Numerical and Experimental Methods for Wake Flow Analysis in Complex Terrain

Francesco Castellani¹, Davide Astolfi¹, Emanuele Piccioni¹, Ludovico Terzi²

¹ Department of Engineering, University of Perugia, Perugia, Italy
² Renvico srl, Via San Gregorio 34, Milano 20124, Italy

E-mail: francesco.castellani@unipg.it

Abstract. Assessment and interpretation of the quality of wind farms power output is a non-trivial task, which poses at least three main challenges: reliable comprehension of free wind flow, which is stretched to the limit on very complex terrains, realistic model of how wake interactions resemble on the wind flow, awareness of the consequences on turbine control systems, including alignment patterns to the wind and, consequently, power output. The present work deals with an onshore wind farm in southern Italy, which has been a test case of IEA-Task 31 Wakebench project: 17 turbines, with 2.3 MW of rated power each, are sited on a very complex terrain. A cluster of machines is investigated through numerical and experimental methods: CFD is employed for simulating wind fields and power extraction, as well as wakes, are estimated through the Actuator Disc model. SCADA data mining techniques are employed for comparison between models and actual performances. The simulations are performed both on the real terrain and on flat terrain, in order to disentangle the effects of complex flow and wake effects. Attention is devoted to comparison between actual alignment patterns of the cluster of turbines and predicted flow deviation.

1. Introduction

The assessment of power output quality of wind farms operating in complex terrains is extremely challenging. The present-day abundance of SCADA control systems and the increasing computational power have provided a significant boost to the interpretation of wind farm performances. Basically, three are the main drivers: the wind flow itself, which might have rather extreme features on peculiarly complex sites, wake interactions and the response of the control system to the intertwining of these two phenomena. These challenges even force to revisit techniques which are well established for performance assessment of offshore wind farms. For example, in [1] it has been shown that, for onshore wind farms, farm efficiency analysis as a function of the wind direction (commonly known as polar efficiency) can not be tackled as in the offshore case [2, 3, 4, 5, 6] because it is not mathematically consistent. A novel definition is therefore proposed, which is by construction mathematically consistent; its physical interpretation is presented through three test cases, on terrains of increasing complexity (from very gentle to extremely challenging). The most complex wind farm analysed in [1] is also a test case of the IEA-Task 31 Wakebench project [7], aiming at developing a framework for the evaluation of wind farm flow models operating at microscale level, and it is also the object of this investigation. The terrain of this wind farm is indeed quite steep, with very high slopes
(up to 60%) close to the turbines; also the layout is complex and large, resulting in non-trivial combination effects of complex wind flow and wake interactions. For some precious insight on wind flow on complex terrains, see for example [8] and [9].

The aim of the present paper is heavily combining the approaches above summarized with experimental SCADA data analysis. Wakes and topographical flow acceleration manifest in meandering wind, which the nacelle of the turbine under wake can not follow optimally. Therefore, clusters of turbines tend to behave as a whole, rather than a collection of individuality, and peculiar alignment patterns arise. In [10] it is shown, on the test case of two subclusters lying on very different terrains, that recurrent alignment patterns display huge performance deviations with respect to each other. In the present Paper, precisely one of the subclusters of turbines analysed in [10] is investigated, through numerical and experimental analysis. Further, the numerical simulations shall be performed both on the actual terrain and on flat terrain, in order to try to disentangle the effect of terrain-induced wind flow acceleration from pure wake effect.

The structure of the Paper is as follows: in Section 2 the test case wind farm is briefly described, in Section 3 the numerical methods and the SCADA data post-processing techniques are introduced. In Section 4 the results are collected, and finally in Section 5 some concluding remarks are sketched and further directions of the present work are proposed.

