DEVELOPMENT OF A LARGE-EDDY SIMULATION FRAMEWORK FOR WIND ENERGY STUDIES

Yu-Ting Wu[1]

[1] *Assistant Professor, Department of Engineering Science, National Chun Kung University, Tainan, Taiwan,* bulawu@gmail.com

ABSTRACT

A modeling framework is proposed and validated to simulate turbine wakes and associated power losses in wind farms. It combines the large-eddy simulation (LES) technique with blade element theory and a turbine-model-specific relationship between shaft torque and rotational speed. In the LES, the turbulent subgrid-scale stresses are parameterized with a tuning-free Lagrangian scale-dependent dynamic model. The turbine-induced forces and turbine-generated power are modeled using a recently developed actuator-disk model with rotation (ADM-R), which adopts blade element theory to calculate the lift and drag forces (that produce thrust, rotor shaft torque and power) based on the local simulated flow and the blade characteristics. In order to predict simultaneously the turbine angular velocity and the turbine-induced forces (and thus the power output), a new iterative dynamic procedure is developed to couple the ADM-R turbine model with a relationship between shaft torque and rotational speed. This relationship, which is unique for a given turbine model and independent of the inflow condition, is derived from simulations of a stand-alone wind turbine in conditions for which the thrust coefficient can be validated. Comparison with observed power data from the Horns Rev wind farm shows that better power predictions are obtained with the dynamic ADM-R than with the standard ADM, which assumes a uniform thrust distribution and ignores the torque effect on the turbine wakes and rotor power. The results are also compared with the power predictions obtained using two commercial wind-farm design tools (WindSim and WAsP). These models are found to underestimate the power output compared with the results from the proposed LES framework.

KEYWORDS:

Large-eddy simulation framework

In this study, we use a modified version of the LES code developed by Albertson et al. (1999), Porté-Agel et al. (2000), Porté-Agel (2004), Stoll and Porté-Agel (2006), Wu and Porté-Agel (2011; 2013; 2014). The code solves the filtered continuity equation, and the filtered Navier-Stokes equations (written here in rotation form and using the Boussineq approximation), and the filtered heat equation:

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j\left(\frac{\partial \tilde{u}_i}{\partial x_j} - \frac{\partial \tilde{u}_j}{\partial x_i}\right) = -\frac{1}{\rho}\frac{\partial \tilde{p}^*}{\partial x_i} - \frac{\partial \tau_{ij}^d}{\partial x_j} + \nu\frac{\partial^2 \tilde{u}_i}{\partial x_j^2} - \frac{f_i}{\rho} + \delta_{i3} g\frac{\tilde{\theta} - \langle\tilde{\theta}\rangle}{\theta_0} + f_c \varepsilon_{ij3}\tilde{u}_j + \mathcal{F}_i \tag{2}$$

$$\frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_j\frac{\partial \tilde{\theta}}{\partial x_j} = -\frac{\partial q_j}{\partial x_j} + \alpha\frac{\partial^2 \tilde{\theta}}{\partial x_j^2} \tag{3}$$

where the tilde represents a three-dimensional spatial filtering operation at scale Δ, t is time, $\tilde{u}_i$ is the resolved velocity in the i-th direction (with i = 1,2,3 corresponding to the streamwise (x), spanwise (y) and vertical (z) directions in a Cartesian coordinate system), $\tilde{\theta}$ is the resolved potential temperature, θ_0 is the reference temperature, the angle brackets represent a horizontal average, g is the gravitational acceleration, f_c is the Coriolis parameter, δ_{ij} is the Kronecker delta, ε_{ijk} is the alternating unit tensor, ρ is the air density, $\tilde{p}^*$ is the modified pressure, τ_{ij}^d is the deviatoric part of the SGS momentum flux, ν is the kinematic viscosity of air, q_j is the SGS heat flux, α is the thermal diffusivity of air, f_i is an immersed force (per unit volume) for modeling the effect of wind turbines on the flow, and F_i is a forcing term (e.g., a mean pressure gradient). Based on the Boussinesq approximation, both ρ and θ_0 in Eq. (2) are assumed to be constant. The SGS fluxes of momentum and scalar (i.e., heat) are modeled using Lagrangian scale-dependent dynamic models. An immersed force (per unit volume) f_i is parameterized using a recently-developed wind turbine model. Periodic boundary conditions are used along the horizontal directions and a stress-free boundary condition is employed at the top of the domain. Monin-Obukhov similarity theory is applied to compute the instantaneous (filtered) surface shear stress as a function of the velocity field at the lowest vertical grid point. More details on the numerical method of the LES code can be found in Porté-Agel et al. (2000), Porté-Agel (2004), Stoll and Porté-Agel (2006; 2008).

