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Annual report 2016

Optimal design of wind energy projects: An integrated approach

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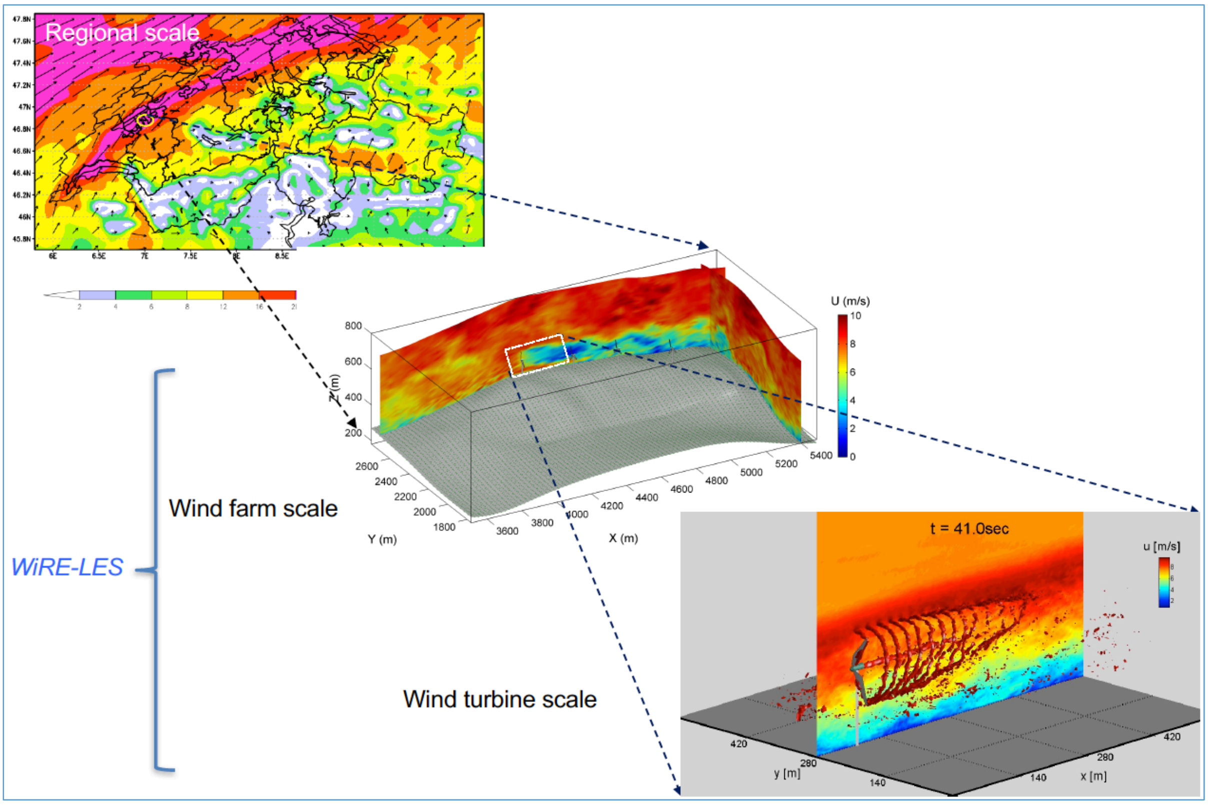

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List of abbreviations

LiDAR	Light Detection and Ranging
LES	Large-eddy simulation
SCADA	Supervisory Control and Data Acquisition
WiRE	Wind Engineering and Renewable Energy Laboratory (EPFL)

Project goals

The main goal of this project is to develop and validate numerical models for the accurate prediction of wind farm performance. To achieve that, a unique combination of computer simulations, field experiments and wind-tunnel experiments are used. This project will ultimately help optimize the design of future wind energy projects and, thus, guarantee their feasibility in Switzerland (within the 2050 Swiss Energy Strategy) and worldwide.

Summary

The main goal of this project is to develop and validate a 'Virtual Wind Simulator' for the optimal design (layout) and operation of wind energy projects. During the first year of the project, progress has been made, as planned, on tasks corresponding to the three main work packages. The activities and main results for each task are briefly summarized below:

- ***Numerical Simulations***: The development of the EPFL Virtual Wind Simulator has focused on improving the ability of our computational models to simulate wind turbine performance on complex terrain. The new tool has been validated for the only case of airflow through wind turbines over topography for which wind tunnel flow data is currently available for validation. This first validation exercise has shown an excellent performance of our large-eddy simulation (LES) code.

- ***Wind-tunnel experiments***: An optimized miniature wind-turbine model has been designed and built to be used in controlled wind-tunnel experiments. Its performance (power and thrust coefficients) is more realistic than any turbine model used in wind tunnels before. This model turbine is currently being used at the EPFL-WiRE wind-tunnel facility to carefully characterize its performance and the wake flow (using laser-based techniques) under different conditions. These experiments are providing unique datasets that will soon be used for further validation of the EPFL Virtual Wind Simulator.

- ***Field experiments***: Field experiments have continued, as planned, in Collonges, where a new volumetric scanning technique using the three laser-based EPFL wind LiDARs has been tested. The measurements are giving interesting new insights on how the turbine wake (shadow) flows is affected by atmospheric conditions. This in turn would affect the performance of downwind turbines in wind farms.

