Why do wind farms underperform compared to their pre-construction energy assessment?

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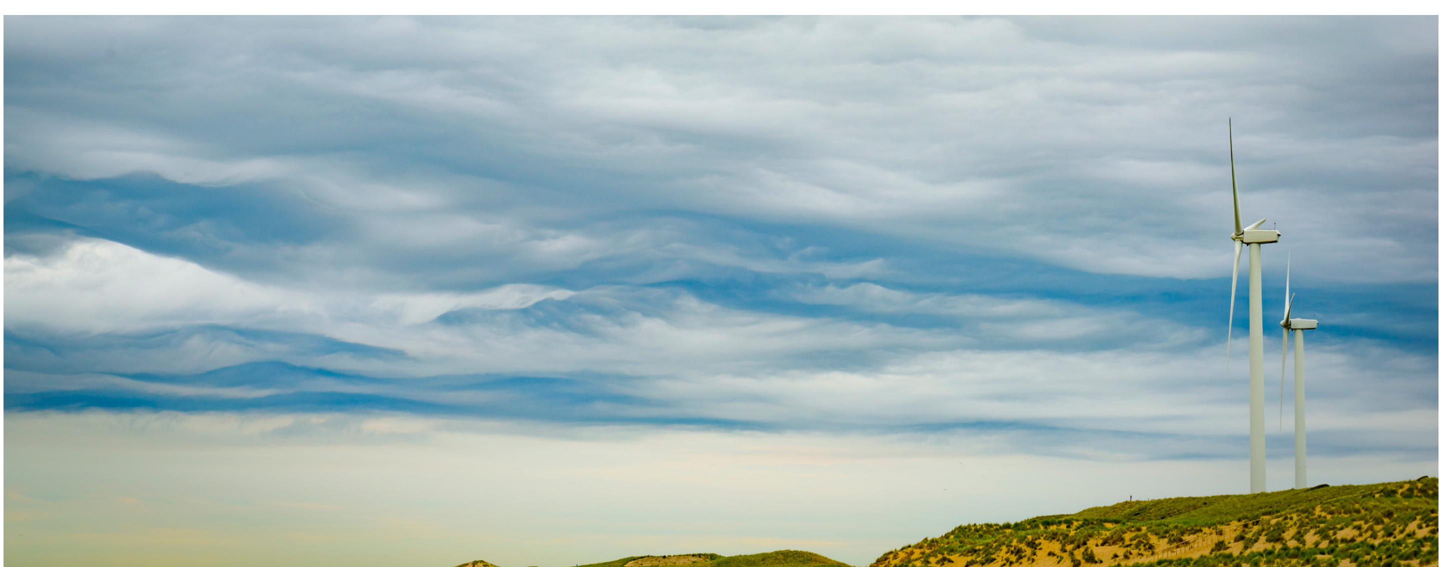
Executive summary

The wind industry is in a state of evolution. While growth and development dominated its early years, precision and optimization are now driving the future. To ensure any new project meets the expectations of investors, deep knowledge of the variables behind performance is a requirement.



A history of underperformance

Pre-construction energy assessments play an essential role in financing a wind farm. When the accuracy and precision of the assessment are off, the profitability of a project often goes down. The wind industry has a history of overpredicting pre-construction energy estimates, overpredicting 10%-20% of its estimates in the early 2000s. This is largely because the wind industry primarily focused on development during that time, lacking adequate communication among stakeholders and access to sophisticated wind farm operations management systems.

A big step towards solving the challenge of inaccurate estimates came with the formation of the Power Curve Working Group in 2012 and the Consortium for Advancement of Remote Sensing Working Group in 2018. Wind industry stakeholders banded together to reduce prediction errors through continuous methodology adjustments, resulting in a decrease to under 5% of errors over the past few years.

The industry is now optimizing to reduce the uncertainty of pre-construction energy estimates, including measuring wind at higher heights to reliably use remote sensing devices, finding ways of applying nonstandard conditions on power output, and quantifying the effects of climate change on pre-construction estimates.

The factors behind overprediction

When calculating energy estimates, several critical factors tend to create the greatest challenges for accuracy. Last-minute changes to the turbine layout or hub height due to unforeseen permitting or construction issues, wind hysteresis, and project location can, of course, impact output. But the following considerations are frequently to blame for underperformance.

