APPENDIX D:

WIND ENERGY TECHNOLOGY OVERVIEW

APPENDIX D:

WIND ENERGY TECHNOLOGY OVERVIEW

Modern wind energy technologies rely heavily on the very complex scientific discipline of fluid dynamics (which includes the study of the atmosphere) and the equally complex engineering discipline of aerodynamics. A comprehensive treatment of either of these disciplines is well beyond the scope of this programmatic environmental impact statement (PEIS). The discussions that follow are intended only to establish a basic understanding of wind technology and the factors that control its evolution. References are provided for those who wish to have a more detailed understanding of wind technology.

This appendix provides an overview of the fundamentals of wind energy and wind energy technologies, describes the major components of modern wind turbines, and introduces terms that are unique to the field of electric power generation using wind energy. Important site characteristics and critical engineering aspects of wind energy technologies are presented, and their respective influences on future development decisions are discussed.[1] An overview of the current state of wind energy technology and ongoing research and development (R&D) is provided. Descriptions of a typical wind energy project and the major actions associated with each phase of development — site monitoring and testing, construction, operation, and decommissioning — are presented in Chapter 3 of this PEIS.

D.1 IMPORTANT TERMS AND CONVENTIONS

Discussions in the following sections introduce important terms and conventions, some of which are unique to the wind energy industry. The terms and conventions are described in the text where they are first introduced. Additional details are provided in the glossary of this PEIS (Chapter 10).

D.2 WIND ENERGY

Wind represents the kinetic energy of the atmosphere. In simplest terms, wind is the movement of air in the earth's atmosphere relative to a fixed point on the earth's surface. The major initiator of that movement is the uneven heating of the earth's surface by solar radiation. The materials that compose the patchwork of the earth's surface (e.g., vegetation, exposed rock, snow/ice cover, water) react differently to solar radiation, absorbing heat energy and reflecting some of that energy back into the atmosphere at different rates. The result is a nonequilibrium condition in which adjacent air masses have different heat energies and, as a result of adiabatic expansion or compression, different barometric pressures. Wind is one result of the atmosphere's

---

1 Wind farm developers and their investment capitalists must select among myriad options related to turbine design and site development and operation. Only those factors that have direct relationships to direct or cumulative impacting factors that are analyzed in this PEIS are discussed here.

attempt to normalize those differences and return to the lowest possible equilibrium state. The rotation of the earth around its axis initially causes a generally uniform global flow of air from west to east; however, many other factors add complexity to the dynamics of the earth's atmosphere. The text box on the next page has additional information on atmospheric motion.

D.3 EXTRACTING THE POWER OF THE WIND

The kinetic energy of wind is related to its velocity. This relationship is represented mathematically by the following equation:

$$P = ½ \times \rho \times A \times V^3 , \qquad \text{(D.1)}$$

where

P = wind power (W),

ρ = air density (typically 2.70 lb/m^3 [1.225 kg/m^3] at sea level and 59°F [15°C]),

A = cross-sectional area of the wind being measured (m^2), and

V = mean velocity of the wind within the measured cross section (m/s).

A careful examination of this power equation reveals the following important fundamental truths about wind energy. Both the air's density and the cross-sectional area of the wind being intercepted have a direct relationship to wind power. The air's density varies with temperature, elevation, and humidity, but, in all instances, the density remains relatively low. Thus, any changes to air density have a minimal effect on the wind's inherent power. Doubling the cross-sectional area of a wind front leads to a doubling of the intrinsic power. Most important to wind farmers is the fact that the wind's power is proportional to the cube of its average velocity. Thus, a doubling of the average or mean wind speed results in an eightfold increase in its power.

As a practical matter, wind energy technologists focus on the wind's "power density" or power per unit area of wind being intercepted, expressed in W/m^2. Simple manipulation of the above power equation allows power density to be calculated by using the following expression:

$$\text{Power density} = P/A = ½ \times \rho \times V^3. \qquad \text{(D.2)}$$

The height of the wind above the earth's surface also affects the average wind speed. Frictional drag and obstructions near the surface of the earth generally retard wind speed and induce a phenomenon known as wind shear (the change in a wind's speed with elevation). The rate at which wind speed increases with height varies on the basis of local conditions of the topography, terrain, and climate, with the greatest rates of increase observed over the roughest terrain. Unique local conditions notwithstanding, a reliable approximation is that wind speed increases approximately 10% with each doubling of height (Gipe 1995).

