Wind Plant Performance Prediction (WP3) Project

Operational Analysis Uncertainty Propagation

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Wind Plant Financing

Energy yield assessment (EYA)

*Provides expected annual yield of (planned) power plant, with uncertainties, to investors and other stakeholders.*
Wind Plant Financing (continued)

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Probability of exceedance (P-value)

The level of confidence that the energy output realized in a given year will meet or exceed a certain production value.

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A wind plant’s financing package for development can contribute up to 20% of the project’s capital expenses.

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WP3 Project

A joint collaboration between power plant owners and operators, consultancies, turbine manufacturers, investors, and the research community to validate EYA methods.

*Platform for sharing data, including preconstruction and operational data from more than 100 constructed modern wind projects.*
A joint collaboration between power plant owners and operators, consultancies, turbine manufacturers, investors, and the research community to validate EYA methods.

*Platform for sharing data, including preconstruction and operational data from more than 100 constructed modern wind projects.*

How certain is this “observed” annual energy output?
Operational Data Analysis

1. Turbine-level SCADA Sensor Data
2. Turbine-level SCADA Status Codes
3. Met-tower Sensor Data
4. Point of Revenue Meter Power Data
5. Point of Revenue Grid Curtailment Data
6. Historical Meteorological Data (MERRA-2)
7. Plant Asset Metadata

**Apply the fewest adjustments to wind farm production levels to determine an energy production value comparable to preconstruction EYAs.**
Operational Data Analysis (continued)

Apply the fewest adjustments to wind farm production levels to determine an energy production value comparable to preconstruction EYAs.

Note: Most data sources will be associated with measurement or modeling uncertainties.
Uncertainty Sources

• Data measurement uncertainties
  
  **Data required:** wind speed, power, wind direction, blade pitch, temperature, and so on.

  **Uncertainty sources:** calibration error, acquisition resolution, mounting, statistical variation, and so on.
Data Measurement Uncertainty

AIE
Theoretical production, given observed wind resources, if all turbines had been ideally operational at all times.
Wind speed mean ($u_{avg}$) and standard deviation ($u_{std}$) at 10-minute intervals.

Uncertainty sources:
- Calibration: $\Delta_{cal}$
- Mounting: $\Delta_{mount}$
- Data acquisition: $\Delta_{da}$
- Site classification: $\Delta_{class}$
- Statistical: $\Delta_{stat}$

$$\Delta u_{avg} = \sqrt{\Delta_{cal}^2 + \Delta_{mount}^2 + \Delta_{da}^2 + \Delta_{class}^2 + \Delta_{stat}^2}$$
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**Uncertainty propagation:** Model each 10-minute wind speed measurement as normal distribution with $\mu = u_{avg}, \sigma = \Delta u_{avg}$. Resample each 10-minute interval measurement from its associated distribution.
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• Method parameter selection in data processing
Data Processing Parameter Variation

1. Turbine-level SCADA Sensor Data
2. Turbine-level SCADA Status Codes
3. Met-tower Sensor Data

Data Cleaning and Filtering → Power Curve Model → Annualized Ideal Energy (AIE)

Turbine mean power output at 10-minute intervals.
Turbine mean power output at 10-minute intervals.

Uncertainty propagation: Assume each filter parameter can be described as a uniform distribution over a range that will yield “reasonable” results.
Uncertainty Sources

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  **Data required:** wind speed, power, wind direction, blade pitch, temperature, and so on.

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• Method parameter selection in data processing
  
  **Processing parameters required:** run-length encoding filter threshold, bin filter width and standard deviation threshold, power deviation from expectation, pitch threshold, and so on.
• Data measurement uncertainties

  **Data required:** wind speed, power, wind direction, blade pitch, temperature, and so on.

  **Uncertainty sources:** calibration error, acquisition resolution, mounting, statistical variation, and so on.

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  **Processing parameters required:** run-length encoding filter threshold, bin filter width and standard deviation threshold, power deviation from expectation, pitch threshold, and so on.

• Model choice selection in overall methodology
Choice of what filters should be applied and in what order.
Data Processing Method Variation (continued)

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2. Turbine-level SCADA Status Codes
3. Met-tower Sensor Data

Choice of what filters should be applied and in what order.

![Graphs showing data processing methods and filtering examples.](Image)
Choice of model (e.g. Logistics 5 Parameter or Generalized Additive Model) to be used in fitting filtered data so that “fully operational” power for any input wind resource condition can be predicted.
Uncertainty Sources

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  Data required: wind speed, power, wind direction, blade pitch, temperature, and so on.

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• Method parameter selection in data processing
  
  Processing parameters required: run-length encoding filter threshold, bin filter width and standard deviation threshold, power deviation from expectation, pitch threshold, and so on.

• Model choice selection in overall methodology
  
  Method choices required: applied data filters (binning, Bayes filter, and so on), power curve model (linear, five-parameter, generalized additive model, and so on), integrated data sources (MERRA, ERA, and so on).
Uncertainty Propagation

• Data measurement uncertainties
  Bootstrap resampling of each measurement over normal distribution, with the standard deviation defined by combined uncertainty.

• Method parameter selection in data processing
  Bootstrap resampling of each data processing parameter over uniform distribution within “reasonable” range.

• Model choice selection in overall methodology
  Direct comparison between several different “reasonable” methodologies.
Evaluation Metrics

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AME
The summed metered energy as observed at the point of revenue.
Evaluation Metrics (continued)

APE
Metered energy adjusted for curtailment and windiness.
Example Wind Power Plant

- One hundred turbines, four permanent meteorological towers
- Central Texas location

Wind rose from all towers at all times
Results

- Measurement uncertainties (mUQ): negligible variation in AME
- Parameter variation (pUQ): ~8% of AME for first filtration method (f1) and 2% for second filtration method (f2).
- Power curve choice variation: negligible variation in AME.
- Filtration method choice: ~15% of AME.
Conclusions

• When considering yearly metrics aggregated over the array, uncertainties in data measurements are of negligible magnitude.

  *Note that measurement uncertainties may still be highly significant in other analysis contexts, such as individual turbine control and operation.*

• Parameter selection for cleaning and filtration of the data can have a highly significant impact on determined metrics.

  *Note that this has implications for the creation of operational performance benchmarks against which wind plant simulation models are validated and calibrated.*

• Selection of filters, models, and methods used in the operational analysis may have significant impacts on determined metrics.

  *Further evaluation required.*
• Implement computationally efficient algorithm for propagation of uncertainties

A more efficient approach to uncertainty propagation may be a nested implementation of the Dempster-Shafer evidence theory or interval analysis to propagate method parameter uncertainties and a stochastic collocation surrogate model to propagate the data measurement uncertainties.

• Develop advanced analysis methods

Potential methods of analysis exist which do not require as much analyst choice and instead rely on learning directly from the data; within such methods, uncertainty quantification is often inherently incorporated.
Thank You!

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Photo by Dennis Schroeder, NREL 39967