Challenges to the Classical Approach to Uncertainty Calculation

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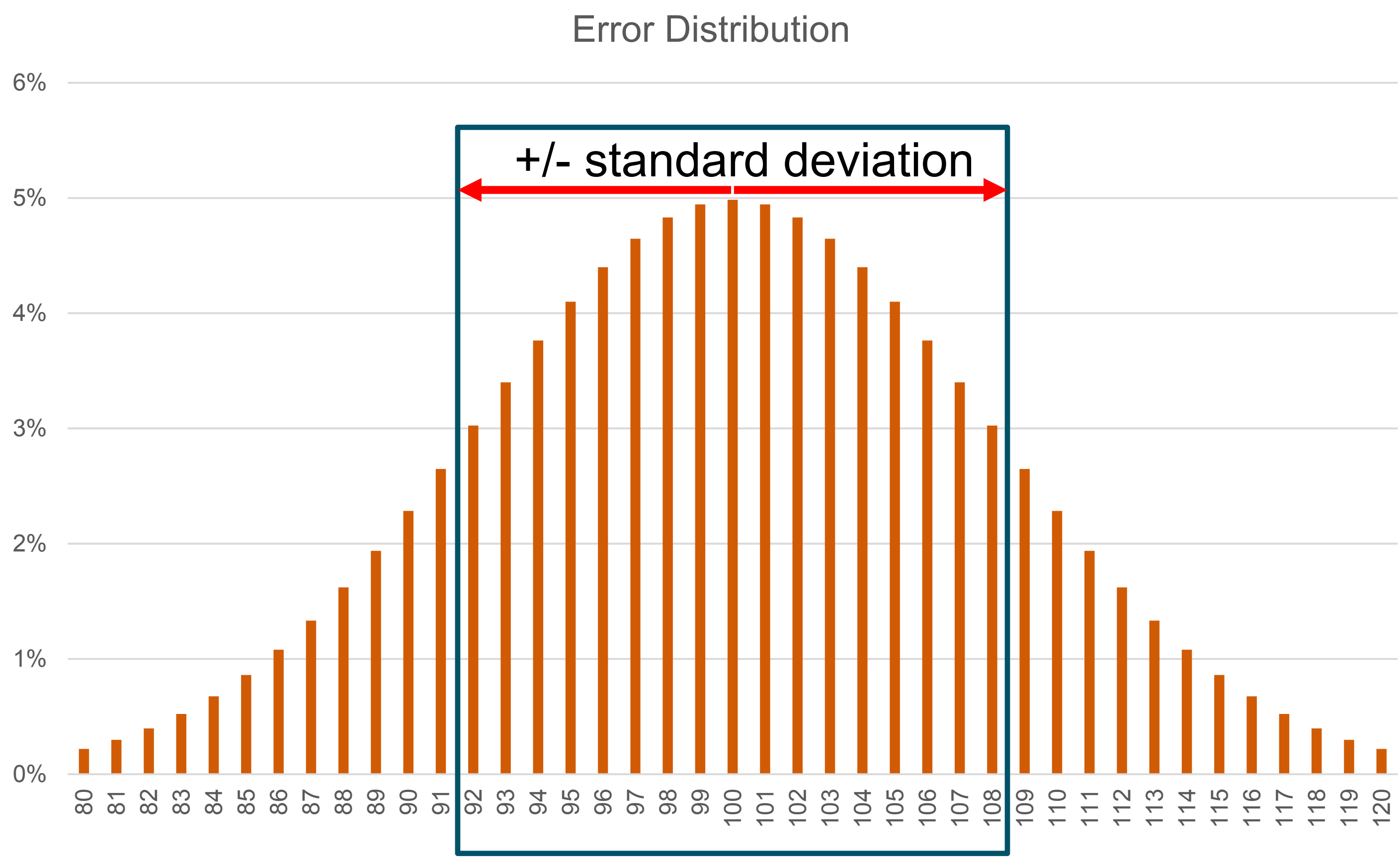
What is uncertainty?

- What we are really interested in is financial risk.
- The way we commonly model financial risk is with sensitivity cases based around probability of exceedance (P-values)
- Since that's a lot of information, we commonly use a generic term 'uncertainty' to describe the risk.
- In wind assessment, we usually define uncertainty to be the standard deviation of a normal error distribution. Because of climate variability, we attach a time frame to our uncertainty estimates (ie monthly, 1-year, 10-year)

Simple Uncertainty Explanation



There is a 68% chance that the truth is within the uncertainty (1 standard deviation) of the primary estimate.