Understanding Atmospheric Motion

Wind represents the earth's atmosphere in motion. Understanding the development and progression of wind involves understanding the complex array of forces that constantly act upon the earth's atmosphere and cause its continuous motion. The velocity, direction, and variability of wind are products of those collective forces. The major forces at play include basic laws of thermodynamics, the force of the earth's gravity, frictional forces and obstructions imposed by the topography of the earth's surface, and the Coriolis effect caused by the earth's rotation. Thermodynamics governs the ways in which a given air mass behaves as it exchanges heat energy with its surroundings. Although the atmosphere's density is quite low, the gravitational forces of the earth nevertheless exert a constant downward force on the atmosphere that continuously affects its behavior.

It can be intuitively understood that the surface of the earth over which wind passes can also have some influence on wind, especially in the planetary boundary layer (the portion of the atmosphere immediately above the earth's surface). Topography can either increase or decrease wind speed in localized areas. Topography can also contribute to or induce wind shear (the rapid change of direction of wind with altitude). When other overriding forces are absent, topographic obstructions and friction at the earth's surface generally result in higher wind speeds at higher altitudes, with the highest wind speeds being achieved when all surface influences disappear. This wind is called the geostropic wind. The height or thickness of the planetary boundary layer varies over the surface of the earth (and actually changes slightly over the course of the day as a result of solar heating), reaching to thousands of feet in some locations. For the practical purpose of harvesting wind energy, the wind regime of greatest interest is contained completely within the boundary layer and, ideally, is composed largely of geostrophic wind.

The force commonly referred to as the Coriolis effect is more difficult to comprehend. Although it is easy to understand wind as being the motion of the atmosphere relative to one's point of observation on the surface of the earth, it is also important to recognize that one's point of observation, while it is fixed on the earth's surface, is not fixed in space, and it is itself moving as the result of both the earth's rotation and its orbit around the sun. The Coriolis effect is most easily defined as that apparent force on the wind that would not have otherwise occurred except for the earth's rotation and movement through space. It is manifested as a bending or redirection of the wind into circular patterns as air masses move from high-pressure to low-pressure areas. The magnitude of the Coriolis effect is a function of latitude. Winds directly above the earth's equator and moving in a direction parallel to the earth's axis of rotation experience very little in the way of a Coriolis effect. Winds occurring at other latitudes experience a Coriolis effect that is roughly proportional to the distance of that latitude from the equator. This fact can be easily understood by recognizing that any given point on the earth's surface along its equator is traveling at roughly 373 mph (600 km/h) around the earth's axis of rotation, while both the north and south poles have virtually no angular momentum.

Other characteristics of atmospheric motion that are of great practical significance to wind energy development are those factors that contribute to its variability over both time and geographic location. These factors include topography-induced variations, annual and seasonal wind speed variability, synoptic variations (resulting from or influenced by broad-area weather patterns and storm fronts), diurnal variations (reflecting changes in levels of solar radiation over a 24-hour cycle), turbulence (the uneven, chaotic motion of air), wind gusts, and extreme wind speeds. All such factors are critical to identifying ideal wind regimes and to designing wind turbines that can capture wind energy with the greatest efficiency while still withstanding the forces to which they will be exposed over their lifetimes. Since most of these forces exhibit their greatest influence on atmospheric motion in the planetary boundary layer (the portion of the atmosphere in which wind turbines normally operate), their influence on siting decisions and turbine design is substantial. While many of these variability factors can be intuitively understood, many others cannot. This uncertainty leads directly to the difficulties that now exist in accurately predicting weather. This uncertainty also greatly increases the complexity involved in selecting and developing the ideal wind farm.

Because wind flows not only more quickly but also more uniformly as the elevation from the earth's surface increases, the power contained in the wind is both greater and more easily extractable at higher elevations. Because turbulence decreases as the distance from surface obstructions increases, power actually increases faster with height than the relationship of power to the cube of the wind's speed would indicate. Thus, for example, a fivefold increase in height results in nearly a doubling of available wind power. To take advantage of this relationship, wind turbine developers pursue designs that not only allow the capture of the greatest cross-sectional area of wind but also allow the capture of wind at the highest practical elevation possible. There are trade-offs, however. Higher turbine elevations require more substantial support systems (both towers and their foundations) and substantially greater initial investments. Higher altitudes also subject the rotor and the nacelle, as well as the tower itself, to greater aerodynamic forces, which can require extensive design modifications and can shorten the expected operating lives of the tower and its components. Finally, operation and maintenance (O&M) activities can also be more complicated and costly with increases in the elevation of the rotor.

