NEW US WIND ENERGY POTENTIAL ESTIMATES

Background and Explanation of Changes from Prior Estimates

Michael Brower, CTO

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AWS Truepower, LLC | 463 New Karner Road | Albany, NY 12205

awstruepower.com | info@awstruepower.com | +1-877-899-3463

INTRODUCTION

AWS Truewind and the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) have developed new wind potential estimates for each of the lower 48 states of the United States (US) based on AWS Truewind's ***windNavigator®*** system, the only seamless, high-resolution wind resource dataset available for the US.

The collaborative project, which was put in motion to help support federal and state policy initiatives, provides the first comprehensive state-level assessment of the onshore wind resource potential since 1993. The estimates indicate the potential megawatts of rated capacity that could be installed in each state in various ranges of gross capacity factor (without losses), assuming a generic turbine model with a hub height of either 80 m or 100 m. The gross capacity factor (CF) data were developed by AWS Truewind from high-resolution wind resource maps and modeled historical wind speed frequency distributions. The analysis of wind potential, including land area exclusions, was carried out by NREL.

It is important that members of the wind energy community understand the process used in creating the new potential estimates and the reasons why, in some cases, estimates differ from previous figures published or circulated by NREL.

This document is divided into three main sections and aims to provide transparency to all industry stakeholders. Section I describes how the gross CF data were developed by AWS Truewind. Section II discusses the main reasons why some of the new estimates differ from previous estimates, and Section III provides an in-depth explanation of the differences for certain key states.

In addition to the new estimates, wind resource maps for all 48 states will be released by NREL. These maps employ a slightly different color scheme than AWS Truewind's *windNavigator* application, however, the data and values are the same.

Tables, charts and PDF maps are available online from AWS Truewind's *windNavigator* website.

METHOD OF ESTIMATING CAPACITY FACTORS

The estimates of gross CF were created using two wind resource databases developed by AWS Truewind: a set of seamless, high-resolution mean wind speed maps of the United States (available through AWS Truewind's *windNavigator* system, www.windnavigator.com), and a modeled historical wind speed data set called *windTrends*. The two data sets were combined to produce a speed frequency distribution for each 200 m grid point in the lower 48 states. These distributions were then passed through the assumed turbine power curve to estimate the CF. The three main elements of this process are described in more detail below.

windNavigator® Maps

The method AWS Truewind uses to create high-resolution wind resource maps has been described often elsewhere (see windNavigator FAQ for details). Here we focus on the process used to combine various state and regional maps into one seamless map of the lower 48 states, and the adjustments applied to the seamless map to reduce discrepancies with observations.

The various "raw" state and regional maps can be divided into two groups: (1) those previously mapped for NREL and the WPA program, which include all the Western states, the Mid-Atlantic states, the Northeastern states, and various Midwestern states including Indiana, Ohio, Illinois, Missouri, and Arkansas; and (2) those mapped by AWS Truewind but not previously released (including Texas, Minnesota, North and South Dakota, Iowa, and the Southeastern states). The process AWS Truewind followed to combine and adjust the maps in both groups is described below.

1. Certain adjustments that had been made to published resource maps based on prior validation were removed. The motivation was to enable AWS Truewind to update the validation and implement new adjustments for the entire country using additional observational data and a new bias-correction method.

2. Problems discovered in the elevation data of some older maps were rectified, and the resolution of the Pacific Northwest maps was updated from 400 m to 200 m. The procedures for making these adjustments shifted some terrain features laterally up to several hundred meters, but otherwise had little impact on the wind resource estimates.
3. The Southwest and Northeast were remapped with updated techniques and assumptions. AWS Truewind also mapped other states that had not previously been mapped or released.
4. Adjoining areas of states and regions mapped at different times were blended using a distance-weighted average across zones approximately 10-20 km wide at the boundaries of one or both areas. All states were projected from UTM to a common, geographic coordinate system.
5. The combined speed maps at 50 m, 70 m, and 100 m heights were projected to 60 m, 80 m, and 100 m through a power-law interpolation.
6. A bias-correction procedure was applied to the map speeds to reduce discrepancies with observations. This procedure was as follows:
    a. A data base of mean wind speeds for just over 1300 ASOS stations and tall towers was created. The data came from a wide range of sources, including the National Weather Service, various state-level wind resource assessment programs, and private clients. In an especially important decision, pre-ASOS weather stations were excluded because it has been found that they tend to overstate wind speeds, especially in low-wind-resource areas.
    b. For each station, the mean wind speed was projected to 80 m height using either the observed wind shear exponent (where available), an exponent derived from the wind maps, or an exponent estimated from regional experience and local land cover and topography.
    c. A bias was calculated between the map and the extrapolated-observed speed for each station. Where a significant deviation between the actual and modeled elevation was observed, a correction was applied.
    d. A software program interpolated the biases to create a bias-correction map. Note that this process was not intended to eliminate the bias at every station, as this could produce unreasonable adjustments in some areas, but to eliminate *spatially correlated* biases.
    e. Objective estimates of the adjusted map's mean bias and uncertainty margin (one standard error) were derived by withholding each tower in turn from the adjustment. After accounting for uncertainties in the observed-extrapolated speeds, AWS Truewind concluded the mean bias to be virtually zero and standard error to be about 0.35 m/s.
    f. The bias correction was applied to the 60 m and 100 m maps in such a way as to preserve the expected shear exponent between the three heights.