So how do we often calculate uncertainty?

Met tower	Met 1	Met 2	Met 3
Avg Wind Speed (m/s)	6.5	6.8	6.9
Wind Energy Sensitivity	1.8	1.8	1.8
Long term reference length (years)	18	18	18
Future prediction period(years)	10	10	10
Inter-annual variability (%)	4.0%	4.0%	4.0%
Energy Predicted per Met Tower (GWh)	35	150	180

- Average wind speed used to scale uncertainties that are in percent when combining
- Wind energy sensitivity is the percent change in energy to a one percent change in wind speed. Used to translate between wind speed & energy
- Length of reference & inter-annual variability used for climate uncertainties
- Prediction period and inter-annual variability used for future climate uncertainty

Wind speed uncertainties at the met tower

Met tower	Met 1	Met 2	Met 3
Measurement uncertainty	2.0%	2.2%	2.1%
Historic variability	0.9%	0.9%	0.9%
Correlations (intra/reference)	1.9%	2.1%	2.3%
Vertical Extrapolation	1.2%	1.2%	0%
Met Tower Historic Uncertainty (% wind speed)	**3.2%**	**3.4%**	**3.3%**

- Measurement is often related to uncertainty of anemometer calibration and can be varied if local conditions like poor quality data exist.
- Historic variability derived from inter-annual variability. Usually IAV / sqrt(number of years). In this example $4\%/\sqrt{18} = 0.9$
- Little standardization in correlation uncertainties. Usually function of training period and error statistics.
- Vertical extrapolation usually a function of vertical extrapolation distance and shear exponents

Project uncertainties in terms of energy

Project	(%)	GWh / year
P50		365
Measurement uncertainty	3.8%	14.0
Historic variability	1.7%	6.2
Correlations (intra/reference)	3.9%	14.3
Vertical Extrapolation	1.1%	4.0
Met Tower Historic Uncertainty (% wind speed)	**5.8%**	**21.3**
Topographic	3.0%	11.0
Wake losses	2.0%	7.3
Other loss factors	3.0%	11.0
Future wind variability (10 years)	2.3%	8.3
Energy uncertainty (10 years)	**7.8%**	**28.6**

Uncertainty combinations using root sum square.

Future variability calculated same way as historic.

- Wind speed as a percent is aggregated to the project level and converted to energy using wind speed energy sensitivity.
- Other uncertainties applied at the energy level like wake and losses

Assumptions

- Normal distributions
- Root sum square combinations imply that uncertainty categories are independent
- Often complete dependence assumed between uncertainties derived at each met tower
- Rules of thumb for many complex parameters (measurement uncertainty, inter annual variability, spatial uncertainty, losses)

Things we do with measurements

- Quality control of data
- Selective averaging of sensors at multiple heights
- Intra-tower data synthesis
- Intra-project data synthesis
- Vertical extrapolation to hub height
- Extrapolation to long term
- Spatial extrapolation to turbine locations where they are used as input to a turbine simulation

Propagation of uncertainty through shear calculation

Power law formula for wind shear

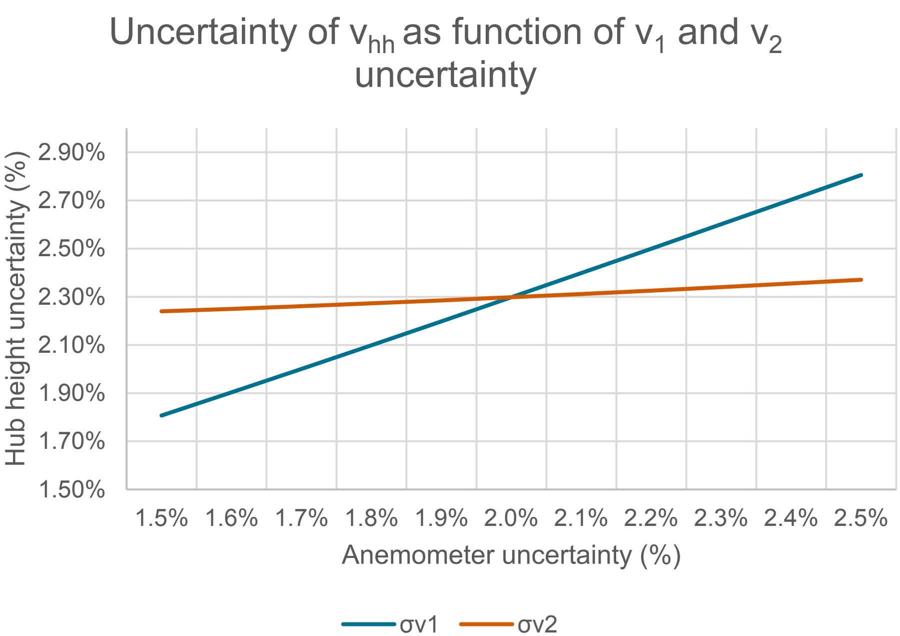
$$\propto = \left(\frac{\ln\left({}^{v1}/_{v2} \right)}{\ln\left({}^{h1}/_{h2} \right)} \right)$$