D.3.1 Characterizing Candidate Sites and Site Selection

The wind energy industry has adopted a convention by which annual average wind power densities and speeds are divided into seven power classes. It is also common practice to represent wind speed at a specified elevation above the land surface to allow comparative evaluations of sites within a given class to be made. To facilitate the identification of ideal wind regimes, the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) has developed comprehensive wind maps for the United States that show the spatial distributions of these power classes. These maps were derived from meteorological data collected at thousands of locations. Figure D-1 shows the wind resource distribution map for the contiguous 48 states. (Power density maps have also been developed for Alaska and Hawaii. However, since lands administered by the Bureau of Land Management [BLM] in those states are outside the scope of this PEIS, maps for those two states are not displayed here.) A more detailed discussion on the distribution of ideal wind regimes and more detailed maps showing ideal wind regimes on BLM-administered lands and their locations relative to existing electric power transmission lines are provided in Appendix B. Developers using currently available wind turbine technologies have found that sites with wind power densities at Class 4 or higher represent economically viable sites for a wind farm.

These wind maps serve only as a preliminary screening tool for site selection. Developers must still investigate the properties of the wind regime at any candidate site in much greater detail before assigning a practical value to the site and deciding on a course of development. The principal limitation to the wind power distribution map displayed here is that it shows only the annualized average wind speeds and power densities. Two sites with identical annual average wind speeds and power densities may have arrived at those average values by entirely different paths. Sites whose average speeds and power densities are the product of widely varying instantaneous wind speeds over time are much less attractive than sites displaying lesser wind speed variations over time with few or no instances of excessive, potentially damaging wind speeds.