Figure 1 presents a scatter plot comparing the predicted and observed/extrapolated 80 m mean speeds for all stations for the final, adjusted map.

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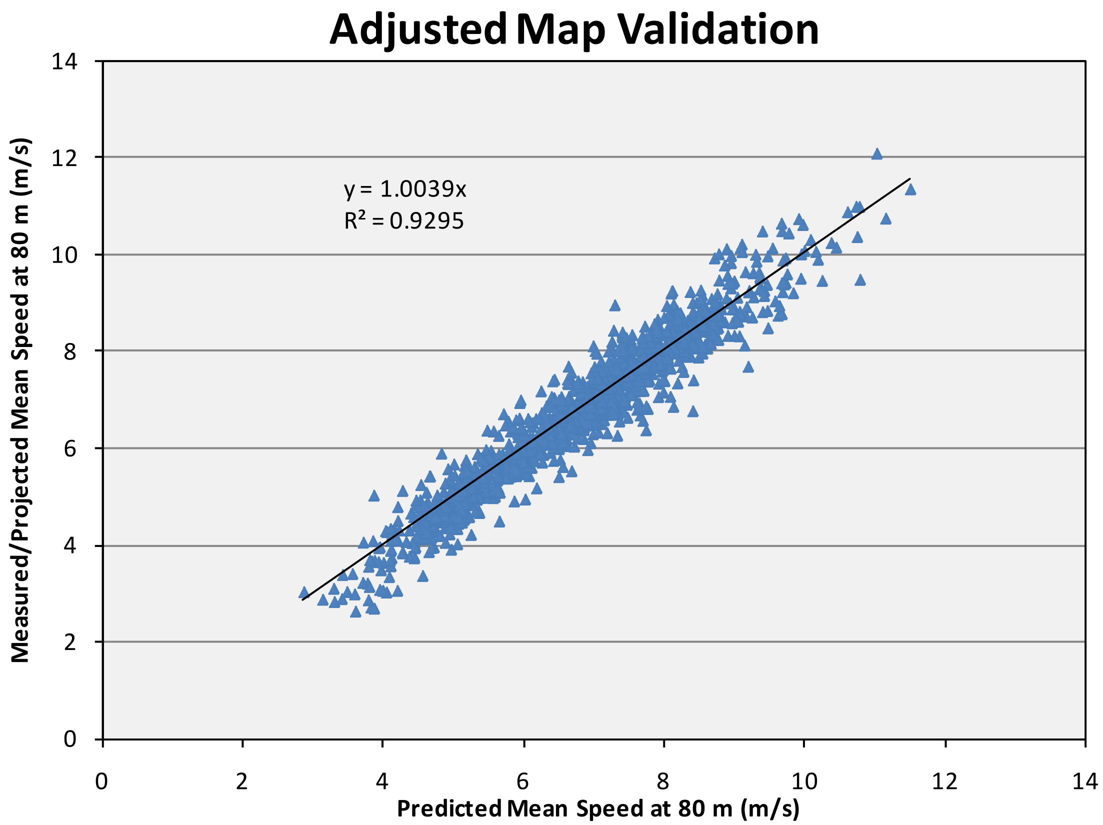

Figure 1. Scatter plots of predicted speeds from the adjusted national wind map and observed/extrapolated mean wind speeds at 80 m.

windTrends Data Set

windTrends is a data base of weather conditions for the conterminous United States and southern Canada spanning 1997 to the present. It provides, on a 20 km grid, a snapshot of weather every hour at several heights above ground. Included in each record are variables such as wind speed, direction, temperature, pressure, humidity, solar radiance, precipitation, and cloud base. The data set was created with the Mesoscale Atmospheric Simulation System (MASS), a numerical weather prediction model, which was run in a sequence of two-week periods starting from an initialization by the NCAR/NCEP Global Reanalysis (NNGR) data set, and assimilating rawinsonde data every 12 hours to control model drift.

