Effects of wind veer on turbine performance

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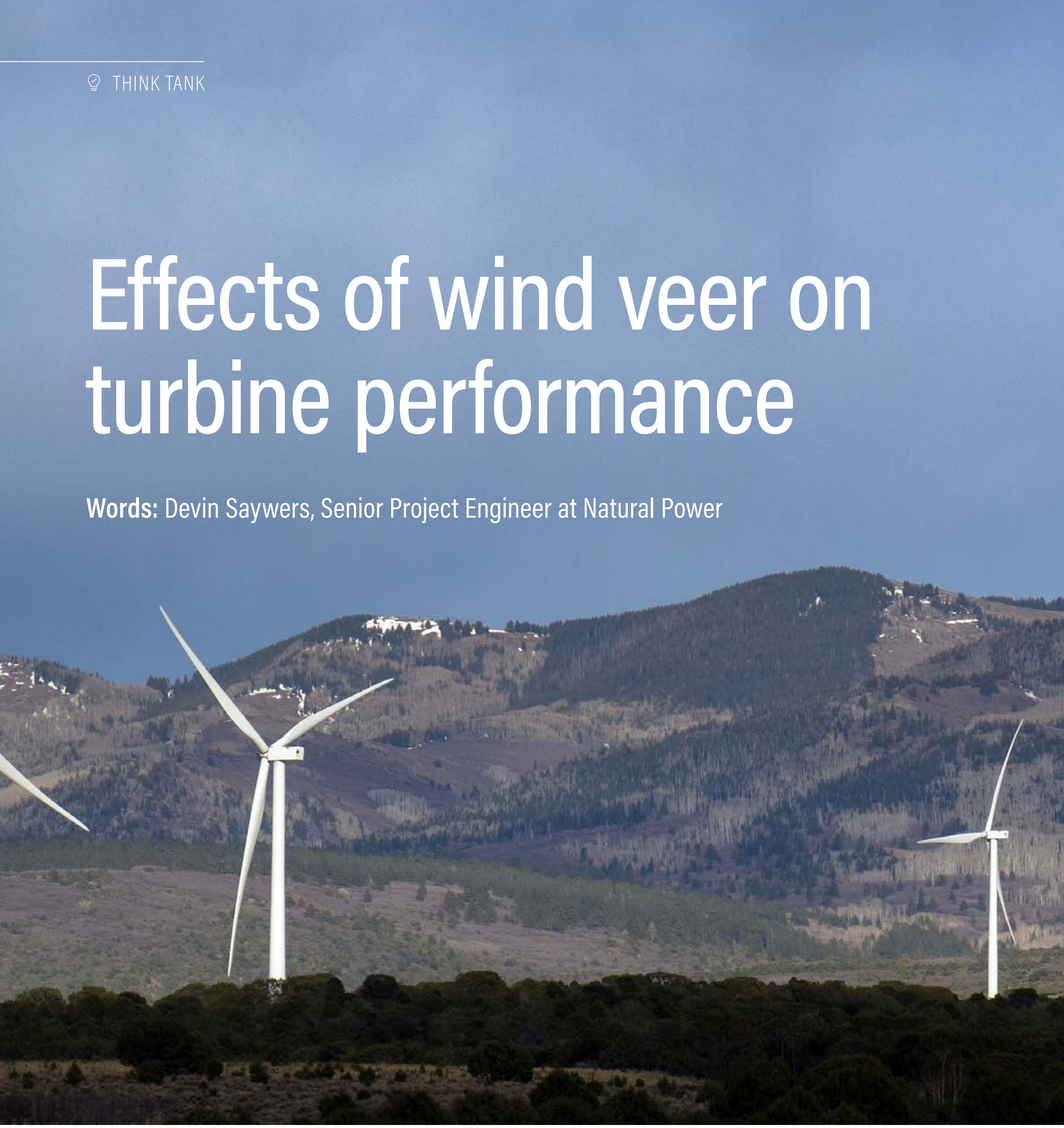

As rotor diameters and hub heights of wind turbines continue to increase, it is common for turbines to experience significant changes in wind direction with height across the rotor plane. With more remote sensing devices being deployed, it is becoming easier to directly observe and quantify these high veer conditions. However, the direct impact of wind veer on turbine performance is only just beginning to be understood.

Wind turbines can be idealised as real-time vector normalising machines, whereby the incoming wind is a field of vectors representing the velocity and direction of the wind field relative to the wind turbine rotor plane. The normalised force, i.e. useful energy, imparted by the field of wind vectors varies due to both the wind speed and direction of the wind vectors across the rotor plane.