Availability

Pre-construction estimates usually assume an availability loss of 2%-3%, the warranted or contractual value established between the developer and the turbine manufacturer. This assumption does not include non-contractual availability losses due to high or low wind and temperature events or grid and balance of plant outages, scheduled maintenance, or environmental curtailment. Current actual availability averages around 4%-7% for a typical wind farm.

Wake effects

The wake effect is the impact of one upstream turbine on another downstream turbine as it extracts energy from the atmosphere and reduces downstream wind speeds. This expands the wake until it recovers to free stream velocity. The loss associated with wake effects is called "wake loss," and wake loss is highly dependent on prevailing wind direction, wind velocity, and turbulence intensity.

Interplant and neighboring-plant wake effects are typically calculated using numerical models validated against idealized and stable atmospheric conditions. In the real world, prevailing wind speed, direction, turbulence intensity, and atmospheric stability are constantly changing. So, numerical methodologies may fail to accurately account for the complex and nonlinear ways that turbine wakes interact with each other. These methodologies result in an increase in wake losses and a decrease in power generation of the overall wind farm.

As the world's fleet of onshore and offshore wind farms increases, existing wind farms may be exposed to wake effects from new, neighboring wind farms. The best wind farm locations include a strong wind resource, developable and accessible land, and proximity to transmission lines and roads. As the wind industry grows, preferred locations become saturated with numerous wind farms. An upwind wind farm generates wake effects that reduce the energy generation and revenue—and increase structural fatigue and stress—of a downwind wind farm. Given there are currently no state or federal statutes or regulations regarding wind waking or relative wind rights, it is important to include the impact of upstream wake on any investment planning.

Another factor that affects the performance of wind farms is blockage. The blockage effect is when wind approaches turbine arrays, and its flow slows down and diverts around the array. Traditionally, the wind industry has used the "wakes-only" approach, where a turbine can only affect downstream turbines. In 2019, some independent engineers started using numerical models combined with computational fluid dynamics that include blockage effects on the annual energy production of wind farms.

Turbine underperformance

For the wind projects to hit their forecasted power output, owners and operators must ensure that their turbines operate at peak performance to ensure optimal energy extraction from the available wind resource. But, given the vast quantity of supervisory control and data acquisition (SCADA) at a wind farm and the variability of the wind resource, performance issues are not easily identified. The main factors affecting the wind turbines' underperformance are yaw and blade pitch misalignment, sub-optimal control systems, and power curve performance.

Every turbine has the technology to measure wind direction and adjust the nacelle orientation and blade pitch to maximize the power extracted from the flow. Yaw and blade pitch misalignment occurs when the wind turbine and its blades are not directly facing the wind direction. A difference between the measured wind direction and the nacelle position of the turbine is known as "yaw error." When the yaw error is zero degrees, the turbine is ideally pointing directly into the wind.

Dynamic yaw misalignment occurs when the wind changes direction due to its stochastic nature, and the wind turbine cannot react instantaneously to these changes. When the measured yaw error reaches a turbine-specific limit for a defined period, the turbine control system uses the yaw motors to move the nacelle back to zero degrees error, temporarily eliminating the dynamic yaw misalignment.

Static yaw misalignment is more difficult to detect. It occurs when the turbine is not pointing directly toward the wind direction, even when the yaw error is at zero degrees. Physical wind vane misalignment and software issues are the leading causes of yaw misalignment, which is invisible to the turbine controller.

Analysis of various onshore wind farms shows that a 5-degree static yaw misalignment can lead to 2% energy loss. This loss exponentially increases to 13% if the yaw misalignment increases to 15 degrees. On top of this, yaw misalignment affects the lifetime of a wind turbine through asymmetric loading on blades and rotors, as well as higher maintenance and repair costs.

Pitch misalignment occurs due to human error in setting the blade pitch angle reference at the very end of the manufacturing process, hub manufacturing tolerances that move the blade axes from the intersection point on the rotor axis, and sub-optimal control settings. SCADA data analysis and visual inspection can identify pitch misalignment issues. These issues reduce the optimum power production of the turbine and decrease its lifetime due to higher unbalanced loads. Pitch misalignment of 5 degrees can contribute to 15% energy loss.

