RAM Associates

Resource Assessment & Micrositing

On the Use of RAMWind Terrain Modeling as a Tool to Detect Turbine Performance Problems

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Executive Summary

Ensuring that all turbines are operating at optimal levels is a goal for all wind farm operators. Poorly-performing turbines result in lower revenue and depending upon the cause for the under-performance, they could also increase maintenance costs. Both of these are worth consideration and something to avoid, if at all possible.

However, detecting under-performance is no simple task and is further complicated as terrain complexity increases, since separating terrain effects on the wind from turbine performance-related variability becomes increasingly difficult.

Through the use of the patented RAMWind terrain modeling technology, RAM Associates has developed a method that has proven to be effective in identifying turbines suspected of under-performance, or in some cases, that out-perform the fleet. This methodology has been employed at two operating wind farms with excellent results. The analysis was initially performed in order to normalize terrain effects on the wind, and thus turbine power, a crucial step required for wake model validation, a topic that will be covered in a similar report at a later date. In the two case studies presented here, it will be shown that the variability in observed turbine power output, a surrogate for wind speed, can be explained by terrain variability, expressed as RAMWind terrain exposure calculations, to a high degree of accuracy. Under-performing turbines can be identified as sites with an average power output that is lower than expected based on their terrain exposures.

Performance data from two wind farms has been analyzed and suspected underperforming turbines were identified at one. The performance data for these was analyzed to look for clues related to the nature and possible cause of the underperformance.

RAMWind – A Brief Introduction

Anyone who has observed the differences in wind speeds across a wind farm, as indicated by data from meteorological towers, is aware that terrain is an important factor in the observed, and often mysterious variations. Over vast areas of the American Great Plains and Mountain West, the surface roughness tends to be quite uniform over an area the size of many wind farms, so the variation in wind speed is produced to a large degree by terrain variability. And although such variability may appear to be subtle, it can have a significant effect on wind speed, and thus, turbine power generation.

This is not to discount the effects of atmospheric stability, which are considerable. But over the area of a typical wind farm, the atmospheric stability and overall wind forcing are quite consistent and, in the absence of significant changes in surface roughness, the prime driver of wind speed variability is the terrain.

Various wind flow models have been developed to provide estimates of wind speed across a wind farm and their accuracy varies. RAMWind was developed in response to the observation that the required accuracy was not being achieved by existing models. This was coupled with the notion that each site is unique and that the wind data collected on a given project site, when combined with an effective means of characterizing the terrain variation, could be used to produce a wind model tuned to the local conditions at the project site, thus providing more accurate wind speed estimates at turbine sites.

The heart of the RAMWind model is an algorithm that was developed to calculate terrain exposure values, which are essentially an integration of the elevation differences between the point of origin (a met tower or a turbine site) and the surrounding terrain, usually in 12 or 16 direction sectors, using digital elevation data sets. The elevation differences are weighted inversely with respect to the distance from the origin to each node in the elevation data set. The RAMWind terrain model was awarded a US patent in 2013.

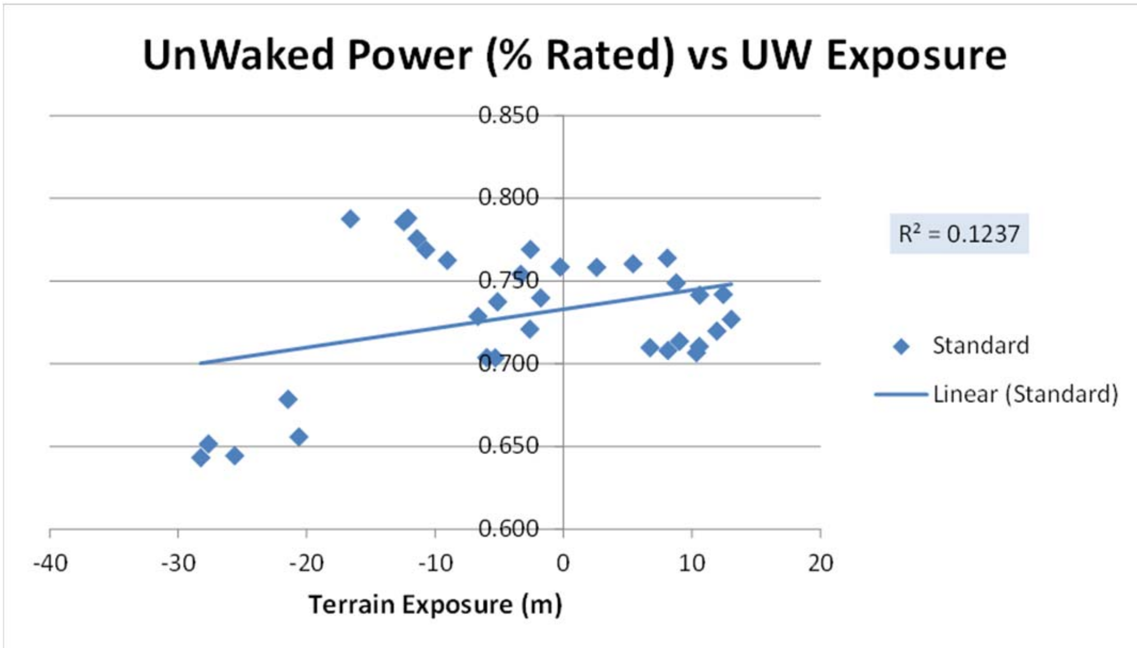
As a wind modeling technology RAMWind has proven to be more accurate than WAsP and CFD models [1,2] and was used to normalize turbine performance data for terrain effects in the last wake validation study that has been presented at an AWEA event [3]. The work presented here is a continuation and expansion of the capabilities of RAMWind in wind farm development and in optimization of wind farm operation.

