Wind Turbine Wake Interactions At Field Scale An Les

Experiments have been conducted in a large wind tunnel set-up in order to study the flow structures within the near-wake region of a horizontal axis wind turbine. Particle Image Velocimetry (PIV) has been employed to quantify the mean and turbulent components of the flow field. The measurements have been performed in multiple adjacent horizontal planes in order to cover the area behind the rotor in a large radial interval, at several locations downstream of the rotor. The measurements were phase-locked in order to facilitate the re-construction of the three-dimensional flow field. Acquiring uniform particle distribution in the measurement planes as well as proper calibration for the process of patching the adjacent measurement planes were the major issues influencing the PIV measurements. The results demonstrate the successful implementation of the PIV technique and the associated post-processing to accurately construct the flow field in the near-wake of a HAWT in a large wind tunnel setup. The mean velocity and turbulence characteristics clearly correlate with the near-wake vortex dynamics and in particular with the helical structure of the flow, formed shortly behind the turbine rotor. The radial velocity is low at the mid section of the blade and increases towards the tip. Close to the rotor and close to the blade tip and root regions the mean and turbulent characteristics of the flow are highly dependent on the azimuth angle of blade due to the tip and root vortices. Further from the rotor, the characteristics of the flow become phase independent. This can be attributed to the breakdown of the vortical structure of the flow, resulting from the turbulent diffusion. In general, the highest levels of turbulence are observed in shear layer around the tip of the blades, which decrease rapidly downstream. The shear zone grows in the radial direction as the iv wake moves axially, resulting in velocity recovery toward the centre of the rotor due to momentum transport. These findings are important in wind farm studies, where it is essential to determine the region of influence of the wake of each wind turbine, to study the interaction of wind turbines in the farm. The findings are also significant, as they point out that in the far wake region, the turbulent characteristics are independent of azimuth angle of the blade, which suggests the possibility of generating simple and robust wind turbine wake models for wind farm analysis. In addition to quantification of mean and turbulent velocity field, the capability and limitation of the Blade Element Momentum (BEM) method in predicting axial velocity profiles at the location of the rotor disc has been assessed. For this purpose, the profiles obtained from PIV measurements have been compared with those acquired from the classical BEM method, as well as with the improved method which involves series of corrections, including tip loss, stall delay and thrust coefficient corrections. In general, the comparison shows good qualitative agreement between velocity profiles obtained from PIV measurements and those obtained by BEM method, when the corrections are applied. Moreover, the PIV results have also been compared with the results obtained from the velocity measurements performed by previous investigators in small wind tunnel set-ups, in order to assess the scaling effects, and in particular the effect of local chord Reynolds number. The tip speed ratio is considered to be similar for all measurement to satisfy the kinematic similarity requirement. The comparison shows that the axial velocity profiles are highly dependent on Reynolds number. This is an important finding in terms of simulating scaled models of wind turbines and wind farms in wind tunnel settings.

The goal of this thesis is to analyze the flow field and power generation from a vertical axis

wind turbine (VAWT) by extending the Actuator Cylinder Model to include the viscous effects. Turbulent flow effects in the Actuator Cylinder Model are modeled by solving the Reynolds-Averaged Navier-Stokes (RANS) equations with the Spalart-Allmaras (SA) turbulence model in ANSYS FLUENT. A study is performed to establish mesh independence of the solutions. Numerical solutions on a fine mesh are compared to existing theoretical results based on inviscid theory for a series of flow conditions and turbine sizes. Similar trends in the present turbulent flow results are found as in the inviscid results for downstream velocity and pressure profiles. The Betz limit is found not to be applicable to vertical axis wind turbines. To consider wake interactions, the Actuator Cylinder Model is extended to two and three turbine cases. Power densities are computed to determine the optimal vertical and downstream distances between turbines. For the application to small scale airborne turbines, an increased freestream velocity is employed with two and three turbine models to simulate the effects on performance and power generation at higher altitudes with greater wind velocity. Differences between the present numerical results and inviscid theory are discussed.
The grouping of wind turbines in arrays introduces two major issues: (1) reduced power production caused by wake wind speed deficits and (2) increased dynamic loads on the blades caused by higher turbulence levels. Depending on the layout and local wind conditions, the drop in power production of downstream turbines can easily reach 40% of the upstream turbines in fully developed wake conditions. These power drops across arrays arise due to wake wind speed deficits. Even when averaged over different wind directions, drops in power production of 8% (onshore arrays), and 12% (offshore arrays) have been recorded. In this dissertation, a large wind array performance evaluation model (LWAP) to evaluate wake

effects in large wind farms is developed. The model accounts for multiple wake interactions and the effect on the vertical wind profile in the atmosphere boundary layer by the wind farm itself. The model predicts wind speed deficits at each turbine and for specific turbine power curves and assesses power for individual turbines and for the entire wind farm. The calculation method converges within seconds for a large wind farm evaluation. To assess the efficacy of the wake model, measured wind speed deficits and turbine power deficits along two wind directions and wind turbine rows in the Horns Rev wind farm were compared with deficits calculated using the model. The mean absolute percentage error is around 2% on average in wind speed evaluation and around 4% on average in wind turbine power evaluation. Case studies predicting row-wise power deficits of turbines arrays in Horns Rev and Nysted wind farms on multiple wind directions were compared to observations. LWAP exhibits the same accuracy on power deficit evaluation as with the CFD based models such as WindFarmer, WakeFarm and NTUA and performs better than the WAsP Park model. The computing time to process an entire full wind farm (e.g., Horns Rev) is on the order of a few seconds, significantly less than the CFD based models. In addition, a wind array layout optimization model (WALOM) is proposed to simulate, evaluate and optimize wind array performance for real wind farm site. Results of optimized wind array layouts are obtained and analyzed on case studies of multiple wind distributions conditions and site conditions. It is found that the optimized results are affected by factors such as wind distribution, wind data resolution, wake model and wind farm site conditions.

With the shortage of fossil fuel and the increasing environmental awareness, wind energy is becoming more and more important. As the market for wind energy grows, wind turbines and wind farms are becoming larger. Current utility-scale turbines extend a significant distance into the atmospheric boundary layer. Therefore, the interaction between the atmospheric boundary layer and the turbines and their wakes needs to be better understood. The turbulent wakes of upstream turbines affect the flow field of the turbines behind them, decreasing power production and increasing mechanical loading. With a better understanding of this type of flow, wind farm developers could plan better-performing, less maintenance-intensive wind farms. Simulating this flow using computational fluid dynamics is one important way to gain a better understanding of wind farm flows. In this study, we compare the performance of actuator disc and actuator line models in producing wind turbine wakes and the wake-turbine interaction between multiple turbines. We also examine parameters that affect the performance of these models, such as grid resolution, the use of a tip-loss correction, and the way in which the turbine force is projected onto the flow field.