Work undertaken and findings obtained

During the first year of the project, progress has been made, as planned, on four Tasks (Tasks 1.1, 1.2, 2.1 and 3.1) covering the three main work packages (WP1, WP2 and WP3). The activities and main findings for each Task are summarized below:

Tasks 1.1 and 1.2 *(Work Package 1: Numerical Simulations)*

The large-eddy simulation (LES) code developed at the EPFL-WiRE Laboratory has been improved (Task 1.1) and validated (Task 1.2) for the simulation of wind and turbulence and their interaction with wind turbines and wind farms over complex terrain. This has been achieved by including a terrain-following coordinate method to represent the topography, together with a rotating actuator disc model (Porté-Agel et al., 2011) to represent the wind turbines. The improved LES code has been validated for the only case of airflow through wind turbines over topography for which wind tunnel flow data is available for validation (Tian et al. 2013).

First, boundary-layer flow was simulated over a two-dimensional hill in order to characterize the spatial distribution of the mean velocity and the turbulence statistics. A flow simulation was then performed through a wind farm consisting of five horizontal-axis wind turbines sited over the same hill in an aligned layout. The resulting flow characteristics were compared with the former case, i.e., without wind turbines. To assess the validity of the simulations, the results were compared with the wind-tunnel measurements of Tian et al. (2013). It is found that LES can reproduce the flow field effectively, and, specifically, the speed-up over the hilltop and the velocity deficit and turbulence intensity enhancement induced by the turbines are well captured by the simulations. Besides, the vertical profiles of the mean velocity and turbulence intensity at different streamwise positions match well those for the experiment (see Figure 2 for sample results). In addition, another numerical experiment was carried out to show how higher (and more realistic) thrust coefficients of the turbines lead to stronger wakes and, at the same time, higher turbulence intensities (see Figure 1, bottom panel, for sample results).

A journal paper with these results has just been published in the journal *Boundary-Layer Meteorology* (Shamsoddin and Porté-Agel, 2017) and it can be found in the attachments. This research was also presented at the Annual meeting of the European Geophysical Union held in Vienna in April 2016.

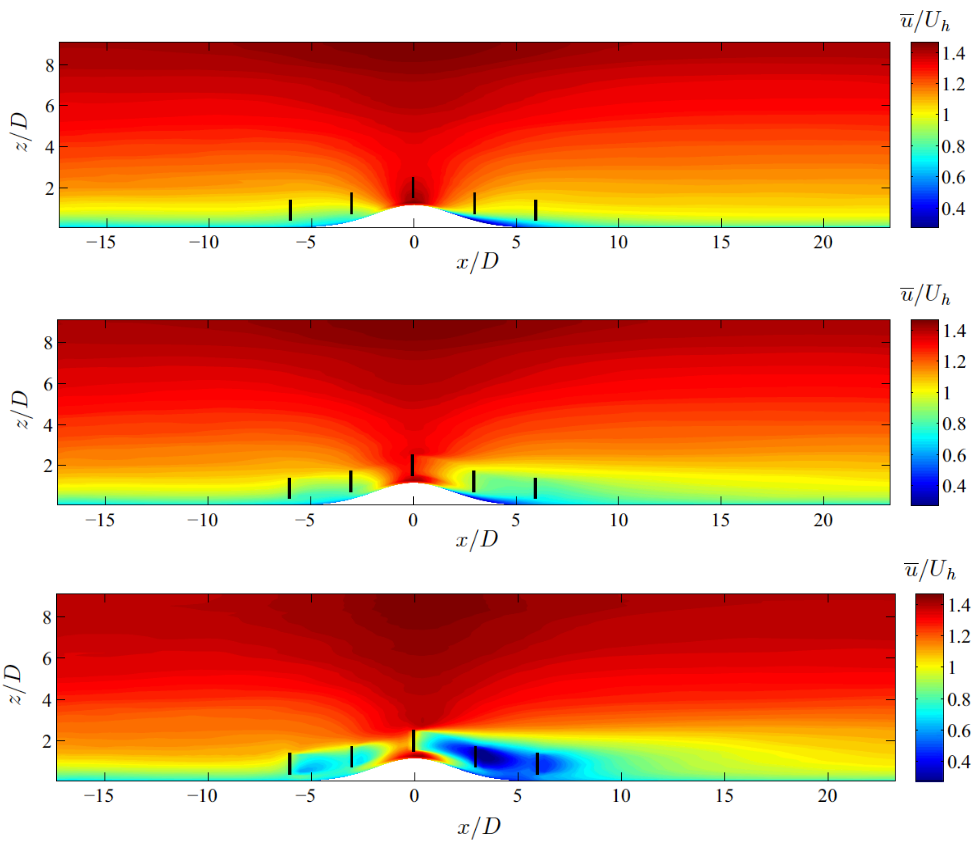

Figure 1. Contours of the simulated mean streamwise velocity component in the vertical midplane of the domain in the case without turbines (top), with the turbines used in the experiment (middle) and with virtual turbines with a more realistic thrust coefficient of C_T=0.8 (bottom).

