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Review paper

A REVIEW OF CHALLENGES IN ASSESSMENT AND FORECASTING OF WIND ENERGY RESOURCES

Pregled izazova u procjeni i prognoziranju energetskog potencijala vjetra

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Abstract: The main issues related to assessment and forecasting of the wind and wind energy have been reviewed. These include the limitations and advantages of wind forecasting and assessment of the wind power density, especially considering trends of increasing penetration of wind-generated power into the utility grid and storage of wind-generated power. Accurate forecasting of the wind power density over a large range of spatial and temporal scales is a critical issue for planning and operations of wind farms. A review of various prediction tools, from simple statistical models to highly complex numerical techniques, was performed for this purpose. The influence of wind variability, atmospheric stability, turbulence, and the low-level jets on wind power density are elaborated on in detail. Furthermore, prediction and assessment of future wind energy resources and their economic implications as well as environmental concerns such as birds' habitats and routes, viewpoint aesthetics, and noise are also discussed in this study. Some climate projection studies indicate minor changes in the wind resources comparable to differences in global models results while others argue that the wind resources will be reduced due to global warming and they call for harvesting wind energy at the maximum rate as soon as possible.

Keywords: Wind energy, wind power density, wind farms, wind turbine wakes, mesoscale modeling, CFD, LES, energy storage, turbulence intensity, climate predictions.

Sažetak: U radu su prikazani osnovni problemi procjene i prognoziranja vjetra i proizvodnje energije vjetra. Tematika uključuje aspekte točnosti procjene i prognoze potencijala energije vjetra, osobito s obzirom na trendove povećanja uključenja energije iz vjetroelektrana u potrošačku mrežu te korištenje različitih metoda uskadištenja energije. Precizno prognoziranje gustoće energije vjetra u širokom rasponu prostornih i vremenskih skala je kritičan uvjet za planiranje i operativno upravljanje vjetroelektranama. Provedena je analiza različitih prognostičkih pristupa u rasponu od jednostavnih statističkih pa sve do složenih numeričkih metoda. Detaljno je razmotren utjecaj jake promjenjivosti vjetra, atmosferske stabilnosti, turbulencije i prizemnih mlaznih struja na gustoću energije vjetra. Dio studije se odnosi i na buduće promjene vjetra u okviru klimatskih promjena, kao i brige za okoliš poput utjecaja vjetroelekrana na smrtnost ptica i promjena njihovih koridora migracije, problema u vezi narušavanja vizualnih vrijednosti okoliša te problema u vezi buke tijekom rada vjetroelektrana. Važno je napomenuti da neke od klimatskih studija i simulacija ukazuju na minimalne promjene u budućem po-

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tencijalu vjetra koje su usporedive s neodređenostima i greškama u globalnim modelima. Nasuprot tome, druge studije naglašavaju da će energetski potencijal vjetra znatno oslabiti uslijed globalnog zatopljenja te sugeriraju da je nužno da se energija vjetra koristi što prije i što je moguće u većem obimu.

Ključne riječi: Energija vjetra, gustoća snage vjetra, vjetroelektrane, mezoskalno modeliranje, CFD, LES, skladištenje energije, intenzitet turbulencije, klimatske projekcije.

1. INTRODUCTION AND HISTORICAL BACKGROUND

The importance and value of renewable energy resources such as wind, water, and solar power in providing for global energy need is discussed by Jacobson and Delucchi (2011). Globally, there is about 10^{14} W of extractable wind power. The extractable power from hydro resources is two orders of magnitude smaller than that of wind resources, and geothermal and tidal resources are about three orders of magnitude smaller. Considering wind as a global renewable energy resource, it is important to emphasize that the total amount of economically extractable wind power is significantly greater than cumulative human power use from all other energy sources. Latitudinal asymmetries in incoming solar energy drive the large scale atmosphere system and generate wind that dissipates through turbulence and friction processes. About 2% of the incoming solar energy is converted into winds, and 35% of that is removed by friction in the lowest kilometer of the atmosphere. It is estimated that only about 10% of the available wind energy can be extracted within the first kilometer of the atmosphere (Gustavson, 1978). If all land non-forested areas were used for wind farms operating at only 20% of their maximum capacity, the generated power would be 40 times larger than the global demand (Lu et al., 2009).

Wind has been utilized as a source of power for thousands of years for such tasks as propelling sailing ships, grinding grain, pumping water and powering factory machinery. People have been harnessing the wind ever since farmers in ancient Persia discovered how to use wind power to pump water. The first known use of wind power was in the first century by Hero of Alexandria, (http://en.wikipedia.org/wiki/Hero_of_Alexandria). Wind power was also used during the 7th to 10th century in the area between today's Iran and Afghanistan (Kaldellis and Zafirakis, 2011). These windmills were mainly used to pump water or grind wheat. These vertical axis turbines used the drag component of wind power generation (Jenkins et al., 2001; Manwell et al., 2002). To work properly, the part rotating in opposite direction compared to the wind had to be protected by a wall. Obviously, devices of this type can be used only in places with a dominant wind direction because they cannot follow changes in incoming wind direction. Review studies of using wind power for grinding grain in Persia in the tenth century and in China in the thirteenth century are described by Fleming and Probert (1984), Sheppard (1994), and Pasqualetti et al. (2002). The first windmills built in Europe, likely inspired by the ones in the Middle East, used a horizontal axis rotor thereby substituting drag force for the lift force (Musgrove, 2010). During the following centuries many modifications and improvements were applied, especially in areas with high directional variability. The best examples are the Dutch windmills that were used to drain water in reclaimed lands.

Wind energy technology is one of the most rapidly expanding areas among renewable energy sources (Blanco, 2009; Kaldellis and Zafirakis, 2011). Worldwide development of wind energy expanded rapidly starting in the early 1990s. The average annual growth rate of world installed capacity of wind power from 1994 to 2010 has been over 31% (see, for example, Burton et al., 2001; Jenkins et al., 2001; Ackerman and Soder, 2000, 2002; Manwell et al., 2002; Ackermann, 2005; Joselin Herbert, 2007; Belu, 2012). Unlike the last surge in wind power development during 1970s and early 1980s which was mainly due to the temporary oil embargo from the OPEC countries, the current wave of wind energy development is driven by many favorable reasons. These include its tremendous environmental, social, and economic benefits, technological maturity, deregulation of electricity markets throughout the world, widespread public support, and government incentives. Wind energy is expected to play an increasingly important role in the future national energy scene (Gipe, 1995; Joselin Herbert, 2007; Frerris and Infield, 2008). In resource-ideal locations, the cost of wind-generated energy is already competitive with that of traditional fossil fuel generation technologies (Blanco, 2009). Experts predict wind power will capture 5% of the world energy market by the year 2020 (Belu, 2012).

Despite environmental benefits and technological maturity, reliability and stability of the power grids represent a challenge to penetration of wind-generated power, due to the highly variable and intermittent nature of the winds. Wind energy resource rely on the incident wind speed and direction, both of which vary in time and space due to changes in large-scale and small-scale circulations, surface energy fluxes, and topography (Pettersen et al., 1998a,b; Klink,1999; Archer and Jacobson, 2003; Belu and Koračin, 2012). Since the wind power density is proportional to the cube of the wind speed (as will be discussed in the next section), any small errors in forecasting wind speeds can result in significant differences between forecasted and actual wind energy outputs. Consequently, accurate assessment and forecasting of the spatial and temporal characteristics of the winds and turbulence remains the most significant challenge in wind energy production. The spatial variability of the wind and its sensitivity to model setups suggest that higher resolution models and multi-model ensemble forecasting are promising tools for improved wind energy predications.

This review is organized as follows. Section 2 presents the basic concepts of wind power extraction. Section 3 discusses the influence of a complex wind regime on wind energy generation focusing on wind variability, low-level jets, effects of air density and temperature, and turbulence effects. Environmental concerns (Section 4) and the economics (Section 5) of wind energy are addressed next. Section 6 addresses storage of wind generated power as a means of mitigating the temporal intermittency of wind. Section 7 discusses methods and tools for wind and wind power forecasting and Section 8 discusses modeling and observations of wind turbine wakes. Section 9 indicates the possible evolution of wind resources under climate change scenarios followed by the concluding remarks in Section 10.

2. BASIC CONCEPTS OF EXTRACTING WIND POWER

The kinetic energy (KE) of the moving air molecules represent a source used for extracting wind energy. Wind turbines are mechanical devices designed to convert part of the wind kinetic energy into useful mechanical and then electrical energy. Several designs have been devised. Most of them use a rotor that is propelled by lift or drag forces, which result from its interaction with the wind. Depending on the position of the rotor axis, wind turbines are classified into vertical-axis and horizontal-axis ones. Turbine power production depends on the interaction between the rotor and the wind; the major aspects of wind turbine performance, such as power output and loads, are determined by the aerodynamic forces generated by the wind. Rotor-wind interactions depend on turbine geometry – including rotor blade profile, number of blades, control methods, and tower shadowing.