Model validation for the proposed framework

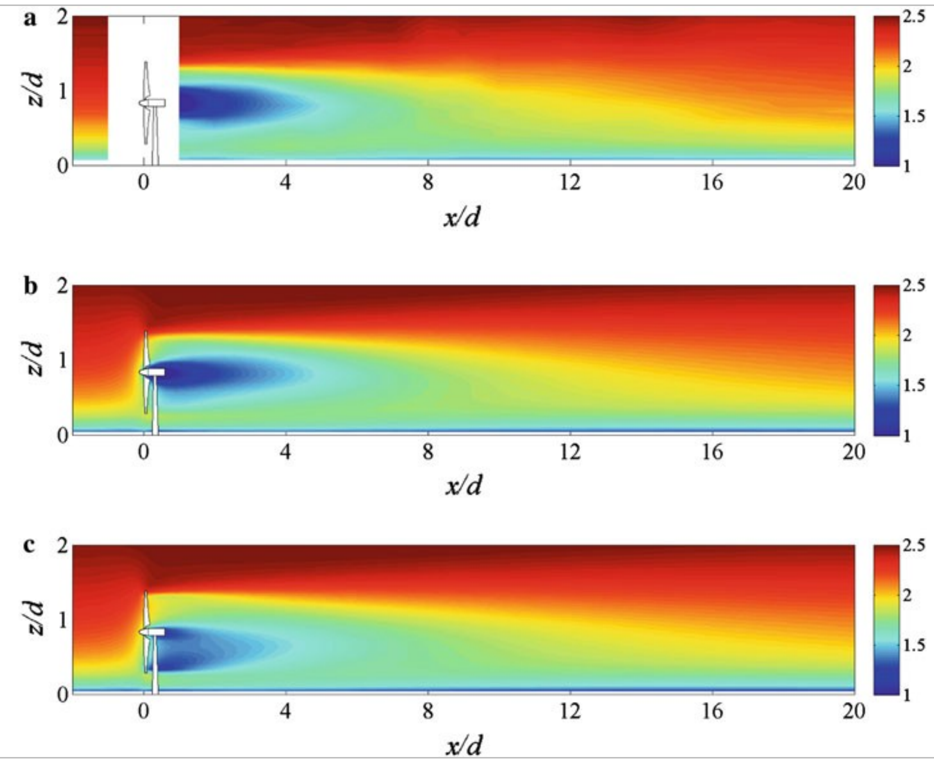

Fig. 1 Contours of the time-averaged streamwise velocity $\overline{u}$ (m s^{-1}) in the middle vertical plane perpendicular to the turbine: **a** wind-tunnel measurements, **b** ADM-R, **c** ADM-NR