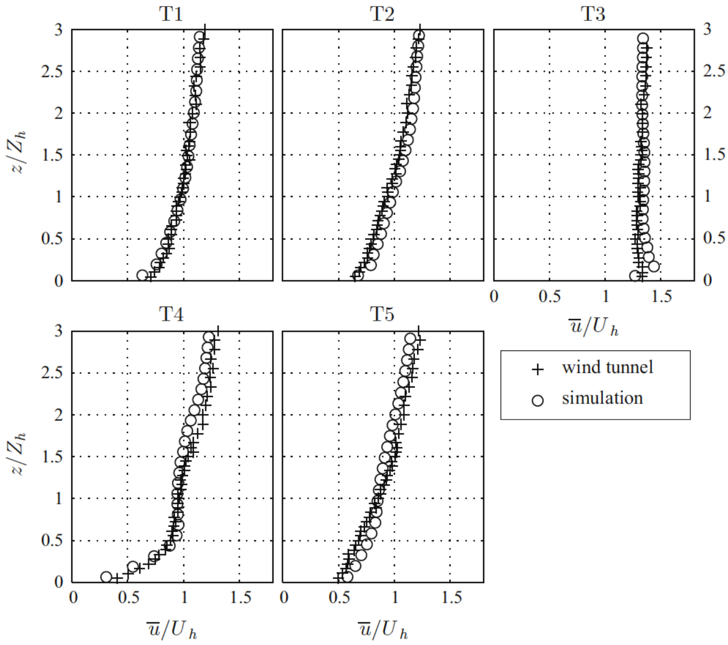

Figure 2. Vertical profiles of the mean streamwise velocity component in five different streamwise positions in the vertical midplane of the domain for the case with the turbines (wind-tunnel data from Tian et al. 2013).

Task 2.1 *(Work Package 2: Wind-tunnel experiments)*

Task 2.1.1 Wind-turbine design

Miniature wind turbines employed in wind tunnel studies commonly suffer from poor performance with respect to their large-scale counterparts in the field. Moreover, although wakes of wind turbines have been extensively examined in wind tunnel studies, the proper characterization of the performance of wind turbines has received relatively less attention. In this regard, the present study concerns the design and the performance analysis of a new three-bladed horizontal axis miniature wind turbine with a rotor diameter of 15 cm. Due to its small size, this turbine, called WiRE-01, is particularly suitable for studies of wind farm flows and the interaction of the turbine with an incoming boundary-layer flow.

The turbine is designed based on Glauert's optimum rotor, and it is built with three-dimensional (3D) printing technology. Especial emphasis was placed on the accurate measurement of the mechanical power extracted by the miniature turbine from the incoming wind. In order to do so, a new setup was developed to measure the torque of the rotor shaft. Its performance (power and thrust coefficients) is more realistic than any turbine model used in wind tunnels before. Specifically, force and power measurements showed that the thrust and power coefficients of the miniature turbine can reach to 0.8 and 0.4, respectively, which are close to the ones of large-scale turbines in the field. Finally, the interaction of the turbine with a turbulent boundary layer was studied. The comparison of the spectral density of the thrust force and the one of the incoming velocity reveals new insights on the use of the turbine as an indicator of incoming flow conditions. High-resolution stereoscopic particle image velocimetry measurements were also performed in the wake of the turbine operating at optimal conditions. These measurements provide a valuable dataset for the validation of numerical models, including our Virtual Wind Simulator (Work Package 1). This validation will be the focus of our future research.

Two journal papers with these results have been submitted and are currently being reviewed in the journals *Physics of Fluids* (Bastankhah and Porté-Agel, 2017a) and *Experiments in Fluids* (Bastankhah and Porté-Agel, 2017b). This research was also presented at the Annual meeting of the European Geophysical Union held in Vienna in April 2016.

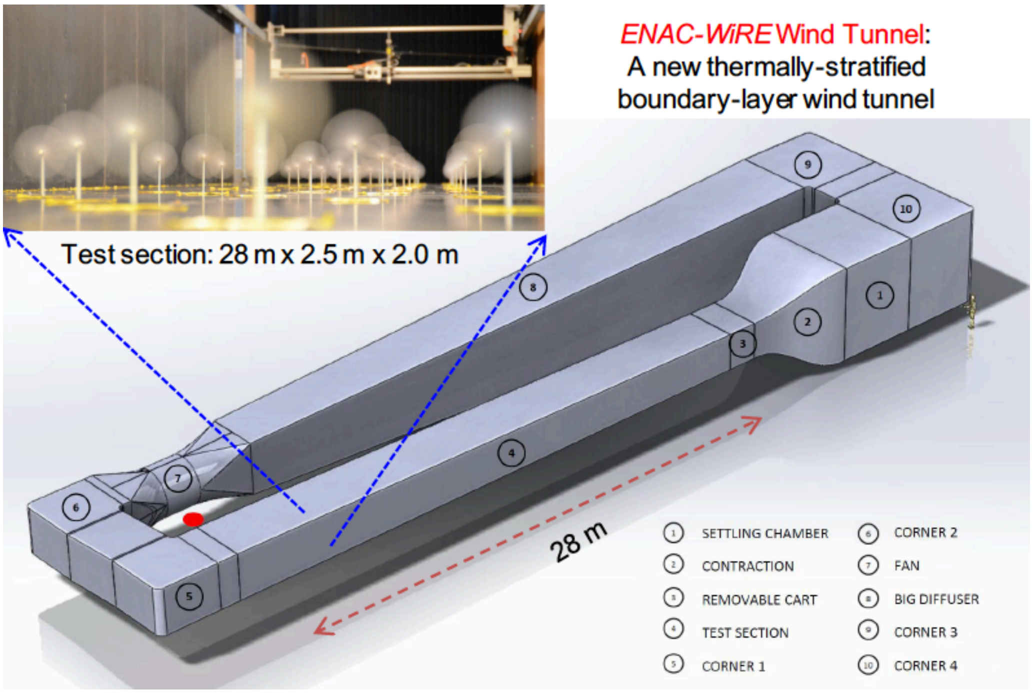

Figure 3. Schematic of the EPFL-WiRE wind tunnel facility and picture of the test section.