From the windTrends data set, AWS Truewind created a speed frequency distribution for every grid point at heights of 80 m and 100 m. This distribution was scaled to match the mean wind speed from the windNavigator maps.

Power Output Conversion

The gross CF at each 200 m grid point was calculated by combining the scaled speed frequency distribution with a power curve for a composite IEC Class II wind turbine. The power curve was adjusted to the mean air density at each point, as estimated from the mean temperature and elevation. No losses were subtracted. The power curve for standard sea-level air density is presented in Figure 2.

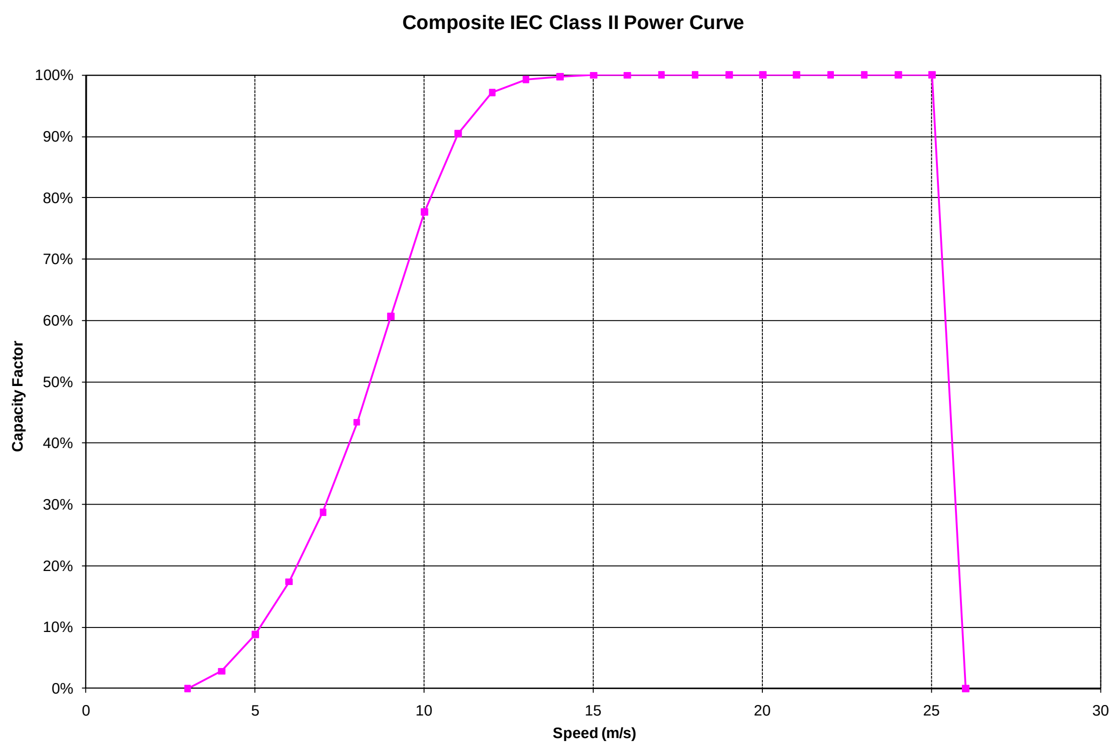

Figure 2. Power curve at standard sea-level air density used to estimate capacity factor.

There is not enough plant production data available at this time to permit a direct estimate of the error margin of the predicted gross CF. Based on the uncertainty in the mean speed, however, and allowing for deviations in the speed frequency distributions, AWS Truewind estimates the uncertainty in gross energy production to be about 10% (assuming a plant with the same power curve and hub height). The uncertainty tends to be larger in low-resource areas both because the mean speed uncertainty is proportionately larger, and because the plant tends to operate more often on the steepest part of the power curve. When aggregated over a large region such as a state, it is likely the uncertainty is smaller (just as the mean bias of the speed map across the whole country is much smaller than the standard error for any given location).

COMPARING WIND POTENTIAL ESTIMATES

Previous estimates of wind energy potential were generally expressed in either square kilometers or megawatts (MW) of potential wind capacity in certain wind power density (WPD) bands or above a certain WPD threshold. The most widely cited statistic is the MW capacity for power class 3 and above, which corresponds to a WPD of at least 300 W/m^2 at 50 m height.

Three factors account for the bulk of the differences between the old and new estimates: the change in height from 50 m to 80 m; the conversion from WPD to CF as a measure of wind resource; and various map adjustments. These factors are discussed in the following sections.

Projecting from 50 m to 80 m

In comparing estimates at different heights, it is important to account correctly for wind shear. Assuming the same shear across the board can produce misleading results, as the shear actually varies a great deal depending on land cover, topography, and meteorological conditions.

