OWA Report 2019

OWA Wake Modelling Challenge

Scope for Participants in the Benchmarking Process

Offshore Wind Accelerator – Wake Effects and Wind Resource

Wake Model Benchmarking

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Contractor: **Email:**	Javier Sanz Rodrigo, CENER jsrodrigo@cener.com
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Summary

The “OWA Wake modelling Challenge” is an Offshore Wind Accelerator (OWA) project that aims to improve confidence in wake models in the prediction of array efficiency. Model developers and end-users will be invited to participate in a benchmarking programme along a suite of validation datasets that spans a wide range of operational conditions in terms of wind farm topology and wind climate characteristics.

The validation strategy focuses on large offshore wind farms and turbines and addresses limitations of engineering wake models, traditionally developed under the assumption of surface-layer inflow conditions (horizontally homogeneous, steady-state). In effect, large wind farms are subject to heterogeneous inflow conditions due to coastal gradients, wakes from neighbouring wind farm clusters and large-scale mesoscale phenomena. The interaction of the atmospheric boundary-layer (ABL) with the wind farm canopy includes different processes from the upstream blockage of the flow to the generation of an internal boundary-layer that, in very large arrays, results in a fully developed wind farm boundary layer where turbulent mixing between wake effects and the outer ABL is in equilibrium and array efficiency becomes constant (deep-array effect). Under stable conditions the ABL height is compressed to a few hundred meters and a low-level jet forms. In the presence of large wind farms, this low-turbulence regime generates long-lasting wakes and introduces significant blockage in the incoming flow which results in important array efficiency reductions compared to neutral or unstable conditions. Within the wind farm, local acceleration effects near corners or within gaps are opportunities for wind farm design optimization. Altogether, the complex system is the result of a multi-scale process that requires a systematic assessment to understand the relative importance of each phenomenon in the prediction of array efficiency for energy yield assessment and wind farm design.

OWA partners will provide operational data from European wind farms which will cover a wide validation range in terms of wind farm topologies and wind climates. A staged benchmarking process will be open for model developers and end-users to participate anonymously.

Initially, blind testing will be the default benchmarking setting around validation flow cases targeting specific bin-averaged wind conditions. In particular, the analysis will focus on two priority areas: the influence of heterogeneous inflow conditions and the influence of stable conditions. Then, an integrated assessment of array efficiency will be conducted for all the sites to quantify the impact of the limitations observed in the models during the blind tests. At the end, some validation datasets will be available (subject to data licensing agreements) for participants to justify how to best use available data to calibrate models and reduce uncertainties.

For each site, corresponding mesoscale simulations, based on the New European Wind Atlas (NEWA) WRF set-up, will be produced to characterize large-scale variability of wind conditions and provide input data for benchmark participants.

The validation programme will be conducted throughout 2019 in the context of the IEA Wind Task 31 Wakebench Phase 3, which is developing an international evaluation framework for multi-scale wind farm modelling. The methodology will be fine-tuned along the process and eventually become part of the Wakebench Wind Energy Model Evaluation Protocol (WEMEP), with the general objective of systematically improving consistency and traceability in the assessment of state-of-the-art wake models for power prediction as more datasets are added in the future.

1. Introduction

The growing size of wind turbines and wind farms in the offshore environment, eventually occupying tens of kilometres and extending beyond 200 m in height, has challenged traditional wind farm models to consider incorporating larger atmospheric scales with greater influence from the full extent of the atmospheric boundary layer (ABL), which is subject to variability from *mesoscale* weather phenomena like land-sea transitions, low-level jets, gravity waves, etc. Furthermore, the growing interest in wind farm control technology is also demanding more realistic characterisation of plant-level aerodynamics encompassing local effects such as blockage (upstream flow deceleration), wake management by wind farm control strategies (de-rating, yaw misalignment, etc.), to deep-array effects in large wind farms reaching fully-developed canopy flow in equilibrium with the atmospheric boundary layer. Only recently has it become possible to bridge silos in flow modelling with advances in high performance computing and large-eddy simulation (LES) models [1]. These high-fidelity atmospheric models coupled to aero-elastic codes can be used to characterize complex flows, test virtual prototypes or to support the design of experiments [2]. Nevertheless, even though these models produce more realistic simulations, they also require more extensive experiments and validation to make sure they are effective references in the design of reduced-order engineering models.

