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TO: Town of Barrington
FROM: David DeLuca, Project Manager and Matt Eberhard, Meteorologist
DATE: 12 December 2008
RE: Virtual Met Tower – Barrington, RI

AWS Truewind created a virtual met tower file for a point near Barrington, Rhode Island as requested by the Town of Barrington. The location of the point (41.7351 N, 71.3239 W) is shown in Figure 1. The virtual met tower file is in Excel format and consists of an annual hourly time series of simulated hourly wind speed, direction, temperature, pressure, and air density at a 65 m height above ground level.

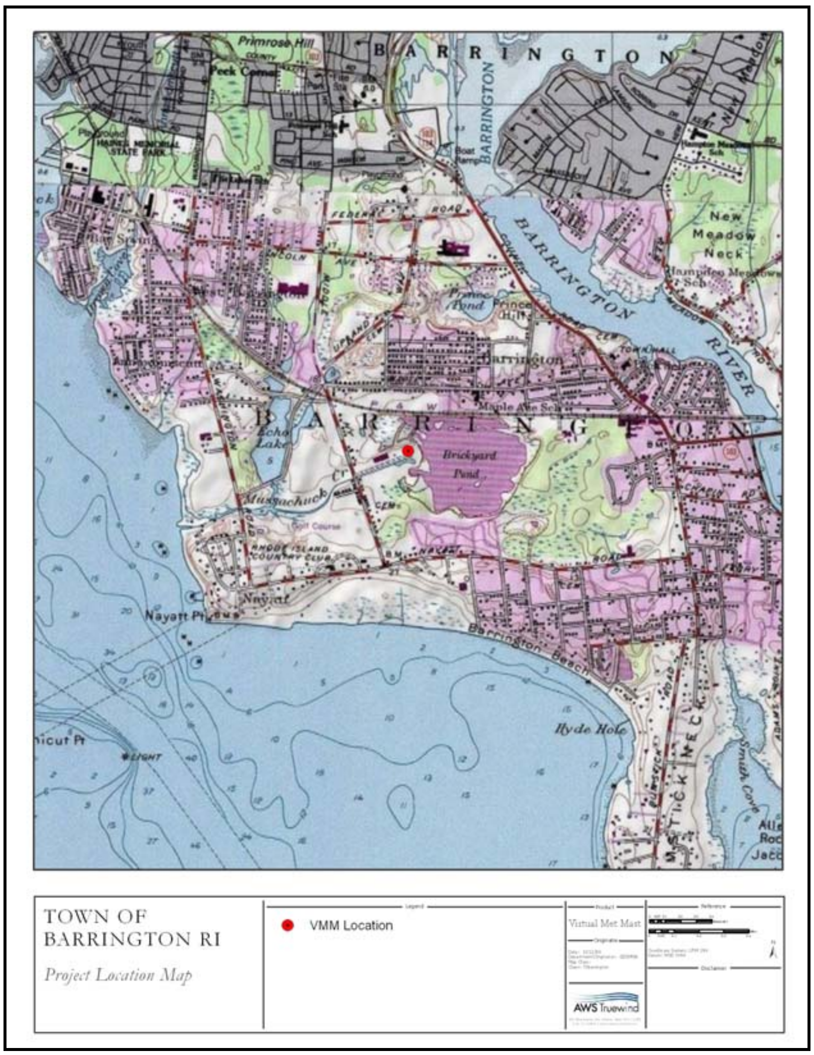
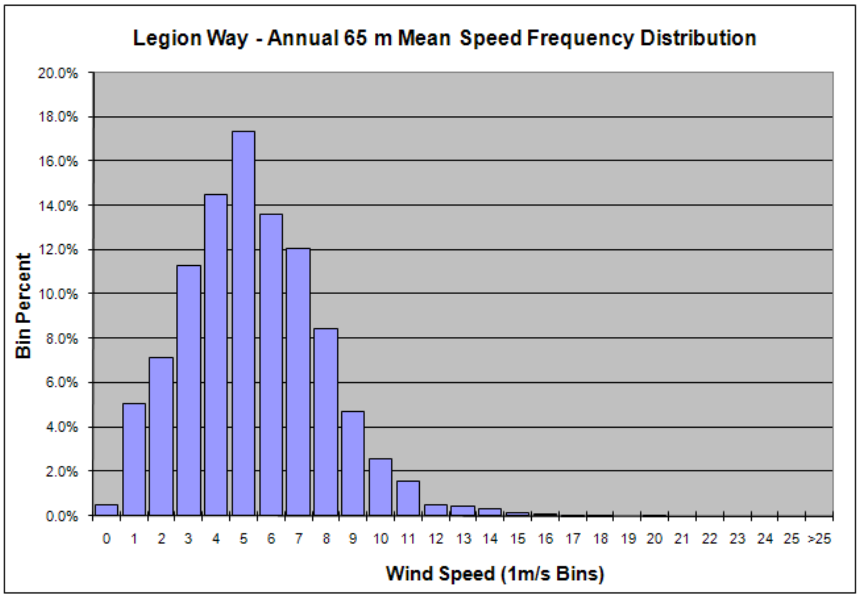