<u>Case Study 1 – Great Plains Site</u>

The wind farm that is the subject of this analysis is located in the Southern Great Plains of the United States. The site has moderate terrain complexity, yet there are significant performance differences across the site. The project is comprised of 66 current era multi-megawatt, variable speed, variable pitch turbines. Of the 66 turbines 40 are not subject to array effects in the prevailing southerly wind direction. One of the unwaked turbines has had low availability and was not included in this study. The remaining 65 turbine sites were included in the initial analysis, which was conducted for a wake model validation study, but the 39 unwaked turbines are the subject of the analysis presented here.

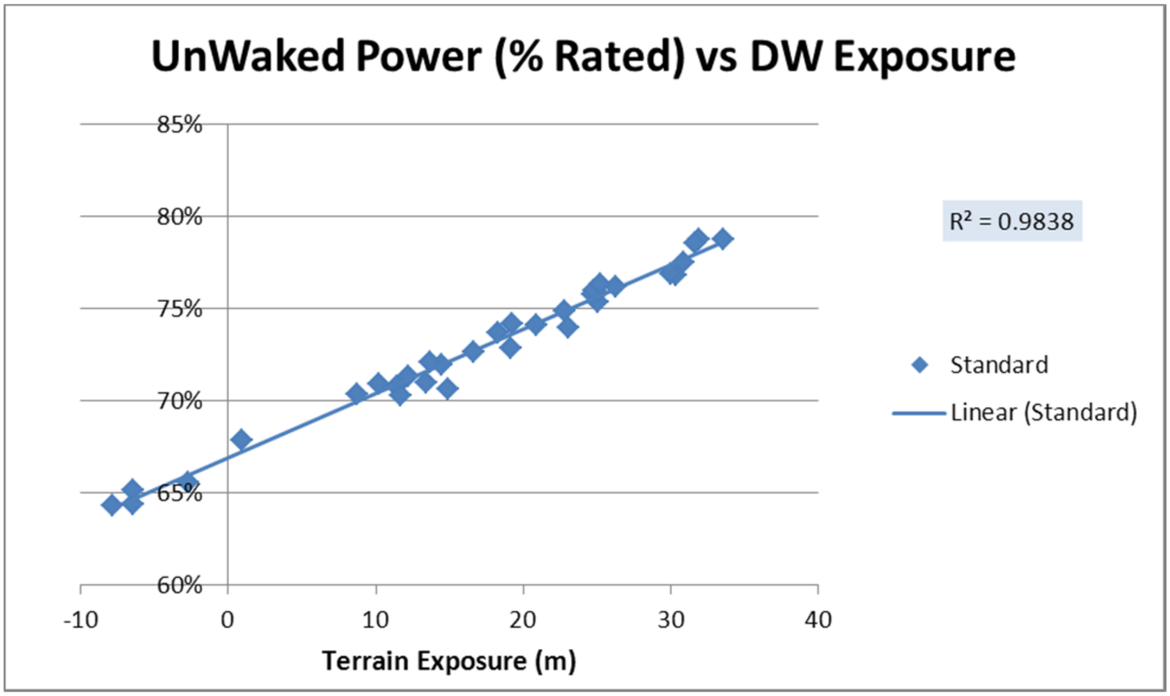
Turbine performance data from the project SCADA system was assembled and the 10-minute data records were filtered to select only records for which the 65 turbines had 100% availability, with all turbines reporting power > 0 kW, with no curtailment imposed and wind directions in a rather narrow band, from 169° to 191°, the prevailing southerly sector, as determined by data from the SCADA system and/or one of the preconstruction met towers that is still operating near the array. Each turbine's 10-minute power values were averaged over all available data records that met the filtering criteria. For purposes of anonymity, the observed average power per turbine was normalized by the rated power for this presentation.

Terrain exposure values were calculated with RAMWind and the average power from the unwaked turbines was analyzed with respect to their respective exposures. Since the observed wind direction for the turbine performance data was southerly, one might expect that the exposure to the south, the upwind direction, would matter the most in terms of affecting the wind that drives turbine power performance. The industry standard wind model, WAsP, uses upwind terrain in the calculation of sector-wise speed-up factors. Below is a graph of the average per-turbine power, normalized by the rated power, for 33 of the unwaked 39 turbines vs. their upwind (UW) terrain exposures, determined by the terrain to the south of each turbine.



