Wind Farm Operational Performance: Use of Top-Down with Bottom-Up Analysis

2022 SANDIA Blade Workshop

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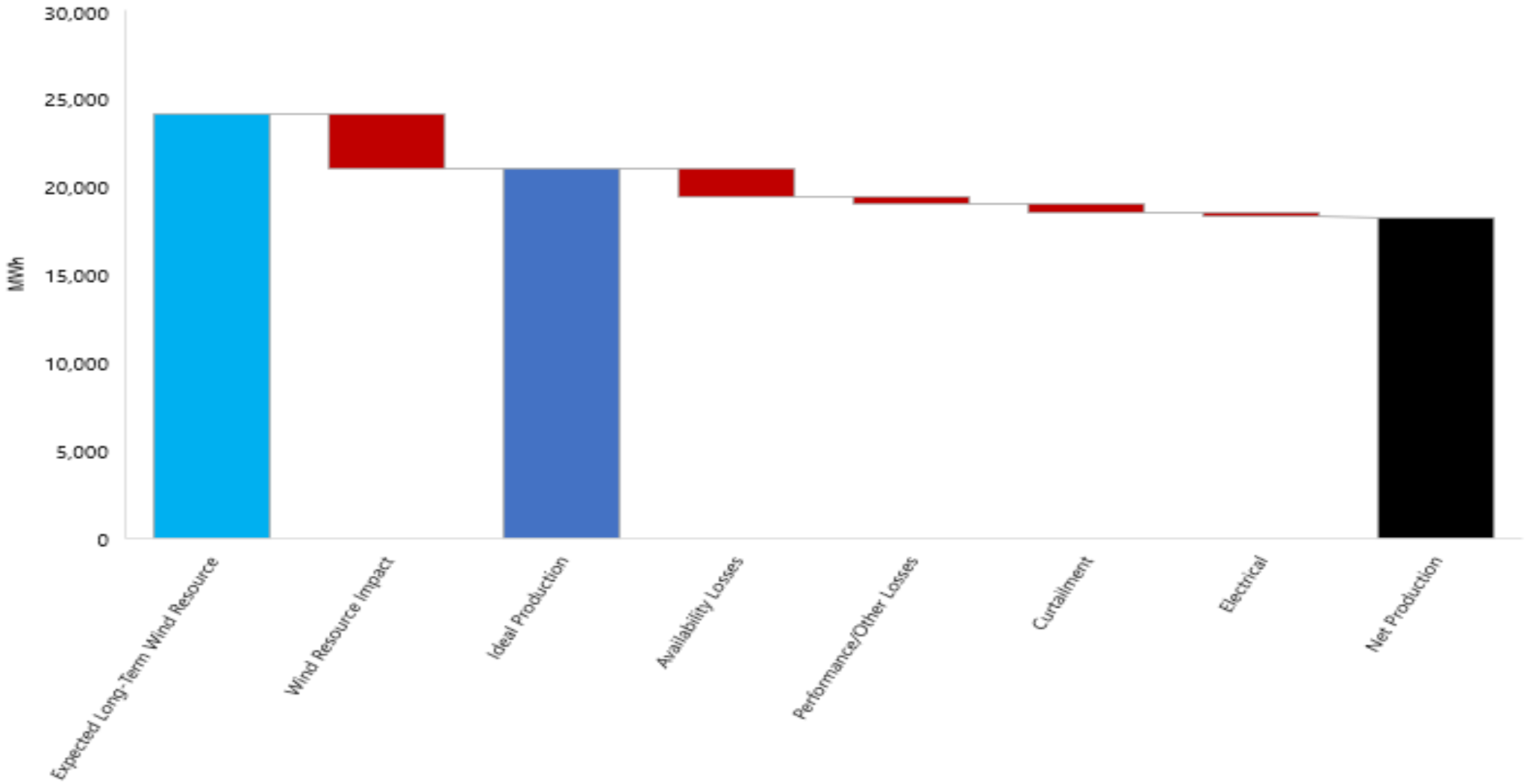
Operational Performance: Use of Top-Down with Bottom-Up Analysis

- Operational performance measurement has business importance:
  - Identify and address reasons for production variance
  - Adjust budgets
  - Provide input for business cases for retrofits/upgrades, services, etc.
  - Due-diligence (financing, M&A, etc.)