Wind Turbine Wake Interactions at Nibe, DenmarkWind Turbine Wake InteractionsCharacterization of Unsteady Blade Forces and the Role of Wake Interactions in Power Variability Control

Wind turbines are one of the most promising renewable energy technologies, and this motivates fertile research activity about developments in power optimization. This topic covers a wide range of aspects, from the research on aerodynamics and control design to the industrial applications about on-site wind turbine performance control and monitoring. This Special Issue collects seven research papers about several innovative aspects of the multi-faceted topic of wind turbine power optimization technology. The seven research papers deal respectively with the aerodynamic optimization of wind turbine blades through Gurney flaps;

optimization of blade design for large offshore wind turbines; control design optimization of large wind turbines through the analysis of the competing objectives of energy yield maximization and fatigue loads minimization; design optimization of a tension leg platform for floating wind turbines; innovative methods for the assessment of wind turbine optimization technologies operating on site; optimization of multiple wake interactions modeling through the introduction of a mixing coefficient in the energy balance method; and optimization of the dynamic stall control of vertical-axis wind turbines through plasma actuators. This Special Issue presents remarkable research activities in the timely subject of wind turbine power optimization technology, covering various aspects. The collection is believed to be beneficial to readers and contribute to the wind power industry.

The second main contribution from this thesis is a proposed Multi-Population Genetic Algorithm (MPGA) simulation model for wind turbine layout optimization which is a long-history research hotspot started from 1983. The optimal turbine layout pattern can increase the power generation of the wind farm, reduce the wake interaction between wind turbines,which otherwise would increase dynamic mechanical load and cause higher fatigue load.Many researchers have been working on this topic with different methods, and the proposed MPGA program has been validated by solving the same wind farm optimization issues. More power generation with a lower cost of energy (COE) demonstrates the advancement of this model.For this optimization program, the focus in this thesis goes further. The new proposed wake model is used in this program with a comprehensive cost model, which considers the local wind farm development conditions including labour cost. By using this optimization simulation model, together with wind farm size, wind data and turbine characteristics as inputs,the simulation model can generate the optimal layout for the turbines with total power generations, COE and wind farm efficiency and so on. It is reported that, for the Case of 'constant wind speed of 12m/s with variable wind direction',using the newly-developed Jenson-Gaussian wake model in the MPGA optimization program make the power generation and wind farm efficiency decreased than that of the Jenson's wake model. The power loss caused by wake effect is about 20%, which is in accordance with previous literatures. Three layout patterns can be chosen before the program is started, i.e. aligned, staggered and scatter ones. Besides, the offshore wind developing conditions in Hong Kong are studied. The total water area suitable for offshore wind farm development is determined after considering the local water conditions, wind condition and water area usage purposes. The potential offshore wind farm area in and beyond Hong Kong's boundary (2 km) is about 357.78 km2 (21.68% of the HK's water area). Finally, four typical offshore wind farm sites located at different water areas in Hong Kong are selected. Using the MPGA optimization program, the top ten optimal layout patterns for each potential site are proposed. The Hong Kong offshore wind power potential is reported with the COE and wind farm efficiency. It is estimated that the optimal wind turbine layout separation is 14.5D in prevailing wind direction and 11.0D in cross wind direction (D represent the turbine rotor diameter). The levelized cost of energy (LCOE) is calculated in HK$ terms, i.e. 1.474/kWh (aligned), 1.467/kWh (staggered), nd 1.290/kWh (scattered). APG (annual energy generation) is determined to be 40.80{604}10x/y8 kWh (aligned), 40.42 {604}10x/y8 kWh (staggered), and 33.98 {604}10x/y8 kWh (scattered), representing 9.48% (aligned), 9.39% (staggered), and 7.89% (scattered) of the annual electricity consumption for HK in 2012.The results can provide guidance for the government or private developers to develop the offshore wind farms in Hong

Kong. In summary,this research project developed a new analytical wake model and proved its practicability as the basic velocity deficits calculation models. The wake characteristics based on the new model are estimated. The newly-developed MPGA optimization program has a good performance on wind turbine layout optimization within wind farm and also, its availability in solving the real-world offshore wind farm turbine micro-siting has been validated. The optimization for Hong Kong offshore wind farm with the offshore wind energy assessment process can provide a new thought and filled the research gaps for the wind farm development and wind energy assessment in this research area.

We performed numerical simulations of small, utility scale wind turbine groupings to determine how wakes generated by upstream turbines affect the performance of the small turbine group as a whole. Specifically, various wind turbine arrangements were simulated to better understand how turbine location influences small group wake interactions. The minimization of power losses due to wake interactions certainly plays a significant role in the optimization of wind farms. Since wind turbines extract kinetic energy from the wind, the air passing through a wind turbine decreases in velocity, and turbines downstream of the initial turbine experience flows of lower energy, resulting in reduced power output. Our study proposes two arrangements of turbines that could generate more power by exploiting the momentum of the wind to increase velocity at downstream turbines, while maintaining low wake interactions at the same time. Furthermore, simulations using Computational Fluid Dynamics are used to obtain results much more quickly than methods requiring wind tunnel models or a large scale experimental test.

This Special Issue “Atmospheric Conditions for Wind Energy Applications” hosts papers on aspects of remote sensing for atmospheric conditions for wind energy applications. Wind lidar technology is presented from a theoretical view on the coherent focused Doppler lidar principles. Furthermore, wind lidar for applied use for wind turbine control, wind farm wake, and gust characterizations is presented, as well as methods to reduce uncertainty when using lidar in complex terrain. Wind lidar observations are used to validate numerical model results. Wind Doppler lidar mounted on aircraft used for observing winds in hurricane conditions and Doppler radar on the ground used for very short-term wind forecasting are presented. For the offshore environment, floating lidar data processing is presented as well as an experiment with wind-profiling lidar on a ferry for model validation. Assessments of wind resources in the coastal zone using wind-profiling lidar and global wind maps using satellite data are presented.

Fundamentals of Wind Farm Aerodynamic Layout Design, Volume Four provides readers with effective wind farm design and layout guidance through algorithm optimization, going beyond other references and general approaches in literature. Focusing on interactions of wake models, designers can combine numerical schemes presented in this book which also considers wake models' effects and problems on layout optimization in order to simulate and enhance wind farm designs. Covering the aerodynamic modeling and simulation of wind farms, the book's authors include experimental tests supporting modeling simulations and tutorials on the simulation of wind turbines. In addition, the book includes a CFD technique designed to be more computationally efficient than currently available techniques, making this book ideal for industrial engineers in the wind industry who need to produce an accurate simulation within limited timeframes. Features novel CFD modeling Offers global case studies for turbine wind farm layouts Includes tutorials on simulation of wind turbine using OpenFoam

