res

wind-up: an open-source tool to assess yield uplift of wind turbines

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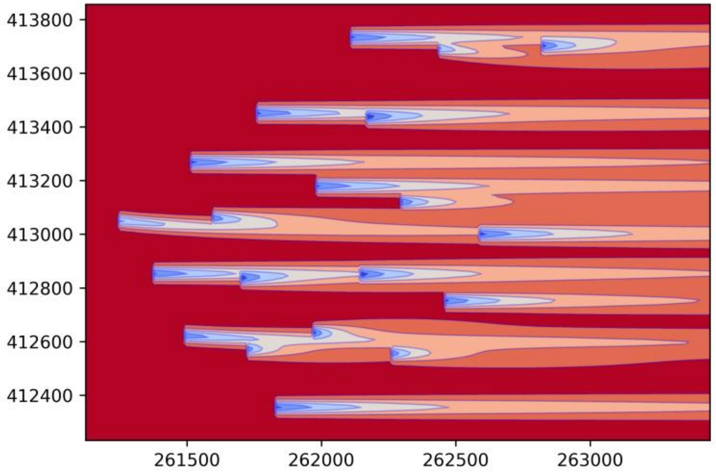
Contents

Motivation

- Accurate AEP* uplift measurement is a crucial capability in the development of technologies which increase wind farm output.
- A high-quality wind measurement (eg LiDAR) is not always available. A method is needed which can use other turbines as references.
- The method should be as consistent with IEC61400-12-1** as possible but allow for deviations:
  - Measure uplift under all conditions, including waked data
  - Enhanced uncertainty calculation
- It is important for the industry to achieve consensus on how to measure uplift (including uncertainty) and extrapolate it to long-term. Therefore, code and examples for the presented method are publicly available in a new tool called **wind-up**: https://github.com/resgroup/wind-up

Vortex generator install

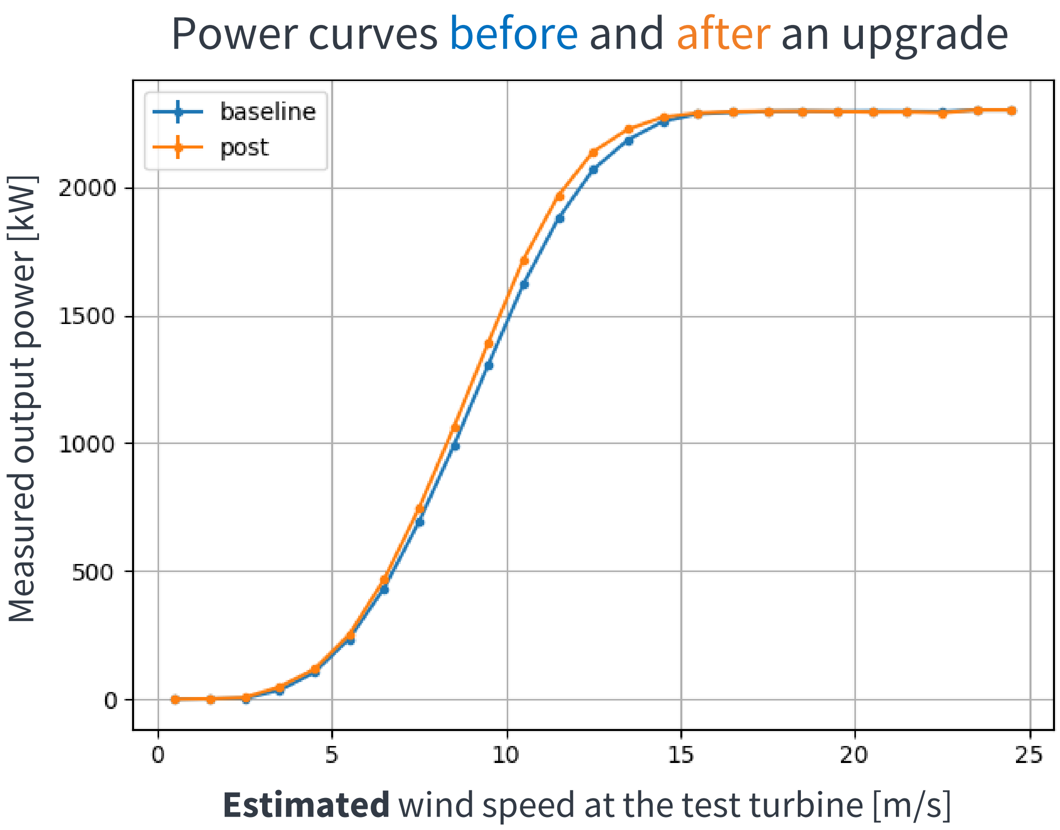


Wake steering simulation

* Annual Energy Production
** International standard for power performance measurements of wind turbines