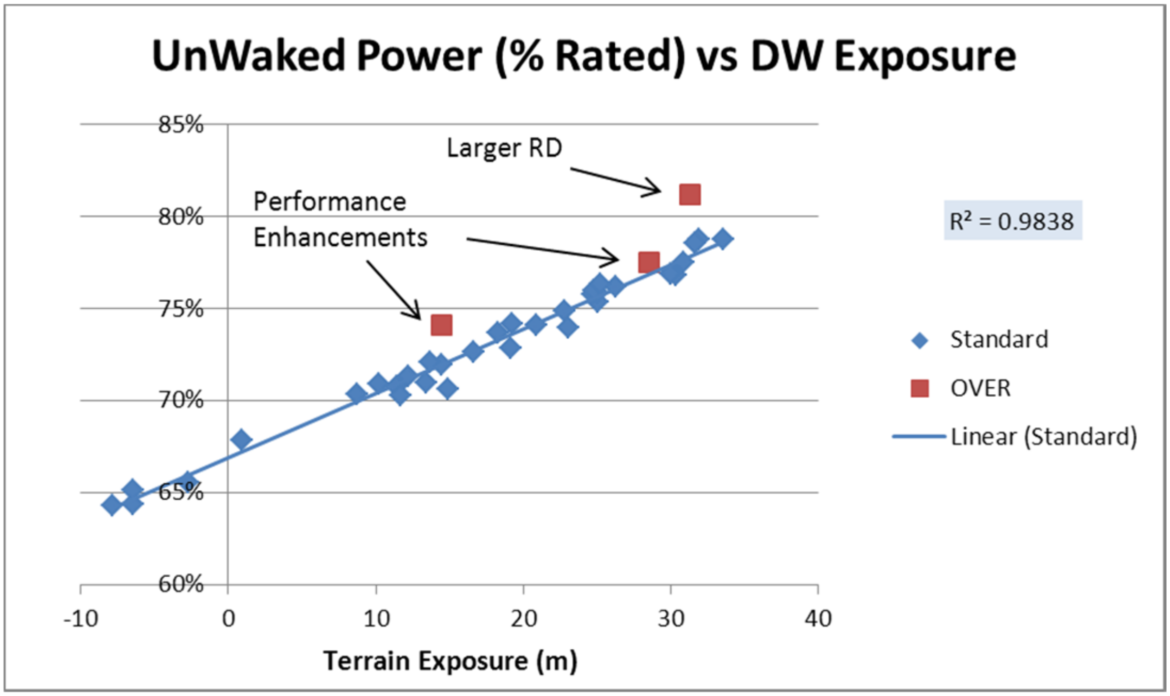
The correlation R^2 is very low with a value of 0.124, indicating that the upwind terrain does not affect the wind and thus turbine performance to a significant degree. A correlation was also performed between the average power with respect to the turbines' elevations and the result was better, but still not very good, with an $R^2 = 0.621$. Average wind speeds from nacelle anemometers are used in some instances to gauge turbine performance, but the correlations, while better than by using upwind terrain exposure or elevation, are not sufficient to clearly show performance anomalies, and an R^2 on the order of 0.87 has been calculated under similar conditions at this site.

Analysis of wind data at numerous sites has shown that it is the downwind terrain that is the prime driver in determining how fast the wind flows through each turbine site, or met tower within a project development area and that the upwind terrain, and perhaps elevation, typically play a secondary and supporting role. Below is a similar graph, showing the relationship between the same 33 turbines' average power and their downwind terrain exposures, as determined by the terrain to the north of each turbine site.



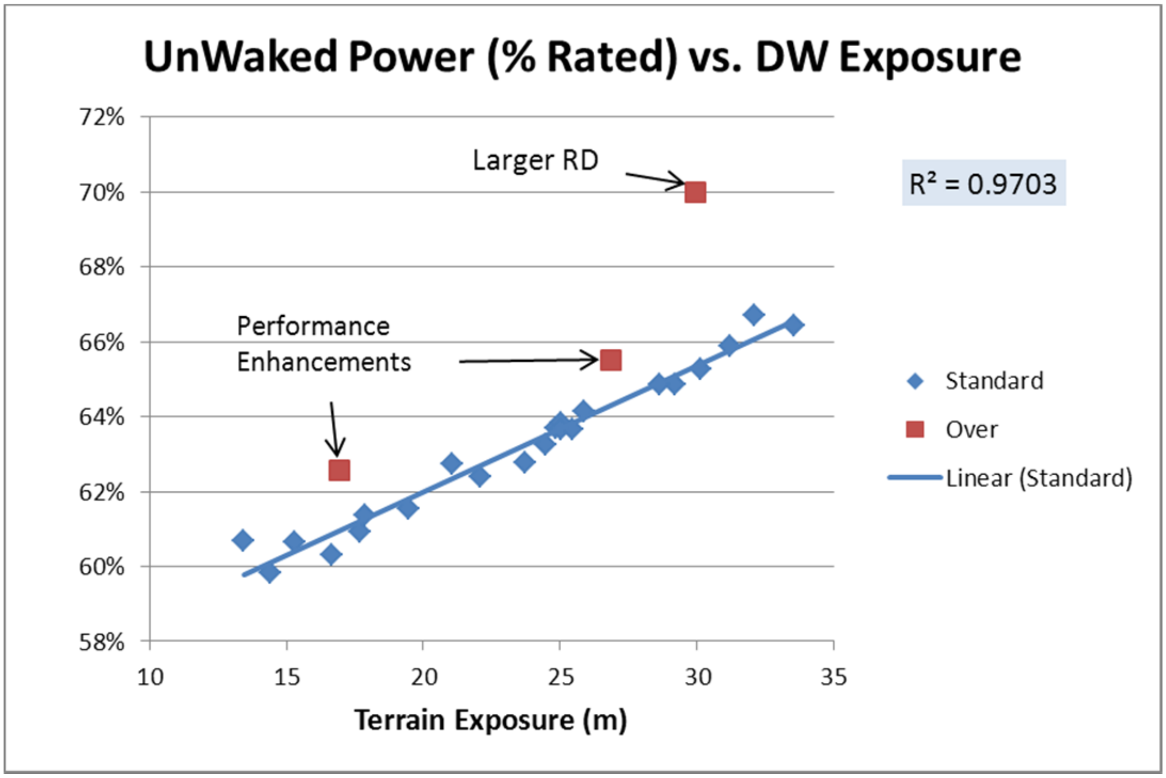
In that analysis we observe a very highly correlated relationship between the average power for the same 33 turbines and their downwind exposures. This clearly indicates that, indeed, the downwind terrain has a huge impact on how fast the wind blows, and, perforce, how much power the turbines will produce.