- High-level challenges:
  - Consistency and quality of data and methods
  - Cost and effort (person-time)

Operational Performance: Use of Top-Down with Bottom-Up Analysis

- Operational performance monitoring should reconcile various key reports/KPIs (e.g. metering reports, availability measures, wind resource measures, etc.)



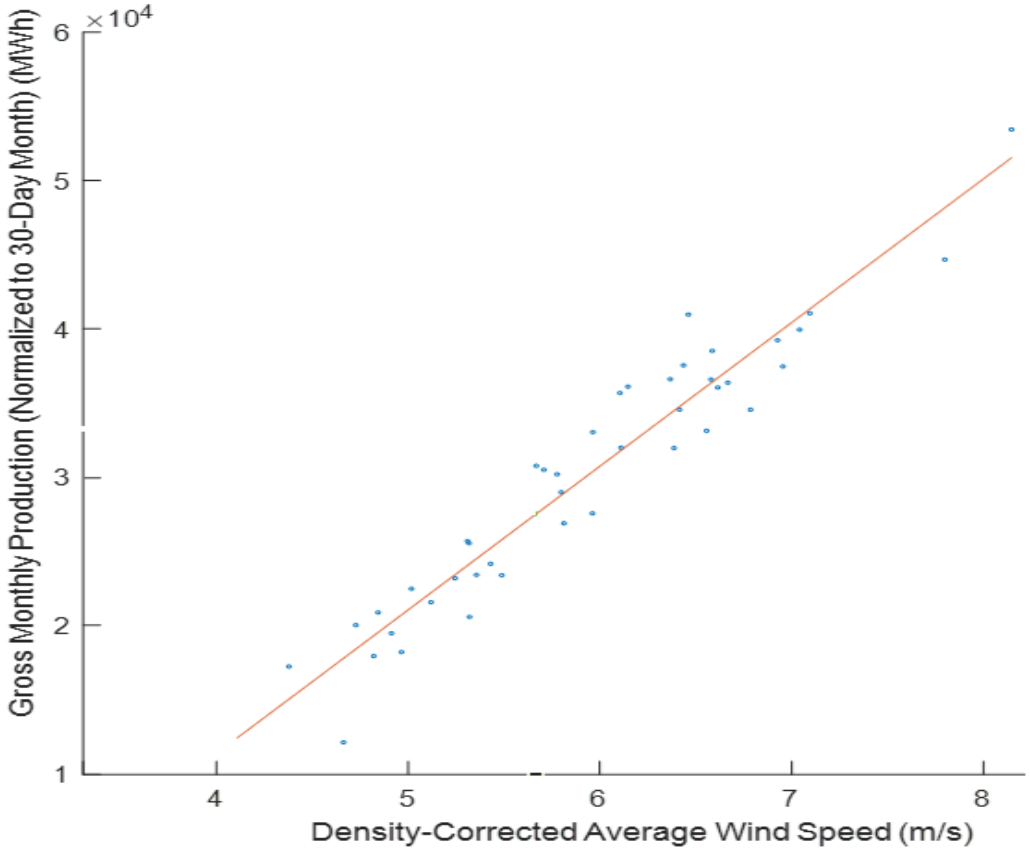
Operational Performance: Use of Top-Down with Bottom-Up Analysis

- Some detailed issues with bottom-up SCADA (10 min or better data) analysis:
  - Missing/bad SCADA data and instrument drift/error (not always easily detectable)—filling gaps may bias results
  - Cost/efficiency dictates use of automation to carry out analysis—improperly handled exceptions can lead to errors
  - Quantification of losses depends on accurately and consistently estimating "ideal production" (based on limited measurement information)
  - While there are standards that covers some parts of this analysis, there are no over-arching industry standards that guide it "end-to-end"
  - Methods are evolving so analysis performed several years apart may apply different techniques, with no guarantee the results are completely consistent

- Given the importance of operational analyses, assessing the accuracy/validity of "bottom-up" SCADA analysis is important

Operational Performance: Use of Top-Down with Bottom-Up Analysis

- Measure-Correlate-Predict (MCP) approaches provide an alternate form of operational assessment
- Actual production is grossed up by losses (typically assessed by separate analysis) and then correlated with a measure of the wind resource (typically avg. wind speed)
- Often used to investigate long-term expected production
  - If the wind resource measure is chosen to be a representative, consistent long-term reference, the average of this measure and the derived relationship can be used to estimate long-term production
- A "top-down" operational analysis
- MCP provides limited operational insights due to:
  - Some losses being considered inherent depending on gross up
  - Crude loss estimates (e.g. contractual availability) may lead to weaker correlation
  - Lack of granularity by time/turbine
  - Correlation of gross production with average wind speed can result in a weaker correlation due to spatial and temporal effects



