



# Validating wake steering with open data: LiDAR measurements and uplift analysis from a commercial wind farm

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- Controller and campaign
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## Executive Summary:

**0.7%** AEP uplift and a reduction in yaw activity with **Dynamic Yaw** (RES wind farm control product) [1].

The total uplift from control optimization at Hill of Towie is **1.7%** with 1.0% from **TuneUp** verified in 2024 [2][3].

Control was implemented safely and easily with just a single computer added to site.

Campaign data and analysis have been published openly



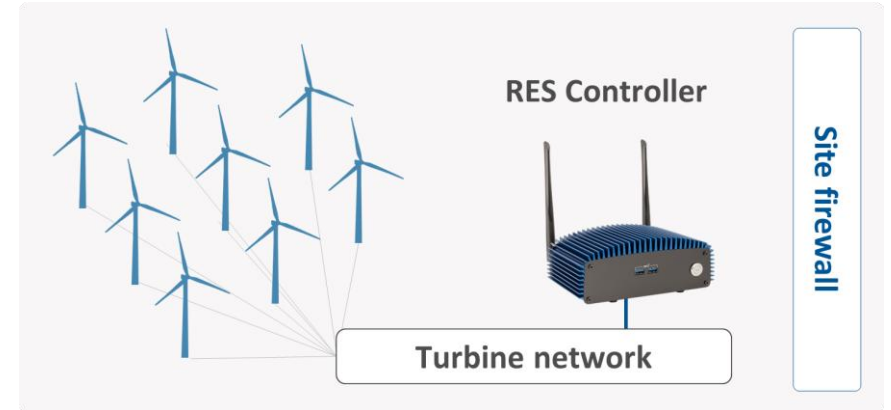
*Hill of Towie  
wind farm*

# Summary of controller

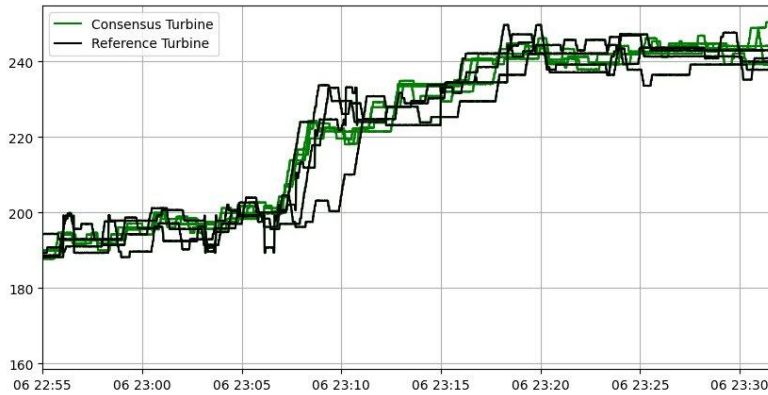
The **Dynamic Yaw** controller implements collective yaw control [4] and wake steering.

The controller uses Anemo technology [5] to safely send commands to the 21x Siemens 2.3MW turbines through their native control protocol, thus **no additional hardware** is added to the turbines. Only one computer was added to site.

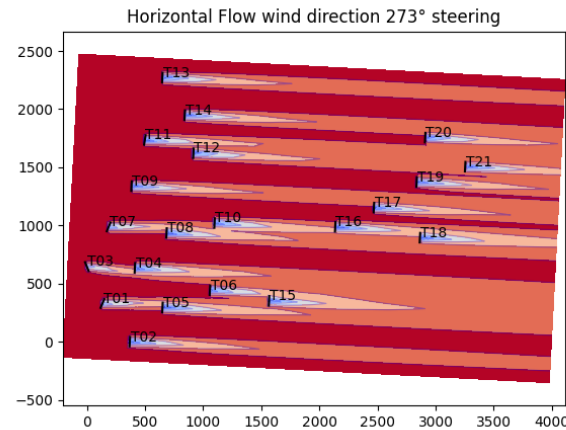
Design work included aeroelastic simulations to confirm minimal impact of the defined wake steer strategy on the wind farm loading



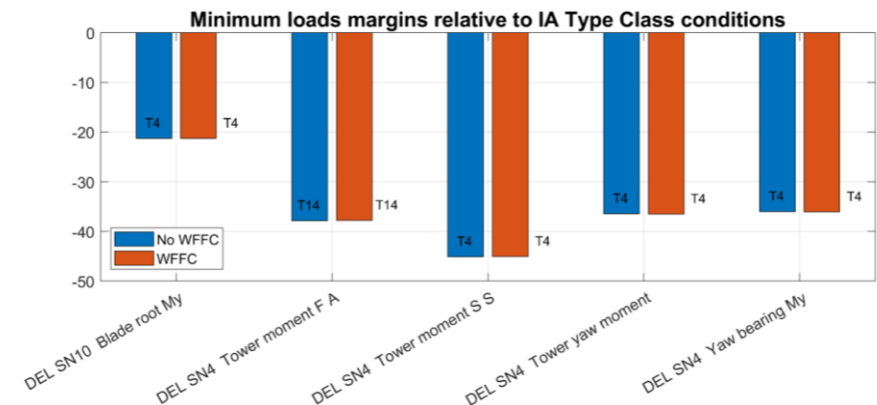
Control achieved with a **single computer** in the substation



Example of collective yaw control



Example wake steer simulation of Hill of Towie with FLORIS [6]



Sample of results from aeroelastic simulations with and without WFFC (wind farm flow control)

# AEP measurement campaign









**collective yaw control (CC) and wake steering (WS) measurement campaign** ran during January to April 2026.

13 of the 21 turbines are controlled with toggling (50min ON, 50min OFF)

T7 is not controlled but is a test WS benefiting turbine

Note Lidars are for validation, they are not part of the control system.