At sites that are subject to high veer, the incident angle of the wind vector varies across the rotor plane, meaning there is less energy flux normal to the rotor plane available to convert to useful energy.

Not only does this mean less useful energy is being extracted from the wind field, but high wind veer results in turbines experiencing operational challenges due to increased loading associated with non-optimal pitch and yaw over the upper and lower rotor areas.

With a typical wind shear profile, wind speeds increase with height above ground level, as depicted in Figure 1. Similarly, wind veer, the angle at which wind is directed toward the rotor plane, can change with height above ground level, as shown in Figure 2.

Natural Power examined the issue in detail by investigating past research on the topic, exploring in which regions of the US and Europe high veer is most seen, and examining the underlying atmospheric drivers of the phenomenon.

Nocturnal low-level jets

Natural Power focused particularly on one common atmospheric driver of veer, nocturnal low-level jets. These are common

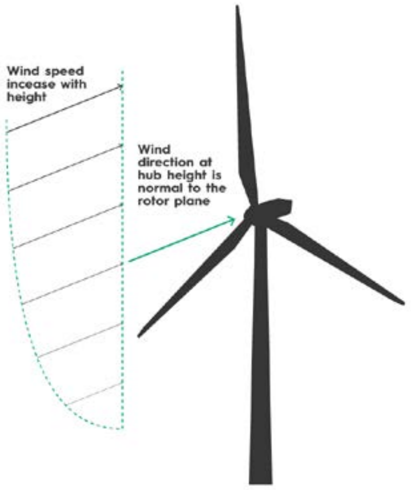

Figure 1: Wind shear

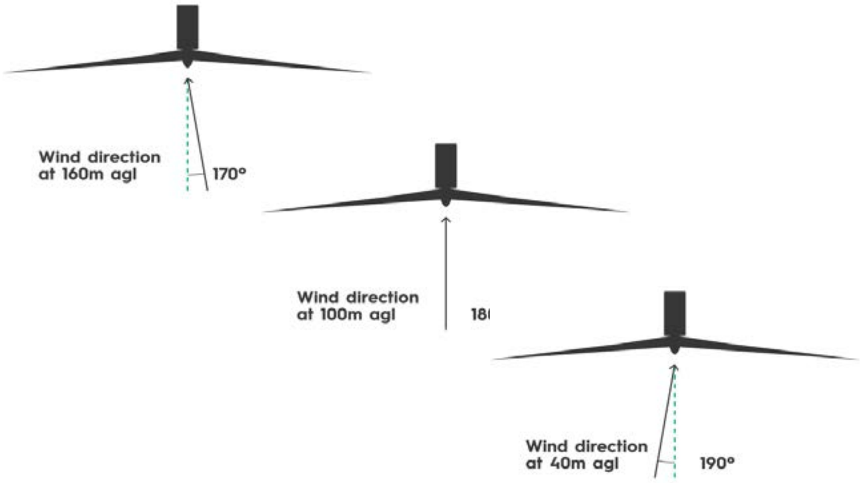

Figure 2

in the Great Plains due to decoupling of the boundary layer from the surface wind at night and temperature or elevation gradients between the higher western plains near Eastern Colorado and lower eastern plains closer to the Great Lakes.

Figure 3 shows typical altitudes that low-level jets occur in comparison to meteorological tower heights as well as past and present turbine model heights and rotor sweep areas. This shows that the typical maxima, or core, of the low-level jets is occurring near the upper tip height of recently deployed wind turbine models.

Past generations of turbine models experienced more ideal shear and veer conditions that occur well below the maxima of the low-level jet. Near the maxima of low-level jets many complex atmospheric phenomena can be observed, such as non-ideal wind shear and veer, both of which result in reduced turbine performance.

The frequency, intensity, and height of the nocturnal low-level jet phenomenon is largely seasonally driven. However, research around longer-term variations from the El Nino–Southern Oscillation is ongoing and could shed more light on interannual variability of wind resource (Yu, 2016). Understanding this phenomenon is critical to improving the seasonal wind energy resource predictions and to accurately assess lifetime load calculations for the latest generation of large rotor diameter, high hub height wind turbines.

Coastal low-level jets

Coastal low-level jets are driven by pressure gradients associated with land-seas temperature gradients; whereby coastal water temperatures change more slowly than land temperatures. These low-level jets form most often at night and transitional periods, with the maxima, or core, height of the low-level jet varying from 100m to 600m above sea level, similar to nocturnal low-level jets.

