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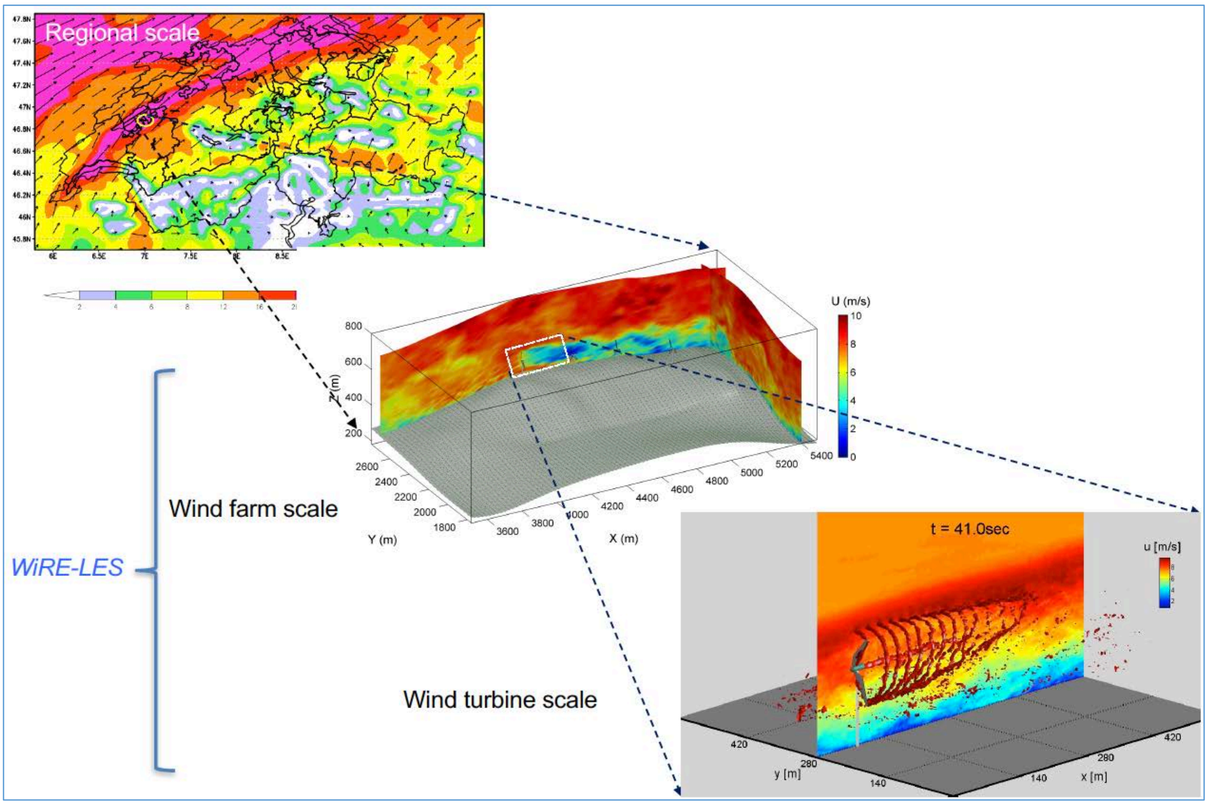
Department of the Environment, Transport, Energy and Communication
DETEC

Swiss Federal Office of Energy SFOE
Energy Research

Final Report

Optimal design of wind energy projects: An integrated approach



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Author:
Prof. Fernando Porté-Agel, EPFL ENAC IIE WIRE, fernando.porte-agel@epfl.ch

SFOE head of domain: Dr Katja MAUS – OFEN, Bern
Katja.maus@bfe.admin.ch

SFOE program manager: Lionel Perret – Planair SA, la Sagne
Lionel.perret@planair.ch

SFOE contract number: SI/501337-01

Swiss Federal Office of Energy SFOE
Mühlestrasse 4, CH-3063 Ittigen; postal address: CH-3003 Bern
Phone +41 58 462 56 11 · Fax +41 58 463 25 00 · contact@bfe.admin.ch · www.bfe.admin.ch

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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. The tools developed and tested during 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 course of the project, substantial progress has been made on all the planned tasks, corresponding to the three main work packages highlighted in the original proposal. 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, as well as wind-turbines subjected to active yaw control. The new tool has been validated for both topography and active yaw control against wind tunnel flow data collected for that purpose. This unique validation exercise has shown an excellent performance of our newly-developed 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 has been 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 for the validation of the EPFL Virtual Wind Simulator (e.g., LES) of wake flows of wind turbines subject to topography effects as well as yaw control strategies.

- ***Field experiments*:** Three field experiments have been carried out, as planned, using the EPFL-WiRE scanning doppler lidars. The experiments were performed in Collonges (single turbine; ground-based lidars), Iowa (single turbine; nacelle-based lidars), and Colorado (wind farm with active yaw control; nacelle-based lidars). The measurements have provided interesting new insights on how the turbine wake (shadow) flows are affected by atmospheric conditions and yaw control strategies. The datasets are being used to validate numerical models.

Work undertaken and findings obtained

During the three years of the project, progress has been made, as planned, on seven Tasks covering the three main work packages (WP1, WP2 and WP3). The activities and main findings for each Task are summarized below:

Work Package 1: Numerical Simulations

Tasks 1.1. and 1.2: Implementation and validation of the WiRE large-eddy simulation (LES) framework of flow through wind farms in complex terrain

The turbulence-resolving 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 new terrain-following coordinate method to represent the topography, together with an 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). 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. In addition, another numerical experiment was carried out to show how higher (and more realistic) thrust coefficients of the turbines lead to stronger wakes (see Figure 1, bottom panel, for sample results). A journal paper with these results has been published in the journal *Boundary-Layer Meteorology* (Shamsoddin and Porté-Agel, 2017).