Figure 1 – Virtual Met Tower Location

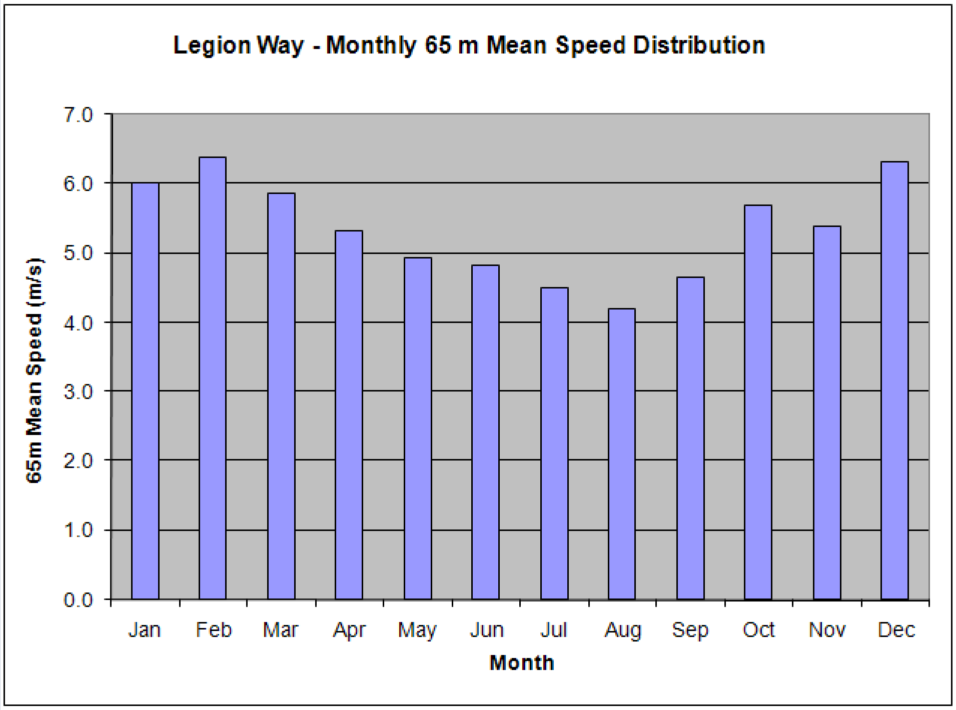
The 65 m mean wind speed at the point is estimated to be 5.33 m/s. The mean wind resource is based on the published AWS Truewind US national map and typically has an uncertainty of 0.35 m/s, with slightly higher uncertainty in complex terrain. All resource estimates should be confirmed by measurement. The average air temperature, air pressure, and air density at the site are 10.6^{o} C, 1007.6 mb, and 1.239 kg/m^3, respectively. Figure 2 shows the predicted annual wind speed frequency distribution for the site. We determined that the Weibull distribution that best fits the modeled frequency distribution has a scale parameter (A) of 6.07 and a shape parameter (k) of 2.36.



