2012 BACKCAST STUDY

Verifying AWS Truepower's Energy and Uncertainty Estimates

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EXECUTIVE SUMMARY

The renewable energy industry depends on accurate assessments of the energy production capabilities of wind and solar power plants. Over the past two decades, AWS Truepower, LLC, has prepared energy production estimates for more than 60,000 MW of wind and solar plants in over 60 countries. The 2012 Backcast Study is part of AWS Truepower's continuous process improvement program, which seeks to ensure that the company's energy estimation methods are as accurate as possible.

As in the previous 2009 Backcast Study, the 2012 Backcast Study compares AWS Truepower's current methods for estimating energy production with operational experience. The study sample has more than doubled since 2009 to include 106 plant years from 24 operational wind plants. It encompasses 12 turbine models representing most of the major turbine manufacturers.

The 2012 Backcast Study finds that AWS Truepower's current methods are broadly in line with operational experience. However, a mean windiness-corrected "underperformance gap" of 3.6% (±1.4%) is observed. After a thorough evaluation of possible factors contributing to the differences, AWS Truepower concludes that the most important factor, accounting for approximately two-thirds of the mean gap, is the deviation of turbine output from advertised power curves. Greater-than-expected blade degradation plays a secondary role.

Furthermore, AWS Truepower observes good overall agreement between its current uncertainty estimates and the spread of the 2012 Backcast Study results. However, the uncertainty in long-term average production is found to be slightly lower than the corresponding variance in actual production.

Lessons learned are being incorporated into AWS Truepower's methods. In the typical case, assumed losses will increase by about 2.7%. Uncertainties in the long-term (e.g., 10-year) energy production will increase slightly because of an increase in the uncertainty associated with plant performance; however, the wind resource uncertainty will decrease. The annual uncertainty will remain largely unchanged. Effects on particular projects will vary.

BACKGROUND

Wind plant underperformance versus pre-construction estimates has been cited as one of the top challenges facing the wind industry[1]. Over time, deviations of operational experience from long-term wind energy production forecasts can reduce returns on existing investments, create difficulties in securing financing for new wind projects, and highlight the need to carefully evaluate the acquisition of operating assets. Previous studies[2] have found that North American wind plants installed before 2008 performed, on average, about 10% below their pre-construction forecasts. AWS Truepower's own internal assessments supported this finding, and led to significant changes in the company's methods and assumptions, particularly regarding availability and other losses[3]. Figure 1 sets these changes in the context of the overall evolution of AWS Truepower's methods since 2000.