Operational Performance: Use of Top-Down with Bottom-Up Analysis

- Reanalysis data is complimentary to SCADA data
  - Potential to provide a SCADA-independent measure for use in operational analysis if spatial and temporal limitations can be addressed
- Different sources:
  - NASA modern-era retrospective analysis for research and applications MERRA-2
  - European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis ERA-5

	SCADA Data	Reanalysis Data
STRENTHS	• High spatial and temporal resolution • Available in real-time	• No missing values • Consistent reference • Not subject to local effects (e.g. wakes, icing)
WEAKNESSES	• Bad/missing data • Instrument drift • Interference from topography, wakes, etc.	• Low spatial and temporal resolution • Not always immediately available

Operational Performance: Use of Top-Down with Bottom-Up Analysis

- Desire for assessing performance analysis validity and the complementary nature of SCADA and reanalysis data suggest the possibility of using “top-down” and “bottom-up” analysis together

- Strong correlation between from bottom-up and top-down analysis requires:
    1) Actual production + losses estimated by “bottom-up” SCADA analysis to be representative of ideal production (based on wind resource)

    AND

    2) Gross (ideal) production estimated by “top-down” reanalysis data to be representative of ideal production

- Lack of consistency indicates breakdown in assumptions/errors in analysis

- To make this work, don’t want lack of consistency due to spatial/temporal “distortion”/”blunting” introduced by re-analysis data

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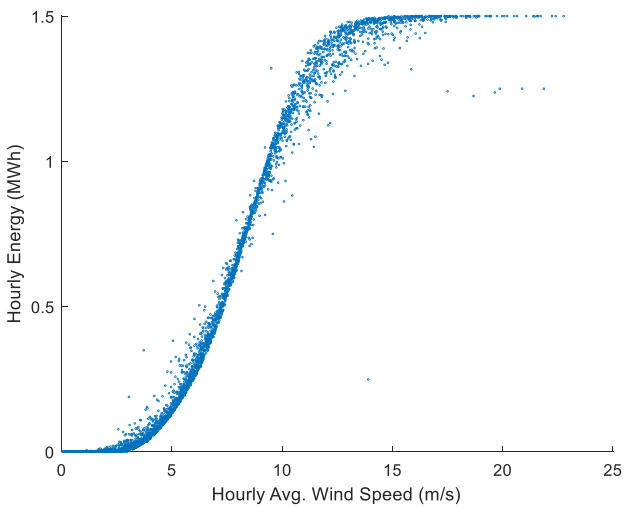
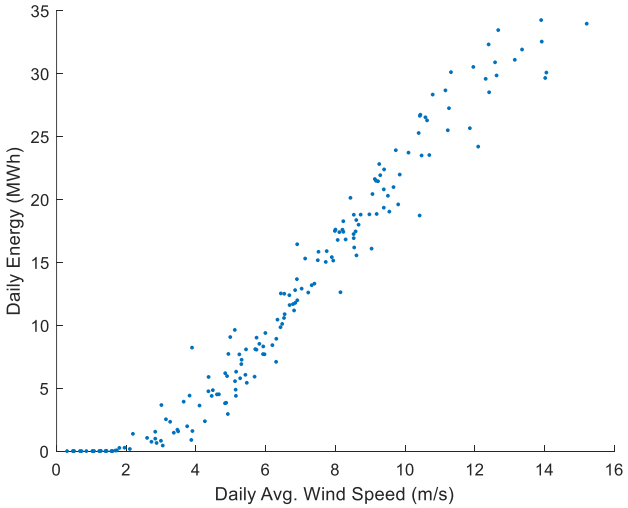
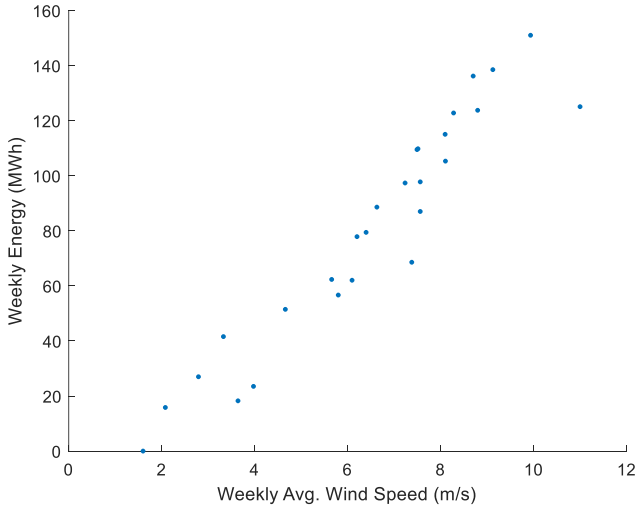
- Temporal resolution:
  - Should consider use of hourly data; avoid temporal averaging
  - "Averaging error" increases quickly when averaging daily, weekly, etc.
  - Below sequence shows the effect of using average wind speed as a predictor for production (real 10 min wind dataset applied to a theoretical 1.5MW turbine)

