Offshore Wind Energy - Chances, Challenges, and Impact from a Meteorological Point of View

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Abstract

Offshore wind parks are expected to contribute a greater share to the electricity generation from renewable energies in future. Chances of offshore electricity generation are the wide space available, higher wind speeds, less turbulence, less vertical wind speed gradients at hub height of the wind turbines and the invisibility of the installations to the general public. Whilst the first two arguments guarantee higher yields, the next two arguments mean lesser loads on the turbines. The last argument helps in getting permits.

Offshore wind energy generation has to face meteorological challenges which come in addition to the well-known logistic challenges. Higher wind speeds and less surface friction can lead to higher wind speed extremes. Low turbulence intensity prolongs wakes behind single turbines and entire wind parks. Therefore, turbine and park spacing has to be larger than onshore in order to ensure the same yield for a given wind speed.

Longer wakes means higher impact of offshore wind parks on each other and on the local and regional climate. Climate modifications could be, e.g., enhanced cloud formation and changed precipitation patterns. A recently launched research project (WIPAFF, WInd PArk Far Fields) funded by the German Ministry of Economic Affairs and Energy will investigate these impacts within the next three years.

Chances

Offshore electricity generation from the kinetic energy of the wind (wind energy) is expected to contribute a larger share to the future electricity generation, because it can benefit from several chances. First of all, ocean surfaces are much smoother than land surfaces. This leads to higher mean wind speeds, reduced turbulence intensity and less vertical wind gradients over the rotor plain of the turbines. In addition, wide space for wind parks is available offshore and the turbines remain invisible to the general public.

Energy yields from the German offshore wind parks in 2015 demonstrate that theses chances are real and can actually be used. On the average about 6 % of the installed wind power in Germany (2.5 GW out of 38.6 GW) was installed offshore in 2015 [1]. But, these offshore installations produced more than 11 % (7.9 TWh out of 71.1 TWh) of the total electric energy generated from wind energy in Germany in 2015 [2].

This higher efficiency of offshore wind parks comes from higher and steadier wind speeds over the sea. Part of this higher steadiness of offshore wind speeds is due to the missing stability-driven diurnal cycle of wind speeds due to the thermal inertia of the ocean water. Fig. 1 shows the electric power available from all German offshore wind parks in the North Sea for four days in November 2015 as an example. For a larger wind speed range between 8 and 20 m/s at Helgoland (this is not hub height wind speed at the turbines but 10 m wind speed over the island of Helgoland) the electric power is constant at about 2.4 GW. The lower values on November 27 and 29 are most probably due to turbines or entire parks which were switched off for maintenance. Essentially, two and a half days of constant power was delivered from the ensemble of wind parks in the German North Sea during those four days.

Fig. 1 shows another important and interesting feature: the impact of the cut-off wind speed on power generation. In the evening of November 29, 2015, wind speed at Helgoland exceeded 20 m/s for about three to four hours. This meant widespread exceedance of the cut-off wind speed of 25 m/s at hub height in the wind parks in the German North Sea. The consequence is a drastic dip in the power curve. Power declined from 2.2 GW down to 0.4 GW within 2.5 hours and recovered within the next 1.5 hours from 0.4 GW to 2.0 GW. Such a large and rapid change is a large challenge for grid operators if such events appear unexpectedly. For comparison: the power dip due to the solar eclipse in Germany on March 20, 2015 was even sharper. Nationwide solar power dropped from 13.3 GW to 5 GW within one hour and then recovered to 19.5 GW with the next one and one quarter hours [3]. Grid operators were well prepared and managed to run the German electricity grid without any disturbance.

