<u>Results of a Wind Flow Modeling Side-by-Side Comparison: WAsP, OpenWind and Continuum</u>

August 30th, 2015

<u>Introduction</u>

At the heart of every wind resource assessment is the wind flow model. It describes the wind resource variability across a project area. If the model is flawed or biased, then all subsequent calculations and estimates will inherit those flaws. It is therefore very important for the wind flow model to accurately characterize the wind resource in order for the wind farm's maximum net energy production to be realized.

Currently, in the wind energy industry, there are a number of commercially-available wind flow models. In this study, three are tested in a side-by-side comparison where each was used to model the wind resource at a project site with eleven met towers. Using the same met data in each software program, wind flow models were generated and then a 'Round Robin' (or 'Leave One Out') approach was used to test the relative accuracy of each model. The results of this side-by-side comparison are summarized in the tables and plots below.

<u>Description of Wind Flow Models Tested</u>

The three wind flow models included in this study are WAsP 10, OpenWind 1.06 and Continuum 2.0.

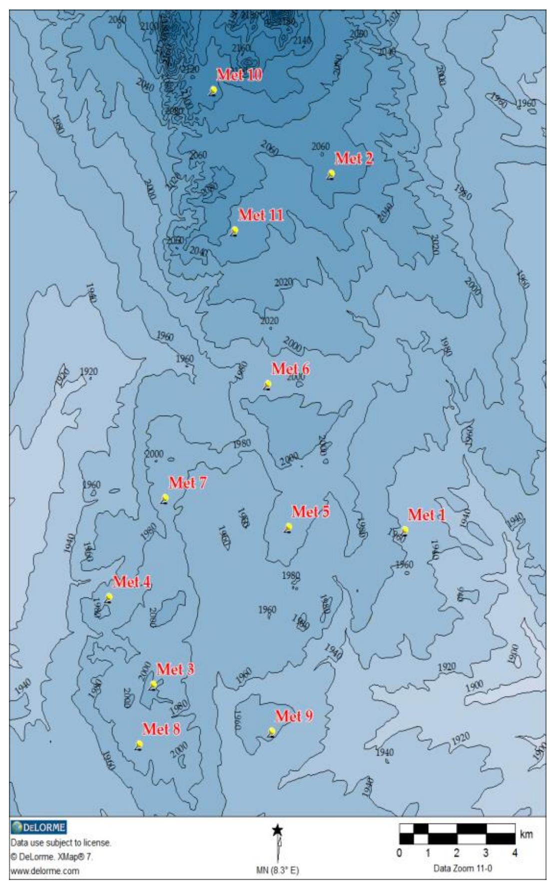

Figure 1: Validation Site with 11 Met Sites

1. WAsP

WAsP was developed and is distributed by DTU (Danish Technical University) and has been widely used in the wind industry for more than 20 years. The wind flow model behind WAsP is based on a theoretical model developed by Jackson & Hunt (1975) which describes the flow over a small hill under neutral atmospheric conditions. WAsP is typically referred to as a linear model.

2. OpenWind

OpenWind is offered by AWS Truewind and is described as a wind project design and optimization software. The wind flow model used in OpenWind is called 'Wind Map' and is based on a mass-conservation wind flow model.

3. Continuum 2.0

Continuum 2.0 is developed and distributed by Cancalia

Engineering & Consulting and was introduced to the industry in January 2015. The model behind Continuum is based on the conservation of momentum theory and analyzes the change in the upwind and downwind terrain exposure as well as the change in the surface roughness to estimate the wind speed variability across a project area.

Description of Test Site

The site used in this side-by-side comparison is located in the U.S. and is described as moderately complex. The wind speed and wind direction were measured at eleven met towers installed across the project area and were adjusted to represent long-term mean conditions. The location of the eleven met sites used in the study are shown on the topography map in Figure 1.

The prevailing wind direction at the test site is generally from the west with the west-southwest to west-northwest wind direction sectors accounting for more than 60% of the measured wind (Figure 2).