The study of wind farms within realistic atmospheric boundary layer (ABL) conditions is critical to understand the governing physics of the system and to design optimal operational protocols. Aerodynamic wake interactions between individual wind turbines typically reduce total wind farm energy production 10-20% and increase the cost of electricity for this resource. Further, in large wind farms, the collective farm efficiency is in part dictated by the interaction between the wind farm and the turbulent ABL and, correspondingly, the vertical transport of kinetic energy into the turbine array. Coriolis forces, arising from the projection of Earth's rotation into a non-inertial rotating Earth-fixed frame, modify the interaction of a wind farm with the ABL. The traditional approximation made in typical ABL simulations assumes that the horizontal component of Earth's rotation is negligible in the atmospheric boundary layer. When including the horizontal component of Earth's rotation, the boundary layer and wind farm physics are a function of the geostrophic wind direction. The influence of the geostrophic wind direction on a wind farm atmospheric boundary layer was characterized using conventionally neutral and stable boundary layer large eddy simulations (LES). In the Northern hemisphere, geostrophic winds from west-to-east establish the horizontal component of Earth's rotation as a sink term in the shear Reynolds stress budget whereas the horizontal component manifests as a source term for east-to-west geostrophic winds. As a result, the magnitude of entrainment of mean kinetic energy into a wind turbine array is modified by the direction of the geostrophic wind, and correspondingly, the boundary layer height and wind speed and direction profiles depend on the geostrophic wind direction. Historically, wind farm control protocols have optimized the performance of individual wind turbines which results in aerodynamic wake interactions and a reduction in wind farm efficiency. Considering the wind farm as a collective, a physics- and data-driven wake steering control method to increase the power production of wind farms is developed. Upwind turbines, which generate turbulent energy-deficit wake regions which impinge on downwind generates, are intentionally yaw misaligned with respect to the incident ABL wind. While the yaw misaligned turbine may produce less power than in yaw aligned operation, the downwind generators may significantly enhance their production, increasing the collective power for the farm. The wake steering method developed combines a physics-based engineering wake model with state estimation techniques based on the assimilation of the wind farm power production data, which is readily available for control decisions at operational wind farms. Analytic gradients are derived from the wake model and leveraged for efficient yaw misalignment set-point optimization. The open-loop wake steering control methodology was tested in a multi-turbine array at a utility-scale operational wind farm, where it statistically significantly increased the power production over standard operation. The analytic gradient-based wind farm power optimization methodology developed can optimize the yaw misalignment angles for large wind farms on the order of seconds, enabling online real-time control. The dynamics of the ABL range from microscale features on the order of meters to mesoscale meteorological scales on the order of hundreds of kilometers. As a result of the broad range of scales and diversity of competing forces, the wind farm interaction with the turbulent ABL is a complex dynamical system, necessitating closed-loop control which is able to dynamically adapt to the evolving wind conditions. In order to rapidly design and improve dynamic closed-loop wind farm controllers, we developed wind farm LES capabilities which incorporate Coriolis and stratification effects and which permit the experimentation of real-time control strategies. Dynamic, closed-loop wake steering controllers are tested in simulations with full Coriolis effects and, altogether, the results indicate that closed-loop wake steering control can significantly increase wind farm power production over greedy operation provided that site-specific wind farm data is assimilated into the optimal control model.

Energy production from wind is an increasingly important component of overall global power generation, and will likely continue to gain an even greater share of electricity production as world governments attempt to mitigate climate change and wind energy production costs decrease. Wind energy generation depends on wind speed, which is greatly influenced by local and synoptic environmental forcings. Synoptic forcing, such as a cold frontal passage, exists on a large spatial scale while local forcing manifests itself on a much smaller scale and could result from topographic effects or land-surface heat fluxes. Synoptic forcing, if strong enough, may suppress the effects of generally weaker local forcing. At the even smaller scale of a wind farm, upstream turbines generate wakes that decrease the wind speed and increase the atmospheric turbulence at the downwind turbines, thereby reducing power production and increasing fatigue loading that may damage turbine components, respectively. Simulation of atmospheric processes that span a considerable range of spatial and temporal scales is essential to improve wind energy forecasting, wind turbine siting, turbine maintenance scheduling, and wind turbine design. Mesoscale atmospheric models predict atmospheric conditions using observed data, for a wide range of meteorological applications across scales from thousands of kilometers to hundreds of meters. Mesoscale models include parameterizations for the major atmospheric physical processes that modulate wind speed and turbulence dynamics, such as cloud evolution and surface-atmosphere interactions. The Weather Research and Forecasting (WRF) model is used in this dissertation to investigate the effects of model parameters on wind energy forecasting.

WRF is used for case study simulations at two West Coast North American wind farms, one with simple and one with complex terrain, during both synoptically and locally-driven weather events. The model's performance with different grid nesting configurations, turbulence closures, and grid resolutions is evaluated by comparison to observation data. Improvement to simulation results from the use of more computationally expensive high resolution simulations is only found for the complex terrain simulation during the locally-driven event. Physical parameters, such as soil moisture, have a large effect on locally-forced events, and prognostic turbulence kinetic energy (TKE) schemes are found to perform better than non-local eddy viscosity turbulence closure schemes. Mesoscale models, however, do not resolve turbulence directly, which is important at finer grid resolutions capable of resolving wind turbine components and their interactions with atmospheric turbulence. Large-eddy simulation (LES) is a numerical approach that resolves the largest scales of turbulence directly by separating large-scale, energetically important eddies from smaller scales with the application of a spatial filter. LES allows higher fidelity representation of the wind speed and turbulence intensity at the scale of a wind turbine which parameterizations have difficulty representing. Use of high-resolution LES enables the implementation of more sophisticated wind turbine parameterizations to create a robust model for wind energy applications using grid spacing small enough to resolve individual elements of a turbine such as its rotor blades or rotation area. Generalized actuator disk (GAD) and line

(GAL) parameterizations are integrated into WRF to complement its real-world weather modeling capabilities and better represent wind turbine airflow interactions, including wake effects. The GAD parameterization represents the wind turbine as a two-dimensional disk resulting from the rotation of the turbine blades. Forces on the atmosphere are computed along each blade and distributed over rotating, annular rings intersecting the disk. While typical LES resolution (10-20 m) is normally sufficient to resolve the GAD, the GAL parameterization requires significantly higher resolution (1-3 m) as it does not distribute the forces from the blades over annular elements, but applies them along lines representing individual blades. In this dissertation, the GAL is implemented into WRF and evaluated against the GAD parameterization from two field campaigns that measured the inflow and near-wake regions of a single turbine. The data-sets are chosen to allow validation under the weakly convective and weakly stable conditions characterizing most turbine operations. The parameterizations are evaluated with respect to their ability to represent wake wind speed, variance, and vorticity by comparing fine-resolution GAD and GAL simulations along with coarse-resolution GAD simulations. Coarse-resolution GAD simulations produce aggregated wake characteristics similar to both GAD and GAL simulations (saving on computational cost), while the GAL parameterization enables resolution of near wake physics (such as vorticity shedding and wake expansion) for high fidelity applications. For the first time, to our knowledge, this dissertation combines the capabilities of a mesoscale weather prediction model, LES, and high-resolution wind turbine parameterizations into one model capable of simulating a real array of wind turbines at a wind farm. WRF is used due to its sophisticated environmental physics models, frequent use in the atmospheric modeling community, and grid nesting with LES capabilities. Grid nesting is feeding lateral boundary condition data from a coarse resolution simulation to a finer resolution simulation contained within the coarse resolution simulation's domain. WRF allows the development of a grid nesting strategy from synoptic-scale to microscale LES relevant for wind farm simulations; this is done by building on the results from the investigation of model parameters for wind energy forecasting and the implementation of the GAD and GAL wind turbine parameterizations. The nesting strategy is coupled with a GAD parameterization to model the effects of wind turbine wakes on downstream turbines at a utility-scale Oklahoma wind farm. Simulation results are compared to dual-Doppler measurements that provide three-dimensional fields of horizontal wind speed and direction. The nesting strategy is able to produce realistic turbine wake effects, while differences with the measurements can mostly be attributed to the quality of the available weather input data.