-  Reference turbines (no toggling)
-  Ground-based LiDAR
-  WS benefiting + Nacelle LiDAR
-  WS + CC toggling
-  WS benefiting + CC toggling
-  CC toggling

# Open data and analysis



The wind farm control campaign is available as version 2 of the Hill of Towie wind farm open dataset [7]

Additional data in v2 includes:

- SCADA record increased from 8 years to 10 years (ends April 2026)
- 10min and fast data from both Lidars
- >10GB of fast data for west turbines (high wake steering activity)

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** tested on 9 test turbines March 2024 – September 2024
- **TuneUp** deployed to all turbines January 2025
- **Dynamic Yaw** toggle test January-April 2026

All analysis shown in this presentation can be reproduced with the code here [8]:

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

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

Published May 18, 2026 | Version 2.0.0

**Hill of Towie wind farm open dataset**

Clerc, Alex (Data curator) · Lingkan, Elizabeth (Data curator)

5K VIEWS | 8K DOWNLOADS

Versions

Version	Published
Version 2.0.0	May 18, 2026
Version 1.0.0	Mar 28, 2025

External resources

Indexed in

OpenAIRE

Keywords and subjects

SCADA | RES | TRIG | wind turbine

<https://zenodo.org/records/20204946>

resgroup / hill-of-towie-open-source-analysis

Hill of Towie wake steering analysis #21

aclerc wants to merge 117 commits into main from hot-wake-steering

Conversation | Commits 117 | Checks 1 | Files changed 60

aclerc commented 3 weeks ago · edited

Goal of this PR is to analyse v2 of the Hill of Towie open data which includes a wind farm control campaign Jan-Apr 2026

Repo is also re-organized

# Energy yield validation method

- Two upgrades tested simultaneously: **collective yaw control** (CC) and **wake steering** (WS)
- WS uplift and AEP extrapolation need special consideration:
  - For WS we need **net uplift** for upwind-downwind pairs in their wake direction
  - Long-term (LT) extrapolation needs to account for wind direction and atmospheric stability
- Approach is therefore to split the campaign data into two parts, analyse them appropriately, and then combine results:

## WS uplift analysis:

1. Identify timestamps and turbines which can be part of wake steering
2. Follow the standard wind-up [9] method except work on **net uplift** of two turbines (*upwind-downwind*) instead of uplift of one turbine.
3. Run FLORIS wake flow model for the same turbine pair both for the campaign period and long-term to calculate extrapolation factors of uplift and yaw activity.

## CC uplift analysis:

CC is a normal wind-up run where each turbine is analysed individually against reference turbines

**Total uplift:** Combine the CC and WS uplift weighted by the expected long term energy contribution from their respective wind directions.

- Change in yaw activity also needs to be measured and extrapolated to long term in a similar way.