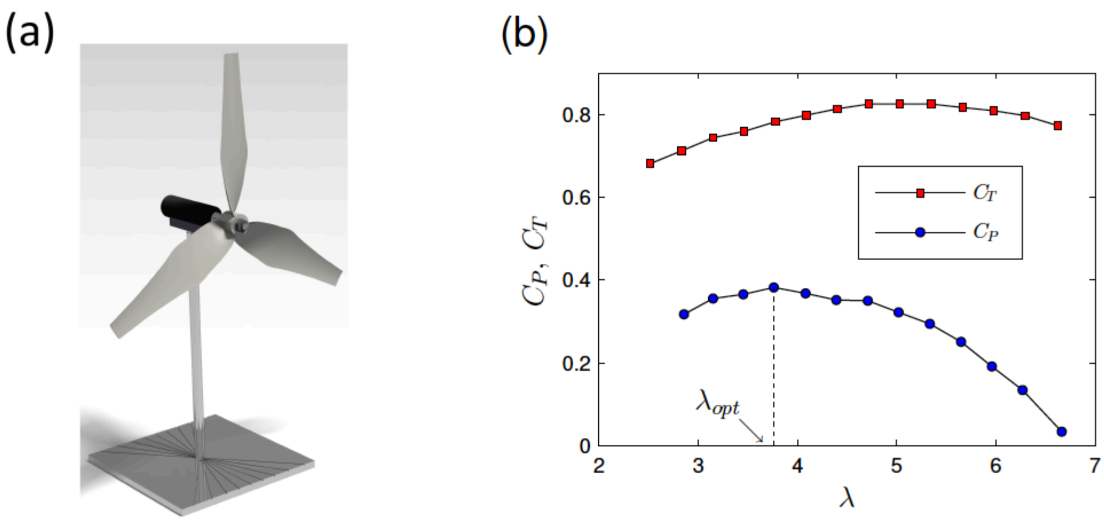

Figure 4. Schematic of the miniature wind turbine placed in the turbulent boundary layer. (b) Variation of C_T and C_P with the tip-speed ratio λ for the new miniature turbine placed in the boundary layer.

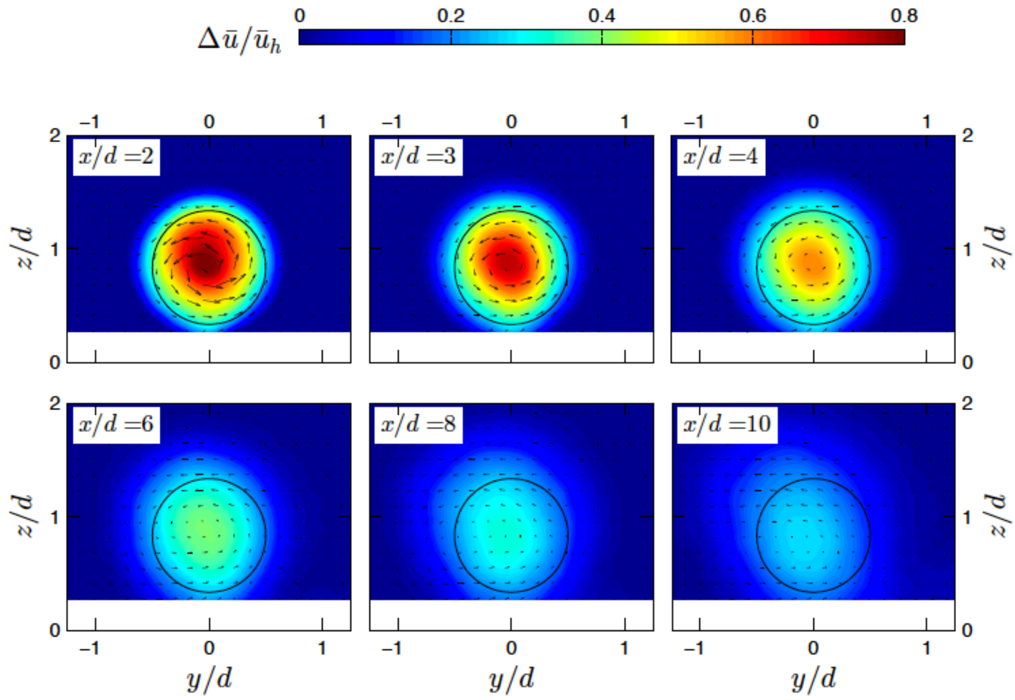

Figure 5. Contours of the normalized velocity in y-z planes at different downwind locations for the miniature turbine operating in optimal conditions. The vector field represents the in-plane velocity components. The black circles show the frontal area of the wind turbine. Dimensions are normalized with the rotor diameter *d*.

2.1.2. Study of turbine yawing as a potential wake mitigation strategy

Yawing of wind turbines has the potential to deflect the wake, thus reducing its impact on downwind turbines. This work is dedicated to systematically studying and predicting the wake characteristics of a yawed wind turbine immersed in a turbulent boundary layer. To achieve this goal, wind tunnel experiments were performed to characterize the wake of a horizontal-axis wind turbine model. A high-resolution stereoscopic particle image velocimetry system was used to measure the three velocity components in the turbine wake under different yaw angles γ and tip-speed ratios λ (Figs. 6 and 7). Moreover, power and thrust measurements were carried out to analyze the performance of the wind turbine. These detailed wind tunnel measurements were then used to perform a budget study of the continuity and Reynolds-averaged Navier–Stokes equations for the wake of a yawed turbine. This theoretical analysis revealed some notable features of the wakes of yawed turbines, such as the asymmetric distribution of the wake skew angle with respect to the wake center. Under highly yawed conditions, the formation of a counter-rotating vortex pair in the wake cross-section as well as the vertical displacement of the wake center were shown and analyzed (Fig. 8). Finally, this study enabled us to develop general governing equations upon which a simple and computationally inexpensive analytical model was built. The proposed model aims at predicting the wake deflection and the far-wake velocity distribution for yawed turbines. Comparisons of model predictions with the wind tunnel measurements show that this simple model can acceptably predict the velocity distribution in the far wake of a yawed turbine. Apart from the ability of the model to predict wake flows in yawed conditions, it can provide valuable physical insight on the behavior of turbine wakes in this complex situation.