One of the current major challenges in wind energy is to maximize energy production of wind farms. One approach in this effort is through control of wind turbine wake interactions, since undesirable wake interactions can introduce additional mechanical stresses on turbines, leading to early failures and reduce overall energy production of

wind farms. To develop control strategies that can minimize wake interactions, it is essential to simulate wake behaviors accurately and quickly. In this work, a fast and accurate turbine wake model capable of modeling turbine wakes under yaw is presented. This model builds upon the work of existing wake models and is capable of producing results comparable to that of conventional full CFD simulations using a fraction of the computational cost. The accuracy and speed of the proposed model allows for the development of real-time turbine control strategies to maximize power output. The results of the proposed model are validated with previous numerical and experimental data found in the literature. Wind tunnel tests were also designed and conducted in order to validate the models' ability to simulate overlapping wakes, a requirement for producing realistic results of a complete wind farm simulation.
Wind measurements are fundamental inputs for the evaluation of potential energy yield and performance of wind farms. Three-dimensional scanning coherent Doppler lidar (CDL) may provide a new basis for wind farm site selection, design, and control. In this research, CDL measurements obtained from multiple wind energy developments are analyzed and a novel wind farm control approach has been modeled. The possibility of using lidar measurements to more fully characterize the wind field is discussed, specifically, terrain effects, spatial variation of winds, power density, and the effect of shear at different layers within the rotor swept area. Various vector retrieval methods have been applied to the lidar data, and results are presented on an elevated terrain-

following surface at hub height. The vector retrieval estimates are compared with tower measurements, after interpolation to the appropriate level. CDL data is used to estimate the spatial power density at hub height. Since CDL can measure winds at different vertical levels, an approach for estimating wind power density over the wind turbine rotor-swept area is explored. Sample optimized layouts of wind farm using lidar data and global optimization algorithms, accounting for wake interaction effects, have been explored. An approach to evaluate spatial wind speed and direction estimates from a standard nested Coupled Ocean and Atmosphere Mesoscale Prediction System (COAMPS) model and CDL is presented. The magnitude of spatial difference between observations and simulation for wind energy assessment is researched. Diurnal effects and ramp events as estimated by CDL and COAMPS were inter-compared. Novel wind farm control based on incoming winds and direction input from CDL's is developed. Both yaw and pitch control using scanning CDL for efficient wind farm control is analyzed. The wind farm control optimizes power production and reduces loads on wind turbines for various lidar wind speed and direction inputs, accounting for wind farm wake losses and wind speed evolution. Several wind farm control configurations were developed, for enhanced integrability into the electrical grid. Finally, the value proposition of CDL for a wind farm development, based on uncertainty reduction and return of investment is analyzed.

This book is comprised of the proceedings of the Euromech Colloquium 464b "Wind

Energy". It comprises reports on basic research, as well as research related to the practical exploitation and application of wind energy. The book describes the atmospheric turbulent wind condition on different time scales, and the interaction of wind turbines with both wind and water flows. These influence the design, operation and maintenance of offshore wind turbines.

The book contains the research contributions belonging to the Special Issue "Numerical Simulation of Wind Turbines", published in 2020-2021. They consist of 15 original research papers and 1 editorial. Different topics are discussed, from innovative design solutions for large and small wind turbine to control, from advanced simulation techniques to noise prediction. The variety of methods used in the research contributions testifies the need for a holistic approach to the design and simulation of modern wind turbines and will be able to stimulate the interest of the wind energy community.

A computational fluid dynamics tool for prediction of wakes and their interactions within a wind turbine column is presented. A Reynolds-averaged Navier-Stokes (RANS) solver is developed for axisymmetric wake flows using parabolic and boundary-layer approximations, in order to achieve a good trade-off between computational cost and accuracy, with the aim of application in optimization problems of wind farms. Boussinesq hypothesis and a length scale varying as a function of the streamwise location, calibrated from higher accuracy large eddy simulation (LES) dataset, are modeled through a mixing length model and a parabolic transport equation of the turbulent kinetic energy. The novelty of this work consists in modeling the mixing length to accurately predict time-averaged velocity field in the presence of wake interactions as well as varying incoming free-stream turbulence. The actuator disc model is implemented in the parabolic scheme for simulating turbine effects and estimating power production. The RANS simulations have a good agreement with the LES dataset in comparing the wake field, time-averaged turbulence statistics and power production, for cases designed to test effects of tip speed ratio, spacing between turbines and free-stream turbulence. Furthermore, the RANS solver is also assessed with good agreement with wind tunnel experiments of a turbine model. The tool is then leveraged in optimization problems considering different algorithms and objective functions. The proposed Parabolic RANS (P-RANS) solver is a great alternative for analytical and engineering wake models in obtaining more accurate predictions while requiring two orders of magnitude lesser computation than LES.

This book collects papers presented in the Invited Workshop, Liutex and Third Generation of Vortex Definition and Identification for Turbulence, from CHAOS2020, June 9-12, 2020, which was held online as a virtual conference. Liutex is a new physical quantity introduced by Prof. Chaoqun Liu of the University of Texas at Arlington. It is a vector and could give a unique and accurate mathematical definition for fluid rotation or vortex. The papers in this volume include some Liutex theories and many applications in hydrodynamics, aerodynamics and thermal dynamics including turbine machinery. As vortex exists everywhere in the universe, a mathematical definition of vortex or Liutex will play a critical role in scientific research. There is almost no place without vortex in fluid dynamics. As a projection, the Liutex theory will play an important role on the investigations of the vortex dynamics in hydrodynamics, aerodynamics, thermodynamics, oceanography, meteorology, metallurgy, civil engineering, astronomy, biology, etc. and to the researches of the generation, sustenance, modelling and controlling of turbulence.

The book encompasses novel CFD techniques to compute offshore wind and tidal applications. Computational fluid dynamics (CFD) techniques are regarded as the main design tool to explore the new engineering challenges presented by offshore wind and tidal turbines for energy generation. The difficulty and costs of undertaking experimental tests in offshore environments have increased the interest in the field of CFD which is used to design appropriate turbines and blades, understand fluid flow physical phenomena associated with offshore environments, predict power production or characterise offshore environments, amongst other topics.

Understanding the aerodynamic interactions between turbines in a wind farm is essential for maximizing power generation. In contrast to horizontal-axis wind turbines (HAWTs), for which wake interactions between turbines in arrays must be minimized to prevent performance losses, vertical-axis wind turbines (VAWTs) in arrays have

demonstrated beneficial interactions that can result in net power output greater than that of turbines in isolation. These synergistic interactions have been observed in previous numerical simulations, laboratory experiments, and field work. This dissertation builds on previous work by identifying the aerodynamic mechanisms that result in beneficial turbine-turbine interactions and providing insights into potential wind farm optimization. The experimental data presented indicates increased power production of downstream VAWTs when positioned offset from the wake of upstream turbines. Comparison with three-dimensional, three-component flow measurements demonstrates that this enhancement is due to flow acceleration adjacent to the upstream turbine, which increase the incident freestream velocity on appropriately positioned downstream turbines. A low-order model combining potential flow and actuator disk theory accurately captures this effect. Laboratory and field experiments were used to validate the model's predictive capabilities, and an evolutionary algorithm was deployed to investigate array optimization. Furthermore, changes in upstream turbine performance are related to variations in the surrounding flow field due to the presence of the downstream rotor. Finally, three-dimensional vortex interactions behind pairs of VAWTs are observed to replenish momentum in the array's wake. These effects are described along with their implications for wind farm design.
Wind farms are clusters of wind turbines deployed over a relatively small area. During operations, the wake from upstream turbines may impinge on trailing turbines causing a

