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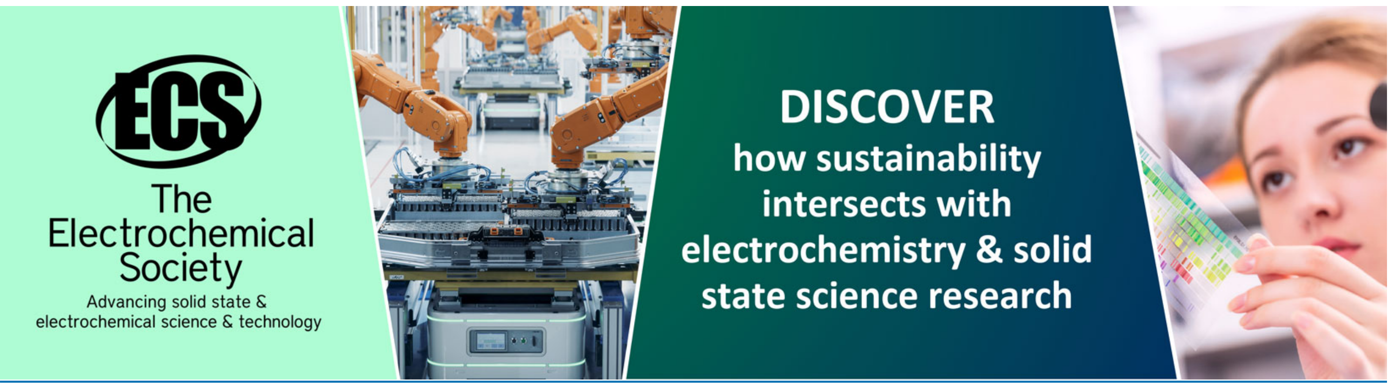

# Atmospheric Impacts on Power Curves of Multi-Megawatt Offshore Wind Turbines

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**Abstract.** Power curves for offshore wind turbines within the German offshore wind farm *alpha ventus* were derived based on the IEC standard. Binning in groups of shear and turbulence intensity as measures of atmospheric stability were performed. The derived power curves show a strong dependency on these two parameters. Differences of up to 15 % in power output between unstable and stable stratification in the non-wake case occur. For wind turbines within the wake of others the effects are even more pronounced. Here, the differences in power production between the stability classes approach 20 %. This dependency of the power curves on stability can cause significant miscalculations of instantaneous power production, long-term energy yield and loads. Parameters other than the hub height wind speed are often not taken into account in state-of-the-art wind power forecasts. This can lead to substantial over- or underestimation of the resulting power.

## 1. Introduction

Europe's wind energy capacity is expected to grow up to a total of 400 GW in 2030 of which more than one third (150 GW) is expected to be located offshore [1]. Most of the projects are concentrated in rather small regions, resulting in a high density of wind farms, mainly in the Southern North Sea. Thus, variations in the atmospheric conditions are very important.

The IEC standard for the derivation of power curves [2] is based on a single point wind speed measurements in a distance of 2-4 rotor diameters (D) upstream of the wind turbine. A measurement of atmospheric stability and related parameters is not part of the procedure.
The dependency of power performance on atmospheric stability for onshore wind turbines has been studied before (eg. [3],[4],[5],[6],[7]). Albers et al. [3] found that increasing turbulence intensity (TI) leads to higher power coefficients below rated power; in the transition region to rated power, lower power coefficients were observed with increasing TI. Moreover, they found a decreasing power coefficient with increasing wind shear (SH). Wharton et al. [7] found average power output differences between stable and unstable stratification of up to 20 %. They investigated a subset of six turbines of a North American onshore wind farm. The differences for single turbines of this subset ranged from 10 % - 20 %.

For offshore wind turbines the influence of atmospheric stability on power curves of wind turbines has hardly been investigated. To our knowledge, this is the first paper following a systematic way of investigating first the non-wake and then single- and double-wake situations.