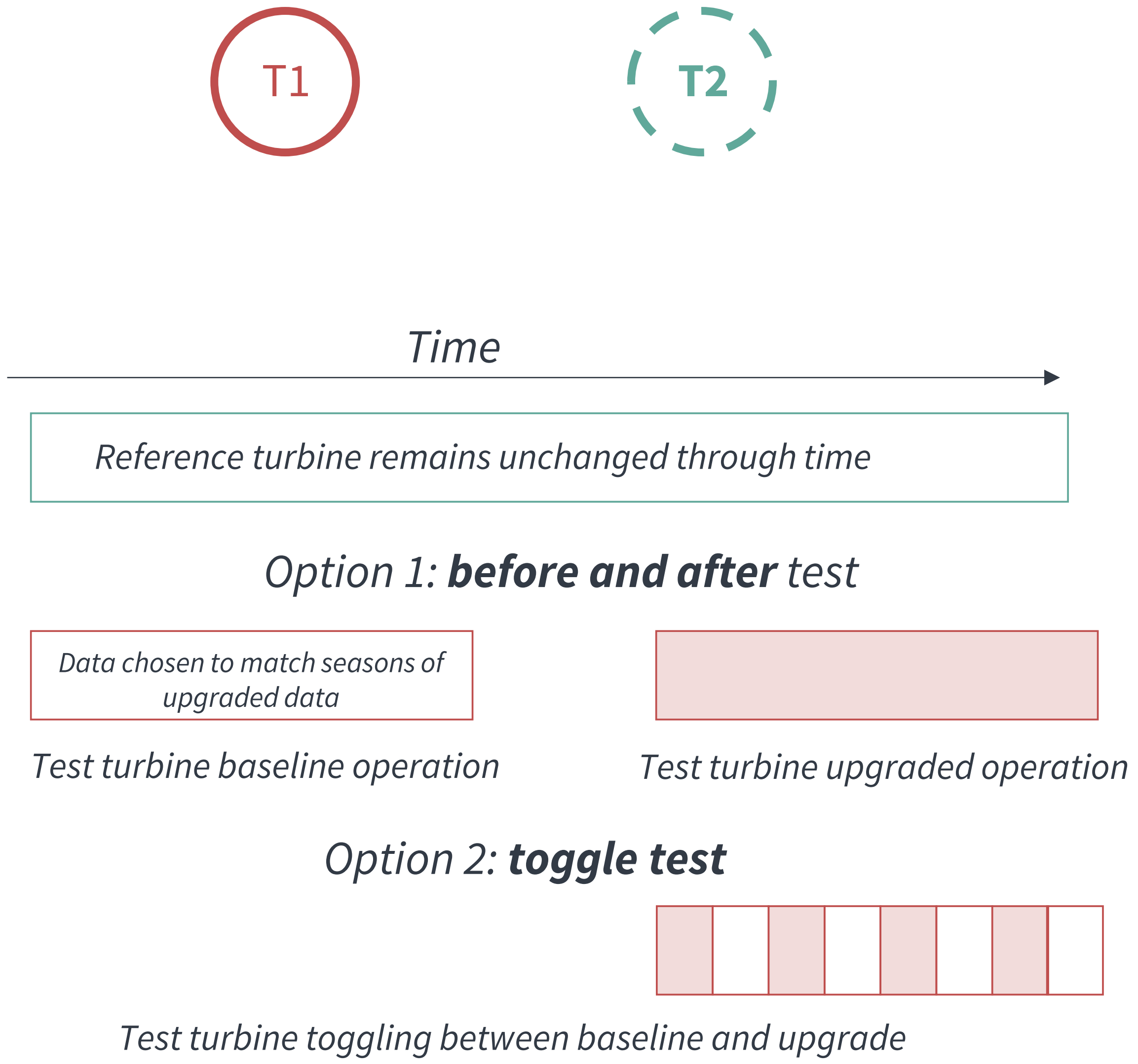
Analysis method: overview

- The core of a wind-up assessment is defining two power curves (baseline and post upgrade) and calculating yield from each curve. Uplift is the change in yield.
- The y axis variable is simple: it's the test turbine's power!
- The x axis variable is more complicated. It is an **estimate** of **baseline** (pre-upgrade) wind speed **at the test turbine**. This estimate cannot directly use measurements from the test turbine itself because they might be biased from the upgrade.
- Ideally the wind speed estimate is based on a high-quality nearby wind measurement consistent with IEC61400-12-1. Otherwise, it's possible to construct the estimated wind speed from surrounding reference turbines.



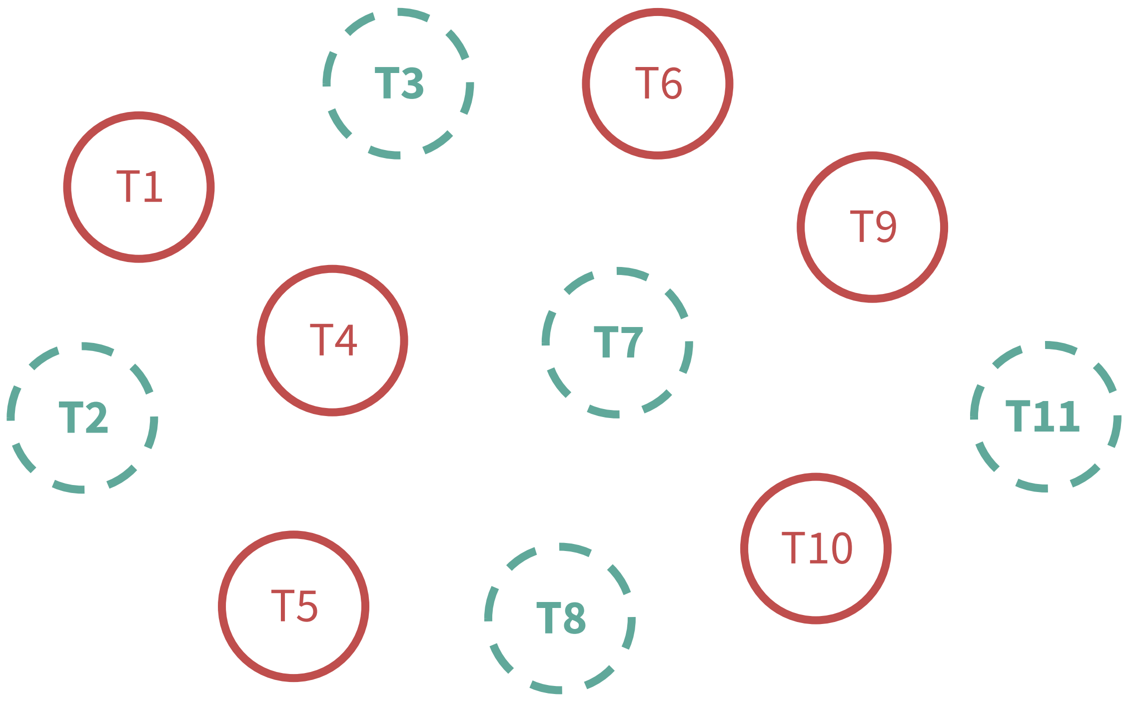
Analysis method: side by side

- It's commonplace to use reference turbines ("side by side validation") when LiDAR or masts are not available
- Wind direction data comes from the reference turbine so accurate northing correction is crucial
- For some upgrades (eg blade add-ons) there is no choice but to perform a **before and after test**
- If possible use a **toggle test**. This greatly reduces the risk of bias due to reference drift and weather unfairness.