This is especially important for offshore wind developers that face significant financial costs due to uncertainties in wind resource assessment [3]. Understanding how these uncertainties originate from wind farm design tools is a fundamental challenge to mitigate these losses.

It is not well established how high-fidelity models can be used to build more robust, cost-effective and physically insightful engineering models that can systematically decrease the uncertainty in the assessment of energy yield and design conditions. A formal process for model-chain verification and validation (V&V) and uncertainty quantification between high-fidelity models, engineering models and observational data is lacking, partly due to the inherent complexity of the full system, requiring large investments in field and laboratory experiments [4][5]. Due to the wide range of operational conditions in which wind turbines operate it is necessary to combine research experiments, targeting the validation of specific physical phenomena, with operational data from a wide range of conditions to assess the significance of the validation process and improve the predictive capacity of the models through statistical inference methods [6].

*Then, the **challenge** is to establish this ambidextrous validation strategy, that identifies relationships between high-fidelity and engineering models, based on a suite of validation datasets on flow cases targeting relevant physical phenomena in the multi-scale wake process, as well as quantifying the impact that these phenomena have in improving the overall accuracy on array efficiency prediction for a relevant range of wind farm configurations and operational conditions. By mapping performance metrics against operational conditions it is possible to identify knowledge gaps that should be prioritized in next experiments and validation efforts, leading to improving the credibility and predictive capacity of wind farm design tools.*

A complementary challenge was formulated in the definition of a validation strategy within the New European Wind Atlas (NEWA) project, for the development of methodologies that incorporate mesoscale-to-microscale flow modelling for the assessment of design wind conditions and gross annual energy prediction, i.e. free of wake effects. The *NEWA Meso-Micro Challenge* [7] was launched in 2017 to exploit a database of field experiments carried out in the project covering a wide range of site characteristics and European wind climates [8].

The “OWA Wake Modelling Challenge” will complement the third phase of the IEA Task 31 WAKEBENCH that extends until June 2021 to establish an *International Wind Farm Flow Modelling and Evaluation Framework*. The framework will be documented in the *Wind Energy Model Evaluation Protocol* (WEMEP) [5], which describes how to conduct a formal V&V process, and guides the execution of model intercomparison benchmarks targeting specific objectives for model development. These benchmarks constitute the main collaborative activity of the Task towards the generation of peer-reviewed validation repositories that can be considered by the corresponding community as *golden benchmarks* for the assessment of state-of-the-art models in connection to design tools and industry standards such as IEC-61400-15 (site suitability and energy yield assessment) or IEC-61400-12-4 (numerical site calibration).

2. Scope and Objectives

The primary objective of the project is to understand the limitations of wake models used by industry for the prediction of array efficiency over a relevant range of operational conditions in the offshore environment. It is expected that the project will secure access to datasets that span a wide range of operational conditions in terms of wind conditions and wind farm topology.

While the main focus is on engineering wake models used by industry in wind farm design and optimisation, higher-fidelity models (RANS and LES-based) are also necessary to understand knowledge gaps and provide insights on the potential of incorporating these models in multi-fidelity methodologies.

The expected outcome of the benchmarking programme rolled out over the next year will be an independent assessment of wake models for power prediction. To this end the following individual objectives will be pursued:

- Evaluate wake modelling and power prediction methods and validate the results with measured data.
- Examine the accuracy of specific models, quantify uncertainty bands and highlight modelling trends.
- Define an open-access model evaluation methodology that can systematically improve consistency and traceability in the assessment of state-of-the-art wake models for power prediction as more datasets are added.

An important ambition of the project is the development of a transparent evaluation method that can be improved and scaled to additional datasets in the future as part of Task 31 activities or other projects.

3. Array Efficiency Modelling Framework

From the flow modelling point of view, the offshore environment offers the advantage of simplified site characteristics compared to onshore conditions, which is advantageous to gain insights about the interplay between wake effects and the background atmospheric boundary layer (ABL), free of microscale onshore site effects like terrain and vegetation changes.