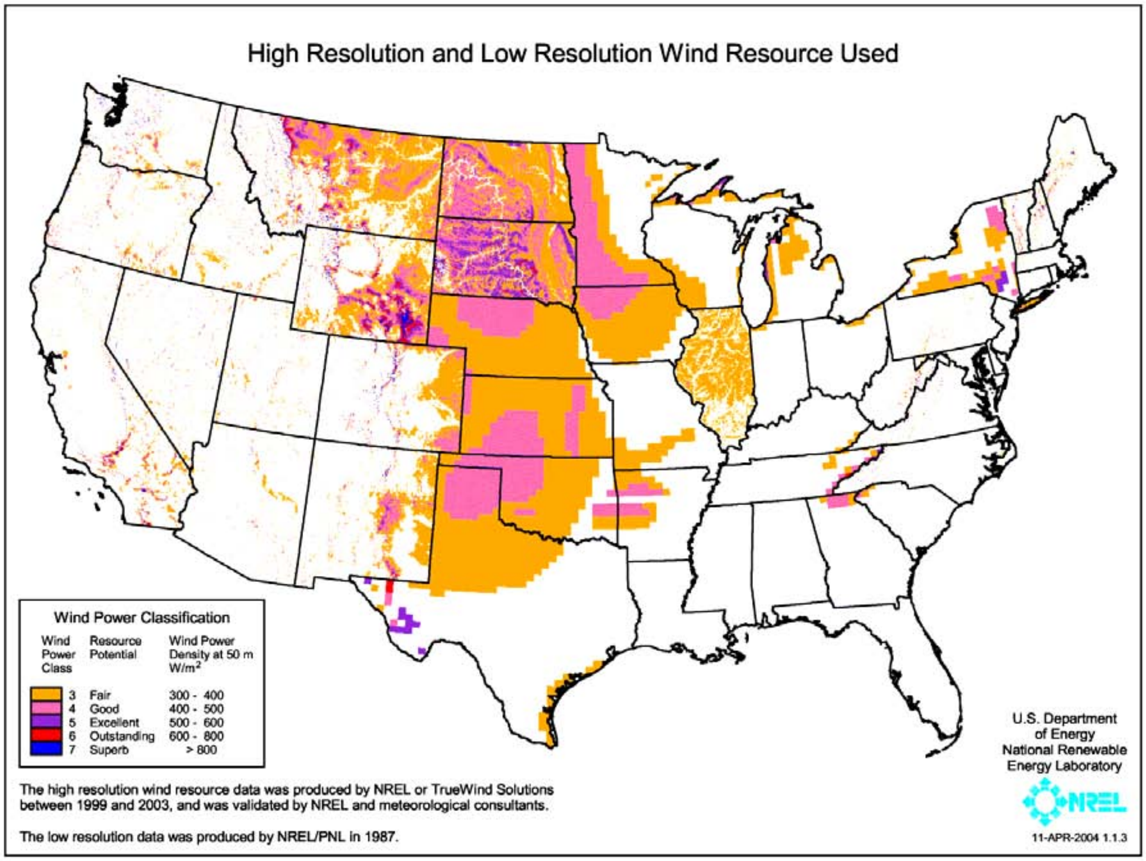

FIGURE D-1 Wind Resource Distribution Map for the 48 Contiguous United States (Source: EERE 2004b)

The developer must understand the time variability of the instantaneous wind speed. The ideal wind regime is one at which the instantaneous wind speed is near the upper limit of the operating range of commercially available wind turbines for the greatest percentage of time over the course of the year, thus maximizing annual energy production. (See Section D.5.3 for additional discussion on turbine operating ranges.) Therefore, the first step in any future wind farm development involves the collection of meteorological data (primarily wind speed and direction) at a potential candidate site for at least 1 year. For candidate sites in complex terrain or in areas with weather extremes, as many as 3 years of meteorological data may be necessary to support site development decisions. To realize their fullest value, the data must be collected at various locations within the site to support "micrositing" decisions (e.g., selecting the precise positioning of a wind turbine) and at various elevations to validate wind turbine decisions (e.g., selecting a turbine model and tower in which the rotor hub can be positioned at or near the elevation of maximum wind speed within its operating range and at a sufficiently high elevation so as to be above the chaotic and potentially damaging wind turbulence at or near the ground surface).[2] When the wind regime is precisely mapped, wind farms can consist of a variety of turbine models operating at different hub elevations to reach maximum sitewide efficiency. However, this type of composition complicates site development, construction, operation, and maintenance and may also complicate the collection and conditioning of the electric power that is generated. The use of various turbine models is unlikely; however, placing turbines at different hub elevations is technically feasible.

D.3.2 Other Factors in Site Selection

Site selection primarily involves matching wind regimes to turbine performance characteristics. The wind's elevation profiles and variability over time and location, as well as the range of extant wind speeds, must be matched to turbine designs (and vice versa). All such efforts to find the perfect match are conducted with the intention of maximizing the capacity factor of each turbine. This capacity factor is the ratio of expected energy output to the turbine's maximum rated power capacity, expressed as an annualized percentage (see additional discussion on capacity factors in Section D.5.3). A wind farm's expected capacity factor is the single greatest influence on the farm's return on investment (ROI).

Obviously, selecting a location with the highest average wind speed within the operating range of the proposed wind turbine for the greatest percentage of time is a principal site selection objective. In practice, many other circumstantial factors, such as transmission access and road access, substantially affect the costs of site development and O&M; therefore, they also play a key role in site selection.

D.4 WIND TURBINE TECHNOLOGIES

The centuries-old history of efforts to harvest wind energy is fascinating, and an extensive discussion is beyond the scope of this PEIS. However, many excellent sources exist, including Gipe (1995), Hau (2000), Burton et al. (2001), Manwell et al. (2002), and Spera (1994) and the references therein, as well as Web sites maintained by the DOE Office of Energy Efficiency and Renewable Energy (EERE 2004a), NREL (2004a), Sandia National Laboratories (2004a), the National Wind Coordinating Committee (NWCC 2004), and the American Wind Energy Association (AWEA 2004c).