A total moving mass of air passing through the wind turbine blades in a certain time is an extractable power (Burton et al., 2001; Jenkins et al., 2001; Manwell et al., 2002). Knowing the wind statistics and annual wind variation at a given site or for an area is important, but is not sufficient for assessing the economic viability of a wind energy development. For that purpose the level of wind resource is often defined in terms of the wind power density (W m^{-2}). Power is the rate at which the kinetic energy of the air is used. In a time interval Δt, blades can extract power from a cylindrical volume of air that is equal to the product of the rotor swept area A_R and the length equal to the product of the velocity (v) and the time interval Δt. So, the extractable wind power (P_W) is:

$$P_W = \frac{\Delta\left(Kinetic\,energy\right)}{\Delta\left(time\right)} = \Delta\left(\frac{mass \cdot v^2}{2}\right)\frac{1}{\Delta t} = \cdot$$

$$= \frac{\rho\, A_R\, v\, \Delta t\, v^2}{2\,\Delta t} = 0.5 \cdot \rho \cdot A_R \cdot v^3 \qquad (1)$$

Where ρ is the air density. The mean wind power density per unit area is:

$$\frac{P_{w,mean}}{A_R} = 0.5 \cdot \rho \cdot \langle v^3 \rangle \tag{2}$$

Where the mean value of the wind speed cube is expressed as:

$$\langle v^3 \rangle = \int_0^\infty v^3 \cdot p(v) dv$$

Consequently, the wind power per unit area is proportional to the cube of the wind, and thus small changes in the wind speed result in large variations in the wind power. The actual turbine power (P_{wT}) that is captured from the wind field is lower than the above stated maximum theoretical extraction, and can be described by a nonlinear function:

$$P_{wT} = 0.5 \cdot \rho \cdot C_P(\alpha,\lambda) \cdot A_R \cdot \langle v^3 \rangle \tag{3}$$

Here $C_P(\alpha,\lambda)$ is the wind turbine capacity factor or the aerodynamic efficiency of the rotor, and v is the effective wind speed. $C_P(\alpha,\lambda)$describes the fraction of the power in the wind that may be converted by the turbine into mechanical work. If one assumes that the maximum efficiency of the rotor is independent of the effective wind speed, the captured power can grow with the cube of the wind speed. The rotor power coefficient is usually given as a function of the tip-speed ratio λ and the blade pitch angle α. The blade pitch angle is defined as the angle between the plane of rotation and the blade cross-section chord. The tip speed ratio is defined as:

$$\lambda = \frac{\omega R}{v} \tag{4}$$

Where ω is the angular velocity of the rotor, and R is the rotor radius (blade length). The maximum rotor power efficiency, regardless of configurations, has a theoretical maximum value of 59%; however, in practice the fraction of power extracted will always be less because of loss factors such as friction, shear, and coherent eddies (Burton et al., 2001; Jenkins et al., 2001; Manwell et al., 2002).

3. FACTORS AFFECTING COMPUTATIONS OF THE WIND POWER DENSITY

Since the effects of wind shear, turbulence intensity, and atmospheric stability on wind turbine energy production are not fully understood, wind resource assessment studies can have large uncertainties. The estimation of the magnitude of the uncertainty source is often related to empirical considerations rather than analytical calculations. Some studies suggest probability models for the natural variability of wind energy resources that include air density, mean wind velocity and associated Weibull parameters, surface roughness exponent and error for prediction of long-term wind velocity (e.g., Kwon, 2010). Depending on atmospheric conditions, waking by upstream turbines and terrain/roughness interactions, wind turbines often operate far from the ideal conditions, and field-deployed power curves can be very different from certified ones (Rohatgi and Barbezier, 1999; Sumner and Masson, 2006; Antoniou et al., 2009; Wagner et al., 2009; Wharton and Lundquist, 2011; Belu and Koračin, 2012). Better predictions of power or loads require more representative wind measurements and power computations over the rotor-swept area for individual wind turbines. There is a need for adoption of new measurements and power estimation methods.

3.1 Wind variability

One of the main challenges in harvesting wind energy is that wind is generally intermittent and variable in speed and direction (e.g., Justus and Mikhail, 1976). Depending on the flow properties and scales of motion, the flow can become turbulent with stochastic and chaotic properties (Stull, 1999; Davidson, 2004). There are three main aspects that can reduce the intermittency problem: spatial distribution of wind facilities, accurate forecasting methods, and storage systems. Although a single wind setup is subject to large variations of the wind, if the facilities are spatially distributed and connected to the same utility grid, a total output at any time becomes more uniform and reliable (http://www.bwea.com/pdf/RAEIntegrationfinal.pdf). For example in Denmark, which is relatively flat terrain and has high penetration of wind energy (20%), while output from a single wind farm may occasionally change by 100% within an hour, total power output from an entire network of wind farms are generally less than +/-3% of its initial value (Ford and Milborrow, 2005).

3.2 Low-level jet

The low-level jet is a mesoscale phenomenon associated with the nighttime very stable boundary layer that can have a width of hundreds of kilometers and a length of a thousand kilometers (Stull, 1999). They have been observed worldwide (Kraus et al., 1985; Anderson, 1976; Bonner, 1968; Smedman et al., 1996; Banta et al., 2002, 2006; and Storm et al., 2009). During nighttime over land, the ground surface cools at a faster rate than the adjacent air and stable stratification forms near the surface and propagates upward. Downward mixing of the winds is reduced and winds aloft become decoupled from the surface and accelerate. The maximum wind speeds are usually 10-20 ms^{-1} or more at elevations of usually 100-300 m and occasionally as high as 900 m above the ground. Consequently, it is not possible to accurately estimate winds aloft at hub and blade heights from routine surface measurements. Additionally, a strong wind shear and associated turbulence develop at the bottom and top of the jet layer. An example of the effects of the low-level jet on wind energy assessment is shown by Kelley et al. (2004).

3.3 Air density and temperature

Since wind speed generally increases with height, higher elevation sites often offer greater wind energy resources than comparable lower elevation sites. However, the decrease of air density with height can make an impact on the computed power, since wind power density is directly proportional to air density. Air density is usually calculated from temperature and pressure measurements. In most of the cases, it is advantageous to site turbines at higher elevations to take advantage of higher wind speeds. Power and the power curve of a particular turbine depend on the air density (see Equations 1 to 4). As an example, the air density values encountered at measurement sites in western Nevada shown by Belu and Koračin (2009) were mostly between 0.936 kgm^{-3} and 1.025 kgm^{-3} with a multi-annual mean value of 0.982 kgm^{-3}, significantly lower than the mean standard air density of 1.25 kgm^{-3}. Power curves for various values of the air density must be accounted for in order to improve the power output estimate accuracy. Depending on the turbine's method of control, either the power or velocity is normalized (Rohatgi and Barbezier, 1999; Sumner and Masson, 2006; Wagner et al., 2009; Wharton and Lundquist, 2011; Belu and Koračin, 2012) for use in power density calculations. For the case of a turbine with active pitch control, the velocity is normalized with the reference air density ρ_0:

$$v_{norm} = \bar{v}\left(\frac{\bar{\rho}}{\rho_0}\right)^{1/3} \tag{5}$$

Although the correction for air density appears to be relatively small, this parameter is also subject to change – generally to decrease due to global warming (Ren, 2010).

3.4 Effects of turbulence, wind shear and wind gusts on fatigue of wind turbine blades

At today's usual hub-heights of 80 m or more, turbine rotors encounter large vertical gradients of wind speed and turbulence. Rotors are susceptible to fatigue damage that results from turbulence (Sutherland, 2002; Hand et al., 2003). Understanding the impact of turbulence on the blades can help in designing long-term operational and maintenance schedules for wind turbines. Consequently, this understanding can lead to the development of advanced control schemes to mitigate loads such as an active control of the blade pitch angle. Quantification of the effects of turbulence on wind turbine is usually done by computing an equivalent fatigue load parameter, F_e (kNm), as a function of the amplitude of the wind fluctuations within an averaging period, blade material properties, number of counting averaging bins and the total number of samples (Kelley et al., 2000). As an example, Hand et al. (2003) considered a usual averaging period of 10 min with a sampling rate of 40 Hz. Based on experimental data, they found that the highest blade root flap bending moment equivalent fatigue load does not correspond to the greatest wind speeds, but to the class of wind speeds that has the highest amplitude of fluctuations. Turbulent fluctuations are the main source of blade fatigue, and can also be present in the stable boundary layer (Sim et al., 2009).

3.4.1 Turbulence intensity

The turbulence intensity (*TI*) is a measure of the overall level of turbulence and is defined as (Sumner and Masson, 2006; Antoniou et al., 2009; Wagner et al., 2009):

$$TI = \frac{\sigma_v}{v} \tag{6}$$

where σ_v is the wind speed standard deviation (ms^{-1}) at the nacelle height over a specified averaging period (10 min). For example, Belu and Koračin (2009) found that, from the power curves for different turbulence intensity classes and for low to moderate wind speeds (4 to 10 ms^{-1}), high *TI* classes yield the most power while for the higher wind speeds (10-15 ms^{-1}), low *TI* classes yield the most power, also reported elsewhere (Wharton and Lundquist, 2011). There also are differences in the standard deviations of the output power. In the wind speed range 4-15 ms^{-1} the standard deviation of certain turbulence intensity classes (4 - 8% and 10 -15%) differs up to 50% with the standard deviation for all turbulence intensities. *TI* is often affected by atmospheric stability, which can affect the performance of theoretical wind turbine power curves. Wharton and Lundquist (2011) and Vanderwende and Lundquist (2012) used the wind power law coefficient and the bulk Richardson number to separate time periods by stability to generate regime-dependent wind turbine power curves. Their results indicate under-performance during stable regimes and over-performance during convective regimes at moderate wind speeds. A correction factor is often applied to account for *TI* (Sumner and Masson, 2006; Antoniou et al., 2009; Wagner et al., 2009; Wharton and Lundquist, 2011; Belu and Koračin, 2012):

$$v_{corr} = v_{norm}\left(1+3(TI)^2\right)^{1/3} \tag{7}$$

Here, *TI* is the turbulence intensity as given by Equation (6).