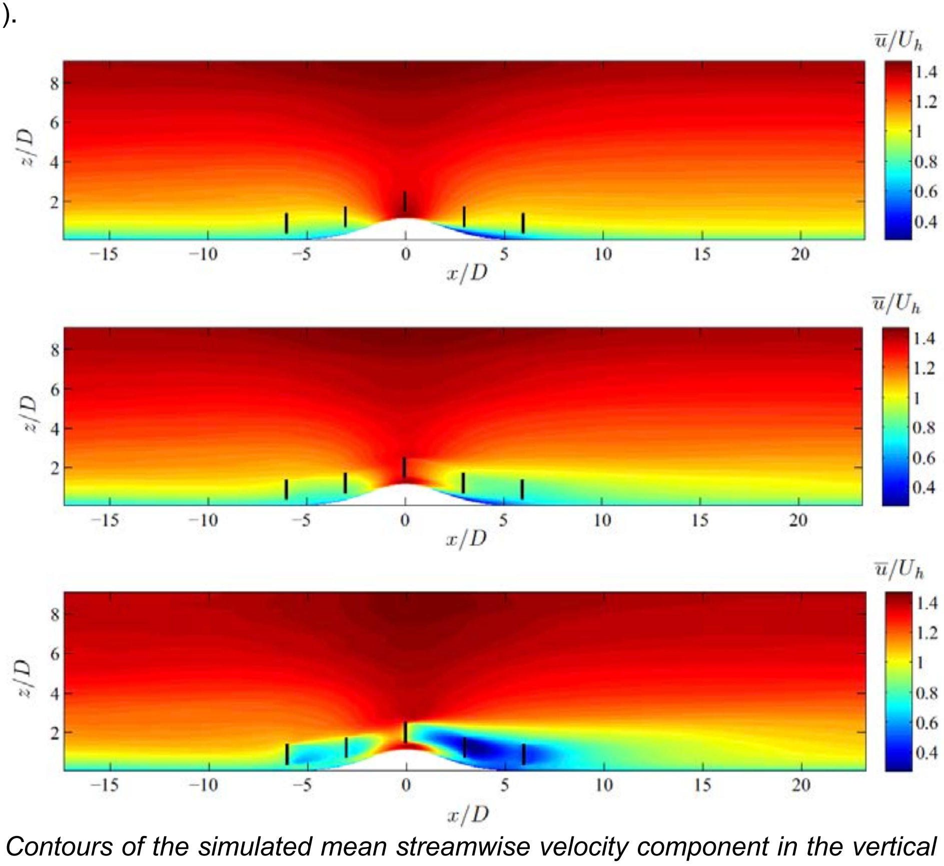

Figure 1: *Contours of the simulated mean streamwise velocity component in the vertical midplane of the domain in the case without turbines (top), with the turbines used in the experiment (middle) and with virtual turbines with a more realistic thrust coefficient of* C_T*=0.8 (bottom).*

Tasks 1.3: A new wind-turbine model for yawed turbines in LES

Active yaw control consists of deliberately misaligning the orientation of a wind turbine with respect to the incoming wind direction with the goal of redirecting the turbine wakes and reducing their impact on downwind turbines. Its potential to mitigate wake-induced power losses has been recently recognized in the wind energy community (see review by Porté-Agel et al., 2020). We have developed and validated a wind-turbine parameterisation (called the ADMR) for turbulence-resolving large-eddy simulation (LES) of yawed wind-turbine wakes. LES results using a new ADMR model were validated with wind-tunnel measurements (see Work Package 2) of the wakes behind a stand-alone miniature wind turbine model with different yaw angles. Comparisons were also made with the predictions of analytical wake models. In general, LES results using the yawed ADMR are in good agreement with both wind-tunnel measurements and analytical wake models regarding wake deflections and spanwise profiles of the mean velocity deficit (Figs. 2 and 3). Moreover, the power output of the yawed wind turbine is directly computed from the tangential forces calculated by the yawed ADMR, in contrast with the indirect power estimation used in the standard actuator disk model. As a result, we found significant improvement in the power prediction from LES using the yawed ADMR over the simulations using the standard actuator disk without rotation, currently used in the wind energy community (Fig. 4), suggesting a good potential of the yawed ADMR to be applied in LES studies of active yaw control in wind farms. More details can be found in the journal paper by Lin and Porté-Agel (2019).

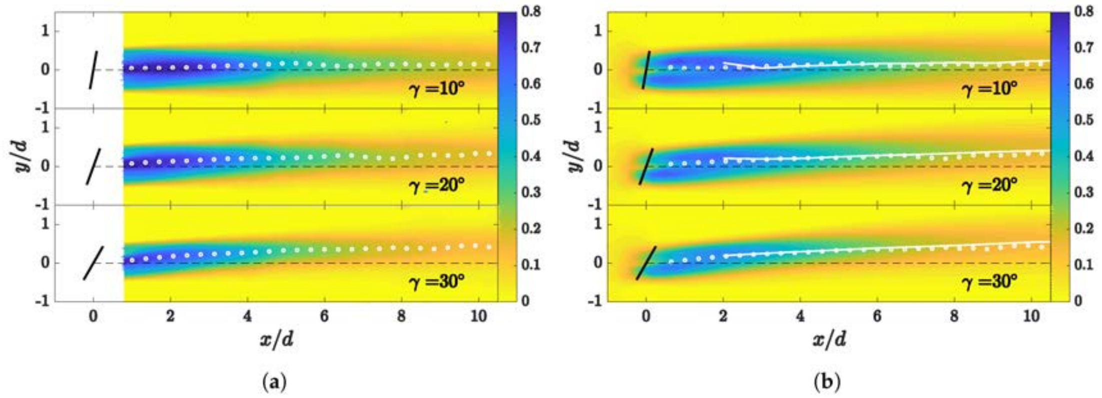

***Figure 2:** Contours of the normalised streamwise mean velocity deficit in the spanwise x-y cross-section plane at the hub height obtained from: (**a**) the wind-tunnel experiments; and (**b**) the LES using the yawed ADMR. The wake-centre trajectories are represented by white circles for the experiment results and by white solid lines for the simulation results. d is the turbine rotor diameter.*

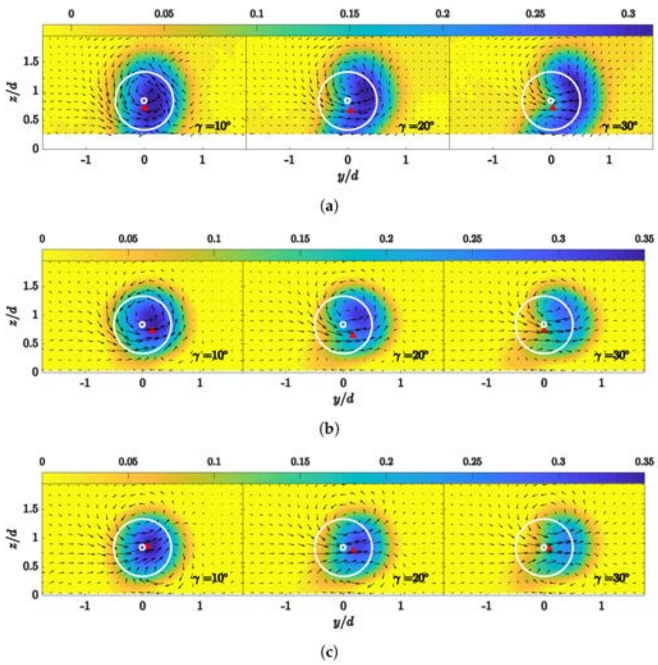

***Figure 3:** Contours of the normalised streamwise velocity deficit for different yaw angles γ, overlapped with vector fields of the in-plane velocity in the vertical y-z cross-section plane at x/d=6: (**a**) wind-tunnel measurements; (**b**) LES using the yawed ADMR; and (**c**) LES using the standard ADM. White circles outline the edges of the non-yawed turbine rotor. Red triangles outline the locations of the CVP centre. Distances are normalized with rotor diameter (d).*