However, this relationship is for 33 of the 39 turbine sites. In the two graphs presented above, the index refers to them as "Standard", for they are what might be classified as "standard performance" models of the turbine. It turns out that three of the remaining six unwaked turbines have non-standard equipment: one has a larger rotor than standard at this wind farm, but the same rated power and two have performance enhancements on the rotor blades, although both of those turbines do not have the same enhancements. When these three turbines are added to the analysis, this is what is observed, shown in the graph below.



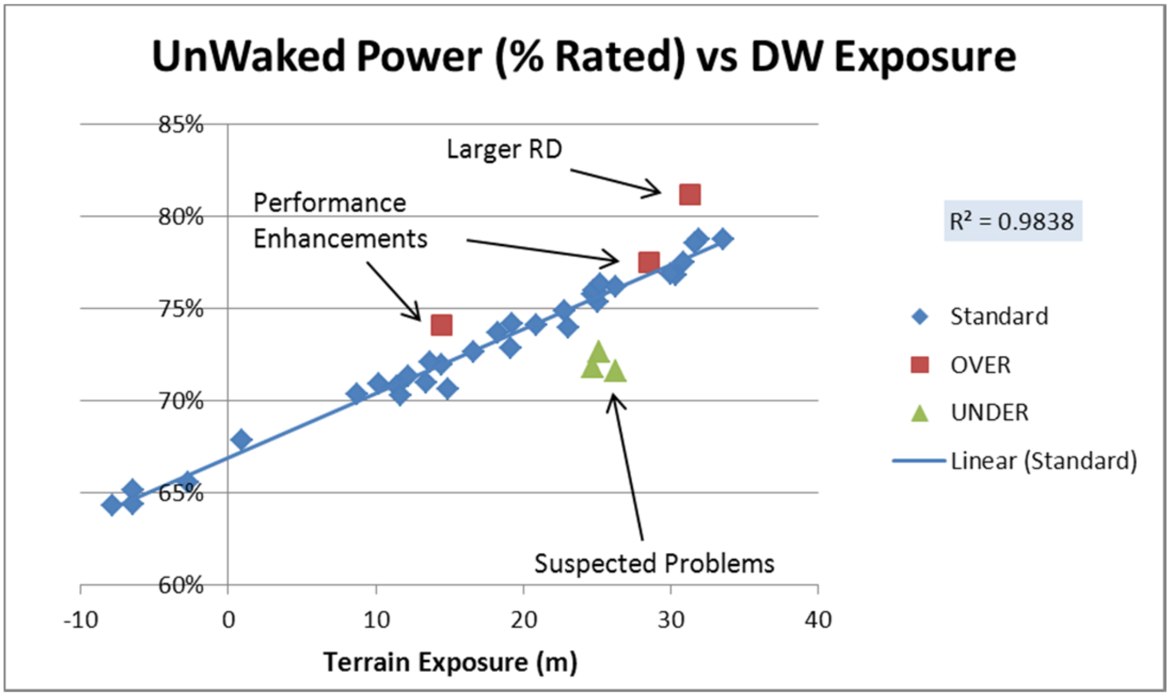
The turbine with the larger rotor has an average power that is clearly well above the trend established by the 33 standard turbines and the two with the blade enhancements have average power above the trendline. It is noted that the data set in this analysis includes data records before the performance enhancements were added, so their effect is not indicated as clearly as when the data are filtered again by time to include only data records when the enhancements were in place.

Note: In fact, the performance enhancements noted in the above graph had been observed in an earlier analysis that included only 25 of the unwaked turbines for a similar, although broader range of wind directions. Hence, there were more data records, which included overall lower power levels. In that analysis the performance differences were more clearly observed, as shown in the next plot of average power vs. exposure.