3.4.2 Wind shear and wind profile

Vertical wind shear is an important consideration as wind turbines are becoming larger (Elliot and Cardogan, 1990). Wind speed is usually recorded at the standard meteorological height of 10 m, while wind turbines usually have hub heights near 80 m or beyond. In cases which lack elevated measurements, hub-height wind velocity is estimated by applying a vertical extrapolation coefficient to surface measurements (Peterson and Hennessey, 1977). However, the vertical extrapolation coefficient can contain errors and uncertainties due to terrain complexity, atmospheric stability, and turbulence. Various methods exist for the extrapolation of wind speed to the wind turbine hub height. The theoretical background of the wind extrapolation methods is based on the Monin-Obukhov similarity theory (Sumner and Masson, 2006). However, the wind speed $v(h)$ at a height h can be calculated using the roughness length z_0 from the wind speed $v(h_0)$ at height h_0 (usually the standard measurement level) from the logarithmic law:

$$v(h) = v(h_0)\frac{\ln\left(\frac{h-d}{z_0}\right)}{\ln\left(\frac{h_0-d}{z_0}\right)} \tag{8}$$

Obstacles can cause the displacement of the boundary layer from the ground, which is expressed by the parameter *d*. For widely scattered obstacles, parameter *d* is zero, while in other cases it is expressed as 70% of the obstacle height (Justus and Mikhail, 1976; Peterson and Hennessey, 1977; Petersen et al., 1999a,b; Burton et al., 2001; Jenkins et al., 2001). The roughness length (z_0) describes the height at which the wind is zero by definition, meaning that surfaces with a large roughness length have a large effect on the wind. It ranges from 0.0002 m for open sea, 0.005-0.03 m for open land, 0.03-0.1 m for agricultural land, and 0.5-2 m for very rough terrain or urban areas. In a case when only surface measurements are available, the increase of wind speed with height should be taken into account for the installation of large wind turbines. Thus the surveys must rely on simpler expressions and secure satisfactory results even when they are not theoretically accurate. For $h_0 = 10$ m and $z_0 = 0.01$ m, the parameter $\alpha = 1/7$, which is consistent with the value of 0.147 used in the wind turbine design standards (IEC standard 61400-3, 2005) to represent the change of wind speeds in the lowest levels of the atmosphere. This equation is sometimes called a 1/7 power law or the empirical Hellmann exponential law, expressed as:

$$\frac{v(h)}{v_0} = \left(\frac{h}{h_{ref}}\right)^{\alpha} \tag{9}$$

where $v(h)$ is the wind speed at height h, v_0 is the speed at h_{ref} (usually 10 m height), and α is the friction coefficient or power law index. This coefficient is a function of the surface roughness at a specific site and the thermal stability of the Prandtl layer. It is frequently assumed to be 1/7 for open land. However, this parameter can vary diurnally and seasonally as well as spatially. Sisterson et al. (1983) found that a single power law is insufficient to adequately project the power available from the wind at a given site, especially during nighttime and also in the presence of the low-level jets. Belu and Koračin (2009) found significant discrepancies of values for α for western Nevada, ranging from 0.09 to 0.120, quite smaller compared to the standard 0.147 value. Another formula, known as the simple logarithmic wind profile law (neglecting the obstacle parameter d in Equation (8)) is also widely used for wind speed extrapolation:

$$\frac{v(h)}{v_0} = \frac{\ln\left(\frac{h}{z_0}\right)}{\ln\left(\frac{h_{ref}}{z_0}\right)} \tag{10}$$

If the type of ground cover is known, the wind speed at other heights can be estimated.

In addition to the wind shear from the ground level to hub height, wind shear over the rotor disc area can also be significant. The standard procedure for power curve measurements is given by the IEC standard (IEC Standard 6–1400–12–1, 2005) where the wind speed at the hub height is considered to be representative of the wind over the whole turbine rotor area. This assumption can lead to considerable wind power estimate inaccuracies (Sumner and Masson, 2006; Antoniou et al., 2009), since inflow is often non-uniform and unsteady over the rotor-swept area.

3.4.3 Wind gusts

An additional wind property that can make an impact on wind turbine operations is wind gustiness (Weggel, 1999). Proper design and operation of a wind turbine for a specific wind climate requires knowledge of wind extremes and gustiness, often defined by a wind gust factor. This is especially true in areas where wind climate is determined by inherently strong gusty winds, such as downslope windstorms (Bajić, 1989; Belušić et al., 2004; Grisogono and Belušić, 2008; Horvath et al., 2009). At sites with high ambient turbulent intensity and gusty winds, turbines are subject to extreme structural loading and fatigue (Jelavić and Perić, 2009). The gust factor (G) is defined as (Weggel, 1999):

$$G = \frac{u_g}{U} - 1 \tag{11}$$

where u_g is the gust speed and U is the mean daily wind speed. One expects higher gusts to be associated with higher mean speeds; however, one may also expect that the normalized gust speed u_g/U and, consequently, the gust factor, G, decreases with increasing mean speed. The following equation relates the gust factor to the mean daily wind speed:

$$G = AU^n \tag{12}$$

where the parameters A and n are obtained by using a least-square fit of the logarithm of G vs. the logarithm of the mean daily wind speed.

While gusts generally decrease as wind speed increases, in extreme cases the wind gusts can easily reach over to twice the strongest wind speeds ($v > 20$ ms^{-1}) and damage a wind turbine. However, wind gusts over 25 ms^{-1}, the upper wind speed limit of a large wind turbine, are quite unlikely in many areas. Belu and Koračin (2009) used four and half years (2003-2009) of composite data sets and found that winds over 25 m s^{-1} occurred only about 2% of the time at locations in western Nevada. Gusts associated with stronger winds may cause considerable losses by reducing the energy production of the wind turbine which would otherwise operate at nominal output power. Another effect of wind gusts is additional stress on the wind turbine structure, which may reduce its lifespan.

4. ENVIRONMENTAL CONCERNS REGARDING WIND POWER GENERATING FACILITIES

Issues of concern over wind power generating facilities include aesthetic impact (visual degradation of the scenery), noise, and mortality of birds and bats. In general, the environmental impact of fossil-fuel plants is much greater than that of wind farms. Being a non-depletable source of energy, extracting power from the wind does not pose the threat of overexploiting limited natural resources as does oil, gas or coal. Wind energy production does not impact air quality, and, outside of construction, and installation, is without carbon emissions. Many communities resist installation of the wind plants in favor of viewshed preservation. Another frequent complaint is that the wind generators make a constant, low "swooshing" noise. This issue is becoming less frequent due to mandatory standoff distances and advancements in noise-reduction technology.

As a comparison, noise at the turbine (approximately 100 dB) is equivalent a noise of a adjacent lawn mower, while at a distance of 400 m, wind turbine noise is same as the noise of a refrigerator (40 dB) (http://www.darvill.clara.net/altenerg/images/large-wind-turbine.jpg). The potential exists for birds and bats to collide with operating wind turbine blades, construction cranes, elevated power lines, and meteorological towers. There are also studies arguing that noise and human activities associated with the wind facility could impact bird nesting behavior and alter bird habitats. However, avian impact due to wind farms is far less than that of buildings or domestic cats.

5. ECONOMICS OF WIND ENERGY

Generating electricity from the wind is environmentally and economically beneficial. Producing and selling electricity from the wind is no different from any other businesses in that, to be economically viable, the cost of making the electricity has to be less than its selling price. The price of electricity from any source depends on the cost of generation and other factors that affect the market, such as energy subsidies, taxes, and externalization of social costs. Generally, the cost of generating electricity (Belu, 2012) consists of: 1) capital cost - building the power plant and connecting it to the grid; 2) operating costs - operating, fuelling, and maintaining the plant; and 3) financing - the cost of repaying investors and banks. The decision whether to implement a wind energy project is based on a feasibility study, whose purpose it is to evaluate a project based on information on all aspects of implementation and operation of the project. Data to be collected for the feasibility study can be divided into: 1) wind resource assessment; 2) electrical system; 3) land availability; 4) soil conditions; 5) load pattern; 6) implementation expenses and capital costs; 7) operation and maintenance; 8) financing; and 9) organizational data and information. Reliable assessment and analysis of the wind regime and characteristics is critical for the project success and requires a sufficiently long and accurate wind data set and/or modeling for the actual area or site.

It is also evident from the previous sections that the wind turbine performance at a site depends heavily on the efficiency with which the wind turbine interacts with the wind regime (Rohatgi and Barbezier, 1999; Sumner and Masson, 2006; Antoniou et al., 2009; Wagner et al., 2009; Wharton and Lundquist, 2011; Belu and Koračin, 2012). Hence, it is essential that the characteristics of the turbine and the wind regime at which it works should be properly matched. The capacity factor of the system can be a useful indicator for the effective matching of the turbine and wind regime. For turbines with the same rotor size, rated power and conversion efficiency, the capacity factor is influenced by the availability of the turbine to extract the prevailing wind. In other words, the turbine should be individually designed for a specific wind regime, and the turbine characteristics should be defined according to the site characteristics. However, wind turbines of different ratings and functional velocities are available in the market. A wind energy project planner can choose a system that is best suited for a specific site or location. The performance estimation methods discussed above can be used for such analysis.

6. STORAGE OF WIND-GENERATED ENERGY

The production of electricity is generally highly centralized and often located a long distance away from end users. Load levelling is initially based on a prediction of daily and seasonal needs. When production is not sufficient the contribution of secondary modes such as pump-storage hydro facilities and thermal plants is used. Dispersed and distributed electricity production and the introduction of variable and fluctuating sources such as wind and solar increase the difficulty of stabilizing the power network due to demand–supply imbalances, which can be mitigated to a certain extent by storage. Energy storage systems such as batteries (Bayar, 2011; Holmbacka et al., 2012), flywheels (Hebner et al., 2002), compressed air energy systems (CAES) (EPRI, 1979), and pump-storage hydro systems (PSHS) (Deane et al., 2010; Yang and Jackson, 2011) have been used to balance wind variability and differences in production and consumption. For more information about energy storage methods and use, interested readers are directed to review such as by EPRI-DOE(2003), Ibrahim et al.(2008), Chen et al.(2009), Sundararagavan and Baker (2012), and Shoppe (2010). Some of the key applications of electric energy storage systems in relationship to wind integration include: (a) load shifting, which uses off-peak storage for on-peak dispatch at the system level; (b) regulation, which provides voltage and frequency support at the transmission and distribution level; and (c) power quality, which aids in smoothing fluctuations at the distribution level (Ibrahim et al., 2008; Chen et al. 2009; Sundararagavan and Baker, 2012).

