HIGH RESOLUTION WIND RESOURCE MAPS AND DATA

Methods and Validation

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Information Services

January 2012

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INTRODUCTION

Established in 1983, AWS Truepower is one of world's leading renewable energy consulting firms providing planning and evaluation services to project developers, electric utilities, government agencies and financial institutions. Our company has an extensive background in wind and solar energy applications and supports the complete development lifecycle. Our firm is well known for its expertise in plant siting and design, field measurements, resource modeling, technology assessment, performance evaluation and forecasting. We have evaluated over 40,000 MW of planned and operational projects in over 60 countries.

This report describes the methods and models behind the high resolution wind resource maps and the validation of subsequent data available on AWS Truepower's Wind Site Assessment Dashboard.

METHODS AND MODELS

There are three types of data available through the Wind Site Assessment Dashboard: wind resource maps, wind resource distribution charts and tables, and virtual met masts. The following sections describe the methods and models used to create these products.

Wind Resource Maps

High resolution maps of estimated mean annual wind speed are created with AWS Truepower's proprietary MesoMap® system. They are subsequently fine-tuned with direct measurements from a large network of wind monitoring stations. Figure 1 illustrates the process.

The *MesoMap* system is a combination of two atmospheric models: a mesoscale numerical weather prediction model (MASS[1]) and a microscale wind flow model (WindMap[2]). The mesoscale model simulates weather conditions for a representative meteorological year (366 days sampled from a recent 15-year period) on a horizontal grid of 2.5 km. The microscale model then refines the wind fields from the mesoscale model to capture the local influences of topography and surface roughness changes at a resolution of 200 m.

The atmospheric models use meteorological and geophysical data from a wide variety of sources. The mesoscale simulations are initialized by the NCAR/NCEP Global Reanalysis (NNGR) database, which provides a snapshot of weather conditions every 6 hours on a 2.5-degree resolution grid. NNGR incorporates weather observations from many thousands of platforms around the world, including surface stations, rawinsonde stations (instrumented balloons that provide soundings from the surface to high in the atmosphere), satellites, aircraft, and others. In the course of the simulations, MASS also assimilates observations directly from rawinsonde stations. The geophysical data include topography, land cover, sea-surface temperatures, and soil temperatures and moisture.

The objective of the fine tuning is to minimize discrepancies between predicted and observed mean wind speeds. To accomplish this AWS Truepower creates databases of long-term mean wind speeds for numerous surface weather stations, as well as tall towers instrumented for wind resource assessment. The data come from a wide range of sources, including public, private, and governmental sources. Public data is often available through various state-or-province-level wind resource assessment programs, or from the academic or research disciplines. Many countries also maintain government-sponsored or funded measurement programs. Privately-funded data is often provided by clients of AWS Truepower and is used only with permission. Where possible, the mean speeds from short-term measurement programs are adjusted to represent long-term conditions; stations with periods of record of less than one year are not considered.

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[1] Manobianco, J., J. W. Zack and G.E. Taylor, 1996: Workstation-based real-time mesoscale modeling designed for weather support to operations at the Kennedy Space Center and Cape Canaveral Air Station. Bull. Amer. Meteor. Soc., 77, 653-672. Embedded equations are described in Zack, J., et al., 1995: MASS Version 5.6 Reference Manual. MESO, Inc., Troy, NY.

[2] Brower, M.C., 1999: Validation of the WindMap Model and Development of MesoMap, Proc. of Windpower 1999, American Wind Energy Association, Washington, DC.