Another factor that causes turbine underperformance is the actual measured power curve deviating from the reference power curve in real-world atmospheric conditions. Typically, a power curve is only strictly valid for a subset of all atmospheric conditions, also known as the inner range conditions. The wind energy industry performs power performance tests on wind turbines to test the site-specific power production of wind turbines.

These tests calculate the difference between the power predicted by the reference power curve (often provided by the turbine manufacturers) and actual power production at different wind speeds. However, these power performance tests and associated warranties are usually limited to inner range conditions. In reality, wind turbines operate in the outer range frequently, leading to power-production deviations from the reference power curve.

Poor measurement campaign

A high-quality wind measurement campaign is crucial to reducing uncertainty in predicting the energy production from a wind project and, consequently, improving bankability in terms of better financing terms and reducing project risk. A measurement campaign involves identifying wind characteristics such as speed, direction, turbulence, and shear across the site while considering the long-term climate attributes. Project size, terrain complexity, turbine hub height, layout density, and atmospheric conditions dictate the number of measurement locations, heights of measurements, and type of observation devices (meteorological mast and remote sensor) needed for a measurement campaign.

These tips can keep the measurement uncertainty as low as possible:

- For a medium-complexity site, the average weighted distance of turbines to the observation locations should be less than 2 km. If the site has significant complexity, a 1 km space is more appropriate.
- Vertical extrapolation from the highest elevation of the measurement device to the hub height is optimal when the distance is less than 20–30 meters.
- Remote sensing devices such as LiDAR (light detection and ranging) and SoDAR (sonic detection and ranging) can be collocated with meteorological masts for at least a year to create shear profiles that cover the entire swept area of the turbine at various locations of the site.
- More than one measurement location is needed, and careful attention to placement is essential in complex terrain.

Global warming

Climate change and extreme weather are linked to events that can cause downtime, damage to infrastructure, and lower turbine lifetimes. On top of that, climate change may influence wind energy production, as it can alter current wind patterns' spatial and temporal characteristics. Since wind energy scales with the cube of wind speed, slight differences in wind speed can significantly affect the energy extracted. Additionally, as expected with climate change, increasing air temperatures will lead to slight declines in air density and power output.

Our teams work with climate experts who provide site-specific analysis to quantify climate risk for a given project, but this practice is not yet widespread.

Operational wind farm performance

We analyzed the operational performance of eight wind farms across the United States. The capacity of each project varied from 70 to 200 MWs, with the commercial operation date (COD) ranging from 2007 to 2018. Figure 1 shows the approximate locations of these projects. The analysis considered a total of 32 years of wind farm data. The first year of operation was ignored to avoid issues related to staged construction or other "teething" issues.