### *1.1. Alpha Ventus Wind Farm*

Within the RAVE-OWEA (Verification of offshore wind turbines) project we examined the influence of different parameters as shear and turbulence intensity on the power output of wind turbines in the offshore wind farm *alpha ventus*. The wind farm *alpha ventus* is located about 45 km north of the westernmost German island Borkum in the North Sea. It consists of twelve - 5 MW wind turbines (see Fig. 1). A 103 m met mast (FINO 1) is located west of the AV04 wind turbine. There, important meteorological variables are measured in different heights up to 100 m. For our investigations the SCADA data of the two northernmost rows within the wind farm (AV01-AV06) were available. These variable-speed turbines are of the same type with a hub height of 93 m and a rotor diameter of 126 m (1 D).
The location of the FINO1 met mast allows studying the undisturbed inflow into the wind farm for a westerly wind sector (prevailing wind direction). The distance of the met mast (3.2 D) to the wind turbine AV04 enables the calculation of the power curve as described in the IEC standard [2] for westerly winds.

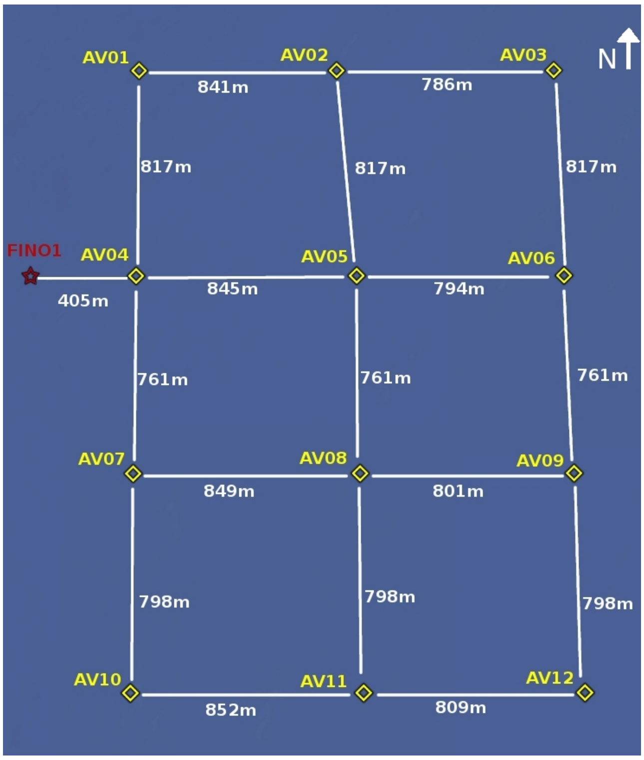


**Figure 1.** Map of the alpha ventus wind farm

## 2. Methodology

The power data of the wind turbine (1 min averages) from the SCADA-system of the wind farm were combined with the wind speed measurements at the FINO1 met mast. To take the time delay between the wind and the power measurement into account, the authors suggested the following formula to calculate the wind speed dependent delay between the two locations, assuming Taylor's hypothesis.

$$t_{del} = \sum_{i=1}^{3} \frac{L_i}{c^{(i-1)} V_{90,FINO}} \tag{1}$$

with: $L_i$ distance of the met mast to the turbine ($L_1 = 405$ m) or in between the turbines (wake case) ($L_2 = 845$ m respectively $L_3 = 794$ m), $V_{90,FINO}$ the wind speed in a height of 90 m and $c$ is a constant (0.8) indicating the wind speed deficit.

Power curves from one year time series were derived afterwards, following the IEC standard [2]. The data was filtered for westerly winds (262° ± 8°). This way, clear single and double wake cases for the turbines (AV05, AV06 resp. AV02, AV03) within the wind farm were ensured and mast shadow effects impacting the wind speed measurements at FINO1 were excluded. The cup anemometer measurements at 90 m height were used as hub height wind speeds (92 m). A density correction was performed using the (height corrected) 20 m pressure measurement and the 70 m air temperature measurement. Dry air was assumed as deviations between dry and humid air density for temperatures below 25° C are negligible [2].