The modelling challenge for offshore array efficiency prediction is illustrated in the mind map of Annex 1, where it is highlighted the most relevant physical processes (in yellow), the inputs quantities (in blue) and the modelling building blocks (in grey). A review on the interaction between wind farms and the atmosphere can be found in [1] or [9].

The model-chain is divided into three elements corresponding to the characterization of atmospheric inflow conditions, the wind farm system and the statistical process that integrates individual simulations to describe array efficiency prediction as a function of wind climate characteristics, typically defined in terms of wind direction, wind speed and stability bins.

The binning methodology is constrained by the number of simulations that can be reasonably done in the wind farm design and optimisation process. To this end, systematic or stratified sampling methods will be used to derive the mean annual array efficiency based on a limited set of simulations. Systematic sampling will span wind conditions evenly based on predefined classes while stratified sampling will consider the non-uniform distribution of the wind climate to minimise the mean array efficiency sampling error. Uncertainty analysis propagates input and parameter uncertainties in the model to assess the spread of the prediction. Wake loss uncertainty is a major contributor to the overall uncertainty of the annual energy prediction (AEP) [10][11]. Previous activities in the frame of the OWA have determined that the uncertainty of engineering wake models is of the order of 25% of the wake loss. This uncertainty can be further reduced when several models are combined to form a multi-model ensemble [12].

Inflow conditions have been traditionally defined in engineering wake models as idealised horizontally homogeneous conditions, described in terms of best-fit logarithmic profiles to mast or lidar observations, following Monin-Obukhov similarity theory (MOST). Beyond the surface layer, MOST is not valid and it is necessary to adopt ABL approaches that include the effect of Coriolis [13] and the stratification of turbulence from the surface to the free-atmosphere, which depends on local atmospheric stability [14]. The effect of atmospheric stability in wind farm performance has received significant attention over the last decade and it is widely accepted now as a third dimension in describing wind conditions besides wind speed and direction (e.g. [15],[16] and [17]).

Uniform forcing of the flow is assumed by adjusting the inflow to match wind speed and direction at a reference height (typically hub-height). This corresponds to a uniform geostrophic wind (horizontal pressure gradient) in ABL models. A capping inversion layer in the potential temperature limits the growth of the boundary-layer setting the transition to the free-atmosphere [18].

Departure from the log-law is particularly evident in stable conditions where the boundary-layer is compressed to a few hundred meters and a low-level jet forms. In the presence of large wind farms, this regime introduces significant blockage in the incoming flow and, eventually, the displacement of the boundary-layer and the excitation of gravity waves [19].

The interaction of the ABL with the wind farm canopy includes different processes from the upstream blockage of the flow [20] to the generation of an internal boundary-layer that, in very large arrays, results in a fully developed wind farm boundary layer [21] where turbulent mixing between wake effects and the outer ABL is in equilibrium and array efficiency becomes constant (deep-array effect [22]). The wind farm topology and control strategies will introduce local effects within the canopy flow that can be used to optimise the wind farm design. These local effects include flow acceleration towards corner turbines, wake recovery through internal gaps ("missing turbines") or control strategies like de-rating turbines or yaw-misalignment to steer wakes away from downstream turbines [23]. These control strategies are particularly effective within the initial rows of the wind farm, where turbines can benefit from more frequent undisturbed inflow conditions that they can more easily manage. Then, induction and near-wake effects at the rotor subsystem level become relevant at describing the processes of wake generation, expansion and interaction with downstream turbines. Rotor modelling for array efficiency prediction has been traditionally based on the actuator disk approach showing good performance in the far-wake but failing to predict accurately the near-wake conditions. The actuator line approach, popular among LES models, provides a more realistic description of the rotor aerodynamics but also demanding more computational effort and more detailed rotor input data. A review of rotor models can be found in [24].

The definition of a reference hub-height wind speed that determines the operational characteristics of the turbine is not evident under disturbed wake conditions. Furthermore, the "free-stream" conditions, assumed homogeneous in most engineering models, can present spatial variability across large wind farms due to the presence of the coast, other wind farms or due to mesoscale weather effects. These heterogeneous inflow conditions can be characterized using mesoscale modelling to complement site measurements with a more realistic description of the variability of the large-scale forcing of the flow [14]. The integration of mesoscale effects in engineering wake models constitutes a major challenge in the development of multi-scale wind farm flow modelling.

