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An international benchmark for wind plant wakes from the American WAKE ExperimeNt (AWAKEN)

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An international benchmark for wind plant wakes from the American WAKE ExperimeNt (AWAKEN)

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Abstract. This article introduces the first benchmark study within the International Energy Agency Wind Task 57 framework, focusing on wind plant wakes. Leveraging data from the American WAKE ExperimeNt (AWAKEN), the benchmark aims to assess the accuracy of simulation tools in modeling wind plant wakes and their impact on the downstream flow under diverse inflow conditions. The AWAKEN field campaign, conducted in Oklahoma from 2022 to 2024, provides unprecedented observations of wind plant-atmosphere interactions, thus offering a large dataset to validate numerical models of different complexity. The benchmark will include three phases—code calibration, blind comparison, and iteration—allowing participants to refine their numerical models based on the feedback from the benchmark team. This article describes the benchmark case study selected from observations providing details on atmospheric conditions, wake evidence, and wind turbine operation. The benchmark's structure and timeline, along with the expected publication of results, are discussed as well. This collaborative effort aims to enhance the accuracy of wind plant wake simulations, thus contributing to the improvement of wind energy production estimates.

1. Introduction

Wind plant efficiency is tied to the impact of wind turbine and wind plant wakes, where the wind flow downstream of single wind turbines and whole wind plants induces lower speed and higher turbulence that significantly impact the performance of neighboring turbines and wind plants [1]. From a numerical perspective, accurately modeling wake-induced power losses across spatiotemporal flow scales is a challenging task due to their sensitivity to the variability of wind speed, direction, turbulence, atmospheric stability, and terrain morphology or sea state. At the same time, accurately modeling and properly mitigating the effects of wind plant wakes are crucial aspects for optimizing overall energy output from wind plants [2]. The increasing availability and capability of computational tools allow wind plant wakes to be modeled in several ways that consider trade-offs between fidelity and cost, depending on the target application. However, the broad availability of simulation tools and setups coupled with the inherent complexity of flow physics within wind plant wakes may produce significantly different model outputs, which have a major influence on design and control decisions in wind energy systems [3, 4].

To systematically assess the skills and quantify the uncertainty of various models for wind plant wakes and other wind-energy-related processes, the International Energy Agency (IEA) recently established the Wind Task for the Joint Assessment of Wind Energy Models (Task 57). IEA Wind Task 57 will contribute to the strategic evolution and expansion of the previous IEA Wind Task 31 WakeBench (2011–2021, [5, 6]), which also focused on the assessment of wind and wake models through multiple benchmarks. During its 10-year operation, Task 31 established a forum for the collaborative benchmarking of models and created a multinational community to ensure that technology development, deployment, and operation are based on reliable simulations. Task 57 will build on Task 31's model evaluation framework to tackle unanswered questions (e.g., how can the wind industry use advanced uncertainty quantification techniques to better reduce the large spread among preconstruction energy estimates using different industry tools) by leveraging new, more comprehensive datasets to build confidence in and promote adoption of improved wind flow, wind turbine, and wind plant models.

The first benchmark being developed within the IEA Wind Task 57 framework is focused on wind plant wakes. The goal of this benchmark is to assess the ability of a variety of simulation tools to model wind plant wake characteristics (i.e., momentum deficit, added turbulent mixing and transport, and boundary-layer height) and their impact on downstream wind plants under different inflow conditions and wind plant geometry. This article presents the benchmark case study, selected based on the experimental observations collected during the American WAKE ExperimeNt (AWAKEN). The selected case study will serve as a reference for international participants to test and optimize their models to simulate wind plant wakes.

The article is organized as follows: Section 2 summarizes the AWAKEN field campaign. Section 3 presents the selected case study for the benchmark based on a single day of observations, with more details on the observed atmospheric conditions on that day provided in Section 4. Section 5 includes details on the turbine characterization for this benchmark, before summary and next steps are provided in Section 6.