2. The Wind Farm
The layout of the test case wind farm is sketched in Figure 1: seventeen aerogenerators are installed on site, with 2.3 MW of rated power at around 12 m/s; the rotor diameter is 93 meters and the hub height is 80 meters. Six met-masts have been installed for site assessment: nowadays the only active, whose data shall be employed for the present work, is the one slightly north of the turbine SGM10, collecting data at hub height. From the topographic contour lines of Figure 1, the challenging complexity of the site is manifest: actually slopes up to 60% can be found in proximity of the turbines. The severity of the slopes has been quantified through the Ruggedness Index (RIX value), computed at a given point through the Wind Atlas Analysis and Application Program [11, 12] as the fractional extent of the surrounding terrain which is steeper than a certain critical slope. RIX values at turbine sites are displayed in Table 1. The site, which has been chosen as test case of the IEA-Task 31 Wakebench project [7], is also characterised by significant icing and lightning effects.

Figure 1. Wind farm layout.

Figure 2. Wind rose: percentage of occurrence.
Table 1. Ruggedness Index at turbine site.

| Turbine | RIX value (%) |
|---------|---------------|
| SGM10   | 24.9          |
| SGM11   | 23.1          |
| SGM12   | 21.7          |
| SGM13   | 20.4          |

The analysis of the present Paper is focused on the subcluster SGM10-SGM13 of the wind farm, which is zoomed in Figure 3.

Figure 3. Layout of SGM10-SGM13 subcluster and met-mast

Figure 4. Wind turbine power and thrust curve.

The inter-turbine distance is such that considerable wake effects are expected: actually all the couples of nearby turbines of the subcluster are at around 2.8 rotor diameters one from the other. Further, the complexity of the terrain induces non-trivial wind flow, such that, from the very populated 270° sector (as shown in the wind rose of Figure 2), turbine SGM13, which is the most downstream, is by far the best performing [1]. Also, the met-mast lies very close to the cluster, and it can be considered a reliable landmark for undisturbed wind flow. On the grounds of the considerations above, the subcluster SGM10-SGM13, when the wind blows from the 270° sector, has been chosen as testing ground of the present work.

3. The numerical and experimental methods

The numerical simulations have been performed with the WindSim numerical tool [13]: this code is based on the numerical core PHOENICS, which solves the Reynolds Averaged Navier-Stokes (RANS) equations on a Cartesian grid; different solvers can be used and in the present work the General Collocated Velocity method (GCV) is employed for its capability in reaching convergence on very steep terrains. The objective is simulating the behaviour of the SGM10-SGM13 cluster of turbines when there are certain conditions at met-mast. Two test cases have been chosen: 10 and 6 m/s at met mast. The inlet boundary is assumed to be a logarithmic profile blowing from 270°, whose intensity at the top of the boundary layer (assumed equal to 800 meters above ground level) is iteratively adjusted, in order to obtain 10 (6) m/s at hub height at met-mast position. The procedure is as follows: iterations are run, in order to provide an acceptable degree of convergence and stability. Subsequently, 100-iterations blocks are run. At the end of each of them, the target values are checked: in this case, wind intensity at met-mast. Deviation from the pre-run and from the expected results are evaluated, and boundary layer values are finely tuned for a new run, and so on. The two regimes have also been investigated.
by the point of view of free wind flow, producing a prediction for the undisturbed wind speed, wind direction and turbulence intensity at each turbine site. The presence of the rotors has been simulated through the Actuator Disc model [14, 15, 16, 17] both on the real terrain and on flat terrain. The turbulence model is RNG k-ε. It has been checked that it provides better convergence with respect to k-ω and modified k-ε, despite its inherent inability of optimally resembling the near-wake wind field. As shall arise throughout the discussion, the stream flow is driven mainly by the complexity of the terrain, and for this reason RNG k-ε provides better results. Similar considerations arise in [18], where the complex terrain of Askervein hill (also a test case of IEA-Task 31 Wakebench project [7]) is analyzed: it is shown that RNG k-ε is the computational scheme providing better performances. The computational domain for the AD model is divided in a coarse area and a refined area: the former is necessary to simulate the main wind field blowing in the mesoscale, the latter is needed for evaluating the interaction between the wind field and the turbines, modeled by the disk, on a local scale through the thrust coefficient. A grid independence study has been performed as a preliminary issue for the objectives of IEA-Task 31 Wakebench project [7]. For the present work, in particular, peculiar attention is deserved to grid independence of wind intensity at upstream turbine SGM10. The refined area employs a grid based on 22 subdivisions per turbine diameter. In [17] it is shown that results with the AD model do not depend on refined area grid resolution, as long as there are not less that 16 subdivisions per turbine diameter. The power production \( P \) is estimated through an integral post-processing method [16], using the local wind speed and the maximum pressure drop across the rotor area \( A \) (Equation 1).