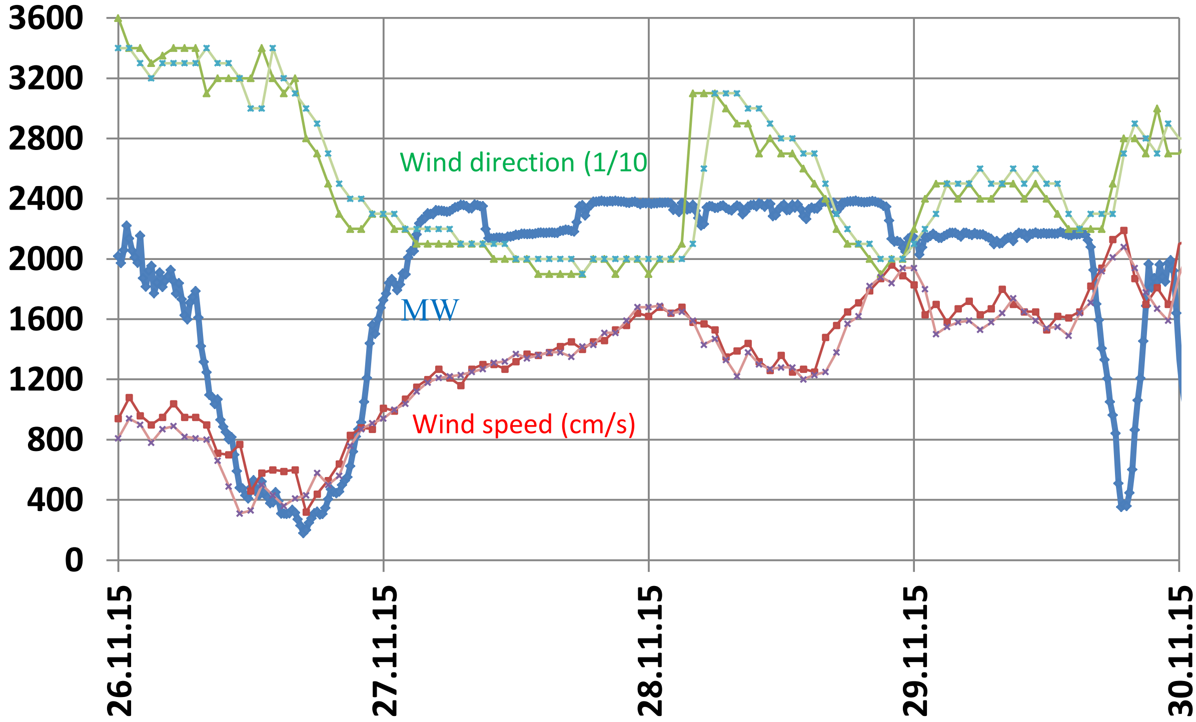


Fig. 1. Four days (November 26 to 29, 2015) of electric power in MW from all German offshore windfarms in the North Sea (blue curve) [5], wind speed in cm/s measured at UFS Deutsche Bucht and Helgoland (red curves), and wind direction in 1/10 of degrees at UFS Deutsche Bucht and Helgoland (green curves) [6].

It could be questioned whether a sharp shut-down of wind turbines at cut-off wind speed is the best option for a larger number of powerful turbines in a relatively small area. Maybe, a smoother transition from full operation to a complete stand-still over a wind speed range of several metres per second could be a solution [4].

Challenges

Higher mean wind speeds offshore are connected to higher extreme wind speeds as well. FINO1 data has already been analysed for extreme 10 min wind speeds [7]. Fig. 2 top shows FINO1 data from 2003 to 2007 on Gumbel paper.