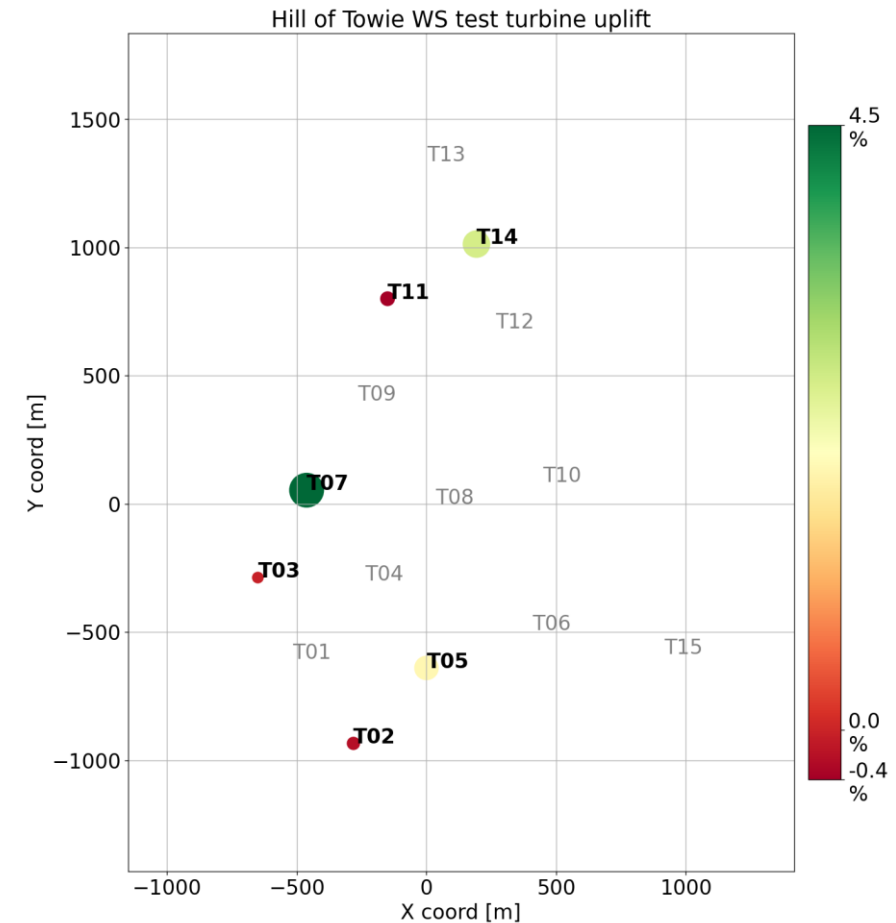
# Wake steering uplift results

- Only 3 turbine pairs (out of 6 WS test turbines) collected enough data (>100 hours) to be considered in the AEP uplift assessment (slightly below the IEC 61400-12 recommendation of 140 hours):

Upwind / steering turbine	Downwind turbine	Wind directions	Hours Toggle OFF	Hours Toggle ON	Upwind turbine uplift	Downwind turbine uplift	Net Uplift P50*	Net Uplift P95
T11	T14	228°-255°	168.4	164.1	-0.4%	2.6%	<b>1.0%</b>	0.3%
T03	T07	192°-224°	123.6	118.3	0.0%	4.5%	<b>2.1%</b>	0.2%
T02	T05	211°-241°	113.0	112.3	-0.2%	1.9%	<b>0.8%</b>	-0.9%

\* The net uplift considers the average power of each upwind and downwind turbine rather than one uplift minus the other to account for different long-term production.

- Wake Steering (WS) uplift results for the campaign (steering directions):
  - **Net P50 uplift 1.32%, uncertainty 0.54%**



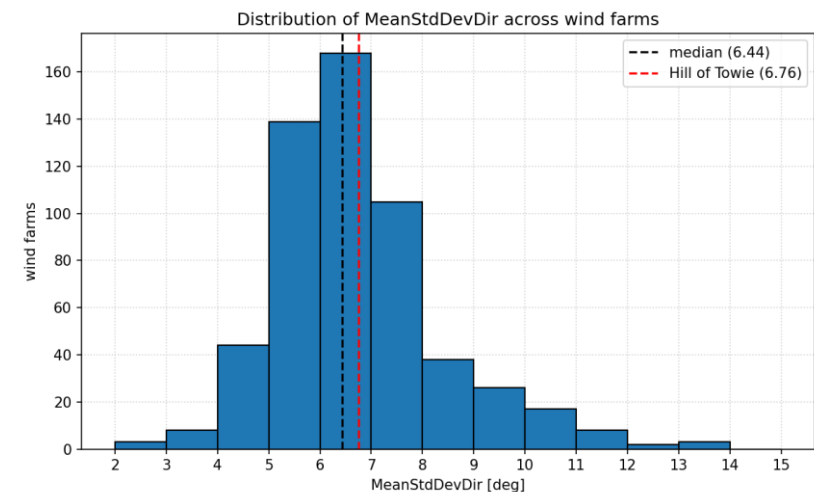
# Wake steering uplift results - Hill of Towie context

➤ These positive results are welcome given Hill of Towie is not an ideal site for wake steering due to the following reasons:

- Rotor low to ground (59m hub height, 82m diameter -> 18m low tip height)
- Relatively high turbulence. The Hill of Towie pre-construction mast data has a mean wind direction standard deviation (proxy for wind farm turbulence) of  $6.76^\circ$  which is higher than median for a population of over 500 sites developed by RES (see histogram below).
- Modest wake loss limits WS potential: pre-construction estimate of wake loss is only 7.6%