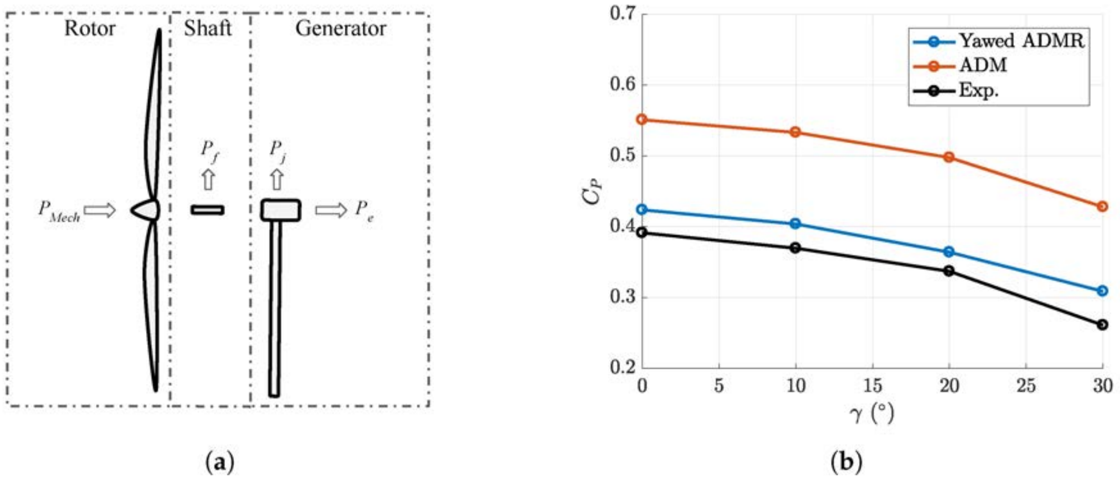

Figure 4: *(**a**) Conversion of power in the miniature wind turbine model: Mechanical power P_{Mech}, Shaft friction loss P_f, Electrical loss P_j and Electrical power P_e. (**b**) Mechanical power coefficient C_p for yaw angles 0°–30° obtained from the LES results and the wind-tunnel experiments.*

Tasks 1.4: Implementation of the EPFL WiRE simulation framework to a case study in Switzerland

A first study was conducted to assess a commercial Computational Fluid Dynamics (CFD) software, WindSim, regarding its ability to perform accurate wind power predictions in complex terrain. Simulations of the wind field and wind farm power output in the Swiss Jura Mountains at the location of the Juvent Wind Farm during winter were performed. The study site features the combined presence of three complexities: topography, heterogeneous vegetation including forest, and interactions between wind turbine wakes. Various turbulence models, forest models, and wake models, as well as the effects of domain size and grid resolution were evaluated against wind and power observations from nine Vestas V90's 2.0-MW turbines. The results show that WindSim is able to predict the performance of the wind farm with sufficient accuracy, but only after careful tuning of the multiple modelling parameters involved, thus making it difficult to generalize it to different conditions (Tabas et al., 2019). This highlights the importance of developing and testing more accurate and robust simulation tools such as the WiRE LES, which does not require any parameter tuning.

Recently, the tuning-free WiRE LES framework has been implemented for the simulation of flow over the complex terrain of the Juvent wind farm. Fig. 5 shows an instantaneous turbulent wind speed field simulated over the wind farm for one selected wind direction. We plan to extend this research in the near future to study and evaluate the ability of the LES-based numerical framework and other forecasting tools for the prediction of the wind farm performance. For that, a collaborative agreement has recently been reached with BKW Energies, the company managing the Juvent wind farm.

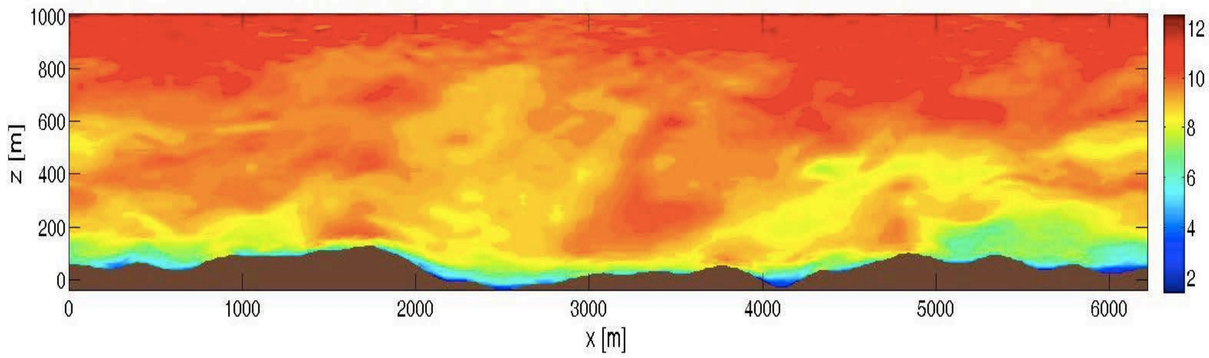

Figure 5: *Preliminary results obtained with the WiRE LES and the terrain-following coordinate transformation method: Instantaneous two-dimensional velocity field (m/s) over the complex terrain around the Juvent wind farm site in the Jura. The complexity, strong local variability and highly turbulent nature of the flow are evident.*

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 (see, e.g., Task 1.1 results). 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 (Fig. 7a). 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. 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 (Fig. 7b). Finally, the interaction of the turbine with a turbulent boundary layer was studied at the EPFL-WiRE wind tunnel facility (see schematic in Fig. 6). High-resolution stereoscopic particle image velocimetry measurements were performed in the wake of the turbine operating at optimal conditions. These measurements provide a valuable dataset for the validation of numerical models, including LES, as discussed in Work Package 1 (e.g., Figs. 2,3 and 4). This research has been published in four journal papers in the journals *Physics of Fluids* (Bastankhah and Porté-Agel, 2017a) and *Energies* (Bastankhah and Porté-Agel, 2017b,c).

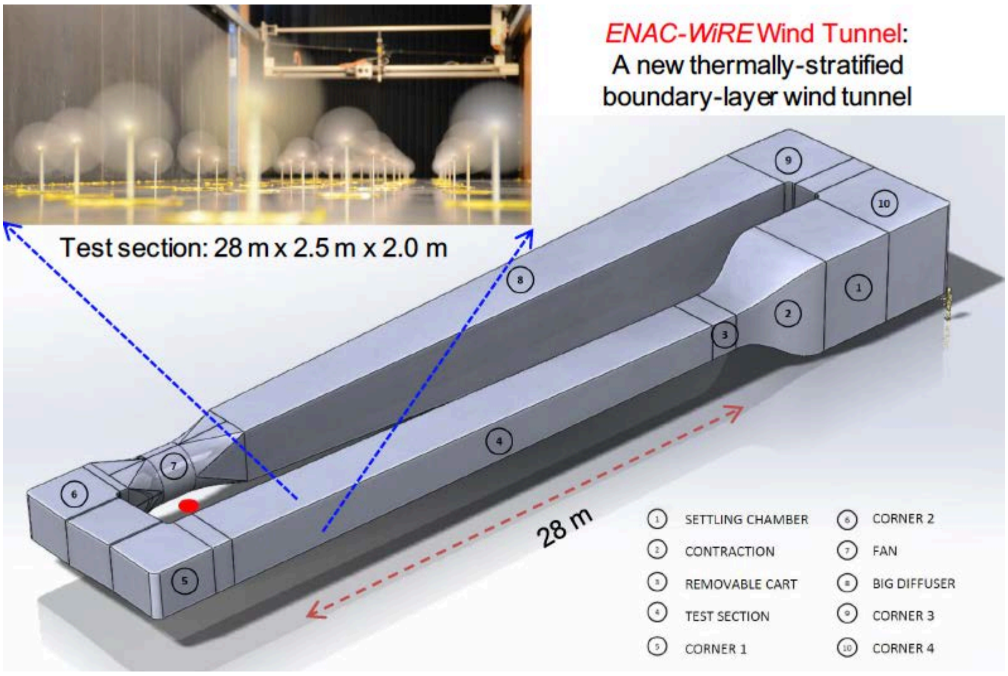

Figure 6: *Schematic of the EPFL-WiRE wind tunnel facility and picture of the test section.*