Battery systems with about 70% efficiency and capacities of about 1 MW (acid and nickel types) are still not able to capture large-scale utility needs. Flywheels have an efficiency of about 80-90% and a capacity of about 10 MW, but with a time scale of seconds to tens of minutes. The CAES systems have capacities of about 300 MW, but efficiencies of only 66%. The compressed air during a higher wind generation is burned with natural gas during the reverse generation. The use of natural gas for the energy storage reserve operation may cause environmental concerns and, together with the relatively low efficiency, may represent a sufficient reason for avoiding this type of storage in some cases. The most appropriate large-scale utility storage is a PSHS system, which has an efficiency of about 80% and average capacity generally in the range 100-1000 MW. PSHS systems include reversible pumps/generators connecting upper and lower water reservoirs (Yang and Jackson, 2011). Although there are some operational issues due to rain, evaporation, snowmelt, droughts and high and low temperatures, this is still the best carbon-free large-scale utility storage. These systems are also cheaper to build than CAES systems. PSHS systems have a quick operational response - they can be set in operation, and convert from pumping to generation or vice versa within 3-4 minutes (Khartchenko, 1998). Historical development of the PSHS systems as well as advantages and barriers in using the PSHS system are described in Yang and Jackson (2011). Ingram (2009) estimated that the total capacity of the PSHS facilities is 127 GW worldwide with expectations of additional capacity of 76 GW by 2014. Some additional storage systems include Superconducting Magnetic Energy Storage (SMES) and Advanced or “Super” Capacitors (AC). The EPRI-DOE report (2003) discusses these systems and others in detail with respect to technology, installed capacity, facility size range, and commercial availability. The report also confirms the advantages of using PSHS with dominant installed capacity up to 2.1 GW compared to other storage systems (EPRI-DOE, 2003).

7. WIND AND WIND POWER FORECASTING

Due to its high temporal and spatial variability, wind power is a fluctuating source of energy. The main task of utility grid operators and managers is to balance supply and demand, i.e., generation, transmission, and loads, which can be challenging due to the variability of the wind over different operational periods (Smith et al., 2007), especially for a grid with high penetration of wind energy production (Watson et al., 1994). Smaller percentages of wind penetration do not represent a problem for the utility grid, while larger fractions may require grid redesign and restructuring. However large scale wind energy penetration requires solutions to a lot of problems such as competitive market designs, real-time grid operation, interconnection standards, ancillary service requirements, power quality, transmission system capacity, power system stability and reliability, pollutant emission reductions, and optimal wind penetration (Lund, 2005; Amjady et al, 2011; Foley et al., 2012). Improved wind power forecasting is well accepted as an efficient tool to overcome many of these problems. In principle, thermal generation plant for reserve power generation are always needed, and in some cases curtailment of wind energy can be prescribed to avoid overloading the grid. If the wind is provides 10% of the resources, then the needed reserve is approximately 3-6%, while for the wind generation fraction of 20%, the reserve should be about 4 to 8% (Ford and Milborrow, 2005). In depth discussions of wind forecasting issues related to high penetration of the wind energy into the grid are presented by Wu and Hong (2007) and Marquis et al. (2011). Comprehensive reviews of wind energy incorporation into power systems are presented by Steftos (2000), Wu and Hong (2007), Lange and Focken (2005, 2008), Freris and Infield (2008), Costa et al. (2008), Lei et al. (2009), Monteiro et al. (2009), Blanco (2010) and Foley et al (2012).

In today's competitive energy markets, where grid operators need to plan in advance capacity operations of conventional plants depending on wind-generated power penetration, wind forecasting plays an instrumental role in business planning and is useful for power system operations, unit commitment, and economic dispatch. Creating and using accurate models for prediction of output power and monitoring of wind turbines or wind farms are challenging tasks which requires evaluation of a large number of parameters (Kusiak et al., 2009) over a wide range of timescales – minutes or less for active turbine operations, hours for grid variability, and days for energy trading and scheduling maintenance of turbines and transmission systems. An evaluation of short-term wind speed prediction techniques is shown by Sreelakshmi (2008). The cost-benefit ratio on the use of predictive technologies in electrical systems with high penetration reaches 1:100 (EWEA, 2010). Various classifications according to timescales or methodology are available for wind power forecasting (Lydia and Kumar, 2010; Amjadfy et al., 2001; Foley et al 2012). An important feature of forecasting methods is their time horizon. The time horizon is defined as the time period in the future for which the wind generation will be forecasted. The timescales of wind power forecasting can be classified into three types: very-short term forecasting (up to 8 hours ahead), short-term forecasting (day ahead), and long-term wind power forecasting (multiple days ahead). Wind power forecasting can be classified based on their methodology into three main groups: physical, statistical and learning techniques (Lange and Focken, 2005, Lei et al. 2009, Wu and Hong, 2011). The physical approach consists of simple or complex mathematical models that use numerical techniques to solve nonlinear equations describing atmospheric dynamics and thermodynamics. They can provide results for wind resources in space and time, and consequent wind power can be diagnosed from these results. The physical approach also includes specifics of site wind conditions, hub heights of the turbines, and wind turbine operational power characteristics. In the statistical approach, also known as Measure-Correlate-Predict (MCP), the relationship between measurements, weather forecasts, and output power production from the time series in the past is analyzed and described such that it could be used in future. The models using Artificial Intelligence (AI) techniques learn the relationship between input data (model predictions or/and measurements) and output data (power output) using algorithms that implicitly describe highly complex, nonlinear relationships between the inputs and the outputs, unlike explicit statistical approaches. The learning approach makes use of software computing techniques such as artificial neural networks, Bayesian networks, and fuzzy logic to learn the relationship between the forecast wind and power outputs from the time series of the past (Lange and Focken, 2005, 2008; Lei et al., 2009). As an example, principles of AI such as neural networks in combination with wavelet transform (Catalao et al., 2011), ridgelet neural networks (Amjady et al., 2011), and time series and regression analysis can be used for short-term forecasting. The latter incorporates various techniques such as Autoregressive Integrated Moving Average (ARIMA) models, or bilinear and smooth threshold autoregressive models. AI techniques also include the use of Multi-Layered

Perceptrons, Radial Basis Functions, Recurrent Neural Networks as well as Fuzzy Logic and the combination of a Fuzzy Classifier with a Temporal Neural Network. For very short-term forecasting, artificial neural networks with adaptive Bayesian learning and Gaussian process approximation can be also used (Blonbou, 2011).

For forecasting time periods of one day or longer, numerical weather prediction (NWP) models operated on regional scales and mesoscales can be used. NWP models solve the Reynolds-averaged Navier-Stokes (RANS) equation and the effect of turbulence is accounted for using a turbulence closure model. The forecast values from the NWP model are used as input to these wind forecasting approaches. NWP forms the basis of the source data for most of the wind power forecasting and prediction methods. NWP models are usually most appropriate for several days ahead. There are three steps in wind power forecasting: 1) calculating the wind speed and direction from the models; 2) calculating the wind power output forecast or prediction; and 3) regional forecasting or downscaling, which may occur over different time horizons. Very short time wind power forecasting up to several hours is usually statistics and AI based. Together with learning approaches, they use a large amount of historical time series data. Mesoscale NWP model applications to wind energy studies include the Penn State/National Center for Atmospheric Research Mesoscale Model 5 (MM5; Grell et al., 1994; Jimenez et al., 2007; Horvath et al., 2012), the Weather Research and Forecasting model (WRF; Skamarock et al., 2008; Storm and Basu, 2010; Horvath et al., 2012), the Regional Atmospheric Prediction System (RAMS; Pielke et al., 1992; Baidya Roy and Traiteur, 2010), Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS; Hodur, 1997; Jiang et al., 2008), Aire Limitee Adaption DynamiqueDeveloppement International (ALADIN; ALADIN International Team, 1997) model (Žagar et al., 2006; Horvath et al., 2011), and the Mesoscale Atmospheric Simulation System (MASS; Kaplan et al., 1982; Zack et al., 2000).

In general, the use of mesoscale models at higher grid resolutions presumably provides more accurate representation of the spatial and temporal wind variability and reduces the systematic errors, such as of the mean and of the standard deviation. The benefits of increasing the resolution of mesoscale models are also often found in predictions of higher wind speeds and near-surface wind shear, which are essential for wind power forecasting. Verification in spectral space typically shows improvement associated with the mesoscale portion of the kinetic energy spectrum and more accurate simulation of observed spectral power density functions (Horvath et al., 2012). Nevertheless, the improvement in accuracy brought by systematically increasing the resolution of mesoscale models may not necessarily be a systematic one. Mesoscale model predictions may also suffer from so-called “double-penalty” errors, i.e., errors in time and space, which may grow with resolution and in some applications diminish the positive effects of higher resolution (e.g., Rife and Davis, 2005). Furthermore, mesoscale predictions might be of limited accuracy for simulation of stably-stratified nocturnal flows due to excessive mixing for flows with large Richardson numbers (Cuxart et al., 2006). Finally, the highest-resolution mesoscale models configured with sub-kilometer horizontal grid spacing still lack the energy of motions on scales of around few hours and shorter and generally provide simplified representation of turbulence. The relative importance of these constraints, however, highly depends of the type of the wind climate at a given wind generating site. For understanding and predicting micro-scale processes such as the detailed structure of the flow and turbulence, optimum set-up of the turbines (micro-siting) and the effect of the wind farms on the boundary layer, more complex tools need to be applied for maximizing wind energy production and minimizing wind turbine fatigue load.

