VAYU
Wind Energy Optimization

Memorandum
Re: Wind Turbine Loads Analysis
By: August Kiles, VP Product
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The focus of this inquiry is the potential impact of power optimization through yaw offsets on turbine integrity based on scientific assessment. In examining the impact of yaw offsets on the yawed turbine the one common trend across all research is that the loads on misaligned turbine blades decrease with positive yaw angles and increase with negative yaw angles. Meanwhile, loads on other turbine components are either unaffected by yaw, or show far less impact than the trends observed in the loads on turbine blades. Notably, research also points to yaw offsets as diminishing loads on downwind turbines as a result of wake steering.

In the seminal research analysis on power optimization through yaw offsets, "[Wind plant power optimization through yaw control using a parametric model for wake effects- a CFD simulation study", (Gebraad, et al]), multiple sources are mentioned that confirm the fact that positive yaw angles decrease turbine blade loads while negative yaw angles increase loads. The first of the sources mentioned is by Paul Fleming, et al entitled "[Simulation Comparison of Wake Mitigation Control Strategies for a Two Turbine Case]". This study, performed on two turbines, notes that loads tend to either increase or decrease, depending on the direction of the yaw misalignment.This concept is illustrated by graphs that demonstrate a marked decrease in the blade out of plane moment on the upwind turbine (denoted by blue bars) with positive yaw angles. Meanwhile drivetrain loads decrease for all yaw angles, yaw bearing loads show a slight decrease with positive yaw angles, and tower based loads show a slight increase with positive yaw angles. Here we refer only to the upwind turbine loads, since there is no yaw on the downwind turbine (Loads on downwind turbines in general will be discussed below). Of the four types of loads measured here, only the tower based loads increase with positive yaw angles. When aggregated over the whole turbine, this small increase is more than made up for by larger decreases in blade out of plane moments, drivetrain loads, and yaw bearing loads. Even more promising, other studies have shown that tower based loads do not necessarily increase with positive yaw angles.

One such study, also by Fleming, et al is entitled "[Evaluating Techniques for Redirecting Turbine Wakes Using SOWFA]".
A key table in their paper (p. 7) shows relationships between yaw offset and all different types of loads. Very encouragingly, there is a negative trend in every single type of load as we move towards positive yaw angles, including turbine tower loads. It is important to note that once again the magnitudes in the change of turbine tower loads are far smaller than the magnitudes in the change of the turbine blade out of plane loads. In other words, turbine tower loads are less significant and show greater variation than turbine blade loads.

There exist a number of other studies on these concepts. In general, every study we encountered demonstrates lower turbine blade loads when positive yaw angles are used. Some studies, such as "[Assessment of wind turbine component loads under yaw-offset conditions]" by Damiani, et al look at blade flapwise and edgewise loads as opposed to blade out of plane loads. These two measures are combined into an aggregate root blade moment, which gives a solid picture of the overall loading on the turbine blades. Despite somewhat different trends in flapwise and edgewise moments (we observe slight increases in flapwise moments, and significant decreases in edgewise moments as yaw angles are increased), when they are combined into the root blade moment we observe an overwhelmingly negative trend in loading as we move towards positive yaw angles, similar to the blade out of plane moment in other studies. Root blade moments, as it turns out, are not as good of a measure of the relationship between yaw offset and turbine blade load, because unlike blade out of plane moments they are highly reliant on gravitational effects. (See Gebraad, et al p. 2) In other words, it is possible to see variations in edgewise and flapwise moments that are not at all due to yaw offsets.

This phenomenon can be observed in "[Wind Turbine Blade Load Characterization Under Yaw Offset at the SWift Facility]" by Ennis, et al. Whereas in the previous study, flapwise moments increased and edgewise

moments decreased with yaw angle, this study observes the exact opposite trends. However, just as in the previous study these two measures, when aggregated into the root blade moment, result in a desirable negative trend in loads as yaw angles move in the positive direction. In other words, edgewise and flapwise moments are unreliable measures due to their reliance on other factors. Despite this, they tend to result in an overall reduction in turbine blade loads regardless of their individual trends.
Damiani, et al also discuss turbine tower loads in their study, and their results confirm our assertion above that these loads are more unpredictable, smaller in magnitude, and far less related to yaw offset. At a wind velocity of 10 m/s, both computer-based simulations and real measurements are compared. The results show that simulated top of tower bending moments have no relationship with yaw offset, while measurements reveal a very slight increase in loads with positive yaw angles. However, the room for error on the measurements is so large that no real conclusions can be drawn (a significant decrease in loads would be well within the margin for error, as would a significant increase). Bottom of tower bending moments, on the other hand, show a decrease in loads as yaw offsets increase both in a simulated environment and in practice. This is a promising result, but it is important to keep in mind that the margin for error is once again too large to draw any meaningful conclusions from these measurements. At 14m/s the top of tower bending moments exhibit a more positive trend in loads as yaw angles increase, while bottom of tower bending moments remain constant. This is a less desirable result, however since 14 m/s is above rated conditions for most turbines, yaw offsets have little to offer in terms of power gains. (reduced velocity in turbine wakes is great enough that the power output of downwind turbines will not be reduced). Therefore, there is little reason to yaw turbines at this velocity for the purpose of power optimization, and we do not expect to implement many yaw offsets (if any) in these conditions.

In general, wake steering does not impact the loads on downwind turbines because neutrally aligned turbines (no yaw offset) do not attempt address this issue. In other words, in their normal state wind turbines are just as likely to place loads on downwind turbines as they would be with yaw offsets. There is no difference.

In fact, the situation is actually better with yaw offsets. Gebraad, et al find that their power optimization actually resulted in far lower turbine loads than under normal conditions. (See p. 15) They attribute this both to decreased loads on upwind turbines thanks to positive yaw offsets, and to the fact that they are directing wakes away from downwind turbines. Additionally, yawing upwind turbines serves to reduce the effects of wake on downwind velocity, thereby also reducing loads on downwind turbines. At very high velocities this could be an important principle, because loads on downwind turbines tend to be much greater when the wind is blowing harder. In this case we might choose to apply yaw offsets not for power increases but in order to reduce the loads on downwind turbines to a lower level than could be achieved without wake steering.

To recap, yaw offsets have the potential to not only increase a wind farm's power output, but also to diminish the fatigue loading on its turbines. There is a chance of modest increases tower based loads by yawing turbines, but these effects are not consistent across different studies and are more than made up for by significant decreases in blade loads for upwind turbines, and all types of loads for downwind turbines. Not only that, but as we conduct more research going forward and establish a more complete picture of the effects of loads on turbines, we will be able to implement optimizations on wind farms that consider both power output and turbine wear and tear, optimizing for overall revenue/costs as opposed to just energy produced. This type of analysis should allow us to increase the profit margins of a wind farm by an even greater amount than we are able to with our current, power output centered model.