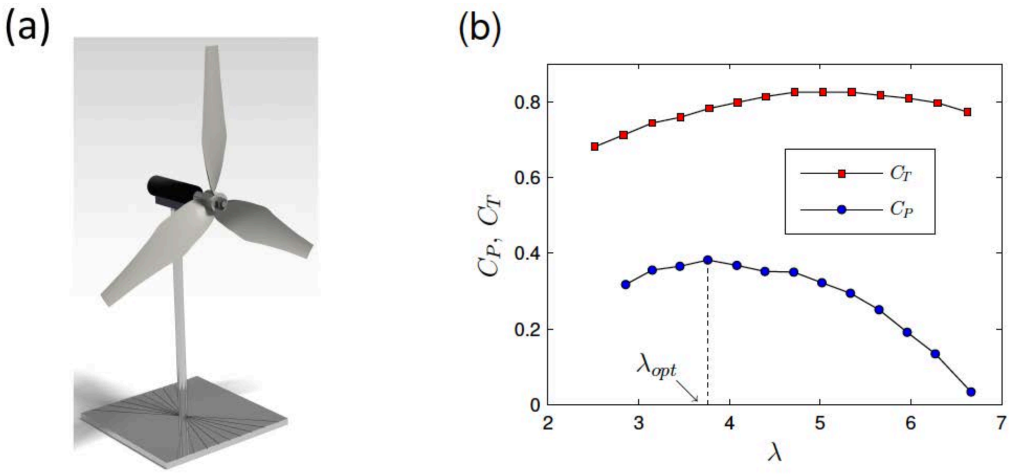

Figure 7: *Schematic of the miniature wind turbine placed in the turbulent boundary layer. (b) Variation of C_T and C_P with the tip-speed ratio λ for the new miniature turbine placed in the boundary layer.*

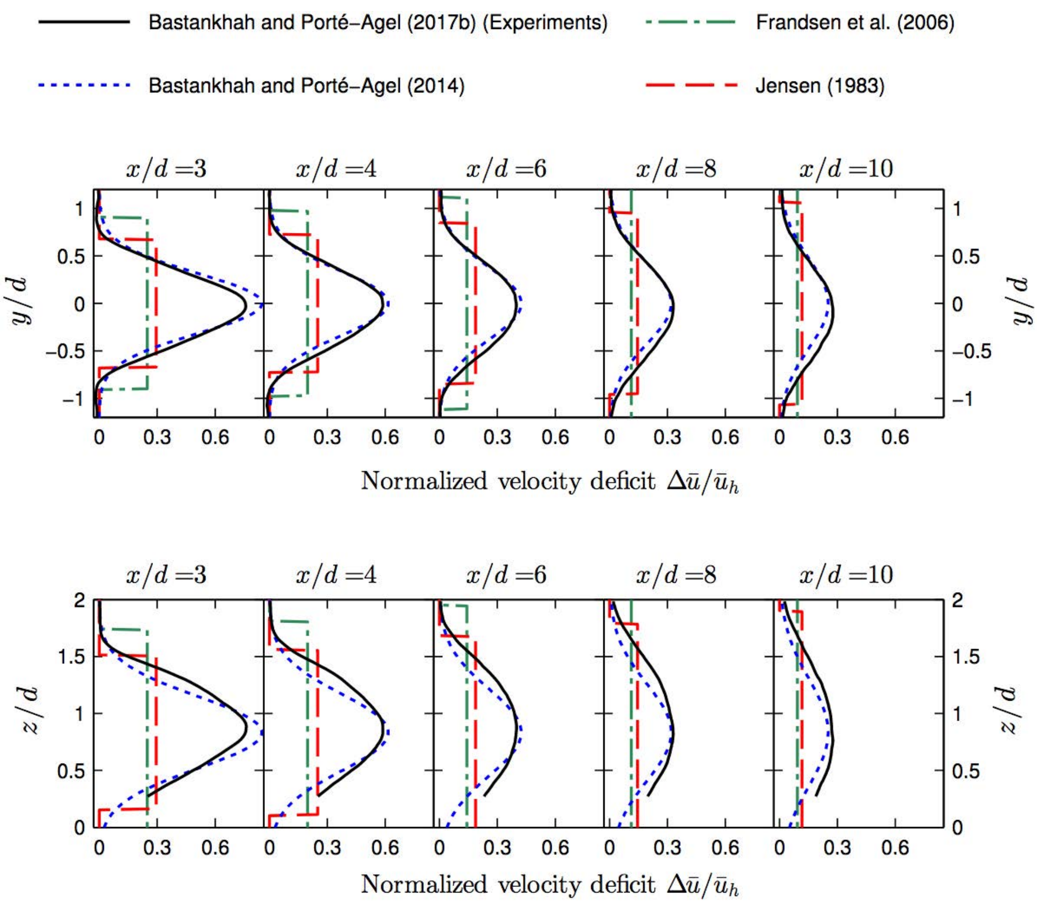

***Figure 8**: Lateral (top) and vertical (bottom) profiles of the normalized velocity deficit through the hub level at different downwind locations. The data obtained from wind-tunnel measurements (Bastankhah and Porté-Agel 2017b) are shown by black solid lines. The predictions of analytical models developed by Jensen (1983), Frandsen et al. (2006) and Bastankhah and Porté-Agel (2014b) are shown by red dashed lines, green dash-dot lines and blue dashed lines, respectively. More details can be found in the recent review paper by Porté-Agel et al. (2020).*

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

As mentioned above, 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 the newly developed WiRE-01 wind turbine. 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 (Figs. 6 and 7). Moreover, power and thrust measurements were carried out to analyze the performance of the wind turbine. A theoretical analysis of the measurement 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 been published in the *Journal of Fluid Mechanics* (Bastankhah and Porté-Agel, 2016).