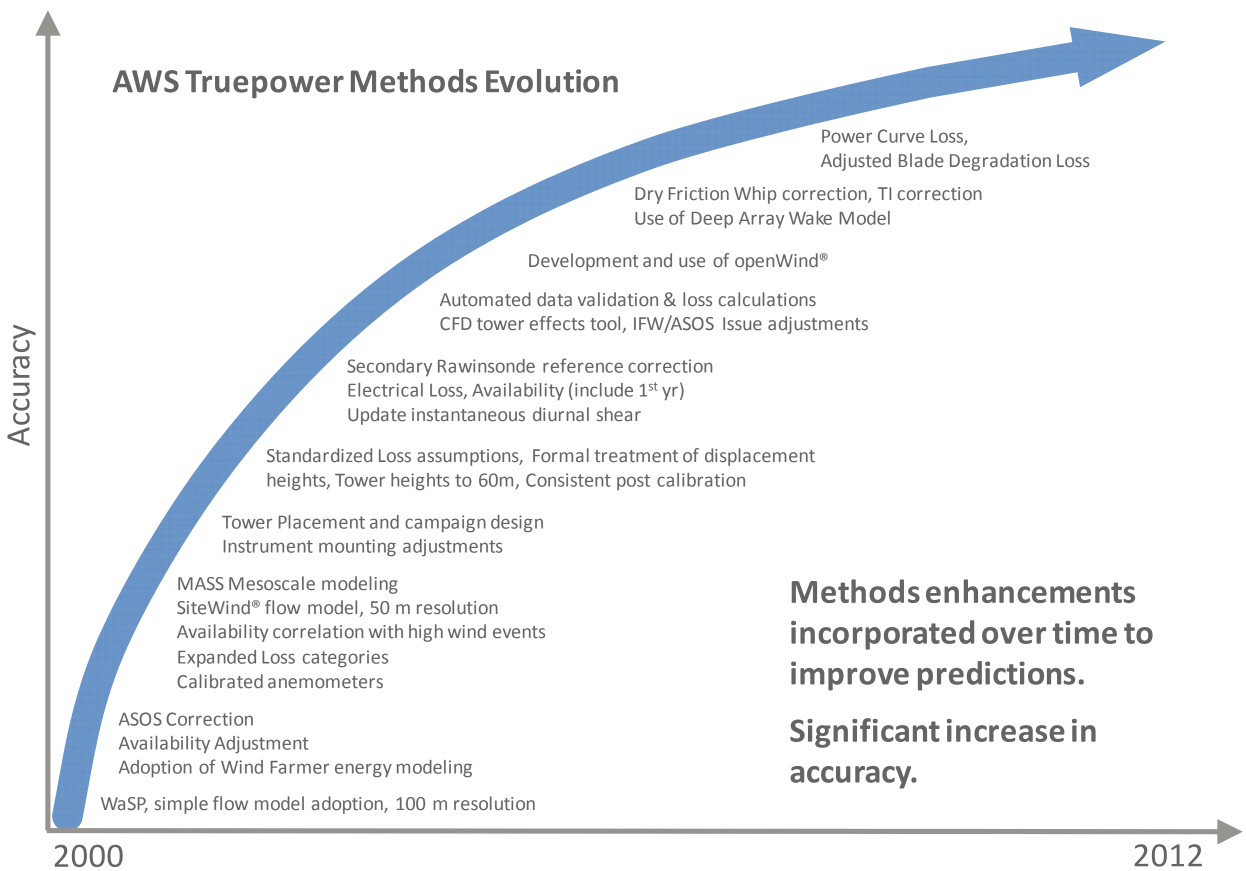

Figure 1. Evolution of AWS Truepower energy production estimation methods

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[1] J. Eber, JP Morgan, AWEA Finance Conference, October 2007

[2] J. Deloney, "Understanding U.S. Wind Fleet Underperformance," *North American Windpower*, August 2008

[3] E. White, AWS Truepower, Closing the Gap on Plant Underperformance, 2008, 2009, 2010.

PLANT DATABASE

AWS Truepower partnered with wind plant developers, owners, and operators to obtain both pre-construction wind resource data and operational energy production data for existing wind plants. Data for a total of 24 wind plants and 106 plant years from 10 states and provinces in North America were acquired. This more than doubled the size of the previous Backcast Study database (Table 1). The plants are believed to be representative of plants built and operated in North America since 2001. They are in a variety of wind resource regimes, terrain types, and land cover, and represent most major wind resource areas including Texas and the southern Great Plains, Upper Midwest, Northeast, Inter-mountain West, and California. The plants span a range of rated capacity from 10 MW to 210 MW, and have been in operation an average of 4.4 years since their Commercial Operation Date (COD). Figure 2 shows the frequency distribution of the number of years of operation. Twelve turbine models from eight manufacturers are represented (Figure 3).