In many cases deterministic single-value forecasts lack sufficient accuracy due to imperfect model parameterizations and inherent uncertainties and errors in initial (IC) and boundary conditions (BC). Probabilistic forecasting with ensembles of predictions of the same case can be obtained by using multiple model's perturbations in ICs and BCs and variations in physics parameterization options (Anthes et al., 1989; Stensrud, 2001). New approaches of probabilistic approaches in support of the wind power forecasting are shown in Taylor et al. (2009) and Pinson and Madsen (2009) and applications for system operators are shown in Matos and Bessa (2010). Ensembles can be generated using multiple models or an accumulation of overlapping time-lagged averaged single forecasts (Kalnay, 2003), in which a single model is initialized and run, for example, every 6 hours for 48 hours in advance, and the overlapping forecasts are averaged to form the ensemble. Ensemble forecasts are often generated using variants of the same model - different data assimilation techniques (optimal interpolation, 3D-Var or 4D-Var), different numerical integration schemes, different frameworks (Eulerian or Lagrangian), different physical parameterization options, or/and using multiple models. Another type of ensemble applies perturbations to ICs and BCs.The IC perturbations are compatible with the realistic error in the analysis at the time zero (the first model guess field), i.e. uncertainty in the model due to the sparse near surface and upper air meteorological observational network used for model initialization. Studies have shown that the ensemble means generally outperform any of the individual members (Lewis, 2005). The European Centre for Medium Range Weather Forecasts (ECMWF) in Reading provides ensemble forecasts twice a day with 50 members. The U.S. National Centers for Environmental Prediction (NCEP) provides ensemble forecasts with 11 members.

In summary, there is a strong need to further advance models for operational management and resource assessments with respect to model and parameterization development, improvement of initial and boundary conditions, data assimilation, and ensemble forecasting methodologies.

8. MODELING AND OBSERVATION OF WIND TURBINE WAKES

The simplest tool for assessment of the effect of wind turbine wakes describes wake expansion and recovery using empirically derived tunable coefficients (Katic et al., 1986). Computational fluid dynamics (CFD) models employ the Reynolds-averaged Navier-Stokes (RANS) equations in fully elliptical or parabolicized form with a wake model to calculate flow properties (Sørensen and Shen, 2002; Gómez-Elvira et al., 2005; Troldborg et al., 2007; Jimenez et al., 2008; El Kasmi and Masson, 2008). A review of CFD approaches to wind turbine modeling is provided in Sanderse et al. (2011). Direct numerical simulations have yet to be applied to wind turbine simulations due to their large computational expense and associated limitations on the Reynolds number conditions. However, another method –large eddy simulation (LES) – has been used for turbine wake research. In this method the large scales of the flow are computed explicitly and the effects of small scale turbulence on the flow are modeled using a subgrid scale (SGS) model. Some examples include the work of Ivanell (2009), Calaf et al. (2010), Stovall et al. (2010), Porté-Agel et al. (2010), Conzemius et al. (2010), Churchfield et al. (2010), Wu and Porté-Agel (2011), and Lu and Porté-Agel (2012). Recent applications include parameterizations of wind farms in the Weather Research and Forecasting model (Fitch et al., 2012) and in the Regional Atmospheric Modeling System (RAMS; BaidyaRoy, 2010).

With the current dearth of observations available for verification of turbine models and parameterizations, the fully waked (exact-row) case for Horns Rev wind farms (Barthelmie et al., 2010) has emerged as an important ground-truth benchmark for many eddy resolving simulations. Some researchers have also begun to focus on fully waked cases at other wind farms such as Lillgrund (Churchfield et al., 2012) and complex wake merging scenarios as well (Smith et al., 2012). The lack of observations is currently a large hindrance to the implementation of accurate and verified parameterizations of wind farms in operational NWP models.

Observations of wind turbine wakes and their effect on wind farm performance, traditionally done using SCADA (Supervisory Control and Data Acquisition) (e.g., Barthelmie et al. 2010) or meteorological tower data (Schepers et al., 2012), are increasingly being done with second generation commercial sodar and lidar platforms which can measure wind velocity up to a few hundred meters above ground level. Comparisons to traditional meteorological tower measurements has been performed for the ZephIR vertically profiling lidar (Pena et al., 2009). Lidars also offer the possibility to measure momentum flux (Mann et al., 2010) and TI (Sathe et al., 2011). Offshore application of vertically profiling lidars for wind energy applications have also been explored (Pichugina et al., 2012). ZephIR lidars have been mounted forward-facing in turbine nacelles to study oncoming wind profiles for enhancing turbine control (Mikkelsen et al., 2012), and rearward-facing to study turbine wakes (Bingöl et al., 2010). Scanning lidars show great potential for characterization of wind turbine wake recovery (Iungo et al., 2012) as well as direct measurement of resources over the farm-scale for assessment and micro-siting purposes (Krishnamurthy et al., 2012).

9. WIND RESOURCES IN CLIMATE PROJECTIONS

Just as with the other aspects of climate, wind statistics are subject to natural variability on a wide range of time scales. Like other meteorological parameters, such as temperature, rainfall, or other climate variables, wind speeds and directions change on time scales of minutes, hours, months, years, and decades. Future climate change is expected to alter the spatial and temporal distribution of surface wind speeds and directions, with associated impacts on wind-based electricity generation. In the context of wind energy generation, even small changes in the wind speed magnitude can have major impacts on the productivity of wind power plants, as the wind power relationship (Equation 1) is directly proportional to the cube of the wind speed. However, the predictions for the direction and magnitude of these changes hinge critically on the assessment methods used. Decadal and multi-decadal variability in wind speed statistics currently introduce an element of risk into the decision process for siting new wind power generation facilities. Recent findings from the atmospheric science community suggest that climate change may introduce an added risk to this process. Many climate change impact analyses, including those focused on wind energy, use individual climate models and/or statistical downscaling methods rooted in historical observations. Wind speed and direction vary on small scales, and respond in complex ways to changes in large-scale circulation, surface energy fluxes, and topography. Thus, whereas multiple climate models often agree qualitatively on temperature projections, wind estimates are less robust (e.g., Pryor et al., 2006; Pryor and Barthelmie, 2010). The spatial variability of wind and its sensitivity to model structure suggest that higher resolution models and multi-model comparisons are particularly valuable for wind energy projections.

The IPCC report by Wiser et al. (2011) emphasizes the value of growing wind energy generation in reducing current and future greenhouse gas (GHG) emissions. Although wind power generation in 2009 accounted for only 1.8% of total power generation, it is expected to grow to 20% by 2050. U.S. DOE (2008) recognizes that climate change has potentially significant financial consequences on wind plant facilities. For long-term planning of wind resources, it is imperative to analyze historical datasets and establish monitoring at hub-height using meteorological towers and remote sensing. Marquis et al. (2011) emphasized the need to investigate the impacts of intraseasonal and multi-year variability and climate oscillations such as ENSO and PDO on wind resources.

A comprehensive review of climate change impacts on wind energy is shown by Pryor and Barthelmie (2010). They discussed the main changes in the wind resources due to climate evolution. In particular, they focused on northern Europe, where there is already significant penetration of the wind energy. According to the analysis, until the middle of the current century natural variability will exceed the effect of climate change in the wind energy resources. They conclude that there is no detectable trend in the wind resources that would impact future planning and development of wind industry in northern Europe. Pryor et al. (2006) downscaled winds from ten global climate models at locations in northern Europe and found no evidence of significant changes in the 21st century compared to the 20th century. Predicted changes in the downscaled mean and 90th percentile are found to be small and comparable to the variability associated with different global climate models. Using another approach, Ren (2010) proposed a power-law relationship between global warming and the usable wind energy. The power-law exponent was calibrated using results from eight global climate models. He found that reduction of wind power scales with the degree of warming according to method and estimated that 2-4 degrees Celsius increase in the temperatures in mid to high latitudes would result in a 4-12% decrease in wind speeds in northern latitudes. Ren (2010) suggested that an early maximized harvesting will be more beneficial and should be carried out as soon as possible while global warming is not fully developed. More studies are needed to resolve all uncertainties and errors in climate projections of wind resources under various future emission scenarios.

10. CONCLUDING REMARKS

Many factors influence accurate assessment and prediction of wind energy production. A primary issue is adequate understanding of the effects of wind variability, atmospheric stability and turbulence on production. Non-negligible error is incurred when the effects of shear, TI, and atmospheric stability on the wind turbine power performance are ignored, as in the IEC standard, 61400-12-1 (2005). The standard procedures are valid only for ideal neutral conditions and a small wind turbine. Besides the dominant cubic dependence of the wind speed on the wind power density, there are smaller but still important corrections to the air density that are important to harvesting wind energy at high-elevation sites. Corrections that account for these factors must be included in the power output estimates, and more accurate predictions will help alleviate production-consumption imbalances. These imbalances can also be ameliorated through the use of storage devices. The most appropriate and efficient large-scale utility storage of wind-generating power appears to be pump storage hydro systems compared to other storage types such as batteries, flywheel, and compressed air energy storages.

With increasing penetration of wind-generated power into the grid, forecasting on a wide range of temporal scales is becoming significantly more important for operations and planning. Accurate wind and wind power predictions are required for high penetrations of wind-generated power to help maintain the grid stability. Many modeling tools of various sophistications have been used for predictions of wind and turbulence regimes - mesocale models have been used for regional and wind farm-scale assessment and forecasting of wind characteristics, while large eddy simulations and CFD have been used to model the detailed structure of wind and turbulence at and around wind generating facilities.