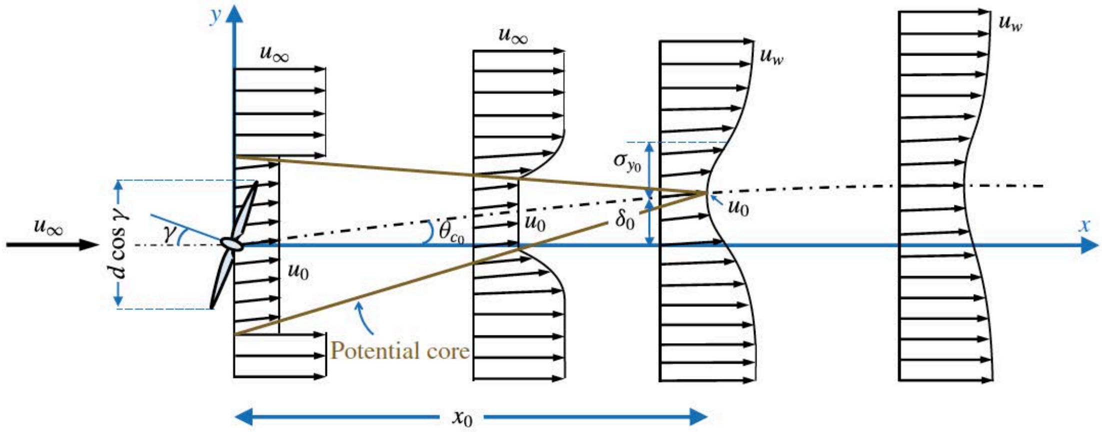

Figure 6: *Schematic of the wake of a yawed wind turbine.*

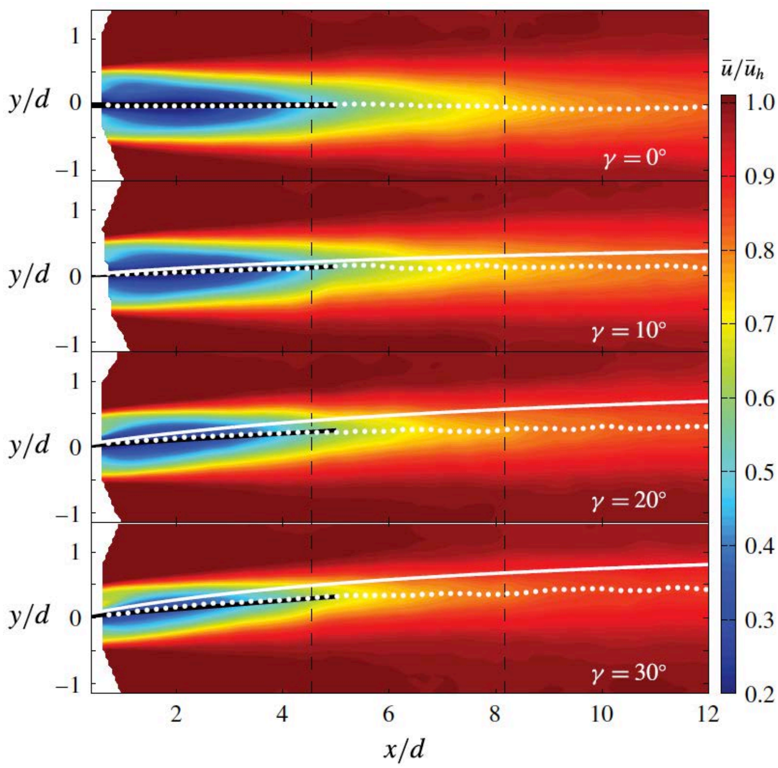

Figure 7: *Contours of the normalized mean streamwise velocity in the horizontal plane at hub height downwind of a turbine for different yaw angles (γ). White dots and white lines represent the wake-center trajectory in the horizontal plane obtained from the wind tunnel measurements and Jiménez* et al.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

As set of wind tunnel experiments were also conducted to study the performance of a model wind farm with five turbine rows under a wide variety of yaw angle distributions. Electrical servo controllers are used to monitor and control operating conditions of each model wind turbine, which consists of a recently developed WiRE-01 rotor. Each turbine is operated with an optimal rotational velocity, regardless of their yaw angles or inflow conditions. Wind farm power measurements are carried out for more than 200 cases with different yaw angle distributions. Our results show that yaw angle control can increase the overall wind farm efficiency as much as 17% with respect to fully non-yawed conditions. Especial emphasis is placed on studying yaw angle distributions with different levels of simplicity and power improvement. Among different yaw angle distributions, the most successful ones are those with a relatively large yaw angle value for the first turbine row, and then the yaw angle decreases progressively for downwind rows until it eventually becomes zero for the last one (Fig. 8). In addition, power measurements show that yaw angle control can improve wind farm efficiency more noticeably for larger number of turbine rows although this improvement is expected to reach a plateau after several rows. A journal paper with these results has been published in the *Journal of Renewable and Sustainable Energy* (Bastankhah and Porté-Agel, 2019).

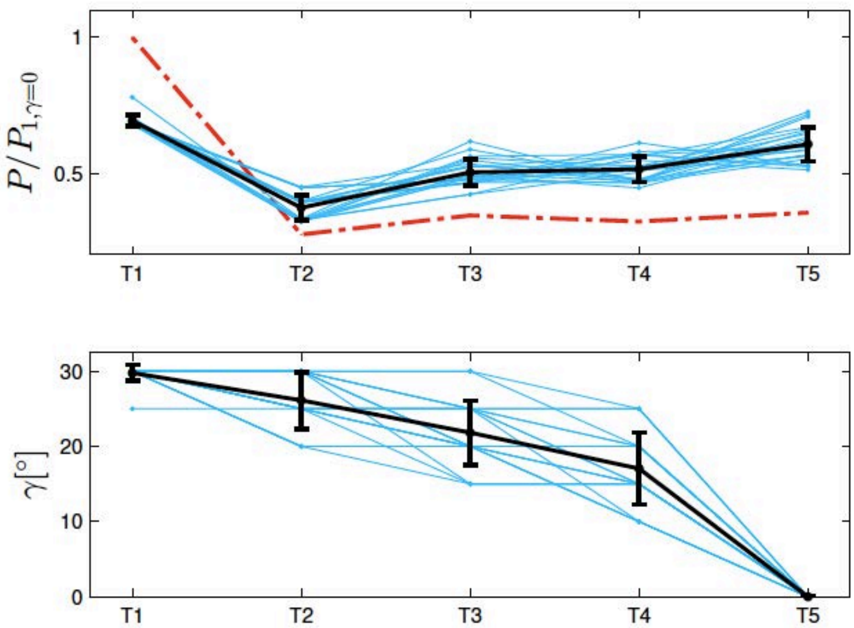

Figure 8: *Distributions of power and yaw angle for the top decile of the tested scenarios when ranked by the magnitude of* ΔP_{tot} *. The values of turbine powers are normalized with the one of the first turbine (T1) with zero yaw angle. Black curves show the mean values, and the error bars indicate the standard deviation. The red dashed curve shows the power distribution for fully non-yawed conditions.*

Task 2.1.2. Study of turbine wakes on topography

A set of experiments has been carried out during the last months of the project to systematically investigate the wake behind a single turbine located on an escarpment, using stereoscopic particle imaging velocimetry. Different escarpment geometries are used, which vary in the shape of the escarpment leading edge from forward facing steps with different curvatures to ramp shapes with different slopes. Wakes over forward facing step escarpments show a mixing between the wake and the flow separation from the escarpment leading edge, with high turbulence production compared to the ramp-shaped escarpments. The results show also a strong influence of the escarpment on the turbine performance as well as the structure of the turbine wakes (see Fig. 9).