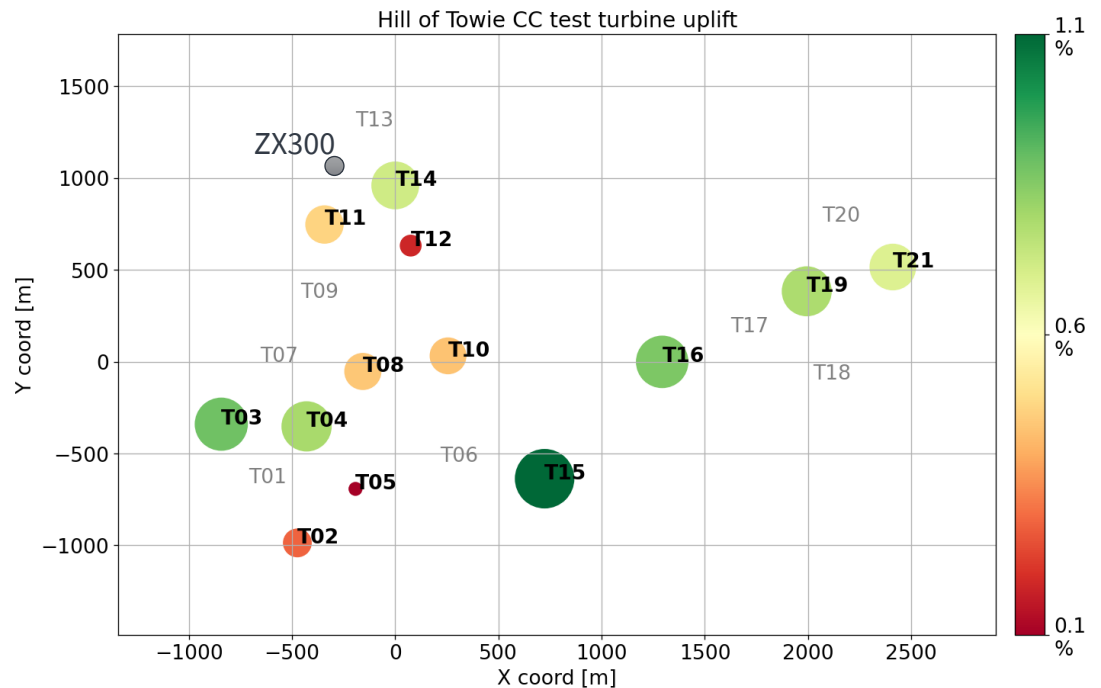
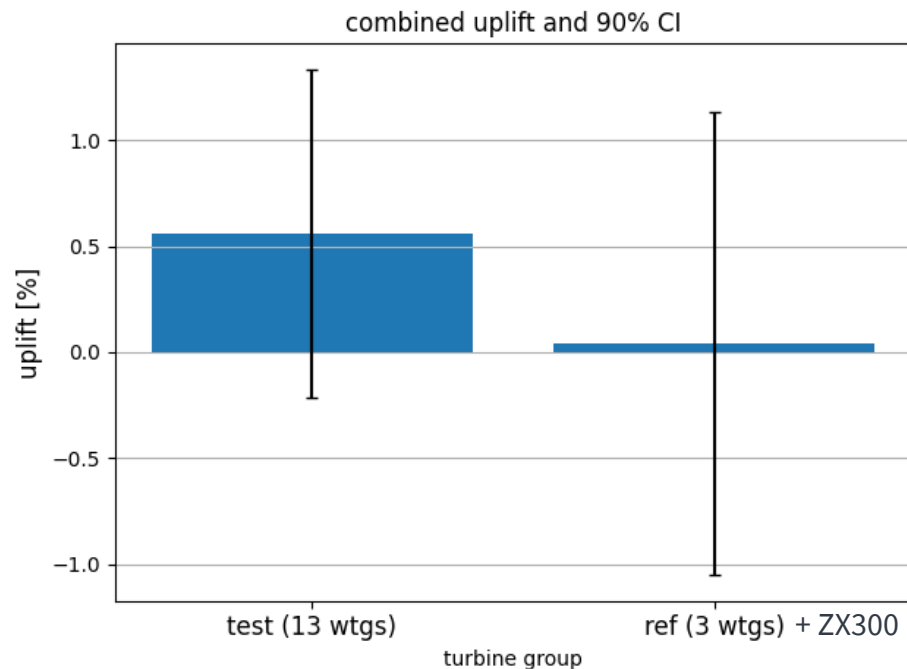
➤ Ideal sites for wake steering would have:

- Low turbulence (stable wakes, easier to track wind direction)
- High wake loss (more loss to eliminate)



# Collective Yaw Control uplift results

- All 13 CC test turbines were assessed using their toggle on / toggle off data against references.
- 3 reference turbines (T01, T13 and T18) and the ground-based Lidar (ZX300) were used. This collection of reference measurements covers all wind directions and measures 0.04% uplift against themselves.
- The CC uplift results are: **P50 AEP uplift 0.56%, uncertainty 0.47%**

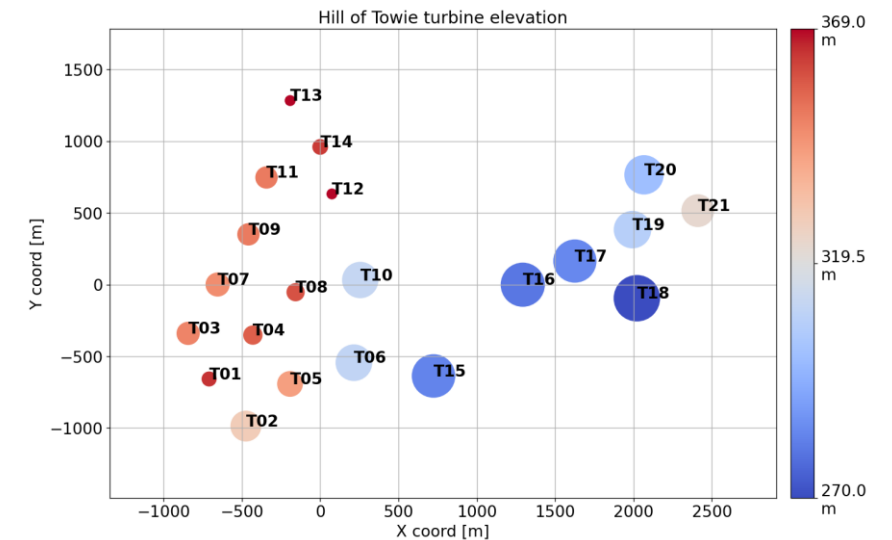
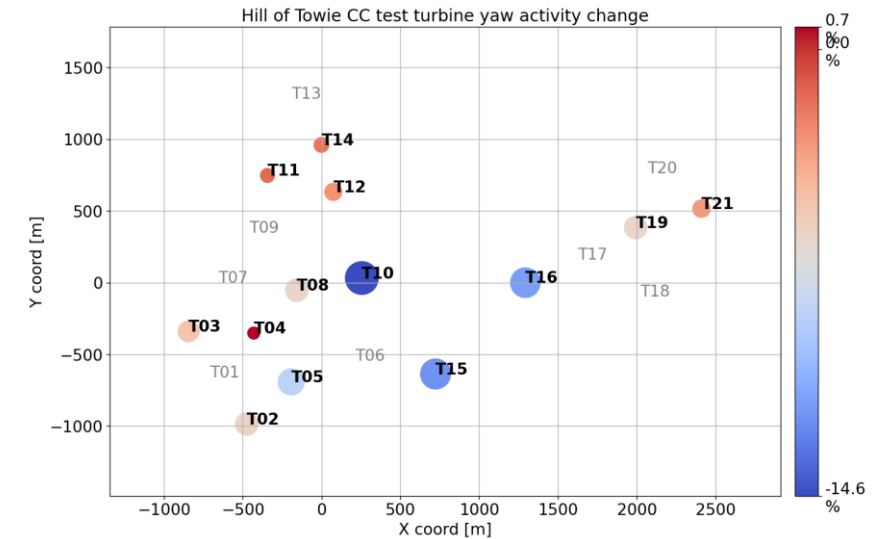