Analysis method: choosing reference turbines

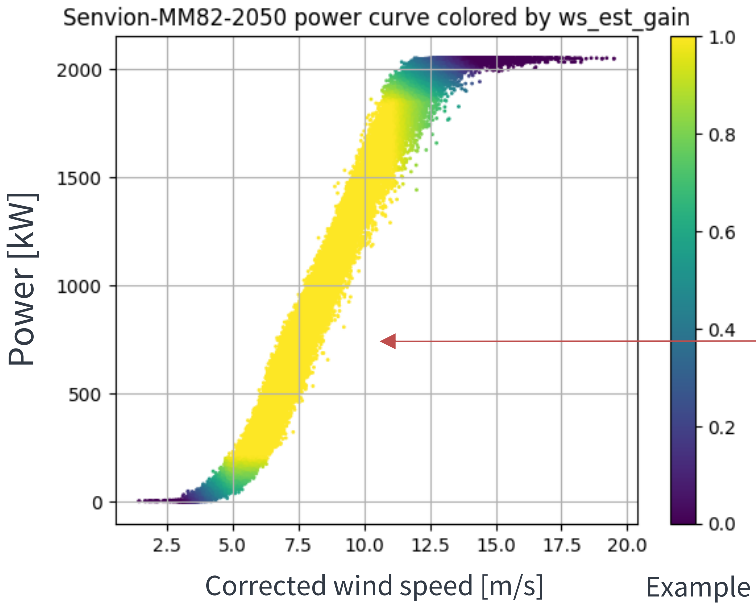
- When planning a validation campaign without a mast or LiDAR the choice of turbine roles is crucial.
- For each **test turbine** try to ensure:
  - There are at least three nearby **reference turbines**
  - Wake-free locations are valuable; ideally share them equally between test and reference turbines
- In the fictitious example shown on the right more than half (6 of 11) of the turbines can be tested.
- If the upgrade can be toggled the risk of bias reduces so the number of references can arguably be reduced
- Different approaches are needed for certain upgrades (eg wake steering)



In addition to analysing each test turbine using the nearby **references**, **each reference turbine should also be analysed against the other references** to confirm the reference turbines are stable.

Analysis method: estimating wind speed (1/2)

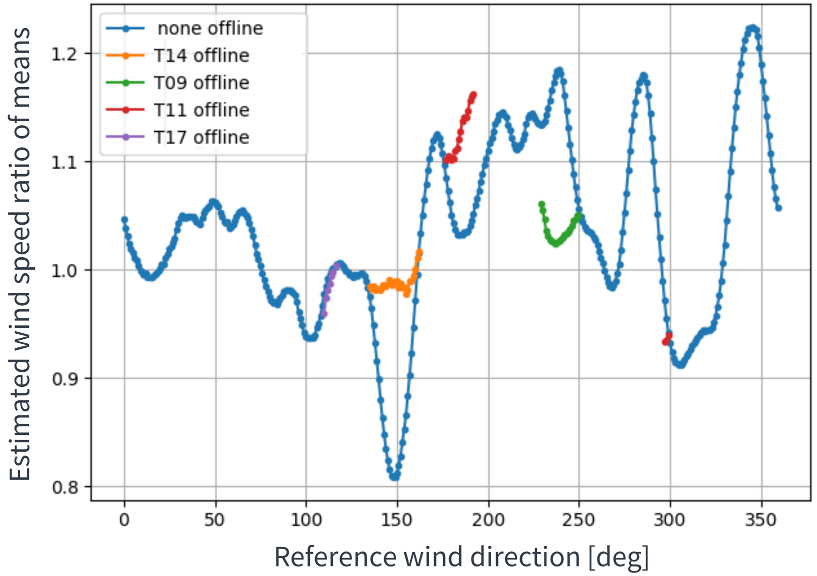
- For each reference turbine it's possible to make a wind speed signal which is mainly derived from the turbine's power.
- Power cannot be used to estimate wind speed near 0 power and near rated power, so the (corrected) anemometer signal is blended in.
- Wind speed at a reference turbine location can be translated to wind speed at the test turbine location by defining a directional lookup based on past data ("**directional detrending**"). The **wind-up** tool helpfully splits data into availability scenarios of all surrounding turbines.