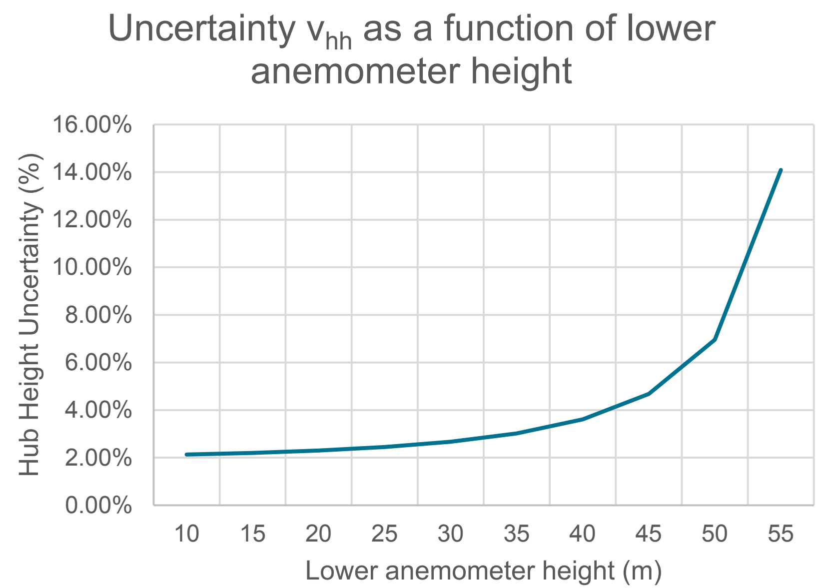
Extrapolation of wind to hub height using calculated shear

$$v_{hh} = v_1 \left(\frac{h1}{h2} \right)^{\propto}$$

Error of each of the inputs (*v1, v2, h1, h2)* have to be propagated through the above formulas.

Hub height uncertainty as a function of measurement heights and uncertainty





Assumptions

- 2% measurement uncertainty when not specified
- 60m mast height, 90m hub height
- 20m lower sensor height when not specified
- Simple propagation of single upper & lower anemometer error through power law

Result Statement

- Simple changes to met tower configuration can have impact on propagation of measurement uncertainty of several percent in wind speed. Which is usually increased when converted to energy.