    (left = hourly, middle = daily, right = weekly)
  - Empirically observed error in using hourly data ~1%
  - So temporal resolution of hourly reanalysis data is not a major limitation, but further time averaging should be avoided







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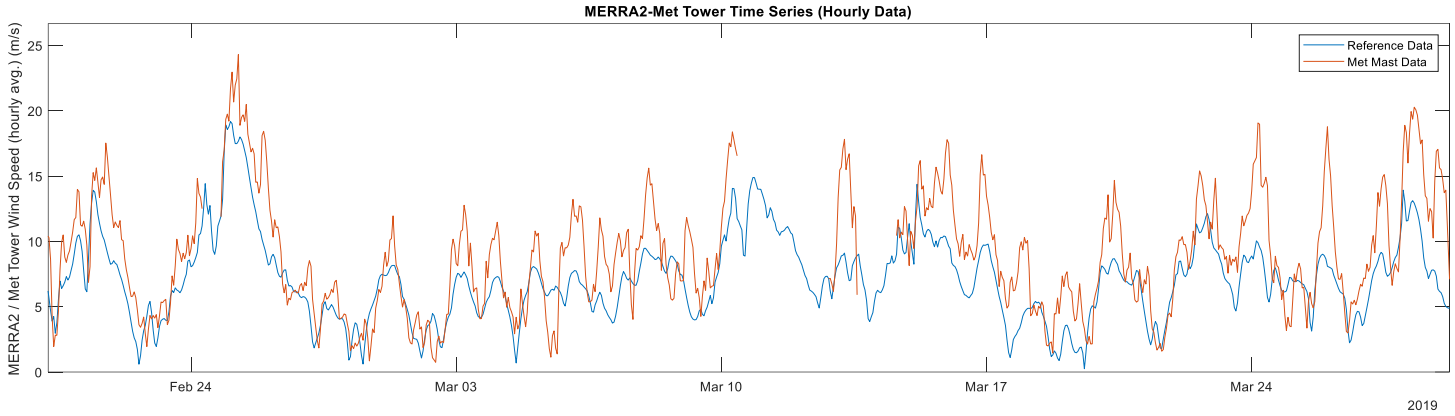
- Spatial resolution:
  - Consider a 67 WTG site with 80mHH situated on complex terrain (280m variation in elevation between WTGs) with forestry…