decrease in power production. Wind farm control strategies aim at mitigating the effect of wake interactions. In this dissertation, model-free control strategies for wind farm power maximization have been evaluated using numerical simulations of the flow through wind farms. A model-free approach does not require a priori assumptions on the physical system, but learns on-line the system dynamics, avoiding modeling uncertainties. The control strategies are based on extremum-seeking control (ESC), a real-time gradient-based optimization algorithm. Either the turbine generator torque or the rotor yaw angle is used as the control parameter tuned by ESC to optimize the wind farm power production. The generator torque adjusts the turbine angular speed and the momentum deficit in the trailing wake, while the yaw angle serves to vary the direction of the wake and avoid trailing turbines. We first consider several implementations of ESC and assess their performances and practical feasibility. Both torque- and yaw-based ESC enhance power production, but the latter has a larger margin for improvement. For idealised turbine arrays, ESC achieves a potential power improvement of at least 7–8% compared to operations with design settings for an isolated turbine. After this calibration, we perform an optimization study for a real wind farm and obtain a quantitative evaluation of the impact of the control strategy in annual energy production. Large-eddy simulations with rotating actuator disk are used, in the first place, to provide a virtual wind farm to test the control algorithms. Additionally, the numerical data are investigated to gain a physical insight on the mechanisms underlying the performance improvement and broaden the impact of the optimization. This book presents the results of the seminar “Wind Energy and the Impact of Turbulence on the Conversion Process” which was supported from three societies, namely the EUROMech, EAWE and ERCOFATC and took place in Oldenburg, Germany in spring 2012. The seminar was one of the first scientific meetings devoted to the common topic of wind energy and basic turbulence. The established community of researchers working on the challenging puzzle of turbulence for decades met the quite young community of researchers, who face the upcoming challenges in the fast growing field of wind energy applications. From the fluid mechanical point of view, wind turbines are large machines operating in the fully turbulent atmospheric boundary layer. In particular they are facing small-scale turbulent inflow conditions. It is one of the central puzzles in basic turbulence research to achieve a fundamental understanding of the peculiarities of small-scale turbulence. This book helps to better understand the resulting aerodynamics around the wind turbine’s blades and the forces transmitted into the machinery in this context of puzzling inflow conditions. This is a big challenge due to the multi-scale properties of the incoming wind field ranging from local flow conditions on the profile up to the interaction of wake flows in wind farms.

To maximize the effectiveness of the rapidly increasing capacity of installed wind energy resources, new models must be developed that are capable of more nuanced control of each wind turbine so that each device is more responsive to inflow events. Models used to plan wind turbine arrays and control behavior of devices within the farm currently make questionable estimates of the incoming atmospheric flow and update turbine configurations infrequently. As a result, wind turbines often operate at diminished capacities, especially in arrays where wind turbine wakes interact and inflow conditions are far from ideal. New turbine control and wake prediction models must be developed to tune individual devices and make accurate power predictions. To that end, wind tunnel experiments are conducted detailing the turbulent flow in the wake of a wind turbine in a model-scale array. The proper orthogonal decomposition (POD) is applied to characterize the spatial evolution of structures in the wake. Mode bases from distinct downstream locations are reconciled through a secondary decomposition, called double proper orthogonal decomposition (DPOD), indicating that modes of common rank in the wake share an ordered set of sub-modal projections whose organization delineates underlying wake structures and spatial evolution. The doubly truncated basis of sub-modal structures represents a reduction to 0.015% of the total degrees of freedom of the wind turbine wake. Low-order representations of the Reynolds stress tensor are made using only the most dominant DPOD modes, corrected to account for energy excluded from the truncated basis with a tensor of constant coefficients defined to rescale the low-order representation of the stresses to match the original statistics. Data from the wind turbine wake are contrasted against simulation data from a fully-developed channel flow, illuminating a range of anisotropic states of turbulence. Complexity of flow descriptions resulting from truncated POD bases is suppressed in severe basis truncations, exaggerating anisotropy of the modeled flow and, in extreme cases, can lead to the loss of three dimensionality. Constant corrections to the low-order descriptions of the Reynolds stress tensor reduce the root-mean-square error between low-order descriptions of the flow and the full statistics as much as 40% and, in some cases, reintroduce three-dimensionality to severe truncations of POD bases. Low-dimensional models are constructed by coupling the evolution of the dynamic mode coefficients through their respective time derivatives and successfully account for non-linear mode interaction. Deviation between time derivatives of mode coefficients and their least-squares fit is amplified in numerical integration of the system, leading to unstable long-time solutions. Periodic recalibration of the dynamical system is undertaken by limiting the integration time and using a virtual sensor upstream of the wind turbine actuator disk in to read the effective inflow velocity. A series of open-loop transfer functions are designed to inform the low-order dynamical system of the flow incident to the wind turbine rotor. Validation data shows that the model tuned to the inflow reproduces dynamic mode coefficients with little to no error given a sufficiently small interval between instances of recalibration. The reduced-order model makes accurate predictions of the wake when informed of turbulent inflow events. The modeling scheme represents a viable path for continuous time feedback and control that may be used to selectively tune a wind turbine in the effort to maximize power output of large wind farms.

This thesis investigates two flow fields that a wind turbine in a wind farm might experience. The first is the near-wake of a wind turbine where the focus was on the helical tip and root vortices. Two scalemodel wind turbines were investigated using PIV. A geometrically scaled rotor was observed to generate a chaotic wake due to poor aerodynamic performance at the experimental Reynolds number. Flowvisualisations on a static 3D wing confirmed laminar separation is likely on the geometrically scaled model.A research orientated model was designed based on the optimum Glauert rotor to investigate the stability of the tip and root vortices. A pairing instability was observed in the tip vortices. The onset ofthis instability was found to be dependent on the tip speed ratio. The root vortices become unstable due to their proximity to the turbine support structures.The influence of freestream turbulence was studied by varying the turbulence intensity using passive turbulence grids including a novel tethered sphere grid. Increased turbulence intensity was observed tohasten the breakdown of the vortices, via turbulent diffusion rather than the pairing instability which was absent in the phase-locked average velocity fields.Tip and root vortices of both turbine models were characterised using Galilean invariant vortex identification schemes. The meander of the vortices was observed to be Gaussian at early vortex ages when interaction between vortices is minimal. Meander magnitude was shown to increase with distance absolutely. However, the magnitude of meander was found to be dependent on tip speed ratio and freestream turbulence intensity.A secondary focus was the flow fields above complex terrain features, a common location for wind farms. The recirculation region which formed downstream of various escarpment geometries was characterisedusing PIV. The size of the recirculation region was found to be dependent on the escarpment angle, the boundary layer to step height thickness ratio, the Reynolds number and the freestream turbulence intensity. An application of POD phase-averaging revealed the dynamic nature of the recirculation region. The wind speed-up above theescarpment beneficial in a wind energy sense was

observed to be coupled to a vertical velocity component. Further, significantturbulence generation in the separated shear was observed which questions the appropriateness of complex terrain as a wind farm location.
With the increasing development of wind energy, it has become essential to study the interactions of turbines within wind farms. Wind turbines create wakes when harnessing the energy in the wind for electricity. Reduced velocities in the wakes and increased turbulence pose problems on nearby turbines. Therefore, to better understand the behaviour of wakes, experiments were conducted at the University of Waterloo Wind Generation Facility to study the behaviour of a wake behind a 3.3 m diameter turbine. To ensure accuracy of measurements inside the facility, the flow distribution was measured upwind of the turbine to obtain a profile. This was completed through the development of a structure to orientate pitot tubes in front of the area of the turbine. The device allowed for various fan configuration settings of the facility to be tested to attempt to obtain an even flow distribution profile. A completely uniform flow distribution could not be achieved, however improvements to the profile were made. Experiments were conducted through the use of ow visualization techniques to gain an initial understanding of the behaviour of the wake in both un-yawed and yawed turbine configurations. This was performed in two methods, to ignite a smoke emitter upstream of the