The wind speed estimate is fully defined from power for data in yellow

Example directional detrending lookup table

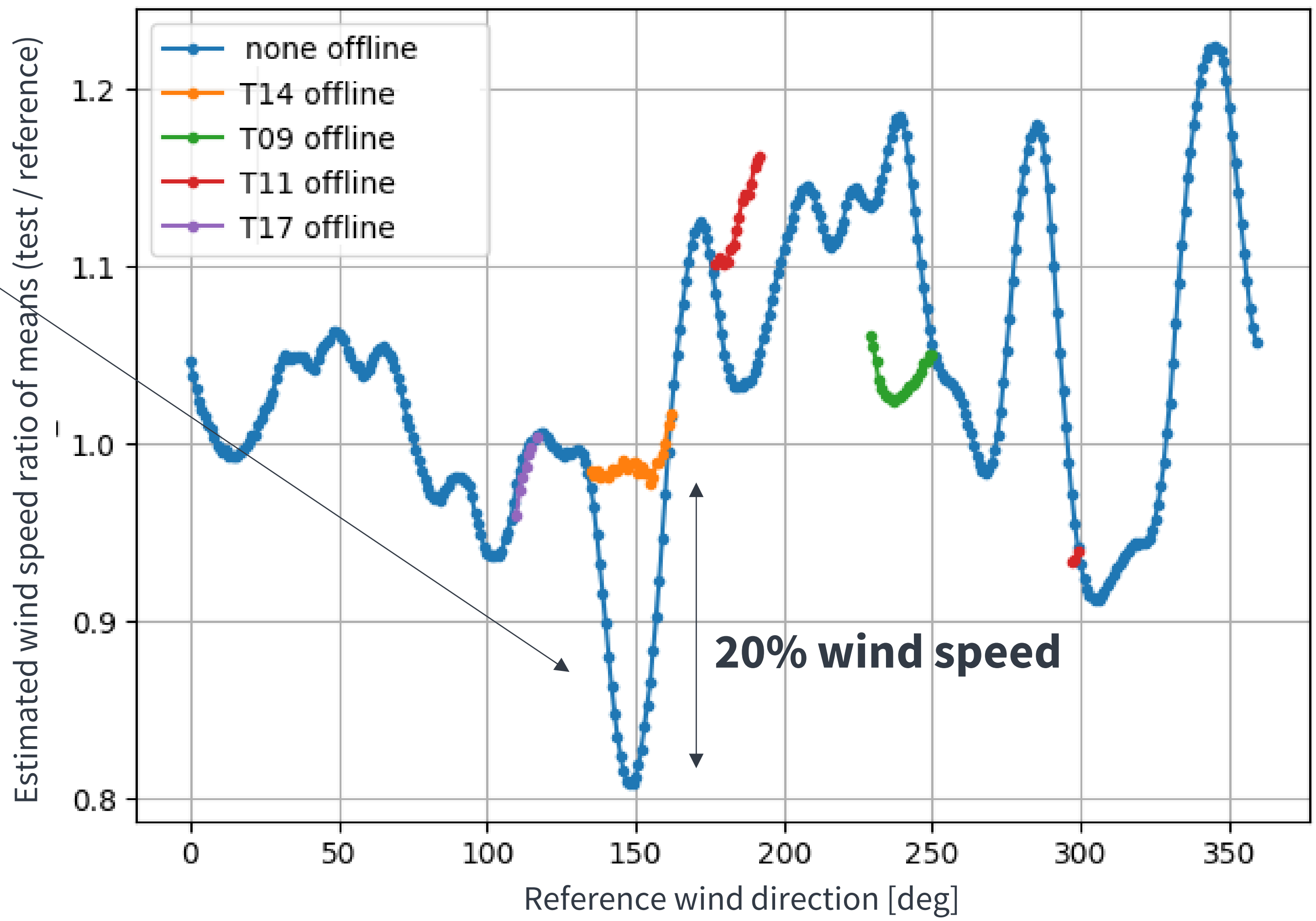
Example of directional detrending (more detail on next slide)



Analysis method: estimating wind speed (2/2)

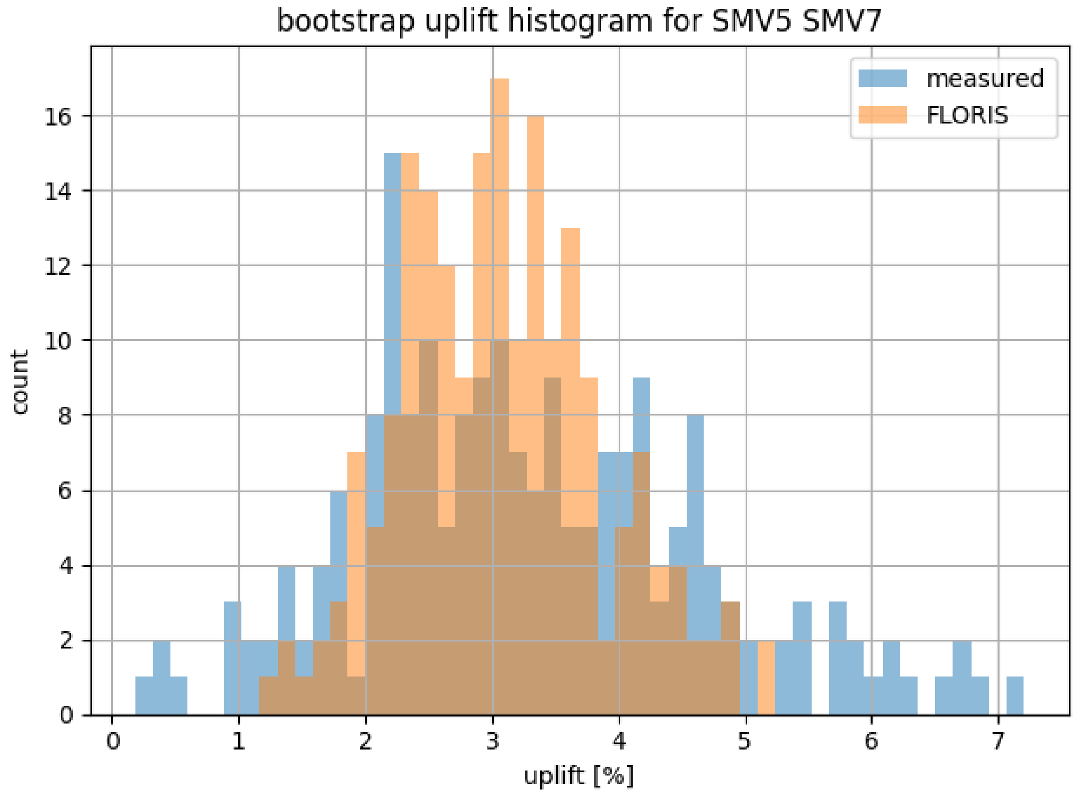
- In this example T14 is south-east of the test turbine and does not affect the reference turbine in that sector
- Note the large wake when T14 is online and no wake when it is offline.
- It is crucial to account for the timeseries waking status of surrounding wind turbines; these effects can easily overwhelm the uplift measurement.