What made this analysis even more interesting is that at the time, the fact that performance enhancements had been added to the rotor blades of the two subject turbines had not been shared, although the larger rotor diameter was known. When the realization struck that the other two turbines were also the two turbines used in the power performance validation for the project, there was a strong suspicion that there was a deception being perpetrated by the OEM. However, when these facts were presented to the project operators, the fact of the performance enhancements was revealed. Yet, it is good to see that the enhancements are providing higher power output, on the order of 1.5% in this data set.

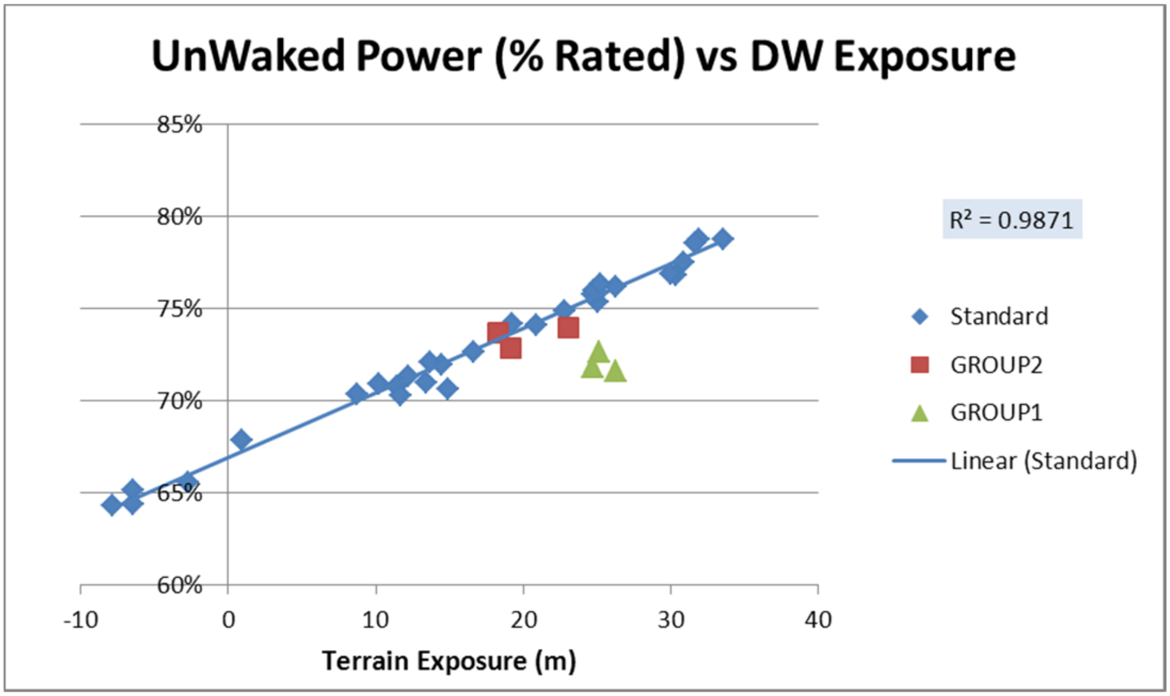
Nevertheless, continuing with the main topic; there are still three turbine sites that have not been included in the analysis of power vs. terrain exposure, which are added in the graph below.



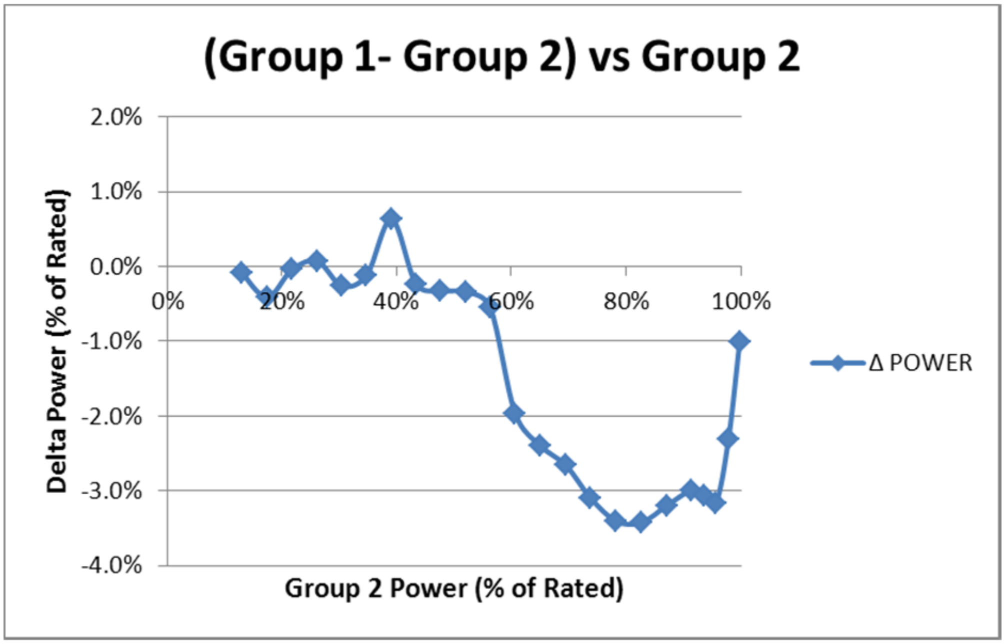
The average power for the last three turbines added to the analysis falls well below where their exposure, and the established relationship between exposure and power performance for the standard turbines, indicates they should be. Based on this analysis, it is possible that there are performance problems with these three turbines that have gone undetected. The magnitude of the underperformance is on the order of 5%, based on the performance of the other turbines that have terrain exposures of the same magnitude. Due to the strong relationship between terrain exposure, which is basically a surrogate for wind speed, and power output at the other turbine sites, there is evidence that their relatively low performance is not entirely due to low wind.