Climate projections and trends of wind resources in changing climate are a topic of a debate in the literature and require a thorough investigation of models' uncertainties and errors and understanding the complex interaction of atmospheric dynamics and thermodynamics. This will contribute to understanding the extent to which some of the predicted trends are the result of the weather and climate variability or the result of inadequate physical parameterizations in global and regional climate models. In order to account for uncertainties and errors in inputs and model imperfections, there is a need to further develop probabilistic wind and wind power predictions on weather and climate scales.

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REFERENCES

Ackermann, T., L. Söder, 2000: Wind energy technology and current status: a review, Renew. Sustain. Energy Rev., 4(4), 315-374.

Ackermann, T., L. Söder, 2002: An overview of wind energy-status 2002, Renew. Sustain. Energy Rev., 6(1-2), 67-127.

Ackermann, T. (ed), 2005: Wind Power in Power Systems, Wiley, England, 2005.

ALADIN International Team, (1997) The ALADIN project: Mesoscale modelling seen as a basic tool for weather forecasting and atmospheric research. *WMO Bull.*, **46**, 317–324.

Amjady N., F. Keynia, H. Zareipour, 2011: Short-term wind power forecasting using ridgelet neural network, Electric Power Systems Research, 81, 2011, 2099-2107.

Anderson, D. L. T., 1976: The low-level jet as a western boundary current, Mon. Wea. Rev., 104, 907-921.

Anthes, R. A., Y.-H. Kuo, E.-Y.Hsie, S. Low-Nam, and T. W. Bettge, 1989: Estimation of skill and uncertainty in regional numerical models. Q. J. R. Met. Soc., 115, 763-806.

Antoniou, I., S. Pedersen, P. D. Enevoldsen, 2009: Wind shear and uncertainties in power curve measurement and wind resources,Wind Engineering, 33, 449-468.

Archer,C.L, M.Z. Jacobson, 2003: Spatial and temporal distributions of US winds and wind power at 80 m derived from measurements, J. Geophys. Res., 108, doi:10.1029/2002/D002076.

Baidya Roy, S., 2011: Simulating impacts of wind farms on local hydrometeorology. J. Wind Eng. Ind. Aerodyn. http://www.atmos.illinois.edu/~sbroy/publ/dx.doi.org/10.1016/j.jweia.2010.12.013

Baidya Roy, S., J.J. Traiteur, 2010: Impacts of wind farms on surface temperatures. PNAS, 107, 17899–17904.

Bajić, A., 1989: Severe bora on the northern Adriatic. Part I: Statistical analysis. Rasprave-Papers, **24**, 1-9.

Banta, R.M., R. K. Newsom, J. K. Lundquist, Y. L. Pichugina, R. L. Coulter, L. Mahrt, 2002: Nocturnal low-level jet characteristics over Kansas during CASES-99. Boundary Layer Meteor., 105, 221–252.

Banta, R.M., Y.L. Pichugina, W. A. Brewer, 2006: Turbulent velocity-variance profiles in the stable boundary layer generated by a nocturnal low-level jet. J. Atmos. Sci., 63, 2700–2719.

Barthelmie, R. J., S. C. Pryor, S. T. Frandsen, K. S. Hansen, J. G. Schepers, K. Rados, W. Schlez, A. Neubert, L. E. Jensen, and S. Neckelmann, 2010: Quantifying the impact of wind turbine wakes on poweroutput at offshore wind farms. *J. Atmos. Oceanic Technol.*, **27**, 1302–1317, doi:10.1175/2010JTECHA1398.1

Bayar, T., 2011: Batteries for energy storage: New developments promise grid flexibility and stability. http://www.renewableenergyworld.com/rea/news/article/2011/08/batteries-for-energy-storage-newdevelopments-promise-grid-flexibility-and-stability.

Belu, R, D. Koračin, 2009: Wind Characteristics and Wind Energy Potential in Western Nevada. Renewable Energy, 34(10), pp. 2246-2251.

Belu, R., D. Koračin, 2012: Effects of Complex Wind Regimes and Meteorological Parameters on Wind Turbine Performances, IEEE EnergyTech 2012, Cleveland, Ohio, USA, May 28-31, 2102 (CD Proceedings)

Belu R., 2012, Wind Energy Conversion and Analysis, Encyclopedia of Energy Engineering & Technology (Ed. Sohail Anwar), Taylor and Francis (in press).

Belušić D, M. Pasarić M, and M. Orlić, 2004: Quasi-periodic bora gusts related to the structure of the troposphere. *Q. J. R. Meteorol. Soc.*,**130**, 1103–1121.

Bingöl, F., Mann, J. and Larsen, G. C., 2010: Light detection and ranging measurements of wake dynamics part I: one-dimensional scanning. *Wind Energy*, 13: 51–61. doi: 10.1002/we.352

Blanco, M.I., 2009: The Economics of Wind Energy. Renewable and Sustainable Energy Reviews, (13:6–7), 1372–1382.

Blonbou, R. 2011: Very short-term wind power forecasting with neural networks and adaptive Bayesian learning, Renew. Energy, 36 (3), 1118–1124.

Bonner, W. D., 1968: Climatology of the low-level jet. Mon. Wea. Rev., 96, 833-850.

Burton, T., D. Sharpe, N., Jenkins, E., Bossanyi, 2001: Wind energy handbook. Chichester, UK: J. Wiley & Sons.

Calaf, M., C. Meneveau, J. Meyers, 2010: Large eddy simulation study of fully developed wind-turbine array boundary layers, Physics of Fluids, 22, 015110, doi:10.1063/1.3291077.

Catalao, J.P.S., H.M.I. Pousinho, V.M.F. Mendes, 2011: Short-term wind power forecasting in Portugal by neural networks and wavelet transform, Renew. Energy 36, 1245–1251.

Chen, H., T. Cong, W. Yang, C. Tan, Y. Li, Y. Ding, 2009: Progress in electrical energy storage system: a critical review, Progress in Natural Science,19, 291 - 312.

Churchfield, P., J. Moriarty, G. Vijayakumar, J.G. Brasseur, 2010: Wind Energy-Related Atmospheric Boundary Layer Large-Eddy Simulation Using OpenFOAM. 19th Symposium on Boundary Layers and Turbulence, Keystone, Colorado, August 2-6, 2010.

Churchfield, M.J., S. Lee, P. J. Moriarty, L. A. Martinez, S. Leonardi, G. Vijayakumar, and J. G. Brasseur, 2012. A large eddy simulation of wind-plant aerodynamics, 50th AIAA Aerospace Sciences Meeting, Nashville, Tennessee January 9-12, 2012

Conzemius, B., H. Lu, L. Chamorro, Y.-T. Wu, and F. Porte-Agel, 2010: Development and testing of a wind farm simulator at an operating wind farm. Presentation from AWEA 2010 Wind Power Conference and Exhibition, Dallas, Texas.

Costa, A., A. Grespo, J. Navarro, G. Lizcano, H. Madsen, E. Feitosa, 2008: A review of the young history of the wind power short-term prediction, Renew. Sustain. Energy Rev., 12(6), 1725-1724.

Cuxart, J., and Coauthors, 2006: Single-column model intercomparison for a stably stratified atmospheric boundary layer. *Bound.-Layer Meteor.,* **118,** 273–303.

Davidson, P. A., 2004: Turbulence: An Introduction for Scientists and Engineers, Oxford University Press. ISBN 978-0-19-852949-1.

Deane, J.P., B.P. Gallachóir, E.J. McKeogh, 2010: Techno-economic review of existing and new pumped hydro energy storage plan, Renew. Sustain. Energy Rev., 14(4), 1293–1302.

El Kasmi, A., and C. Masson, 2008: An extended k-e model for turbulent flow through horizontal-axis wind turbines. Journal of Wind Engineering and Industrial Aerodynamics, 96, 103-122.

Elliott, D. L., J.B. Cadogan, 1990: Effects of wind shear and turbulence on wind turbine power curves 1990 European Community Wind Energy Conf. and Exhibition (Madrid, Sept. 1990).

EPRI, 1979: Technical and Economic Assessment of Advanced Compressed Air Storage Concepts, EPRI Report EM-1289, December 1979.

EPRI-DOE, 2003: Handbook of Energy Storage for Transmission & Distribution Applications.1001834, Final Report, December 2003.

European Wind Energy Association (EWEA), 2010: Powering Europe: wind energy and the electricity grid. Available on http://www.ewea.org/

Fitch, A. C., J. B. Olson, J. K. Lundquist, J. Dudhia, A.K. Gupta, J. Michalakes, I. Barstad, 2012: Local and Mesoscale Impacts of Wind Farms as Parameterized in a Mesoscale NWP Model, Mon. Wea. Rev., 140, 3017–3038, doi: http://dx.doi.org/10.1175/MWR-D-11-00352.1

Fleming, P.D. and S. D. Probert, 1984: The evolution of wind-turbines: An historical review. Applied Energy, 18, 163-177.

Foley, A.M., P.G. Leahy, A. Marvuglia, E.J. McKeogh, 2012: Current methods and advance in forecasting of wind power generation, Renewable Energy, 37, 1-8.

Ford, R., and D. Milborrow, 2005: Integrating renewables. British Wind Energy Association 2005; http://www.bwea.com/pdf/RAEIntegrationfinal.pdf.

Freris, L., D.G. Infield, 2008: Wind Energy in Power Systems. John Wiley and Sons, U.K., 284 pp.

Gipe, P., 1995: Wind Energy Comes of Age, John Wiley & Sons, New York.

Gómez-Elvira, R., A. Crespo, E. Migoya, F. Manuel and J. Hernández, 2005: Anisotropy of turbulence in wind turbine wakes. Journal of Wind Engineering & Industrial Aerodynamics, 93(10), 797-814.

Grell, G.A., J. Dudhia, and D.R. Stauffer, 1994: A description of the fifth-generation Penn State/NCAR mesoscale model (MM5). NCAR Tech. Note NCAR/TN-398+STR, 122 pp.