Example directional detrending lookup table



Analysis method: uncertainty

- Uplift uncertainty is estimated using a method similar to the IEC61400-12-1 Category A uncertainty calculation
- Uplift uncertainty is also estimated in two more ways:
  - Block bootstrapping, where the data is resampled many times with replacement
  - A reversed analysis, where the roles of test and reference are swapped to check for bias
- Overall uncertainty for a test turbine can be reduced by combining measurements from multiple references if the errors are not correlated



Bootstrapping can be used to repeat the uplift measurement many times with a different sample of the original data.
In this example a model of the uplift (FLORIS model of wake steering) is simultaneously bootstrapped to inform uncertainty modelling.

WeDoWind Turbine Performance Quantification

- The following slides present wind-up results for the WeDoWind Turbine Performance Quantification Collaboration

- Uplift is calculated for two upgrade datasets which each include a mast, a test turbine and a reference turbine:

    - Vortex Generator (VG): 14 months worth of data in the period before the upgrade and around eight weeks of data after the upgrade

    - Pitch Angle: artificial upgrade data. About eight months of data before the upgrade and eight and a half weeks after the upgrade

- Thank you Professor Yu Ding and the WeDoWind team for sharing data and facilitating this collaboration!

- Dataset citation: Ding, Y. (2021). Turbine Upgrade Dataset [Data set]. Zenodo. https://doi.org/10.5281/zenodo.5516556

WeDoWind

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December 11th, 2023

Introducing our new Turbine Performance Quantification Collaboration

In the first half of 2023, we successfully completed the Power Curve Modelling Benchmarking Challenge as part of our Data-Driven Turbine Performance Analysis space with Professor Yu Ding from Georgia Tech, author of the Data Science for Wind Energy book. The results of this challenge will be presented in March 2024 at the Wind Europe Annual Event in Bilbao. In the meantime, we are happy to announce our new Turbine Performance Quantification Collaboration within the same space, which starts in January 2024!

Description of the new collaboration

While it is highly important to develop new technologies for better designs/configurations/controls or materials/manufacturing of wind turbine blades and drive trains, an equally critical question is how one can be certain that a newly proposed technology could deliver the proposed/promised improvement in energy capture in a real-world, commercial operation environment, measured in terms of the percentage change in AEP. It is not exaggerating to say that quantifying a wind turbine's holistic, system-level power production efficiency in its commercial operating condition is one of the keys to reducing the levelized cost for energy of wind energy.

With this collaboration, we would like to tackle the long-overdue question of **how to best to quantify a wind turbine's holistic, system-level power production efficiency and detect a turbine's performance change under its commercial operating conditions.** Through our collective effort, we hope to produce better understandings of the issue, as well as methods and/or tools of a higher degree of credibility.

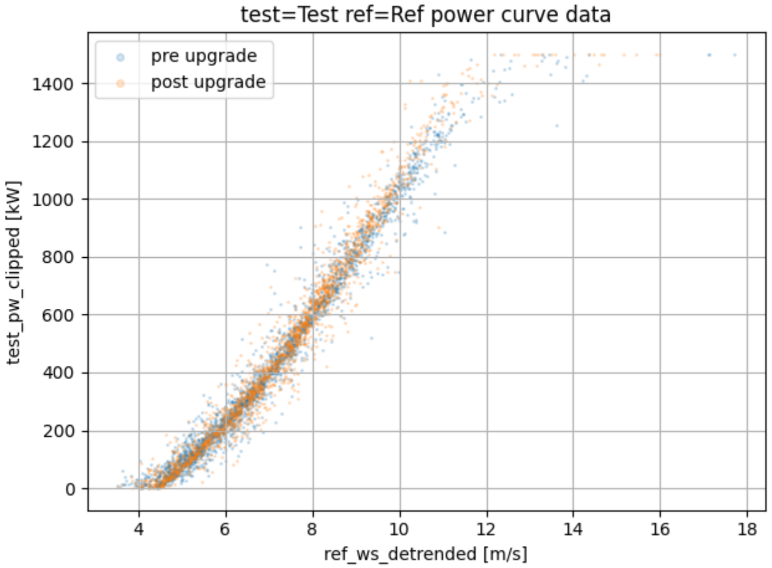
In this collaboration, we will use the Turbine Upgrade Dataset released through the publication of the book, Data Science for Wind Energy, to discuss, test, develop, and refine methods for the question posed above, i.e., how to quantify a wind turbine's holistic, system-level power production efficiency and detect a turbine's performance change under its commercial operating conditions.