Power values >250 kW ( 1/20 of rated power) were used as lower accepted boundary, to ensure that the turbines were feeding into the transmission grid. Due to non-disclosure reasons the power curves were normalized with arbitrary wind speed and power values or another power curve. Afterwards a binning of the power curves into groups of turbulence intensity (eqn. 2) and shear (eqn. 3) (hub height wind speed divided by lower blade tip wind speed) was performed.

$$TI = \frac{\sigma_{V90}}{V_{90}} \tag{2}$$

$$SH = \frac{V_{90}}{V_{40}} \tag{3}$$

with: $V_{40}, V_{90}$=cup anemometer measurement in 40 m resp. 90 m height, $\sigma_{V90}$= standard deviation of the cup anemometer measurement in 90 m height.

Atmospheric stability is commonly defined by the Monin-Obukhov similarity theory. An often used stability parameter is the Obhukov length $L$, indicating a height at which buoyant production of turbulent kinetic energy is balanced with the turbulence production of the wind (shear) [8]. Tambke et al. (2006) [9] showed that the Obukhov length $L$ is strongly connected to shear and that shear can be used as a measure of atmospheric stability at the FINO1 met mast. A stably stratified atmosphere comes along with strong shear and a low turbulence intensity. Turbulence is suppressed by a stable stratification of the atmosphere.

## 3. Results

Fig. 2 shows the relation between TI and shear based on the FINO1 measurements. A westerly flow (262° ± 20°) was investigated. Shear was binned in groups of 0.1 SH. The errorbars were defined by one standard deviation. The figure indicates that there is an inverse connection between turbulence intensity and shear. The error bars are particularly large in the high shear situation, which is mainly an effect of a low number of measurements with a shear greater than 1.4. Based on histograms of TI and SH, classes were defined, representing three groups of atmospheric stratification (stable, neutral, unstable) (see Table 1). These groups are used for further systematic investigation of power curves.

### *3.1. Wind Farm Efficiency*

Fig. 3 shows the dependency of the wind farm efficiency (AV01-AV06) on shear (red) and turbulence intensity (blue) for westerly winds (262° ± 20°). The wind farm efficiency was calculated as the sum of the power output of all six turbines divided by six times the power output of a reference turbine. Afterwards, the efficiency was normalized by subtraction of the

**Table 1.** Groups of atmospheric stratification

| Stratification | Shear (SH) | Turbulence Intensity (TI) |
|---|---|---|
| stable (st) | $SH > 1.14$ | $TI < 3\%$ |
| neutral (ne) | $1.04 < SH < 1.14$ | $4.5\% > TI > 3\%$ |
| unstable (us) | $SH < 1.04$ | $TI > 4.5\%$ |

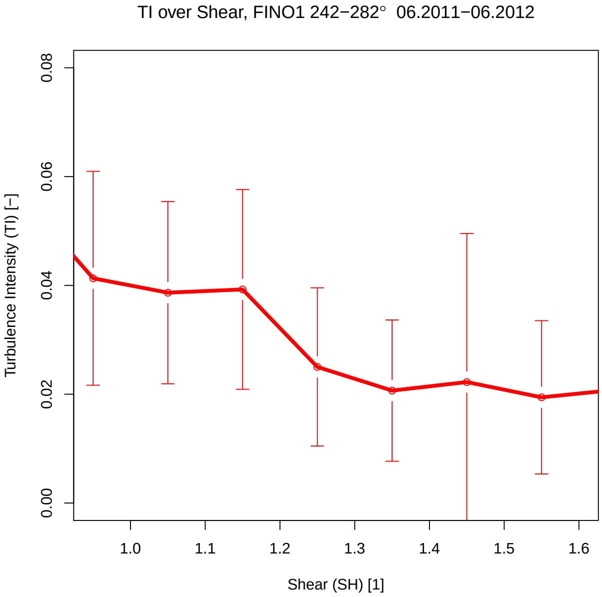


**Figure 2.** Dependency of shear on ambient turbulence intensity for a westerly flow ($262 \pm 20°$), period: June 2011 - June 2012

