditions, with low turbulence and low wind speed a decreased power performance can be found (see figure 13).

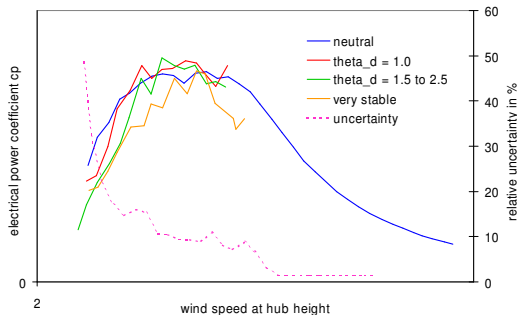


Fig. 13 Power coefficient at different stratifications

*Note: The database for the very stable stratification has been very small. The absolute values may not be correct, but the trend is.*

**3.6 Influence of the stratification on loads**  
 The fatigue loads decrease with higher stability of the stratification, which leads to the conclusion, that the turbulence is the most significant parameter for loads (see figure 14). It's not clear why the loads increase in very stable conditions (database is also very small).

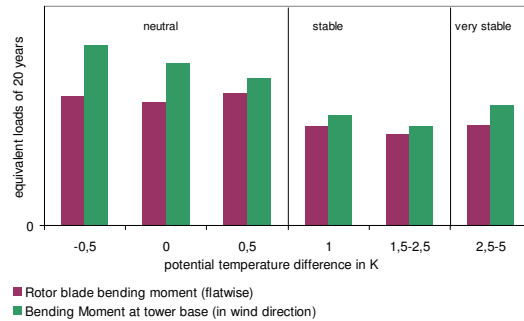


Fig. 14 Fatigue loads for different stratifications

#### 4 Comparison of the meteorological parameters onshore and offshore

Finally a (non representative) comparison of the used meteorological parameters for an onshore and an offshore site is done. Facts of the sites:

Onshore:

- average North German coastal site
- mean wind speed: 6,6m/s (measured, long term mean wind speed: 7,8m/s)
- hub height: 100m
- 2 month summer measurement campaign

Offshore:

- offshore sea station Fino 1 (about 45km distance to coast)
- mean wind speed:12,4m/s
- estimated hub height 90m
- 2 years measurement campaign

##### 1. Wind speed at hub height.

Figure 15 shows that the wind speed is much higher offshore than onshore. A wind turbine would operate most of time at rated power.

##### 2. Turbulence and wind gradient.

Both plotted versus the potential temperature difference in figure 16. The turbulence and the wind gradient are offshore significantly lower than onshore. This suggests that offshore a decreased power performance must be expected.

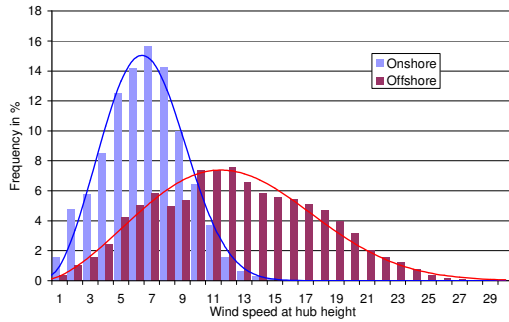


Fig. 15 Wind speed distributions onshore and offshore compared

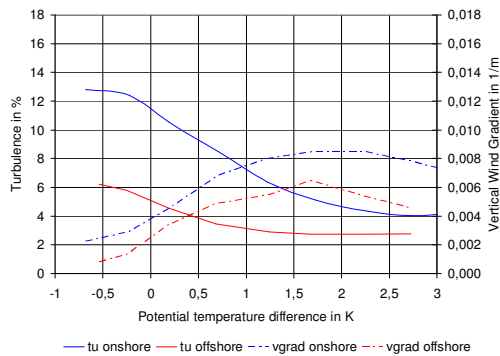


Fig. 16 Turbulence and wind gradient onshore and offshore compared versus potential temperature difference

*Note: The data onshore and offshore are neither from the same time period nor from the same wind direction, so the absolute values are not correct, but again the trends are.*

## 5 Conclusion

Turbulence has a strong influence on the operational behavior of wind turbines: power performance and loads increase significantly with increasing turbulence.

The wind gradient has minor influence on the operational behavior of wind turbines, but power performance and loads also increase with higher wind gradients.

The turbulence and the wind gradient are connected by the atmospheric stratification. A high turbulence comes along with a low wind gradient and vice versa. The absolute values of both parameters depend on the site.

Offshore very different meteorological conditions can be expected with less turbulence and a smaller wind gradient, which will decrease power performance. This effect will however be masked by the favorable wind conditions.

/1/ Bleibler, Kevin; Untersuchung der meteorologischen Einflüsse auf das Leistungs- und Lastverhalten des Prototypen der Multibrid M5000 Windenergieanlage; Diplomarbeit am Institut für Aerodynamik und Gasdynamik, Stuttgart, 2006

/2/ Strack, Martin; Albers, Axel: Analyse und Extrapolation des Windprofiles am 130 Meter Messmast des DEWI; DEWI Magazin Nr. 8; Wilhelmshaven, Februar, 1996

/3/ Albers, Axel; Hinsch, Christian: Abhängigkeit des Leistungsverhalten großer Windenergieanlagen von verschiedenen meteorologischen Parametern; DEWI Magazin Nr. 9; Wilhelmshaven, August, 1996