FLOW Final Report

Project title : **DUWIND's far offshore wind farm design**

WP 1: Far Shore Wind Climate Modeling

1. Project Summary

Offshore atmospheric conditions are expected to be favourable for wind energy purposes, however due to the distance and expenses involved in offshore atmospheric measurement campaigns, little is known about actual atmospheric conditions far offshore. To optimize wind turbine design and improve wind turbine performance far offshore, there is an urgent need to understand offshore atmospheric conditions. This should not only contribute to optimization of wind turbine design, but it should also result in a reduction in the uncertainty of atmospheric conditions that wind turbines experience in their lifetime. As such, improving our understanding of far offshore atmospheric conditions contributes to increasing the economic competitiveness of offshore wind energy.
In this PhD research project, theory is combined (and validated where needed) with observation data to obtain a physical description of the offshore atmosphere. Besides, based on numerical simulations with state of the art wind turbine design simulation software, the influence of the obtained atmospheric conditions on wind turbine performance is studied. In scope of the academic nature of the research, a reference wind turbine (5MW, 90m hub height and 126m rotor diameter) is used for simulations to compare results. Although the offshore atmosphere has a profound interaction with the sea surface, hydrodynamic loads are not considered explicitly to obtain fundamental knowledge on the interaction between wind conditions and wind turbine performance.

In the first part of the research meteorological conditions are studied in detail. It is found that scaling theories that are commonly used to describe the onshore atmosphere are also valid offshore. Besides, atmospheric conditions most important for wind turbine purposes (i.e., wind shear and turbulence characteristics) are found to be dependent upon atmospheric stability, in contrary to the assumption sometimes used that the offshore environment is neutral stratified. A more elaborate research on wind shear profiles has been executed, and we have obtained a wind shear profile not only valid in the lowest 100m of the atmosphere, but for the entire atmospheric boundary layer. This is expected to be a useful addition in scope of the size of state of the art wind turbines. Besides extending simple shear models up to the top of the boundary layer, also the occurrence of so called low-level jets offshore has been studied. Low-level jets are typical wind shear profiles where a local wind maximum is observed relatively close to the surface, say in the lowest 300m of the atmosphere. It is found that indeed low-level jets occur offshore as well, up to once or twice every three days depending on the criteria you set to detect a low-level jet (see Figure 1 for an overview). Though jets occur on numerous days throughout the year, they are found to persist for fairly short times (less than an hour typically), hence the influence on lifetime power production of single wind turbines is likely limited. The observed jets are found to have maximum wind speeds indeed in the lowest 200m of the atmosphere, with maximum wind speeds up to 20 m/s. Clearly these jets are of significance for wind energy purposes. As such, it has been decided to define an empirical low-level jet wind shear profile that allows to assess the influence of low-level jets on wind turbine performance.

In a second part of the research, the influence of the specified far offshore atmospheric conditions on wind turbine performance has been studied. It is found that if one incorporates the proposed atmospheric scaling theories in wind turbine design, simulated fatigue loads of the reference turbine considered reduce by up to 30% (Figure 2). The overestimation of lifetime fatigue loads found when using empirical relations to prescribe wind shear and turbulence characteristics is not necessarily caused by statistical incorrect shear and turbulence relations. Instead, it is found that wind shear and turbulence are coupled and both dependent upon atmospheric stability (Figure 3). In guidelines however this coupling is typically not included. Since hydrodynamic loads are not considered in this

study, lifetime fatigue loads in actual conditions are expected to reduce less than 30%. The boundary layer wind profile that has been derived has also been put into perspective of wind turbine performance. Results have been compared to using simple surface layer wind profiles. For both wind profiles, it is found that wind shear causes a decrease in wind turbine power production. When using the boundary layer wind shear profile, which is found to be a more accurate description of reality, wind turbine power production decreases most when the atmosphere is stable stratified. At the same