To estimate the impact of shear on the wind potential, the mean shear exponent for each state was calculated for sites with a WPD of 300 W/m^2 at 50 m, i.e., the threshold between power class 2 and 3. The state-average shear exponent for these "class 3 threshold" sites ranges from a low of about 0.08

(Nevada) to a high of 0.24 (Nebraska). There are significant regional patterns. In the Southwestern states, where the shear is lowest, the mean is about 0.125, whereas in the Great Plains states, where it tends to be highest, it averages 0.219. Because of these differences, the average Southwestern site with a WPD of 300 W/m^2 at 50 m will have a WPD of 359 W/m^2 at 80 m, whereas the average Great Plains site with the same 50 m WPD will have a WPD of 406 W/m^2 at 80 m. The other regions of the country fall in between. These differences in shear have the effect of reducing wind energy potential estimates in the Southwest compared to other regions, and of increasing the estimates in the Great Plains compared to other regions.

Converting from Wind Power Density to Capacity Factor

The WPD represents the amount of power available for conversion to electricity. The CF represents the amount of power actually produced by the turbine, as a fraction of its rated capacity. Aside from the wind shear, the relationship between the two depends on a variety of factors, most important among them the turbine's power curve and the site's air density and speed frequency distribution.

Specifically, turbines at sites with a broader speed frequency distribution tend to produce less output for the same WPD because the turbines spend more time above their rated wind speed, at the top of the power curve. In this range, efficiency decreases with increasing speed because the turbines cannot increase their output beyond the rated capacity.

To gauge the impact of this factor on the state-level energy potential estimates, we looked at the turbine specific output, or energy-capture efficiency, which is defined as the annual turbine output per square meter of rotor area divided by the WPD at 80 m. For the same class 3 threshold sites defined previously, we found that the specific output varies from a low of 29.0% to a high of 34.5%, with a mean of 31.9%. Again, there are regional patterns, though they are somewhat less pronounced than is the case for wind shear. The average specific output is 30.8% for sites in the Northwest (the lowest) and 33.0% for sites in the Great Plains (the highest). These patterns most likely reflect the variability of wind resource.

The influence of shear and specific output on gross CF are summarized in Table 1 for class 3 threshold sites. Regions with a higher shear exponent and higher specific output have a greater gross CF.

Table 1. Mean shear, WPD at 80 m, specific turbine output, and gross CF, by region, for class 3 threshold sites.

Region	Shear Exponent	WPD at 80m (W/m^2)	Specific Output	Gross CF
Northwest	0.171	382	30.8%	36.2%
Southwest	0.125	359	31.6%	34.8%
Great Plains	0.219	409	33.0%	41.6%
Northeast	0.186	390	32.5%	38.9%
Southeast	0.160	377	32.3%	37.1%
All US	0.177	386	32.3%	38.2%

Wind Map Adjustments

The other main reason for differences between the old and new wind potential estimates is that adjustments have been applied to the wind resource maps. These adjustments fall into three categories: (1) some prior adjustments were removed, (2) some previously released states were remapped; and (3) the bias-correction process adjusted all states to varying degrees to bring the maps closer in line with available wind measurements.

The prior adjustments that were removed were confined to just a few states. The only state where they had a substantial impact is Arizona, where one large area of positive adjustment in the northeastern part of the state was removed. Small areas of positive adjustment in extreme southern Nevada, and small areas of both positive and negative adjustment in Michigan, were also removed.

Although some states (particularly the Southwestern and Northeastern states) were remapped, the bias-correction process accounted for the bulk of the changes. Table 2 summarizes the changes for class 3 threshold sites in different regions of the country. There were moderate increases in the estimated wind resource in the Southwestern and Great Plains states, and substantial decreases in other regions.

As a rule of thumb, a 1% increase or decrease in mean speed produces a 2% increase or decrease in turbine output.

Table 2. Mean speed adjustments at 80 m for class 3 threshold sites (defined as 300 W/m^2 adjusted WPD at 50 m).

Region	Unadjusted Speed at 80 m (m/s)	Adjusted Speed at 80 m (m/s)	Speed Change (m/s)	Speed Change (%)	Est. CF Change (%)
Northwest	7.69	7.31	-0.37	-4.9%	-9.8%
Southwest	7.06	7.24	0.18	2.6%	5.2%
Great Plains	7.45	7.58	0.14	1.8%	3.6%
Northeast	7.65	7.27	-0.38	-5.0%	-10.0%
Southeast	7.64	7.12	-0.52	-6.8%	-13.6%
All US	7.54	7.30	-0.24	-3.2%	-6.4%

Aggregate Impact of Changes on Wind Potential Estimates

At any given site, all three factors described here may, to varying degrees, affect the estimated energy output of a wind project. How this affects the MW wind potential above a certain threshold of capacity factor depends on the steepness of the supply curve within the state in question. A steep supply curve means the MW potential changes rapidly for a relatively small across-the-board change in CF. Figure 3 shows the aggregate supply curve for the lower 48 United States (without exclusions, and assuming 5 MW/km^2 density). The two curves above and below the middle curve indicate the effect of changing the CF by plus or minus 3 percentage points. For a CF of 35%, moving from the middle to the top curve represents a 20% increase in total wind potential. For individual states, the relative curve is much steeper.