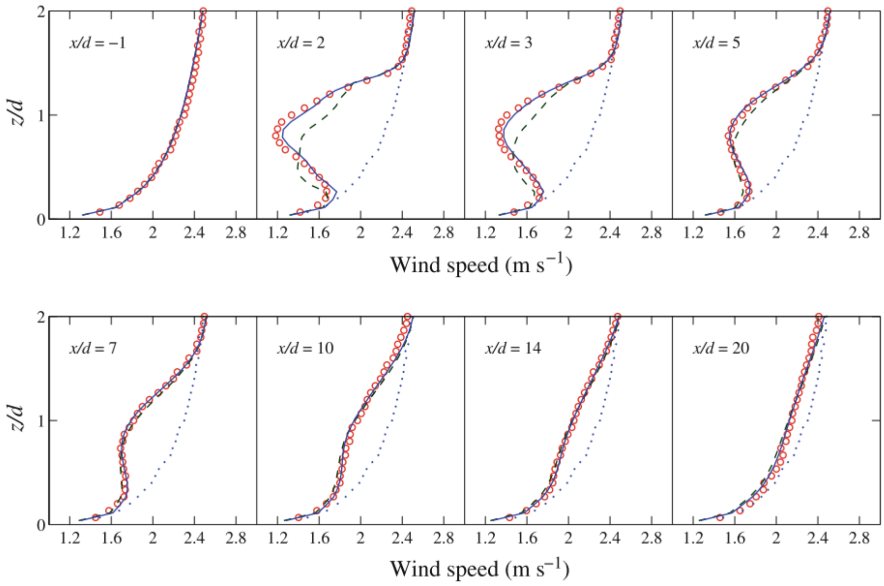

Fig. 2 Comparison of vertical profiles of the time-averaged streamwise velocity $\bar{u}$ (m s^{-1}): wind-tunnel measurements (*open circle*), ADM-R (*solid line*) and ADM-NR (*dashed line*). The *dotted line* represents the inflow profile

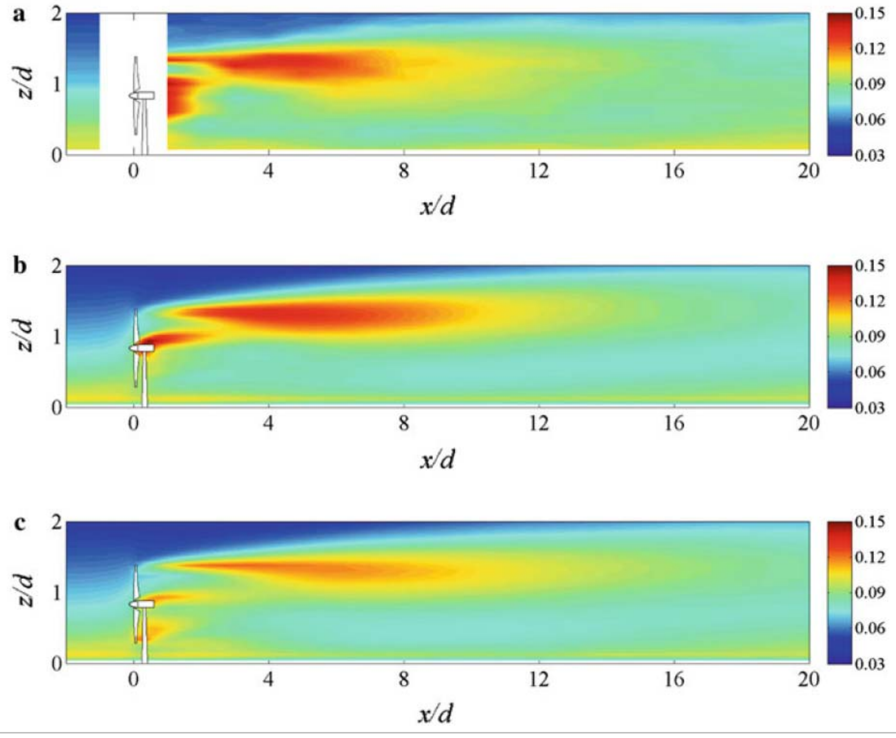

Fig. 3 Contours of the streamwise turbulence intensity $\sigma_u/\bar{u}_{hub}$ in the middle vertical plane perpendicular to the turbine: a wind-tunnel measurements, b ADM-R, c ADM-NR