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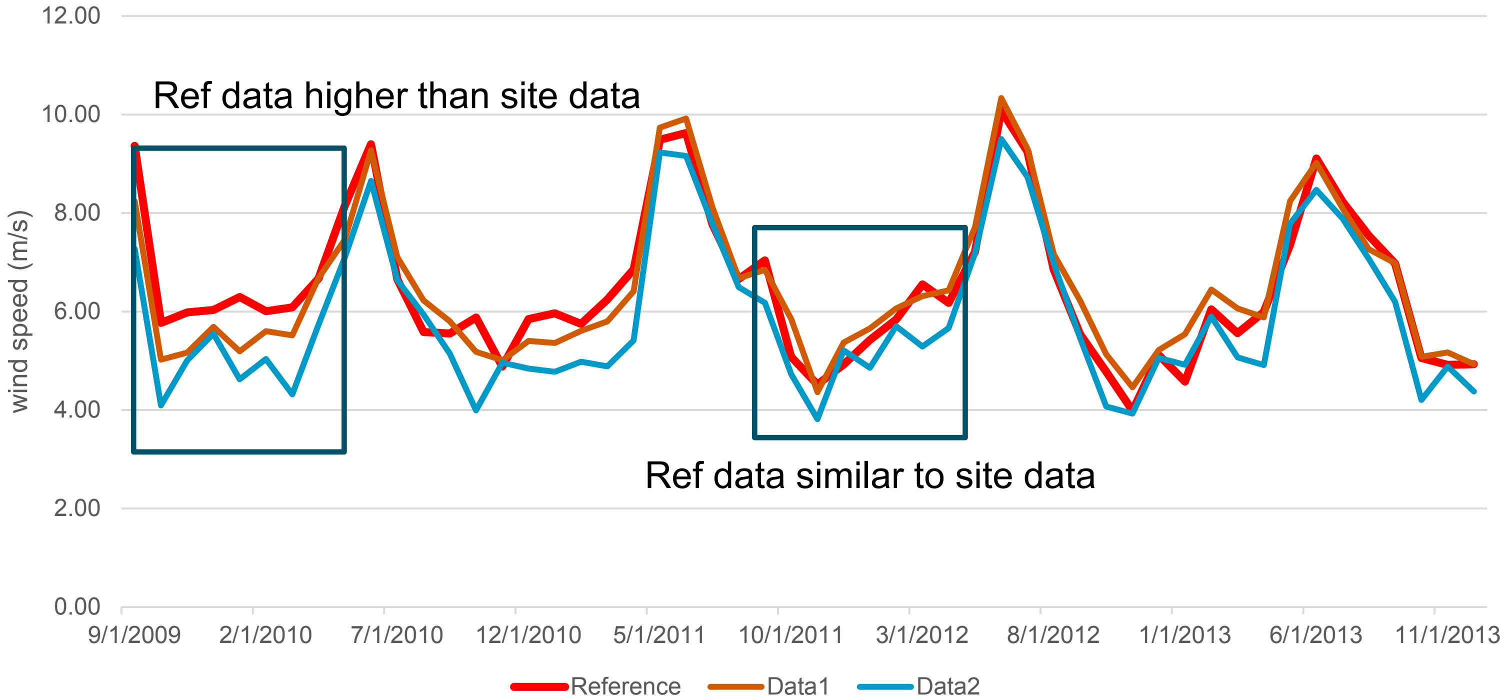
Covariance between met towers in MCP process



- 2 met towers correlated to the same reference over the same period will share error of reference data.
- 2 met towers correlated against a reference over different period will have independent correlation error

Demonstrating MCP covariance

- Study used 3 wind speed datasets: 2 targets and 1 reference
- Each dataset had over 4 years of concurrent data
- Simple MCP process using concurrent 12 month periods to develop monthly ratios that are applied to the average wind speeds at the reference
- Simulated data is compared to target data across 4+ year period
- MCP run 13,000 times choosing 12 random months at both target datasets.
- Each met not required to be trained on same months.
- 4 year average of both targets chosen as target metric
- Simulated data compared to actual as a function of overlapping months within 12 selected months

Simulation Results

Overlapping Months	R^2 of Met1 & Met2 Error	Count	Avg Error
0	0.193	38	1.36%
1	0.043	199	1.47%
2	0.031	486	1.43%
3	0.000	831	1.60%
4	0.018	1065	1.72%
5	0.065	1193	1.68%
6	0.093	1236	1.72%
7	0.163	1225	1.75%
8	0.276	1267	1.85%
9	0.379	1251	1.87%
10	0.574	1256	2.01%
11	0.697	1147	1.95%
12	0.899	1806	2.06%

- Correlation of error between target data increased as period of overlap increased
- Average error increased as correlations increased

MCP Result Statement

- Assumptions on covariance of overlapping training period error in an MCP process can impact project wind uncertainty results by up to 1%.

Summary

- Classical uncertainty methods have been used for many years. While simple to calculate these methods have very simple assumptions with regards to how uncertainties combine.
- Two examples show that improperly treated covariance between uncertainties can lead to a misstatement of total project uncertainty
- Many more examples exist for other parts of process (selective averaging, vertical extrapolation spatial modeling, etc…)
- Uncertainty models that do not deal with these covariance layers will have less sensitivity and hence less ability to capture true uncertainty