Turbine Performance Analysis

An investigation into the cause of the apparent underperformance of the three apparently under-performing turbines was conducted. The concurrent power output data from the three turbines in question, which will be referred to as Group 1, was compared to the power output from the three adjacent turbines in the same string. These will be referred to as Group 2. The Group 2 turbines are on terrain that has almost exactly the same elevation as Group 1, although the exposures for Group 2 are lower. Based on the observed relationship between turbine performance and exposure, as in the above graphs, the Group 1 turbines should have higher average power than Group 2, but the opposite is the case, the average power for the Group 1 turbines is lower than Group 2. Note that the Group 2 turbines are among the 33 "Standard" turbines, depicted in the graph below.



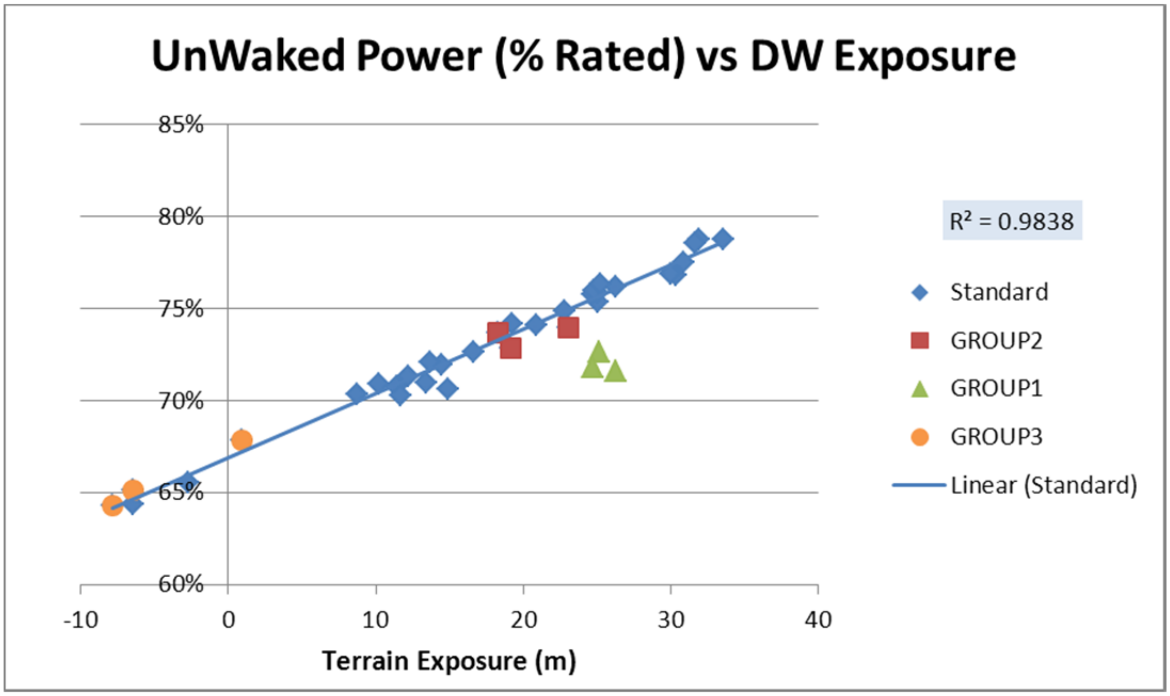
In one investigative analysis, the average power for both groups was calculated using a binning process referenced to the average power for the Group 2 turbines, the group of turbines that appear to be operating properly. The concurrent average power from Groups 1 and 2 was calculated in each power bin (bin width of 100 kW) over the range from 100 kW up to full rated power. In each mean power bin, the difference in average power between Group 1 and Group 2 was calculated. The graph below shows the difference in power (Δ Power) versus the average power from Group 2, with some smoothing applied so that the trends are more easily observed. The Δ power values are expressed as percent of rated power.