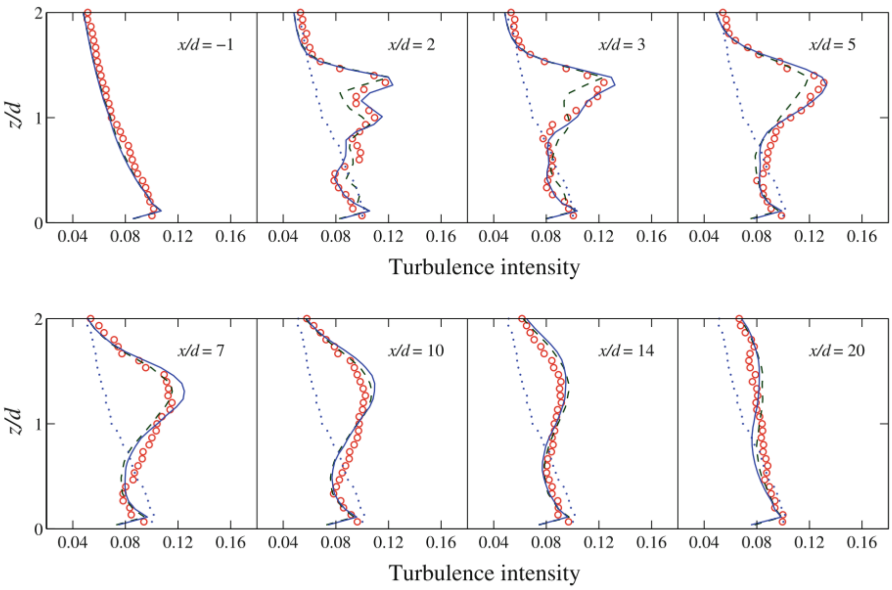

Fig. 4 Comparison of vertical profiles of the streamwise turbulence intensity $\sigma_u/\bar{u}_{hub}$: wind-tunnel measurements (*open circle*), ADM-R (*solid line*) and ADM-NR (*dashed line*). The *dotted line* represents the inflow profile

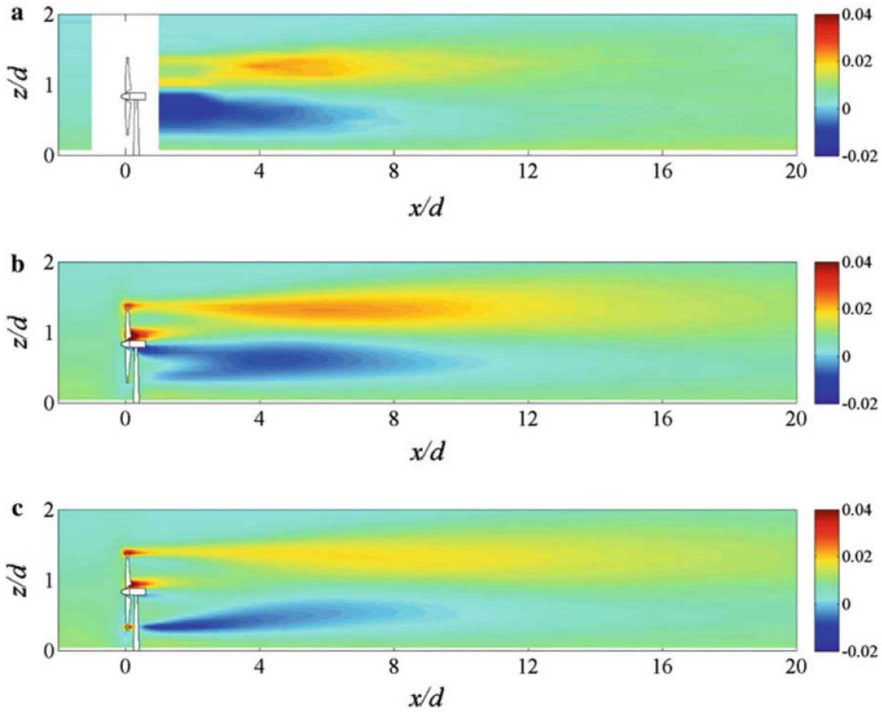

Fig. 5 Contours of the kinematic shear stress $-\overline{u'w'}$ (m^{2}s^{-2}) in the middle vertical plane perpendicular to the turbine: a wind-tunnel measurements, b ADM-R, c ADM-NR