Coastal topography plays a key role in the formation and strength of these low-level jets, meaning a coastal project off the coast of Norway with its complex coastal topography would experience vastly different low-level jets than a coastal

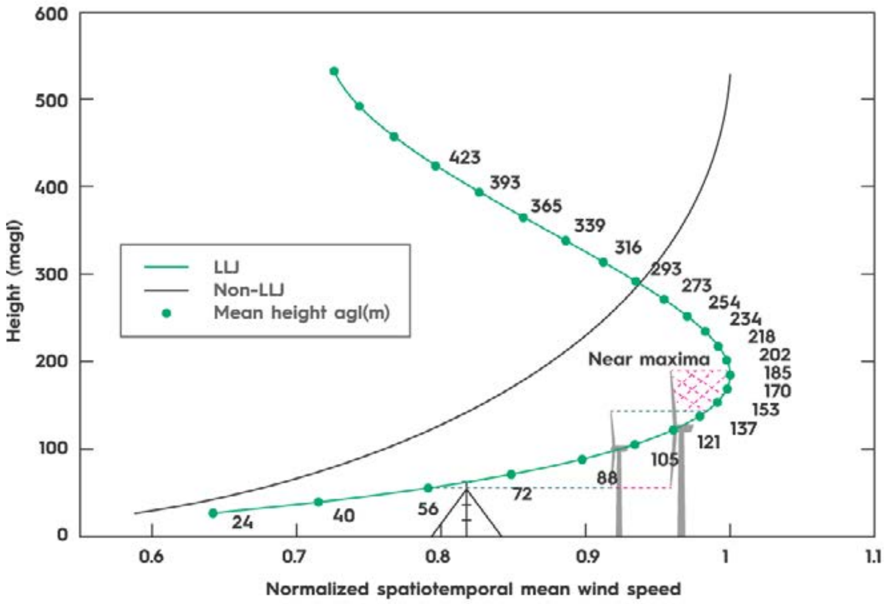

Figure 3: Typical altitudes that low-level jets occur. Source: https://doi.org/10.5194/wes-6-1015-2021

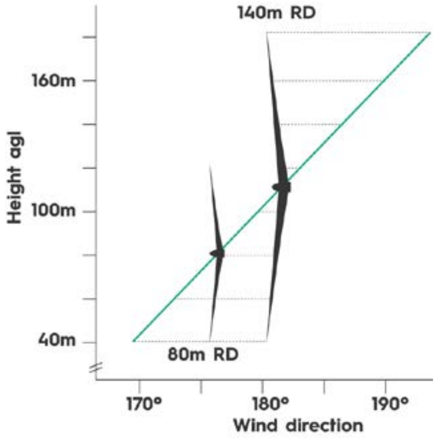

Figure 4: Impact of wind veer on rotor diameters

project off the coast of the Northeastern US where coastal topography is simpler.

Coastal low-level jets play a critical role in the siting of offshore wind turbines, as low-level jets typically amplify periods of high wind speeds; however, this increase in wind resource due to coastal low-level jet can also be accompanied by higher wind veer across the rotor plane that would reduce the useful wind energy.

Other atmospheric drivers of veer

There are additional atmospheric drivers of high wind veer. Cyclone-induced low-level jets are common in the mid-latitudes and occur when the warm sector of a cycle interacts with a cold front. Valley/canyon effects occur where there are temperature/pressure gradients due to uneven heating that can cause localised nocturnal low-level jets.

Outflow from thunderstorms can cause wind veer because of the strong outflow winds into warm moist air at the ground with cooler air aloft which can produce density currents. While these phenomena are less common than nocturnal or coastal low-level jets for most active wind development regions, in other regions such as the southwest US or Chile, these could be the main atmospheric drivers of wind veer.

Quantifying and modelling the impact of veer

Wind veer has a smaller impact on shorter turbines with smaller rotor diameters because they are effectively sampling less of the atmosphere and therefore, experience less variance in the wind vector field. With larger rotor diameters and higher hub heights, the turbine rotor plane samples more of the atmosphere leading to greater variance in wind direction and speed across the entire rotor plane (Figure 4).

