Wind Energy Science wes-2025-130

Responses to Reviewer 1

This paper addresses a practical topic of bidirectional wake effects in complex terrain using SCADA data and wake modeling. Comparative studies contributed to the selection of wake models in complex terrain. The following comments are intended to help strengthen the manuscript for potential publication.

Author response: We appreciate your time and effort in reviewing our manuscript and providing supportive and valuable comments. We have incorporated your suggestions into the revised manuscript. The authors' responses to the reviewer's comments are described below. The symbol "**Author response**" means the author's responses.

1. Abstract:

The abstract lists the work and results but does not clearly articulate the motivation and contributions of the study. It is recommended that the authors restructure the abstract to begin with a broader background, narrow down to the specific focus on bidirectional wake effects, and end with a stronger conclusion that clearly states the novelty and significance of the work.

Author response: As recommended by the reviewer, we revised the abstract as follows.

- [The 2nd sentence of the abstract]
  We added the sentence below to explain the background and motivation of this study.
  "The extent to which complex terrain affects wake behavior has not yet been fully studied."
- [The last sentence of the abstract]
  We added the sentence below to enhance the novelty and significance of our work.
  "This comparative study contributes to understanding the additional effects of topography on wake effects in onshore wind power plants and offshore wind power plants near the coast."

2. Article Structure:

The overall structure of the paper could be reorganized; for example, lines 54-63 seem more appropriate in the methodology section rather than the introduction.

Author response: Thank you for this suggestion. Following your suggestion, we moved the descriptions on the study site to Section 2.1 and the descriptions on wind climate to Section 2.3. In the fourth paragraph of Section 1, we only mention the results of Sasanuma and Honda (2022; 2024) to review the previous studies.

Additionally, some subheadings could be more informative. For instance, a title such as "2.1 Two Turbines" is too generic, and “2.2 SCADA” does not concisely describe the content of the section.

Author response: Thank you for your suggestion. We revised the subheadings in Sections 2.1, 2.2, 2.3, and 2.6 to be more informative and clearer as below.

- 2.1 “Study site and two wind turbines” from "Two wind turbines".
- 2.2 "SCADA data at the two wind turbines” from "SCADA".
- 2.3 “Wind climate” from "Wind farm climate".
- 2.6 “Flow simulations with wake models” from "Flow wake models".

3. Introduction:

The background does not effectively introduce the primary object of the study. Moreover, literature reviews were unable to identify the progress and the key research gaps of the research. It is recommended to supplement the review with more recent and relevant work.

Author response: Thank you for your suggestion. Following your suggestion, we fully revised the fourth paragraph of Introduction (Section 1) to cite and review the previous and recent studies that focus on wind turbine wakes over complex terrain. In response to comment 6 of Reviewer 1, we listed the studies cited in the paragraph. Owing to the revision, we could clarify the key research gaps and the scope of our paper and highlight the fact that focusing on bidirectional wakes over complex terrain is a new approach.

4. Methods:

The theoretical framework is unclear. The authors defined the “wind speed ratio” and conducted analyses based on it. It is recommended to provide a mathematical formula and a detailed explanation.

Author response: Thank you for your suggestions.

- Following your suggestion, we added the mathematical formula WS_2 / WS_1 for northeasterly wind and WS_1/WS_2 for southwesterly wind to Section 2.5, where WS_1 is wind speed at WT1 and WS_2 is that at WT2.
- In addition, we added Table 1 to Section 2.5 to clearly show the definitions of wind speed ratio according to the combination of wind direction and wake condition.

- In Section 2.2, we also added a mathematical formula to define turbulence intensity as σ / WS, where σ is the standard deviation of wind speed, and WS is the 10-minute mean wind speed.

Table 1. Definition of wind speed ratio according to the combination of wind direction and the presence or absence of wake. White shading indicates the condition that the upstream wind turbine is not in operation, and gray shading indicates the condition that the upstream wind turbine is in operation.

	Northeasterly wind	Southwesterly wind
No-wake conditions	WS_2 / WS_1	WS_1 / WS_2
Wake conditions	WS_2 / WS_1	WS_1 / WS_2

5. Validation and Analysis:

For this wind field test, using wake models to validate the observed SCADA data seems unreasonable.

Author response: Thank you for pointing this out. We gave the following two responses.