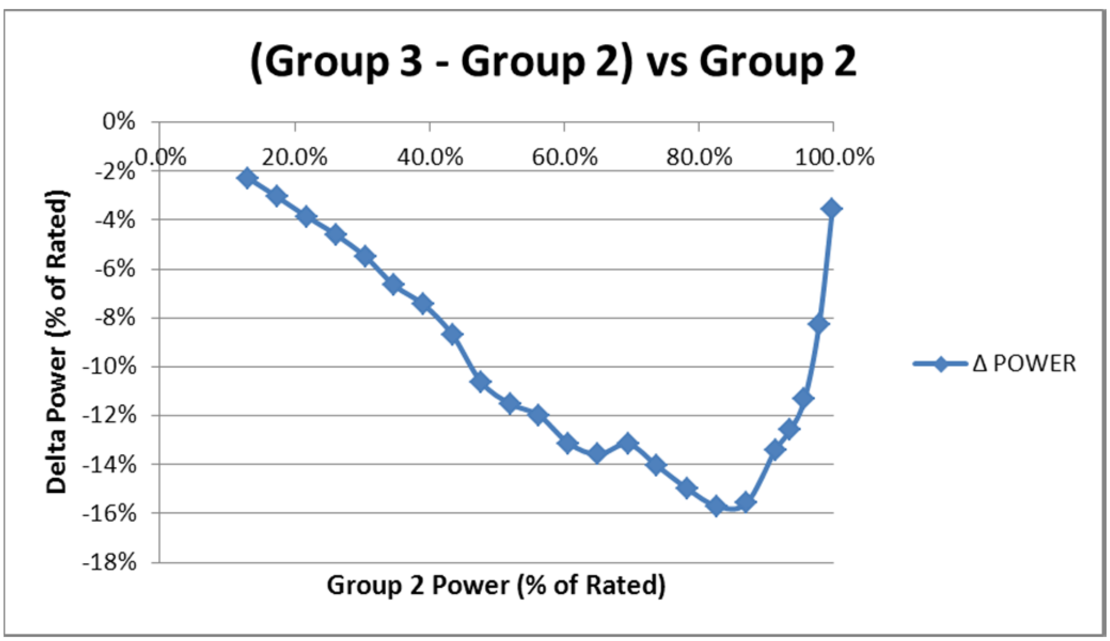
It is observed that up to around 50% of rated power from Group 2, the Group 1 Δ power is quite small, fluctuating around 0%, but as the power output of Group 2 increases beyond ~50% of rated, the Group 1 power output decreases quite noticeably with respect to Group 2. The observed change in relative performance at ~50% of rated power looks suspicious and occurs at around the power level when the blades begin to pitch. This is a clue to a possible cause of underperformance, which was suspected to be related to improper blade pitch control.

However, in the interests of objectivity, one must consider the possibility that for whatever reason the observed relationship between average power and exposure exhibited by the 33 standard turbines may not hold for the apparent underperforming turbines in Group 1 and that what looks like underperformance is really due to lower wind speed. This hypothesis is put to a test by analyzing the performance data to answer the question: if turbines are operating properly but just have lower wind speed, how would their performance compare to turbines at higher wind speed sites? This question is addressed by performing a similar analysis as the one described above, but for a group of turbines that has lower wind speed.

For this analysis, a third group of three turbines from the same row was selected. These will be referred to as Group 3 and they are the next three turbines on the other side of Groups 2. Groups 1 through 3 constitute nine contiguous turbine sites in the same string. The Group 3 turbines are among the lowest producers of the standard turbines. They have low average power, low exposure and low elevation, but fit in the analysis of power vs. exposure with the other standard turbines, as depicted in the graph below.



The same analysis of Δ power (Group 3 – Group 2) vs. Group 2 average power was performed using the same binning process as for Group 1, with smoothing again applied to the results. Below is a graph that shows the relationship that was observed.



In the case of turbines that appear to be performing properly, but have a less-energetic wind resource, the relationship is quite regular and consistent up to the point where Group 2 is producing at approximately 85% of rated power. Above that power level Group 2 is approaching the knee of the power curve but Group 3 is not and the relative power difference begins to decrease, as Group 2 approaches rated power.

Considering the results for Groups 1 and 3 relative to Group2 the behavior of Group 1 is not consistent with low wind speed sites and reinforces the suspicion that there is or are operational problems of some kind that result in power performance that is lower than it should be. Further, more detailed analysis of time series SCADA data has been conducted, which has revealed more clues, but finding conclusive proof of underperformance is not a simple matter, as these turbines are highly complex machines with many inter-related operational components, and they are driven by an inherently chaotic entity - the wind, which adds further complications, particularly over relatively short time periods.