Parameter	2009	2012
Wind Plants	11	24
Total Plant Years	45	106
Average Years per Plant	4.2	4.4
Min-Max Years per Plant	1 - 7	1 - 11
Average Plant Capacity	74 MW	82 MW
Min-Max Plant Capacity	10 – 160 MW	10 – 210 MW

Table 1. Summary of the 2009 and 2012 Backcast Study datasets

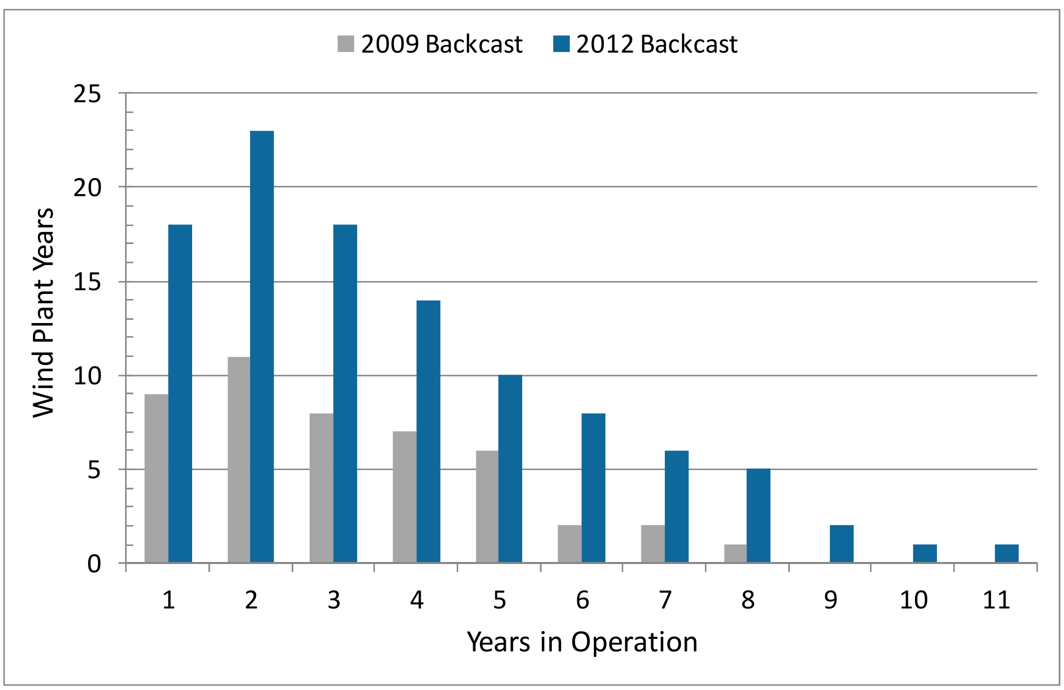

Figure 2. Distribution of number of years of operational data since COD in the 2009 and 2012 Backcast datasets