2. The AWAKEN field campaign

2.1. Site description and instrumentation

The AWAKEN [7] project constitutes a comprehensive large-scale field campaign focused on observing and simulating the interactions between the atmospheric boundary layer and operating wind plants. This ambitious field campaign, which started in the fall of 2022 and is running through the fall of 2024, is focused on a region encompassing five closely spaced wind plants in northern Oklahoma (three of which are shown in Figure 1). Multiple research institutions, primarily funded by the U.S. Department of Energy (DOE) and led by researchers at the National Renewable Energy Laboratory (NREL), are actively participating in this campaign. With 14 scanning lidars (both ground-based and nacelle-mounted), 8 profiling lidars, 2 X-band radars, several sonic anemometers, thermodynamic profilers, and other meteorological instruments deployed across 13 ground-based sites and 5 instrumented wind turbines, the

AWAKEN campaign aims to collect an unprecedented amount of observations to accurately quantify the complex interactions between wind plants and the surrounding atmosphere. Detailed information about the timeline of the instrument deployment at the various sites can be found at `https://a2e.energy.gov/project/awaken`.

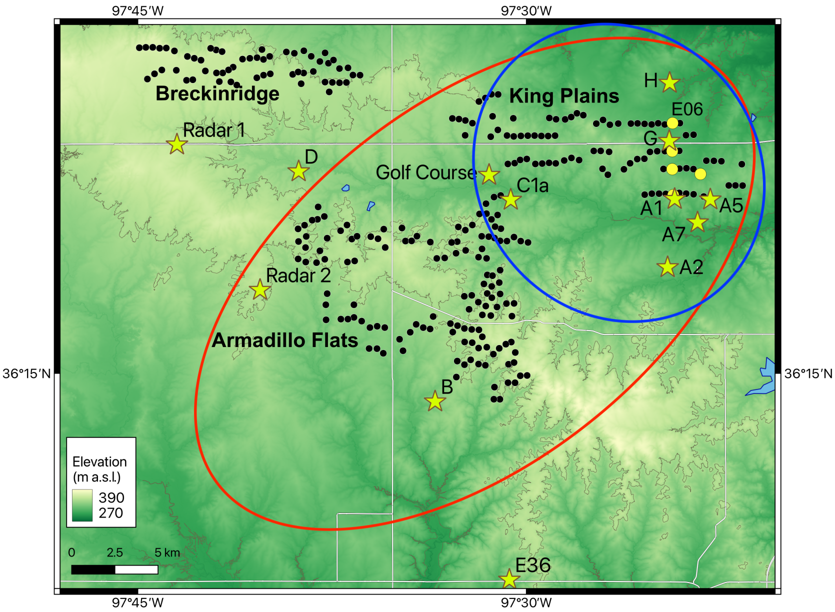

Figure 1. Instrumented sites (yellow stars) and turbine locations (black circles) at the AWAKEN field campaign. The red ellipse shows the region of interest for southwest wind, and the blue ellipse highlights the main area of interest for southern wind.

The phenomena of interest in AWAKEN include wakes behind both individual turbines and wind plants, blockage upstream of the wind plants, internal boundary-layer growth over the wind plants, increased turbulence within and downwind of the wind plants, and changes in the local meteorology, such as increased mixing and evapotranspiration downwind of the plants. For each of these core phenomena, the AWAKEN research team aims to establish internationally recognized benchmark exercises starting with wind plant wakes, whose detailed characterization and modeling are the highest-priority science goal for the project.

2.2. Wind turbine characterization

The locations and dimensions of the wind turbines in the wind plants in the area of the AWAKEN field campaign can be found in the U.S. Wind Turbine Database published by the United States Geological Survey [8]. A summary of the wind turbine characteristics of the two wind plants considered in this benchmark are included in Table 1.

Table 1. Wind plants of interest for the AWAKEN wind plant wake benchmark.

Wind plant	Total power	Number of turbines	# of each turbine model	Rotor diameter
King Plains	248.2 MW	88	GE 2.82 MW	127 m
Armadillo Flats	241.8 MW	126	80 x GE 1.7 MW 46 x GE 2.3 MW	103 m 116 m

An open-source wind turbine model for all three types of turbines listed in Table 1 is provided by NREL [9]. The turbine model contains a wide range of information, from thrust and power coefficient curves (shown in Figure 2) to aerodynamic information about the turbine blades.

