Open-source dataset and AEP validation from a real-world case study of turbine upgrades worth 5% AEP

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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.

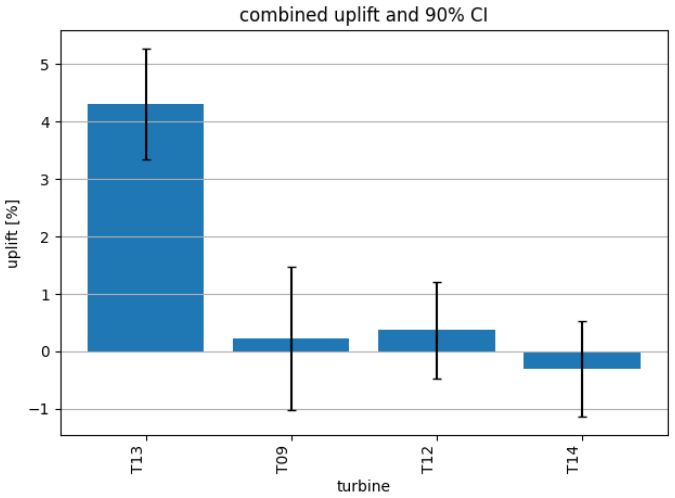
The method should be as consistent with IEC61400-12-1** as possible but allow for deviations:

- 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) representative of all long-term operating conditions. Therefore, all data and code for the presented case study are publicly available: https://github.com/resgroup/hill-of-towie-open-source-analysis

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

Vortex generator install



Uplift measurement with uncertainty

Hill of Towie dataset

Hill of Towie is an onshore 21 turbine wind farm in Scotland developed by RES and owned by TRIG.

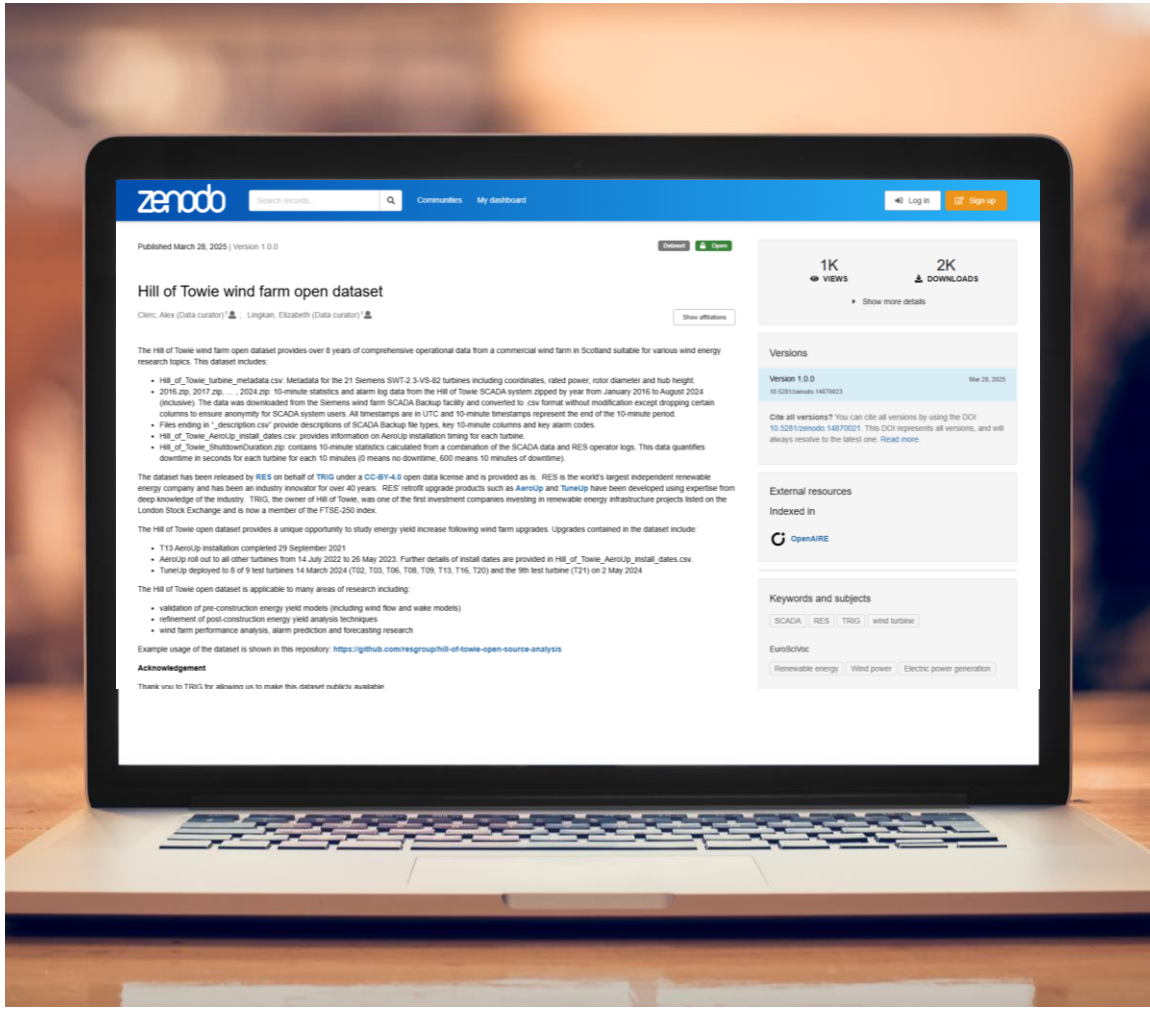
The new **Hill of Towie wind farm open dataset** provides over 8 years of comprehensive SCADA data*:

Interesting upgrades occur during the data record:

- One **AeroUp** test installation in September 2021 (T13)
- AeroUp roll out to all other turbines from July 2022 to May 2023
- **TuneUp** deployed to 9 test turbines in March 2024

The Hill of Towie open dataset is applicable to many other areas of research

Thank you to TRIG for allowing us to make this dataset publicly available!



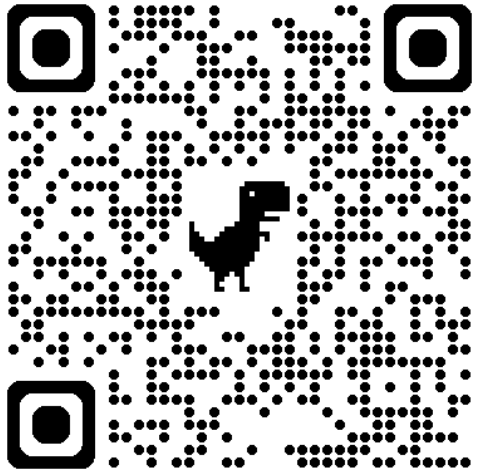
*https://zenodo.org/records/14870023

Open-source wind farm data

Slido poll: is there enough open-source wind farm data now?

Advice for future dataset creators:

- Remember the General Data Protection Regulation (GDPR)
- Aspire to FAIR. See **RDA Wind Energy Community Standards**
  - **F**indable
  - **A**ccessible
  - **I**nteroperable
  - **R**euseable
- Get the dataset checked prior to release. **Thank you to Charlie Plumley, Sarah Barber and Yuriy Marykovskiy** for advice on this dataset prior to release.
- Host an activity using the data. For Hill of Towie a WeDoWind machine learning challenge using the dataset is underway.



WeDoWind

Analysis method: overview

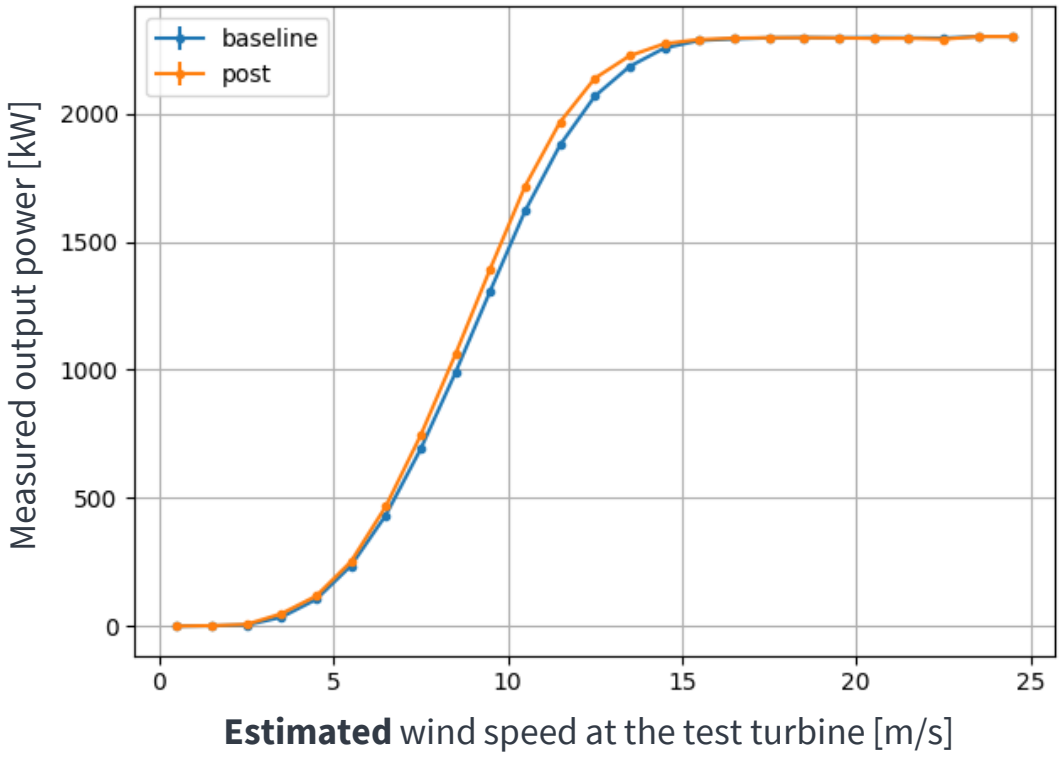
The core of a wind-up assessment is defining two power curves (baseline and post upgrade) and calculating yield from each curve with a long-term wind distribution. Uplift is the change in yield.