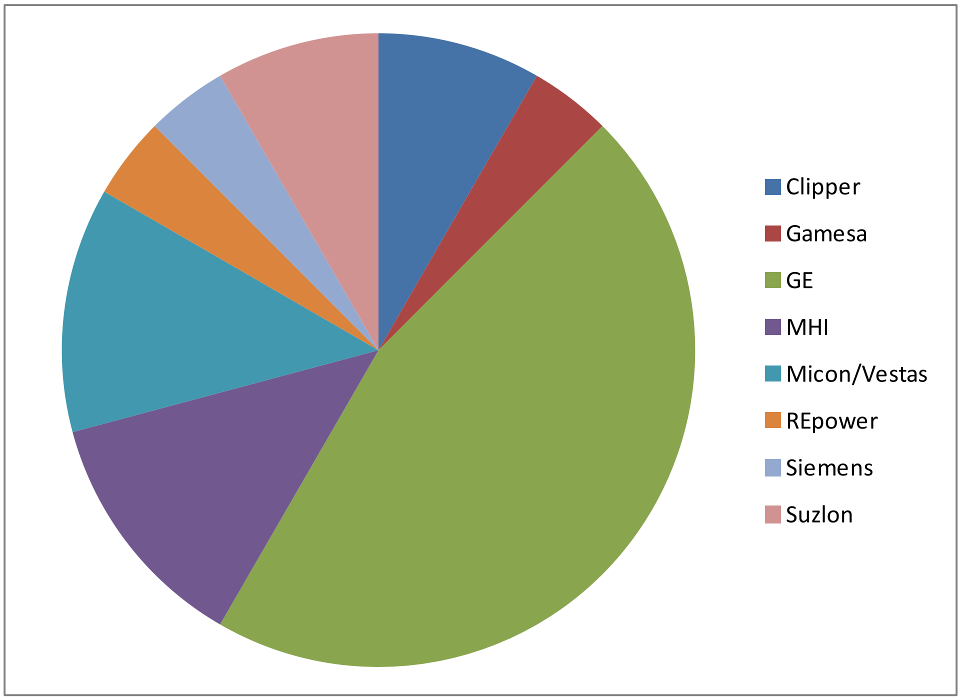

Figure 3. Representation of turbine manufacturers in the 2012 Backcast Study dataset

METHOD OF ANALYSIS

The main steps in the analysis were as follows:

Step 1. The monthly plant production data were quality-controlled, adjusted for relative windiness, and aggregated to annual values. The windiness correction, which is part of AWS Truepower's standard procedure for long-term energy production estimates based on operational data, is intended to remove the effects of short term variations in mean wind speed on plant production.

Step 2. For each plant, AWS Truepower performed an independent energy production estimate using the available pre-construction wind resource data and AWS Truepower's current methods. The wake effects of neighboring wind plants were estimated with the AWS Truepower Deep Array Wake Model (DAWM), taking into account each neighboring plant's installation date.

Step 3. The production ratio (PR) – defined as the actual (operational) energy production divided by the expected production – was calculated for each plant year, and the overall mean PR and its standard error (uncertainty in the mean) were determined. A PR of 1.0 indicates that the actual wind plant production, after correction for windiness, equals the expected energy production. A PR of less than 1.0 indicates the plant produces less power than expected. An investigation was carried out to determine the possible causes of any statistically significant gap between the mean observed PR and the ideal value of 1.0, as well as the variations between plants and from year to year.

KEY FINDINGS

The main results are presented in Figure 4. This chart shows the frequency distribution of PR values for all 106 plant years. The bars represent the number of plant years that fall within each PR bin of width 0.025. For example, 10 plant years have a PR in the bin centered on 0.9, which includes values from 0.8875 to 0.9125.

The mean PR for all plant years is 0.964. This corresponds to an underperformance gap of 3.6%. This deviation is less than the typical uncertainty of long-term energy production estimates (about 8%). Nevertheless it appears to be statistically significant. Based on a Monte Carlo analysis of random draws of equivalent data sets, the standard error in the mean is 1.4%.