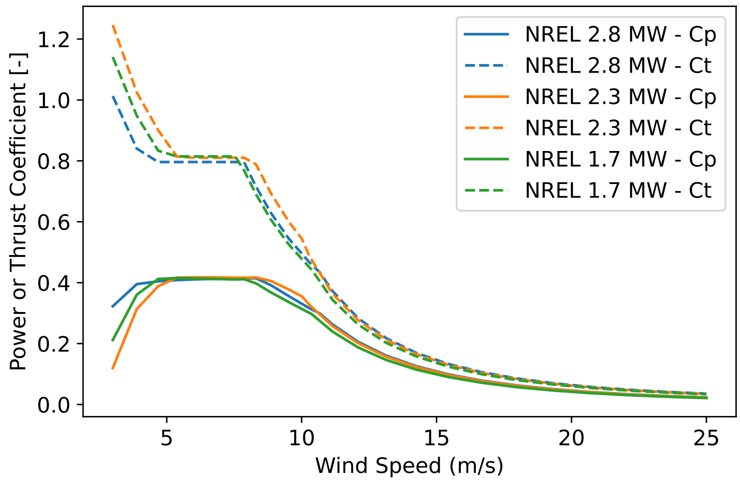

Figure 2. Curves of the thrust and power coefficients from NREL's open-source model for the wind turbines in the King Plains and Armadillo Flats wind plants.

3. Selected benchmark case

The target case for the first AWAKEN benchmark focuses on the wakes from the King Plains and Armadillo Flats wind plants (Figure 1), around which the majority of the AWAKEN instruments were deployed. Therefore, the selected case focuses on wind coming from the south and southwest, which represent the dominant wind directions according to previous studies [7]; in this way, both the wakes within King Plains (intra-farm effects), and the impact of the wakes from Armadillo Flats on the King Plains wind farm (inter-farm effects) will be quantified. Given the long duration of the AWAKEN field campaign and the large amount of observations available, we adopt an automated search algorithm to select the benchmark reference case. In particular, we focus on hours where the following conditions are met:

- Percentage of turbines in the King Plains wind plant operating normally greater than 80%.
- Percentage of turbines in the Armadillo Flats wind plant operating normally greater than 80%.
- Availability of nacelle-mounted lidar data from the northernmost instrumented turbine (E06).
- Availability of ground-based lidar data at sites A1 and H.
- 90-m wind direction (as observed at Site A1) between 135° and 225°.

About 700 hours of recorded conditions meet all the requirements above. However, only a handful of cases feature these conditions throughout a day, which is a crucial feature to fully capture a diurnal cycle in the proposed benchmark. Based on these considerations, we select 24 August 2023 as the case to consider in the benchmark since, in addition to the criteria listed above, it displays further canonical conditions, such as thermodynamic profiles, absence of drops in turbine availability throughout the day, and availability of measurements collected downwind of the King Plains wind plant by a truck-mounted lidar, as detailed in the next section.

4. Observed conditions during the selected benchmark

4.1. Upwind conditions

As previously described, the scope of the benchmark is to validate outcomes from numerical simulation tools against observations collected by AWAKEN instruments during the selected