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.

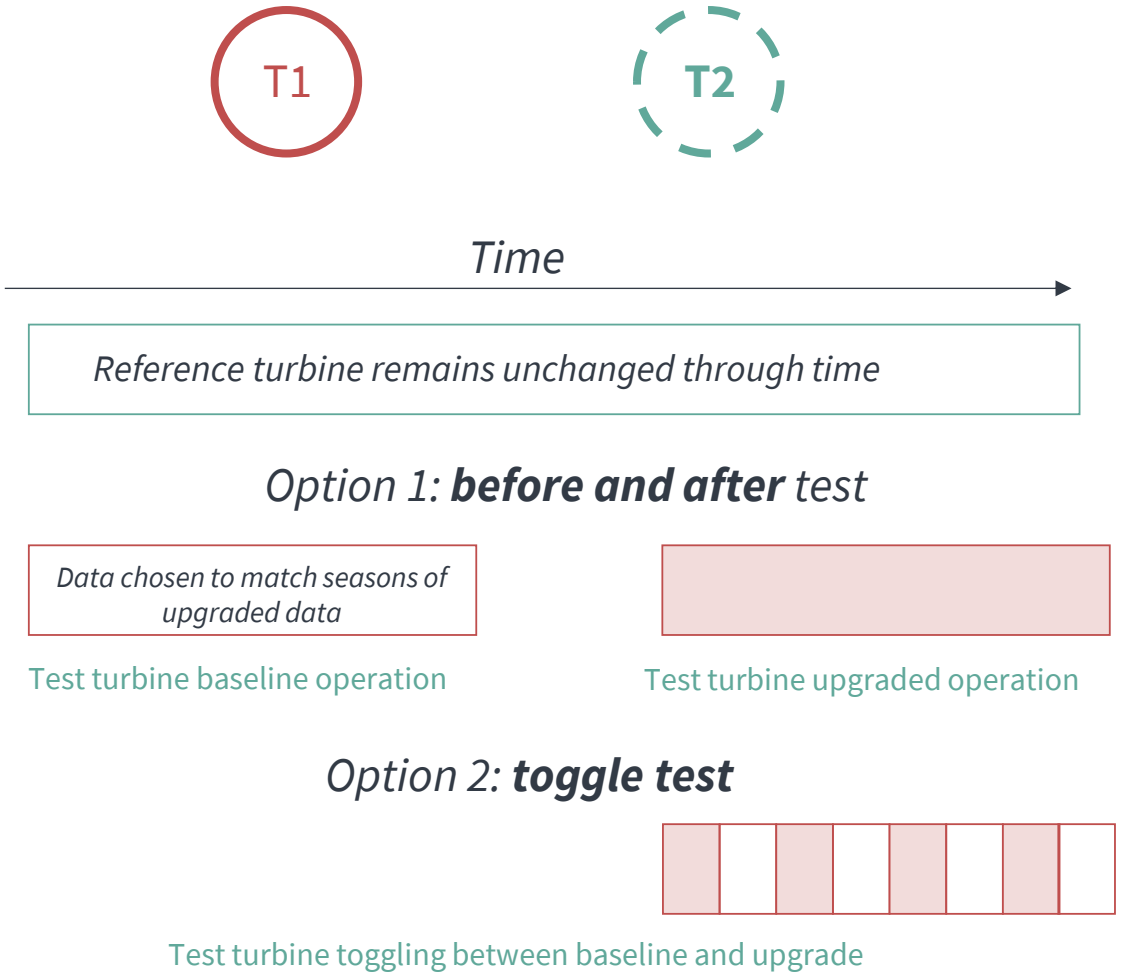
Ideally the wind speed estimate is based on a high-quality nearby wind measurement consistent with IEC61400-12-1. Otherwise, it's possible to construct the estimated wind speed from surrounding reference turbines.

Power curves before and after an upgrade



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.

