INTRODUCTION

A shortcoming of current resource assessment methods is the lack of a rigorous model of how the uncertainty varies across a project site. In most resource studies, the uncertainty is assumed either to be constant or to vary in proportion with distance from the nearest tower. In reality, it varies in complicated ways according to the topography, meteorological conditions, and locations and characteristics of monitoring towers and remote sensing systems.

The purpose of uncertainty maps is to represent the spatial distribution of the resource uncertainty. Their use should lead to better design of monitoring campaigns and well as more optimal placement of turbines to reduce project risk.

Uncertainty maps can also be used as an alternative approach to solve the practical challenge of combining the information from the various masts in estimating the energy production, as nowadays most wind energy projects employ more than one mast. One common approach is to divide the project area into sections, each of which is assigned to one mast; however, this may introduce discontinuities close to each section’s boundaries.
A smoother result can be obtained with the other industry standard method, which is the blending of the predicted wind resource from the different masts. The challenge is to determine a suitable method of weighting. A relatively simple blending technique is to weight each mast’s prediction according to the inverse of the squared distance to that mast.

Distance-weighted blending is relatively easy, but is not necessarily the best approach. It assumes implicitly that the uncertainty associated with the prediction from any given mast depends strictly on the distance to that mast. However, distance is only one factor influencing the accuracy of wind flow modeling. The previously introduced concept of uncertainty maps can be used to objectively determine the weights for blending the information from the different masts available in a project area.

**CONSTRUCTION OF UNCERTAINTY MAPS**

Wind flow modeling uncertainty is related to the degree to which wind conditions differ between points. The more two points differ in their wind characteristics, the more difficult it is for a model to accurately predict the resource at one point based on measurements at the other. Although distance can contribute to such differences, other factors such as terrain slope and aspect, variations in land cover, and temperature gradients can also be important. The challenge is to devise a quantitative measure of wind resource differences between points, and to link that measure to the wind flow modeling uncertainty.

We proposed two possible measures of wind resource variation, one based on the predicted directional speed-up ratios between points, the other on the predicted differences in directional frequencies between points. The speed deviation formula is,

\[
SD = \left[ \sum_{i=1}^{ND} f_i^{(r)} \left( \frac{V_i^{(r)}}{V_r^{(r)}} - 1 \right)^2 \right]^{1/2}
\]  

(1)

The direction deviation formula is,
The sums are over ND wind directions, where ND is typically 12 or 16. \( f_i \) refers to the frequency of occurrence (scaled between zero and one) of direction \( i \), and \( v_i \) is the mean speed for that direction. The superscripts \( t \) and \( r \) refer to the target and reference points, respectively. The reference can be thought of as a mast, while the target is a proposed turbine location. However, the formulas can be applied to any two points.

An analysis of data from a large number of tall towers at diverse wind project sites was conducted, and it was found that there exists a statistically significant relationship between the proposed measures and wind flow modeling errors. From this analysis we derived a function relating wind flow modeling uncertainty to the relevant parameters. This function allows the creation of uncertainty maps for any location and combination of measurements. A set of four such maps, along with the corresponding topographic map, is shown in Figure 1.

\[
DD = \left[ \sum_{i=1}^{ND} \left( f_i^{(t)} - f_i^{(r)} \right)^2 \right]^{1/2}
\]  

(2)

**Figure 1.** An example of four uncertainty maps created from four separate masts at a wind project site.
Uncertainty maps can support project development in several ways. For example, they can help answer such questions as, "Where should I place my next tower, and by how much will the uncertainty in energy production be reduced?" (see for example Figure 2) or “What is the best way to combine the information from my measurement systems to achieve minimum overall uncertainty in plant output?” They can also be used to design turbine layouts that maximize the P90 or P99 production, rather than the P50, thus lowering risk.

![Figure 2. Illustration of how uncertainty maps can be used to inform monitoring campaign design](image)

**OPTIMAL USE OF MAST INFORMATION**

None of the commonly used methods for combining the information from various masts is perfect. The division of the project area into sections, where one single mast “dominates” the area, can be defined by distance. However, depending of site characteristics, other kind of division criteria can be much more appealing, but also more subjective, as topographic similarity. A typical example of this can kind of division is the association of ridgetop sections with ridgetop masts. This approach is pragmatic, but it can be awkward when, as often happens, there is a discontinuity in the predicted wind resource where two sections meet. The resulting energy production estimate can change abruptly (and unrealistically) when a turbine is moved from one side of the dividing line to the other.
The blending method is more esthetically pleasing, but not necessarily more accurate. It adopts the assumption that every mast offers at least some useful information about the wind resource at any point, and that the weighted average of several estimates should be more reliable than any single estimate alone. But as mentioned before, the challenge is to determine a suitable method of weighting. Although distance plays for sure a role, other factors such as terrain slope and aspect, variations in land cover, and temperature gradients can also be important.