Operational Performance: Use of Top-Down with Bottom-Up Analysis

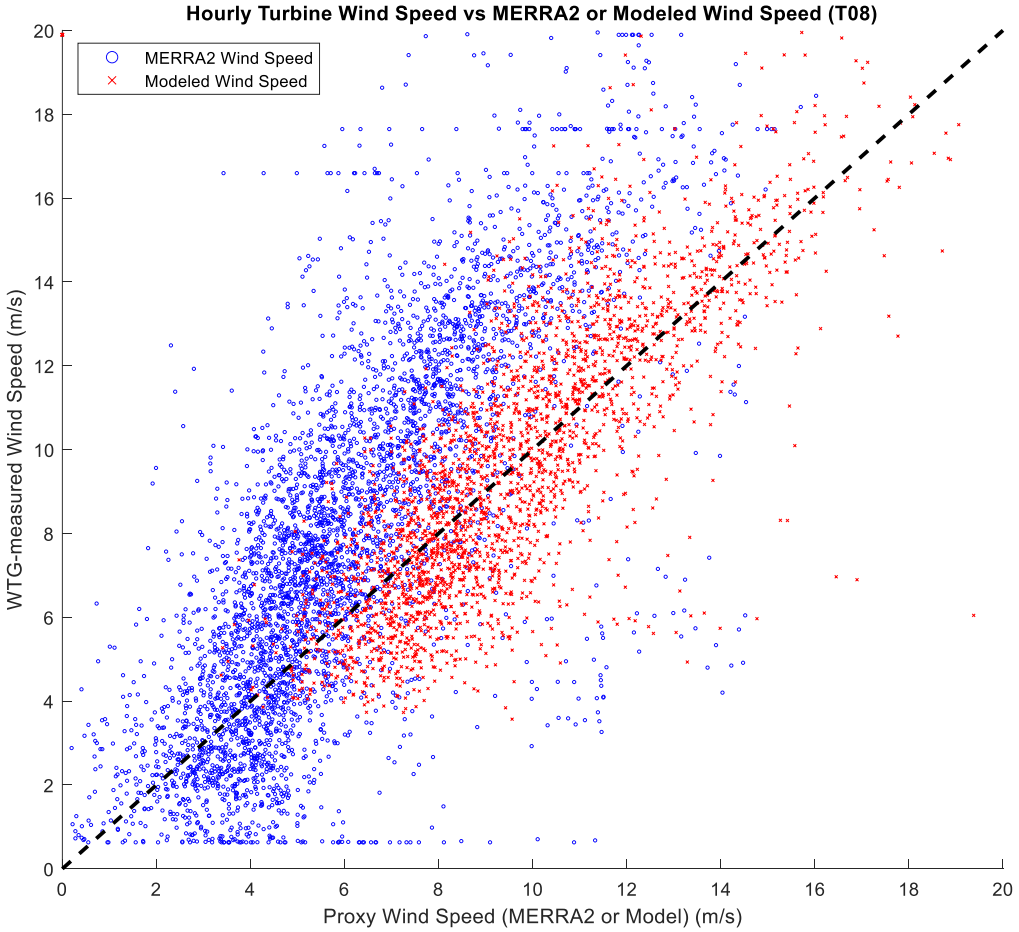
- Spatial resolution:
  - Generally, reanalysis data has poor spatial resolution: e.g. MERRA-2 resolution is ~50km x 50km
  - Shear, topographical effects are important considerations, especially on sites with complex terrain
  - Use of advanced siting tools for refinement of reanalysis data is not usually an option due to time & cost
  - Market solutions are available to directly provide spatially (and sometimes temporally) refined reanalysis data

Operational Performance: Use of Top-Down with Bottom-Up Analysis

- Outline of (one possible) method for using reanalysis data with bottom-up SCADA analysis:
  - First step: selection of "best reanalysis" data set that is strongly correlation with a local measure of the wind resource (e.g. meteorological tower)



- Further refinement achieved by fitting a turbine-pad-specific sector-wise model (after applying appropriate filtering of data) to correct the hourly (density corrected) reanalysis wind speed data
  - Shear and topographic corrected together (avg. waking in sector assumed to be captured also)
  - Generally requires 6+ months of data
  - Figure on right is an example using 15^0 sector-wise first-order linear model (blue = unfiltered raw MERRA2 wind speed, red = filtered modeled wind speed)