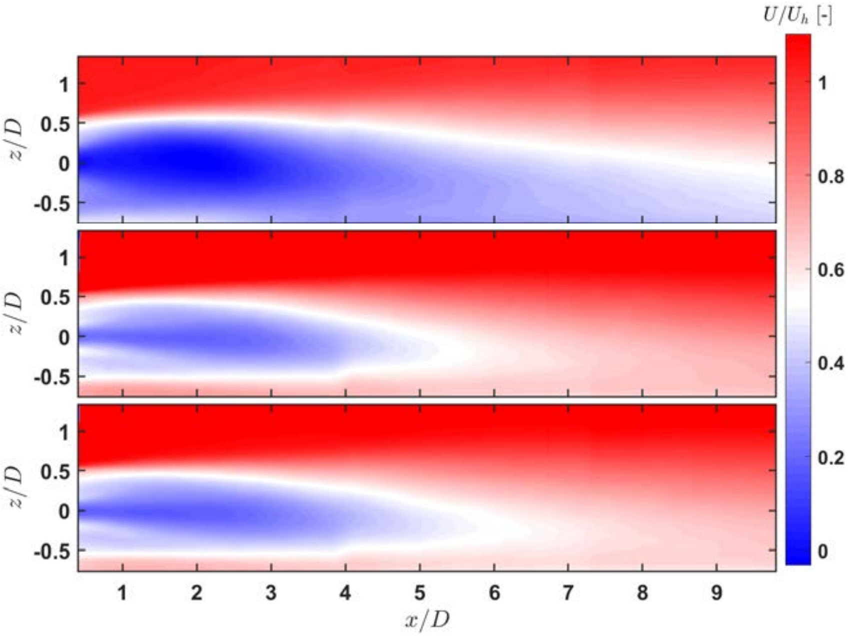

Figure 9: *Normalized averaged streamwise velocity component measured in the wake of wind turbines places behind a escarpment with different angles: from top to bottom: Sharp 90° edge, 33° slope, 21.5° slope.*

Work Package 3: Field experiments

Three field experimental campaigns using the EPFL-WiRE scanning Doppler lidars were carried during the course of this project. They are briefly summarized below.

Task 3.1: Field experiments with ground-based lidars in Collonges (Switzerland)

Field experiments were carried out during the first year, as planned, in Collonges, Switzerland. Specifically, a new volumetric scanning technique using the three EPFL wind LiDARs were developed and used to characterize the wake flow under different atmospheric conditions (see Fig. 10). The measurements allowed us to reconstruct, for the first time, the mean velocity field in a volume behind the wind turbine (see sample measurement in Fig. 11). 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. These field measurements have allowed us to quatify and show a difference in the growth rate of the wind turbine wake in the spanwise and 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 (Porté-Agel et al., 2020). Note that some numerical models currently used to predict turbine wakes assume that turbine wakes are axisymmetric. The results from this research were presented at the *International Conference in Boundary Layers and Turbulence* (Fuertes and Porté-Agel, 2016).

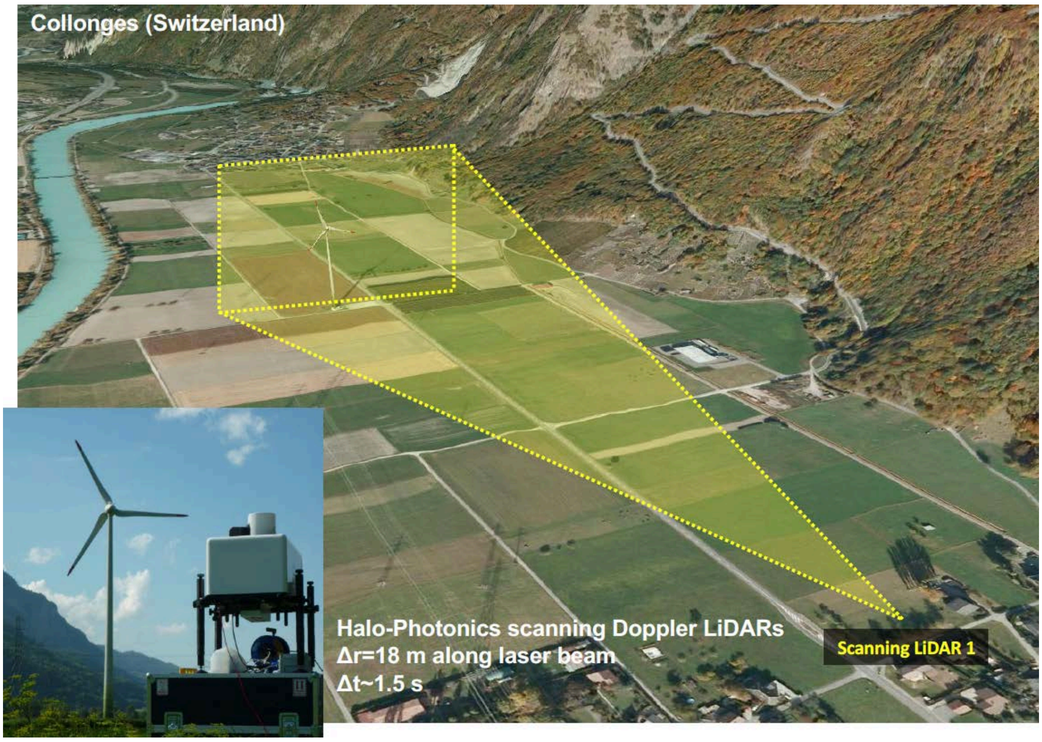

***Figure 10:** View of the experimental site with the sampling volume (in yellow) obtained with one of the three LiDARs. Bottom left: Picture of the LiDAR and the wind turbine in the background.*

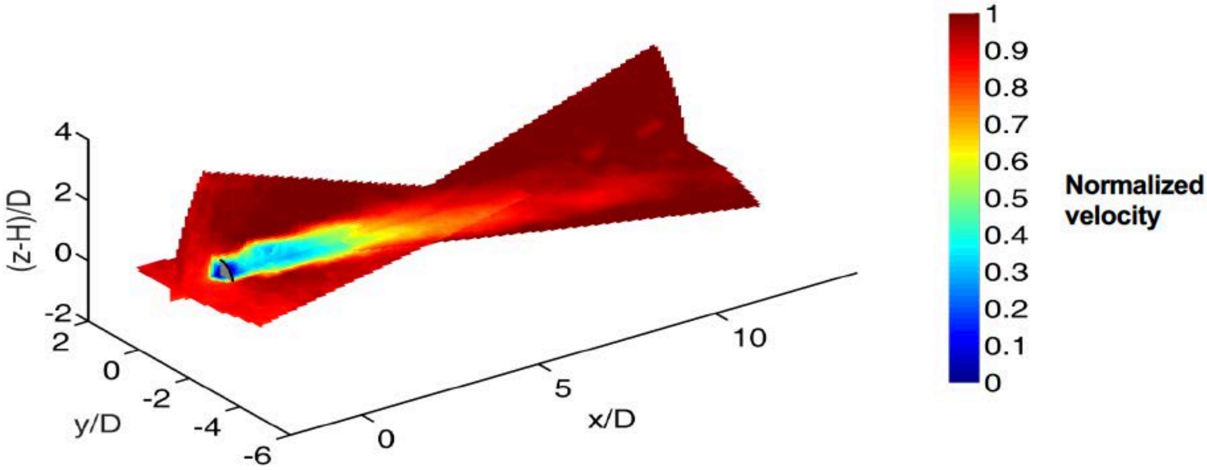

***Figure 11:** Horizontal and vertical contour plots of the mean velocity intersecting the turbine axis and obtained from the volumetric scan. The presence of the wake, characterized by a reduction in wind velocity, is evident from these measurements.*