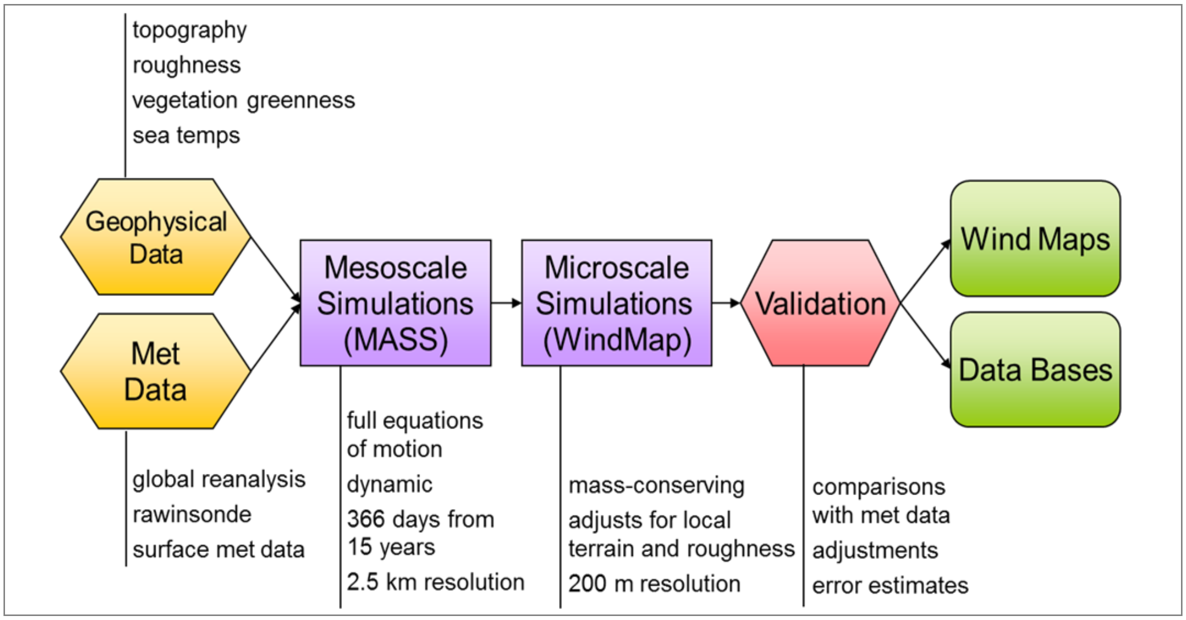


Figure 1. Schematic of the *MesoMap* process.

For each station, the mean speed is projected to the map height using either the observed wind shear exponent (where available), an exponent derived from modeling, or an exponent estimated from regional experience and local land cover and topography. A bias is then calculated between the raw (unadjusted) wind map and the extrapolated-observed speed for each station.

Finally, a software program developed by AWS Truepower interprets the biases to create a bias-correction map, and applies the correction to create the final wind map. This process does not eliminate the bias at every station, as this could produce unreasonable adjustments in some areas. Instead, it is designed to eliminate spatially correlated biases affecting regions of a significant size (roughly the mean spacing between stations, about 50-100 km).

Wind Resource Distributions and Virtual Met Masts

In addition to wind maps, the Wind Site Assessment Dashboard provides access to wind resource distribution data and virtual met masts (VMMs). Both types of data are generated from AWS Truepower's database of weather conditions.

The database of weather conditions is created in two stages. First, the MASS model is run in a sequence of two-week simulations from 1997 to the present. As in the *MesoMap* system, the simulations are initialized from NNGR data, and rawinsonde data are assimilated every 12 hours to control model drift. To accommodate the multi-year simulations, however, the grid resolution is 20 km rather than 2.5 km. In addition, the rawinsonde stations are carefully selected to ensure that wind and other weather trends are consistent through time. In the second stage, the WindMap model is applied to correct for local topographic and land cover influences, and the resulting speeds are scaled so that the mean speed matches the wind resource map.

The result is a time series of hourly wind speed, direction, temperature, and pressure values for a selected location and height above ground. From this VMM, frequencies by speed and direction are derived, along with mean speeds by time of day and time of year. Other statistics, such as interannual variability, wind power density, and maximum speeds, are also calculated.

VALIDATION

Wind Resource Maps

To produce an objective estimate of the map accuracy, each station in AWS Truepower's database is withheld in turn from the fine-tuning procedure and the difference between the map speed and the observed speed at that station is determined. Then all the deviations are analyzed and error statistics are derived.

Based on this procedure, the mean bias of the high-resolution wind maps is found to be very small or virtually zero. Errors tend to be largest where the terrain and vegetation cover are more complex. The mean bias and standard error for each region currently covered in the Wind Site Assessment dashboard are presented in Table 1.

In all cases, AWS Truepower recommends that the wind resource be measured on-site before committing funds to a wind energy project of a substantial size.