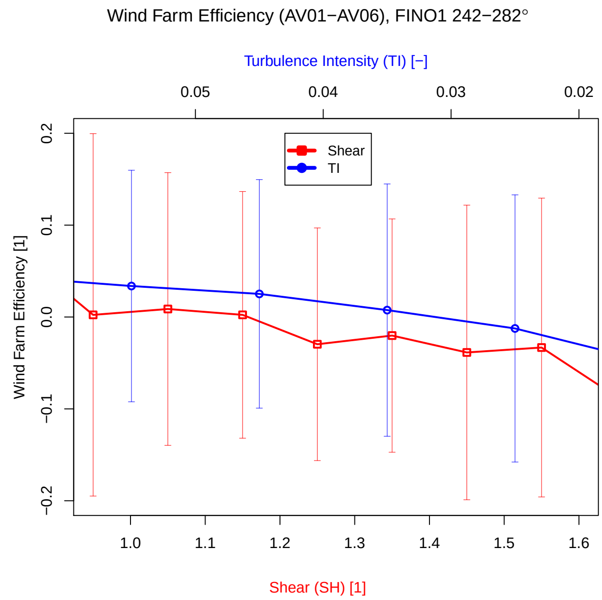


**Figure 3.** Dependency of wind farm efficiency on shear and turbulence intensity, June 2011 - June 2012, westerly winds ($262 \pm 20°$)

mean wind farm efficiency. Wind turbine AV04 was chosen as reference wind turbine. This turbine is for a westerly wind sector in a non-wake situation and directly downstream of the FINO1 measurement location, from which turbulence intensity and shear were derived.

Fig. 3 indicates that wind farm efficiency is influenced by atmospheric stratification. A difference up to 10 % in between highest/lowest SH was found. The error bars on both turbulence intensity as well as shear are large, even though the trend towards lower wind farm efficiencies for increasing shear and decreasing turbulence intensity ( i.e. increasing atmospheric stability) is distinct. This effect was reported in several other studies (e.g. [10]).

In the following subsections the influence of TI and SH on power curves is studied based on a systematic investigation of a non-wake case, followed by single- and double-wake situations.

### *3.2. Non-Wake Case*

Fig. 4 and 5 show a non-wake situation for the wind turbine AV04 for westerly winds. AV04 is situated approximately 3.2 D downstream of the FINO1 met mast. The figure is non-dimensionalised with the IEC [2] power curve for AV04.