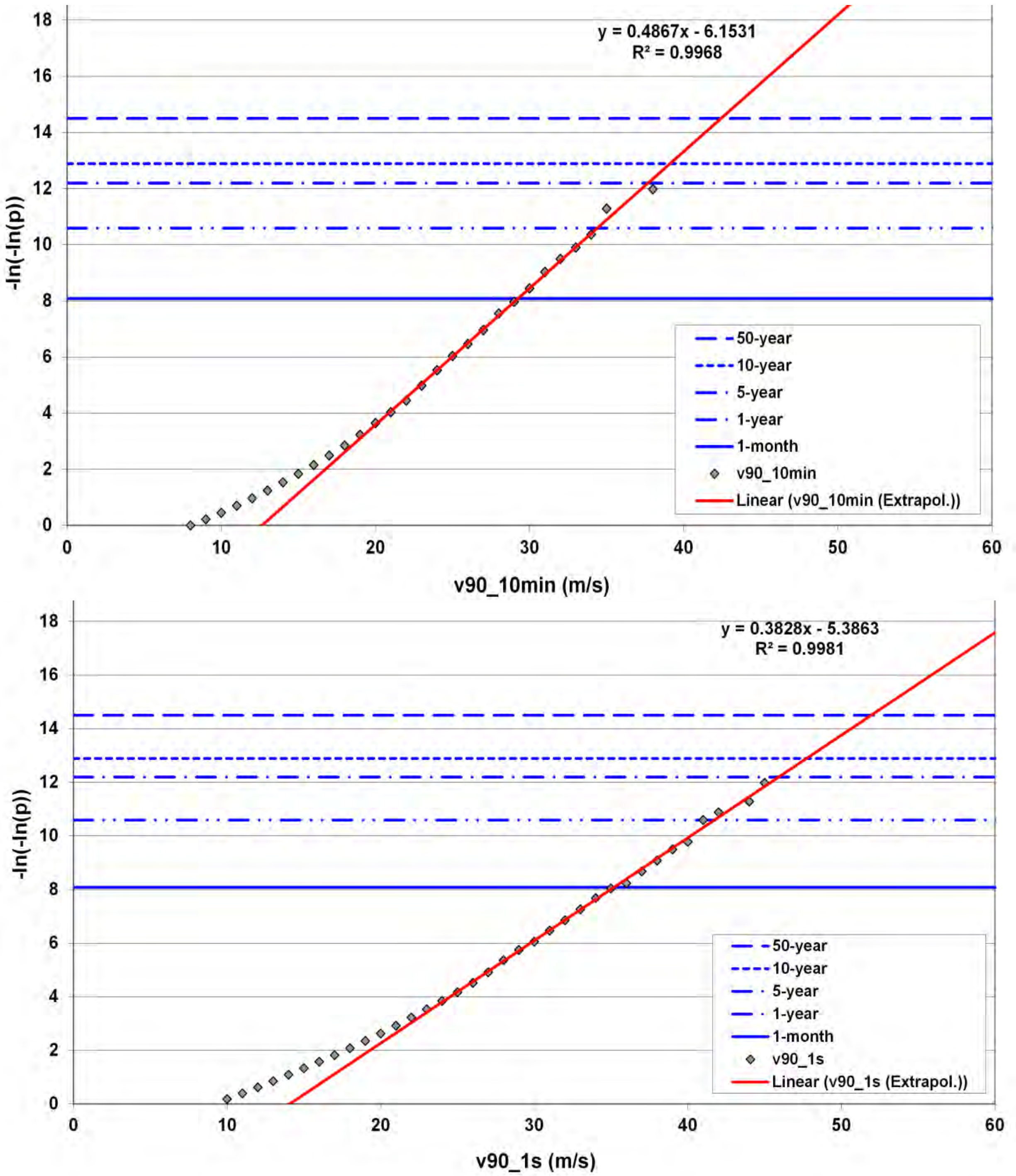


Fig. 2. Gumbel plot for the 10 min mean wind speed (top) and the 1 sec gust (below) at 90 m height at FINO1 for the years 2003 to 2007. 1-m/s bins have been used to aggregate the wind speed data. Red lines indicate linear extrapolation; horizontal blue lines give threshold values for different return periods. p denotes accumulated probability.

The data for 1 sec gusts has been added here as well (Fig. 2 below). Both, the FINO1 10 min and 1 sec wind speed data follow Gumbel extreme value statistics for wind speeds above roughly 20 m/s. Therefore, linear extrapolation can be made (red lines in Fig. 2). For 10 min mean winds about 35 m/s can be expected with a one-year return period and about 43 m/s with a 50 year return period. For 1 s gusts about 42 m/s can be expected with a one-year return period and about 53 m/s with a 50 year return period. Offshore wind turbines have to be designed for such extreme wind speeds. When the development continues for larger 10 MW to 50 MW turbines, segmented and morphing downwind-aligned rotor blade concepts [8] [9] become necessary in order to stand the high loads acting on the blades.

The next offshore challenge is long wakes behind turbines and wind parks due to the low turbulence intensity which does not provide a high enough turbulent momentum flux to refill the wakes as rapidly as it happens over land.

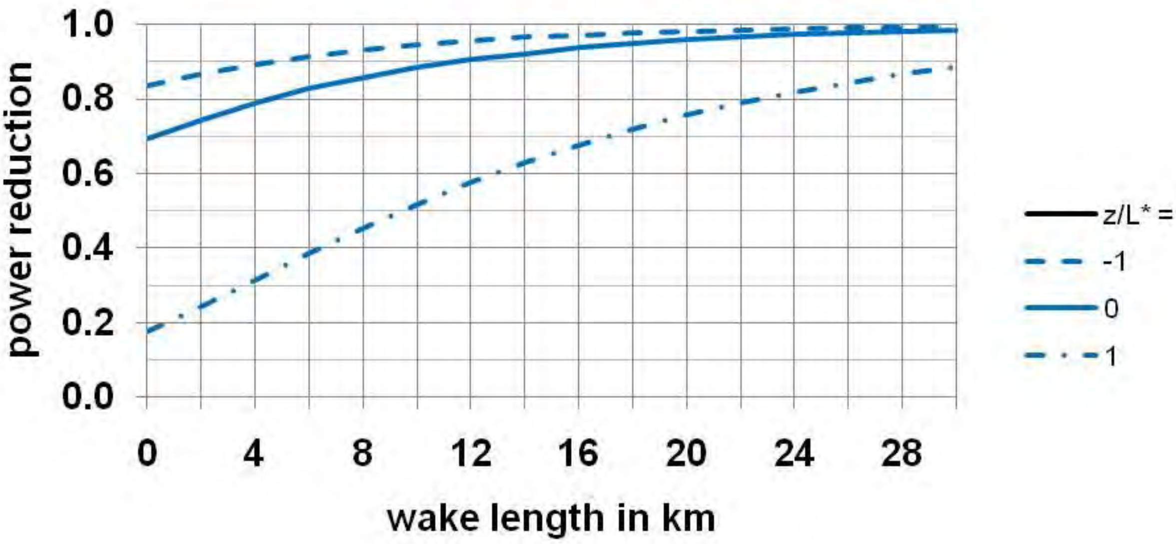


Fig. 3. Power reduction in the wake behind a very large offshore wind park with turbine density 10 (square root of park area over total rotor area) for different atmospheric stabilities (dashed line: unstable, full line: neutral, dash-dotted line: stable) computed from an analytical model [10].