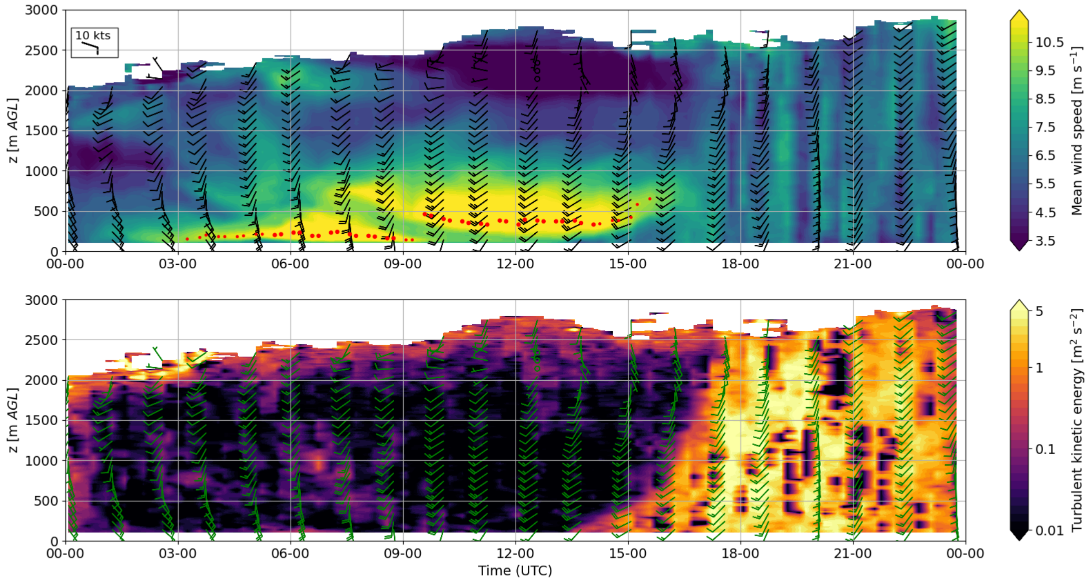

Figure 3. Time-height cross sections of wind speed (top) and turbulence kinetic energy (bottom) as measured by a scanning lidar used in vertical profiling mode at AWAKEN Site A1 on 24 August 2023. Lidar data have been filtered according to the dynamic filtering approach presented in [11]. Barbs indicate wind direction; red dots indicate the nose of the low-level jet (LLJ), and the size of the dots increases with the class of the LLJ; vertical dashed lines show sunset (left) and sunrise (right).

period. To do so, a certain number of observed quantities of interest (extracted from experimental data) must be provided to the participants, both to initiate the numerical simulations and to assess the results.

In the initial phases of the benchmark, participants will be provided with input observations, which they will attempt to match as closely as possible in simulation tools. These reference data include vertical profiles of wind speed, wind direction, and turbulence kinetic energy (TKE) measured by lidars upwind of the AWAKEN wind plants (Figure 3). During 24 August 2023 (UTC day), southeast wind is present during the earliest part of the day (00:00 AM to 07:00 AM, cf. with Figure 3 top), followed by wind from the south-southwest for the rest of the day within the height interval relevant for wind energy ($\leq 2,000$ m). Furthermore, a distinct low-level jet (LLJ) occurs at night, featuring wind exceeding 10 m/s within the lowest 500 m above ground. The daily variability of lidar-derived TKE exemplifies a canonical cycle (Figure 3 bottom), with quiescent conditions at night and stronger turbulence during the local daytime [10].

Thermodynamic conditions affect wake propagation. At AWAKEN, five thermodynamic profilers, namely three Atmospheric Sounder Spectrometers for Infrared Spectral Technology (ASSIST-II) and two Atmospheric Emitted Radiance Interferometers (AERI), were deployed at five different sites upstream, within and downstream of the Armadillo Flats and King Plains wind plants, so that the impacts of wind plants on local thermodynamic processes could be observed. We will provide participants with time-resolved vertical profiles of temperature and humidity (obtained via the TROPoe algorithm [12]), which, for 24 August 2023, show a classic stability-driven diurnal variability (Figure 4), with warmer temperatures during the day and colder conditions at night, in addition to a peak in humidity in the morning. The presence of canonical diurnal variability for the selected thermodynamic quantities further affirms the current dataset as a reliable reference for the benchmark.