4. Validation Priorities and Approach

The project will focus on large offshore wind farms and large wind turbines up to and including 6MW. The relative importance of physical phenomena depends on the particular characteristics of each wind farm but, in general, all of them occur in every large offshore wind farm. The assessment process will map model performance against predictor quantities that describe the wind conditions and wind farm topology.

The ultimate goal is to test the predictive capacity of wake models for a number of wind farms and determine how performance correlates with different flow drivers. To this end, OWA partners will provide operational data from multiple wind farms to cover a wide range of operational conditions.

A staged benchmarking process will be open for model developers and end-users to participate anonymously. Initially, blind testing will be the default benchmarking setting around validation flow cases targeting specific bin-averaged wind conditions. Flow cases will be based on ensemble-averaged data from 30º wind direction sector. Using wide sectors helps filtering out meandering effects which are not simulated by steady-state wake models. It also leads to better statistical significance due to the larger sample size.

In particular, the analysis will focus on two priority areas:

- **Stability effects**, in particular, the simulation of low-turbulence stable conditions compared to well-mixed neutral or unstable conditions. Horizontally homogeneous inflow conditions will be selected to analyze the interaction of ABL and array effects in "idealized" inflow conditions. In these conditions it is easier to interpret microscale effects due to the interplay between wind farm layout characteristics (array spacing, wind farm size, etc.) and turbulence.
- **Heterogeneous inflow**, due to the presence of the coast or neighboring wind farm clusters. Once baseline microscale effects have been characterized, we can add heterogeneity to the inflow conditions, by means of mesoscale simulations, to understand the impact on array efficiency on the spatial variability of wind conditions. Neutral conditions will be selected initially to avoid coupling with stability effects and facilitate the interpretation of the results. The results will be compared to simulations where homogeneous inflow is assumed to understand the value of the added modelling complexity.

For each site, mesoscale simulations, based on the New European Wind Atlas (NEWA) WRF set-up, will be produced to characterize large-scale variability of wind conditions and provide input data for benchmark participants. These data will complement site measurements as a consistent database across all the sites for the assessment of surface-layer stability and large-scale gradients. The quality of these data will be evaluated in those sites where pre-construction meteorological measurements are available.

Then, an integrated assessment of array efficiency will be conducted for all the sites to quantify the impact of the limitations observed in the models during the blind tests. The validation will focus on array efficiency η and its associated uncertainty $\sigma(\eta)$, post-processed from SCADA data in terms of bin averages and standard deviation for the wind farm and for the individual turbines. A bin will be defined in terms of wind speed, direction and atmospheric stability at a reference site.

At the end of the benchmarking process, a select number of validation datasets will be available (subject to data licensing agreements) for participants to justify how to best use available data to calibrate models and reduce uncertainties.

While formal validation should always be blind, to quantify performance against independent observational data, this final step acknowledges calibration as an important element in model development practices to mitigate the limitations of engineering models by making use of available data from experiments or operational wind farms. All engineering models include calibration but it is difficult to track how this has been done and this leads to different flavours of, for instance, the Jensen model.

5. The Benchmarking Process

This document acts as the beginning of the benchmarking process to gather expressions of interest from potential participants. Participants should commit to contributing to the whole validation process in order to produce a consistent assessment among all the models. An introductory webinar will be organized to solve questions, receive feedback about other interests from the modelling community and start the registration of participants.

The first benchmark round will be a pilot to develop the evaluation methodology with feedback from the participants. An evaluation script will be provided, using Jupyter notebooks, so each participant can test the methodology with own data and determine which results to submit. The GABLS3 diurnal-cycle benchmark provides an example of an evaluation script, in this case, for ABL models [25][26].

Each participant will be assigned a participant ID number so they can remain anonymous if required and always be able to identify their individual results throughout the process. Every two months there will be a checkpoint to evaluate ongoing results and launch additional benchmarks.

A sponsorship budget of £10.000 is available to support additional simulations from the best contributors. These simulations will contribute to obtaining additional insights that help interpret the results, calibrate models or quantify uncertainties.

Access to calibration data or sponsorship funds will depend on the following criteria:

- Completeness in the submission of simulations (50%).
- Clear documentation about the modelling approach (30%).
- Modelling performance (20%).