Model calculations [10] show that the length of the wake depends strongly on atmospheric stability. Fig. 3 demonstrates that behind a very large wind farm it takes about 5 km before the available wind power has returned to about 90 % of the undisturbed value under unstable conditions (z/L = -1, L is the Monin-Obukhov length). It takes 12 km for neutral conditions and it even takes about 30 km for stable conditions (z/L = 1). In this context, 'very large' means that horizontal mixing for refilling the momentum deficit in the wakes can be neglected. Refilling is done by vertical turbulent momentum fluxes only.

Analysis of the correlation between wind speeds, wind direction and atmospheric stability from FINO1 data has shown that stable conditions prevail in the sector of most frequent wind directions (195° to 255° in Fig. 4). Simultaneously, highest wind speeds occur within this sector. The reason for this correlation are moving cyclones which convey warm air from the Southwest over colder water in the warm sector of the cyclones before the cold front is passing and which advect cold air from the Northwest behind the cold front. We expect to find a similar behaviour on the southern hemisphere with one difference only: there, the distribution should be just mirrored along a horizontal line from 270° to 90°.

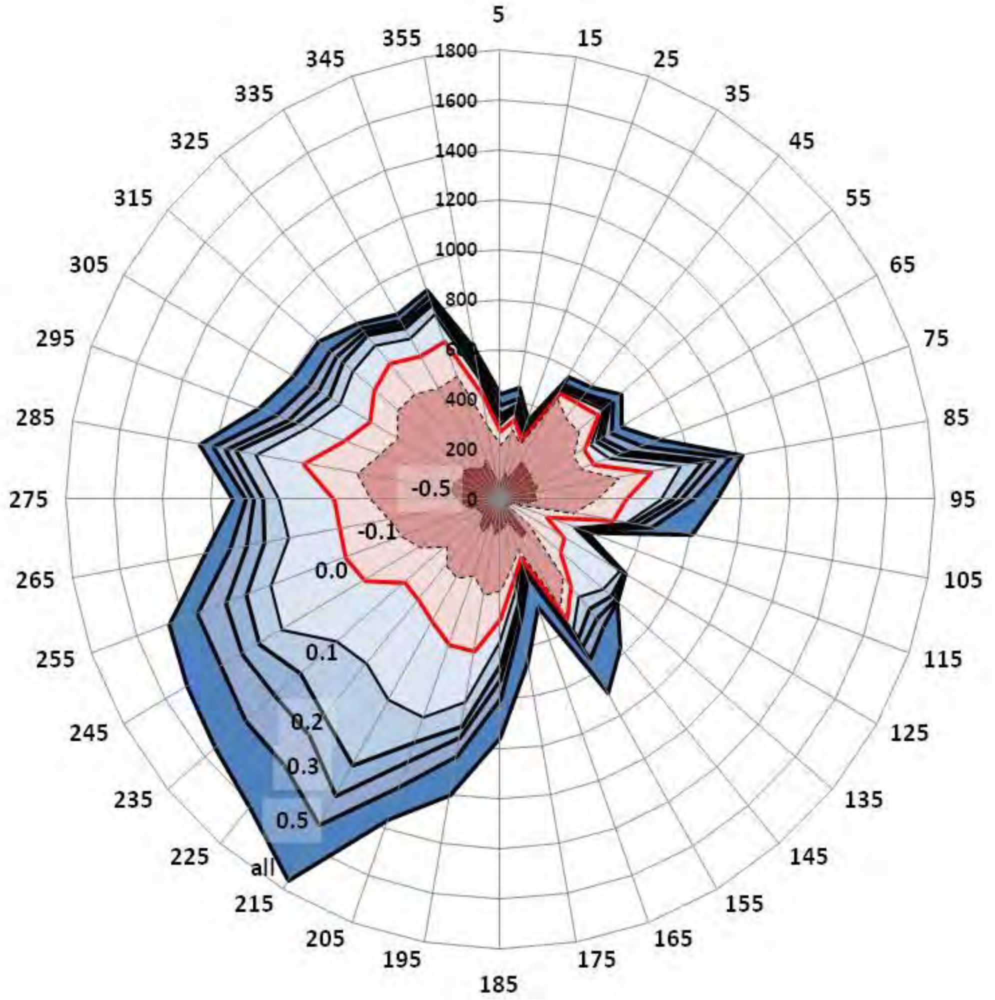
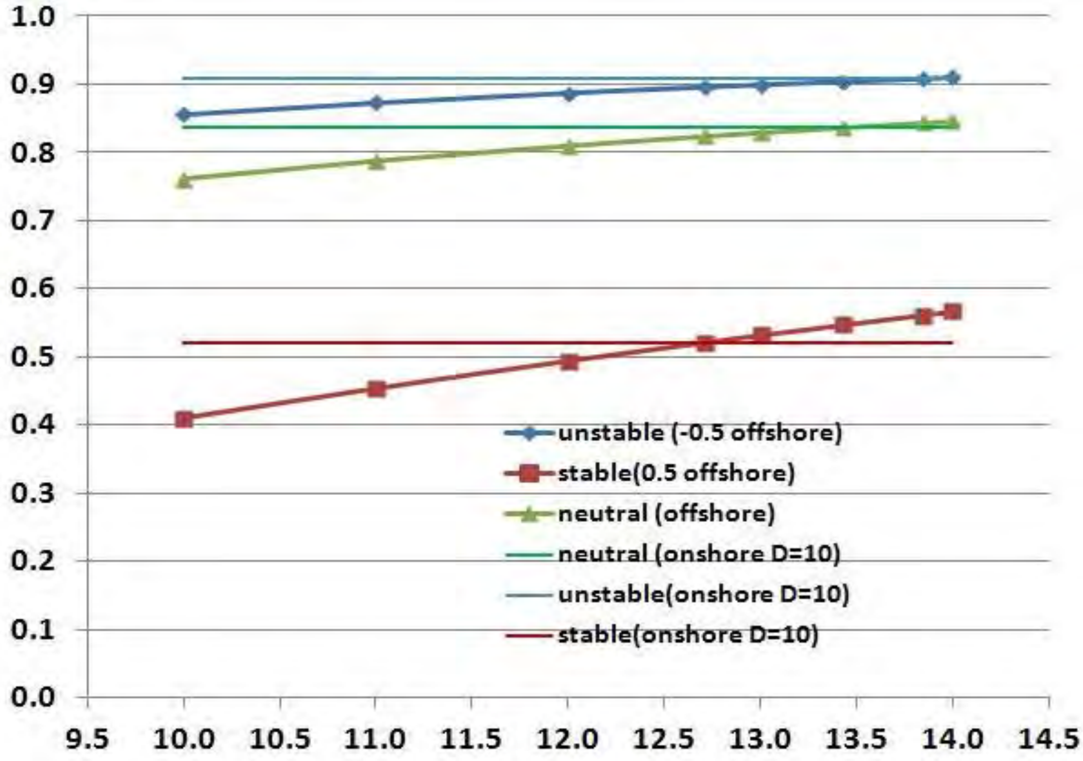