A journal paper with these results has just been published in the *Journal of Fluid Mechanics*

(Bastankhah and Porté-Agel, 2016) and it can be found in the attachments. This research was also presented at the Annual meeting of the European Geophysical Union held in Vienna in April 2016.

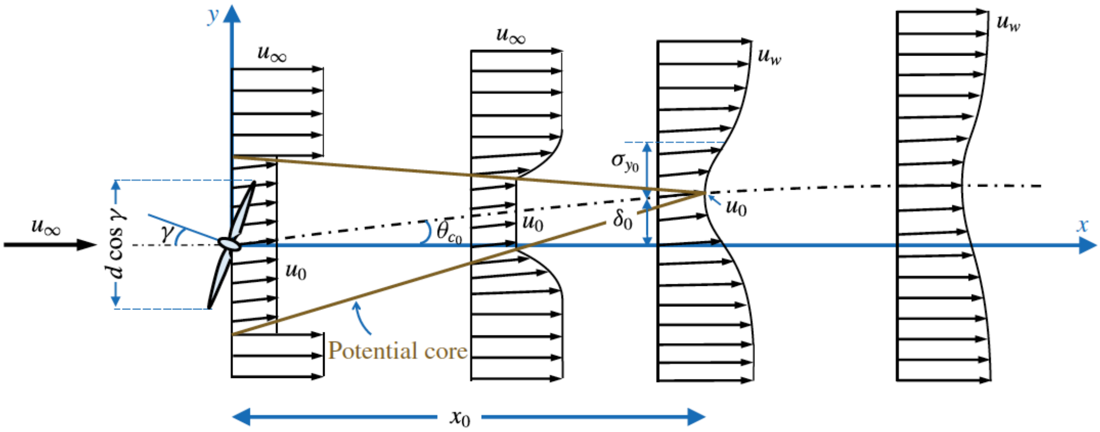

Figure 6. Schematic of the wake of a yawed wind turbine.

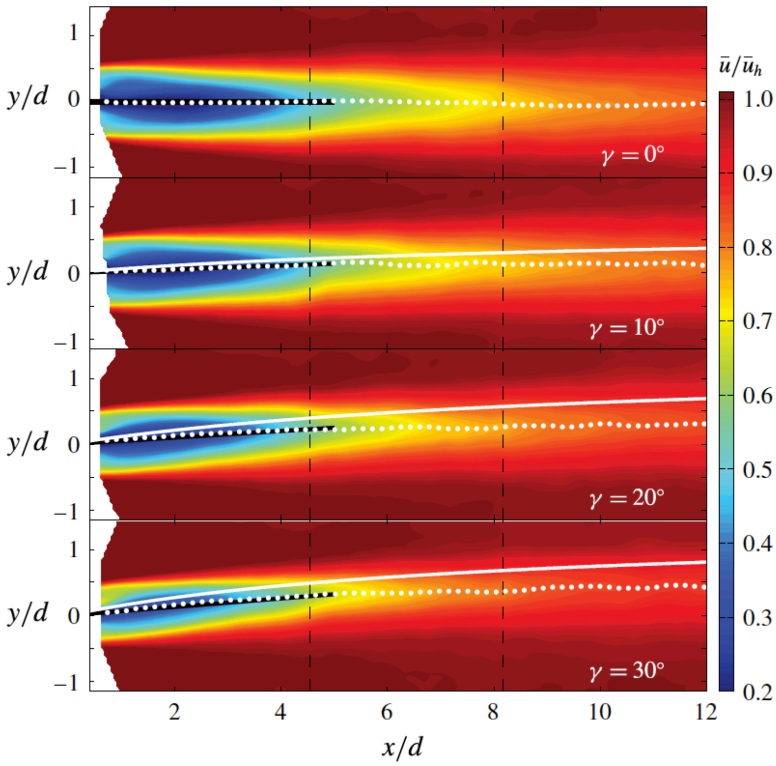

Figure 7. Contours of the normalized mean streamwise velocity in the horizontal plane at hub height downwind of a turbine for different yaw angles (γ). White dots and white lines represent the wake-center trajectory in the horizontal plane obtained from the wind tunnel measurements and Jiménez *et al.* (2010), respectively.