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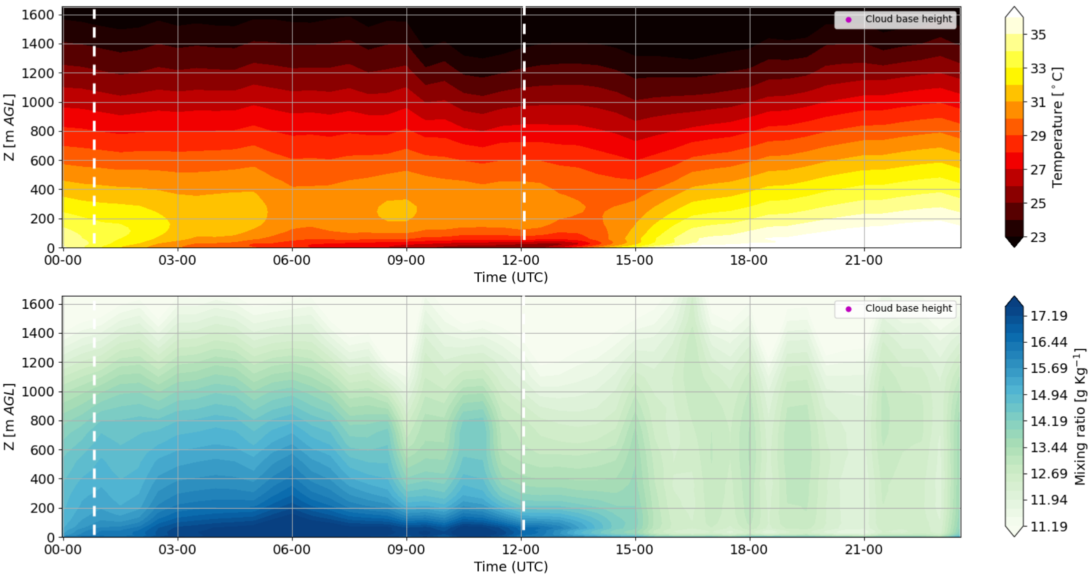

Figure 4. Time-height cross sections of temperature (top) and mixing ratio (bottom) as measured by an ASSIST-II thermodynamic profiler at AWAKEN Site B on 24 August 2023. Vertical dashed lines show sunset (left) and sunrise (right).

In addition to remote-sensed data throughout the atmospheric boundary layer, near-ground measurements from surface flux stations will be provided as well to inform participants about the conditions upstream of the wind farms, namely wind speed, wind direction, Obukhov length, sensible heat flux, temperature, and friction velocity. Finally, all the remote sensing data will be used to retrieve the atmospheric boundary layer height upwind of the wind plants.

4.2. Turbine operation
Benchmark participants will have access to subsets of King Plains and Armadillo Flats supervisory control and data acquisition (SCADA) data for the selected case. The majority of turbines from both wind plants were operating normally throughout 24 August 2023, where normal operation is defined by limiting allowable deviation from the nominal power curve. No significant drops in turbine availability occur during the selected day (Figure 5), outside of some limited high-frequency variability. Also, most turbines were operating in Region 2 of their power curve, when thrust coefficient is high and wakes are the strongest.

4.3. Waked conditions
During the second phase of the benchmark, experimental data for model validation will be provided. In particular, we will quantify the observed wind plant wake effects through profiling and scanning lidars (deployed on the ground, on turbine nacelles, and on a mobile truck) in addition to the above-mentioned thermodynamic and surface flux data. Focusing on the King Plains wind plant during southerly wind conditions, the overall wind farm wake can be hinted from the difference between the wind speed observed by scanning lidars used in vertical profiling mode at the downwind Site H (roughly located 22 rotor diameters, D, north of King Plains' northernmost turbines) and the upwind Site A1 (roughly $2D$ south of King Plains' southernmost turbines). A wake-induced wind speed deficit is expected when the wind is blowing from the south or southwest, so that Site H is downwind of King Plains' turbines. On 24 August 2023, a deficit in wind speed (larger than 3 m/s, Figure 6, top) occurs at Site H for heights corresponding

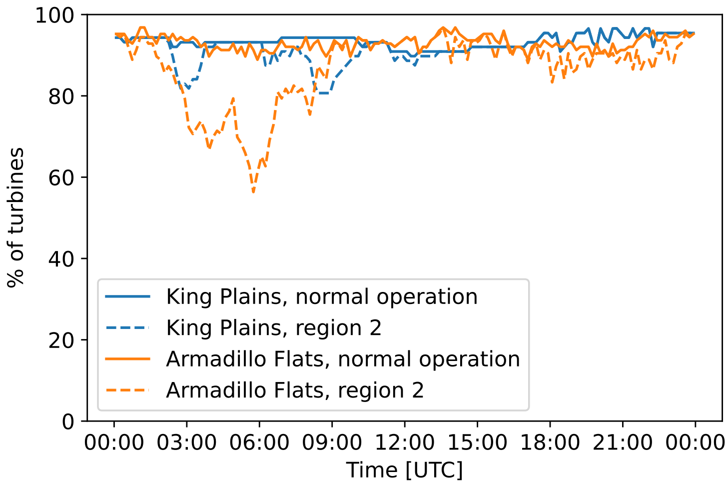

Figure 5. Time series showing the percentage of turbines operating normally and in Region 2 on 24 August 2023, for the King Plains and Armadillo Flats wind plants.