Task 3.2: Field experiments with nacelle-mounted scanning lidars (Iowa, USA)

A second measurement campaign was performed in Cedar Rapids, Iowa, in collaboration with Prof. Corey Markfort from the University of Iowa. The study was dedicated to the characterization of full-scale wind turbine wakes under different inflow conditions. The measurements were obtained from two pulsed scanning Doppler lidars mounted on the nacelle of a 2.5 MW wind turbine. The first lidar is upstream oriented and dedicated to the characterization of the inflow with a variety of scanning patterns, while the second one is downstream oriented and performs planar and volumetric scans of the wake (see Fig. 12). The calculated velocity deficit profiles exhibit self-similarity in the far wake region and they can be fitted accurately to Gaussian functions. This allows for the study of the growth rate of the wake width and the recovery of the wind speed, as well as the extent of the near-wake region. The results show that a higher incoming turbulence intensity enhances the entrainment and flow mixing in the wake region, resulting in a shorter near-wake length, a faster growth rate of the wake width and a faster recovery of the velocity deficit (see Fig 13). Three-dimensional scans have been used to study the effect of wind veer and test the performance of a recently proposed numerical model (Fig. 14). The relationships obtained are compared to analytical models for wind turbine wakes and allow to correct the parameters prescribed until now, which were obtained from wind-tunnel measurements and large-eddy simulations (LES), with new, more accurate values directly derived from full-scale experiments. Two journal articles have been published in the Remote Sensing journal (Fuertes et al., 2018; Brugger et al., 2019).

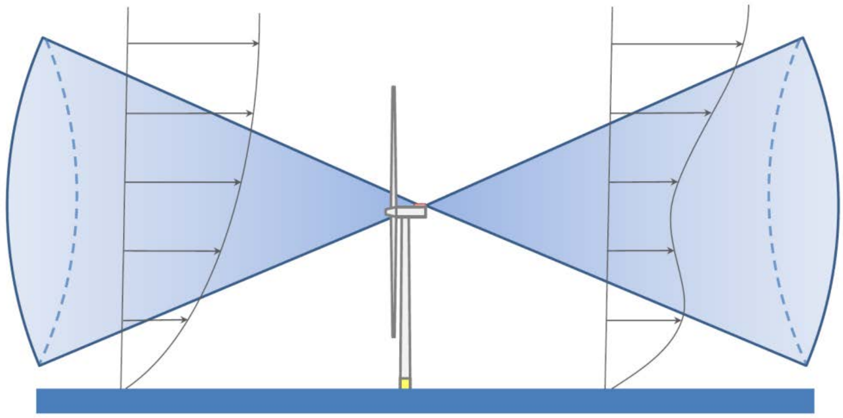

Figure 12*: Schematic of the experimental setup used in the Iowa experiment. Two scanning lidars were mounted on the turbine nacelle, one forward-looking (the measure the incoming wind), and the other one backward looking (to measure the wake flow).*

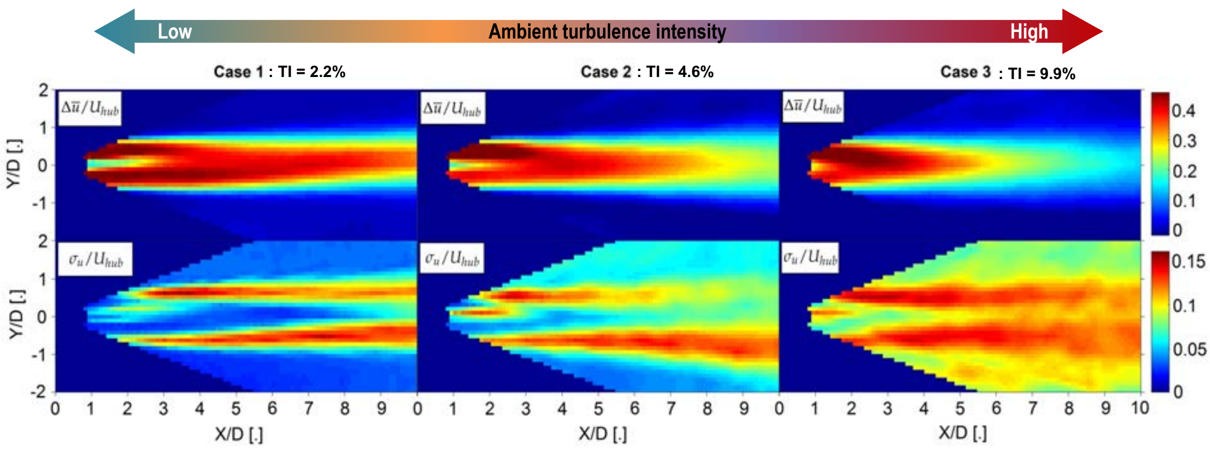

Figure 13*: Wake measurements collected using the nacelle-mounted scanning lidar for different ambient turbulence intensity levels of the inflow. Top: Normalized velocity deficit. Bottom: Streamwise turbulence intensity. For more details, see Fuertes et al. (2018).*

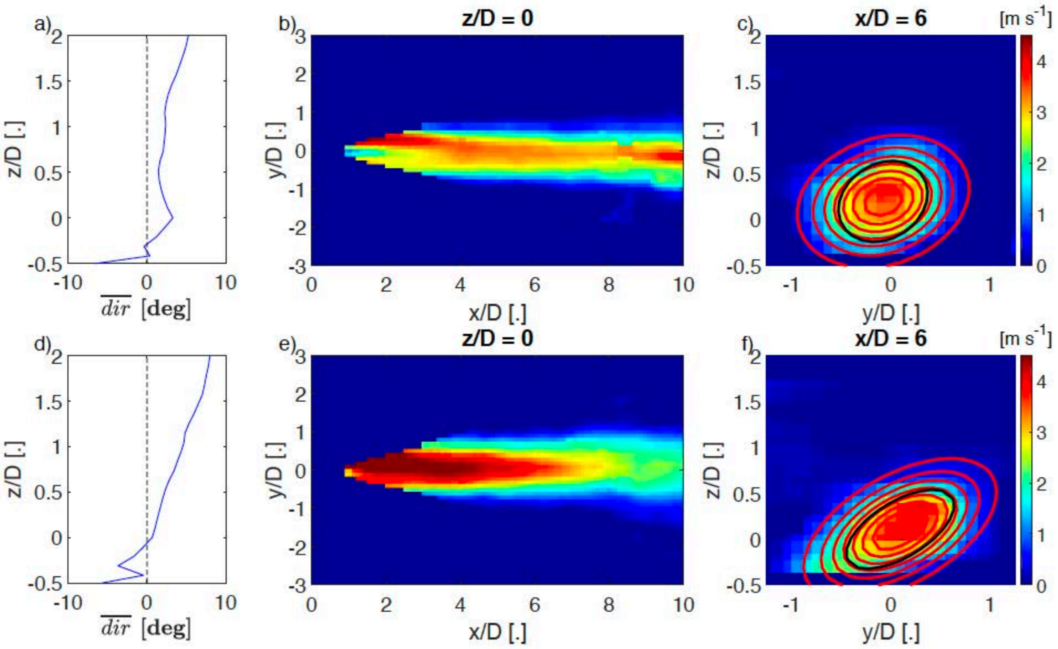

Figure 14: *Nacelle-mounted lidar measurements of the wake velocity deficit (m/s) from volumetric scans of the turbine wake for two cases with different wind veer (variation of wind direction with height). Left: Vertical distribution of the incoming wind direction. Center: Horizontal contours of the wake velocity deficit at hub height. Right: Spanwise-vertical contours of the wake velocity deficit, showing the deformation of the wake produced by the strong veer. The measurements are also used to validate the model of Abkar et al. (2019) (black line in the right plots). More details on this experiment and results can be found in Brugger et al. (2019).*