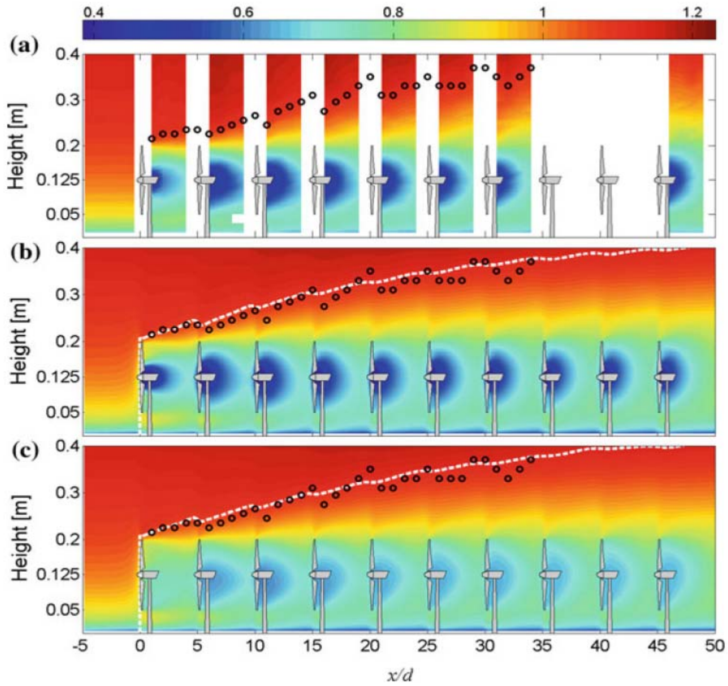

Fig. 6 Contours of the normalized time-averaged streamwise velocity $\sigma_u/\bar{u}_{hub}$ in the vertical plane at zero span (y = 0): wind-tunnel measurements (*top*), ADM-R (*middle*), ADM-NR (*bottom*). *Circles* in the three subplots denote the edge of the measured farm wake. *White dashed lines* in the subplots **b** and **c** denote the edge of the simulated farm wake obtained from the ADM-R and ADM-NR, respectively. The edge of the farm wake is defined as the height where the time-averaged streamwise velocity is 99% of the mean inflow velocity at that height

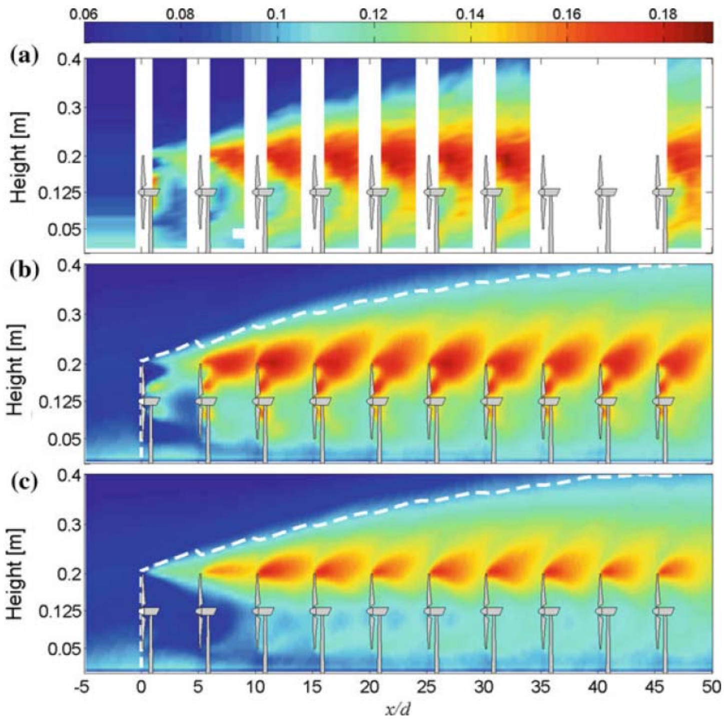

Fig. 7 Contours of the streamwise turbulence intensity $\sigma_u/\bar{u}_{hub}$ in the vertical plane at zero span (y = 0): wind-tunnel measurements (*top*), ADM-R (*middle*), ADM-NR (*bottom*). *White dashed lines* in the subplots **b** and **c** denote the edge of the simulated farm wake obtained from the ADM-R and ADM-NR models, respectively