Sailing ships probably represent the earliest attempt to harness the wind. Windmills, the most familiar wind technology, have been used for myriad applications, most commonly to grind grain and pump water and crude oil. There is speculation that the earliest windmills went into service more than 3,000 years ago. More reliable historical documentation dates the earliest use of windmills to 200 B.C. in Persia (now Iraq) (Sandia National Laboratories 2004a). There is

---

2 Although actual measurements of wind profiles at candidate sites are preferred, statistical methods can be utilized to extrapolate wind data from one site to nearby sites. An exhaustive discussion of these statistical methods is beyond the scope of this PEIS; additional information can be obtained from appropriate engineering texts (e.g., Burton et al. 2001; Manwell et al. 2002).

also evidence that windmills may have been used much earlier in China to drain rice fields, but the earliest dates of service are unclear. The use of windmills to generate electricity began in the late 19th century to provide electric power in rural areas, before the advent of far-ranging power transmission and distribution systems. Many windmills used in rural areas of Europe and the United States to pump water were converted for the production of electricity. Windmills such as the one shown in Figure D-2 were used to generate small amounts of electricity, normally to satisfy the demand for electric power in the immediate vicinity.

FIGURE D-2 Great Plains Windmill (Source: EERE 2004a)

Windmills are the progenitors of the modern wind turbine.[3] In fact, they share a common fundamental function: converting the kinetic energy of the wind into the mechanical energy of a rotating shaft. Throughout the development and evolution of the windmill, a variety of designs have been explored. The evolution of wind turbine design has followed a similar path. The earliest windmills had their axis of rotation oriented vertically, and vertical-axis wind turbines (VAWTs) were also developed. Later-model windmills have their axis of rotation in the horizontal position, and the analogous horizontal-axis wind turbines (HAWTs) also evolved. Although the orientation of the rotational axis defines the two primary design categories of wind turbines, many variations exist within each category.

Early sailing ships and the earliest windmills utilized the principle of "aerodynamic drag" to capture wind energy. Applying this principle involves installing an obstruction in the path of the wind. Depending on how this obstruction is oriented and what it is connected to, the force of the wind striking it can cause work to be performed (e.g., propelling a square-rigged sailing ship through the water). The common instrument for measuring wind speed, the cup anemometer, is an example of a present technology that still utilizes aerodynamic drag. Machines utilizing aerodynamic drag are easy to construct, and they make few design or operational demands. However, despite the relative simplicity of aerodynamic drag machines, their overall efficiency is generally low.

---

3 For this discussion, a wind turbine is defined as any device operated expressly for generating electricity, regardless of whether that electricity is utilized locally or introduced into power transmission and/or distribution systems.

No modern wind turbine operates on the principle of aerodynamic drag; instead, "aerodynamic lift" is utilized. When this principle is utilized, the wind turbine's blades do not obstruct the wind; instead, they direct its flow. The cross-sectional shape of all modern wind turbine blades is that of an "airfoil." These blades are similar in shape and purpose to an airplane wing. Wind flowing around an airfoil creates two different regions of pressure: a low-pressure region on the convex or "suction" side of the airfoil, and a higher-pressure region on its concave or "pressure" side. The atmosphere's attempt to return to pressure equilibrium creates the phenomenon of aerodynamic lift. However, whereas an airplane's airfoils are oriented in such a way that aerodynamic lift helps the plane defy the laws of gravity (i.e., air pressure is lower above the wing than below it, causing the wing to "lift"), the orientation of a wind turbine's blades relative to incident wind converts aerodynamic lifting forces into the rotation of the blades around an axis parallel to the direction of the wind.[4] Wind turbines utilizing aerodynamic lift can have power efficiencies up to 50 times greater than the efficiencies of turbines operating on aerodynamic drag (Spera 1994).

As noted previously, wind turbines have been developed with their axis of rotation in both the vertical orientation and the horizontal orientation. The VAWT traces its ancestry farther back in time than does the HAWT, to as early as 200 B.C. (Sandia National Laboratories 2004b). Modern VAWTs are variations of a design first introduced by French scientist Georges Darrieus around 1920. Figure D-3 shows examples of a commercial VAWT in California and an experimental VAWT currently operating as a DOE test facility in Texas.

In theory, both VAWTs and HAWTs should be able to capture the wind's energy by means of the principle of aerodynamic lift. However, VAWTs have a number of practical advantages. Because their blades are always perpendicular to the prevailing wind, they do not need to be reorientated when the wind direction changes in order to operate at their maximum efficiency. Thus, both their design and the complexity of their required operational controls are simplified. They are generally easier to erect than HAWTs and can have serviceable components located at or near ground level, thereby greatly simplifying their O&M. However, some of those same design characteristics contribute to the VAWT's intrinsic limitations. Many VAWT designs are not "free-wheeling" and must use an external energy source to start their rotation. Many also have limited wind speed operating ranges. VAWTs also have certain design limitations with respect to their maximum practical height.