to the upper half of the turbine-swept area and right above it. Wake impacts at Site H are not detected between 00 and 03 UTC, when the wind is from the southeast and King Plains' wakes are deflected away from Site H. By contrast, global wake effects are evident during nighttime stable conditions (03–12 UTC) when the wind comes from the southwest and the low turbulent mixing delays the wake recovery, which in turn allows for a clearer wake detection at Site H located far downwind of the wind plant ($22D$). During daytime (12–24 UTC) convective (unstable) conditions, the difference in wind speed between the two sites is less clear, suggesting that turbulence may erode King Plains' wake before it reaches Site H. Notably, the wake-induced velocity deficit detected at Site H on 24 August 2023 is stronger than the median value (Figure 6, bottom) evaluated over the whole year 2023, when wind speed at A1 is larger than 3 m/s (i.e., a proxy for cut-in wind speed) and wind direction at A1 is between 167° and 210° (so that site H is waked).

It is important to note that it cannot be concluded that all the observed differences are necessarily caused by the wind turbines in the area. In fact, topographic effect and other localized flow features may also impact the variability in wind speed across the AWAKEN domain. For example, the flow acceleration that occurs at night above $\sim$ 200 m in Figure 6 cannot be immediately linked to canonical turbine effects. To explore such effects in more detail, in-house testing simulations (both at the mesoscale and coupled between meso- and microscale) are being conducted prior to the release of the benchmark to shed light into the wind flow variability beyond the specific locations where AWAKEN observations are available. Such considerations need to be taken into account when evaluating the uncertainty associated with the benchmark results.

One of the six nacelle-mounted lidars at AWAKEN was deployed on King Plains' northernmost row of turbines and performed, among other scans, volumetric scans to capture the spatiotemporal variability of wind plant wakes north of King Plains [13]. These wide scans were performed for 20 minutes every 2 hours within 120° to 240° azimuth and −10° to 10° elevation ranges to provide a three-dimensional characterization of how single turbine wakes merge into a wind plant wake. These scans will therefore be one of the primary sources of observations used to validate the simulation tools in the benchmark. The mean streamwise velocity and turbulence intensity (reconstructed through the method described in [14]) are reported in Figure 7 for the selected day. From these observations, wakes appear clearly at hub height during periods where the atmosphere is stably stratified, both in terms of reduced wind speed and increased turbulence.