The directional wind speed ratios are shown in Figure 3 where the dotted black line represents a 1:1 wind speed ratio. Figure 3 shows that the highest wind speeds occurred in the southwest wind direction sector.

The mean wind speed at the eleven sites vary by a fairly large amount with approximately 1 m/s separating the lowest and highest wind speed site.

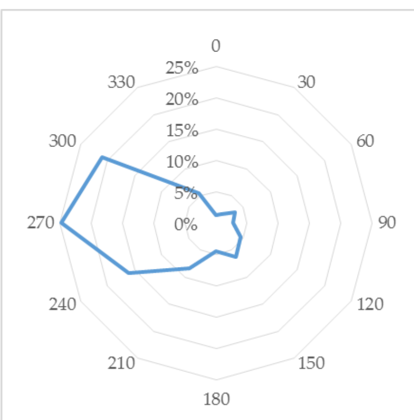

Figure 2: Avg. Wind Rose

Table 1: Avg. Wind Rose

WD, degs	Rose Freq., %
0	1.3%
30	1.7%
60	3.5%
90	2.7%
120	4.5%
150	6.2%
180	4.5%
210	8.4%
240	16.1%
270	24.7%
300	21.0%
330	5.5%

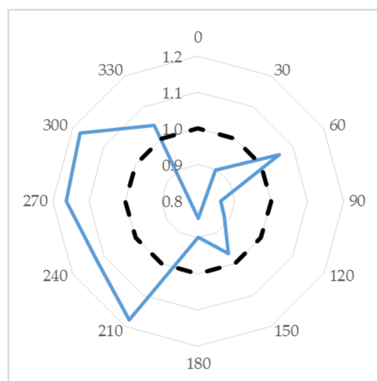

Figure 3: Avg. Directional WS Ratios

Table 2: Avg. Directional WS Ratios

WD, degs	Directional WS Ratio
0	0.752
30	0.898
60	1.058
90	0.862
120	0.882
150	0.967
180	0.899
210	1.179
240	1.122
270	1.162
300	1.176
330	1.042

Round Robin ('Leave One Out') Methodology

In order to directly compare the results of the three models, care was taken to ensure that the methodology used in each model creation was comparable.

Normally, WAsP and OpenWind use one met site to initialize the model creation while Continuum uses all available met sites and creates a site-calibrated model. In 2015, however, OpenWind implemented a site-calibration method, similar to the one used in Continuum, where all of the met sites are used to generate the model and the model coefficients are modified until the met cross-prediction error is minimized. This option in OpenWind was used for this study.

For WAsP, each met was used to generate a resource model and then these grids were averaged together weighted by the inverse distance from the met used in the model creation.

Summary of Round Robin Results

With eleven met sites, the Round Robin test involves systematically omitting one met site and using the remaining ten met sites to create a model and then estimating the wind speed at the excluded site. Table 3 and Figure 4

Table 3: Summary of Round Robin Results: WS Estimate Error, %, at Excluded Site

Excluded Met Site	OpenWind	Continuum	WAsP
Mast 1	-6.6%	0.8%	-5.1%
Mast 2	-4.0%	-1.7%	-5.5%
Mast 3	0.5%	0.6%	1.1%
Mast 4	1.9%	-0.8%	3.9%
Mast 5	-0.3%	-1.1%	-3.0%
Mast 6	3.8%	3.2%	4.9%
Mast 7	2.6%	-0.7%	-0.2%
Mast 8	-1.6%	-1.5%	-1.2%
Mast 9	-1.9%	0.2%	-2.4%
Mast 10	1.7%	2.8%	3.0%
Mast 11	0.5%	-0.5%	-1.1%
RMS Error	**2.93%**	**1.55%**	**3.34%**