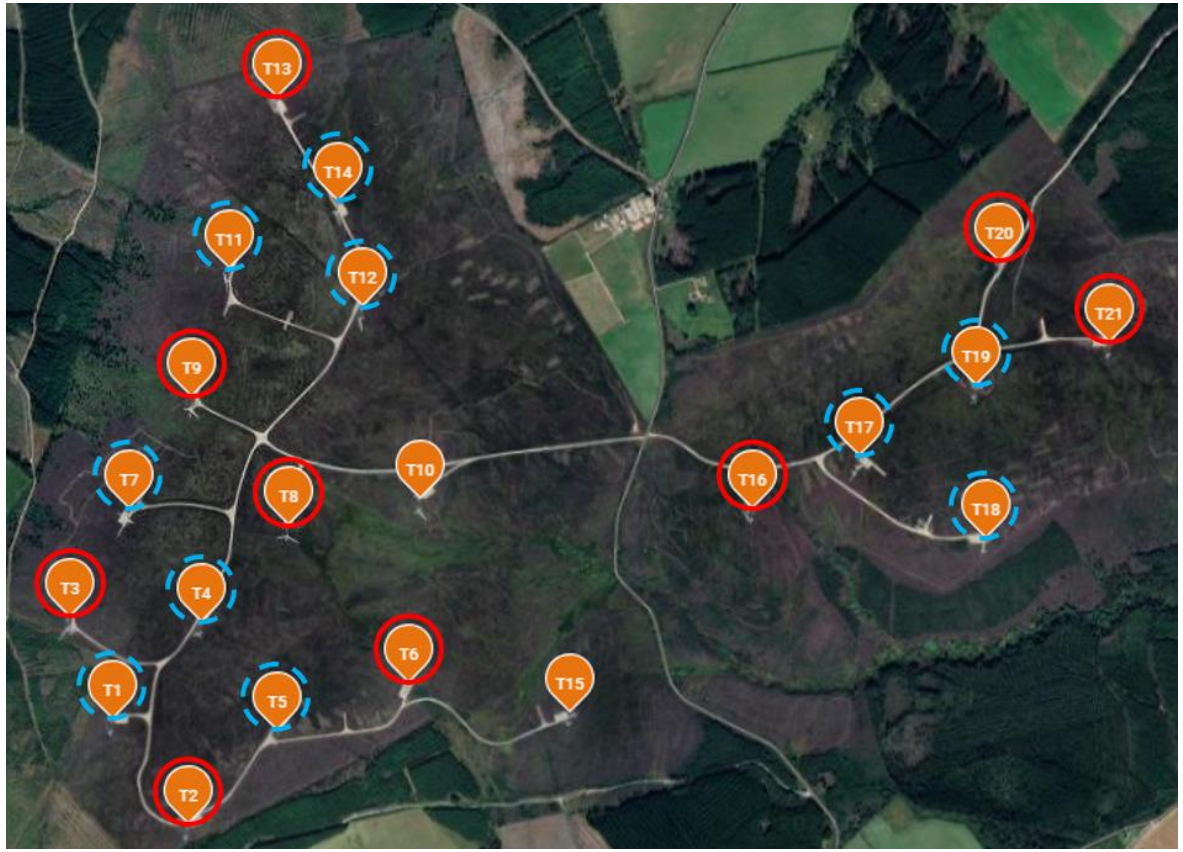
For each **test turbine** try to ensure:

- There are at least three nearby **reference turbines**
- Wake-free locations are valuable; ideally share them equally between test and reference turbines

In the real-world example shown on the right nearly half (9 of 21) 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)



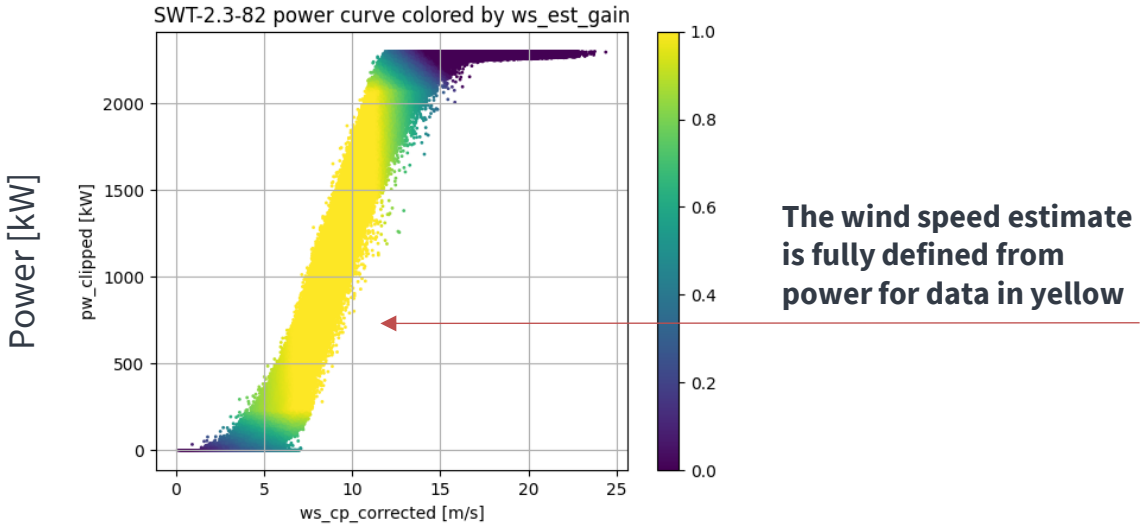
Hill of Towie **test turbines** and **references turbines** used for TuneUp uplift measurement.

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.