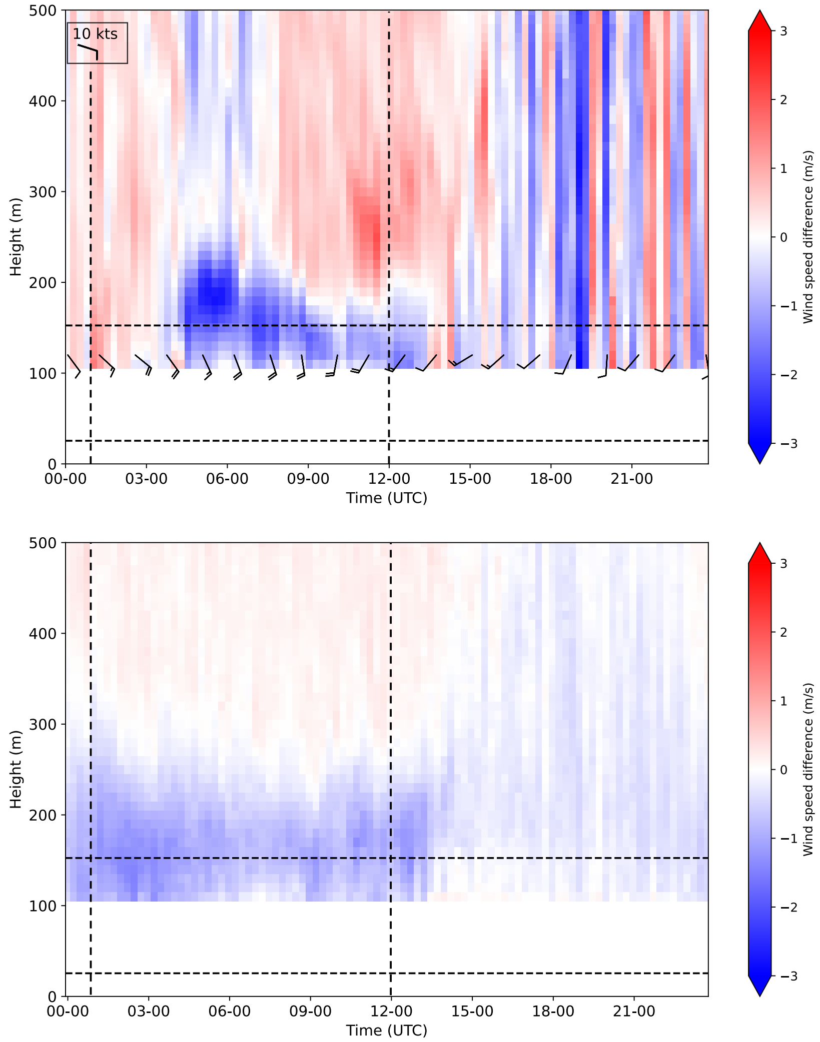

Figure 6. Time-height cross section showing the difference in wind speed between observations from Site H and Site A1's scanning lidars used in vertically profiling mode, for (top) 24 August 2023, and (bottom) as median value in 2023 for selected conditions as detailed in the main text. The top panel also shows the 120-m wind direction measured by the A1 scanning lidar. Vertical dashed lines show sunset (left) and sunrise (right). Horizontal dashed lines show the vertical limits of the turbine rotors.

Finally, during August and September 2023, a truck-mounted motion-compensated micropulsed lidar called PUMAS (PickUp-based Mobile Atmospheric Sounder), owned by the National Oceanic and Atmospheric Administration, was operated within and around King Plains to provide additional measurements of wind plant wakes validation data for this benchmark. The truck-mounted lidar collected measurements across two main north-south transects within and north of King Plains and one east of the wind plant. These measurements will conceptually expand the observations from other lidars further north and capture additional evolution of the wind plant wake.

5. Recommended reanalysis product for the benchmark

Some of the models participating in the benchmark will require continuous space and time boundary condition data to force the simulation.

First, we perform a preliminary evaluation of the skills of two of the most widely used reanalysis products in the wind energy community: MERRA-2 [15] and ERA-5 [16]. We run this preliminary assessment from 1 November 2022 to 31 October 2023 and specifically for 24 August 2023. We consider 50-m wind speed from MERRA-2 and 100-m wind speed from ERA-5 and compare them with the concurrent observations from profiling lidars at AWAKEN sites A2, B, and C1a (we filter for data with signal-to-noise ratio ≥ 23 dB). We derive 50-m wind

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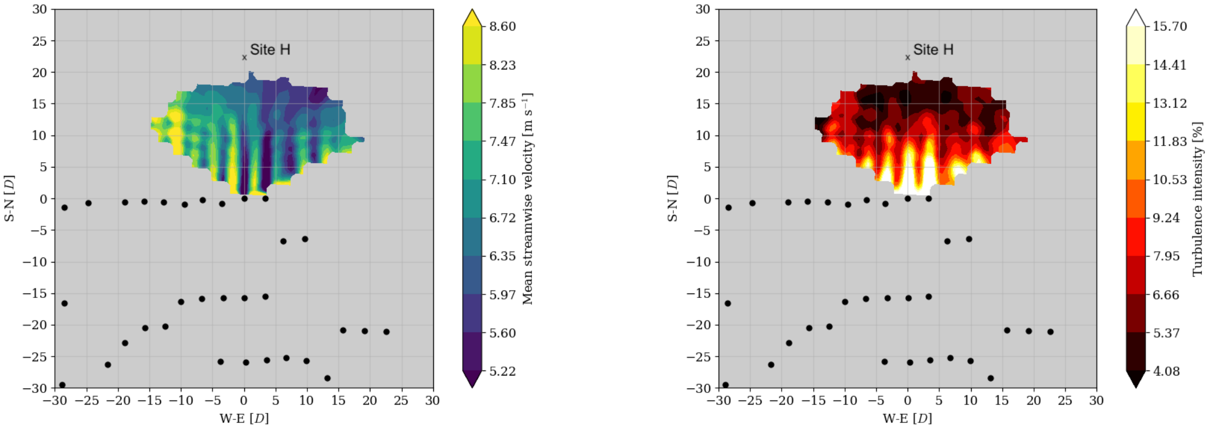