Fig. 4 Frequency of wind directions at 60 m height at FINO1 in 2005 from 10 min mean values for a wind speed range between 5 m/s and 25 m/s. Blue shading indicates stable conditions, red shading unstable conditions. Numbers give the stability parameter z/L.

Bringing the information from Figs. 3 and 4 together, this means that longest wakes appear with high wind speeds from the main wind direction. The planning of turbine distances within wind parks and of park distances should take this correlation into account.

Fig. 5 left compares computed [10] power output and wake lengths of very large offshore wind parks to equally large onshore wind parks. The cross-over of the curves for offshore wind parks with the respective horizontal lines for onshore parks with turbine density 10 indicates the larger turbine density necessary at offshore sites in order to yield the same harvest than from onshore parks (given the same geostrophic wind speed). These cross-overs are at densities 12.7 (stable conditions) to 13.8 (unstable conditions). Such offshore wind parks need 61.5 % to 91.7 % more space than onshore wind parks with the same power.

Offshore wind parks do not only need more space, they also have longer wakes as has already be seen from Fig. 3. Fig. 5 right compares wake lengths (this time a recovery to 95 % of the undisturbed power has been chosen as definition) of offshore wind parks with different turbine densities to the wake length of an onshore wind park with turbine density 10 under neutral conditions (horizontal line). It becomes obvious the wake lengths are a relatively weak function of turbine density only. A turbine density of 14 means a nearly doubling of the space necessary for the park.