Table 1. Mean and standard deviation of biases, in meters / second, for the adjusted 80 m wind maps

United States	Mean	0.00
	Std Dev	0.42
Canada	Mean	-0.01
	Std Dev	0.41
India	Mean	-0.01
	Std Dev	0.44
Europe	Mean	-0.04
	Std Dev	0.54

Wind Resource Distributions and VMMs

The accuracy of the wind resource distributions and VMMs derived from the database of weather conditions is evaluated according to three criteria of relevance to the wind industry: consistency of speed trends over time, accuracy of long-term climate adjustments of short-term observations (measure-correlate-predict, or MCP), and accuracy of energy production estimates based on VMMs.[3] The results outlined in the paragraphs below pertain to our research in the United States; comparable findings have been shown in our international results. Further research is ongoing to further quantify the exact accuracy of these products as our international database grows.

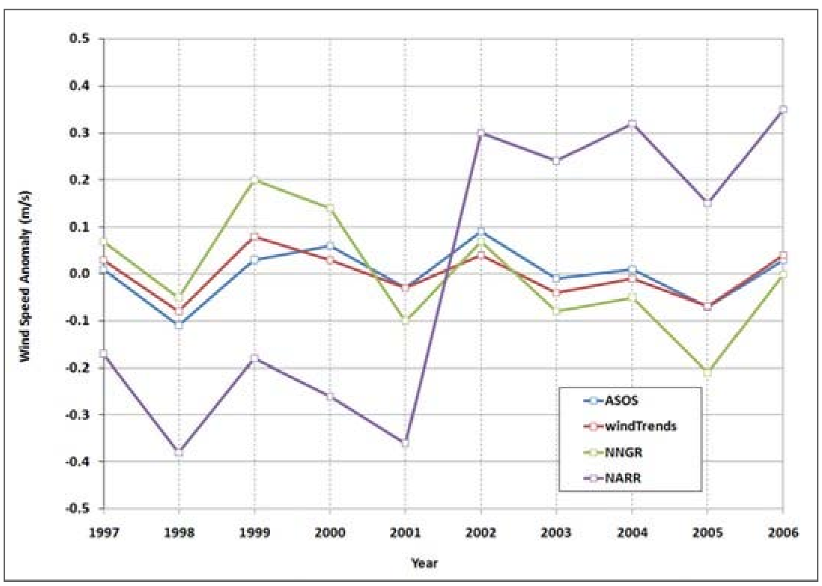


Figure 2. Annual mean wind speed anomalies for 1997 to 2006 according to windTrends, ASOS, NNGR, and NARR data, for 198 representative ASOS station locations in the United States. The wind anomaly is the difference between the mean wind speed in a given year and the 1997-2006 average.

3 Validation of the windTrends data set is described in greater detail in Taylor, M. A. et al., Using Simulated Wind Data from a Mesoscale Model in MCP, Proceedings of Windpower 2009, American Wind Energy Association.

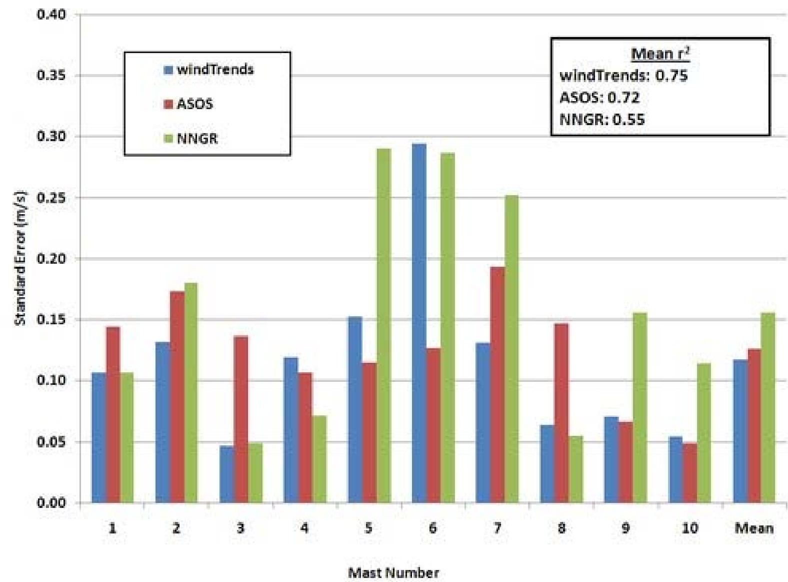


Figure 3. Standard errors of MCP long-term speed estimates using windTrends, ASOS, and NNGR.