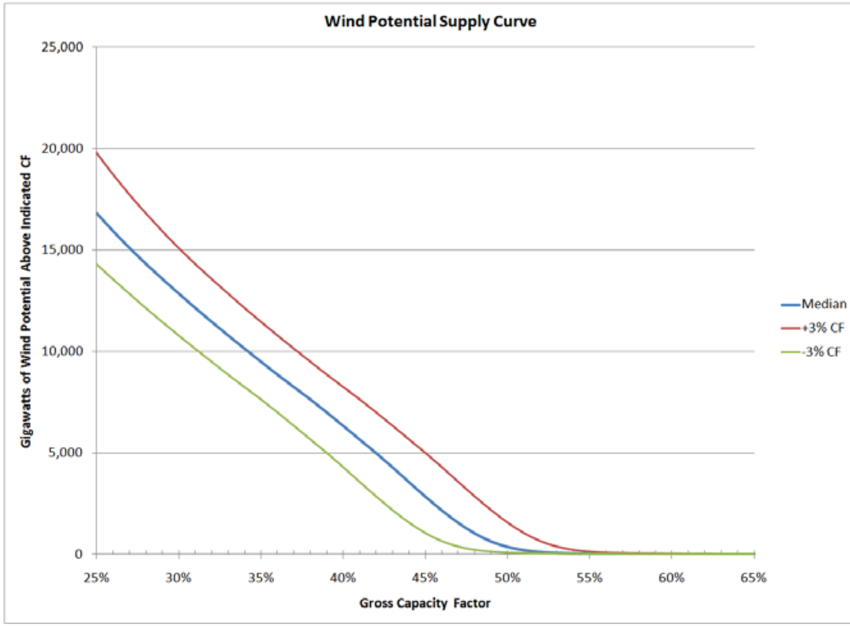

Figure 3. Aggregate supply curve for the United States showing gigawatts (GW) of wind potential above the indicated gross CF. The curves to the right and left of the middle curve indicate the potential assuming a shift of +3% and -3% in the gross CF of all potential wind projects.

ANALYSIS OF KEY STATES

The following regions and states have been identified as having seen significant changes in the wind potential estimates, based on a presumed equivalence of class 3 at 50 m to 35% gross CF at 80 m:

Southwestern States: Arizona, Nevada, Utah
Northwestern States: Washington, Oregon, Idaho
Midwestern States: Ohio, Indiana, Michigan, Missouri
Mid-Atlantic States: North Carolina, Pennsylvania

In the following sections the general factors contributing to changes in these regions are discussed, and charts are presented showing the distribution of wind speed adjustments in each key state. (For the Northwest and Mid-Atlantic states, results are given for the region as a whole.) Note that the changes are averaged across all power classes.

Southwestern States

Wind resource adjustments in the southwestern states were relatively small and on the whole positive. The decreases in apparent wind energy potential in this region is the result mainly of low wind shear, a relatively low gross CF as a proportion of WPD, and the removal of a substantial area of adjustment in northeastern Arizona.

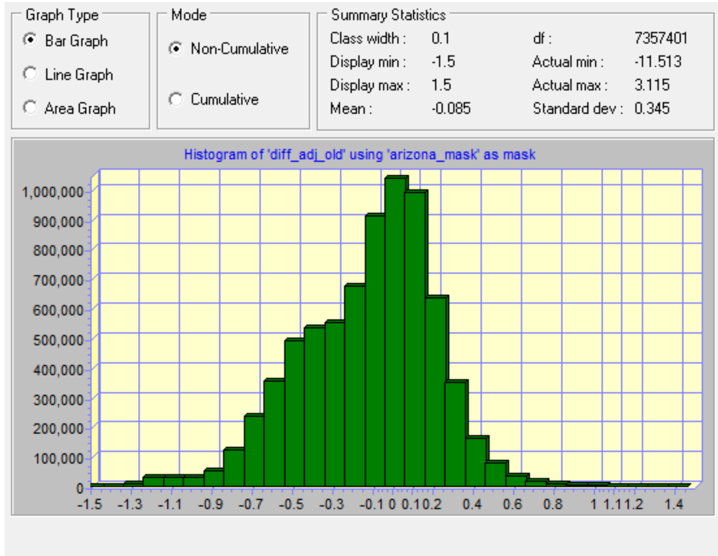

Figure 4. Speed adjustments in Arizona.