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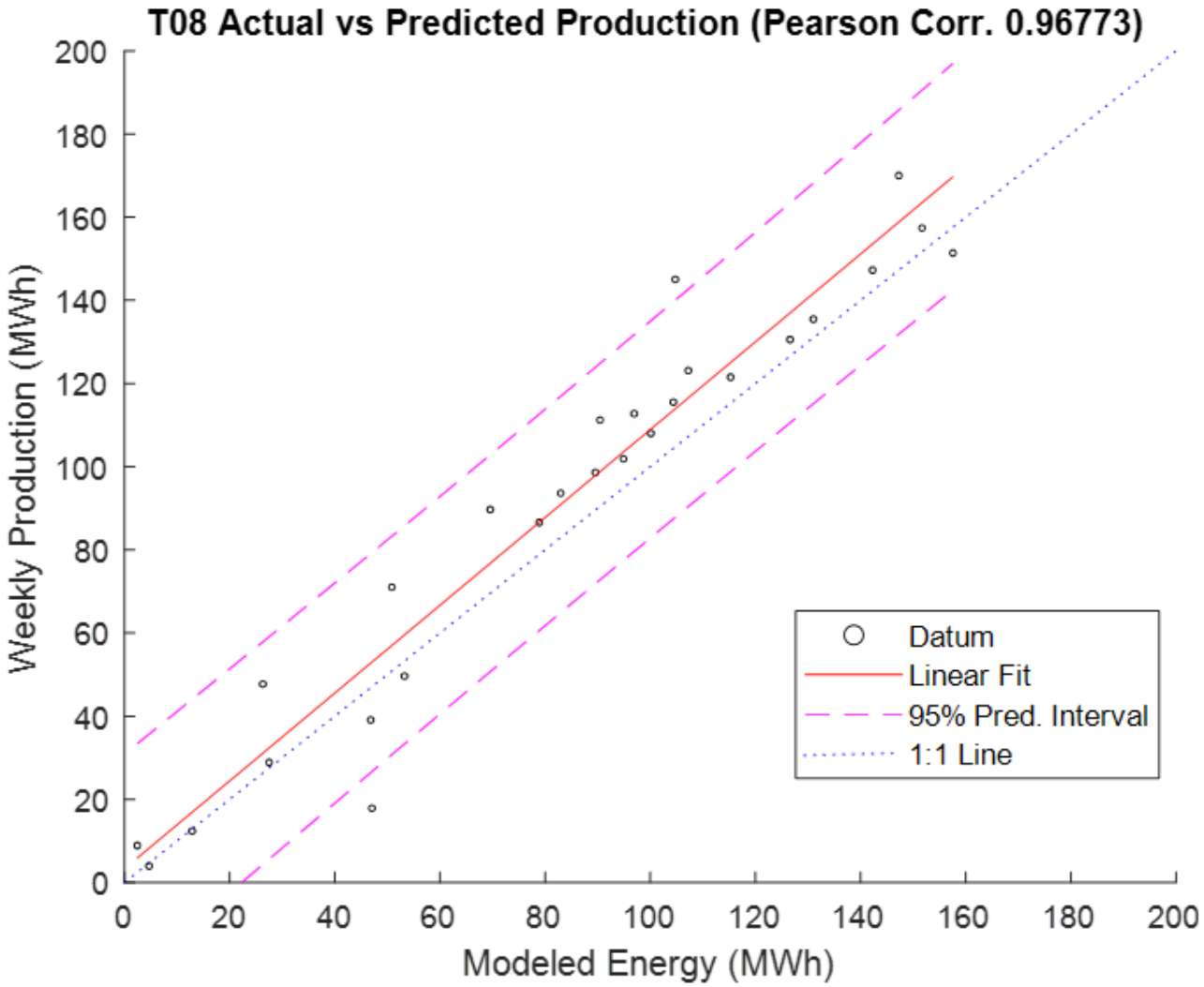
- Next step in using the reanalysis data is to apply a power curve (that is representative of expected performance) to the hourly modeled wind speed to account for the non-linear relationship between energy and wind speed
  - This should allow "ideal" production to be modeled directly
  - This can only be done after appropriate calibration of the wind speed
  - Allows energy aggregation to daily, weekly, monthly time-frames

- Final validation step is carried out using actual data, filtered to only include times when WTGs are known to be operating normally (available, full performance) such that actual production = ideal production