turbine blade and to ignite smoke emitters on the blade tips of the turbine. Using the upstream smoke technique, the tip vortices could be seen to shed from the blades as they moved through the stream of the smoke. The vortices propagated downstream with the movement of the flow. The helical wake distribution of the wake could be seen using the blade ignited smoke technique. An estimate of the wake characteristics were obtained from this experiment, resulting in an approximate near wake length of 1.6 rotor diameters and helix angle of 30?. Measurements of the wake of a wind turbine in un-yawed and yawed positions were conducted using three different measurement methods to gain an understanding of the wake behaviour in the range of 3 rotor diameters downstream of the turbine. The pitot tube structure previously developed was used to measure a two-dimensional profile of the wake at various downstream positions. With this method, the wake centre could be seen as well as temporal changes in the wake. A sonic anemometer was used to traverse the wake at hub height to obtain a horizontal velocity profile at various downstream distances. The velocity profile showed the decay of the wake as well as detection in the yawed turbine measurements. LiDAR measurements were collected by scanning the wake at hub height to obtain a flow distribution throughout the wake of the turbine. Through these measurements a clear wake profile was developed, which showed how the velocity profile progressed behind the turbine. When the turbine was yawed, the wake was seen to detect in the direction of the yaw angle. Wind energy is becoming one of the most significant sources of renewable energy. With its growing use, and social and political awareness, efforts are being made to harness it in the most efficient manner. However, a number of challenges preclude efficient and optimum operation of wind farms. Wind resource forecasting over a long operation window of a wind farm, development of wind farms over a complex terrain on-shore, and air/wave interaction off-shore all pose difficulties in materializing the goal of the efficient harnessing of wind energy. These difficulties are further amplified when wind turbine wakes interact directly with turbines located downstream and in adjacent rows in a turbulent atmospheric boundary layer (ABL). In the present study, an ABL solver is used to simulate different atmospheric stability states over a diurnal cycle. The effect of the turbines is modeled by using actuator methods, in particular the state-of-the-art actuator line method (ALM) and an improved ALM are used for the simulation of the turbine arrays. The two ALM approaches are used either with uniform inflow or are coupled with the ABL solver. In the latter case, a precursor simulation is first obtained and data saved at the inflow planes for the duration the turbines are anticipated to be simulated. The coupled ABL-ALM solver is then used to simulate the turbine arrays operating in atmospheric turbulence.A detailed accuracy assessment of the state-of-the-art ALM is performed by applying it to different rotors. A discrepancy regarding over-prediction of tip loads and an artificial tip correction is identified. A new proposed ALM* is developed and validated for the NREL Phase VI rotor. This is also applied to the NREL 5-MW turbine, and guidelines to obtain consistent results with ALM* are developed.Both the ALM approaches are then applied to study a turbine-turbine interaction problem consisting of two NREL 5-MW turbines. The simulations are performed for two ABL stability states. The effect of ABL stability as well the ALM approaches on the blade loads, turbulence statistics, unsteadiness, wake profile etc., is quantified. It is found that ALM and ALM* yield a noticeable difference in most of the parameters quantified. The ALM* also senses small-scale blade motions better. However, the ABL state dominates the wake recovery pattern. The ALM* is then applied to a mini wind farm comprising five NREL 5-MW turbines in two rows and in a staggered configuration. A detailed wake recovery study is performed using a unique wake-plane analysis technique. An actuator curve embedding (ACE) method is developed to model a general-shaped lifting surface. This method is validated for the NREL Phase VI rotor and applied to the NREL 5-MW turbine. This method has the potential for application to aero-

elasticity problems of utility-scale wind turbines.
Offshore floating wind turbines represent the future of wind energy. However, significant challenges must be overcome before these systems can be widely used. Because of the dynamics of offshore floating wind turbines -- surge, sway, heave, roll, pitch, and yaw -- and the resulting interactions between the rotor and generated wake, the aerodynamic analysis methods and design codes that have found wide use throughout the wind energy industry may be inadequate. Application of these techniques to offshore floating wind turbine aerodynamics may result in off-optimal designs, effectively handicapping these next-generation systems, thereby minimizing their full potential. This dissertation will demonstrate that the aerodynamics of offshore floating wind turbines are sufficiently different from conventional offshore and onshore wind turbines, warranting the use of higher fidelity analysis approaches. It will outline the development and validation of a free vortex wake code, the Wake Induced Dynamics Simulator, or WInDS, which uses a more physically realistic Lagrangian approach to modeling complex rotor-wake interactions. Finally, results from WInDS simulations of various offshore floating wind turbines under different load conditions will be presented. The simulation results indicate that offshore floating wind turbine aerodynamics are more complex than conventional offshore or onshore wind turbines and

require higher fidelity analysis approaches to model adequately. Additionally, platform pitching modes appear to drive the most aerodynamically-significant motions, followed by yawing modes. Momentum balance approaches are shown to be unable to accurately model these dynamic systems, and the associated dynamic inflow methods respond to velocity changes at the rotor incorrectly. Future offshore floating wind turbine designs should strive to either minimize platform motions or be complementarily optimized, via higher fidelity aerodynamic analysis techniques, to account for them. It is believed that this dissertation is the first in-depth study of offshore floating wind turbine aerodynamics and the applicability of various analysis methods.
Growing concerns about the environmental impact of fossil fuel energy and improvements in both the cost and performance of wind turbine technologies has spurred a sharp expansion in wind energy generation. However, both the increasing size of wind farms and the increased contribution of wind energy to the overall electricity generation market has created new challenges. As wind farms grow in size and power density, the aerodynamic wake interactions that occur between neighboring turbines become increasingly important in characterizing the unsteady turbine loads and power output of the farm. Turbine wake interactions also impact variability of farm power generation, acting either to

increase variability or decrease variability depending on the wind farm control algorithm. In this dissertation, both the unsteady vortex wake loading and the effect of wake interaction on farm power variability are investigated in order to better understand the fundamental physics that govern these processes and to better control wind farm operations to mitigate negative effects of wake interaction. The first part of the dissertation examines the effect of wake interactions between neighboring turbines on the variability in power output of a wind farm, demonstrating that turbine wake interactions can have a beneficial effect on reducing wind farm variability if the farm is properly controlled. In order to balance multiple objectives, such as maximizing farm power generation while reducing power variability, a model predictive control (MPC) technique with a novel farm power variability minimization objective function is utilized. The controller operation is influenced by a number of different time scales, including the MPC time horizon, the delay time between turbines, and the fluctuation time scales inherent in the incident wind. In the current research, a non-linear MPC technique is developed and used to investigate the effect of three time scales on wind farm operation and on variability in farm power output. The goal of the proposed controller is to explore the behavior of an 'ideal' farm-level MPC controller with different wind, delay and horizon time scales and to examine the reduction of system power variability that is possible in such a controller by effective use of wake interactions. The second part of the dissertation addresses the unsteady vortex loading on a downstream turbine caused by the interaction of the turbine blades with coherent vortex structures found within the upstream turbine wake. Periodic, stochastic, and transient loads all have an impact on the lifetime of the wind turbine blades and drivetrain. Vortex cutting (or vortex chopping) is a type of stochastic load that is commonly observed when a propeller or blade passes through a vortex structure and the blade width is of the same order of magnitude as the vortex core diameter. A series of Navier-Stokes simulations of vortex cutting with and without axial flow are presented. The goal of this research is to better understand the challenging physics of vortex cutting by the blade rotor, as well as to develop a simple, physics-based, validated expression to characterize the unsteady force induced by vortex.