Grisogono, B. and D. Belušić, 2008: A review of recent advances in understanding the meso- and microscale properties of the severe Bora wind. Q. J. R. Meteorol. Soc., **61**, 1-16.

Gustavson, M.R. 1978: Wind power extraction limits. In Proceedings National Conference, Fall ’78, ed. Vaughn Nelson, p. 101

Hand, M.M., N.D. Kelley, M.J. Balas, 2003: Identification of Wind Turbine Response to Turbulent Inflow Structures. 4th ASME/JSME Joint Fluids Engineering Conference Honolulu, Hawaii, June 6–10, 2003. NREL/CP-500-33465.

Hebner, R.E., J. H. Beno, J.D. Herbst, “Coposite Flywheels for Energy Storage – Design Considerations” Electrical Energy Storage Applications and Technology Conference Record, EESAT 2002, April 15-17, 2002, San Francisco, CA.

Hodur, R. M., 1997: The Naval Research Laoratory’s Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). Mon. Wea. Rev., 125, 1414-1430.

Holmbacka, S., D. Silva, R. Chvalek, J. Konecny, A.O.Kareem, 2012: Energy Storage Utilizing Hydro Pump and Battery Technologies, Proceedings, ICCES8 2012.

Horvath, K., S. Ivatek-Šahdan, B. Ivančan-Picek, and V. Grubišić, 2009: Evolution and structure of two severe cyclonic Bora events: contrast between the northern and southern Adriatic. *Wea. Forecasting*, **24**, 946-964.

Horvath, K., A. Bajić, and S. Ivatek-Šahdan, 2011: Dynamical downscaling of wind speed in complex terrain prone to bora-type flows. *J. Appl. Meteor. Climatol.*, **50**, 1676-1691.

Horvath, K., D. Koračin, R. K. Vellore, J. Jiang, and R. Belu, 2012: Sub-kilometer dynamical downscaling of near-surface winds in complex terrain using WRF and MM5 mesoscale models. *J. Geophys. Res.*, 117, D11111, doi:10.1029/2012JD017432.

Ibrahim, H., A. Ilinca, J. Perron, 2008: Energy storage systems—Characteristics and comparisons Renew. Sustain. Energy Rev., 12(5), 1221-1250.

IEC Standard, 6 1400 12 1, 2005: Power performance measurements of electricity producing wind turbines.

Ingram E., 2009: Pumped storage development activity snapshots, Hydro Review, Dec. 2009, 12–25.

Iungo, G. Y. Wu and F. Porté-Agel, 2012: Field measurements of wind turbine wakes with LiDARs. *J. of Atmos. and Oceanic Tech.*doi: 10.1175/JTECH-D-12-00051.1

Ivanell, S.S.A., 2009: Numerical Computations of Wind Turbine Wakes. Ph.D. thesis, Gotland University, Stockholm, Sweden.

Jacobson, M.Z. and M.A. Delucchi, 2011: Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Policy, 39, 1154-1169.

Jelavić, M. and N. Perić, 2009: Wind Turbine Control for High Turbulent Winds. *Automatika, Journal for Control, Measurment, Electronics, Computing and Communications*, **50**, 3-4, 135-151.

Jenkins, N., T. Burton, D. Sharpe, E. Bossanyi, 2001: Wind Energy Handbook, Wiley & Sons.

Jiang, Q., J. D. Doyle, T. Haack, M. J. Dvorak, C. L. Archer, M. Z. Jacobson, 2008: Exploring wind energy potential off the California coast, Geophys. Res. Lett., 35, L20819, doi:10.1029/2008GL034674.

Jimenez B., F. Durante, B. Lange, T. Kreutzer, J. Tambke, 2007: Offshore wind resource assessment with WAsP and MM5: Comparative study for the German Bight, Wind Energy, 10, 121–134.

Jimenez, A., A. Crespo, E. Migoya and J. Garcia, 2008: Large-eddy simulation of spectral coherence in a wind turbine wake. Environ. Res. Lett., 3 015004 doi:10.1088/1748-9326/3/1/015004

Joselin Herbert, G.M., S., Inyian, E. Sreevalsanet al., 2007: A review of wind energy technology, Renewable &Sustainable Energy Reviews, 11, 1117-1145.

Justus CG, A. Mikhail, 1976: Height variations of wind speed and wind distribution statistics, Geophys. Res. Lett., 3, 261–264.

Kaldellis, J. K., D. Zafirakis, 2011: The wind energy (r)evolution: A short review of a long history. Renewable Energy, 36, 1887-1901.

Kalnay, E., 2003: Atmospheric Modeling, Data Assimilation and Predictability. Cambridge University Press, 342 pp.

Kaplan, M. L., J. W. Zack, V. C. Wong, J. J. Tuccillo, 1982: Initial results from a mesoscale atmospheric simulation system and comparisons with an AVE-SESAME I data set, Mon. Wea. Rev., 110, 1564-1590.

Katic, I. , J. Højstrup and N.O. Jensen, 1986: A simple model for cluster efficiency. *Proc. EWEC'86*, Rome,Vol. 1, 407–410.

Kelley, N.D., J.T. Bialasiewicz, R.M. Osgood, A. Jakubowski, 2000: Using Wavelet Analysis to Assess Turbulence/Rotor Interactions, Wind Energy, 3, 121-134.

Kelley, N., M., Shirazi, D. Jager, S. Wilde, J. Adams, M. Buhl, P. Sullivan, E. Patton, E., 2004: Lamar Low-Level Jet Project Interim Report; NREL/TP-500-34593; National Renewable Energy Laboratory: Golden, CO, USA.

Khartchenko, N.V., 1998: Advanced Energy Systems, Taylor and Francis Publishing. Washington D.C., 285 pp.

Klink, K., 1999: Climatological mean and interannual variance of United States surface wind speed, direction and velocity, Int. J. Climatol, 19, 471-88.

Kraus, H. et al., 1985: Nocturnal low-level jet during PUKK, Bound.-Layer Meteor., 31, 187-195.

Krishnamurthy, R., A. Choukulkar, R. Calhoun, J. Fine, A. Oliver and K.S. Barr, 2012: Coherent Doppler lidar for wind farm characterization. *Wind Energy*. doi: 10.1002/we.539

Kusiak, A., H. Zheng, Z. Song, 2009a: Wind Farm Power Prediction: A Data Mining Approach, J of Wind Energy Ind. Appl., 12, 275-293.

Kusiak, A., H. Zheng, Z. Song, 2009b: Models for monitoring wind farm power, J. of Renewable Energy, 34, 583-590.

Kwon, S.D., 2010: Uncertainty analysis of wind energy potential assessment, Applied Energy, 87, 856–865.

Lange, M., U. Focken, 2005: Physical Approach to Short-term Wind Power Prediction. Springer Verlag, Heidelberg, ISDN 3-540-25662-8

Lange, M., U. Focken, 2008: New developments in wind energy forecasting, IEEE Power and Energy Society General Meeting 2008 – Conversion and Delivering of Electrical Energy in 21st Century, 20-24 July, 2008, Pittsburgh, PA, USA , 1-8.

Lei, M., L. Shiyan, J. Chuanwen, L. Hongling, Z. Yan, 2009: A review on the forecasting of wind speed and generated power, Renew. Sustain. Energy Rev., 13 (4), 915–920.

Lewis, J. M., 2005: Roots of ensemble forecasting. *Mon. Wea. Rev*., **133**, 1865–1885.

Lu, X., M. McElroy, J. Kiviluoma, 2009: Global potential for wind generated electricity. Proc. Natl. Acad. Sci., 106, 10 933–10 938.

Lu, H. and F. Porte-Agel, 2011:Large-eddy simulation of a very large wind farm in a stable atmospheric boundary layer, Physics of Fluids, 23 065101.

Lund, H., 2005: Lagre-scale integration of wind power into different energy systems, Energy, 30(13), 2402-2412.

Lydia, M. and S. S. Kumar, 2010: A comprehensive overview of wind power forecasting. International Power Engineering Conference (IPEC) conference 2010 proceedings, 268-273.

Mann, J., A. Peña, F. Bingöl, R. Wagner, and M. S. Courtney, 2010: Lidar Scanning of momentum flux in and above the atmospheric surface layer, J. Atmos. Oceanic Technol., 27, 959–976, doi:10.1175/2010JTECHA1389.1.

Manwell, J.F, J.G. McGowan, A. L. Rogers, 2002: Wind Energy Explained: Theory, Design and Application, New York, John Wiley and Sons.

Marquis, M., J. Wilczak,, M. Ahlstrom, J. Sharp, A. Stern, J. Smith, S. Calvert, 2011: Forecasting the wind to reach significant penetration levels of wind energy. Bull. Amer. Meteorol. Soc., 92(9), 1159-1171. doi:10.1175/2011BAMS3033.1

Matos, M. A., R. J. Bessa, 2010: Setting the operating reserve using probabilistic wind power forecasts. IEEE Trans. Power Syst., 26, 594–603, doi:10.1109/TPWRS.2010.2065818.

Mikkelsen, T., N. Angelou, K. Hansen, M. Sjöholm, M. Harris, C. Slinger, P. Hadley, R. Scullion, G. Ellis and G. Vives, 2012: A spinner-integrated wind lidar for enhanced wind turbine control.*Wind Energy*. doi: 10.1002/we.1564

Milborrow, D, 2003: Forecasting for scheduled delivery. Wind Power monthly, 19, 12.

Monteiro, C., H. Keko, R. Bessa, V. Miranda, A. Botterud, J. Wang, G. Conzelmann, 2009: Wind power forecasting: state-of-the-art 2009, Decisionand Information Sciences Division Report, Argonne National Laboratory.

Musgrove, P., 2010: Wind power. Cambridge University Press, 323 pp.

Pasqualetti, M.J., P. Gipe, and R.W. Righter, 2002: Wind Power in View. Academic Press, San Diego.