Speed Bin	Frequency
0	0.5%
1	5.1%
2	7.1%
3	11.3%
4	14.5%
5	17.3%
6	13.6%
7	12.0%
8	8.4%
9	4.7%
10	2.5%
11	1.5%
12	0.5%
13	0.4%
14	0.3%
15	0.1%
16	0.1%
17	0.0%
18	0.0%
19	0.0%
20	0.0%
21	0.0%
22	0.0%
23	0.0%
24	0.0%
25	0.0%
>25	0.0%

Figure 2 - Annual 65 m Mean Speed Frequency Distribution

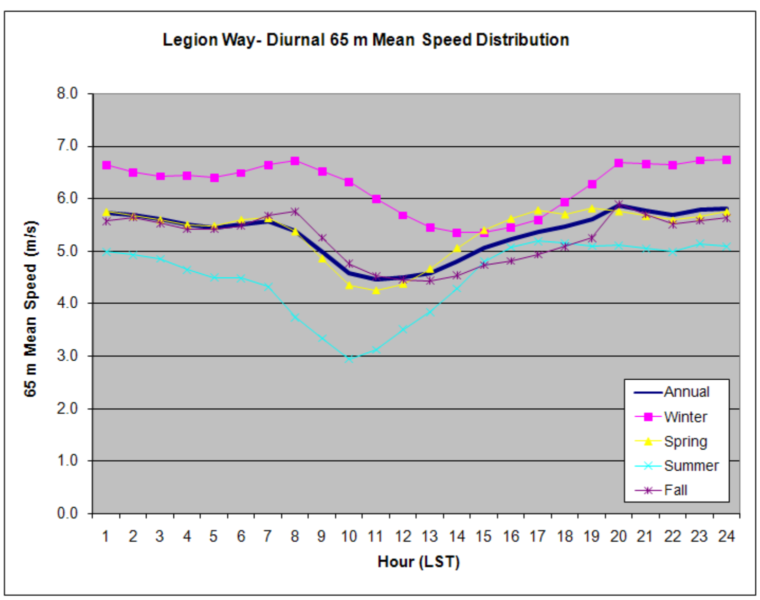
Figure 3 shows the monthly 65 m mean wind speed distribution. As is typical in this type of climate, the highest speeds are found in the colder winter months due to recurring storm systems and large temperature gradients during this time of the year, and the lowest speeds are found in the warmer summer months.



Month	65 m Mean Speed
Jan	6.00
Feb	6.37
Mar	5.85
Apr	5.31
May	4.94
Jun	4.82
Jul	4.49
Aug	4.20
Sep	4.64
Oct	5.68
Nov	5.38
Dec	6.31

Figure 3 - Monthly 65 m Mean Speed Distribution

Figure 4 shows the diurnal 65 m mean wind speed distribution for each season and on an annual average basis. The distributions show that the highest wind speeds generally occur at night. This is because the absence of solar heating and associated convective mixing at night produces a shallow boundary layer, which is often capped by high winds. The effects of local convective winds are greater during the warmer months when winds are light and solar heating is strong. This leads to a more dramatic difference between wind speeds during daylight and nighttime hours.



Hour (LST)	65 m Mean Speed				
	Annual	Winter	Spring	Summer	Fall
0	5.73	6.63	5.75	4.98	5.57
1	5.68	6.50	5.67	4.92	5.64
2	5.60	6.42	5.60	4.85	5.53
3	5.49	6.43	5.50	4.64	5.42
4	5.44	6.39	5.48	4.49	5.42
5	5.51	6.49	5.60	4.48	5.48
6	5.56	6.63	5.63	4.32	5.68
7	5.39	6.72	5.37	3.73	5.76
8	4.98	6.52	4.86	3.33	5.25
9	4.58	6.32	4.34	2.94	4.75
10	4.46	5.99	4.24	3.11	4.52
11	4.49	5.68	4.37	3.50	4.45
12	4.58	5.44	4.65	3.83	4.43
13	4.80	5.34	5.05	4.28	4.53
14	5.06	5.35	5.40	4.79	4.72
15	5.23	5.45	5.62	5.07	4.80
16	5.36	5.58	5.78	5.19	4.93
17	5.46	5.93	5.70	5.16	5.08
18	5.60	6.27	5.81	5.09	5.24
19	5.86	6.68	5.76	5.11	5.90
20	5.77	6.66	5.67	5.04	5.70
21	5.68	6.63	5.58	4.98	5.51
22	5.77	6.73	5.65	5.14	5.58
23	5.79	6.74	5.75	5.08	5.63

Figure 4 - Diurnal 65 m Mean Speed Distribution

Figure 5 shows the directional distribution of the wind resource at the site in the form of a 16-sector wind rose. The wind rose is highly variable, but shows the highest frequency of winds coming from the south-southwest. The most energetic winds are also from the south-southwest.