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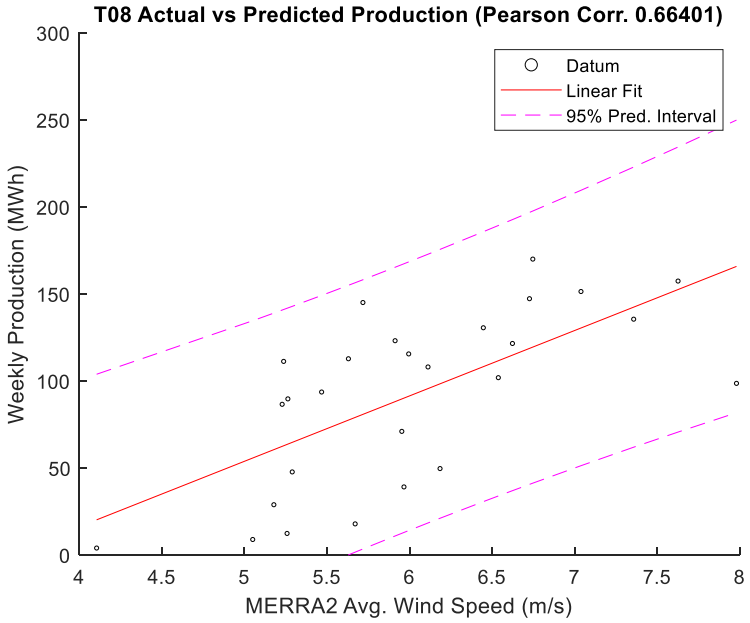
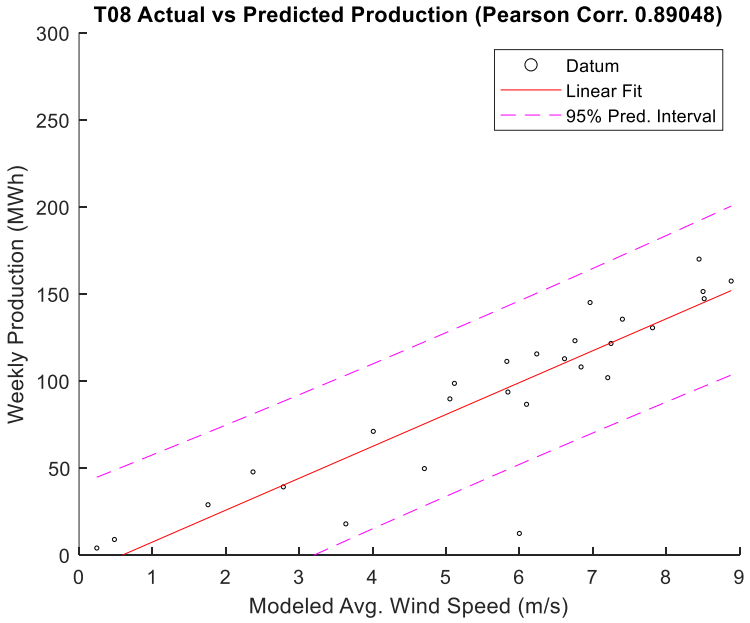
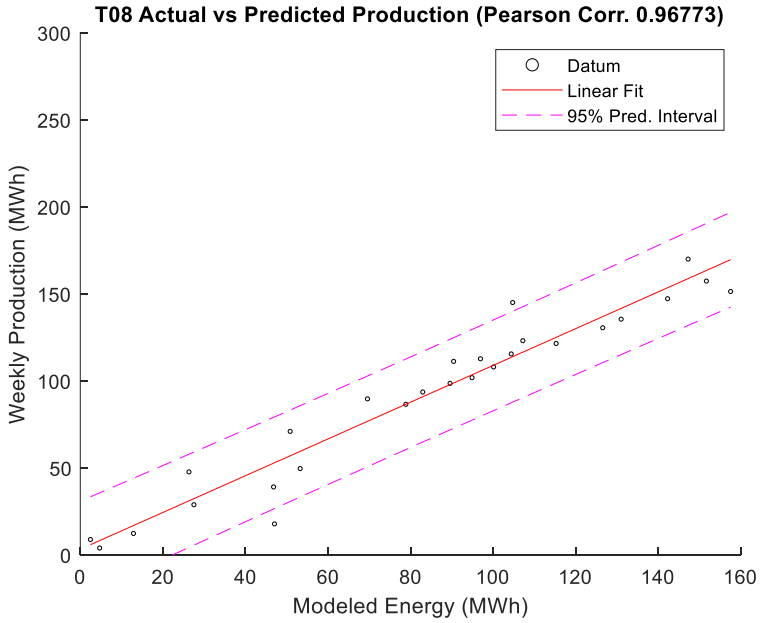
- Below validation plots shows the improvement in the 95% prediction interval after each step in preparing the reanalysis proxy measure (left = use of raw reanalysis wind speed, middle = modeled wind speed, right = modeled energy)
- If prediction intervals do not "tighten" something has gone wrong