A questionnaire will be prepared to gather feedback from the participants in every benchmark. A data template will be also provided to help participants submit their simulation results in the right format for post-processing. All these data will be shared with the benchmark manager in a private folder.

At each stage of the project the OWA reserves the right to remove participants from the process and exclude participants form receiving data to participate in the final calibration phase. This phase will be focusing on models that have demonstrated good performance and consistency in the blind test.

6. Schedule

The following tentative schedule shall be considered by benchmark participants:

- 7 March 2019: Pre-launch webinar. Engagement with participants and launch of 1st benchmark.
- 11-14 March: Discussion at Task 31 annual meeting, hosted by NREL, Boulder, CO.
- 30 April: Submission of round 1 results and launch of round 2.
- June: Submission of round 2 and launch of round 3.
- 27-28 June: Presentation of initial results and publication of first version of model evaluation methodology at the WindEurope Wind Resource Workshop.
- September: Submission of round 3 and launch of round 4 (calibration/sponsorship).
- December: Final workshop together with OWA partners.
- 2020: Presentation of final results in scientific publication/conference.

7. Expected Outcome

Participants to the benchmarking process will obtain an independent evaluation of their models against observations and how they compare with other state-of-the-art models. This code-to-code comparison is very valuable to understand user-dependency in the interpretation of wind conditions and model settings. This is particularly interesting when end-users can verify consistency of their results with those from the model developer.

By the end of the project the evaluation methodology will have been curated and will be ready to be published in a journal or scientific conference. This final peer-review step will qualify the methodology to become part of the Wakebench “Wind Energy Model Evaluation Protocol” (WEMEP). The methodology will be best used in connection to open-access validation repositories that model developers and end-users can use to reproduce validation results. Intrinsic to the benchmarking process will be the demonstration that producing validation datasets based on industry data can be a recurrent activity and the curation and opening of validation repositories the desired outcome of the benchmarking process.

The traceability of data and evaluation methods makes them golden benchmarks as they will be mutually considered by the wind energy community as mutual reference to demonstrate model performance. It is through this recognition that the model evaluation methodology and benchmark repositories can be effectively used in connection to industry standards (like IEC 61400-15).

8. References

[1] Sanz Rodrigo J, Chávez Arroyo R-A, Moriarty P, Churchfield M, Kosović B, Réthoré P-E, Hansen KS, Hahmann A, Mirocha JD, Rife D (2016) Mesoscale to microscale wind farm flow modelling and evaluation. *WIREs Energy Environ*., doi:10.1002/wene.214

[2] Churchfield M, Wang Q, Scholbrock A, Herges T, Mikkelsen T, Sjöholm M (2016) Using High-Fidelity Computational Fluid Dynamics to Help Design a Wind Turbine Wake Measurement Experiment J. Phys.: Conf. Ser. 753 032009, doi:10.1088/1742-6596/753/3/032009

[3] Bailey B.H., Kunkel J. The Financial Implications of Resource Assessment Uncertainty. North American Wind Power 2015, NAW1504, published online

[4] Hills RG, Maniaci DC, Naughton JW (20015) V&V Framework. SANDIA Report SAND2015-7455, September 2015

[5] Sanz Rodrigo J, Moriarty P. (2015) WAKEBENCH Model Evaluation Protocol for Wind Farm Flow Models. Edition 1. IEA Task 31 Report to the IEA-Wind Executive Committee. May 2015

[6] Sanz Rodrigo J (2017) Science-Push and Market Pull: An Ambidextrous Validation Framework. The Wind Vane Blog, May 2017, https://thewindvaneblog.com/science-push-vs-market-pull-in-a-v-v-strategy-for-wind-assessment-b04bc615f16b, accessed January 2019

[7] Sanz Rodrigo J (2017) NEWA Meso-Micro Challenge for Wind Resource Assessment. http://windbench.net/newa-meso-micro-challenge-wind-resource-assessment, accessed January 2019

[8] Sanz Rodrigo J, Mann J, Gottschall J (2017) Open Science in the New European Wind Atlas, Wind Europe Annual Conference, Amsterdam, November 2017, Zenodo, doi: 10.5281/zenodo.1194752

