

# Uncertainty in Wind Resource Assessment

- Wind resource estimates are useful only if their uncertainty is well defined.
- Unless the resource analyst can offer a degree of confidence that the wind resource falls within a specified range, it is not possible to construct a sound financial model for a wind project investment.

- The uncertainty present in all wind resource estimates is primarily related to the following factors:
  - wind speed measurements,
  - the historical climate adjustment,
  - potential future climate deviations, wind shear, and
  - the spatial wind resource distribution.

- The uncertainty estimates are expressed as a percent of the speed and represent one standard error of a normal distribution.
- Not addressed is the relationship between the uncertainty in speed and the uncertainty in energy production, which varies depending on the turbine model, speed frequency distribution, and other factors.

# Measurement Uncertainty

- This is the uncertainty in the wind speed as measured by the anemometers after data validation and adjustments.
- It reflects not just the uncertainty in the sensitivity of the instruments when operating under ideal, wind-tunnel conditions but also their performance in the field.

- The uncertainty associated with anemometer response under ideal conditions (called the sensor response uncertainty) is typically estimated to be **1.0%-1.5%** for a single anemometer.
- A typical range of estimates for a single anemometer mounted in accordance with the guidelines presented in this handbook, and whose data are subjected to high-quality validation procedures, is **1.3%-2.5%**.

- The measurement accuracy can be considerably improved by averaging the data from two sensors mounted in different directions at the same height on the mast.
- For those direction sectors where neither sensor is in the direct shadow of the tower, it is reasonable to reduce the uncertainty by  $\sqrt{2} = 1.414$

# Historical Wind Resource

- This uncertainty addresses how well the site data (after adjustment via MCP) may represent the historical norm.
- It is related to the interannual variability of the wind climate and the correlation of the site data with the long-term reference.