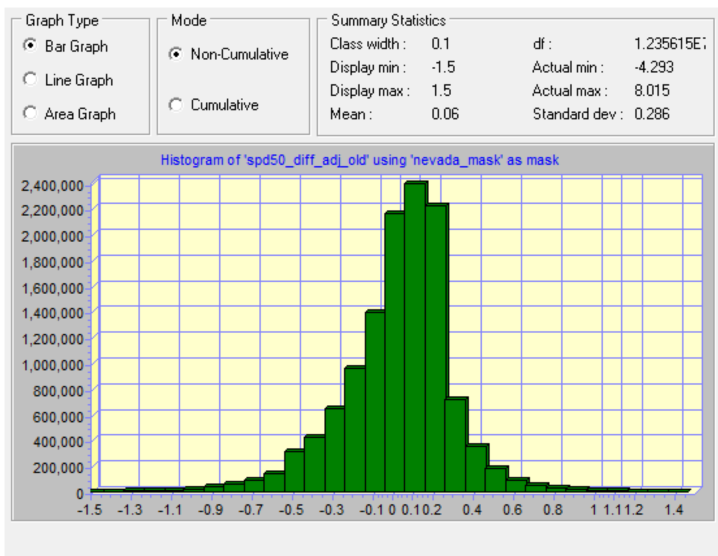

Figure 5. Speed adjustments in Nevada.

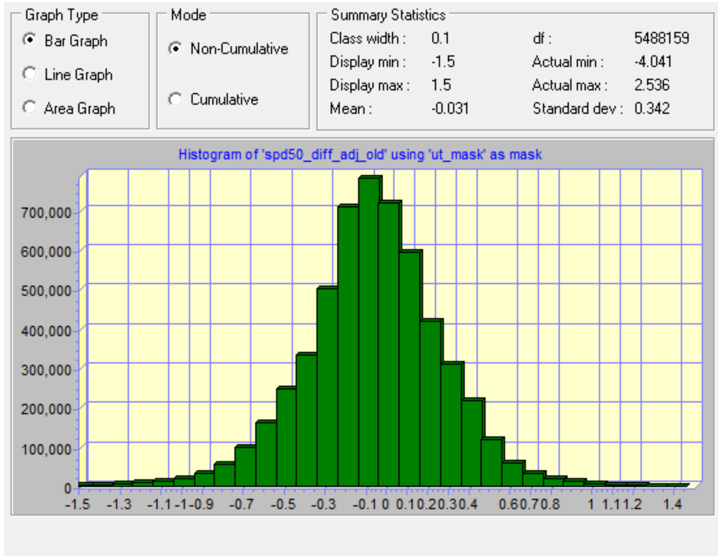

Figure 6. Speed adjustments in Utah.

Northwestern States

The adjustments in this region, which were substantial, reduced the mean wind speed by an average of 0.425 m/s. The Northwest was the first region mapped by AWS Truewind for NREL, and subsequent revalidation by AWS Truewind suggests the original resource estimates were too high. (Similar issues affected maps of the Mid-Atlantic and Northeastern states.) Since that time, significant improvements have been made in AWS Truewind's mapping methods. The changes include a greater surface roughness, in some cases a displacement height, and changes to the MASS model boundary layer formulation to reduce overestimation of nighttime speeds.

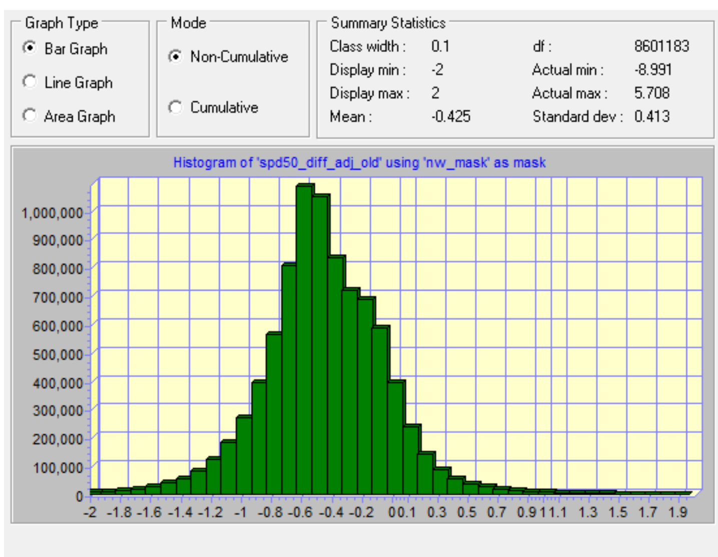

Figure 7. Speed adjustments in the Northwestern states.