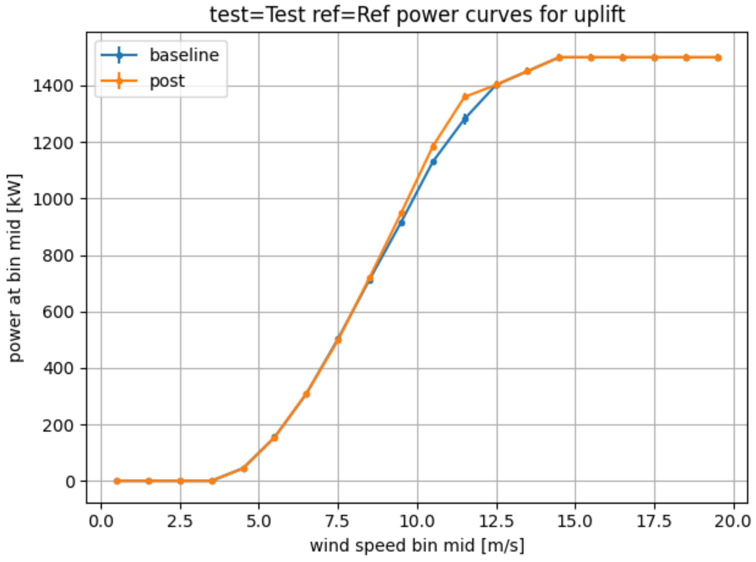
https://www.wedowind.ch/blog/announcement-turbine-performance-quantification-collaboration

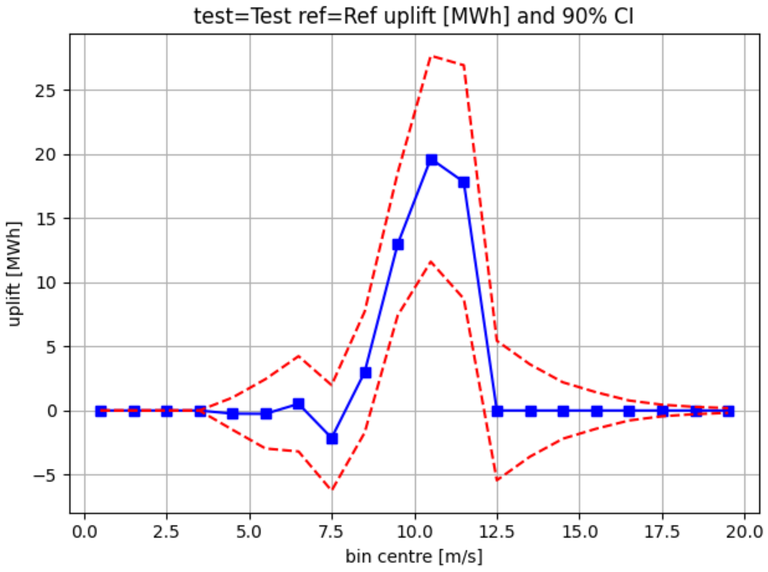
Example: WeDoWind VG

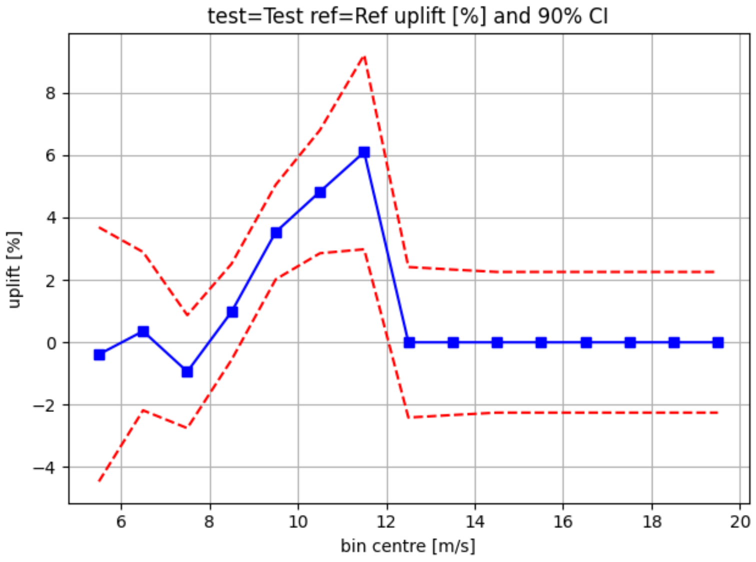
- **2.3% AEP uplift** is measured with reasonably good uncertainty.
- Uplift vs wind speed distribution looks typical for Vortex Generator install on this vintage of turbine.
- Data count is quite low at high wind speeds; ideally measurement campaign would be longer.
- Full analysis is available at https://github.com/resgroup/wind-up/tree/main/examples

energy uplift	uplift P95	uplift P5	valid hours pre upgrade	valid hours post upgrade
2.3%	1.5%	3.2%	396.7 h	348.0 h