1) The previous studies show that applying the wake models to the wind flow over terrain is valid. We mentioned the previous studies below in Section 2.6. Fleming et al. (2020) investigate wake steering for onshore turbines using engineering flow calculation tool with Bastankhah model. Ruisi and Bossanyi (2019) indicate consistent reduction in wind speed due to the wind turbine wake between Bastankhah wake model and observations in an onshore wind farm. zum Berge et al. (2024) evaluated the performance of TurboGaussian wake model using a flight measurement for wind farm clusters in offshore sites. We found that these two wake models (TurboGaussian and Bastankhah models) represent wake effects more consistent with the observations than other wake models. Fischereit et al. (2022) indicate that three wake models (NOJ model, Bastankhah model, and Zong model) accurately simulate the intra-farm wakes. Jeon et al. (2015) verify the prediction accuracy of several wake models, including Jensen and GCL wake models, and found that Jensen wake model is the best for reduction in wind speed due to the wind turbine wake and GCL wake model is relatively accurate for the width of wake flow in an onshore wind farm.

2) Currently, few studies have examined the difference in performance between all the wake models in PyWake in complex terrain. Therefore, we focus on the comparison of the wake models to provide helpful information for selecting wake models in complex terrain. Although the results from some wake models are far from the SCADA results, our scope in this study is not to calibrate the wake models by tuning the parameters to the SCADA results, but to compare the simulated wakes by 12

wake models in default settings. We mentioned the description above in the last paragraph of Section 1.

Farrell, A., King, J., Draxl, C., Mudafort, R., Hamilton, N., Bay, C. J., Fleming, P., and Simley, E.: Design and analysis of a wake model for spatially heterogeneous flow, Wind Energ. Sci., 6, 737–758, https://doi.org/10.5194/wes-6-737-2021, 2021.

Fischereit, J., Schaldemose Hansen, K., Larsén, X. G., van der Laan, M. P., Réthoré, P.-E., and Murcia Leon, J. P.: Comparing and validating intra-farm and farm-to-farm wakes across different mesoscale and high-resolution wake models, Wind Energ. Sci., 7, 1069–1091, https://doi.org/10.5194/wes-7-1069-2022, 2022.

Fleming, P., King, J., Simley, E., Roadman, J., Scholbrock, A., Murphy, P., Lundquist, J. K., Moriarty, P., Fleming, K., van Dam, J., Bay, C., Mudafort, R., Jager, D., Skopek, J., Scott, M., Ryan, B., Guernsey, C., and Brake, D.: Continued results from a field campaign of wake steering applied at a commercial wind farm – Part 2, Wind Energ. Sci., 5, 945–958, https://doi.org/10.5194/wes-5-945-2020, 2020.

Jeon, S., Kim, B., and Huh, J.: Comparison and verification of wake models in an onshore wind farm considering single wake condition of the 2 MW wind turbine. Energy, 93, 1769-1777. https://doi.org/10.1016/j.energy.2015.09.086, 2015.

Ruisi, R. and Bossanyi, E.: Engineering models for turbine wake velocity deficit and wake deflection. A new proposed approach for onshore and offshore applications, in: Journal of Physics: Conference Series, vol. 1222, p. 012004, IOP Publishing, 2019.

zum, Berge, K., Centurelli, G., Dörenkämper, M., Bange, J., and Platis, A.: Evaluation of Engineering Models for large-scale cluster wakes with the help of in situ airborne measurements. Wind Energy, 27(10), 1040-1062. https://doi.org/10.1002/we.2942, 2024.

Similarly, the use of a CFD approach in Section 3.2 as a supplementary analysis of bidirectional wake effects is not fully convincing, as the CFD model itself has not been sufficiently validated for this application.

Author response: Thank you for pointing this out. WAsP CFD is a CFD model integrated into WAsP and is designed for simulating winds over complex terrain. (WAsP has limitations in simulating wind over complex terrain.) WAsP CFD has been used by the following studies, and the resulting wind fields over complex terrain have been analyzed and validated. Thus, WAsP CFD simulation is an effective way to study the flow and wake in complex terrain.