Floating offshore wind turbines in deep waters offer significant advantages to onshore and near-shore wind turbines. However, due to the motion of floating platforms in response to wind and wave loading, the aerodynamics are substantially more complex. Traditional aerodynamic models and design codes do not adequately account for the floating platform dynamics to assess its effect on turbine loads and performance. Turbines must therefore be over designed due to loading uncertainty and are not fully optimized for their operating conditions. Previous research at the University of Massachusetts, Amherst developed the Wake Induced Dynamics Simulator, or WInDS, a free vortex wake model of wind turbines that explicitly includes the velocity components from platform motion. WInDS rigorously accounts for the unsteady interactions between the wind turbine rotor and its wake, however, as a potential flow model, the unsteady viscous response in the blade boundary layer is neglected. To address this concern, this thesis presents the development of a Leishman-Beddoes dynamic stall model integrated into WInDS. The stand-alone dynamic stall model was validated against two-dimensional unsteady data from the OSU pitch oscillation experiments and the coupled WInDS model was validated against three-dimensional data from NREL's UAE Phase VI campaign. WInDS with dynamic stall shows substantial improvements in load predictions for both steady and unsteady conditions over the base version of WInDS. Furthermore, use of WInDS with the dynamic stall model should provide the necessary aerodynamic model fidelity for future research and design work on floating offshore wind turbines. Wind energy is the mainstream source of clean and renewable energy and it is also the fastest-growing source of sustainable energy in the world. In the Global Wind Energy Council's report in 2014, wind industry grew 44% worldwide. In order to optimize the efficiency of wind farms, it is important to observe wake interactions among wind turbines. Computational mathematics and mechanics provide fundamental methods and tools for simulating physical processes. Numerical computation can offer important insights and data that are either difficult or expensive to measure or to perform tests experimentally. In this dissertation, we use Computational Fluid Dynamics (CFD) software OpenFOAM and ANSYS FLUENT to simulate the wake effect of Horizontal Axis Wind Turbines (HAWT) and related problems. Numerical simulation can also help us comprehend and control man-made disasters. Air craft crashworthiness and human survivability are of utmost concerns in any emergency landing situation. Motivated by the air incidents lately, the disappearance of Malaysia Airlines Flight MH370 in March 2014 and Germanwings Flight 9525 crash in March 2015, we use Computational Structural Dynamics (CSD) software ANSYS Explicit Dynamics and LS-DYNA to try different numerical simulations of Airbus A320 crashing into a wall and compare the results to the reality. We calculate three CFD problems in this dissertation: lid-driven problems, one turbine wake problem, and two serial turbines wake problem. We simulate a lid-driven flow in both two- (2D) and three-dimension (3D) to compare the simulation capability of the three turbulence modelings, i.e., Direct Numerical Simulation (DNS), Large

Eddy Simulation (LES), and Reynolds-Averaged Navier-Stokes Equations Simulation (RANS) by OpenFOAM. Among these three turbulence models, we can find that LES is capable of capturing more details of turbulence flow. We simulate the airflow effect of one wind turbine with both fixed angular velocity and wind-driven case, run benchmark tests based on NRELs reports, and compare the numerical results under the same condition by OpenFOAM and FLUENT. For the fixed angular velocity case, we use wind speed 8 m/s and angular velocity of the wind turbine 75 deg/s. For the wind-driven case, we use wind speed 8 m/s and 16 m/s and the angular velocity of the wind turbine calculated by FLUENT converges faster than OpenFOAM case. We simulate the interactions of wake flow for two serial wind turbines by FLUENT. We use wind speed 8 m/s and angular velocity of the wind turbine 75 deg/s. The wake of former turbine affects the rear one and the diffusion of flow caused by two turbines can be seen clearly. For both one and two serial turbines problems, the turbulence model RANS [lowercase kappa][lowercase epsilon] is used. We calculate and simulate Airbus A320 crashing into a wall by ANSYS Explicit Dynamics and LS-DYNA. For ANSYS Explicit Dynamics, we use the angle of approach 0°, 15°, and 30°. For LS-DYNA, we only test the pitch angles 0°. For all cases, we use the speed of aircarft 200 m/s. The deformation of both aircraft and wall can be seen clearly.

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Full-scale wind turbines (WT) operate in the atmospheric boundary layer. The atmospheric boundary layer structure significantly influences the turbulence generated in the wake of the WT. As Atmospheric boundary layer structure is dictated by the stratification of the atmosphere, hence stratifications effects are critical in accurate representation of the turbine wake physics. Due to the dependency of several factors, such as turbulence scales, buoyancy flux, momentum flux, the atmospheric boundary layer turbulence capturing is really challenging. Large Eddy Simulation (LES) has been used as a tool to understand the effects of atmospheric stability on turbine wake turbulence. The differences between the stable and unstable atmosphere on wake of 5-MW turbine has been explored. Differences in tip and root vortex interactions, wake expansion and recovery have been analyzed. The study has revealed for stable ABL low level jets play an important role in wake dynamics and increasing stability delays the wake recovery. Tip vortex is unconditionally unstable in all stability conditions due to mutual inductance mode of stability leading to vortex merging. The study is one of the first studies that accounts for realistic atmospheric boundary turbulence on wake development.

This thesis focuses on the development of techniques for detection of wind turbine wakes and their consequential impact on wind farm efficiency. Performance in power production of an on-shore wind farm is investigated through SCADA data, while the wind field within and around the wind farm is monitored through scanning wind LiDAR measurements and meteorological data. To retrieve these data, a four-month LiDAR field campaign was conducted. The power production of each turbine is analyzed as functions of the operating region of the power curve, wind direction and atmospheric stability. Five different methods are used to estimate the potential wind power as a function of time, enabling an estimation of power losses connected with wake interactions. The most robust method from a statistical standpoint is that based on the evaluation of a reference wind velocity at hub height and experimental mean power curves calculated for each turbine and different atmospheric stability regimes. It is assessed that power losses are larger under stable atmospheric conditions than for convective regimes, which is a consequence of the stability-driven variability in wake evolution. For this wind farm under examination, power loss due to wake shadowing effects is estimated to be about 4% and 2% of the total power production when operating under stable and convective conditions, respectively. However, cases with power losses about 60-80% of the potential power are

systematically observed for specific wind turbines and wind directions. The estimated power losses are ascribed to wake interactions by providing evidence of enhanced wind turbulence on downstream wind turbines. These losses are then analyzed from the perspective of the annual energy production, an important parameter for wind farm design and assessment in the wind energy industry. WAsP simulations of the wind farm are carried out to validate the estimated losses from the SCADA data. Furthermore, LiDAR measurements are analyzed, confirming that wind turbine wakes recover faster under convective regimes, thus alleviating detrimental effects due to wake interactions. As the initial steps to perform a detailed study and a statistical analysis on wake morphology, this thesis describes the methods of post-processing the LiDAR measurements taken of the wind farm. First, a filtering and realignment of the radial velocity into a time- and wind-dependent reference frame is carried out. Then, different techniques to define the main parameters of wind turbine wakes (such as width and center) are described and discussed. Results show that methods such as the center of gravity, which rely on a fitting that considers several measurement points, provide the most robust approach to define wake characteristics.
An estimate of the United States wind potential conducted in 2011 found that the energy available at an altitude of 80 meters is approximately triple the wind