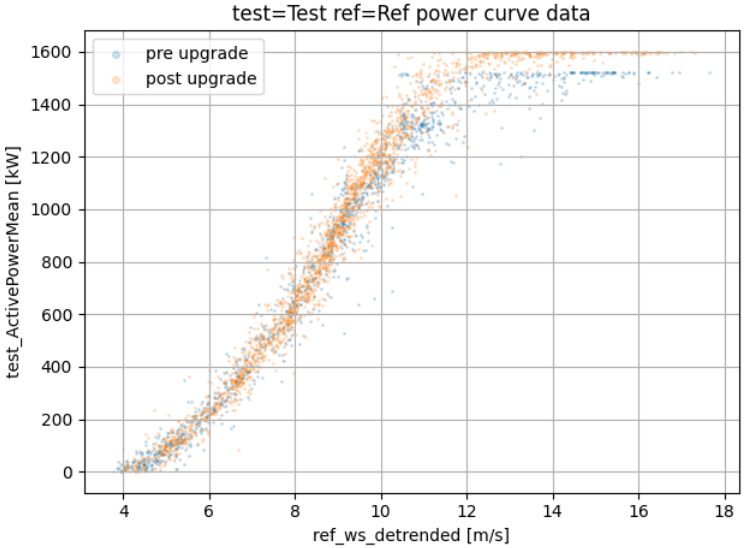


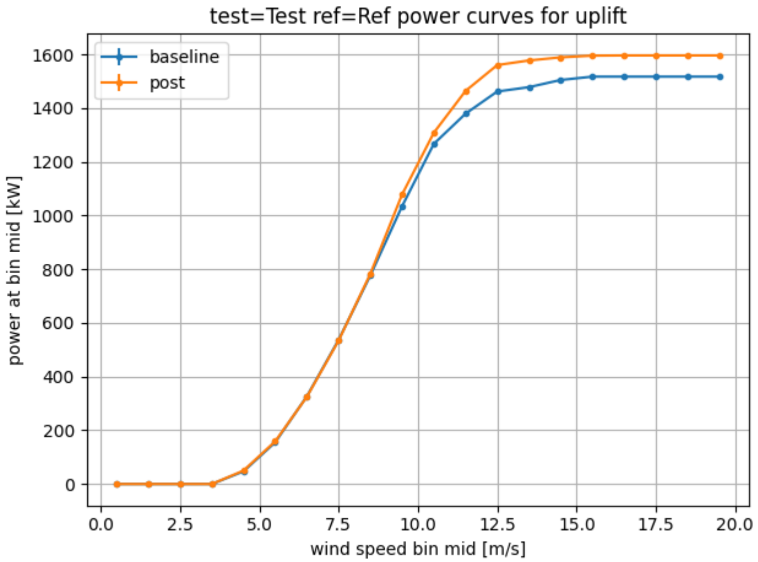


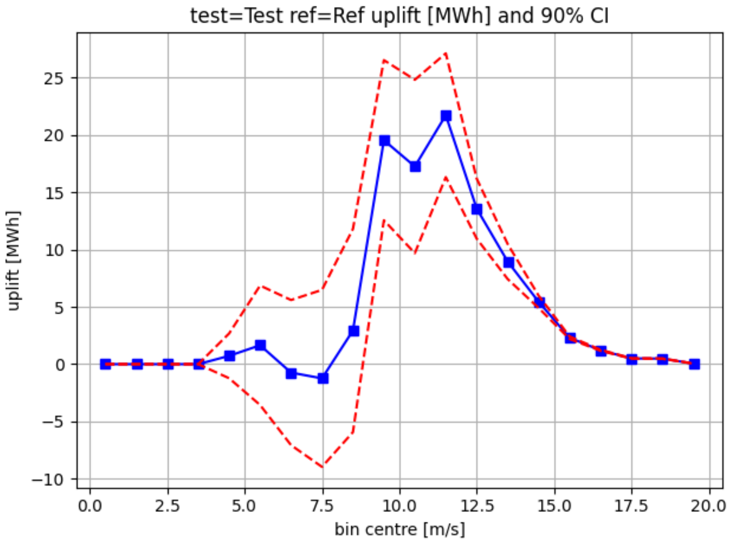
Example: WeDoWind Pitch Angle

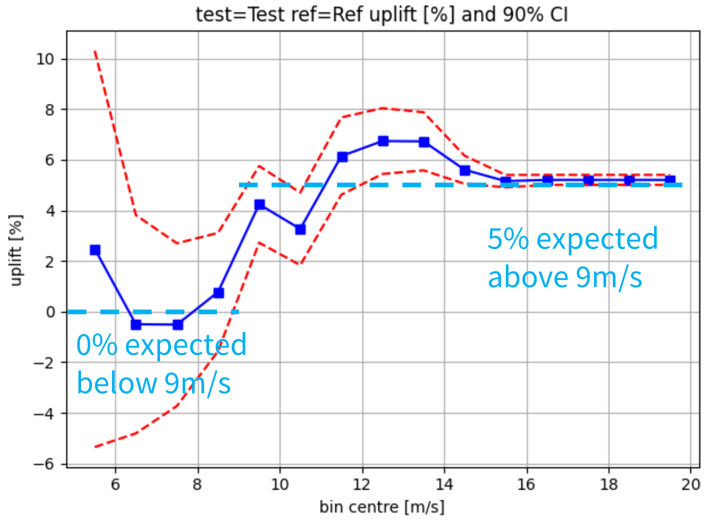
- Artificial example where power was multiplied by 1.05 for wind speeds >9m/s.
- **3.0% AEP uplift** is measured with reasonably good uncertainty.
- Uplift vs wind speed distribution is consistent with expectations (0% below 9m/s, 5% above 9m/s).
- Full analysis is available at https://github.com/resgroup/wind-up/tree/main/examples

energy uplift	uplift P95	uplift P5	valid hours pre upgrade	valid hours post upgrade
3.0%	1.8%	4.3%	206.8 h	349.7 h