\[
P = \int_A v \cdot dp \cdot dA \approx \sum_i \xi_i \Delta p_i v_i
\]  

(1)

The integral of Equation 1 is discretized using weights \( \xi_i \) associated to the grid resolution, \( \Delta p_i \) is the local pressure drop and \( v_i \) is the local wind speed. The weights \( \xi_i \) are normalized to 1 and are proportional to the ranking in relative distance of the \( i \)-th subdivision from the center of the diameter, because the higher the distance from the center of the disk, the higher the annular area spanned, and therefore the torque and the extracted power. The output of the AD model is therefore the active power, from which the undisturbed wind speed \( v_\infty \) is obtained through the power curve (see Figure 4), the turbulence intensity and the wind direction. The details of the computational grids are summarized in Table 2. The volume is described by terrain-following surfaces, close to the topographic surface, and flat surfaces at the top of the computational domain. Figures 5 and 6 show the computational grid at the level of terrain surface.

| Model                  | Cells (X, Y, Z) |
|------------------------|----------------|
| Free Flow              | (279, 215, 30) |
| AD model + terrain     | (256, 111, 61) |
| AD model + flat        | (236, 103, 61) |

The two simulation regimes have been chosen for the following reasons:

- 10 m/s is a critical value because, within one typical standard deviation, velocities associated to rated power are approached. The AD model clearly can not take into account control system dynamics approaching rated power, and therefore is expected not to reproduce brilliantly the interaction between rotor and wind flow.
6 m/s has been instead chosen because, when the wind speed is of this order of magnitude, the thrust coefficient is high and the dynamics is strongly driven by wakes: it is therefore interesting to inquire how much of the actual performances is captured by a pure wake model, i.e. the AD on flat terrain.