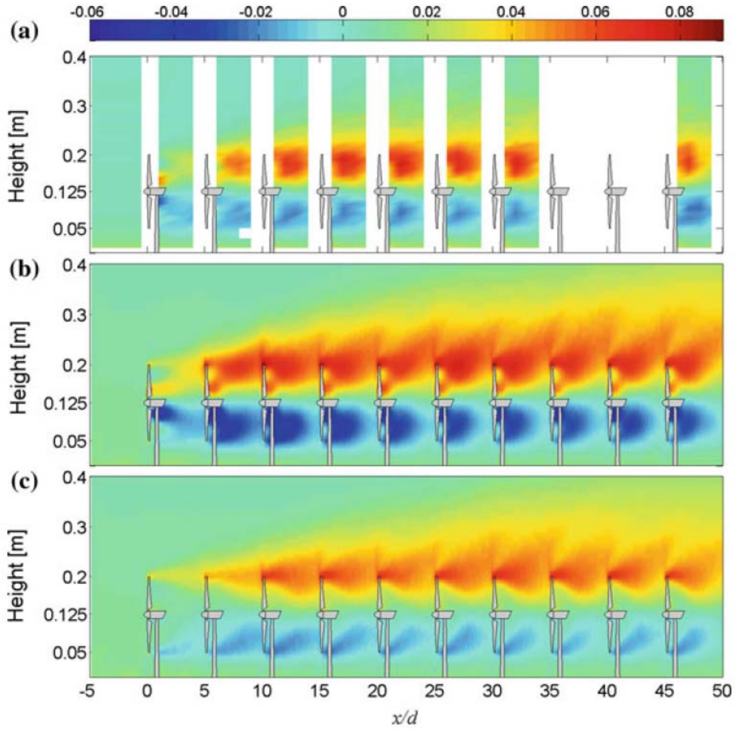

Fig. 8 Contours of the kinematic shear stress τ_{xz} (m^2s^{-2}) in the vertical plane at zero span (y = 0): wind-tunnel measurements (*top*), ADM-R model (*middle*), ADM-NR model (*bottom*)