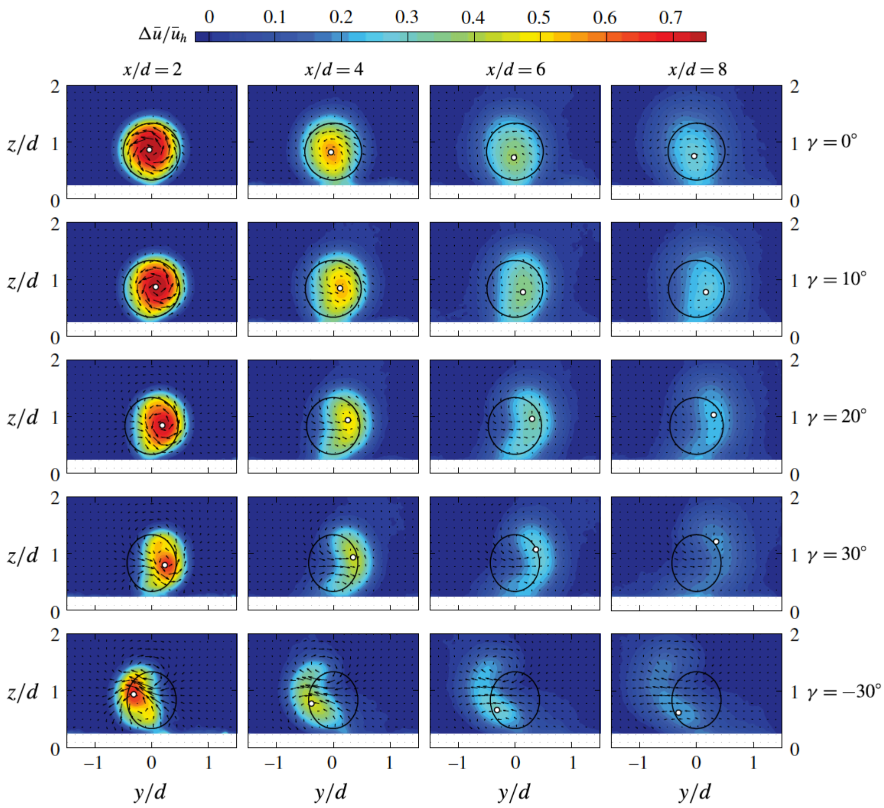

Figure 8. Contours of the normalized streamwise velocity deficit in *y-z* planes at different downwind locations and different yaw angles. Black circles indicate the frontal area of the wind turbine and white dots represent the wake-centre position at each downwind location. The vector field represents the in-plane velocity components.

Task 3.1 *(Work Package 3: Field experiments)*

Field experiments have been carried out, as planned, in Collonges, Switzerland. Specifically, a new volumetric scanning technique using the three EPFL wind LiDARs has been developed and used to characterize the wake flow under different atmospheric conditions (see Fig. 9). The measurements have allowed us to reconstruct, for the first time, the mean velocity field in a volume behind the wind turbine (see sample measurement in Fig. 10). This information is unique and provides interesting new insights on how the rate of recovery of the turbine wake flow changes with atmospheric conditions such as thermal stability. This in turn would affect the performance of downwind turbines in a wind farm.

These field measurements have allowed us to quantify and compare the growth of the wind turbine wake in both the spanwise and the vertical direction. As shown in Fig. 11, the wake is clearly non-axisymmetric and expands faster in the spanwise direction, compared with the vertical direction. This is due to the fact that the turbulence level in the incoming atmospheric flow is stronger in the spanwise direction than in the vertical one. Note that some numerical models currently used to predict turbine wakes assume that turbine wakes are axisymmetric.

The results from this research have been presented at the *International Conference in Boundary Layers and Turbulence* (Carbajo-Fuertes and Porté-Agel, 2016). This research was also presented at the Annual meeting of the European Geophysical Union held in Vienna in April 2016.

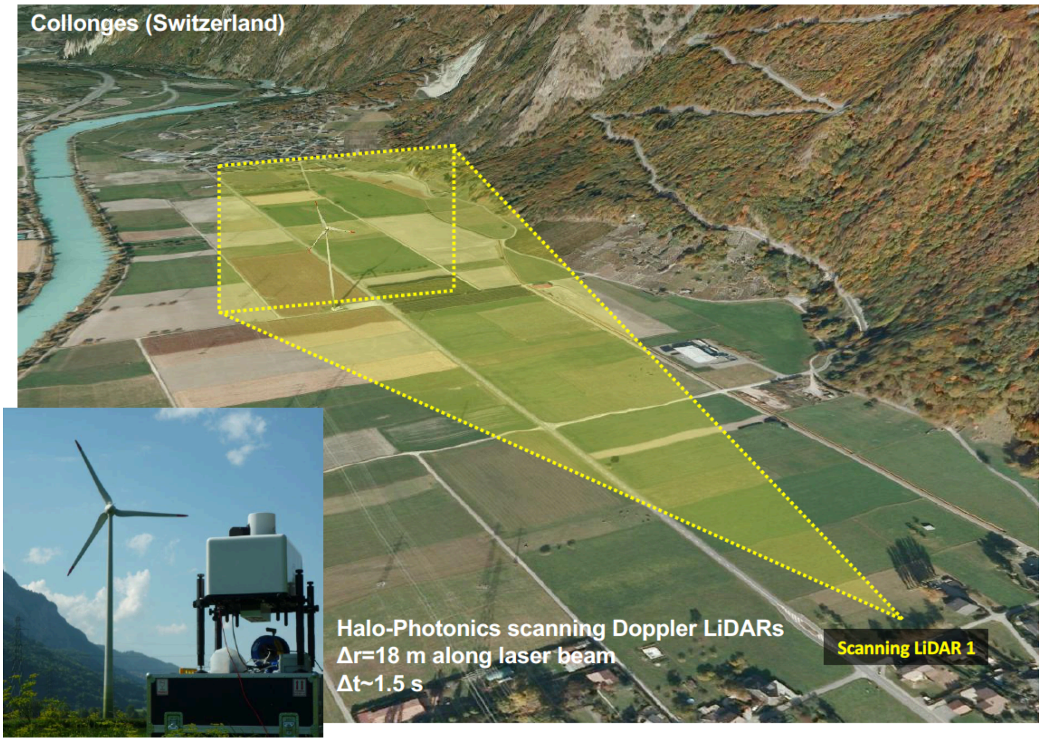

Figure 9. View of the experimental site with the sampling volume (in yellow) obtained with one of the three LiDARs. Bottom left: Picture of the LiDAR and the wind turbine in the background.