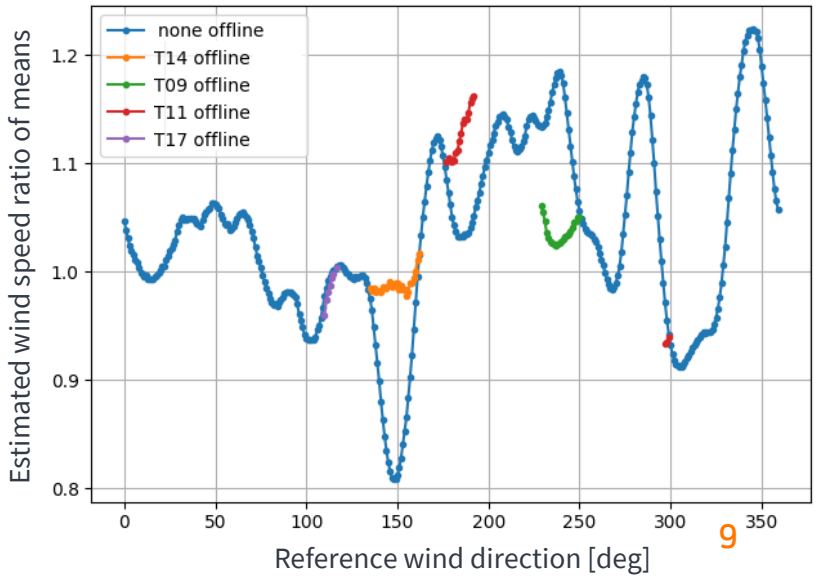
Wind speed at a reference turbine location can be translated to wind speed at the test turbine location by defining a directional lookup based on past data ("**directional detrending**"). The **wind-up** tool helpfully splits data into availability scenarios of all surrounding turbines.



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)

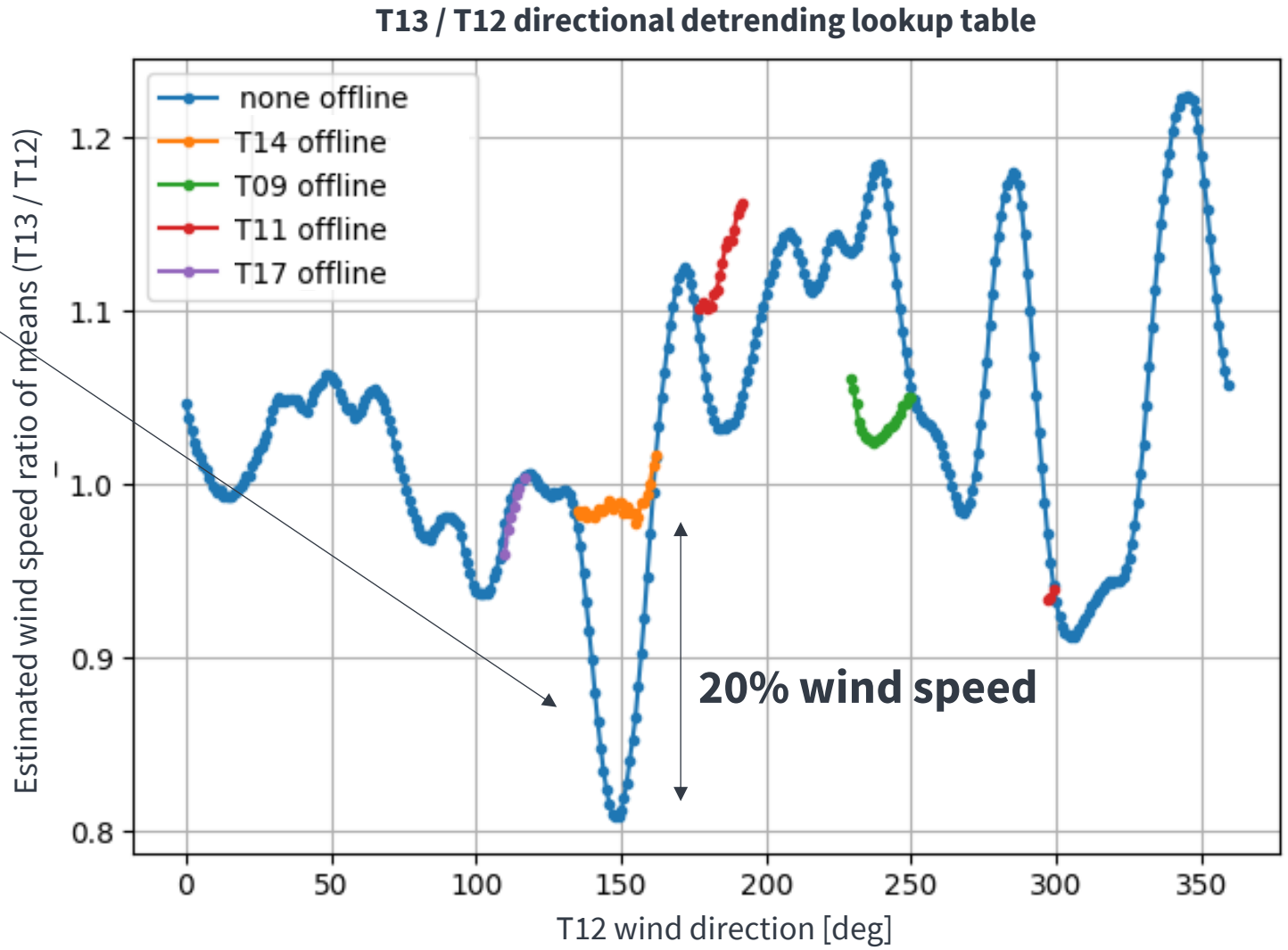


Analysis method: estimating wind speed (2/2)

In this example T14 is south-east of the test turbine (T13) and does not affect the reference turbine (T12) in that sector