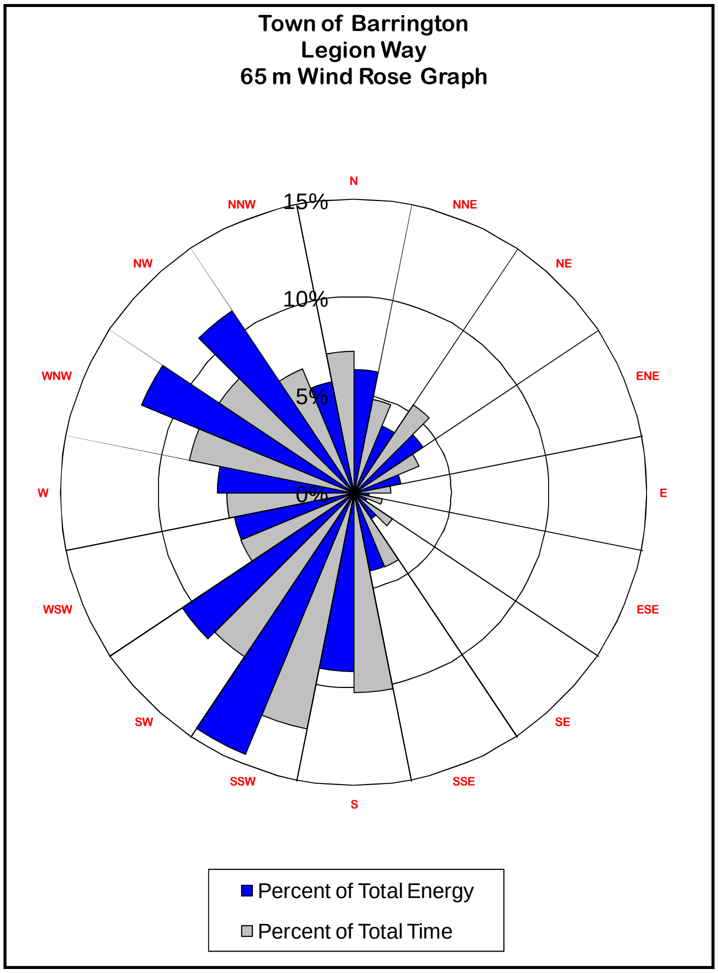
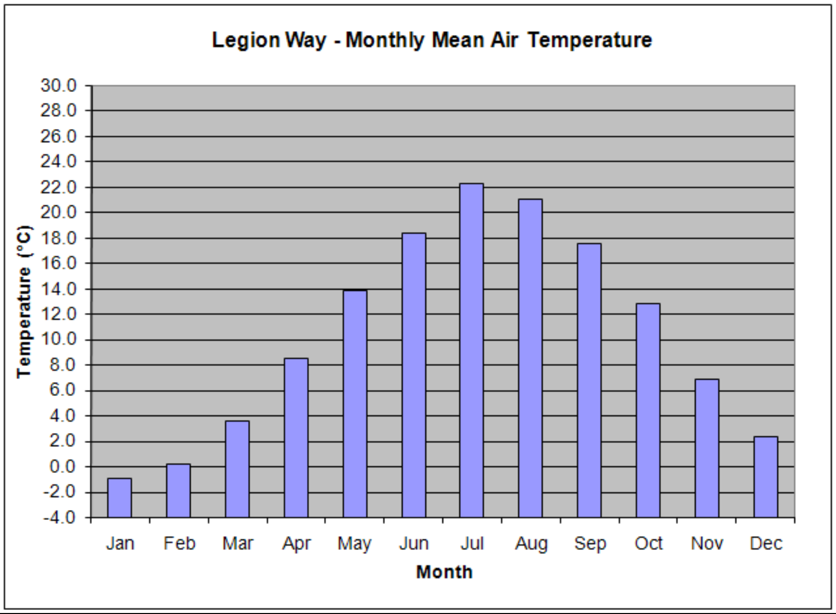