Bechmann, A., N. N. Sørensen, J. Berg, J. Mann, and Réthoré P.-E.: The Bolund Experiment, Part II: Blind Comparison of Microscale Flow Models, Boundary-Layer Meteorology 141 (2): 245–71, https://doi.org/10.1007/s10546-011-9637-x, 2011.

Bechmann, A.: Perdigão CFD Grid Study, DTU Wind Energy E 0120, 2016.

Sharma, P. K., Warudkar, V., & Ahmed, S.: Application of a new method to develop a CFD model to analyze wind characteristics for a complex terrain. Sustainable Energy Technologies and Assessments, 37, 100580. https://doi.org/10.1016/j.seta.2019.100580, 2020.

Troen, I., and Hansen, B. O.: Wind Resource Estimation in Complex Terrain: Prediction Skill of Linear and Nonlinear Micro-Scale Models, Paper presented at AWEA Windpower Conference & Exhibition, Orlando Orange County Convention Center, United States. May 18, 2015.

6. Reference:

The bibliography contains a number of outdated references and lacks literature from the past five years that can reflect the current research status.

Author response: Thank you for your suggestions. Following your suggestion, we added the following papers, including recent ones to the text.

[3rd paragraph in Introduction]

Fischereit, J., Schaldemose Hansen, K., Larsén, X. G., van der Laan, M. P., Réthoré, P.-E., and Murcia Leon, J. P.: Comparing and validating intra-farm and farm-to-farm wakes across different mesoscale and high-resolution wake models, Wind Energ. Sci., 7, 1069–1091, https://doi.org/10.5194/wes-7-1069-2022, 2022.

Fleming, P., King, J., Dykes, K., Simley, E., Roadman, J., Scholbrock, A., Murphy, P., Lundquist, J. K., Moriarty, P., Fleming, K., van Dam, J., Bay, C., Mudafort, R., Lopez, H., Skopek, J., Scott, M., Ryan, B., Guernsey, C., and Brake, D.: Initial results from a field campaign of wake steering applied at a commercial wind farm – Part 1, Wind Energ. Sci., 4, 273–285, https://doi.org/10.5194/wes-4-273-2019, 2019.

[4th paragraph in Introduction]

Berg, J., Troldborg, N., Sørensen, N.N., Patton E. G., and Sullivan, P. P.: Large-Eddy Simulation of turbine wake in complex terrain, J. Phys.: Conf. Se. 854, 012003, 10.1088/1742-6596/854/1/012003, 2017.

Castellani, F., Astolfi, D., Burlando, M., & Terzi, L.: Numerical modelling for wind farm operational assessment in complex terrain. Journal of Wind Engineering and Industrial Aerodynamics, 147, 320-329. https://doi.org/10.1016/j.jweia.2015.07.016, 2015.

Dar, A. S., Berg, J., Troldborg, N., and Patton, E. G.: On the self-similarity of wind turbine wakes in a complex terrain using large eddy simulation, Wind Energ. Sci., 4, 633–644, https://doi.org/10.5194/wes-4-633-2019, 2019.

Letzgus, P., Guma, G., and Lutz, T.: Computational fluid dynamics studies on wind turbine interactions with the turbulent local flow field influenced by complex topography and thermal stratification, Wind Energ. Sci., 7, 1551–1573, https://doi.org/10.5194/wes-7-1551-2022, 2022.

Politis, E. S., Prospathopoulos, J., Cabezon, D., Hansen, K. S., Chaviaropoulos, P. K., & Barthelmie, R. J.: Modeling wake effects in large wind farms in complex terrain: The problem, the methods and the issues. Wind Energy, 15(1), 161-182. https://doi.org/10.1002/we.481, 2011.

Porté-Agel, F., Bastankhah, M. & Shamsoddin, S.: Wind-Turbine and Wind-Farm Flows: A Review, Boundary-Layer Meteorol., 174, 1–59, https://doi.org/10.1007/s10546-019-00473-0, 2020.

Wagner, J., Gerz, T., Wildmann, N., and Gramitzky, K.: Long-term simulation of the boundary layer flow over the double-ridge site during the Perdigão 2017 field campaign, Atmos. Chem. Phys., 19, 1129–1146, https://doi.org/10.5194/acp-19-1129-2019, 2019.