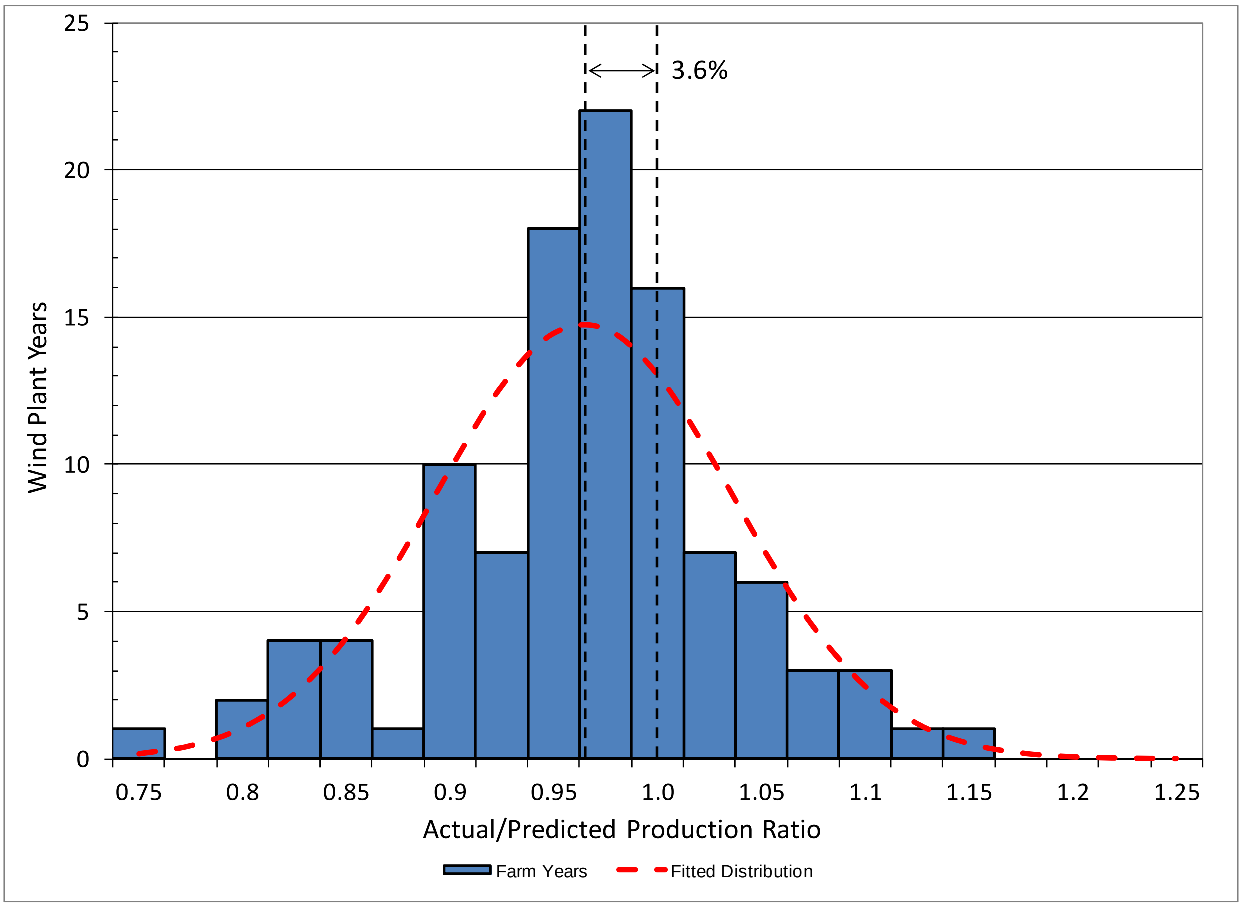

Figure 4. Frequency distribution of production ratios for the 2012 Backcast Study dataset

AWS Truepower conducted a thorough analysis of the potential causes of the observed deviations between actual and expected plant performance. Figure 5 summarizes the possible causes, which include errors in the expected wind speed, expected losses, the production data, the analysis method, and turbine performance.