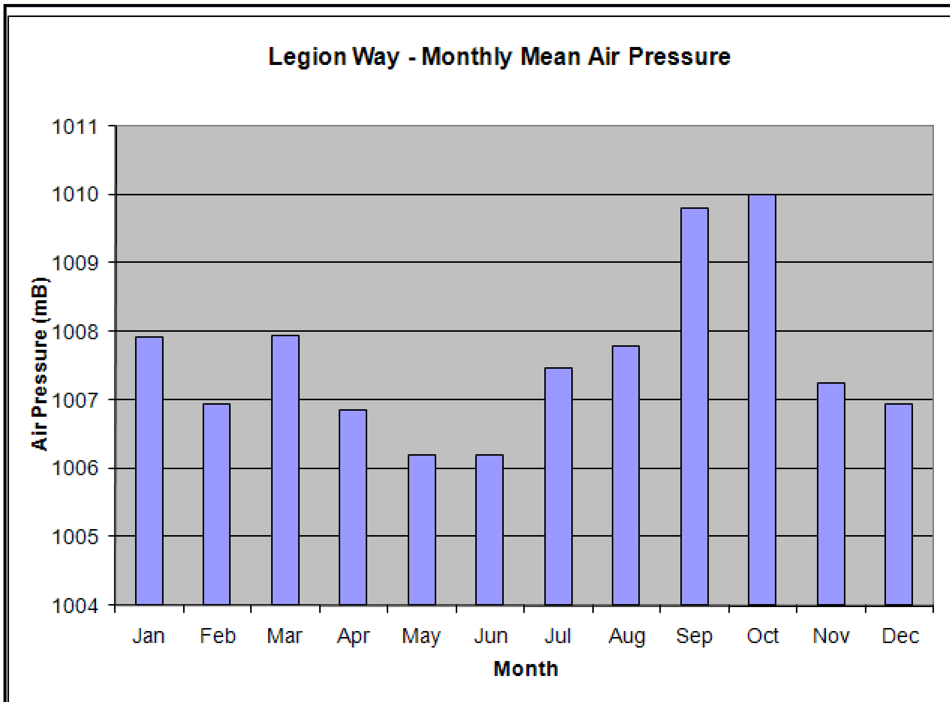
Figure 5 - 16-Sector Wind Rose

Figures 6, 7, and 8 show the monthly mean air temperature, air pressure, and air density, respectively. The site air density is lowest in the summer months as result of higher air temperatures.



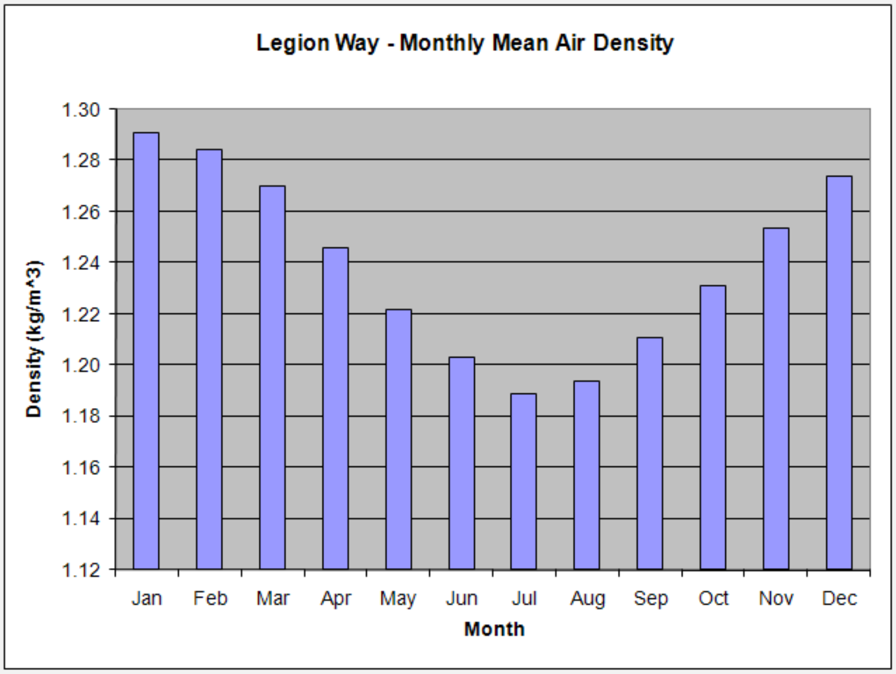
Month	Temperature (deg C)
Jan	-0.94
Feb	0.23
Mar	3.56
Apr	8.57
May	13.87
Jun	18.39
Jul	22.25
Aug	21.11
Sep	17.52
Oct	12.89
Nov	6.90
Dec	2.40