Wenz, F., Langner, J., Lutz, T., and Krämer, E.: Impact of the wind field at the complex-terrain site Perdigão on the surface pressure fluctuations of a wind turbine, Wind Energ. Sci., 7, 1321–1340, https://doi.org/10.5194/wes-7-1321-2022, 2022.

Yang, X., Sotiropoulos, F., Conzemius, R. J., Wachtler, J. N., & Strong, M. B.: Large-eddy simulation of turbulent flow past wind turbines/farms: The Virtual Wind Simulator (VWiS). Wind Energy, 18(12), 2025-2045. https://doi.org/10.1002/we.1802, 2015.

[2.6 Flow simulation and wake models]

Bechmann, A., N. N. Sørensen, J. Berg, J. Mann, and Réthoré P.-E.: The Bolund Experiment, Part II: Blind Comparison of Microscale Flow Models, Boundary-Layer Meteorology 141 (2): 245–71, https://doi.org/10.1007/s10546-011-9637-x, 2011.

Bechmann, A.: Perdigão CFD Grid Study, DTU Wind Energy E 0120, 2016.

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Fischereit, J., Schaldemose Hansen, K., Larsén, X. G., van der Laan, M. P., Réthoré, P.-E., and Murcia Leon, J. P.: Comparing and validating intra-farm and farm-to-farm wakes across different mesoscale and high-resolution wake models, Wind Energ. Sci., 7, 1069–1091, https://doi.org/10.5194/wes-7-1069-2022, 2022.

Fleming, P., King, J., Simley, E., Roadman, J., Scholbrock, A., Murphy, P., Lundquist, J. K., Moriarty, P., Fleming, K., van Dam, J., Bay, C., Mudafort, R., Jager, D., Skopek, J., Scott, M., Ryan, B., Guernsey, C., and Brake, D.: Continued results from a field campaign of wake steering applied at a commercial wind farm – Part 2, Wind Energ. Sci., 5, 945–958, https://doi.org/10.5194/wes-5-945-2020, 2020.

Jeon, S., Kim, B., and Huh, J.: Comparison and verification of wake models in an onshore wind farm considering single wake condition of the 2 MW wind turbine. Energy, 93, 1769-1777. https://doi.org/10.1016/j.energy.2015.09.086, 2015.

Ruisi, R. and Bossanyi, E.: Engineering models for turbine wake velocity deficit and wake deflection. A new proposed approach for onshore and offshore applications, in: Journal of Physics: Conference Series, vol. 1222, p. 012004, IOP Publishing, 2019.

Sharma, P. K., Warudkar, V., & Ahmed, S.: Application of a new method to develop a CFD model to analyze wind characteristics for a complex terrain. Sustainable Energy Technologies and Assessments, 37, 100580. https://doi.org/10.1016/j.seta.2019.100580, 2020.

Troen, I., and Hansen, B. O.: Wind Resource Estimation in Complex Terrain: Prediction Skill of Linear and Nonlinear Micro-Scale Models, Paper presented at AWEA Windpower Conference & Exhibition, Orlando Orange County Convention Center, United States. May 18, 2015.

zum, Berge, K., Centurelli, G., Dörenkämper, M., Bange, J., and Platis, A.: Evaluation of Engineering Models for large-scale cluster wakes with the help of in situ airborne measurements. Wind Energy, 27(10), 1040-1062. https://doi.org/10.1002/we.2942, 2024.

7. Figures:

Four separate figures are used to illustrate the relative positions of the two turbines, which appear redundant. It is recommended to consolidate these into a more informative figure to improve the conciseness and information density of the manuscript.

Author response: Thank you for your suggestion. Following your suggestion, we deleted Figure 1a because Figure 1b is enough to show the locations of wind turbines and the surrounding terrain. However, we believe that both Figures 2a and 2b are necessary and important for understanding the problem setting of this study, including the surrounding environment and locational conditions of the wind turbines. Therefore, we keep Figures 2a and 2b.

8. Language and Readability:

The manuscript would benefit from a thorough proofread to correct grammatical errors (e.g., "is critical issue" should be "is a critical issue" in the introduction). Attention should also be paid to improving sentence structure and logical coherence; in the same paragraph, shifts in voice (active vs. passive) and subject detract from readability.

Author response: We carefully checked the grammatical errors and sentence structures throughout the text. We paid attention to the use of active and passive voice and the shift of subject in the same paragraph.