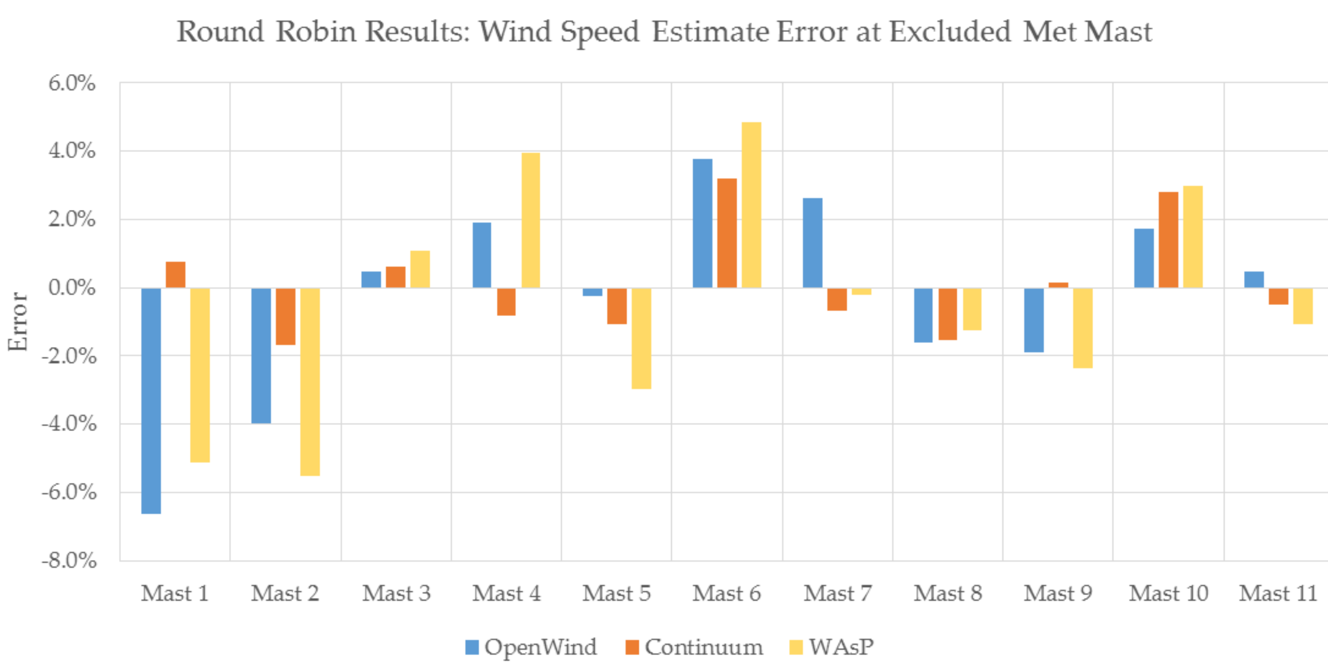

Figure 4: Results of Round Robin Analyses

summarize the results of the side-by-side comparison.

The RMS error of the eleven Round Robin tests are shown at the bottom of Table 3 and show that Continuum achieved the lowest model RMS error at 1.55%. The WAsP model produced the highest RMS error at 3.34% and the results from OpenWind showed an RMS error of 2.93%.

The largest error of any individual Round Robin test was -6.6% for OpenWind, 3.2% for Continuum and -5.5% for WAsP. The smallest error of any test was -0.3% for OpenWind, 0.2% for Continuum and -0.2% for WAsP.

Conclusions

In this side-by-side comparison, three wind flow models were evaluated and the relative accuracy of each was compared. Using a site with eleven met sites in moderately complex terrain, a Round Robin ('Leave One Out') analysis was conducted where each met was omitted from the model creation and was then estimated using the model formed with the remaining ten met sites.

The wind flow model that achieved the lowest RMS error was Continuum, with an error of 1.55% compared to an RMS error of 2.93% using OpenWind and an RMS error of 3.34% using WAsP. Additionally, Continuum had the lowest maximum error of any individual test at 3.2% compared to -6.6% for OpenWind and -5.5% for WAsP.

Based on this comparison, Continuum has proven to be the most accurate wind flow model of the three models tested. Similar comparisons in different flow conditions will be explored in future studies to further test the relative accuracies of the various commercially-available wind flow models.