SCADA data have been post-processed in order to reproduce the regimes simulated through the numerical models. Basically, three filters have been employed. First, the time steps are selected during which the subcluster of interest is producing output in unison. Subsequently, filters have been applied on the wind speed as measured by met-mast (correspondingly to the simulations regimes above), and on the orientation of the upstream SGM10 turbine (270° ± 5° direction). Thresholds for filtering have been estimated as follows: first, the relative error on each wind speed measurement has been computed. This data set has been averaged for a global estimate, amounting at 18%. Therefore, a conservative criterion has been chosen, which guarantees precise resembling to simulated regimes and fair data sets population: 10% of tolerance around the two wind speed values (10 and 6 m/s). Further, the AD model assumes disk orientation under orthogonal directions. The wind is expected to be somehow distorted at turbines SGM11, SGM12, SGM13 site, while within a certain extent it is not at turbine SGM10 site, since this machine is upstream. Similarly, while turbines SGM11, SGM12 and SGM13 are not expected to exactly orientate to the wind in the real world due to turbulence and complexity effects, turbine SGM10 within a certain extent is, because it is upstream when the wind blows from the 270° sector. Therefore it is reasonable to suppose that SGM10 satisfies the assumptions of the AD model and, correspondingly, to filter SCADA measurements in a way which resembles these assumptions. Since the order of magnitude of the standard deviation of nacelle position SCADA measurements is 5°, this value has been chosen as amplitude of tolerance on SGM10 orientation measurements, around the 270° centre. The filter on nacelle positions deserves a deeper discussion: actually it has been checked if the measurements are vexed by a systematic offset. The speed-up ratio between met-mast and the nearest turbine SGM10 has been computed and averaged against 1° amplitude of SGM10 nacelle position intervals: it is expected that it reaches a maximum along the direction joining SGM10 to the met-mast, because the met-mast would be under wake of turbine SGM10. From the layout it is computed that the inclination of the line joining SGM10 to met-mast is 194°. The measured speed-up displays its maximum at 198° and this means that there is a 4° systematic offset in SGM10 nacelle position measurements. The post-processing and the results displayed in Section 4 are to be intended as removed of this systematic bias. This procedure has been adopted, for couples of nearby turbines of the cluster, in order to check reliability of nacelle position measurements of each wind turbine.
results here on are to be intended as removed of this possible bias. On the data sets obtained filtering as described above, wind speed and direction and active power measurements have been averaged and compared against model predictions. The comparison of turbulence intensity model predictions against SCADA measurements deserves a deeper discussion: as pointed out in [19], the Turbulence Kinetic Energy (TKE) is calculated from a closure scheme in CFD models and it is non-trivial to reconstruct from it Turbulence Intensity (TI) and validate against measurements from cup anemometers. In [19] two reconstruction schemes are proposed, which act as lower and upper bounds for comparison against measurements: the approach is validated through the computation of the bias on a testing site in a coastal area of Chile. In the present Paper, the following procedure has been adopted: turbulence intensity, both from models and experimental, has been computed at each turbine site referred to the amount of turbulence at met-mast site. The experimental turbulence intensity at met-mast has been computed filtering measurements according to the same criteria summarized above. This technique circumvents the issue of direct comparison of model and experimental TI and guarantess capability of appreciating the trend, moving from one turbine site to an other. The results are collected and discussed in the following Section 4.

4. Results

Figures 7, 8, 9 and 10 summarize the results for the test case of 10 m/s at met-mast and Figures 11, 12, 13 and 14 display the results for the 6 m/s at met-mast case. They are to be discussed together, because they share some basic features, albeit with non-trivial subtleties. First of all, from Figures 7 and 11 it arises that the free flow model fails in capturing the trend of speed intensity moving from SGM10 to SGM13: actually the model predicts a decreasing trend, while SCADA measurements show that a severe speed loss occurs moving from SGM10 to SGM11, but the trend inverts moving towards SGM12 and especially SGM13. Actually SGM13 displays a velocity even slightly higher that the upstream turbine SGM10, also because it is not quite in line with the other machines, and thus sees a much reduced wake. For this reason, actually, the most challenging testing ground of the numerical models is capturing the trend at turbines SGM11 and SGM12. The velocity (and consequently power) collapse moving from SGM10 to SGM11 is brilliantly captured by the AD model on real terrain. As concerns turbulence ratios, the AD model on flat terrain in general better resembles experimental data, especially in the 6 m/s case. When the wind intensity is 6 m/s, actually, the thrust coefficient is high and the turbulence dynamics is mainly driven by wakes. The intensity distribution instead primarily depends on the main stream flow and the amount of energy it moves: this is strongly guided by the terrain. Therefore, it is not surprising that the AD model on flat terrain better reproduces the local turbulence intensity distribution while the AD model on the real terrain best captures the features of wind speed, and therefore power, distribution. A stimulating subtlety is that the AD model on the real terrain at 10 m/s predicts almost a plateau in turbulence ratio, moving from SGM11 to SGM12, while the AD model on flat terrain predicts a severe increase from SGM11 to SGM12. Even though the orders of magnitude of the turbulence ratio predicted by the AD model on the real terrain are overestimated, it is interesting to notice that if one wants to understand the trend of the turbulence distribution, it becomes important to take into account terrain effects, as the wind intensity increases. It is somehow surprising that the AD model on flat terrain best captures the order of magnitude of turbulence intensity ratio: nevertheless remember it is a ratio between a standard deviation and an average, and therefore strong speed-ups to the wind flow might lead to an underestimate. The role of the terrain is fundamental also to understand the alignment patterns: even though nacelle anemometer is not experiencing the effect of the swirl, it is nevertheless useful to compare experimental data against the trend predicted by the models, also because the AD models are capable of encoding the global flow rather than the near-wake. It is expected that the free flow model can not
simulate the real alignment patterns of turbines SGM11-SGM12-SGM13, because they do not experience the free stream. Particularly for this reason, the free flow model is included: it is interesting to compare how things are in the real world against how they would be if there was only the free stream and not the turbines. From Figure 10 and 14, it arises that the free flow model predicts a anticlockwise tendency moving from turbine SGM10 to SGM13. Actual nacelle orientations indeed display a similar trend, but with a much higher range of variability: $15^\circ$ against $5^\circ$. These are brilliantly captured, especially at turbine SGM11, by the AD model on the real terrain. The general lesson is that in a complex site, as the chosen test case, the actual nacelle alignment patterns can be numerically estimated only if one takes into account also the terrain. The results demonstrate that the AD model is capable of reproducing a realistic flow deviation from the main stream, resembling the actual alignment patterns, even if it is based on the hypothesis of perfectly orthogonal rotors.