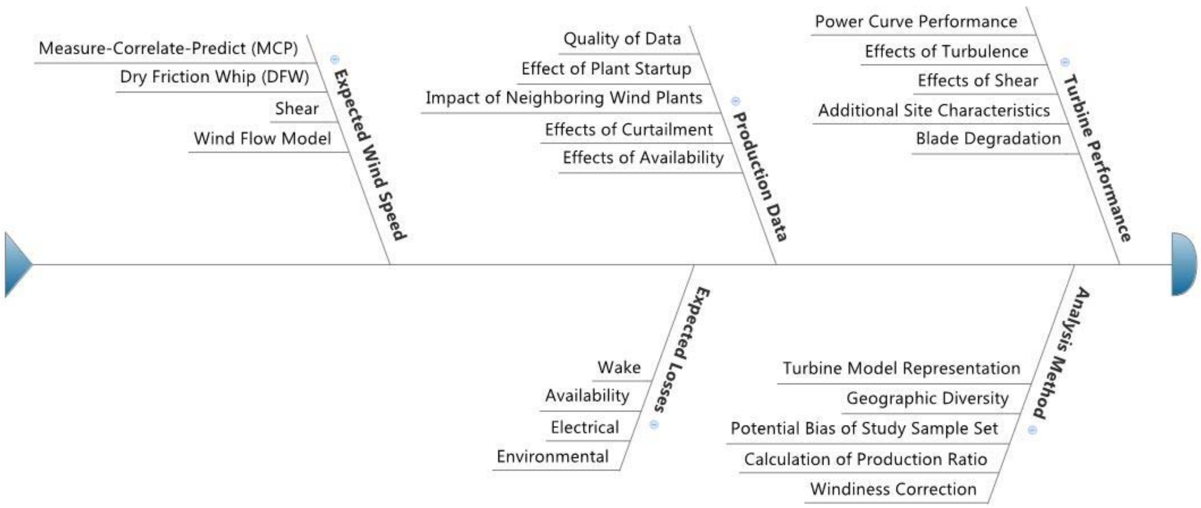

Figure 5. Summary of potential sources of deviations between expected and actual plant performance

Factors Found Not to Contribute to Mean Plant Underperformance

A number of factors were found not to contribute in a significant way to the observed mean plant underperformance. In particular:

- AWS Truepower reviewed its meteorological and wind flow modeling procedures and found that, on average, they exhibit no significant bias[4].
- A review of availability data for the Backcast Study projects as well as other independent data sources supports AWS Truepower's current availability-related loss assumptions.
- Grid curtailment, to the extent it was documented, was found to have an insignificant impact on the mean performance gap.
- Electrical losses were found to be in line with independent third-party electrical assessments.
- Previous research has established that wake losses predicted by DAWM align well with observations for a sample of onshore and offshore projects[5]. Furthermore, in the present study, no significant relationship was found between PR and predicted wake losses, indicating that any bias in the DAWM is relatively small. It was concluded that wake modeling does not contribute significantly to the underperformance gap.
- As in previous studies, it was noted that plant production tends to fall below expectations in the first year due to plant startup problems. This issue is addressed in AWS Truepower's methods by applying greater first-year availability losses.

[4] Wind Flow Model Performance, 2012, AWS Truepower

[5] The openWind Deep-Array Wake Model, 2012, AWS Truepower

- In contrast to the findings of some other consultants, AWS Truepower found no consistent relationship between either wind shear or turbulence and plant performance (Figure 6). Other site characteristics, such as elevation and air density, likewise exhibited no significant correlation.

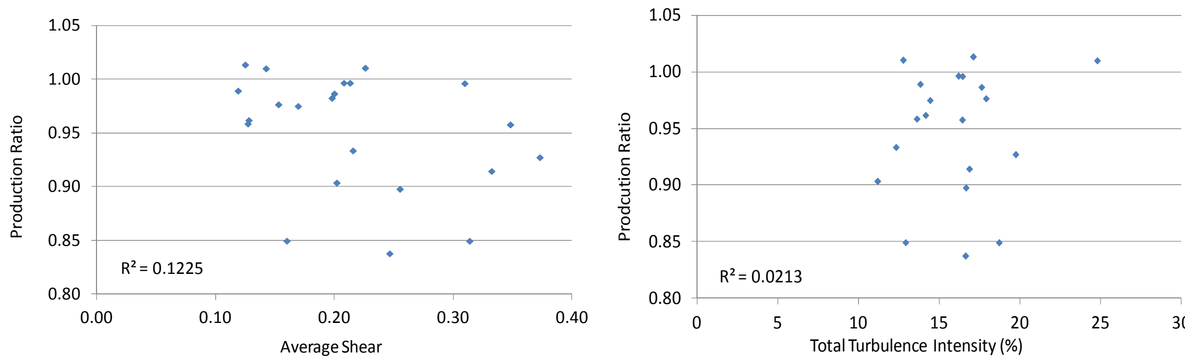

Figure 6. Observed relationships between PR and mean wind shear exponent (left) and turbulence intensity (right). Each point represents the PR for a single plant averaged over its period of operation.

The analysis revealed two factors that appear to contribute to the gap between actual and expected energy production: a deficit between the measured and advertised output of turbines in power performance tests, and higher than expected blade degradation. Together these factors explain about three-quarters of the observed plant underperformance in the Backcast Study.