# Overall uplift results

- ▶ Wake Steering (WS) uplift results for only wind directions where steering is possible:
  - **Net P50 uplift 1.32%, uncertainty 0.54%**
- ▶ Collective Control (CC) uplift results for all other wind directions:
  - **P50 AEP uplift 0.56%, uncertainty 0.47%**
- ▶ The results above are combined to take into account the expected long-term wake steering weight (~18%) as well as the extrapolation from the measurement campaign to the long-term weather and wake steering strategy.
- ▶ The overall uplift result is:
  - **AEP uplift of 0.7% (P50), uncertainty 0.4%, P95 0.0%**

# Yaw activity analysis

- Wake steering has increased yaw activity on steering turbines by 35% (just in the steering directions) on average as they need to yaw more often.
- Collective control has reduced yaw activity by 6% on average, with the largest reduction for turbines at lower elevation (T10, T15 and T16). The physical interpretation is that without collective control these turbines over-respond to turbulence.
- The long-term yaw activity change is a reduction of 2%** (wind farm average). The individual turbine maximum yaw activity change (T03) is an increase of 8%.



# A closer look with LiDAR (ZXTM)

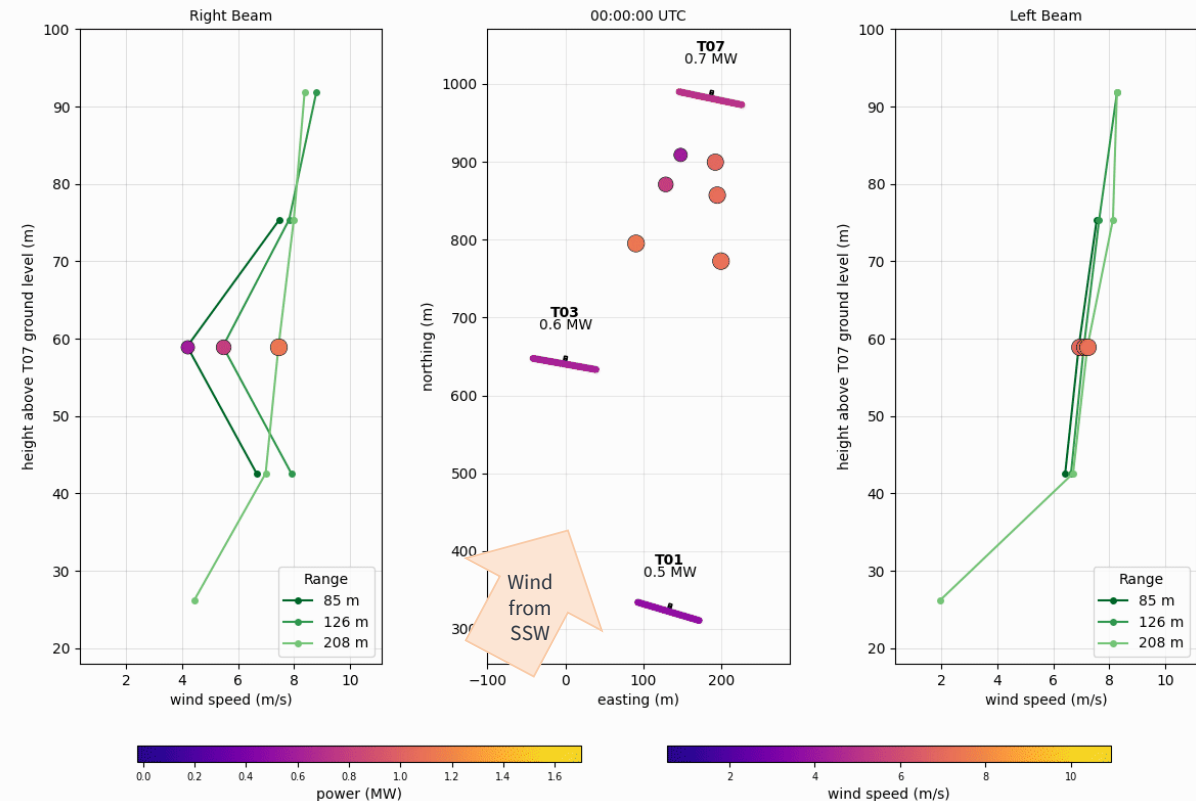
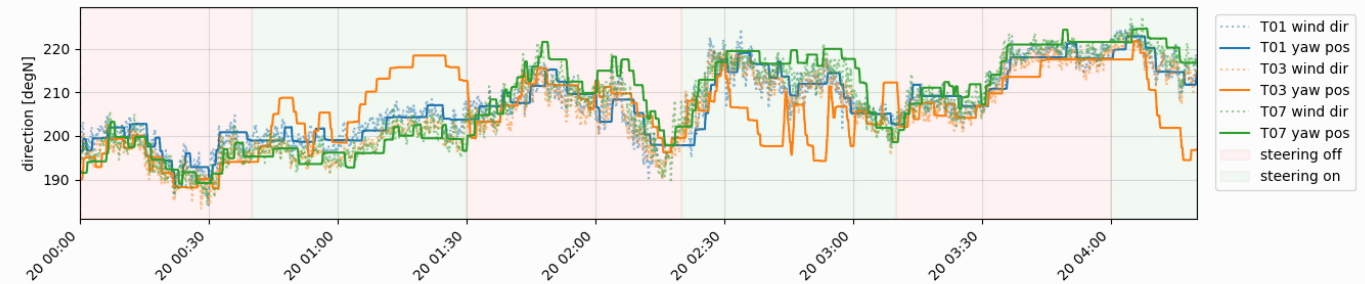
The ZXTM on T07 provides ~1Hz radial wind speed measurements at multiple ranges and heights above ground level.