Speed Trends

Annual and monthly mean wind speeds from the windTrends data set have been compared with data from other sources for a number of locations and for the entire United States. Figure 2 demonstrates that on the whole, the windTrends speeds track ASOS quite closely, and more closely than do two leading climatological data bases, NNGR and the North American Regional Reanalysis (NARR). Both the ASOS and windTrends anomalies fluctuate about zero in similar ways and with little trend. NNGR exhibits a small but noticeable downward trend, while there is a marked discontinuity in the NARR data from 2001 to 2002, which AWS Truepower associates with a change in procedures for assimilating rawinsonde data in that period.

Climate Adjustments

To assess the accuracy of windTrends for climate adjustments, AWS Truepower identified ten tall towers in wind resource areas around the United States with at least four years of high-quality wind speed measurements. For different 12-month sub-periods within each data set, a measure-correlate-predict (MCP) analysis was performed using windTrends, ASOS, and NNGR data. The predicted mean speeds for the entire period of record of each tower were then compared with the observed, and error statistics were derived for each data set.

The results of the analysis are presented in Figure 3. At most sites, the windTrends standard error is comparable to or smaller than those derived from ASOS and NNGR. The only site where windTrends performs substantially worse than ASOS is Mast 6, which is located in a California mountain pass where the wind climate is not well resolved by the mesoscale simulations. These findings confirm both the consistency through time of the windTrends data set and the relatively good correlation between windTrends and observed wind speeds. The average correlation coefficient (r^2) with the tall tower data was 0.75 for windTrends, 0.72 for ASOS, and 0.55 for NNGR.

Energy Production Estimates

Energy production estimates based on windTrends VMMs are compared with estimates derived from observed wind speeds at ten sites across the United States. (The sites are not the same as those used for the MCP analysis.) The simulated speed distributions are scaled so their means match the observed means. Both sets of data are passed through a generic IEC Class II power curve (a composite of three commercial wind turbine power curves), and the bias (predicted minus observed production) is calculated. This approach provides a direct test of the accuracy of the speed frequency distributions independent of errors in the mean speed.

The results are shown in Table 2. Over all sites, the standard deviation of the biases as a percent of average energy production is 5.7%. This result is dominated by a relatively poor prediction at Site 3; excluding this site, the standard deviation is 2.3%. Site 3 is a mountain pass with a low mean speed but very strong summer winds associated with a mesoscale circulation pattern, which the windTrends simulations do not adequately resolve.

Table 2. Capacity factors derived from windTrends and observed speed distributions for the same mean speeds. The capacity factor is the average output divided by the rated capacity.

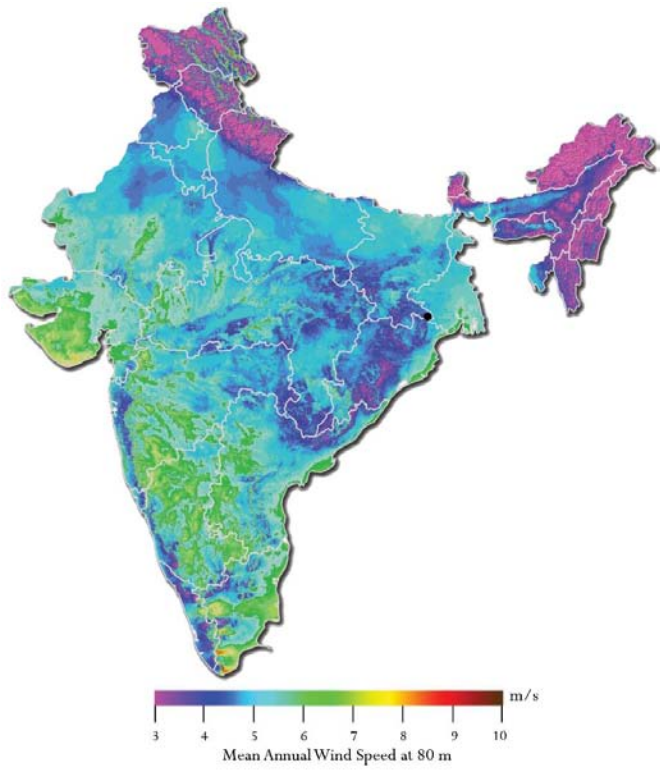
Site	windTrends	Observed	Error (% of Rated)	Error (% of Energy)
Site 1	47.7%	47.9%	-0.3%	-0.5%
Site 2	43.6%	43.8%	-0.2%	-0.5%
Site 3	29.5%	35.4%	-5.9%	-16.7%
Site 4	47.0%	47.1%	-0.1%	-0.2%
Site 5	23.5%	24.1%	-0.5%	-2.2%
Site 6	39.8%	37.9%	1.8%	4.8%
Site 7	38.8%	38.4%	0.4%	1.0%
Site 8	38.2%	37.6%	0.6%	1.7%
Site 9	42.9%	43.0%	-0.1%	-0.3%
Site 10	57.3%	54.8%	2.5%	4.6%
Site 11 (Offshore)	48.9%	48.8%	0.1%	0.2%
Mean			-0.2%	-0.7%
Std Dev			2.1%	5.7%
Mean (excl. Site 3)			0.4%	0.8%
Std Dev (excl. Site 3)			1.0%	2.3%