Turbine Underperformance in IEC-Compliant Power Curve Tests

It is common practice to test a small number of newly installed wind turbines at a wind plant site under controlled conditions defined by the International Electrotechnical Commission (IEC). AWS Truepower had previously assumed that most turbines would achieve close to 100% of expected performance in these tests. To test this assumption, the results of 24 IEC-compliant tests were collected for 8 different sites. The tests were performed either by AWS Truepower or third-party consultants. For each test, the measured and advertised power curves were used to calculate the theoretical annual energy production (AEP) for a range of mean speeds and a Rayleigh speed frequency distribution. The AEP values were then compared. It was found that, on average, the AEP based on the measured curve is 2.4% below that based on the advertised curve for annual average speeds between 5 m/s and 10 m/s. This finding is statistically significant (with a standard error of 0.8%), is consistent with that reported by other consultants, and appears to apply to a wide range of turbine models and manufacturers.

AWS Truepower concludes that turbine underperformance accounts for about 2.4% of the 3.6% mean plant underperformance gap.

Wind Turbine Blade Degradation

Wind turbine blades tend to degrade over time due to a variety of mechanisms including sun exposure, wind-blown dirt and sand, and the freeze/thaw cycle of moisture within micro-cracks on the blade surface. This degradation reduces turbine output. AWS Truepower had previously assumed (based on a cost-benefit analysis) that blades would be refinished approximately once every 5 years. Conversations with plant operators and blade suppliers indicate that a more typical refinishing schedule is once every 10 years. This implies that the 10-year average blade degradation loss is 0.3% greater than previously estimated. For example, for sites where the blade degradation had previously been found to be 0.3%, the new value would be 0.6%.

Uncertainty and Interannual Variability

There is uncertainty in all energy production estimates resulting both from uncertainties in the long-term wind resource and plant performance and from variations in windiness and plant operating efficiency from year to year. The analysis of these factors determines the minimum expected production in any particular year and over the plant life at various confidence levels (e.g., the one-year P99).

To gauge the accuracy of its uncertainty methods, AWS Truepower compared its uncertainty estimates with the observed variance in plant performance for the Backcast projects. It was concluded that the current methods slightly understate the plant-life uncertainty, whereas they accurately capture annual variations in energy production.

To explain these findings, AWS Truepower carried out a thorough review of all components of uncertainty. The following three factors were identified as requiring adjustment.

- There is significant variability in turbine performance that was not previously accounted for. We found a standard deviation of 2.4% between turbines in IEC-compliant power performance tests. This value is consistent with other industry datasets.
- Plant availability and availability-associated losses vary considerably from year to year and between projects. With the addition of data in the Backcast Study, along with third-party data sets, these uncertainties can be more accurately assessed.
- An analysis of wind speeds recorded by ASOS and rawinsonde stations indicates that the interannual variability in mean wind speeds at most sites in the United States is smaller than previously assumed.

CONCLUSIONS AND METHODS CHANGES

The 2012 Backcast Study confirms that AWS Truepower's energy production estimates based on current methods are generally in line with operational experience. The mean underperformance gap of 3.6% is smaller than the typical uncertainty in long-term energy production estimates. Nevertheless, the gap is statistically significant.

AWS Truepower's analysis indicates that turbine performance is the main cause of the observed plant underperformance. A review of IEC-compliant power performance tests indicates that turbines fall below their advertised power curves by an average of 2.4%. An additional loss of 0.3% is associated with blade refinishing practices. These two factors combined explain 2.7%, or three-quarters, of the underperformance gap. The remainder is well within the 1.4% uncertainty band of the Backcast process and therefore requires no further correction (Table 2).

Factor	Impact
Power Curve Loss	2.4%
Change in Blade Degradation Loss	0.3%
Remaining Performance Gap	1.0%

Table 2. Summary of effects of additional losses on mean plant underperformance

AWS Truepower also finds that its current long-term uncertainty estimates are slightly too low. This appears to be due mainly to an underestimation of the uncertainty in plant performance (including turbine performance and availability). Offsetting this, it appears that interannual variations in windiness have been overestimated. Adjusting these factors increases the long-term uncertainty while keeping the annual uncertainty approximately the same (Figure 7).