Figure 6 - Monthly Mean Air Temperature



Month	Pressure (mb)
Jan	1009.81
Feb	1007.59
Mar	1006.04
Apr	1007.26
May	1006.71
Jun	1008.39
Jul	1008.58
Aug	1005.59
Sep	1007.61
Oct	1007.16
Nov	1007.48
Dec	1008.98

Figure 7 - Monthly Mean Air Pressure



Month	Density (kg/m^3)
Jan	1.291
Feb	1.284
Mar	1.270
Apr	1.246
May	1.222
Jun	1.203
Jul	1.189
Aug	1.193
Sep	1.211
Oct	1.231
Nov	1.254
Dec	1.274

Figure 8 - Monthly Mean Air Density

Energy Production Estimate

We have estimated the expected annual energy production at the VMM location based on the frequency distribution from the virtual met mast and the power curve for the Elecon 600kW turbine model. The power curve provided by the Town of Barrington was given for five air temperatures and corresponding air densities and is shown in Table 1. We computed energy estimates for 65 meter and 55 meter hub heights, as the virtual met mast was modeled at 65 meters but the maximum hub height for this turbine as reported by the manufacturer is 55 meters.

AWS Truewind interpolated this power curve to the site air density of 1.239 kg/m^3. The frequency distribution is multiplied by the power curve to compute the expected gross energy production. The gross energy estimate is then reduced by the total energy loss to attain the net energy production. It should be noted that the loss value presented here is a conservative value based on AWS Truewind's experience with similar turbines and environmental conditions. However, lacking direct turbine performance specifications from the manufacturer, we recommend the Town of Barrington confirm all turbine specifications with the manufacturer and undertake a detailed loss analysis before proceeding with development. It should also be noted that in the absence of a turbine layout, we did not account for any array losses and the impact of any site layout change should be assessed before proceeding with development. The net energy production estimates at 65 and 55 meters are 763 MWh/yr and 680 MWh/yr, respectively, and are detailed along with their respective loss estimates in Table 2.

The uncertainty was estimated by comparing the wind map speed at several points in Rhode Island to the observed wind speed. We estimate the uncertainty to be 6.6%, with a corresponding energy production uncertainty of 11.9%. As a result, we expect the net average annual energy production at 65 meters to be 763 MWh/yr, or 14.5% capacity factor, with 50% confidence and 647 MWh/yr, or

12.3% capacity factor, with 90% confidence. This information and the corresponding values for the 55 meter height are summarized in Table 2.

Table 1. Elecon 600kW Power Curve

Wind Speed (m/s)	Electric Power (kW)					
	-10	0	10	20	30	Temperature (°C)
	1.342	1.292	1.247	1.204	1.165	Air density (kg/m^3)
0	0	0	0	0	0	
1	0	0	0	0	0	
2	0	0	0	0	0	
3	2.65	2.55	2.46	2.37	2.29	
4	19.88	19.03	18.28	17.56	16.92	
5	51.95	49.78	47.85	46.02	44.32	
6	98.61	94.5	90.82	87.34	84.2	
7	137.9	132	126.8	121.8	120	
8	237.8	227	217.4	208.4	200.3	
9	361.9	346.5	332.8	319.9	308.2	
10	487.7	468.2	450.7	434.2	419.2	
11	591.7	569.7	549.6	529.1	510.6	
12	600	600	600	600	583.7	
13	600	600	600	600	600	
14	600	600	600	600	600	
15	600	600	600	600	600	
16	600	600	600	600	600	
17	600	600	600	600	600	
18	600	600	600	600	600	
19	600	600	600	600	600	
20	600	600	600	600	600	
21	600	600	600	600	600	
22	600	600	600	600	600	
23	600	600	600	600	600	
24	600	600	600	600	600	
25	600	600	600	600	600	

Table 2. Estimated Average Annual Energy Production and Net Capacity Factors

Hub Height	65 m	55 m
Wind Speed (m/s)	5.33	5.13
Gross Energy Production (MWh/yr)	904	814
Total Loss (%)	16.0	16.0
Net Energy Production, 50% Confidence (P50) (MWh/yr)	763	680
Net Capacity Factor (%)	14.5	12.9
Net Energy Production, 90% Confidence (P90) (MWH/yr)	647	576

Methodology

Virtual met masts are created using the MesoMap system developed by AWS Truewind to map the wind resources of large regions at a high level of detail and accuracy. MesoMap accomplishes this by combining a state-of-the-art numerical weather model for simulating regional (mesoscale) weather patterns with a wind flow model responsive to local (microscale) terrain and surface conditions. Using weather data collected from weather balloons, satellites, and meteorological stations as its main inputs, MesoMap does not require wind data to make reasonably accurate predictions. However such data are still required to confirm the wind resource at any particular location before major investments are made in a wind project. In the past five years, MesoMap has been applied in over 30 countries on four continents. In North America alone, MesoMap has been used to map over 30 US states and several provinces of Canada and states of Mexico. The typical error margin is 5-7%, depending on the complexity of the terrain and the size of the region.