Figure 7. Models vs. experimental data: wind speed. 10 m/s

Figure 8. Models vs. experimental data: turbulence intensity relative to met-mast. 10 m/s

Figure 9. Models vs. experimental data: active power. 10 m/s

Figure 10. Models vs. experimental data: wind direction. 10 m/s

Figures 10 and 14 show that the wind blowing undisturbed from $270^\circ$ is northward distorted by the terrain and the presence of the turbines. This basically explains why turbine SGM13, which is apparently the most downstream, actually is the best performing turbine. The flow of turbulence does not affect it and actually it displays almost the same turbulence ratio amount as the upstream turbine SGM10, while instead turbines SGM11 and SGM12 more or less double with respect to SGM10.
5. Discussion and Further Directions

In the present Paper, a cluster of turbines of an onshore wind farm sited in southern Italy has been analysed numerically and experimentally. The wind farm has been a test case of the IEA-Task 31 Wakebench project [7] because the very complex terrain conspires with wake effects, resulting in a very stimulating arena, which has also been addressed in [1] by the point of view of farm efficiency as a function of wind direction. The objective of the present work has been interpreting the performances of the selected cluster in terms of wake effects and topography, trying to disentangle them, or at least assessing their relevance. CFD Numerical modelling comes at hand: a free flow model and the AD model, for simulating the presence of the rotors, have been employed. The AD models are placed on the actual terrain and on flat terrain, in order to appreciate the different features of the predictions and comparing them against SCADA measurements. In order to have at hand comparable quantities on experimental and numerical sides, appropriate computational and data-mining techniques are employed, which are described in Section 3. The 270° wind direction sector has been chosen because it is the main wind direction (see Figure 2) and because it is a very relevant testing ground for the issues above. Two wind speed regimes have been chosen:

- 6 m/s at met mast, because the dynamics is expected to be dominated by wakes.
- 10 m/s at met-mast, because the topography effects are expected to become more relevant.
and because the wind speed fluctuations might approach regimes associated to rated power. Therefore non-negligible influence of the control system in the machine dynamics is possible.

The results, displayed in Section 4, can be summarized as follows:

- The free flow model is unable to capture the trend of wind speed, moving from turbine SGM10 to SGM13. Actually it predicts decreasing wind speeds, while instead an abrupt fall occurs only from turbine SGM10 to SGM11, and the trend inverts at turbine SGM12 and especially SGM13.