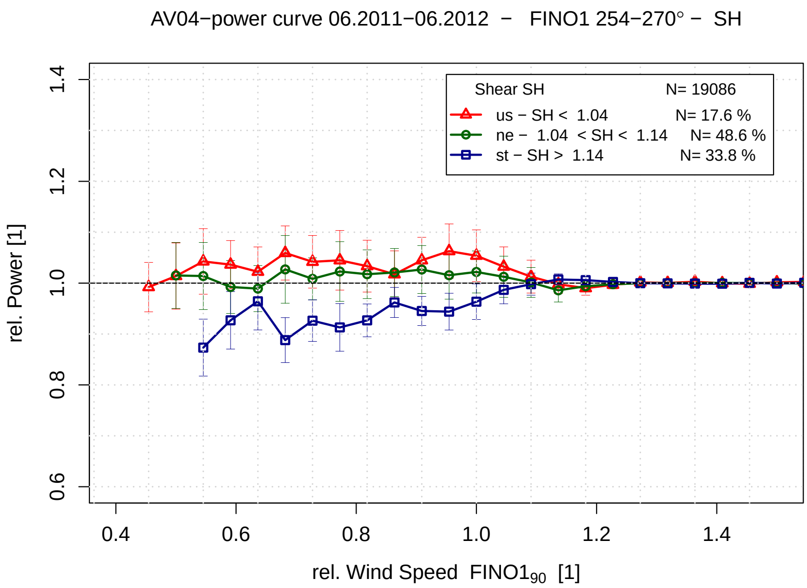


**Figure 4.** Dimensionless non-wake power curve for groups of SH, June 2011-June 2012, westerly winds (262 ± 8°), *us=unstable, ne=neutral, st=stable, N=Number of measured intervals/percentage*

A clear dependency of the power output on stratification is found. The power curves for the three shear regimes show the maximum difference between the classes in the intermediate range of wind speeds (where the steepest slope can be found). Here, the difference in power between stable and unstable stratification exceeds 15 %, when grouped by shear. In a stable stratified atmosphere less energy is harvested than during neutral or unstable stratification. One reason is likely that the slope of the wind speed profile above the hub (not measured at FINO1) is less steep than below the hub, resulting in a more constant wind speed over the entire rotor disk. The difference between the power curves grouped by shear is even more pronounced (Fig. 5). All stability groups are clearly distinguishable, with a maximum difference of up to 20 %. In the transition region to rated power (relative wind speed ≈ 1.2) the effect inverts. Here more power

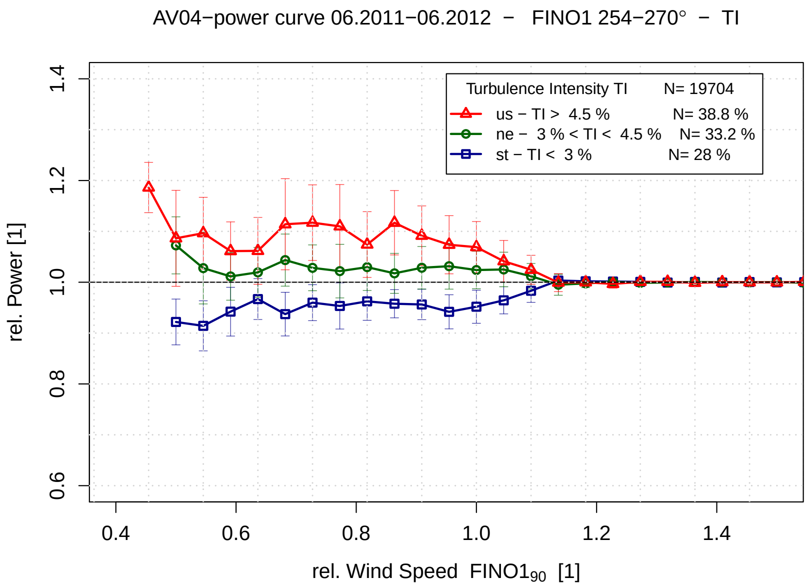


**Figure 5.** Dimensionless non-wake power curve for groups of TI, June 2011-June 2012, westerly winds (262 ± 8°), *us=unstable, ne=neutral, st=stable, N=Number of measured intervals/percentage*

is harvested during stable stratification even though the effect is small (<1 %). This result is in line with the findings of Wharton et al. [7]. For very low wind speeds (relative wind speed ≈ 0.5) an increase in the power difference between the TI classes is found. This effect might emerge from the averaging of the power data. In a turbulent atmosphere the turbine exceeds the cut-in wind speed more often for a given mean value than in a low turbulent case. We are aware of the uncertainties in this region of the power curves due to its hysteresis behaviour. Further investigations are needed to confirm this assumption.

### *3.3. Single-Wake Case*

Fig. 6 and 7 show a single-wake situation. Here, the power output of turbine AV05 was divided by the power output of AV04 which is located 6.7 D upstream of AV05. This way a dimensionless relative power ($P_r$) was derived and power curves of this quantity were calculated according to the method described above.