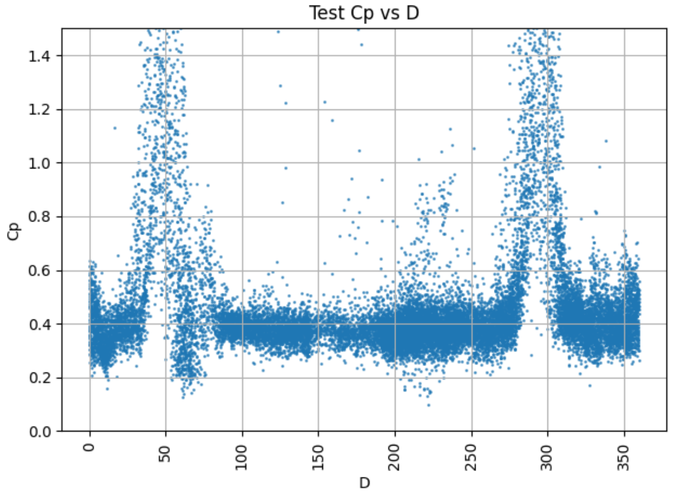




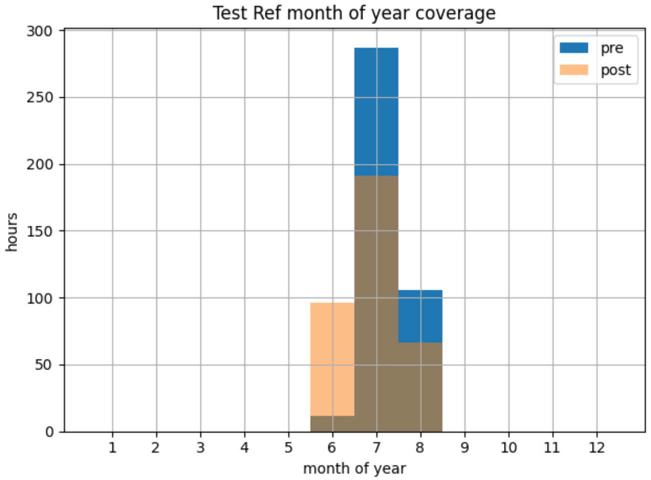


WeDoWind Dataset comments

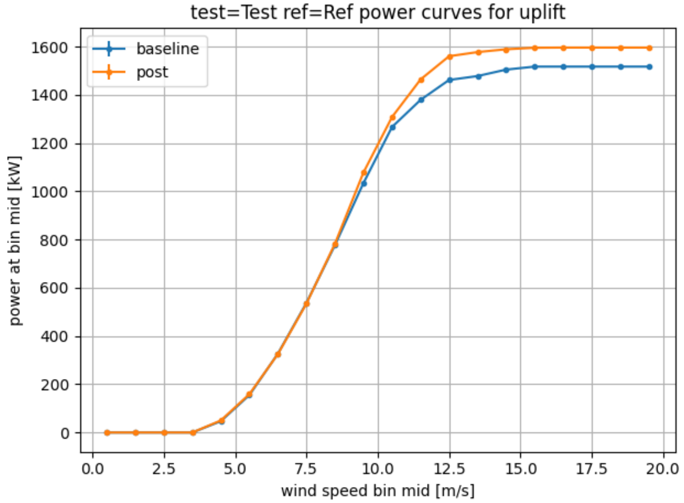
- To use all the features of wind-up more information is needed:
  - Lat longs of all turbines and masts to calculate waking relationships
  - Data for all nearby turbines to calculate waking state for each timestamp
  - More SCADA fields (wind speed, pitch and RPM) to use in filtering
- Due to missing information quite a lot of directional filtering was applied to avoid bias due to wakes. For example, Cp is unrealistic for some directions probably because the mast is heavily waked.
- In the artificial Pitch Angle example rated power is 5% higher after the upgrade. Normally a pitch angle upgrade alone would only increase power in Region 2.
- The Pitch Angle dataset is too short to seasonally match the before and after data. Ideally the before and after datasets are taken from the same time of year.



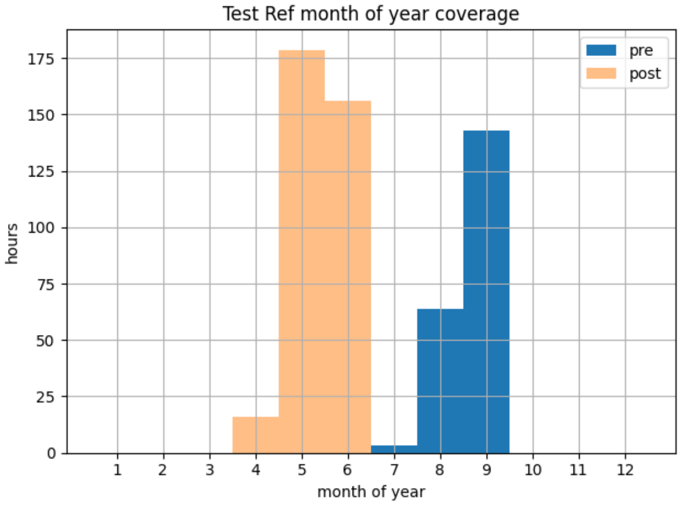
Cp vs direction for VG analysis



Selected data for VG analysis



Measured power curves for Pitch Angle analysis

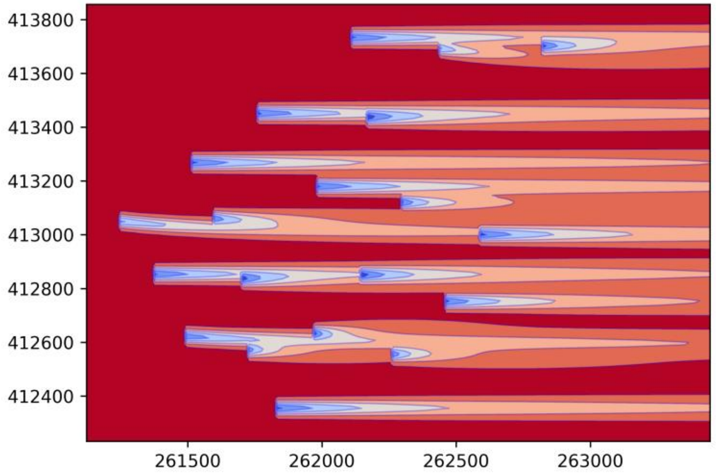


Selected data for Pitch Angle analysis

Summary

- RES has developed a new, innovative method to measure the AEP uplift of wind farm enhancements
- The method is applicable to a variety of upgrades and reference data options
- Reasonable uplift and uncertainty are measured for the WeDoWind datasets
- Code and examples for the presented method are publicly available in a new tool called **wind-up**: https://github.com/resgroup/wind-up

Vortex generator install



Wake steering simulation

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Thank you

The wind-up tool is available at https://github.com/resgroup/wind-up

www.res-group.com

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