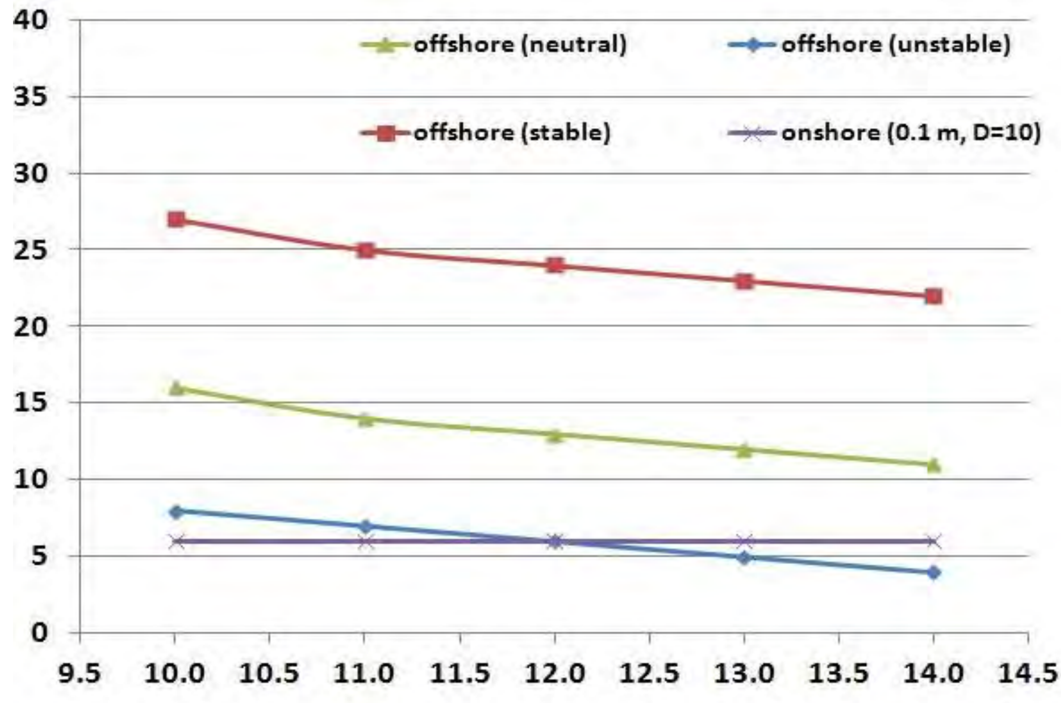


Fig. 5. Left: Reduced power of very large offshore wind parks (y-axis) versus turbine density (x-axis) compared to power reduction within an onshore wind park with a turbine density of 10 for unstable (blue, z/L = -0.5), neutral (green) and stable (red, z/L = 0.5) conditions. Right: As left, but wake length (recovery to 95% of power output) in km (y-axis) versus turbine density (x-axis) compared to wake length of an onshore wind park (roughness length 0.1 m) at neutral conditions. Both results were computed with the analytic model from [10].

Impacts

Longer wakes means higher impact of offshore wind parks on each other and on the local and regional climate. Climate modifications could be, e.g., enhanced cloud formation and changed precipitation patterns. Fig. 6 gives a schematic overview of possible impacts. Offshore wind parks break the wind speed. If flow over a material surface has to slow down, it has to deviate laterally and vertically. Induced vertical motion leads to increased cloud formation and even to increased formation of precipitation, if the humidity content of the atmosphere is high enough. The clouds will move downstream and can influence the incoming short-wave radiation further downstream. Induced precipitation over the parks could mean reduced precipitation downstream. Not much is known so far on these regional climate impacts. A first numerical study can be found in [11].

The aim of the recently launched research project WIPAFF (WInd PArk Far Fields) is the analysis of wind and turbulence conditions in far fields of offshore wind farms, i.e., 10 to 100 km behind the wind farms. This is done in order to estimate the impact of large offshore wind farms on neighbouring wind farms, and to assess by numerical modelling the impact of the whole array of planned wind farms in the North Sea on the regional climate. The existing simple analytical wind farm model [10] is to be validated in order to use it for rapid planning processes. The whole project is a common effort of five joined subprojects headed by the Institute for Meteorology and Climate Research of the Karlsruhe Institute of Technology in Garmisch-Partenkirchen. The other partners are from the University of Braunschweig, the Helmholtz Centre Geesthacht, UL International GmbH (DEWI) in Wilhelmshaven and the University of Tübingen. The project is funded by the German Federal Ministry of Economic Affairs and Energy. The project has started on November 1, 2015 and is projected to run until October 31, 2018.