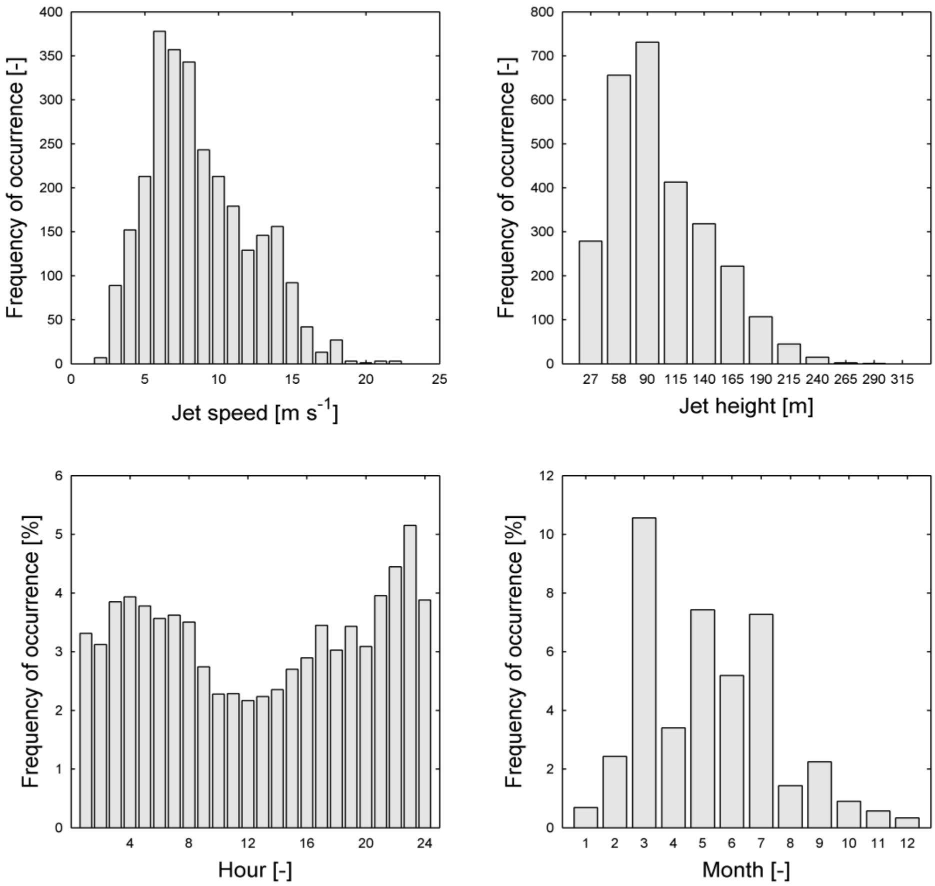

Figure 1: observed jet characteristics, in terms of jet speed (upper left), jet height (upper right) and time of occurrence (during the day, lower left, and during the year, lower right).

time however, blade root fatigue loads also reduce, which could be beneficial for wind turbine design. Next, it is recognised that low-level jets might have a severe impact on wind turbine performance. As such, with the proposed low-level jet model we have assessed the dependence of wind turbine power production and blade root fatigue loads as a function of low-level jet characteristics. It is found that especially the height where the wind maximum of the jet profile occurs is of importance, and typically both power production as well as blade root fatigue loads decrease if a jet occurs exactly at hub height. Lastly, it has been decided to further study turbulence characteristics, and specifically the impact of specific turbulence scales on wind turbine performance. With aid of a spectral filter, turbulent wind fields have been filter in such a way that only coherent structures of specific used-defined scales remained in wind turbine simulations. With aid of subsequent simulations, it has been found that especially turbulent kinetic energy is of great importance for wind turbine performance. First and foremost, a wind turbine is able to convert the mean wind into power, but also energy contained in turbulent motions. This can lead to power production increases up to 10%. At the same time it is found that neither large, not small scale structures influence wind turbine performance.

All combined results not only contribute to enhancing our knowledge of far offshore atmospheric conditions, but we also placed obtained results in perspective of wind turbine performance. As a final step the obtained results are put into perspective of reducing the cost of (far) offshore wind energy. Although we have assessed in detail the influence of accurate wind descriptions on wind turbine power production and wind turbine fatigue loads, the subsequent influence on the cost reduction of offshore wind is highly uncertain. As such we refrain from quantifying in detail the cost reduction, and only consider a potential change in the rate of equity due to increased certainty in lifetime wind farm conditions. Based on a cost model provided in scope of the FLOW research project it is estimated that a change in the rate of equity by 1% would result in a cost reduction of 0.72%. The 1% change in rate of equity however is not validated and thus questionable. Instead, the obtained fundamental insight in offshore atmospheric conditions and the subsequent performance of wind turbines far offshore is potentially much more valuable and can aid in the development of offshore wind energy.