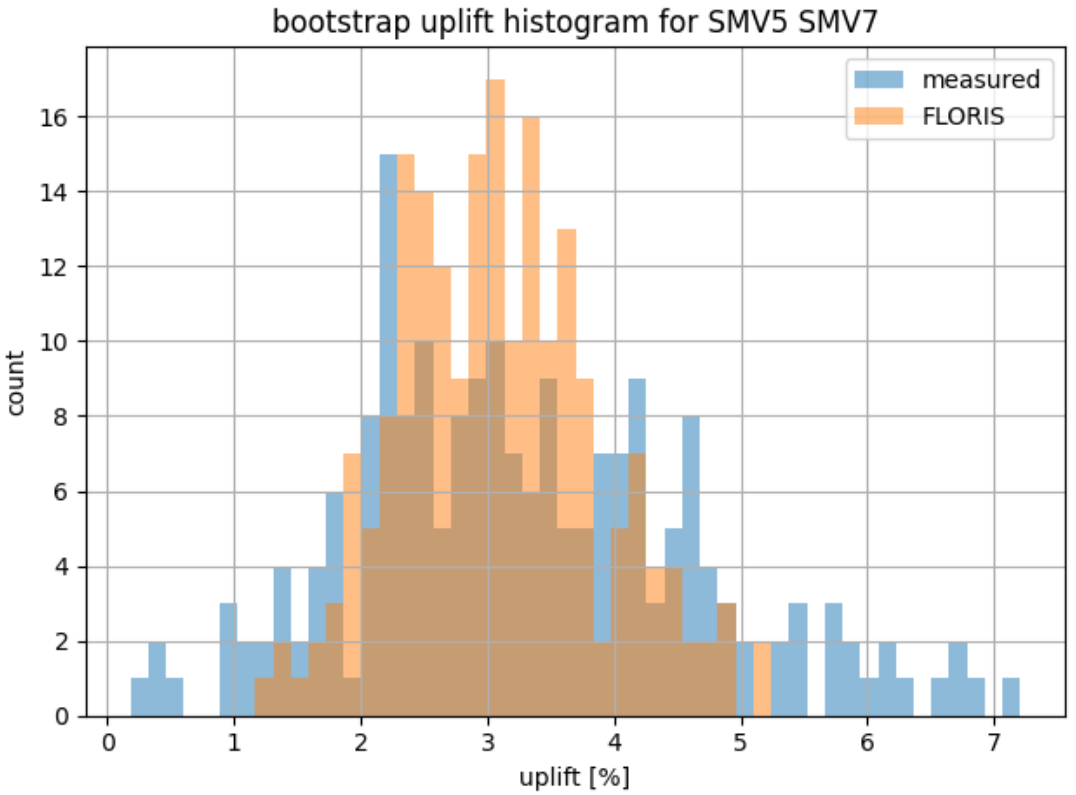
Note the large wake when T14 is online and no wake when it is offline.

It is crucial to account for the timeseries waking status of surrounding wind turbines; these effects can easily overwhelm the uplift measurement.



Analysis method: uncertainty

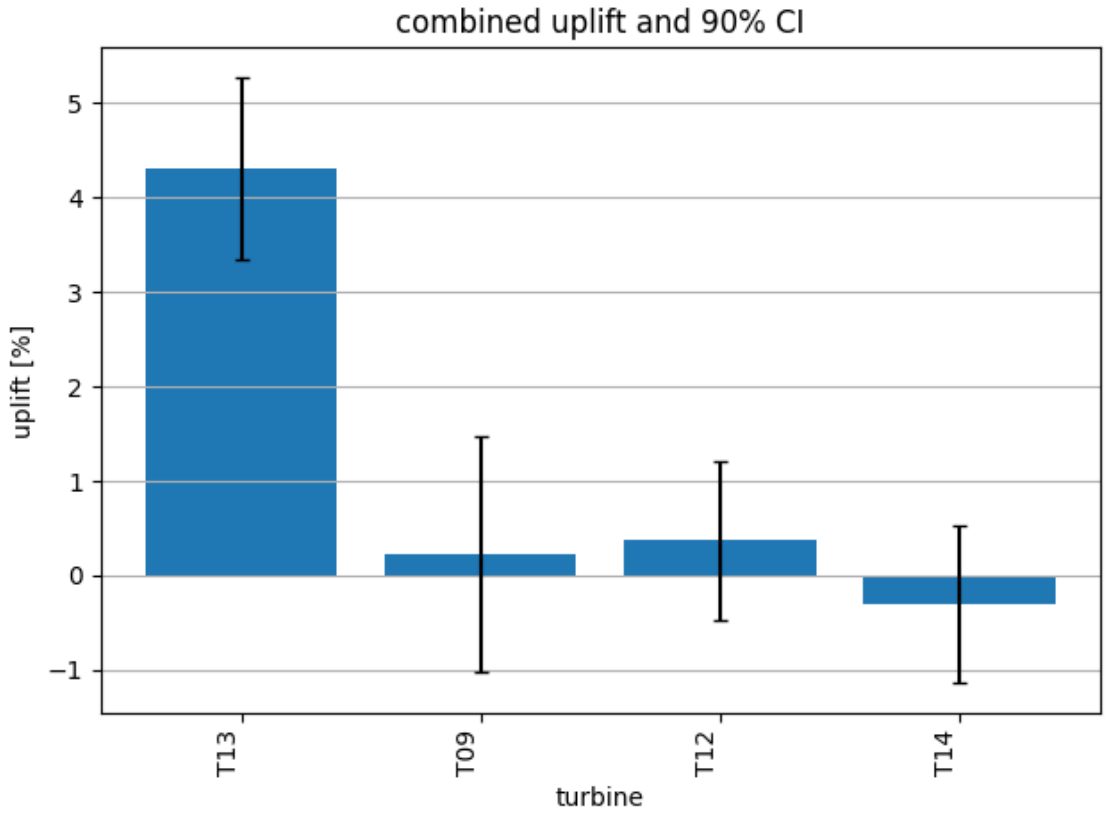
- Uplift uncertainty is estimated using a method similar to the IEC61400-12-1 Category A uncertainty calculation
- Uplift uncertainty is also estimated in two more ways:
  - Block bootstrapping, where the data is resampled many times with replacement
  - A reversed analysis, where the roles of test and 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