Peña, A., C. B. Hasager, S. Gryning, M. Courtney, I. Antoniou and T. Mikkelsen, 2009: Offshore wind profiling using light detection and ranging instruments.*Wind Energy*, **12**, 105-124. doi: 10.1002/we.283

Peterson, E.W., J.P. Hennessey, 1977: On the use of power laws for estimates of wind power potential, J. Appl. Meteorol., 17, 390–394.

Petersen, E.L., N.G. Mortensen, L. Landberg, et al., 1998a: Wind power meteorology. Part I: Climate and turbulence, Wind Energy, 1(1), 25–45.

Petersen, E.L., N.G. Mortensen, L. Landberg, et al., 1998b: Wind power meteorology, Part II: Siting and models, Wind Energy, 1(2), 55–72.

Pichugina, Yelena L., Robert M. Banta, W. Alan Brewer, Scott P. Sandberg, R. Michael Hardesty, 2012: Doppler Lidar–Based Wind-Profile Measurement System for Offshore Wind-Energy and Other Marine Boundary Layer Applications. *J. Appl. Meteor. Climatology*, 51, 327–349.doi: doi: 10.1175/JAMC-D-11-040.1

Pielke R. A. et al., 1992: A comprehensive meteorological modeling system - RAMS. Meteorol. Atmos. Phys. 49, 69-91.

Pinson, P., H. Madsen, 2009: Ensemble-based probabilistic forecasting at Horns Rev. Wind Energy, 12(2), 137-155 (special issue on Offshore Wind Energy).

Porté-Agel, F., H. Lu, Y.-T. Wu, 2010: A large-eddy simulation framework for wind energy applications. The Fifth International Symposium on Computational Wind Engineering (CWE2010), Chapel Hill, NC, May 23-27.

Pryor S.C., R.J. Barthelmie, 2010: Climate change impacts on wind energy: A review, Renew. Sustain. Energy Rev., 14, 430–437.

Pryor, S. C., J. T. Schoof, R. J. Barthelmie, 2006: Winds of change?: Projections of near-surface winds under climate change scenarios, Geophys. Res. Lett., 33, L11702, doi:10.1029/2006GL026000.

Ren, D., 2010: Effects of global warming on wind energy availability. J. Renewable Sustainable Energy 2, 052301; doi: 10.1063/1.3486072

Rife, D. L. and C. A. Davis (2005), Verification of temporal variations in mesoscale numerical wind forecasts, *Mon. Wea. Rev.*, **133**, 3368–3381,doi:10.1175/MWR3052.1.

Rohatgi, J., G. Barbezier, 1999: Wind turbulence and atmospheric stability—their effects on wind turbine output, Renew. Energy, 16, 908–911.

Sanderse, B., S. P. van der Pijl, and B. Koren, 2011: Review of computational fluid dynamics for wind turbine wake aerodynamics. *Wind Energy*, **14**, 799-819. doi: 10.1102/we.458.

Sathe, A., J. Mann, J. Gottschall, and M. S. Courtney, 2011: Can wind lidars measure turbulence? *J. Atmos. Oceanic Technol.*, **28**, 853–868, doi:10.1175/2010JTECH-D-10-05004.1.

Schepers, J.G., T.S. Obdam and J. Prospathopoulos, 2012: Analysis of wake measurements from the ECN Wind Turbine Test Site Wieringermeer, EWTW.*Wind Energy*. **15**(4): 575-591.

Sheppard.D.G.,1994: Historical development of the windmill. In Wind turbine technology, fundamental concepts of wind turbine engineering, ed. David A. Spera, 1.ASME Press: New York.

Shoppe, C., 2010: Wind and Pumped-Hydro Power Storage: Determining Optimal Commitment Policies with Knowledge Gradient Non-Parametric Estimation. B.Sc. thesis.Princeton University.119 pp.

Sim, C., S. Basu, L. Manuel, 2009: The Influence of Stable Boundary Layer Flows on Wind Turbine Fatigue Loads. 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, 5 - 8 January 2009, Orlando, Florida.

Sisterson, D L, B.B. Hick, R.L. Coulter, M.L. Wesely, 1983: Difficulties in using power laws for wind energy assessment, Solar Energy, 31, 201–204.

Skamarock, W. C., J. B. Klemp, J. Dudhia, et al. 2008: A description of the advanced research WRF version 3. NCAR Tech Note. NCAR/TN-475+STR, 125 pp.

Smedman, A., U. Hogstrom, H. Bergstrom, 1996: Low level jets - a decisive factor for offshore wind energy siting in the Baltic Sea, Wind Engineering, 28, 137–147.

Smith, J., M. Milligan, E. DeMeo, B. Parsons, 2007: Utility wind integration and operating impact state of the art, IEEE Trans. Power Syst., 22, 900–908.

Smith, C. M., R. J. Barthelmie, M. J. Churchfiled, P. Moriarty, K. S. Hansen, and J. Madsen, 2012: Complex wake merging phenomena in large offshore wind farms. 20th American Meterological Society conference on boundary layers and turbulence, Boston, Massachusetts, July 9-13, 2012.

Sørensen, J.N. and W.Z. Shen, 2002: Numerical Modelling of Wind Turbine Wakes. Journal of Fluids Engineering, 124, No. 2, 393-399.

Sreelakshmi, R. K., 2008: Performance evaluation of short-term wind speed prediction techniques, Int. J. of Computer Science and Network Security, 8(8), 162-169.

Steftos, A., 2000: A comparison of various forecasting techniques applied to mean hourly wind speed time series, J. of Renewable Energy, 21, 23-35.

Stensrud, D. J. 2001. Using short-range ensemble forecasts for predicting severe weather events. Atmos. Res., 56, 3-17.

Storm, B. and S. Basu, 2010: The WRF Model Forecast-Derived Low-Level Wind Shear Climatology over the United States Great Plains. Energies, 3, 258-276.

Storm, B, J. Dudhia, S. Basu, A. Swift, I. Giammanco, 2009: Evaluation of the Weather Research and Forecasting Model on Forecasting Low-level Jets: Implications for Wind Energy. Wind Energy, 12(1), 81-90. doi:10.1002/we.288.

Stovall, T.D., G. Pawlas, P.J. Moriarty, 2010: Wind farm wake simulations in OpenFOAM. AIAA, Paper 2010-0825.

Stull, R.B., 1999: An Introduction to Bounary Layer Meteorology, Kluwer Academic Publishers, Dorecht.

Sumner, J., C. Masson, 2006: Influence of atmospheric stability on wind turbine power performance curves, J. Sol. Energy Eng., 128, 531–537.

Sundararagavan, S., E. Baker, 2012: Evaluating energy storage technologies for wind power integration, Solar Energy, 86, 2707–2717.

Sutherland, H.J., 2002: Inflow and the Fatigue of the LIST Wind Turbine, 2002 ASME Wind Energy Symposium, AIAA/ASME, 427-437.

Taylor, J.W, P.E. McSharry, R. Buizza, 2009: Wind power density forecasting using ensemble predictions and time series models, IEEE Trans. Energy Convers., 24(3), 775–782.

Troldborg, N., J. N. Sørensen and R. Mikkelsen, 2007: Actuator line simulation of wake of wind turbine operating in turbulent inflow. The Science of Making Torque from Wind, 012063.

U.S. DOE, 2008: Research needs for wind resource characterization. NREL Tech. Rep. 500-43521, 116 pp. [Available online at www.nrel.gov/docs/fy08osti/43521.pdf.]

Vanderwende, BJ, and JK Lundquist, 2012: The modification of wind turbine performance by statistically distinct atmospheric regimes. Environ. Res. Lett., 7 034035.

Wagner, R., I. Antoniou, S.M. Pedersen, M.S. Courtney, H.E. Jørgensen, 2009: The influence of the wind speed profile on wind turbine performance measurements, Wind Energy, 12, 348–362.

Watson, S.J., L. Landberg, J.A. Halliday, 1994: Application of wind speed forecasting to the integration of wind energy into a large scale power system, IEE Proc. – Gener,. Transm.Distrib., 141(4), 357-362.

Weggel, R.J. 1999: Maximum daily wind gust related to mean daily wind speed. J. Struct. Eng., 465–469.

Wharton, S., J. K Lundquist, 2011: Atmospheric stability affects wind turbine power collection, *Environ. Res. Lett.*, 7, 014005 (9pp).

Wiser, R., Z. Yang, M. Hand, O. Hohmeyer, D. Infield, P.H. Jensen, V. Nikolaev, M. O'Malley, G, Sinden, A. Zervos, 2011: Wind Energy. In IPCC Special Report in Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, C. von Stechow (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Wu, Y.-T., F. Porte-Agel, 2011: Large-Eddy Simulation of Wind-Turbine Wakes: Evaluation of Turbine Parametrisations, Bound.-Layer Meteorol., 138, 345–366, doi 10.1007/s10546-010-9569-x

Wu, Y-K., J.S. Hong, 2007: A literature review of wind forecasting technology in the world, IEEE Power Tech 2007 Conference, Lausanne, Switzerland, 504-509.

Yang C. J, R. Jackson, 2011: Opportunities and barriers to pumped-hydro energy storage in the United States. Renewable and Sustainable Energy Reviews, 15(1), 839-844.

Zack, J. W., K. T. Waight, G. E Van Knowe, M. D. Bousquet, 2000: An atmospheric modeling system designed to create simulated wind climatologies to support wind-generated power production. Preprints, 12th Conference on Applied Climatology, Asheville, NC. Amer. Meteor. Soc., 204-207.

Žagar, N., M. Žagar, J. Cedilnik, G. Gregorič and J. Rakovec, 2006: Validation of mesoscale low-level winds obtained by dynamical downscaling of ERA-40 over complex terrain. *Tellus*, 58A, 445–455.