Combined with the uncertainty in the mean speed, AWS Truepower estimates the overall uncertainty in gross energy production to be about 10% for capacity factors over 35%, increasing to 15% for capacity factors of about 25%. The uncertainty is larger in low-resource areas both because the mean speed uncertainty is proportionately larger, and because the turbines tend to operate more often on the steepest part of the power curve where small errors in speed produce large differences in power output.

It should be stressed that errors may be larger in some areas, and that the uncertainty does not consider deviations from ideal turbine production, including wake-related and other losses.

INDIA VALIDATION SUMMARY

The fine-tuning procedure for India was conducted using data from over 88 C-WET stations. To produce an objective estimate of the map accuracy, each station in AWS Truepower's database is withheld in turn from the fine-tuning procedure and the difference between the map speed and the observed speed at that station is determined. Then all the deviations are analyzed and error statistics are derived. The results of this procedure for the India dataset are presented graphically in Figure 4.



Based on this procedure, the mean bias of the high-resolution wind maps of India was found to be -0.01 m/s, with a standard deviation of the biases of 0.44 m/s. Errors tend to be largest where the terrain and vegetation cover are more complex. In all cases, AWS Truepower recommends that the wind resource be measured on-site before committing funds to a wind energy project of a substantial size.

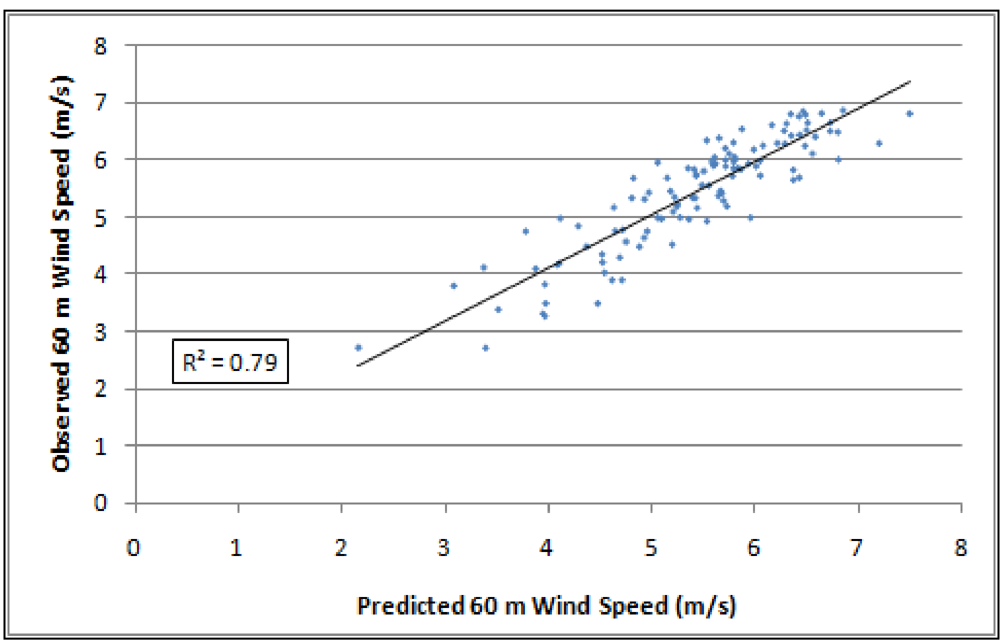
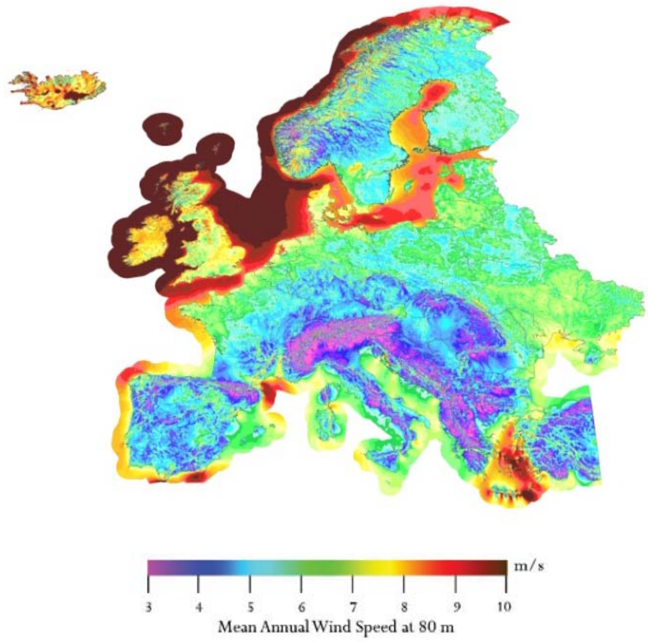