- The AD model on the real terrain brilliantly captures the fall of wind speed from turbine SGM10 to SGM11. Further, it does not capture the rise at SGM12, but at least it predicts an almost flat trend. Instead, the AD model on the flat terrain overestimates the wind speed (and consequently the power) at turbine SGM11 and predicts a further decrease at turbine SGM12. This means that the terrain is fundamental in driving the main stream flow, transporting the energy, and that the terrain effects are crucial in order to interpret the performances of turbines SGM11 and SGM12. In other words, if there were only wakes, we should be expecting SGM12 to perform worst that SGM11, while it exactly does the opposite.

- The distribution of the turbulence intensity is best captured by the AD model on the flat terrain, especially in the 6 m/s case, when the dynamics is expected to be dominated by wake effects. The 10 m/s case is extremely instructive: even though the AD model on the real terrain overestimates the order of magnitude of turbulence intensity ratios, it best captures the trend at SGM12, with respect to the AD model on the flat terrain. This means that at high wind speeds, the effects of terrain are not negligible in understanding how the turbulence intensity distributes.

- The AD model on the real terrain captures the main features of the actual turbine alignment patterns, while instead the AD model on the flat terrain and the free flow model do not capture the amplitude and the trend of northward wind flow distortion, which ultimately explains why performances of turbines SGM12 and SGM13 are far better than in an hypothetical flat terrain. The results demonstrate that the AD model reproduces realistic flow deviation from the main stream, resembling the actual alignment patterns, even if based on the hypothesis of perfectly orthogonal rotors.

The AD model by construction disregards rotational and near-wake effects, but it is a computationally accessible tool for investigating the global wind farm aerodynamic behaviour: it is therefore very appreciable that the AD model captures the main features of the wind speed trend, especially the abrupt fall at turbine SGM11. Yet, several are the possible developments of the present work in order to refine the predictions. The employed data set is an ensemble of 10-minute averages: yaw positions therefore by construction have uncertainty; further, even if data are filtered on a relatively narrow interval centered on 270°, the terrain is so complex that there possibly are several inflow and wake conditions. Since the nature of this source of information can not be circumvented, a more consistent comparison against numerical models can be obtained by encapsulating somehow uncertainty in the computational framework. In [20] a Gaussian weighting of simulation regimes is proposed and on the offshore Horns Rev test case it is shown that is sensibly leads to a more consistent framework for comparing models to reality. It would be valuable to push forward the research of the present work and include such approach, in particular because of the challenging complexity of our test site. Further, as shown in the preliminary analysis of [10], the alignment patterns to the wind in complex flow regimes have a huge impact on the amount of energy extracted: even though, as Figures 14 and 10 show, the actual alignment patterns averagely resemble the predictions from the AD model about the directional flow, an underworld of nacelle configurations exists, basically associated to the same
wind conditions. Discriminating between them and inquiring which of them are energetically and-or mechanically favorable would be an impressive achievement to the issue of SCADA-based custom wind farm optimization and to the perspective of yaw active control systems [21].