The LiDAR is not used by the control system but provides useful data to refine wake modelling and control in future.

All data and analysis code is included in the open data pack and repo, respectively.



Hill of Towie — T03 wake steering for T07 (T01 reference) — 2026-02-20 00:00-04:20 UTC

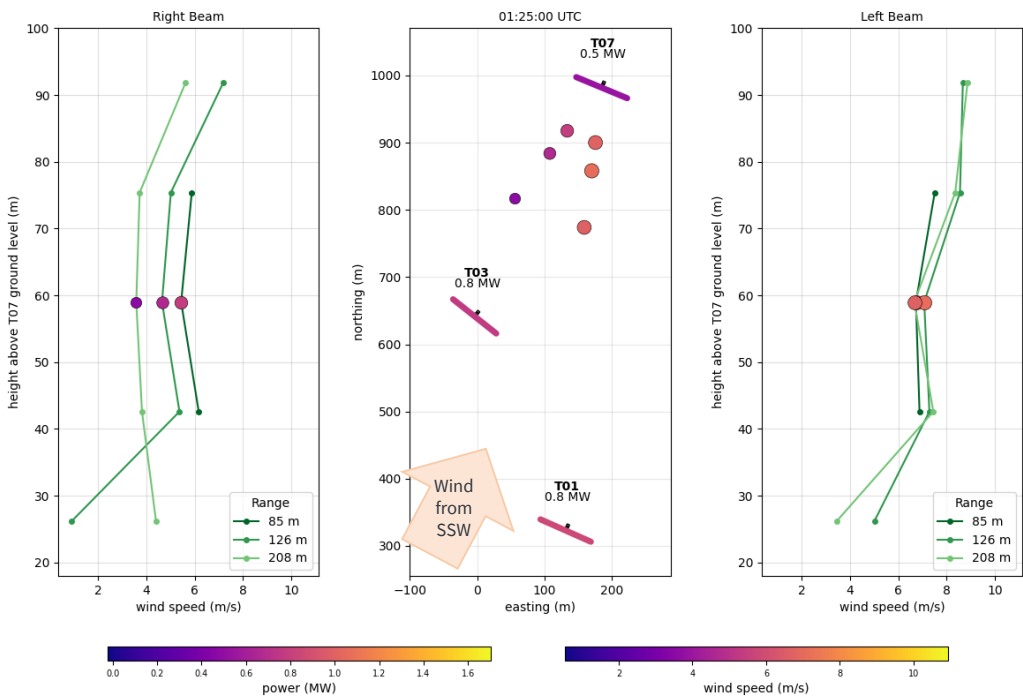
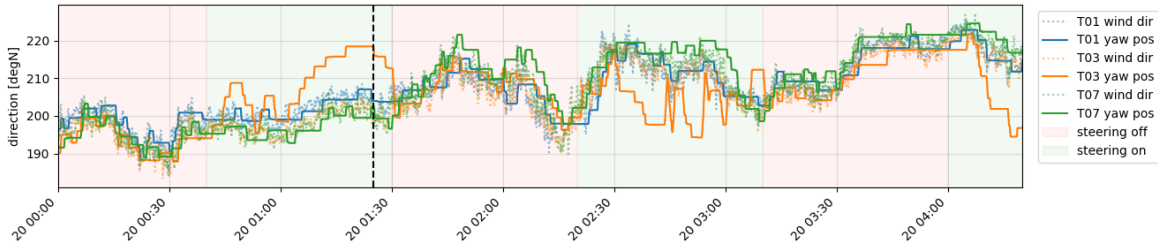