Most important to their commercial application, however, is blade reliability and working life. VAWT blades must pass through the "wind shadow" or wake of their rotational axis, which also serves as the machine's primary support. This region typically exhibits a good deal of turbulence, which not only reduces power capture efficiencies but also subjects the blades to forces that are different and opposite to those that they experience when they are upwind of the center support; thus, significant engineering issues, such as fatigue, are introduced. Considerable research continues even today on how to overcome the intrinsic shortcomings of VAWTs, and VAWTs are being used as test platforms to generally advance the understanding of wind turbine

---

[4] Empirical studies have shown that the greatest turbine efficiencies are realized when the turbine rotor's axis of rotation is tilted slightly from the horizontal.

FIGURE D-3 Examples of VAWTs (Left: FloWind Corporation VAWT at Tehachapi, California. Photo credit: R. Thresher. Source: Photo #04688, NREL 2004b. Right: Darrieus-design VAWT operated as a wind energy technology test bed by Sandia National Laboratories at the U.S. Department of Agriculture research station at Bushland, Texas; 138 ft (42 m) high, 112 ft (34 m) in diameter. Photo credit: Sandia National Laboratories. Source: Photo #01671, NREL 2004b.)

technology. DOE's Sandia National Laboratories play a key role in this effort. However, only a few commercial wind farms that utilize VAWTs have ever been developed, and none are anticipated in the foreseeable future. Wind farms at Tehachapi Pass in California; Pincher Creek in Alberta, Canada; and Cap-Chat in Quebec, Canada, utilize or have utilized VAWTs. The leading manufacturer of commercial VAWTs, FloWind Corporation, is no longer in business. No VAWTs have ever gone into commercial service in Europe (Gipe 1995). Therefore, it is likely that HAWTs will continue to dominate the commercial market in the foreseeable future. Additional discussion of VAWT technology is therefore unnecessary for purposes of this PEIS.

In recent years, HAWTs have become the predominant technology used in commercial wind farms; thus, they are the focus of discussion in this PEIS. Figure D-4 shows an example of a typical front-facing HAWT. Within this category, Manwell et al. (2002) identified the following significant design variants: front-facing or rear-facing rotors and blades, rigid or teetering hubs, rotor rotation controlled by pitch or stall, number of blades (usually two or three), and free or controlled yaw motion. The majority of these design characteristics influence the overall performance of a turbine, but most have little or no influence on the environmental impacts of an operating turbine and thus are not discussed in further detail.

D.5 IMPORTANT CONCEPTS OF MODERN HAWT OPERATION

Figure D-5 shows the major components of a HAWT. As noted previously, many factors influence the design and performance of modern wind turbines. This section focuses on the aspects of wind turbine design and operation that can have direct and/or cumulative environmental impacts. Also discussed here is the spatial arrangement of wind turbines on a wind farm, which can also result in environmental impacts.

FIGURE D-4 Typical Front-Facing or Upwind HAWT (GE's 3.6-MW prototype wind turbine is an example of a front-facing HAWT. It is one of the largest HAWTs in existence, with a rotor diameter of 341 ft [104 m], giving a swept area of the blades of 91,432 ft^2 [8,495 m^2]. Rotor speed is variable between 8.5 and 15.3 rpm. The tower is constructed of concrete [lower portion] and tubular steel. Here, the turbine faces into the wind, which enters from the left. Sources: Photo adapted from EERE 2004c. Turbine specifications available from GE 2004.)

D.5.1 Power Coefficients

Intercepting the greatest practical cross-sectional area of wind creates the opportunity for capturing the greatest amount of energy; therefore, the primary design focus is on the rotor, which is the part of the turbine that actually extracts the wind's energy. No mechanical device, including the wind turbine, is 100% efficient. The practical efficiency of a wind turbine is usually represented as its power coefficient, C_p, defined as that fraction of the wind power that may be captured by the turbine and converted to mechanical work (and, subsequently, electricity). The power coefficient of a wind turbine is almost entirely a function of the rotor's efficiency. The power coefficient is represented by the following expression:

$$P = ½ \times C_p \times \rho \times A \times V^3, \quad \text{(D.3)}$$

where

P = power output of the turbine,

C_p = power coefficient of the rotor,