Figure 4. Modeled versus observed annual mean wind speeds at 60 m hub height

EUROPE VALIDATION SUMMARY

The fine-tuning procedure for Europe was conducted using data from 433 wind monitoring stations, including both tall tower and surface-based measurements. The measurements confirm that the areas of best wind resource are located in the North Sea and along its coast, while the weakest wind resource is generally present in countries bordering the Mediterranean (see inset map).



To produce an objective estimate of the map accuracy, each station in AWS Truepower's database is withheld in turn from the fine-tuning procedure and the difference between the map speed and the observed speed at that station is determined. Then all the deviations are analyzed and error statistics are derived. The results of this procedure for the Europe dataset are presented graphically in Figure 5.

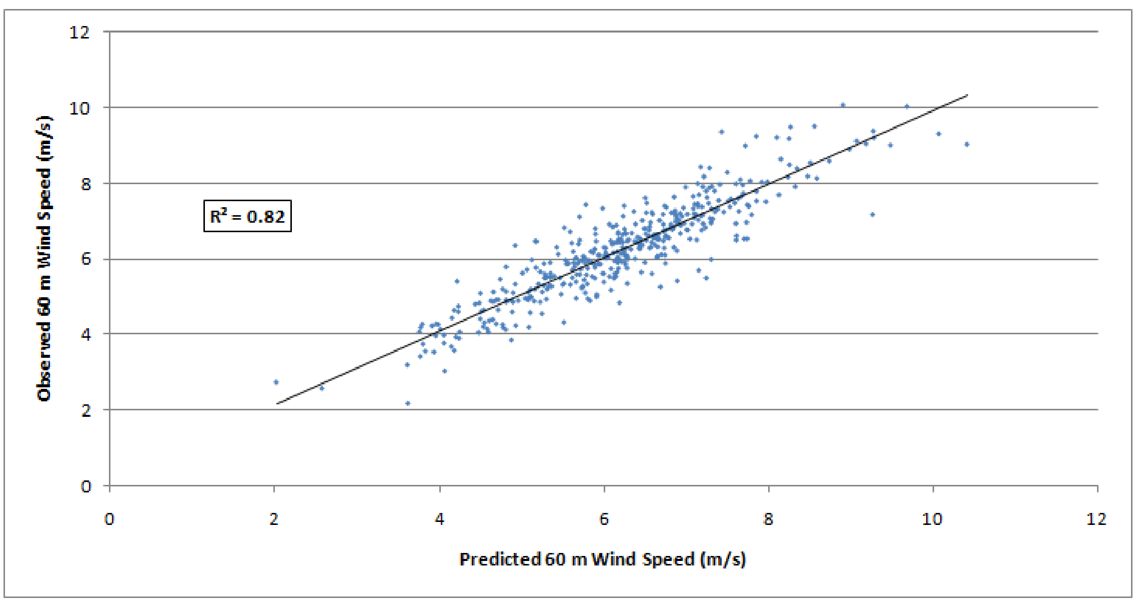


Figure 5. Modeled versus observed annual mean wind speeds at 60 m hub height

Based on this procedure, the mean bias of the high-resolution wind maps of Europe was found to be -0.04 m/s, with a standard deviation of the biases of 0.54 m/s. Errors tend to be largest where the terrain and vegetation cover are more complex. In all cases, AWS Truepower recommends that the wind resource be measured on-site before committing funds to a wind energy project of a substantial size.