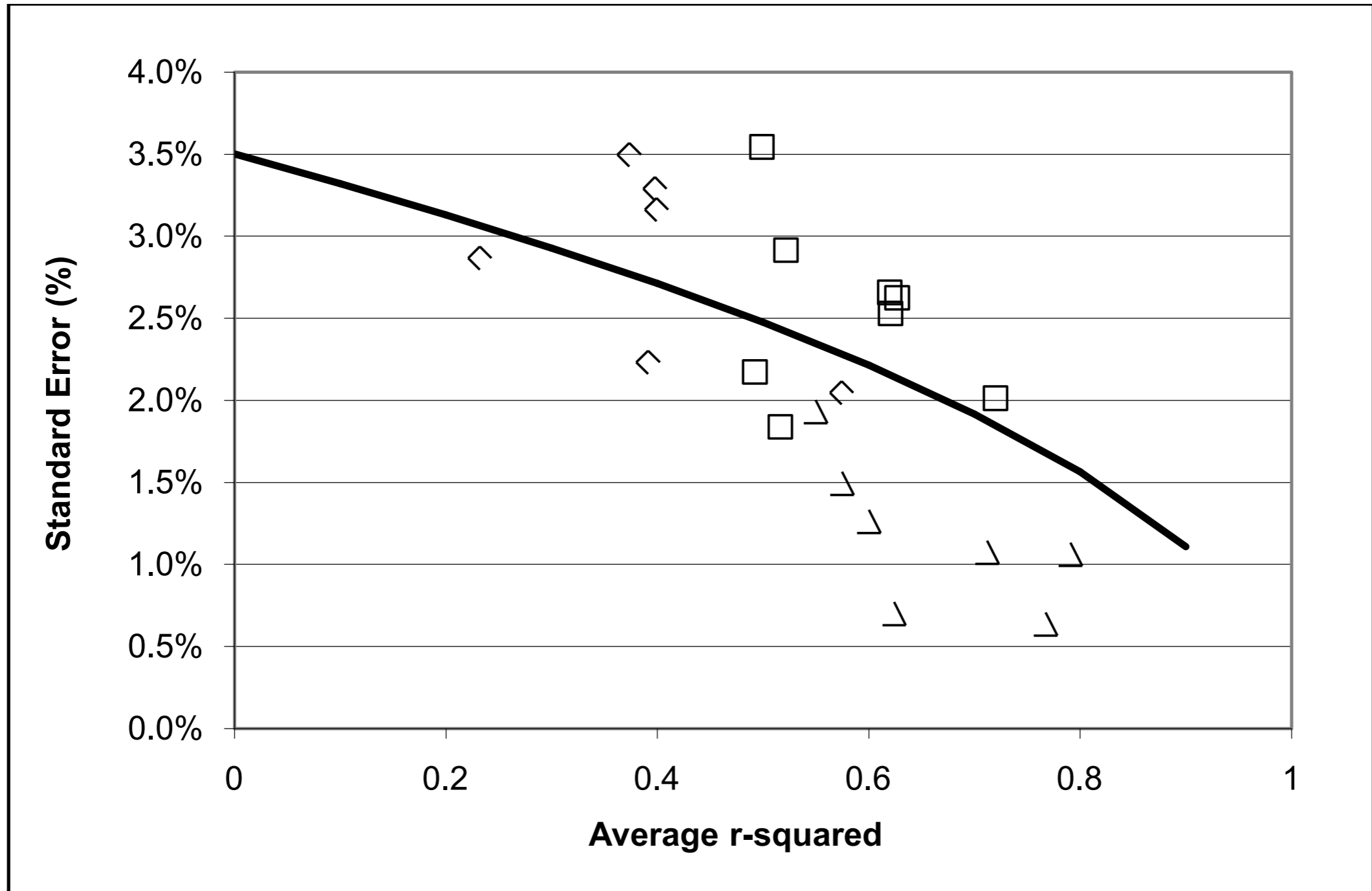


$$\sigma = \sigma_A \sqrt{\frac{r^2}{N_R} + \frac{1-r^2}{N_T}}$$

Here,  $\sigma_A$  is the standard deviation of the annual mean wind speeds as a percentage of the mean, which we assume is the same for the reference and target sites;  $N_R$  and  $N_T$  are the number of years of reference and overlapping reference-target data, respectively;  $r$  is the Pearson correlation coefficient based on a suitable averaging period (such as daily means); **and  $\sigma$  is the uncertainty in the derived historical mean wind speed at the target site.**

- This equation makes a number of assumptions...
- ... and should be applied with caution.
- The most important is that the reference data record is consistent through time, with no discontinuities or trends resulting from changing location, equipment, surroundings, and other factors.

- This assumption is not likely to be valid for reference data older than 15 years.
- Because of seasonal effects, the equation should not be used with much less than one year of overlapping target and reference data.
- Even when these conditions are met, actual errors may depart substantially from the equation, as illustrated in Figure 14-1.



**Figure 14-1 - Results of an experiment to determine the uncertainty of MCP based on 12-month unconstrained linear regressions with three towers. Curve is the theoretical uncertainty assuming 3.5% interannual variations. For explanation, see the text. (Source: M. Taylor et al., "An Analysis of Wind Resource Uncertainty in Energy Production Estimates," AWS Truepower, 2004.)**

$$\sigma = \sigma_A \sqrt{\frac{r^2}{N_R} + \frac{1-r^2}{N_T}}$$

EXAMPLE:

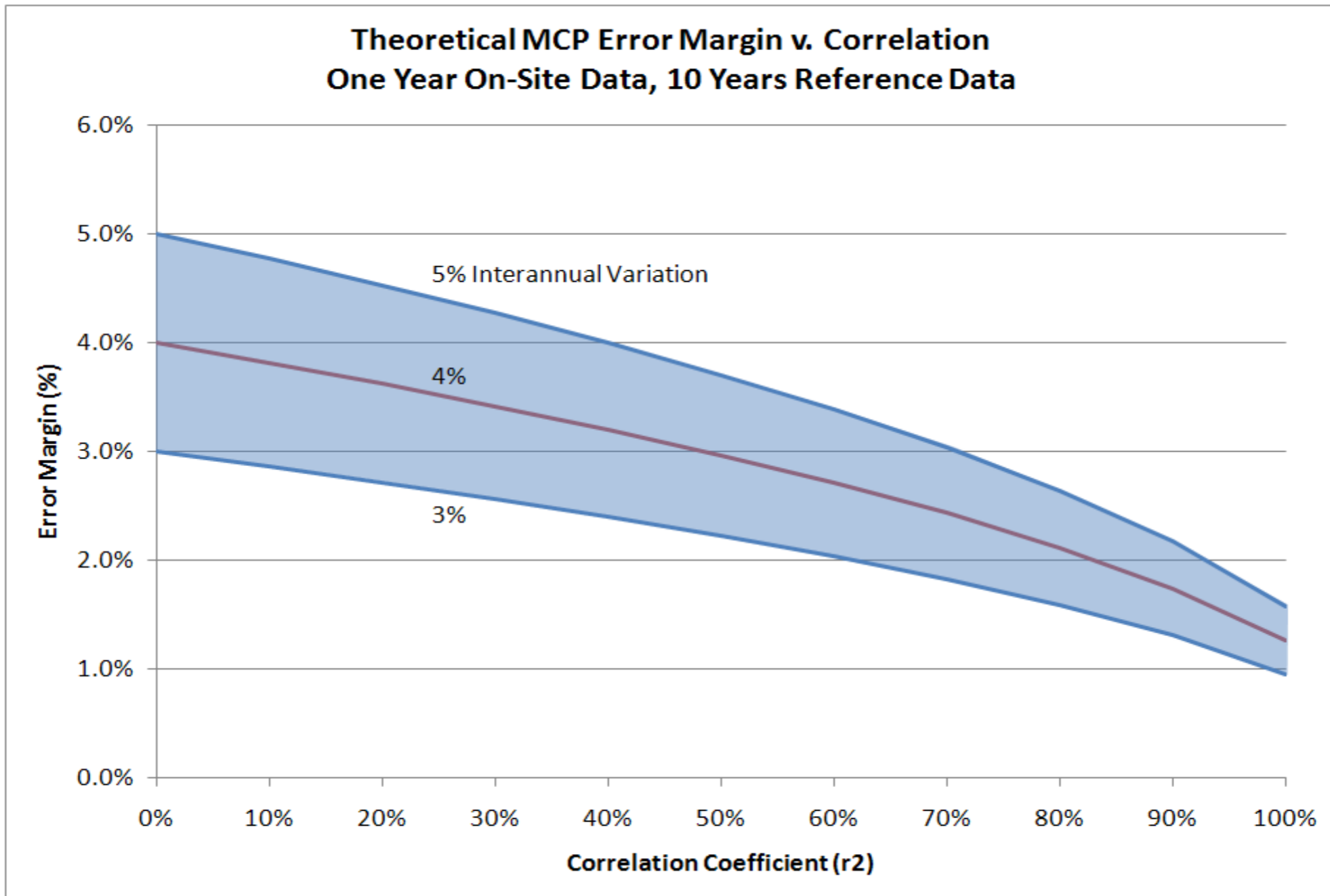
$$\sigma_A = 4\%$$

$$r = 0.7$$

$$N_R = 15$$

$$N_T = 1$$

$$\begin{aligned}\sigma &= 4\% \sqrt{\frac{0.7^2}{15} + \frac{1-0.7^2}{1}} = 4\% \sqrt{\frac{0.49}{15} + \frac{0.51}{1}} \\ &= 4\% \sqrt{0.03 + 0.51} = 4\%(0.74) = 2.9\%\end{aligned}$$



**Figure 12-3 Uncertainty margin in the estimated long-term mean wind speed at a site, assuming one year of on-site data and 10 years of reference data, as a function of the  $r^2$  coefficient between them and of the interannual variation in the wind at the site (the standard deviation of annual mean wind speeds divided by the long-term mean). (Source: AWS Truepower)**

- Historical wind records suggest the standard deviation of annual mean wind speeds ranges from 3% to 5%, and so it is reasonable to assume 4%.
- With this assumption, and for one year of overlapping data, a reference record ranging from 7-to-15 years, and a correlation factor ranging from 0.6 to 0.9, a typical range of uncertainties in the historical mean speed is **1.6%-2.8%**.

# Future Wind Resource

- The uncertainty in the future wind resource can be divided into two components:
  - that due to **normal variability in the wind climate**, and
  - that due to the **risk of long-term climate change**.



Assuming the two components are unrelated, the individual uncertainties can be combined:

$$\sigma = \sqrt{\sigma_{normal}^2 + \sigma_{climate}^2}$$

$$\sigma_{normal} \cong \frac{\sigma_A}{\sqrt{N_P}}$$

- Although the possibility of climate change is more speculative, it should not be ignored.
- We estimate a plausible range of uncertainty from this component to be 0.5%-2%.
- The lower end of this range applies to a plant life of 10 years, while the upper end might apply to a plant life as long as 20-25 years.
- For a plant life of 10 years, the combined uncertainty is 1.4%.
- Over 25 years, it increases to 2.2%.