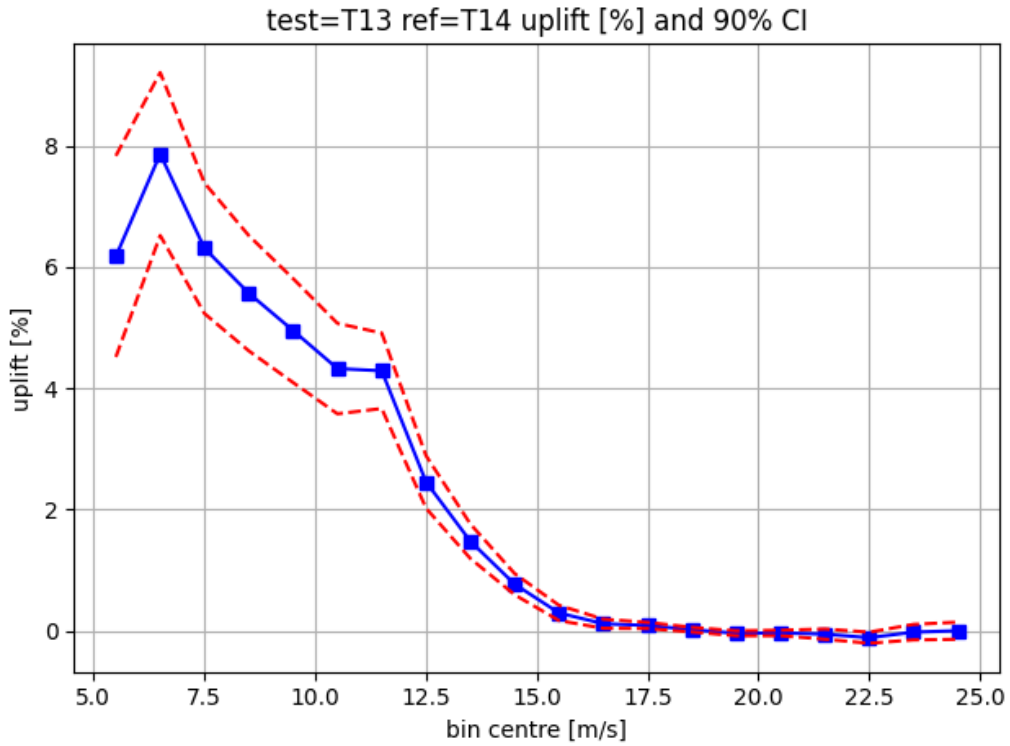


Bootstrapping can be used to repeat the uplift measurement many times with a different sample of the original data.
In this example a model of the uplift (FLORIS model of wake steering) is simultaneously bootstrapped to inform uncertainty modelling.

Results: AeroUp

The script aero_up.py measures uplift after AeroUp for T13.
The result is a P50 uplift of **4.3%** with a 90% confidence interval of 3.3% to 5.3%. Full analysis here*