Midwestern States

On the whole, reductions applied to the wind resource in the Midwestern states were moderate, with the exception of Ohio, where a substantial overestimation was observed at several tall towers in the northern part of the state. In Missouri, although the overall mean wind speed went down by 0.14 m/s, the wind resource in the northwestern part of the state benefited from a relatively high wind shear and high gross CF relative to WPD, both characteristics of the Great Plains.

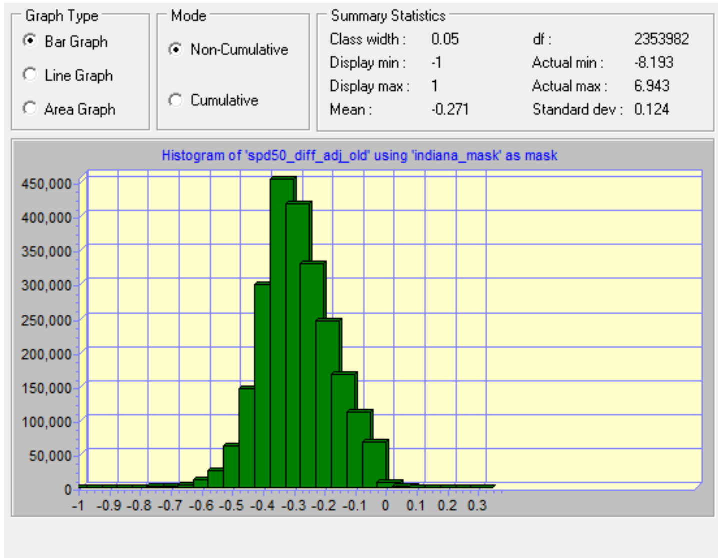

Figure 8. Speed adjustments in Indiana.

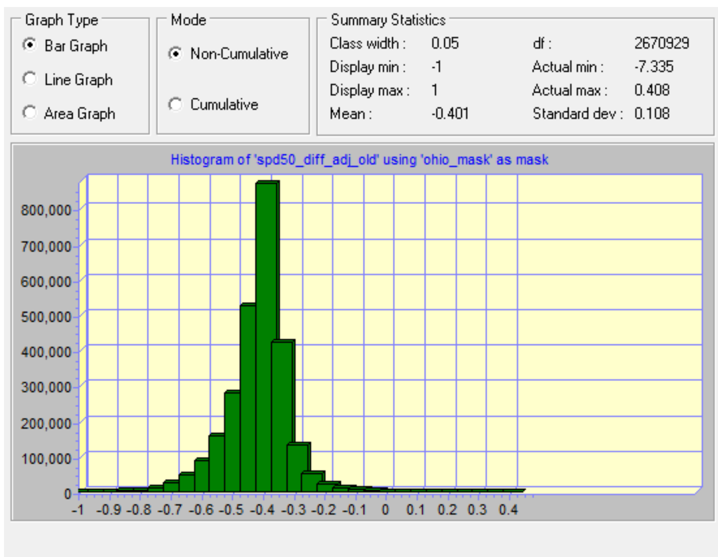

Figure 9. Speed adjustments in Ohio.

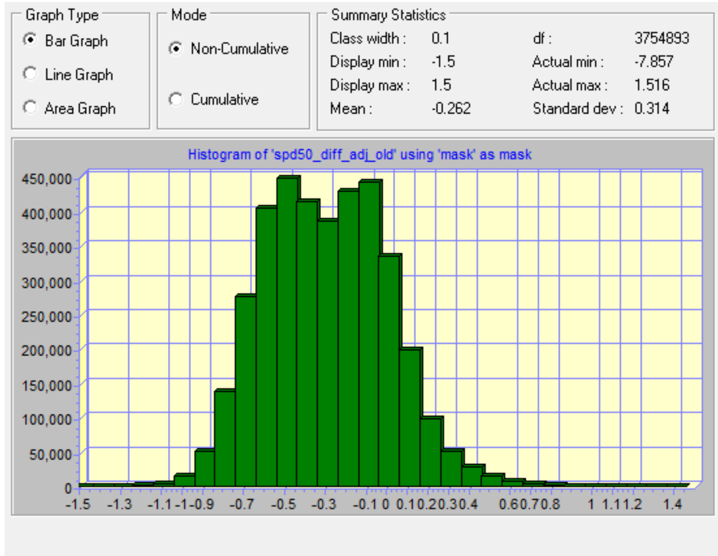

Figure 10. Speed adjustments in Michigan.