[9] Stevens RJAM and Meneveau C (2017) Flow structure and turbulence in wind farms. Annu Rev Fluid Mech 49(1):311–339, https://doi.org/10.1146/annurev-fluid-010816-060206

[10] Clifton A, Smith A and Fields M (2016) Wind Plant Preconstruction Energy Estimates: Current Practice and Opportunities. Technical Report NREL/TP-5000-64735, April 2016

[11] Murcia Leon JP (2017) Uncertainty quantification in wind farm flow models. PhD Thesis, DTU Wind Energy

[12] Chisholm I and Adams I (2015) OWA Benchmarking Year 5, Final Report. FNC 46598/43161R issue 2, December 2015, confidential

[13] van der Laan MP, Hansen KS, Sørensen NN and Réthoré PE (2015) Predicting wind farm wake interaction with RANS: an investigation of the Coriolis force. J. Phys. Conf. Ser. 625:012026, https://doi.org/10.1088/1742-6596/625/1/012026

[14] Sanz Rodrigo J, Churchfield M and Kosovic B (2017) A methodology for the design and testing of atmospheric boundary layer models for wind energy applications. Wind Energ. Sci., 2: 35-54, https://doi.org/10.5194/wes-2-35-2017

[15] Hansen K S, Barthelmie R J, Jensen L E and Sommer A (2012) The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at Horns Rev wind farm. Wind Energy 15 183–96, https://doi.org/10.1002/we.512

[16] Abkar M and Porté-Agel F (2015) Influence of atmospheric stability on wind-turbine wakes: a large-eddy simulation study. Phys. Fluids 27:035104, https://doi.org/10.1063/1.4913695

[17] Witha B, Steinfeld G, Dörenkämper M, Heinemann D (2014) Large-eddy simulation of multiple wakes in offshore wind farms. J Phys Conf Ser 555(1):012108, https://doi.org/10.1088/1742-6596/555/1/012108

[18] Abkar M and Porté-Agel F (2013) The effect of free-atmosphere stratification on boundary-layer flow and power output from very large wind farms. Energies 6:2338–2361, https://doi.org/10.3390/en6052338

[19] Allaerts D and Meyers J (2018) Gravity Waves and Wind-Farm Efficiency in Neutral and Stable Conditions. Boundary-Layer Meteorol (2018) 166: 269, https://doi.org/10.1007/s10546-017-0307-5
[20] Bleeg J, Purcell M, Ruisi R and Traiger E (2018) Wind Farm Blockage and the Consequences of Neglecting Its Impact on Energy Production. Energies 11: 1609, https://doi.org/10.3390/en11061609
[21] Calaf M, Meneveau C and Meyers J (2010) Large eddy simulation study of fully developed wind-turbine array boundary layers. Phys. Fluids 22:015110, https://doi.org/10.1063/1.3291077
[22] Barthelmie R J and Jensen L E (2010) Evaluation of wind farm efficiency and wind turbine wakes at the Nysted offshore wind farm. Wind Energy 13: 573–86, https://doi.org/10.1002/we.408
[23] Fleming PA, Gebraad PM, Lee S, van Wingerden J-W, Johnson K, Churchfield M, Michalakes J, Spalart P and Moriarty P (2014) Evaluating techniques for redirecting turbine wakes using {SOWFA}, Renew. Energ. 70: 211–218, https://doi.org/10.1016/j.renene.2014.02.015
[24] Sanderse B, van der Pijl SP and Koren B (2010) Review of CFD for wind-turbine wake aerodynamics, Wind Energ. 14: 799-819, https://doi.org/10.1002/we.458
[25] Sanz Rodrigo J (2017) GABLS3 diurnal cycle benchmark for wind energy applications. https://windbench.net/gabls-3, accessed February 2019
[26] Sanz Rodrigo J, Allaerts D, Avila M, Barcons J, Cavar D, Chávez Arroyo R, Churchfield M, Kosović B, Lundquist JK, Meyers J, Muñoz Esparza D, Palma JMLM, Tomaszewski JM, Troldborg N, van der Laan MP, Veiga Rodrigues C (2017) Results of the GABLS3 diurnal cycle benchmark for wind energy applications. Journal of Physics: Conference Series, 854: 012037, http://iopscience.iop.org/article/10.1088/1742-6596/854/1/012037

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