The relative power deficit (1 - $P_r$) ranges between 25-40 % for a wide wind speed range. As in the non-wake case, the lowest power is harvested for a stably stratified atmosphere. In the shear case, the maximum difference (20 %) occurs for a relative wind speed of about 1.1. This is of special importance, since this is a frequently occurring wind speed range measured at the wind farm.

When classifying the power curves by TI it is particularly noticeable that the maximum difference between the classes is smaller than for SH. However, for a wide range of wind speeds the difference between the TI classes is constant but opposite to the SH behaviour. Between the class of highest (TI>4.5 %) and lowest TI (TI<3 %), 10-15 % difference in power output are measured. In the non-wake case (see above) the power curves for stable and unstable stratification intersect in the region close to rated power, with an increased power output for stable stratification. This intersection of the power curves does not exist in the single-wake case. The power curves for unstable stratification are above the others for a wide range of wind speeds. The strong dependency of the power curves on TI (atmospheric stability) can be explained as follows: In a stable stratified atmosphere the lack of ambient (inflow) atmospheric turbulence hinders the mixing of the wake with the surrounding air. This way, a subsequent wind turbine receives a more persistent wake, hence resulting in a decreased power output as a result.

A very high relative power is found for very low wind speeds and high turbulence intensities. As mentioned before, this region is marked by great uncertainty and needs to be studied in detail in further studies.

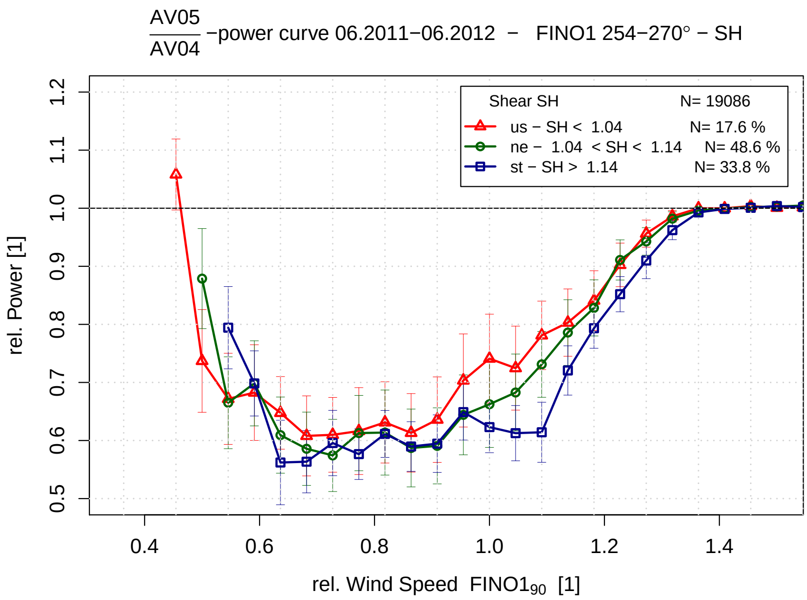


**Figure 6.** Dimensionless single-wake power curve for groups of SH, June 2011-June 2012, westerly winds (262 ± 8°), *us=unstable, ne=neutral, st=stable, N=Number of measured intervals/percentage*

### *3.4. Double-Wake Case*

A double-wake situation is presented in Fig. 8 and 9. Here, the power output of the third turbine (AV06) (downwind of FINO1) is divided by the output of the second turbine (AV05). During a range of low wind speeds (0.4-0.9 rel. wind speed) a relative power >1 is observed, which means that the turbine harvests more energy than the turbine directly upstream of it. The effect of stratification is less pronounced, the classified power curves even overlap.