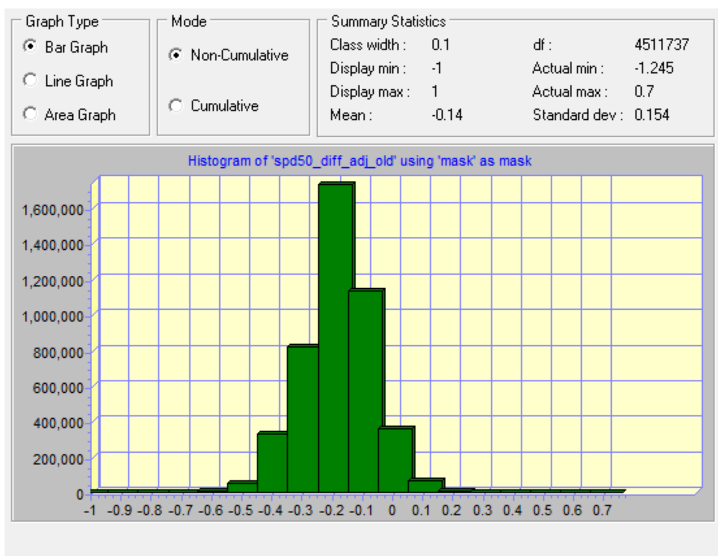

Figure 11. Speed adjustments in Missouri.

Mid-Atlantic States

The Mid-Atlantic states were the most severely affected by the early tendency of the mapping method to overestimate winds in complex, forested terrain. The overall reduction in this region was about 0.6 m/s, the result mainly of the availability of new tall tower data and a reevaluation of weather station data leading to the disregard of pre-ASOS data.

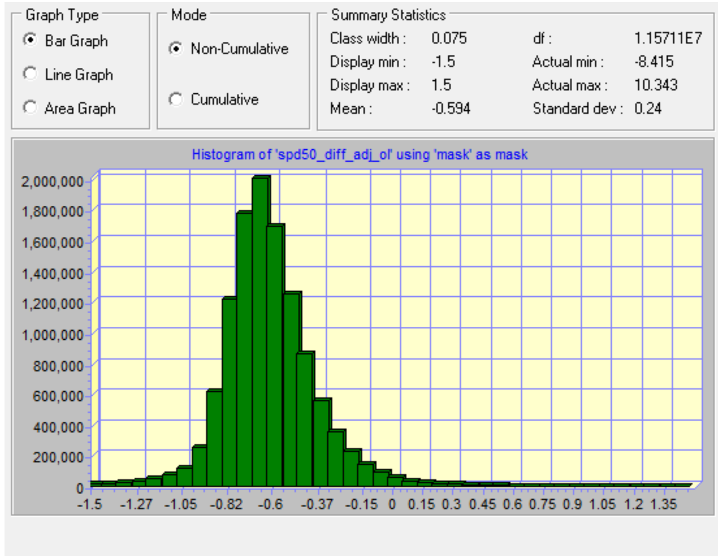

Figure 12. Speed adjustments in the Mid-Atlantic States.

New York

New York was not mapped as part of the NREL/Wind Powering America initiative. However, an early wind map was provided to NREL for developing state-level wind potential estimates. A tendency to overestimate the wind resource was subsequently discovered and corrected by AWS Truewind.

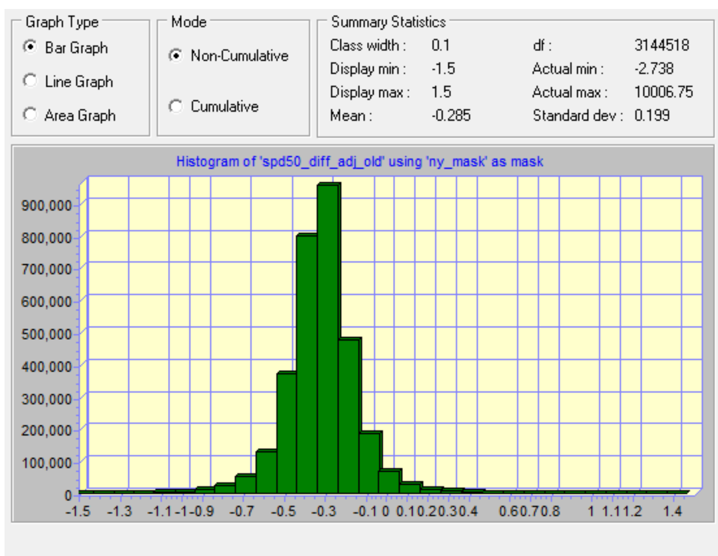

Figure 13. Speed adjustments in New York.