# A closer look with LiDAR (ZXTM)



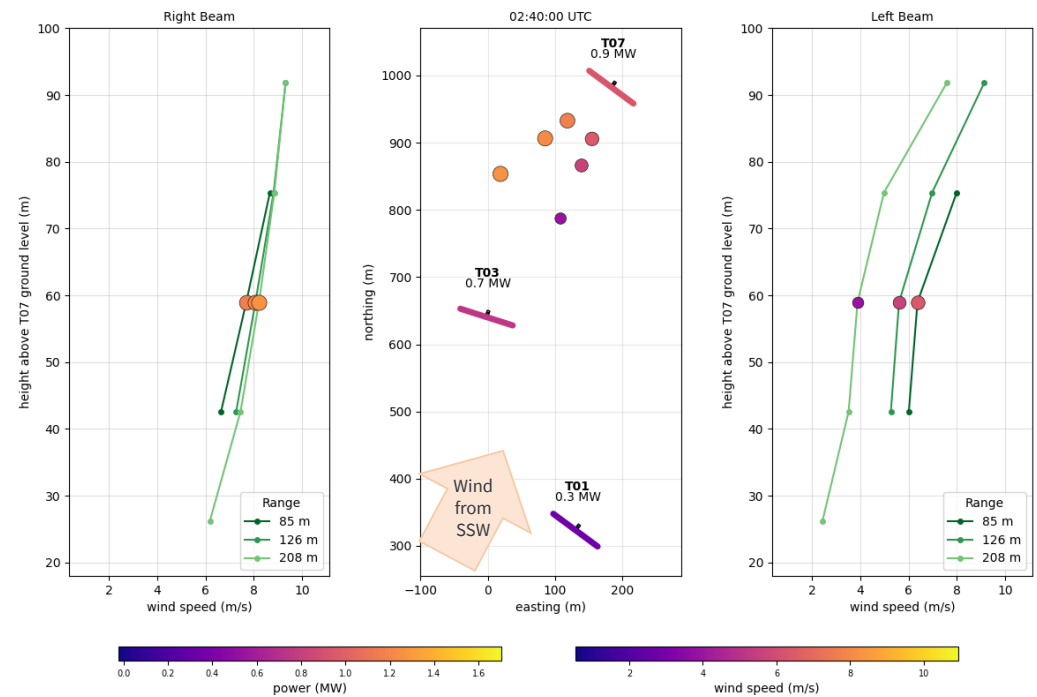
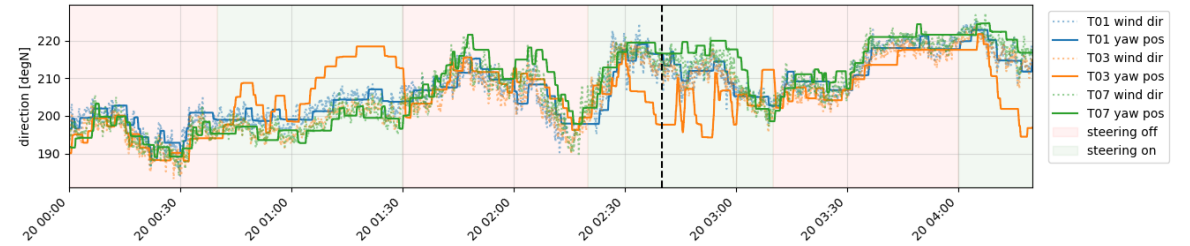
## Example CW steer: wake is deflected west of T07

Hill of Towie — T03 wake steering for T07 (T01 reference) — 2026-02-20 00:00-04:20 UTC



## Example CCW steer: wake is deflected east of T07

Hill of Towie — T03 wake steering for T07 (T01 reference) — 2026-02-20 00:00-04:20 UTC