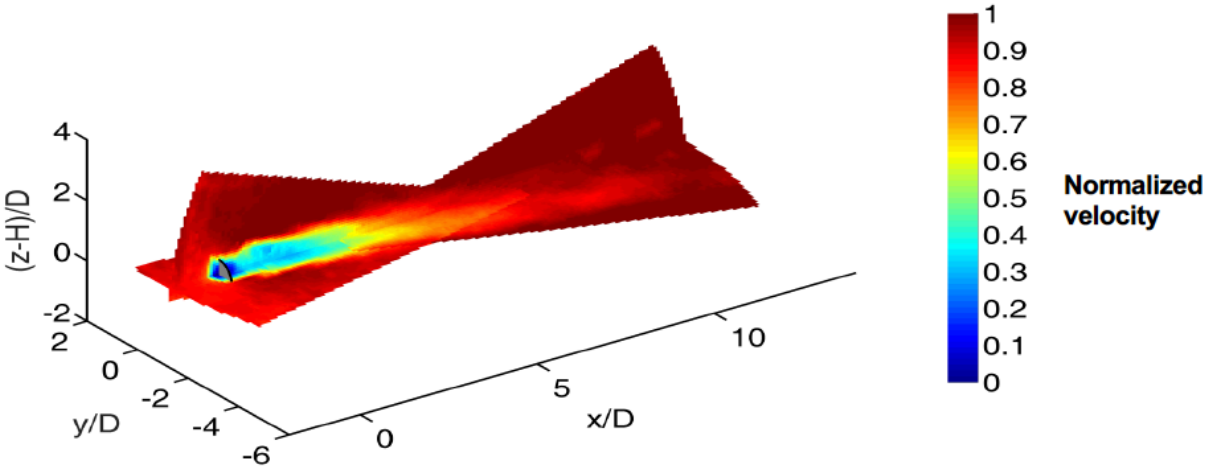

Figure 10. Horizontal and vertical contour plots of the mean velocity intersecting the turbine axis and obtained from the volumetric scan. The presence of the wake, characterized by a reduction in wind velocity, is evident from these measurements.

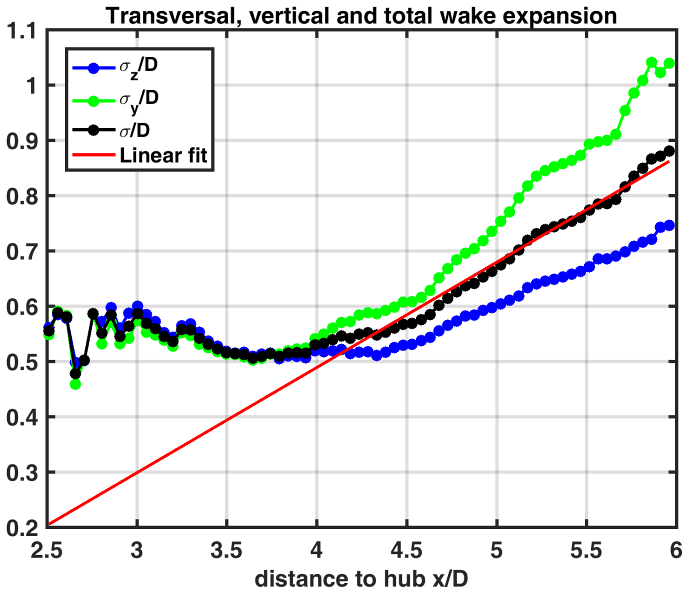

Figure 11. Standard deviation of the wake velocity deficit in the spanwise and vertical directions, and overall (total) standard deviation. These results show a clear non-axisymmetry of the wake, which expands faster in the spanwise than in the vertical.

National cooperation

During the first year of the project, active collaboration has been carried out with the following national partners:

- **The Swiss companies of the group 'EOS Holding' (EOSH):** EOSH is interested in this research and was supporting during 2016 a PhD student (Sina Shamsoddin) who is working on the WiRE LES simulations over topography (Tasks 1.1 and 1.2).

- **Our partners of the SCCER-FURIES Project ('The Future Swiss Electrical Infrastructure'):** Our Laboratory (WiRE) is currently leading a Subtask on 'Energy Power Forecasting Tools', which is focused on the development of prediction tools for renewable energies and their integration to the grid in the context of the Swiss Energy Strategy 2050. Our partners in that Subtask include other Laboratories at EPFL, ETHZ (LEC Laboratory) and the Institute of Computational Science of the USI. In the context of that collaborative research, the ongoing numerical simulations (Task 1), wind tunnel measurements (Task 2) and LiDAR field measurements (Task 3) will be very valuable for the validation of the numerical models that are being developed within the SCCER-FURIES.

- **The Commune de Lausanne** (J.M. Rouller) **and KholeNusbaumer** have provided the SCADA data of the wind turbines and access to the wind turbine in Collognes (Task 3).