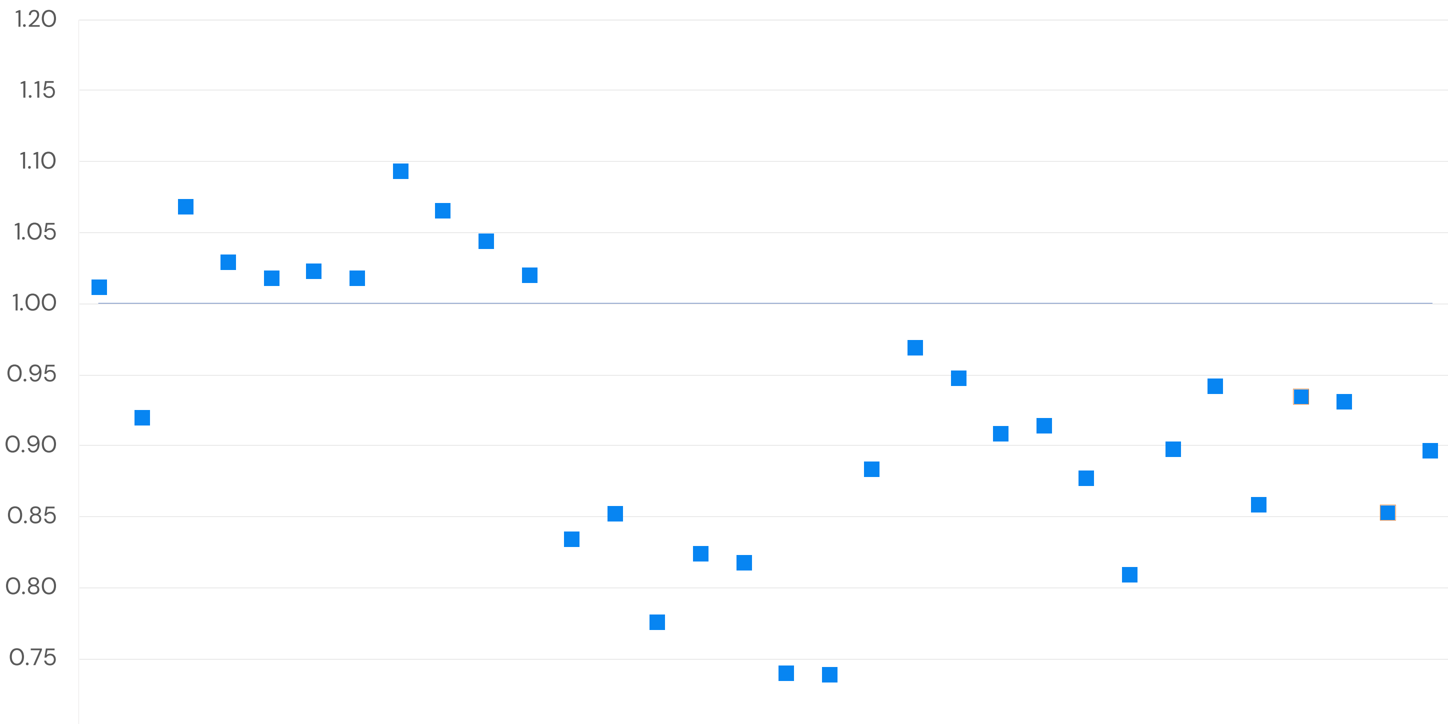
Figure 1. Approximate location of wind farms studied.

Source: ICF

The annual energy production for each project is weather corrected to take the effects of resource variability out of the analysis. This is done based on the best correlation found between the operational data and long-term reanalysis datasets such as Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) and ERA5. Their corresponding pre-construction P50 normalizes actual energy production at a given site, as shown in Figure 2.

Values greater than 1 represent projects that performed better than their pre-construction estimate for a given year. Values below 1 represent projects that underperformed compared to their pre-construction estimate for a given year. In this analysis, wind farms that overperformed their pre-construction estimate have one thing in common—great availability—specifically gross energy availability between 97% and 99%. Other contributing factors are well-designed measurement campaigns, lack of neighboring wind farms, and activities that boost the wind farm's energy production, such as installing vortex generators and updating the wind turbine control software.

Figure 2. Weather-corrected production normalized by P50 pre-construction energy estimate for 32 wind farm years.



Source: ICF

The biggest contributors

The most significant contributors to the underperformance of wind farms are low availability and wake effects. Wind farms with low availability commonly suffer from a large number of major component repairs and replacements. Major components include generators, main bearings, gearboxes, blades, pitch systems, yaw systems, and pad mount transformers. Some turbine models are more prone to require maintenance than others, and in some cases, wind turbines need to be decommissioned due to unforeseen events like fires. These types of events have significant effects on the availability and financials of a wind farm. Also, availability is commonly affected by environmental and grid curtailment.

Wake effects are another vital factor that we often encounter when analyzing underperforming wind farms. New wind farm developments in the vicinity of a given project, underpredicting internal and external wakes, and blockage issues all significantly reduce the annual energy production of wind farms.

Reaching an accurate estimate for a wind project's performance is no simple task. With so many factors and variables to consider, it's no wonder that assessments have historically missed the mark. But today's calculations, when done thoroughly and correctly, can ensure far greater accuracy—and profitability.

About the author

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Dr. Chime is a mechanical engineer with more than 10 years of experience in the renewable energy field. Her academic career spans wind energy, hydrokinetic power, and renewable fuel combustion. After finishing her PhD program at the University of Washington, her passion for wind energy led her to this industry. She has extensive experience in wind resource assessment, production analysis of pre-construction and operational wind projects, layout and measuring campaign optimization, and desktop review of due diligence IE reports. She has served as an independent engineer and owner's advisor for over 2 GW globally-installed wind energy capacity and nearly 3 GW of globally-installed renewable energy capacity.

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