Statistical theory holds that if independent measurements of the same quantity are combined in a weighted average, where the weight accorded each measurement is inversely proportional to its uncertainty squared, the result of this combination has the lowest possible uncertainty. Following this, the use of an uncertainty map to optimally use the information from the masts available is completely justified.

CONCLUSIONS

Current practice in resource assessment fails to give adequate consideration to the spatial variation of resource uncertainty across a project site. A more rigorous approach using uncertainty maps can lead to better wind monitoring campaign, plant design and optimal use of the meteorological information, ultimately meaning higher energy yield and less uncertain projects. The method developed in this research, based on data from a diverse range of wind project sites, illustrates the value of this approach for resource assessment.

The presentation will introduce the concept of uncertainty maps, describe our method of creating them, and focus on its application to resource assessment. Each area of application will be illustrated with a real-world example from Latin America.
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REFERENCES


BIOGRAPHIES

José Vidal – José started his graduate career as researcher and associate professor at the Meteorology Department in the University of Barcelona, in the field of Numerical Weather Prediction. Since 2003 he has been working in AWS Truepower in several applications of Numerical Methods to Wind Resource Assessment, including forecasting, wind mapping and energy assessment. Currently he is the Manager of the Consulting Services for Europe and Latin America.

He holds a BSc in Physics from the University of Barcelona, and a degree in Leadership and Team Management from ESADE Business School. He has been actively participating in several EU funded projects in diverse roles, including Work Package Leader. José is also member of TPWind Working Group in Resource Assessment and for several years has been part of the Scientific Committee in the EWEA Conference.

Santi Vila – Santi has been working in the wind industry since the early 2000s, both in project development as well as in consultancy. He has been working, among others, on site identification,
measurement campaigns, wind flow modeling, turbine layout design, as well as in the production of project energy and uncertainty estimates. He has a Degree in Physics (University of Barcelona) and a MSc. in Renewable Energy Systems Technology (Loughborough University). Mr Vila Moreno works as a Lead Engineer at AWS Truepower.

Joan Aymamí - Joan has been involved in the renewable energy industry for over ten years. As Vice President of International Business he oversees AWS Truepower’s European and Latin American operations and is responsible for a company-wide business development coordination, strategy and market intelligence. Early in his career Joan worked for the meteorology group at the University of Barcelona on different national and international research projects that focused on the use of Mesoscale Numerical Weather Prediction models. In 2003, Joan founded Meteosim SL, a Barcelona University spin-off company that specialized in the development of customized applications and solutions for the renewable industry. In 2007 he founded Meteosim Truewind SL, which later merged with AWS Truepower in 2011. For eight years Joan served as the CEO of Meteosim Truewind and was responsible for managing the company operations, leading business development activities in Europe and Latin America, and building relationships across partners, developers, agencies and other renewable industry members.

Mireia Casinos – Mireia has been project manager and engineering consultant for over 13 years and has performed management and technical services in site selection, campaign design, turbine layouts, energy production, engineering analysis, and field measurements. More recently she has been working in the wind energy technology application and resource assessment fields.

She is currently responsible and director of AWS Truepower of Brazil LTDA and her main role is focused on the development and implementation of business, project management, maintaining good corporate relationships with other companies, and managing business negotiations.

As Country Manager, she is responsible for all commercial aspects of Brazilian projects. She holds a MSc in Engineering and Management from the Polytechnic University of Barcelona and an Advanced Management degree from ESADE University.

Michael Brower – Michael is President and Chief Technical Officer for AWS Truepower. Michael has authored or co-authored several books, including "Wind Resource Assessment: A Practical Guide to Developing a Wind Project" (Wiley 2012). He has also led the development of several new methods supporting the growth of renewable energy, including the application of numerical
weather prediction models to resource mapping and forecasting; advanced wind flow and “deep-array” wake models; and grid integration and impact studies. He holds a Ph.D. in Physics from Harvard University, and lives and works in Boston, Massachusetts, USA.