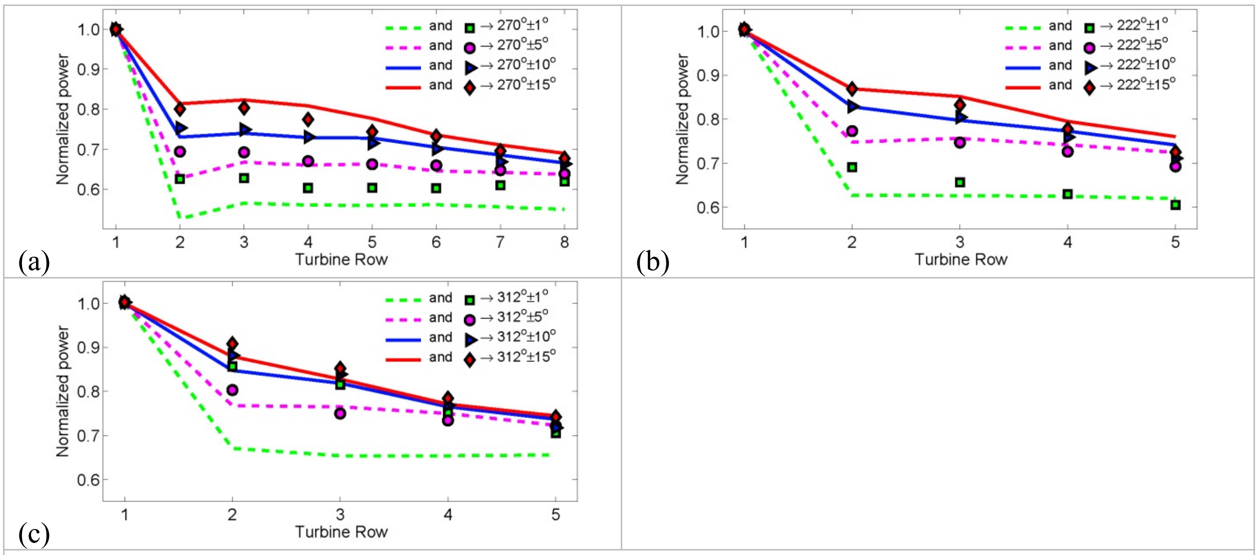

Fig. 9 Comparison of the normalized mean power output data obtained from the observations and simulations with the ADM-R for different wind sectors: (a) $270^o \pm 1^o$, $\pm 5^o$, $\pm 10^o$, and $\pm 15^o$; (b) $222^o \pm 1^o$, $\pm 5^o$, $\pm 10^o$, and $\pm 15^o$; (c) $312^o \pm 1^o$, $\pm 5^o$, $\pm 10^o$, and $\pm 15^o$. Symbols and lines denote the observed and simulated power data, respectively.

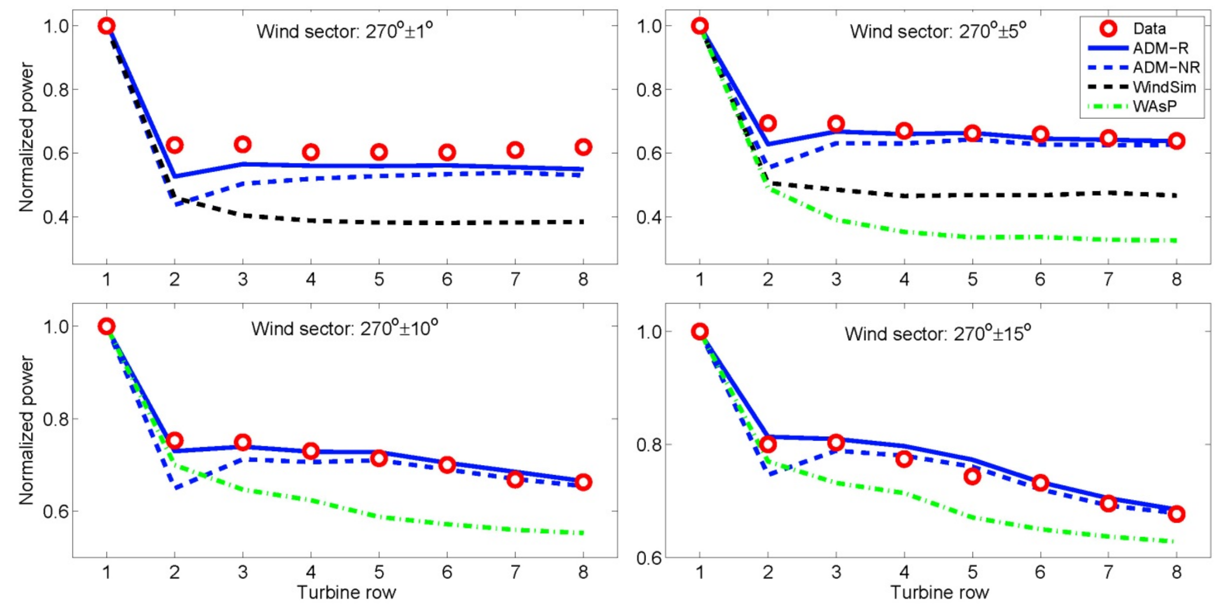

Figure 10 Comparison of the observed and simulated power output data for four wind sectors of (a) $270^o \pm 1^o$, (b) $270^o \pm 5^o$, (c) $270^o \pm 10^o$, and (d) $270^o \pm 15^o$.

References

Wu, Y.-T., and Porté-Agel, F. (2011). "Large-Eddy Simulation of Wind-Turbine Wakes: Evaluation of Turbine Parametrisations." Boundary-Layer Meteorology, 138(3), 345-366.

Wu, Y.-T., and Porté-Agel, F. (2013). "Simulation of Turbulent Flow Inside and Above Wind Farms: Model Validation and Layout Effects." Boundary-Layer Meteorology, 146(2), 181-205.

Wu, Y.-T., and Porté-Agel, F. (2015). " Modeling turbine wakes and power losses within a wind farm using LES: An application to the Horns Rev offshore wind farm." Renewable Energy, 75, 945-955.