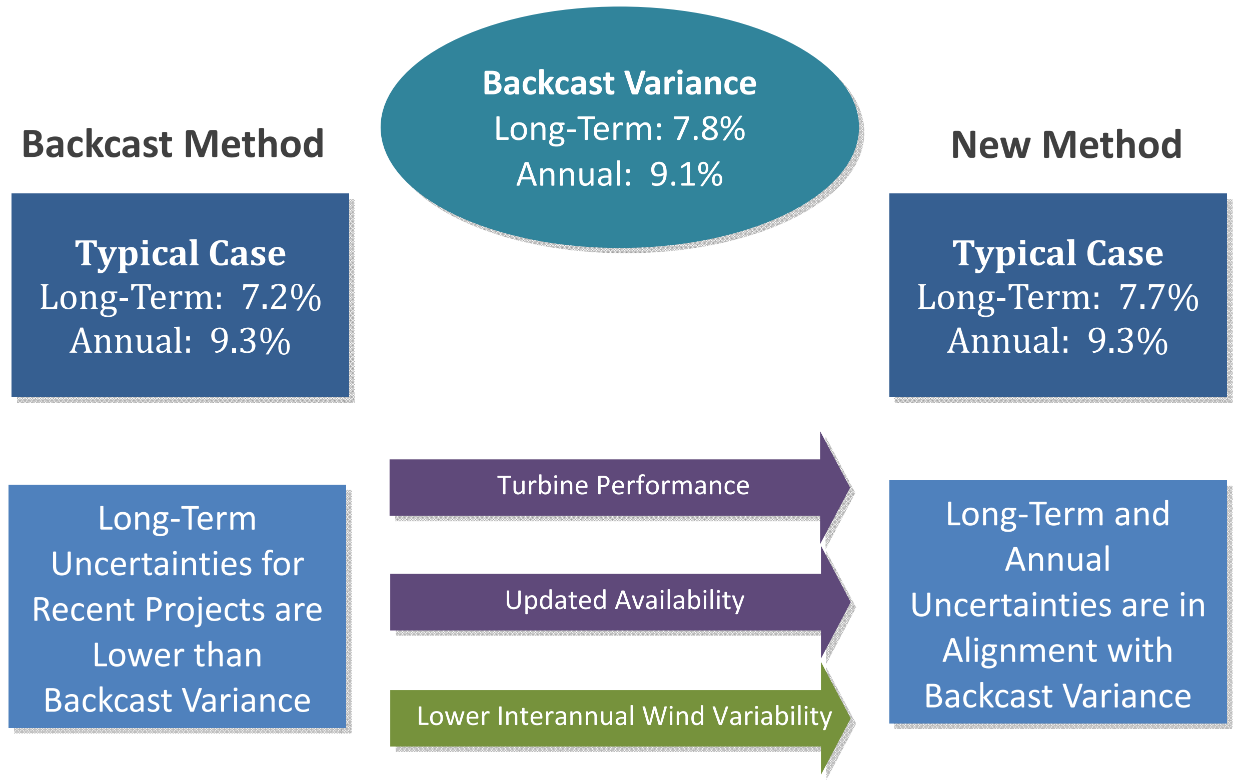

Figure 7. Flowchart of uncertainty review and adjustments

These changes, along with a variety of other process improvements having a minimal effect on expected production estimates and uncertainty, are being incorporated into AWS Truepower's methods as of May 2012. In the typical case, the mean or expected energy production will decrease by 2.7%. This reduction may be mitigated upon consideration of site-specific information. The uncertainty in long-term energy production will increase slightly, while the uncertainty in annual production will remain largely unchanged.

AWS Truepower will continue to assess and verify its methods against industry trends and operational performance to ensure continuing confidence in its energy production estimates.

The authors wish to thank AWS Truepower's clients and others who have shared their data for this study.