One reason for the high relative power at low wind speeds might be a faster recovery of the wake deficit in the third row due to higher TI than in the second row. The inflow of turbine AV06 is greatly affected by the two turbines upstream, which both create turbulence of a larger magnitude than the ambient atmospheric turbulence intensity [11]. This way the turbulence intensity at the turbine AV06 largely exceeds the ambient TI level. This causes a strong mixing process with surrounding (undisturbed) air and thus a faster recovery of the wake. During low wind speed conditions, the mixing process has more time to recover the wake than in a high wind speed situation. With the help of Large-Eddy simulations (LES) we are currently investigating if this assumption holds.

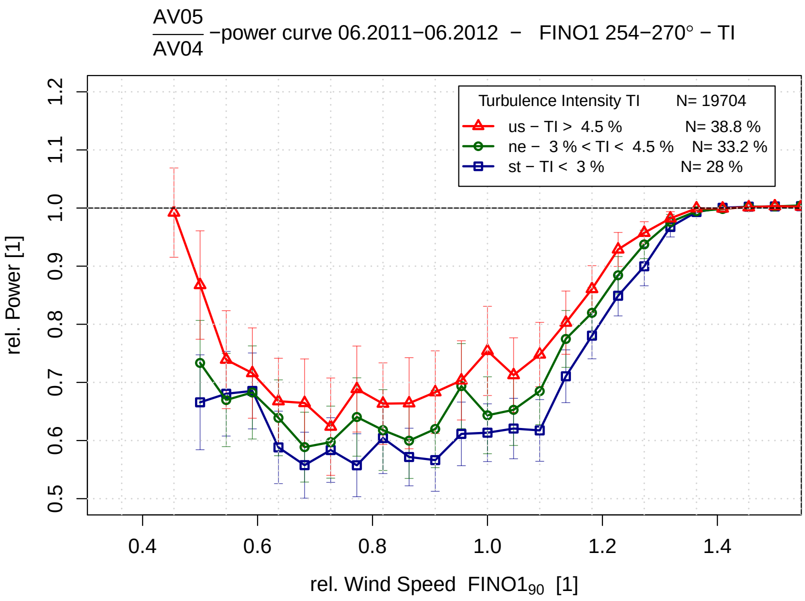


**Figure 7.** Dimensionless single-wake power curve for groups of TI, June 2011-June 2012, westerly winds ($262 \pm 8°$), *us=unstable, ne=neutral, st=stable, N=Number of measured intervals/percentage*

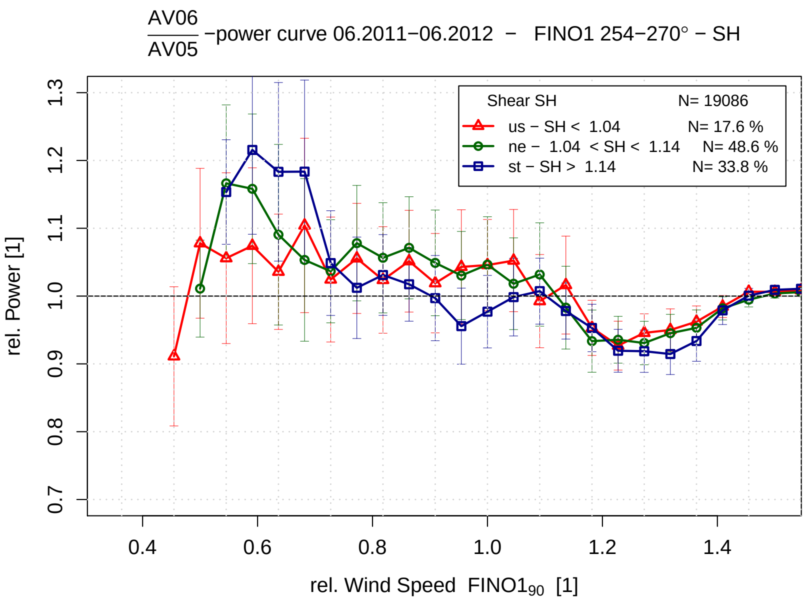


**Figure 8.** Dimensionless double-wake power curve for groups of SH, June 2011-June 2012, westerly winds ($262 \pm 8°$), *us=unstable, ne=neutral, st=stable, N=Number of measured intervals/percentage*