There are various ways to model veer including the bulk veer model which

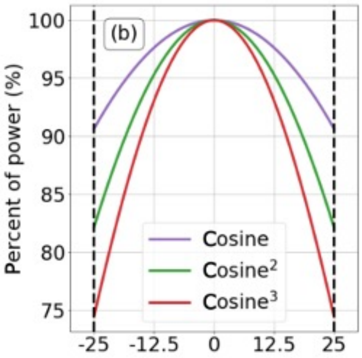

Figure 5a: Theoretical effects of yaw misalignment based on cosine curves

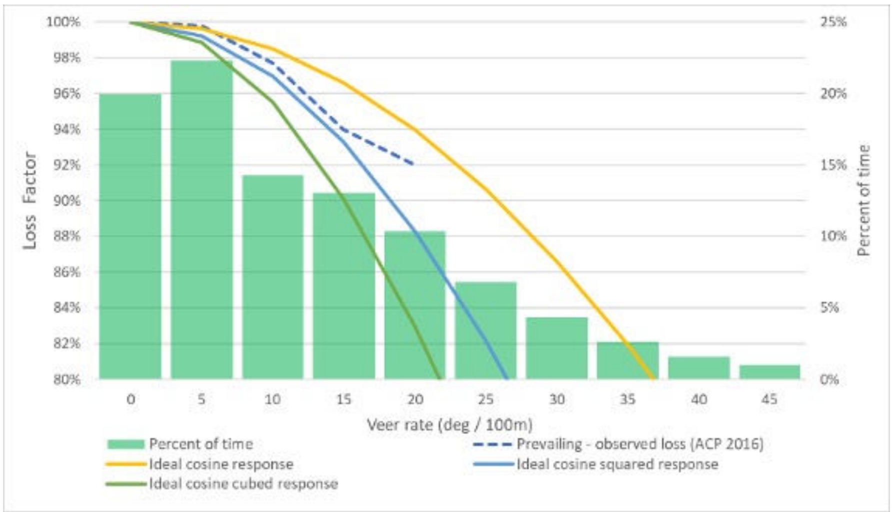

Figure 5b: Comparison of ideal cosine responses to previous study and frequency of veer rates based on cosine curves

considers only the difference in wind direction from the top and bottom of the rotor plane, the discrete veer model which considers the direction as measured at all various heights through the rotor plane, and vector mean which is calculated by addition, tip to tail, of wind speed/direction vectors to calculate a single resultant vector for a given period. Windographer, a commonly used wind analysis software, calculates mean veer rate using this method.

How can veer be incorporated into energy modeling?

To do so, we considered the ideal cosine response of the incoming wind flow's mean vector veer to estimate the lost energy of a non-normal wind vector, as shown in the Figures 5a and 5b.

This method relies on using time series calculations of the mean veer rate across the rotor plane, which simplifies the calculation, but may not fully capture the variance in wind veer across sections of the rotor plane, as it averages the overall veer experienced across the rotor plane into a single average number. This method can work as an approximation for instances where the observed veer exhibits linear behaviour but would fail to predict periods of non-linear veer.

Another option that captures the variance across rotor plane discretely and allows for non-linearity, is to use the rotor equivalent wind speed (REWS) with a cosine factor to integrate the veer angles observed over the entire rotor plane. In this method, the turbine rotor plane is sliced into several segments whereby the wind speed and direction of that segment is evaluated individually, then each slice is integrated according to the formula presented in Figure 6.

Further analysis of the cosine-law and the REWS methods' efficacy in predicting the energy of an operating wind farm is ongoing, and model applicability will depend upon the atmospheric drivers of veer for a given wind farm.

Do we need to include veer modelling in wind energy analysis?

As hub heights have gotten taller and rotor planes larger, directional changes with height have a higher potential impact on turbine performance. Many projects are being developed in areas with known atmospheric prerequisites for veer, such as nocturnal low-level jets in the Great Plains of the US or coastal low-level jets for offshore projects near Norway or the Northeastern US.

To better quantify the potential impact of veer on a given project, not only are better measurement campaigns with remote sensing devices required, but also better analytical methods to isolate technology-driven underperformance from atmospheric-driven underperformance.

While the theoretical impacts are clear, further research is still needed to accurately estimate the real impacts of veer on turbine performance, so the following warrant further exploration. SCADA-based operational analysis of turbine performance during periods of elevated veer to quantify turbine performance impacts and compare with theoretical modelling techniques; REWS vs yaw misalignment cosine approximation. How coupled are stability driven turbine performance metrics and veer?

Can turbine controls optimise pitch and yaw systems to minimise the impact on production when veer is observed? Should they instead be optimised to minimise fatigue loading to maximise turbine life/reliability? And how might veer impact wake modelling and layout design?

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$$\sqrt[3]{\frac{\sum_{i=0}^{n} \square\, A_{z(i) to\, z(i+1)} \left(\frac{U_{z(i+1)}\, cos\, cos\, \left(\Delta\theta_{z(i+1)}\right) + U_{z(i)}\, cos\, cos\, \left(\Delta\theta_{z(i)}\right)}{2}\right)^{3}}{A}}$$

Figure 6: Rotor equivalent wind speed (REWS) with a cosine factor to integrate the veer angles observed over the entire rotor plane

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It has a global reach, employing more than 500 staff across 13 international offices.

Its experience extends across all phases of the project lifecycle from initial feasibility, through construction to operations and throughout all stages of the transaction cycle.