References
[1] F. Castellani, D. Astolfi, L. Terzi, K.S. Hansen, and J.S. Rodrigo. Analysing wind farm efficiency on complex terrains. In Journal of Physics: Conference Series, volume 524, page 012142. IOP Publishing, 2014.
[2] R.J. Barthelmie, K.S. Hansen, and S.C. Pryor. Meteorological Controls on Wind Turbine Wakes. Proceedings of the IEEE, 101(4):1010–1019, April 2013.
[3] R.J. Barthelmie, S.C. Pryor, S.T. Frandsen, K.S. Hansen, J.G. Schepers, K. Rados, W. Schlez, A. Neubert, L.E. Jensen, and S. Neckelmann. Quantifying the impact of wind turbine wakes on power output at offshore wind farms. Journal of Atmospheric and Oceanic Technology, 27(8):1302–1317, 2010.
[4] K.S. Hansen, R.J. Barthelmie, L.E Jensen, and A. Sommer. The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at horns rev wind farm. Wind Energy, 15(1):183–196, 2012.
[5] P. McKay, R. Carriveau, and D. S.-K. Ting. Wake impacts on downstream wind turbine performance and yaw alignment. Wind Energy, 16:221–234, March 2013.
[6] F. Port-Agel, Y.-T. Wu, and C.-H. Chen. A numerical study of the effects of wind direction on turbine wakes and power losses in a large wind farm. Energies, 6(10):5297–5313, 2013.
[7] J.S. Rodrigo, P. Gancarski, R.C. Arroyo, P. Moriarty, M. Chuchfield, J.W. Naughton, K.S. Hansen, E. Macheauf, T. Koblitz, E. Maguire, et al. Iea-task 31 wakebench: Towards a protocol for wind farm flow model evaluation, part 1: Flow-over-terrain models. In Journal of Physics: Conference Series, volume 524, page 012105. IOP Publishing, 2014.
[8] A. Makridis and J. Chick. Validation of a cfd model of wind turbine wakes with terrain effects. Journal of Wind Engineering and Industrial Aerodynamics, 123:12–29, 2013.
[9] M. Lee, S.H Lee, N. Hur, and C. Choi. A numerical simulation of flow field in a wind farm on complex terrain. Wind and Structures, 13(4):375, 2010.
[10] F. Castellani, D. Astolfi, and L. Terzi. Mathematical methods for performance evaluation of onshore wind farms through scada data mining. Recent Advances in Energy, Environment and Financial Planning, 2014.
[11] N.G. Mortensen, L. Landberg, I. Troen, and E. Lundtang Petersen. Wind atlas analysis and application program (wasp). 1993.
[12] A.J. Bowen and N.G. Mortensen. WASP prediction errors due to site orography. 2004.
[13] P. Moreno, A.R Gravdahl, and M. Romero. Wind flow over complex terrain: application of linear and cfd models. In European Wind Energy Conference and Exhibition, pages 16–19, 2003.
[14] B. Sanderse. Aerodynamics of wind turbine wakes. Energy Research Center of the Netherlands (ECN), ECN–E–09-016, Petten, The Netherlands, Tech. Rep, 2009.
[15] P.M. Rétoré, N. Sørensen, and F. Zahle. Validation of an actuator disc model. In 2010 European Wind Energy Conference and Exhibition, 2010.
[16] F. Castellani and A. Vignaroli. An application of the actuator disc model for wind turbine wakes calculations. Applied Energy, 101:432–440, 2013.
[17] G. Craoto, A.R. Gravdahl, F. Castellani, and E. Piccioni. Wake modeling with the actuator disc concept. Energy Procedia, 24:385–392, 2012.
[18] C. Peralta, H. Nugusse, S.P. Kokilavani, J. Schmidt, and B. Stovevandt. Validation of the simplefoam (rans) solver for the atmospheric boundary layer in complex terrain. In ITM Web of Conferences, volume 2, page 01002. EDP Sciences, 2014.
[19] L. Casella, W. Langreder, A. Fischer, M. Ehlen, and D. Skoutelakos. Dynamic flow analysis using an openfoam based cfd tool: Validation of turbulence intensity in a testing site. In ITM Web of Conferences, volume 2, page 04002. EDP Sciences, 2014.
[20] M Gaumond, P-E Rétoré, Sürén Ott, Alfredo Peña, Andreas Bechmann, and Kurt Schaldemose Hansen. Evaluation of the wind direction uncertainty and its impact on wake modeling at the horns rev offshore wind farm. Wind Energy, 17(8):1169–1178, 2014.
[21] P. Fleming, S. Lee, M. Chuchfield, A. Scholbrock, J. Michalakes, K. Johnson, and P. Moriarty. The SOWFA super-controller: A high-fidelity tool for evaluating wind plant control approaches. Technical Report NREL/CP-5000-57175, National Renewable Energy Laboratory, Golden, CO, January 2013. To be presented at EWEA 2013 Vienna, Austria February 4-7, 2013.