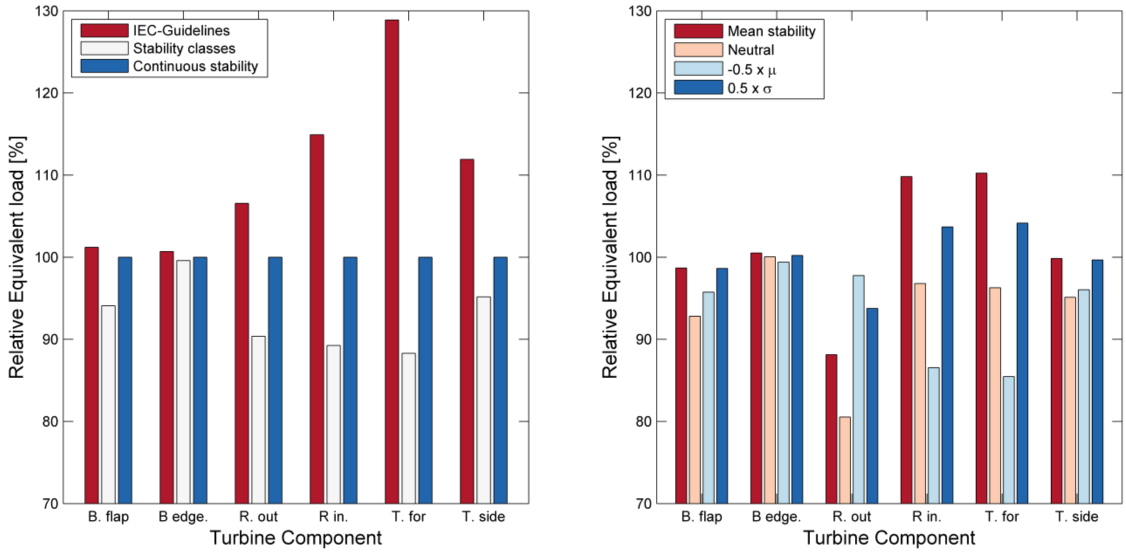

Figure 2: Simulated lifetime equivalent loads for three wind turbine components (each in two directions) for three simulation cases discussed in the text (left panel) and the importance of the distribution of stability on the simulated lifetime equivalent loads (right panel).

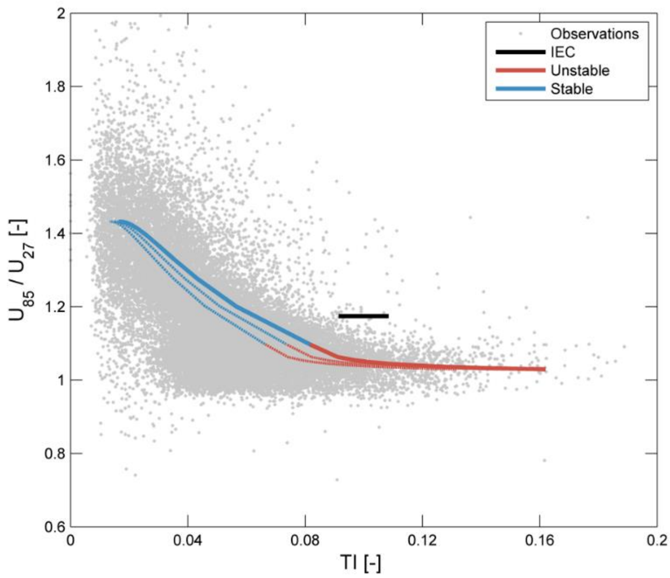

Figure 3: Relation between the observed turbulence intensity and wind shear. Despite scatter, especially for low turbulence levels (i.e., stable conditions), there clearly is a relation with either high wind shear or high turbulence levels, but never a combination of both high shear and high turbulence levels (which would appear in the upper right corner).