energy available 50 meters above ground. In 2012, 43% of all new electricity generation installed in the U.S. (13.1 GW) came from wind power. The majority of this power, 79%, comes from large utility scale turbines that are being manufactured at unprecedented sizes. Existing wind plants operate with a capacity factor of only approximately 30%. Measurements have shown that the turbulent wake of a turbine persists for many rotor diameters, inducing increased vibration and wear on downwind turbines. Power losses can be as high as 20-30% in operating wind plants, due solely to complex wake interactions occurring in wind plant arrays. It is my objective to accurately predict the generation and interaction of turbine wakes and their interaction with downwind turbines and topology by means of numerical simulation with high-performance parallel computer systems. Numerical simulation is already utilized to plan wind plant layouts. However, available computational tools employ severe geometric simplifications to model wake interactions and are geared to providing rough estimates on desktop PCs. A three dimensional simulation tool designed for modern parallel computers based upon lattice Boltzmann methods for fluid-dynamics, a general six-degree-of-freedom motion solver, and foundational beam solvers has been proposed to meet this simulation need. In this text, the software development, verification, and validation are detailed. Fundamental computational fluid dynamics issues of boundary conditions and turbulence modeling are examined through classic cases (Cavity, Jeffery-Hammel, Kelvin-Helmholtz, Pressure wave, Vorticity wave, Backward facing step, Cylinder in cross-flow, Airfoils, Tandem cylinders, and Turbulent flow over a hill) to asses the accuracy and computational cost of developed alternatives. Simulations of canonical motion (falling beam), fluid-structure-interaction cases (Hinged wing and Flexible pendulum), and realistic horizontal axis wind turbine geometries (Vestas v27, NREL 5MW, and MEXICO) are validated against benchmarks and experiments. Results from simulations of the three turbine array at the Scaled Wind Farm Test facility are presented for two steady wind conditions.

This report examines the complex interactions between atmospheric stability and turbine-induced wakes on downwind turbine wind speed and power production at a West Coast North American multi-MW wind farm. Wakes are generated when the upwind flow field is distorted by the mechanical movement of the wind turbine blades. This has two consequences for downwind turbines: (1) the downwind turbine encounters wind flows with reduced velocity and (2) the downwind turbine encounters increased turbulence across multiple length scales via mechanical turbulence production by the upwind turbine. This increase in turbulence on top of ambient levels may increase aerodynamic fatigue loads on the blades and reduce the lifetime of turbine component parts. Furthermore, ambient atmospheric conditions, including atmospheric stability, i.e., thermal stratification in the lower boundary layer, play an important role in wake dissipation. Higher levels of ambient turbulence (i.e., a convective or unstable boundary layer) lead to higher turbulent mixing in the wake and a faster recovery in the velocity flow field downwind of a turbine. Lower levels of ambient turbulence, as in a stable boundary layer, will lead to more persistent wakes. The wake of a wind turbine can be divided into two regions: the near wake and far wake, as illustrated in Figure 1. The near wake is formed when the turbine structure alters the shape of the flow field and usually persists one rotor diameter (D) downstream. The difference between the air inside and outside of the near wake results in a shear layer. This shear layer thickens as it moves downstream and forms turbulent eddies of multiple length scales. As the wake travels downstream, it expands depending on the level of ambient turbulence and meanders (i.e., travels in non-uniform path). Schepers estimates that the wake is fully expanded at a distance of 2.25 D and the far wake region begins at 2-5 D downstream. The actual distance traveled before the wake recovers to its inflow velocity is dependent on the amount ambient turbulence, the amount of wind shear, and topographical and structural effects. The maximum velocity deficit is estimated to occur at 1-2 D but can be longer under low levels of ambient turbulence. Our understanding of turbine wakes comes from wind tunnel experiments, field experiments, numerical simulations, and from studies utilizing both experimental and modeling methods. It is well documented that downwind turbines in multi-Megawatt wind farms often produce less power than upwind turbine rows. These wake-induced power losses have been estimated from 5% to up to 40% depending on the turbine operating settings (e.g., thrust coefficient), number of turbine rows, turbine size (e.g., rotor diameter and hub-height), wind farm terrain, and atmospheric flow conditions (e.g., ambient wind speed, turbulence, and atmospheric stability). Early work by Elliott and Cadogan suggested that power data for different turbulent conditions be segregated to distinguish the effects of turbulence on wind farm power production. This may be especially important for downwind turbines within wind farms, as chaotic and turbulent wake flows increase stress on downstream turbines. Impacts of stability on turbine wakes and power production have been examined for a flat terrain, moderate size (43 turbines) wind farm in Minnesota and for an offshore, 80 turbine wind farm off the coast of Denmark. Conzemius found it difficult to distinguish wakes (i.e., downwind velocity deficits) when the atmosphere was convective as large amounts of scatter were present in the turbine nacelle wind speed data. This suggested that high levels of turbulence broke-up the wake via large buoyancy effects, which are generally on the order of 1 km in size. On the other hand, they found pronounced wake effects when the atmosphere was very stable and turbulence was either suppressed or the length scale was reduced as turbulence in this case was mechanically produced (i.e., friction forces). This led to larger reductions at downwind turbines and maximum velocity (power) deficits reached up to 50% (70%) during strongly stable conditions. At an offshore Danish wind farm, Hansen et al. found a strong negative correlation between power deficit and ambient turbulence intensity (i.e., atmospheric stability). Under convective conditions, when turbulence levels were relatively high, smallest power deficits were observed. Power deficits approaching 35 to 40% were found inside the wind farm during stable conditions. Large canopies interact with the atmospheric boundary layer (ABL) and alter transport of matter, energy, and momentum in accordance to their morphology. Canopy structure influence on turbulent processes can be utilized to achieve favorable interactions. Wind farm and forest canopies spatial arrangement is investigated in this work. Momentum fluxes investigated in a horizontal axis wind turbine (HAWT) array showed the existence of gusts of wind transported both from ABL above the canopy and the unperturbed flow below the canopy through sweep and ejection events. A new wind farm arrangement in which clusters of vertical axis wind turbines (VAWT) are collocated with HAWTs is proposed to enhance power harvested per unit area. An aligned collocated arrangement is found to increase power production by 3.5%. This approach opens possibilities to further optimize the collocation layout and determine the arrangement that extracts most power. Other considerations in terms of renewable energy production are focused on advancing offshore wind farms design by considering their wake flow intermittency due to its consequence in increasing dynamic loading on the turbine structure. It is found that pitch motion increases intermittency in floating wind turbine wake up to five turbine diameters downstream the turbine and shorter in highly turbulent flow. Furthermore, a heterogeneity parameter is developed to measure spatial variations in canopies. The parameter proved successful in measuring heterogeneity of forest canopies with various spatial arrangements. Momentum advection was found to increase up to 14 times that of a homogeneous canopy. Power law relation is determined between heterogeneity parameter and momentum advection. These findings have implications in determining environmentally viable forest management and enhanced weather forecasting. Understanding the dynamics between turbulent processes and spatial variations in canopies is of essence to exploit them in sustainable development.