International cooperation

The following international collaborations have been carried out during the first year of the project:

- Our Laboratory is the Swiss representative at the **WAKEBENCH Task 31 (Benchmarking Wind Farm Flow Models) of the IAE (International Energy Agency) Wind**. Particularly, the datasets being collected in our wind tunnel (Task 2) and in the field (Task 3) will be proposed as cases to be used within WAKEBENCH for validation of numerical models used for the prediction of wind turbine wake flows and power losses in wind farms.

- International collaboration continues with Prof. Charles Meneveau from Johns Hopkins University and Prof. Jens Sorensen from the Danish Technical University (DTU) within the context of the USA-based **WINDINSPIRE project**. Within the framework of the WINSPIRE project, for which EPFL does not receive funding, two bachelor students visited EPFL and participated in the wind tunnel and field experiments.

- International collaboration has also continued within a project partially supported by **EuroTech**, which is a consortium of 4 European technical universities: EPFL, DTU, TU Eindhoven and TU Munich. Majid Bastankhah received partial funding from Eurotech and a collaboration is currently ongoing in the wind-tunnel measurements with TU Munich and DTU.

Evaluation 2016 and outlook for 2017

The project is progressing as planned and substantial progress has been made in most of the tasks, as summarized above. We are particularly pleased by the fact that several scientific papers have been already published and several national and international collaborations have been established during the first year of the project.

During 2017, we plan to continue making progress on the three Work Packages of the project. Specifically, the following tasks will be pursued:

- **Work Package 1 (Numerical simulations):** The 'Virtual Wind Simulator' will be further developed and validated during 2017. Specifically, besides the improvement and testing of the EPFL WiRE LES code, we will work also on the coupling of LES with a large-scale weather model in order to cover the full range of scales (from regional scale to wind turbine scale) and be able to forecast wind farm performance. Moreover, we will use the wind-tunnel data collected during 2016 as well as the new wind-tunnel data and field data collected during 2017 (see below) for the validation of the Virtual Wind Simulator.

- **Work Package 2 (Wind-tunnel experiments):** New wind tunnel experiments will be carried out during 2017 using the improved wind turbine model developed during the first year of the project. Special emphasis will be placed on studying wake flows in wind farms with different layouts, and assessing the potential of wake mitigation strategies such as selective turbine yawing and/or down-regulation in wind farms.

- **Work Package 3 (Field experiments):** A collaboration has been established with the Prof. Corey Markfort from the University of Iowa, and the turbine manufacturer Clipper to carry out a field experiment to study the wake flow around a research wind turbine managed by the University of Iowa. The experiment will be carried out in 2017 and it is unique in that two EPFL wind LiDARs will be installed on the nacelle of the turbine. This novel arrangement will allow us to improve the quality of the wake measurements (by reducing measurement errors) and also maximize the amount of usable data compared with the case of having the LiDARs on the ground (as done in

Colognes in 2016). This is due to the fact that the nacelle-mounted LiDARs will always be fairly well aligned with the wind-turbine axis. Moreover we will keep pursuing further collaborations for field experiments with other national and international partners.

References

Bastankhah M., and Porté-Agel F. (2016). Experimental and theoretical study of wind turbine wakes in yawed conditions. *Journal of Fluid Mechanics*, 806, 506–541.

Bastankhah M., and Porté-Agel F. (2017a). Wind tunnel study of the boundary layer flow interaction with a wind turbine under different operating conditions. Under review in *Physics of Fluids*.

Bastankhah M., and Porté-Agel F. (2017b). A new miniature wind turbine for wind tunnel experiments: design, performance analysis and wake measurements. Under review in *Experiments in Fluids*.

Carbajo Fuertes F., and Porté-Agel F. (2016). Volumetric LiDAR scanning of a wind turbine wake and comparison with a 3D analytical wake model. 22nd Symposium on Boundary Layers and Turbulence. 20-24 June 2016, Salt Lake City, UT, USA.

Porté-Agel F., Wu, Y.-T., Lu H., Conzemius R.J. (2017). Large-eddy simulation of atmospheric boundary layer flow through wind turbines and wind farms. *Journal of Wind Engineering and Industrial Aerodynamics*, 99(4), 154-168.

Shamsoddin S., and Porté-Agel F. (2016). Large-Eddy Simulation of Atmospheric Boundary-Layer Flow Through a Wind Farm Sited on Topography. In press in *Boundary Layer Meteorology*.

Tian W., Ozbay A., Yuan. W., Sarkar P., and Hu H. (2013). An experimental study on the performances of wind turbines over complex terrains. *51st Am. Inst. Aeronaut. Astronaut. Aerospace Sci. Mtg*., Grapevine, TX, USA.

Appendices

The following appendices containing the journal articles that have been published or are currently under review can be found in the attached files.

Appendix 1: Shamsoddin S., and Porté-Agel F. (2016). Large-Eddy Simulation of Atmospheric Boundary-Layer Flow Through a Wind Farm Sited on Topography. In press in *Boundary Layer Meteorology*.

Appendix 2: Bastankhah M., and Porté-Agel F. (2016). Experimental and theoretical study of wind turbine wakes in yawed conditions. *Journal of Fluid Mechanics*, 806, 506–541.

Appendix 3: Bastankhah M., and Porté-Agel F. (2017a). Wind tunnel study of the boundary layer flow interaction with a wind turbine under different operating conditions. Under review in *Physics of Fluids*.

Appendix 4: Bastankhah M., and Porté-Agel F. (2017b). A new miniature wind turbine for wind tunnel experiments: design, performance analysis and wake measurements. Under review in *Experiments in Fluids*.