## 4. Conclusions

We studied the influence of atmospheric stratification, identified by shear and turbulence intensity, on power curves of offshore wind turbines. For our investigations we were able to evaluate

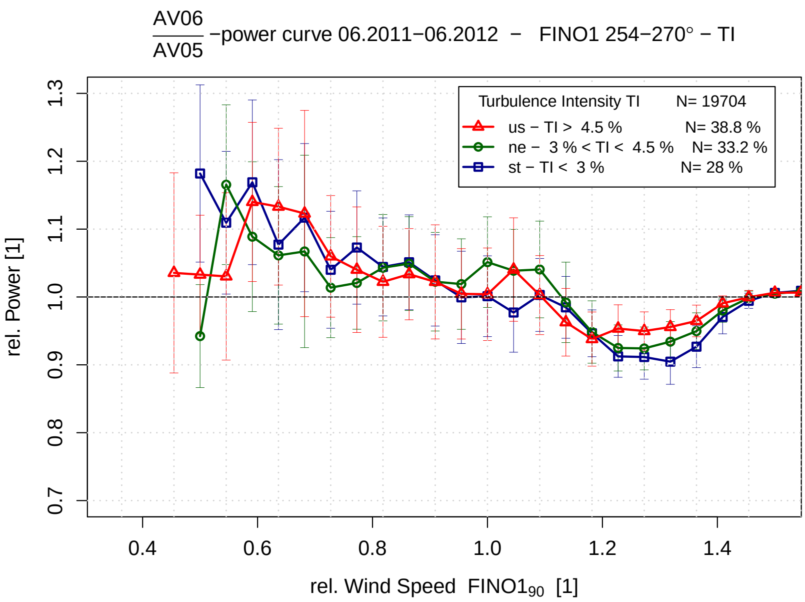


**Figure 9.** Dimensionless double-wake power curve for groups of TI, June 2011 - June 2012, westerly winds (262 $\pm$ 8°), *us=unstable, ne=neutral, st=stable, N=Number of measured intervals/percentage*

the SCADA data of the northernmost six wind turbines of the *alpha ventus* wind farm only. Within this paper we show results from the second row of the wind farm. In the same way as described here, the first row of the wind farm was investigated as well, leading to very similar results.

In a systematic way we first considered a non-wake case, followed by a single-wake situation and a double-wake situation. The power curves show a rather large dependency on the stability of the atmosphere. In the non-wake case, up to 20 % difference in between unstable and stable stratification are observed. In the single-wake case the differences are in the order of magnitude, with a clear distinction of the power curves when stratified by TI. In both cases more power was harvested under unstable stratification than in the stable case. In the double wake case a clear distinction between classes of stability is not possible. The power curves show on average a larger influence on the TI than on the SH, whilst maximum differences are in the same order of magnitude.

All power curves show rather large error bars especially for wind speeds lower than rated power. This error could be reduced in the future by increasing the dataset. It is worthwhile to mention here that all data-points (of the power curves) investigated were calculated based on a larger number of values than suggested as minimum by the IEC norm for power curves [2].

Our results show a substantial impact of atmospheric stratification on the power output of offshore wind turbines. Very often only a neutral stratification is considered in wind power forecasts and wind farm siting.

In the future we want to include the southern part of the wind farm into the analysis, where six 5 MW turbines of another wind turbine manufacturer are situated. Additionally, we plan to investigate the influence of stratification on other wind turbines in other offshore wind farms. These results shall show if there are dependencies on the wind turbine size, the offshore location (other sites with different atmospheric stratifications) as well as on the size and pattern of the wind farm.

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