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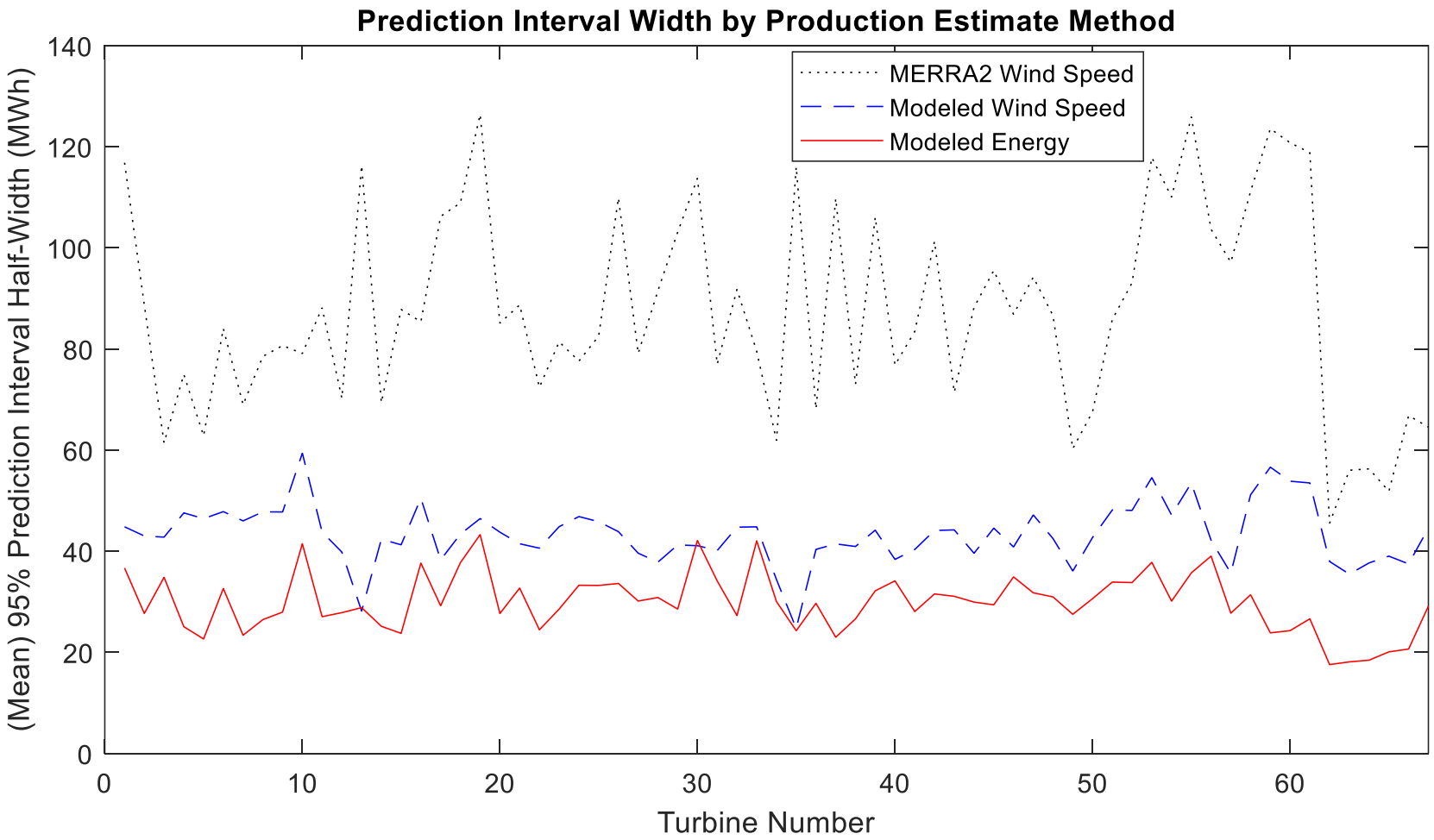
- Correction may not work equally well for all WTGs and should be verified
  - Example: plot to the left shows a first-pass of applying the above steps to a 67WTG farm with complex terrain

- "Modeled Energy" at each WTG, or in aggregate, over daily, weekly, monthly time-frames is now compared to actual + losses from "bottom-up" SCADA analysis



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- Conclusions:
  - In addition to helping to validate routine operational monitoring, there may be situations were there is a desire to gain confidence in existing operational analyses:
    - Use/trial of a new (internal/external/black-box) performance monitoring tool
    - Due diligence situations
    - Historical reports (that used legacy methods/tools)

- Strengths:
  - Provides an independent measure to validate performance measures
  - Relatively straight forward to apply

- Weaknesses:
  - Trades-off in accuracy vs effort (cost)
  - Lag in availability of reanalysis data
  - Source of disagreement may not be immediately evident—important to look at “intermediate results” and model fit
  - Inherent limits on spatial and temporal resolution that cannot be completely addressed

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