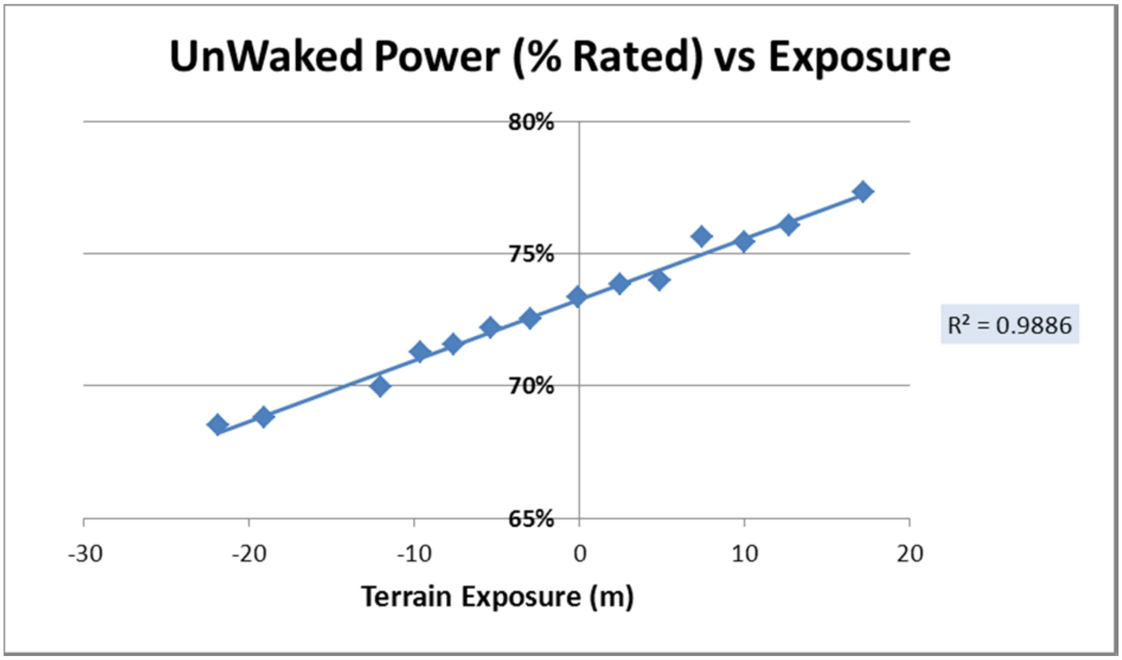
In this case the OEM has been notified of the findings presented in this report. Their investigation did not reveal anything related to blade pitch that might account for the suspected underperformance. As of this writing a measurement program is in development where wind speeds will be measured concurrently upwind (south) of the suspected under-performing turbines (Group 1) and at the neighboring group of turbines (Group 2) to see if the wind speed at Group 1 is higher or lower than at Group 2 and either validate the RAMWind analysis – or not.

Case Study 2 – Mountain West Site

The wind farm that is the subject of this analysis is located in a mountain pass in the Western United States. The site also has moderately complex terrain and fairly significant performance differences across the site. This project is also comprised of 66 current era multi-megawatt, variable speed, and pitch-regulated turbines. Of the 66 turbines only 14 are not subject to array effects in the prevailing southerly wind direction, and these are used in the analysis of average power versus terrain exposure.

As with the Case 1 site, turbine performance data from the project SCADA system was assembled and the 10-minute data records were filtered to select only records for which all 66 turbines had 100% availability, with all turbines reporting power > 0 kW, with no curtailment imposed and wind directions in the southerly sector, as determined by data from the SCADA system. Each turbine's 10-minute power values were averaged over all available data records that met the filtering criteria. For purposes of anonymity, the observed average power per turbine was normalized by the rated power for this presentation.

Terrain exposure values were calculated with RAMWind and the average power from the 14 unwaked turbines was plotted against their respective terrain exposure values, which appear in the graph below.



Once again a very high level of correlation was achieved between terrain exposure and turbine power. This shows that at this site, as well, the wind, which produces the observed turbine performance, is directly influenced by terrain, which was characterized by the exposure calculated with the RAMWind model.

Further analysis did not reveal any obviously under- or over-performing turbines at this project site.

Wake Model Validation

Both of the projects in the two case studies presented here were used in wake model validation studies. The results will be presented in a separate report. At both projects sites, the observed relationships between unwaked turbine power and terrain exposure were used to calculate unwaked power at the remaining, waked turbine sites. The percentage difference between the calculated unwaked power and observed power would represent the apparent wake loss at each turbine. The word "apparent" is used because the possibility exists that under-performance could occur at turbine sites subject to wake losses.

However, with a validated wake model, the ability to identify likely under-performing turbines that are subject to wake effects is also possible. The suspected under-performers would be turbines with apparent wake losses that exceed modeled wake losses by a margin greater than the wake model uncertainty.

Contact Information

For more information on how RAM Associates can assist in identifying under-performing turbines and/or determine the degree to which wake losses are affecting wind farm performance, feel free to contact us.

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The presentations listed in the References section can be downloaded from our website, ramwind.com under the Publications tab.

References

[1] VanLuvanee D., et al: *Comparison of WAsP, MS-Micro3, CFD, NWP, and Analytical Methods for Estimating Site-Wide Wind Speeds*, AWEA Wind Resource Workshop, September 2009.

[2] Vanden Bosche J: *Wind Flow Modeling Software Comparison*, AWEA Wind Resource Workshop, September 2009.

[3] Wolfe, Justin, et al: *Deep Array Wake Loss in Large Onshore Wind Farms (A Model Validation)*, AWEA Wind Resource Workshop, Oklahoma City, OK, September 2010.

[4] Kline, J and Walls, E: *Terrain Effects on Wind Speed Enhanced by Atmospheric Stability*, AWEA Wind Resource Seminar, Pittsburgh, PA, September 2012.