Description

The MesoMap system has three main components: models, databases, and computer systems. These components are described below.

Models

At the core of the MesoMap system is MASS (Mesoscale Atmospheric Simulation System), a numerical weather model that has been developed over the past 20 years by AWS Truewind's partner MESO, Inc., both as a research tool and to provide commercial weather forecasting services.[1] MASS simulates the fundamental physics of the atmosphere including conservation of mass, momentum, and energy, as well as the moisture phases, and it contains a turbulent kinetic energy module that accounts for the effects of viscosity and thermal stability on wind shear. A dynamic model, MASS simulates the evolution of atmospheric conditions in time steps as short as a few seconds. This creates great computational demands, especially when running at high resolution. Hence MASS is usually coupled to a simpler but much faster program, WindMap, a mass-conserving wind flow model developed by AWS Truewind.[2] Depending on the size and complexity of the region and requirements of the client, WindMap is used to improve the spatial resolution of the MASS simulations to account for the local effects of terrain and surface roughness variations.

Data Sources

MASS uses a variety of online, global, geophysical and meteorological databases. The main meteorological inputs are reanalysis data, rawinsonde data, and land surface measurements. The reanalysis database – the most important – is a gridded historical data set produced by the US National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR).[3] The data provide a snapshot of atmospheric conditions around the word at all levels of the atmosphere in intervals of six hours. Along with rawinsonde and surface data, the reanalysis data establish the initial conditions as well as lateral boundary conditions for the MASS runs. The MASS model itself determines the evolution of atmospheric conditions within the region based on the interactions among different elements in the atmosphere and between the atmosphere and the surface. The reanalysis data are on a relatively coarse grid (about 210 km spacing). To avoid generating noise at the boundaries that can result from large jumps in grid cell size, MASS is run in

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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.

[3] Robert Kistler et al., The NCEP/NCAR Reanalysis, Bulletin of the American Meteorological Society (2001).

several nested grids of successfully finer mesh size, each taking as input the output of the previous nest, until the desired grid scale is reached. The outermost grid typically extends several thousand kilometers.

The main geophysical inputs are elevation, land cover, vegetation greenness (normalized differential vegetation index, or NDVI), soil moisture, and sea-surface temperatures. The elevation data used by MASS are from the Shuttle Radar Topographical Mission 30 Arc-Second Data Set (SRTM30), which was produced in an international project spearheaded by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA).[4] The land cover data are from the satellite-based Moderate Resolution Imaging Spectro-radiometer (MODIS) data set.[5] The NDVI data were derived from a predecessor of MODIS, the satellite-based Advanced Very High Resolution Radiometer (AVHRR).[6] The nominal spatial resolution of all of these data sets is 1 km.

Maps of much higher resolution than 1 km can be produced either by MASS or by WindMap if the necessary topographical and land cover data are available. In the past year, 3 arc-second SRTM data have been released for most of the world except the polar regions. These data provide highly accurate elevations on a 90 m horizontal grid (30 m in the United States). A data set called GeoCover, from EarthSat, offers high-quality land cover classifications on a 28 m grid for most of the world.[7] The WindMap model automatically adjusts for differences in elevation and surface roughness between the mesoscale and microscale.

Computer and Storage Systems

The MesoMap system requires a very powerful set of computers and storage systems to produce detailed wind resource maps in a reasonable amount of time. To meet this need AWS Truewind has created a distributed processing network consisting of about 130 Pentium II processors and 10 terabytes of hard disk storage. Since each day simulated by a processor is entirely independent of other days, a project can be run on this system up to 130 times faster than would be possible with any single processor. To put it another way, a typical MesoMap project that would take two years to run on a single processor can be completed in about a week.