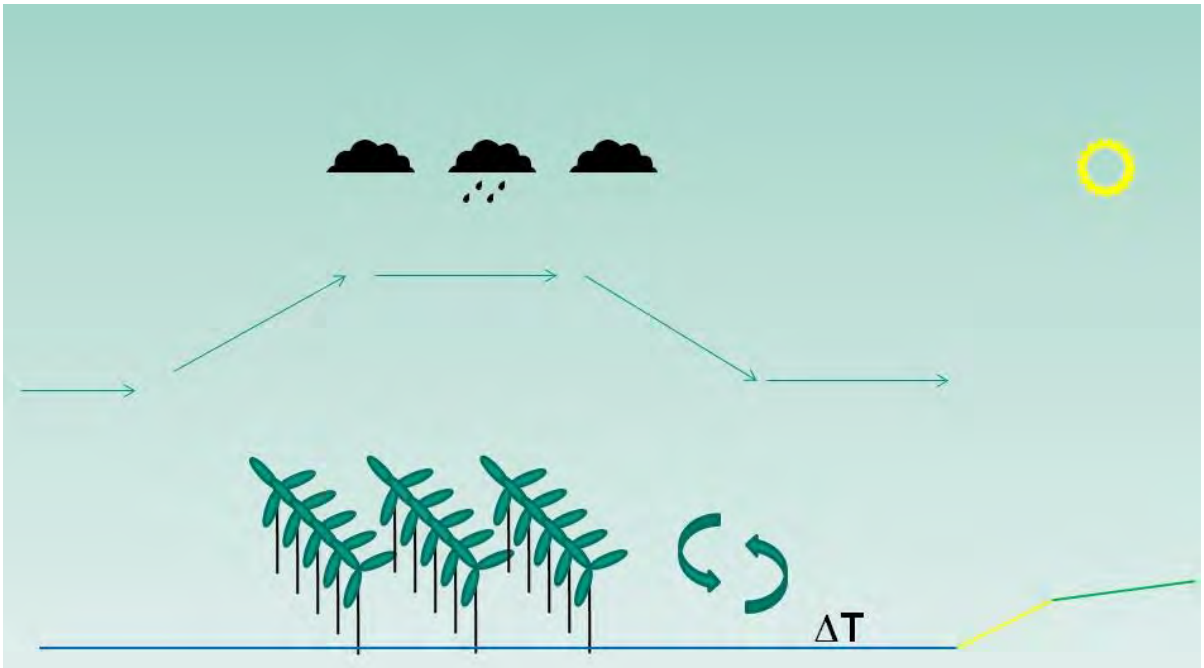
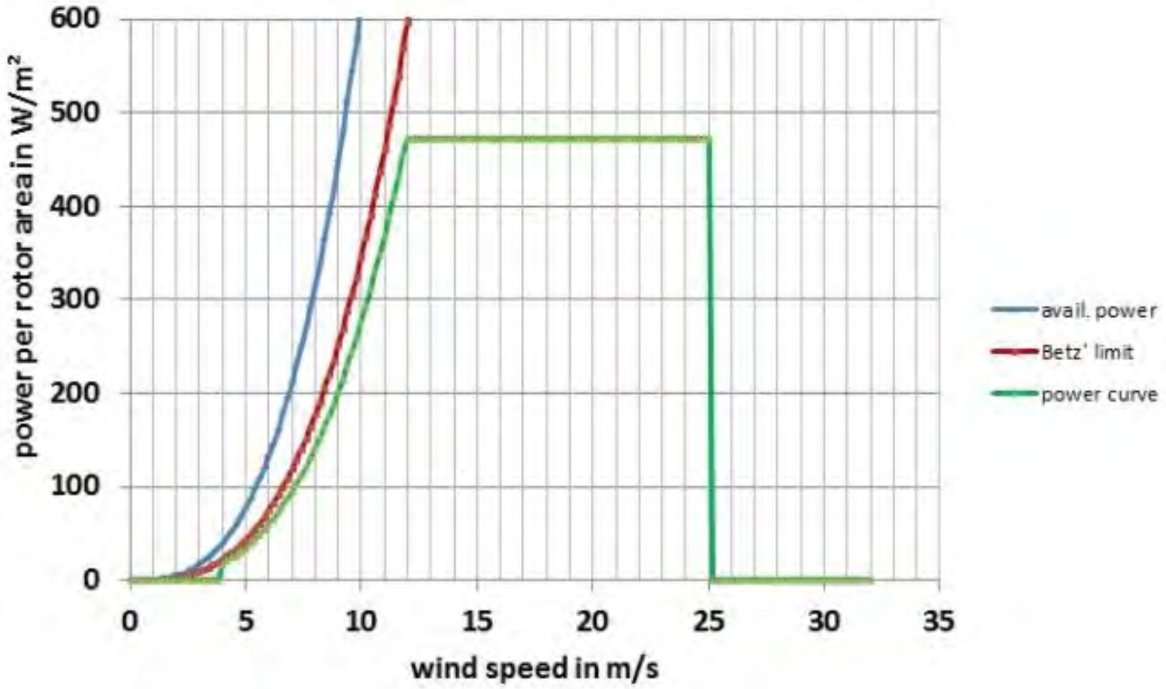


Fig. 6. Schematic of regional climate impact of large offshore wind parks.

The first step is to integrate an existing ocean wave model (WAM, [12]) into the meso-scale wind field model WRF [13] and to test the coupled model. An appropriate parameterization scheme that describes the offshore wind farms is integrated into the model as well. Then the whole updated model is tested and validated with SAR, in-situ and aircraft data obtained and provided by the partnering projects within WIPAFF. The updated and tested model is then used to simulate the interaction of neighbouring wind farms in the North Sea and to assess the