# A closer look with LiDAR (ZX300)

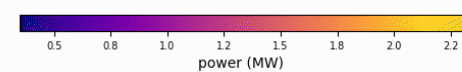
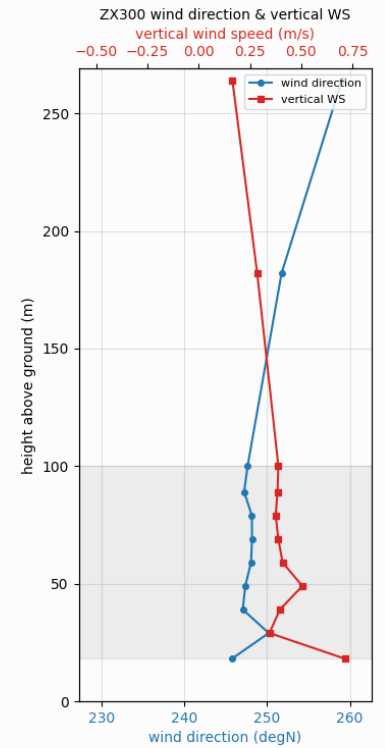
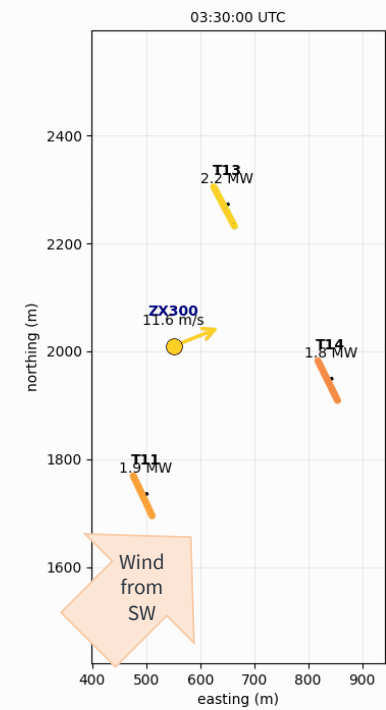
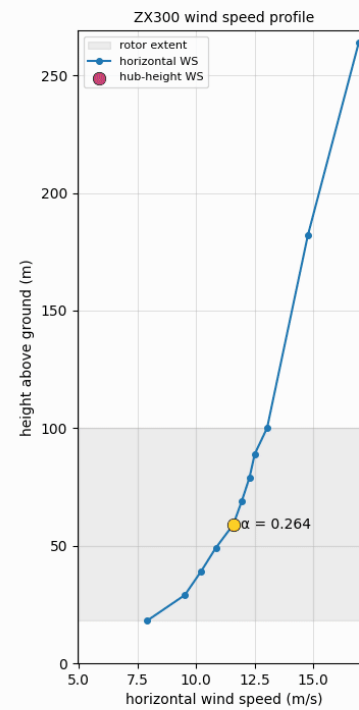
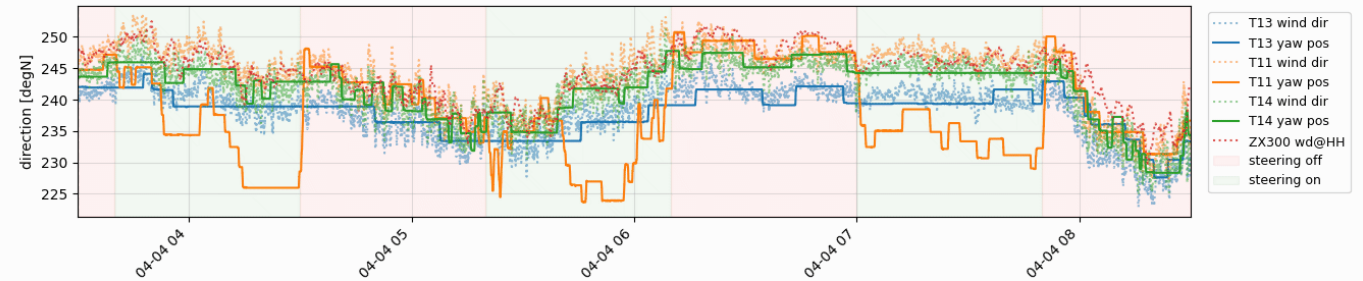
The ZX300 near T11 provides ~0.1Hz wind vector measurements at multiple heights above ground level

The LiDAR is not used by the control system but provides useful data to refine wake modelling and control in future.

All data and analysis code is included in the open data pack and repo, respectively.



Hill of Towie — T11 wake steering for T14 (T13 reference) — 2026-04-04 03:30-08:30 UTC



- **Dynamic Yaw** achieved 0.7% AEP uplift at Hill of Towie with wind farm control
- The total uplift from control optimizations at Hill of Towie is 1.7% with the 1.0% from TuneUp verified in 2024
- Control was implemented safely and easily with just a single computer added to site
- Open data and analysis of the campaign is available to the industry and research community
  - **To our knowledge this is the most comprehensive open wake steering dataset in the world to date**
  - Thank you to TRIG for allowing us to publish the dataset
  - Thank you to the creators of the SMARTEOLE dataset [10] for leading by example

- [1] Alex Clerc et al, Open-source dataset and AEP validation from a real-world case study of turbine upgrades worth 5% AEP, <https://www.res-group.com/aep-validation>
- [2] Dynamic Yaw – increase the value of your wind farm, <https://www.res-group.com/digital-solutions/dynamic-yaw/>
- [3] TuneUp - maximise wind turbine efficiency, <https://www.res-group.com/digital-solutions/tuneup>
- [4] Paul Fleming et al, Field trial of collective consensus control, presentation at WESC May 2023
- [5] Anemo - unlocking the power of your data, <https://res-group.com/digital-solutions/anemo/>
- [6] FLORIS Wake Modeling and Wind Farm Controls Software, <https://pypi.org/project/floris/>
- [7] Alex Clerc & Elizabeth Lingkan (2026), Hill of Towie wind farm open dataset (2.0.0) [Data set], Zenodo, <https://doi.org/10.5281/zenodo.20204946>
- [8] Hill of Towie open-source analysis, <https://github.com/resgroup/hill-of-towie-open-source-analysis>
- [9] wind-up: A tool to assess yield uplift of wind turbines, <https://pypi.org/project/res-wind-up/>
- [10] Thomas Duc & Eric Simley, (2022), SMARTEOLE Wind Farm Control open dataset (1.0) [Data set], Zenodo, <https://doi.org/10.5281/zenodo.7342466>



**Thank you**

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