Task 3.3: Field experiments with nacelle-mounted lidars in a wind farm (Colorado, USA)

A field experiment with Doppler lidar measurements of the wake of full-scale wind turbines under yawed conditions was conducted at a wind farm in Logan County, Colorado, United States. The measurements took place from December 23, 2018, until May 6, 2019, at a cluster of five turbines at the north-western edge of the wind farm. The measurement set-up consisted of two wake scanning Stream Line Doppler lidars that were installed on the nacelles of two neighbouring turbines (Fig. 15). One of those wind turbines was equipped with a yaw controller that introduced a wind speed dependent yaw offset if the second wind turbine was downwind. The goal of wake steering is to deflect the wake away from the downwind turbine with the transvers thrust force introduced by the yaw offset of the upwind turbine. This set-up was supplemented with vertical profiles of the temperature, wind speed, and wind direction from a Wind Cube Doppler lidar and a meteorological mast. Further, a Wind Iris Doppler lidar scanning the inflow was installed on the nacelle of the wake steering turbine and the wind park operator NextEra Energy Resources provided the SCADA data of the turbines.

Figure 15: *Pictures of the recent field experiment carried out in the Peetz wind farm (Colorado, USA). Left: Wind turbine and crane used to lift one of the EPFL lidars on the turbine nacelle. Right: Detail of the mounting structure designed and built to hold the turbine on the nacelle. These measurements were supported by our last OFEN project.*

A yawed example case that visually illustrates the wake deflection is shown in Fig. 16. This figure includes the result of the algorithmic wake center detection from measurement data and the prediction of an analytical model based on the inflow measurements, that together are used for a quantitative validation over the full dataset shown in Fig. 2. The results show an increasing wake deflection with the yaw angle in agreement with wind tunnel experiments (see Work Package 2) and numerical simulations (see Work Package 1). Further, the majority of the investigated cases match the predictions by the analytical models of Bastankhah and Porté-Agel (2016) and Qian and Ishihara (2018) within the expected errors, while the model by Jiménez et al. (2009) shows an overestimation. Further investigations are currently focusing on the effect of wake steering on the available power of the turbines.

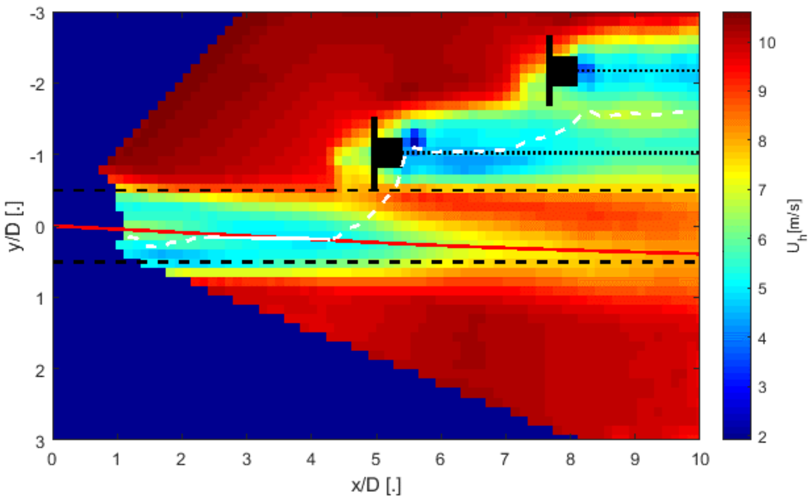

Figure 16: *Sample measurement of the wake deflection while the first (most upwind) turbine was subjected to yaw control with a yaw angle of 18°. The wake deflection is evident in the horizontal contour plots of the velocity deficit at hub height. The predicted wake deflection of the model by Bastankhah and Porté-Agel (2016), developed in Work Package 2, is shown as a red solid line. The dashed white line shows the result of the wake center detection from the measurements and the solid white line indicates the part which past quality assurance. The black dashed line indicates the downwind projection (following the incoming wind direction) of the rotor area of the yawed wind turbine. The locations of the two non-yawed downwind turbines are shown in black, and a black dotted line is used as a visual aid to indicate the downwind direction passing through the hub.*

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 2016-2017 a PhD student (Sina Shamsoddin) who worked 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).

- **A collaboration has just started with the Swiss company BKW Energies AG:** A collaborative agreement has been reached with this company during 2019 to pursue the development of forecasting tools for the Juvent wind farm (the largest wind farm currently in operation in Switzerland).

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 continued during years 1 and 2 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 was carried out during years 2 and 3 with Prof. Corey Markfort from the University of Iowa and the wind-turbine manufacturer company Clipper. This collaboration was essential to coordinate and execute the field campaign in Cedar Rapids, Iowa.

- International collaboration was carried out during year 3, and is still ongoing, with the National Renewable Energy Laboratory (NREL) of the USA. This collaboration was essential to coordinate and execute the field campaign in Peetz, Colorado.

- International collaboration was also pursued 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.

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(***With a number in brackets***, *peer-reviewed journal papers presenting results from this project, and with explicit acknowledgment of the support provided by OFEN)*

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Appendices

The following appendices containing some selected journal articles that are representative of the research conducted during this project.

Appendix 1: ***Review article (requested by the journal editors)***: Porté-Agel F., Bastankhah M., Shamsoddin S. (2020). Wind-turbine and Wind-farm flows: A review. *Boundary Layer Meteorology*, https://doi.org/10.1007/s10546-019-00473-0.

Appendix 2: 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 3: Lin M., and Porté-Agel F. (2019). Large-eddy simulation of yawed wind-turbine wakes: Comparisons with wind tunnel measurements and analytical wake models. *Energies*, 12(23):4574.

Appendix 4: 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 5: Bastankhah M., and Porté-Agel F. (2019). Wind farm power optimization via yaw angle control: A wind tunnel study. *Journal of Renewable and Sustainable Energy*, 11: 023301.

Appendix 6: Fuertes F.C., Markfort C.D., and Porté-Agel F. (2018). Wind turbine wake characterization with nacelle-mounted wind lidars for analytical wake model validation. *Remote Sensing*, 10(5): 668.

Appendix 7: Brugger P., Fuertes F.C., Vahidzadeh M., Markfort C.D., and Porté-Agel F. (2019). Characterization of wind turbine wakes with nacelle-mounted doppler lidars and model validation in the presence of wind veer. *Remote Sensing*, 11(19): 2247.