Figure 7. (Left) Mean streamwise velocity and (right) turbulence intensity at hub height as observed by a nacelle-mounted scanning lidar from 9:40 to 10:00 UTC on 24 August 2023. Streamwise velocity is derived from the lidar-measured line-of-sight velocity by projecting it based on the wind direction measured by the scanning lidar at A1 and the yaw of the turbine where the nacelle-mounted lidar is installed.

speed data by linearly interpolating observations between 40 m and 60 m above the ground, and consider, for each lidar, reanalysis data from the closest numerical grid cell. Note that ERA-5 provides data on a 0.25° × 0.25° (longitude × latitude) grid (roughly 22 × 28 km in this region), whereas MERRA-2 has a resolution of 0.625° × 0.5° (roughly 56 × 56 km in this region). We find that MERRA-2 better captures winds across the AWAKEN domain compared to ERA-5 (Table 2): while the two reanalysis products have a comparable centered root-mean-square error (cRMSE), ERA-5 has a significant negative bias across all considered sites. Similar considerations apply when focusing on the day selected for the wind plant wake benchmark.

However, while promising, it is important to keep in mind that a better agreement between the forcing data set and the available observations does not necessarily lead to better agreement in the downscaled simulations. Therefore, additional testing is underway to confirm the results prior to the official release of the benchmark.

Table 2. Wind speed bias and cRMSE for MERRA-2 (50 m above ground level) and ERA-5 (100 m above ground level) at sites A2, B, and C1a, from 1 November 2022 to 31 October 2023.

	MERRA-2		ERA-5	
	Bias [m/s]	cRMSE [m/s]	Bias [m/s]	cRMSE [m/s]
Site A2	0.25	1.75	-1.18	1.63
Site B	0.17	1.77	-1.18	1.64
Site C1a	0.55	1.73	-0.76	1.62

6. Summary and Next Steps

We have presented the details of the AWAKEN wind plant wake international benchmark, which will serve as the first benchmark for the new IEA Wind Task 57 on Joint Assessment of Wind Energy Models. Building upon the expertise provided by the Task 31 benchmarks [5, 6], the AWAKEN wind plant wake benchmark will include three phases:

(i) Code calibration: The team will release inflow observations at AWAKEN for 24 August 2023, NREL's open-source wind turbine model, and other modeling recommendations (e.g., recommended reanalysis product, recommended product for terrain representation) to the benchmark participants, who will calibrate their simulation tools to be within an acceptable range of the observed inflow values.

(ii) Blind comparison: The benchmark participants will model the wakes from the King Plains and Armadillo Flats wind plants, and the benchmark team will compare their simulated results with the observed values.

(iii) Iteration: After seeing the results of the blind comparison, participants will have an opportunity to improve the accuracy of their simulated wakes.

The AWAKEN wind plant wake benchmark has been released at `awaken-benchmark.readthedocs.io` in conjunction with the TORQUE 2024 conference. Participants have 3 months to submit their first round of simulations for the code calibration, and the expected conclusion of this benchmark will be in summer 2025. A journal publication will summarize results of this exercise. Within the context of IEA Wind Task 57, we expect to release new benchmarks, some of which will also come from AWAKEN, roughly every 6 months, to ultimately improve our ability to accurately simulate and account for a variety of wind turbine and wind plant processes. A follow-up wind plant wake benchmark, focused on leveraging observations collected by dual-Doppler X-band radars at AWAKEN (whose performance around the King Plains wind plant is generally limited for southerly wind directions), is also being considered.

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