## EXAMPLE:

$$\sigma = \sqrt{\sigma_{normal}^2 + \sigma_{climate}^2}$$

$$\sigma_{normal} \cong \frac{\sigma_A}{\sqrt{N_P}}$$

$$\sigma_{climate} \cong 0.5\% - 2.0\%$$

For  $\sigma_A = 4\%$  and  $N_P = 10$ :

$$\sigma = \sqrt{\frac{(4\%)^2}{10} + (0.5\%)^2} = 1.36\%.$$

For  $\sigma_A = 4\%$  and  $N_P = 25$ :

$$\sigma = \sqrt{\frac{(4\%)^2}{25} + (2.0\%)^2} = 2.15\%.$$

# Wind Shear

- The wind shear uncertainty can be likewise divided into two components:
  - the uncertainty in the observed wind shear due to possible **measurement errors**, and
  - the uncertainty in the **change in wind shear above mast height**.
- The two components are independent of one another, so the sum of the squares applies.

- With respect to the first component, the key contributing factors are the uncertainties of
  - the speed ratio between the two heights,
  - the height ratio.
- The speed ratio uncertainty is approximately the uncertainty in the measured speed at each height multiplied by  $\sqrt{2} = 1.414$ .
- The effect of a given uncertainty in the height ratio is considerably less than the effect of the same uncertainty in the speed ratio.

- If the shear calculation uses sensors that are mounted differently, such that their exposure to tower effects is not similar, this should be taken into account in the shear uncertainty.

- The second component is more difficult to estimate and depends very much on the site.
- We estimate the uncertainty in the shear exponent above the top of the mast to be 10% to 20% of the observed shear, depending on the complexity of the terrain and land cover.
- If the observed shear exponent is 0.20 and the terrain is flat and open, we might assume an uncertainty of 0.02; if the observed exponent is 0.30 and the terrain is complex, we might assume 0.06.

- With these assumptions, a typical range of uncertainty in the shear exponent is from 0.04 to 0.07. The corresponding uncertainty in the hub height speed is approximated by the following equation:

$$\sigma_{hh} = 100 \left[ \left( \frac{h_h}{h_2} \right)^{\Delta\alpha} - 1 \right] (\%)$$

- For a mast height of 60 m height and hub height of 80 m, the range of uncertainty in speed is **1.1% to 2.1%**.



# Wind Flow Modeling

- Wind flow modeling uncertainty is defined as the uncertainty in the average wind speed for the turbine array relative to the observed wind speed at the site masts.
- The range of uncertainty can be very wide, as it depends on the model used, the model's resolution, the terrain and wind climate, the quality of wind measurements, the placement of the masts, and other factors.
- It is often not an easy task to estimate it in a rigorous, objective fashion.

- In the ideal case, there are enough masts at the site to test the modeling uncertainty directly.
- Ten or more masts are required for a statistically robust estimate, though as few as five masts may do.
- Each mast is withheld from the modeling in turn, and a prediction for that mast is made based on the others.
- The root mean square error is the estimated error for an arbitrary point.

Assuming the proper conditions are met, the uncertainty in the array-average wind speed can be approximated by

$$\sigma \cong \frac{\sigma_m}{\sqrt{N}}$$

where  $\sigma_m$  is the rmse calculated in the previous step, and  $N$  is the number of masts.

**This equation describes the ideal case in which the masts are distributed more or less evenly within the proposed turbine array in locations that are representative of where the turbines may be installed.**

- As an alternative, one may divide the array into sections assigned to each mast, estimate the uncertainty separately for each section, and then combine the uncertainties to find the uncertainty for the project as a whole.
- This method is especially suited to situations in which the masts are unevenly distributed, so that some masts have more turbines assigned to them than others.

- In practice, errors from numerical wind flow models fall in a very wide range.
- In **simple terrain** with little variation in land cover, and with multiple masts, the uncertainty in the array-average speed may be as low as 2%.
- In more **complex situations**, uncertainties as high as 10% or more may be justified.
- A typical range is **3-6%**.

# Summary

Table 14-1 summarizes the range of uncertainties in each category and the overall uncertainty range for the array-average wind speed for typical wind projects.

Category	Uncertainty
Measurement Accuracy (single anemometer)	1.3%-2.5%
Historical Wind Resource	1.6%-2.8%
Future Wind Resource (plant life of 10-yrs, 25-yrs)	1.4%, 2.2%
Wind Shear	1.1%-2.1%
Wind Flow Modeling	3.0%-6.0%
<b>Overall</b> (plant life of 10 years assumed)	<b>4.1%-7.5%</b>

**Table 14-1 Summary of typical uncertainty ranges by category.**