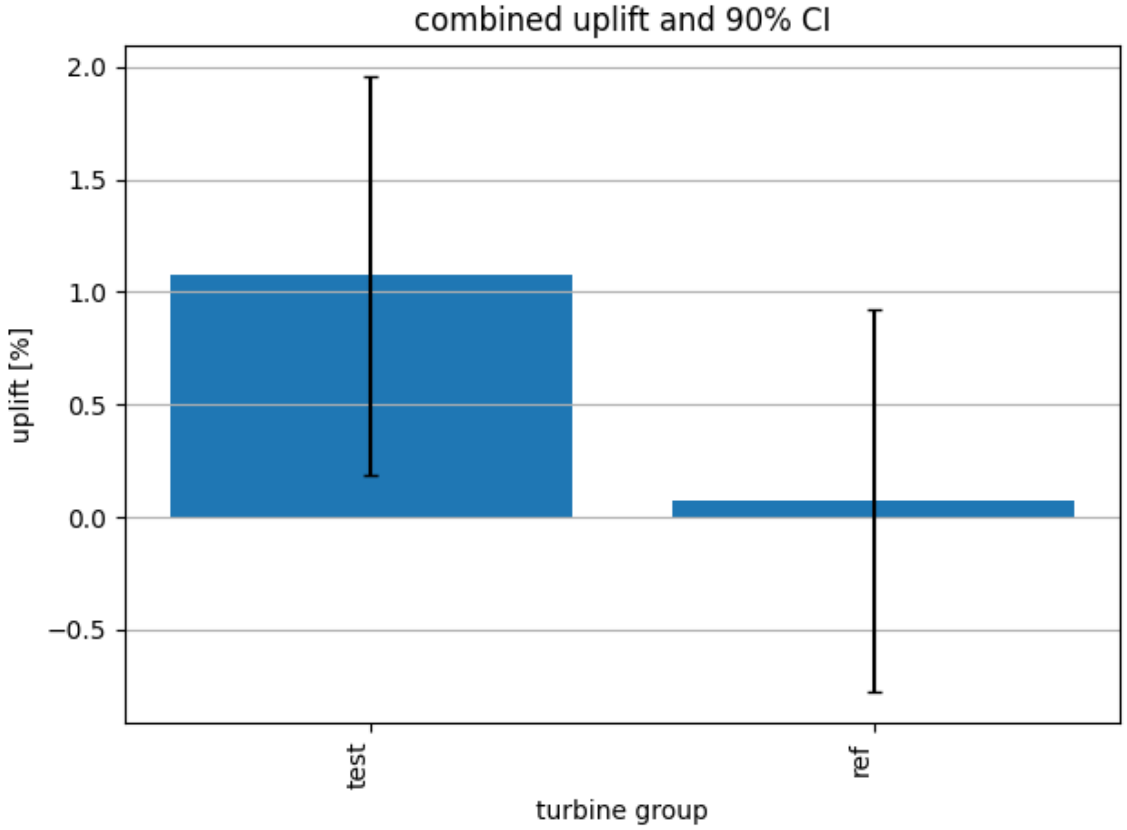


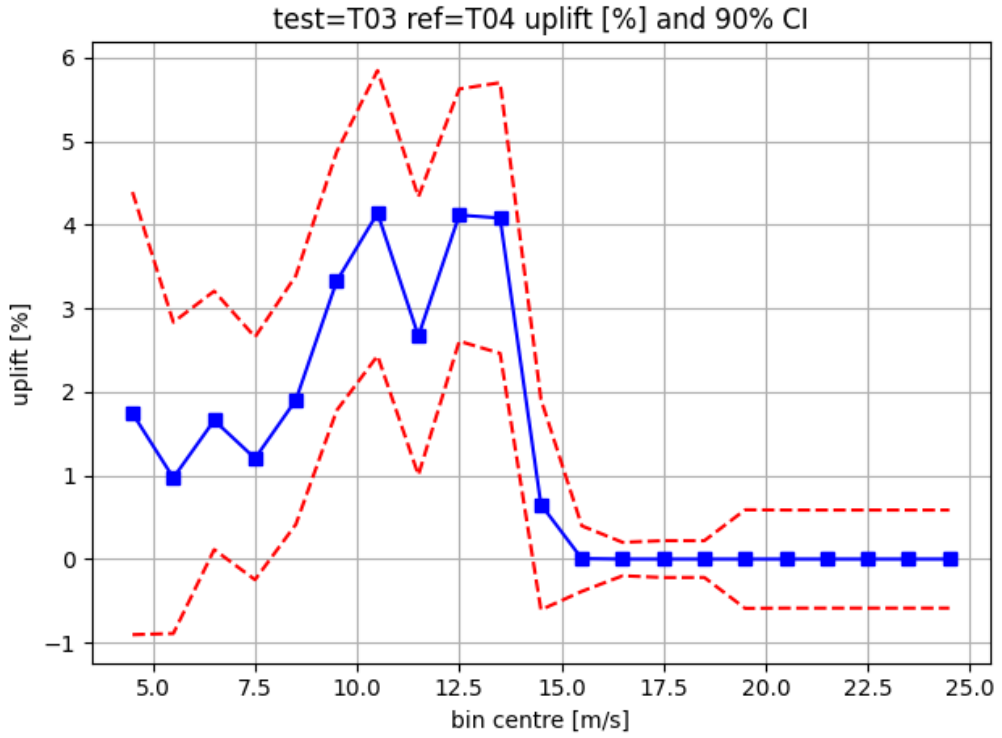


*https://github.com/resgroup/hill-of-towie-open-source-analysis/blob/main/uplift_analysis/aero_up.py

Results: TuneUp

The script tune_up.py analyses the energy uplift thanks to TuneUp for nine test turbines.
The result is a P50 uplift of **1.1%** with a 90% confidence interval of 0.2% to 2.0%. Full analysis here*





*https://github.com/resgroup/hill-of-towie-open-source-analysis/blob/main/uplift_analysis/tune_up.py

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

Data, code and examples for the presented Hill of Towie case studies are publicly available here*

Thank you to TRIG

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*https://github.com/resgroup/hill-of-towie-open-source-analysis

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