The Modeling Process

The MesoMap system creates wind resource information in several steps. First, the MASS model simulates weather conditions over 366 days selected from a 15-year period. The days are chosen through a stratified random sampling scheme so that each month and season is represented equally in the sample; only the year is randomized. Each simulation generates wind and other weather variables (including temperature, pressure, moisture, turbulent kinetic energy, and heat flux) in three dimensions throughout the model domain, and the information is stored at hourly intervals. This information can be used to create virtual met mast hourly time series data.

When the mesoscale runs are finished, the results are summarized in files, which are then input into the WindMap program for the final mapping stage.

Once completed, the maps and data can be compared with land and ocean surface wind measurements, and if significant discrepancies are observed, the wind maps can be adjusted. The most common sources of validation data are tall towers instrumented for wind energy assessment and standard meteorological stations. The validation is usually carried out in the following steps:

1. Station locations are verified and adjusted, if necessary, by comparing the quoted elevations and station descriptions against the elevation and land cover maps. Where there are obvious

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[4]For more information, see http://www2.jpl.nasa.gov/srtm/.
[5]See http://edcdaac.usgs.gov/modis/mod12q1.asp.
[6]See http://edcwww.cr.usgs.gov/products/landcover/glcc.html.
[7]See http://www.mdafederal.com/geocover/geocoverlc.

errors in position, the stations are moved to the nearest point with the correct elevation and surface characteristics.

2. The observed mean speed and power are adjusted to the long-term climate norm and then extrapolated to the map height using the power law. Often, for the tall towers, little or no extrapolation is needed. Where multi-level data are available, the observed mean wind shear exponent is used. Where measurements were taken at a single height, the wind shear is estimated from available information concerning the station location and surroundings.
3. The predicted and measured/extrapolated speeds are compared, and the map bias (map speed minus measured/extrapolated speed) is calculated for each point. If there are enough towers, the mean bias and standard deviation of the biases is calculated. (It is important to note that the bias and standard deviation may reflect errors in the data as well as the map.)
4. If we detect a pattern of bias, the maps are adjusted to reduce or eliminate the discrepancy.

The MesoMap system has been validated in this fashion using data from well over 1000 stations worldwide. We have found the typical standard error, after accounting for uncertainty in the data, to be 5-7% of the mean speed at a height of 50 m.

For a virtual met mast, the final wind speed data are scaled to match the final speeds from the WindMap simulation.

Factors Affecting Accuracy

In our experience, the most important sources of error in the wind resource estimates produced by MesoMap are the following:

- Finite grid scale of the simulations
- Errors in assumed surface properties such as roughness
- Errors in the topographical and land cover data bases

The finite grid scale of the simulations results in a smoothing of terrain features such as mountains and valleys. For example, a mountain ridge that is 2000 m above sea level may appear to the model to be only 1600 m high. Where the flow is forced over the terrain, this smoothing can result in an underestimation of the mean wind speed or power at the ridge top. Where the mountains block the flow, on the other hand, the smoothing can result in an overestimation of the resource, as the model understates the blocking effect. The problem of finite grid scale can be solved by increasing the spatial resolution of the simulations, but at a cost in computer processing and storage.

While topographic data are usually reliable, errors in the size and location of terrain features nonetheless occur from time to time. Errors in the land cover data are more common, and usually result from the misclassification of aerial or satellite imagery. Wherever possible, AWS Truewind uses the most accurate and detailed land cover databases.

Assuming the land cover types are correctly identified, there remains uncertainty in the surface properties that should be assigned to each type, and especially the vegetation height and roughness. A forest, for example, may consist of a variety of trees of varying heights and density, leaf characteristics, and other features affecting surface roughness. An area designated as cropland may be devoid of trees, or it may be broken up into fields separated by windbreaks. Uncertainties such as these can be resolved only by visiting the region and verifying firsthand the land cover data.

Disclaimer

Statistical analysis and validation studies have determined the standard error for annual wind speeds produced by the Virtual Met Mast to be approximately 5 - 7%. However, when the data are stratified by shorter time scales (i.e. monthly), this error may be slightly higher as an anomalously high or low diurnal (24-hour) wind speed time series for a particular site may have a greater effect on smaller averaging periods. The 366-day hourly time series generated by MesoMap for the Virtual Met Mast are not contiguous from one day to the next and should not be considered to be representative of a continual sequence of ambient weather.