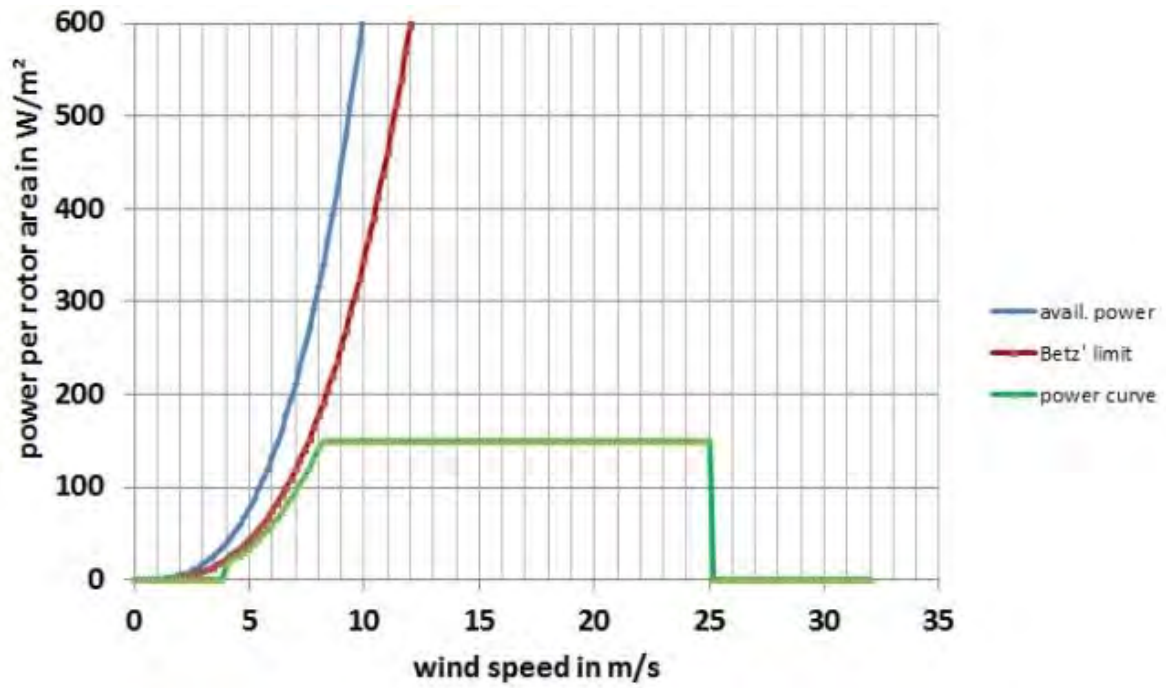


Fig. 7. Hypothetical power curves of two 3 MW turbines. Plotted is the available wind power per m² of the rotor area (blue), the maximum extractable power (Betz' limit, red) and the turbine power curve (green). Cut-in wind speed: 4 m/s, cut-off wind speed: 25 m/s. Rotor diameter is 90 m (left) and 160 m (right).

overall impact of the planned array of wind farms on the regional climate (Fig. 6). Finally, an existing simple analytical wind farm model [10] is validated and optimized by comparison to the numerical model results and the experimental data from the other projects.

Outlook and Innovations

Offshore generation of electric power from the kinetic energy of the wind has become a mature technology today. Nevertheless, there is still space for improvements and innovations.

Presently, the Vestas V164 turbine with a rotor diameter of 164 m and a rated power of 8 MW seems to be the most powerful commercially available wind turbine. The blades of this turbine have a length of 80 m. Even larger is the 7 MW turbine Samsung S7.0 with 83.5 m long blades and a rotor diameter of 171 m. But this trend will continue. Offshore installation and grid connection are very expensive. Cost reduction per delivered amount of energy can only be reached by building even larger turbines. The technological challenges coming with such large turbines are addressed in [8] [9].

Another trend is to install turbines which are not optimized for peak power but for high capacity factors, i.e., for a maximum of time per year within which the rated power of the turbines is available. Turbines with higher capacity factors can be integrated into the electrical grid more easily. Such turbines have larger rotor areas than necessary in order to have a low cut-in wind speed and a very low wind speed at which the rated power is reached [14]. The principle is illustrated in Fig. 7 which displays the power curves of two hypothetical 3 MW wind turbines with 90 m (left) and 160 m (right) rotor diameter. The 90 m turbine delivers the rated power of 3 MW only for a wind speed range between 12 m/s and 25 m/s, the160 m turbine delivers the rated power for a wind speed range from 8 m/s to 25 m/s. Depending on the wind speed distribution at the site, this could mean more than a doubling of the capacity factor. As mentioned already above, designing turbines with a higher cut-off wind speed and a smoother shut-down at high wind speeds is desirable as well [4].

The available area for today’s offshore turbines is limited due to foundation technologies. Water depths of thirty to forty metres yet allow for classical foundations rammed into the ground. But it is desirable to use offshore areas with water depths up to 200 m. This can be achieved by floating foundations. First projects are currently underway [15].

This technological development is accompanied by innovations in wind profile measurement methods as well. For instance, measurement towers become impractical in offshore environments and fixed platforms become only available after the erection of wind parks and related converter stations. Therefore, e.g., wind lidar buoys are under development to detect offshore wind profiles beforehand [16].

Acknowledgements

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