Wind Turbine Technology Overview

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Overview

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This document is one of a series of reports and guides that are all part of the NYSERDA Wind Energy Tool Kit. Interested parties can find all the components of the kit at: www.powernaturally.org. All sections are free and downloadable, and we encourage their production in hard copy for distribution to interested parties, for use in public meetings on wind, etc.

Any questions about the tool kit, its use and availability should be directed to: Vicki Colello; vac@nyserda.org; 518-862-1090, ext. 3273.

In addition, other reports and information about Wind Energy can be found at www.powernaturally.org in the on-line library under "Large Wind."

NOTICE

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Turbine Sizes

Wind generation equipment is categorized into three general classifications:

- Utility-Scale – Corresponds to large turbines (900 kW to 2 MW per turbine) intended to generate bulk energy for sale in power markets. They are typically installed in large arrays or 'wind energy projects,' but can also be installed in small quantities on distribution lines, otherwise known as distributed generation. Utility-scale development is the most common form of wind energy development in the U.S.
- Industrial-Scale – Corresponds to medium sized turbines (50 kW to 250 kW) intended for remote grid production, often in conjunction with diesel generation or load-side generation (on the customer's side of the meter) to reduce consumption of higher cost grid power and possibly to even reduce peak loads. Direct sale of energy to the local utility may or may not be allowed under state law or utility regulations.
- Residential-Scale – Corresponds to micro- and small-scale turbines (400 watts to 50 kW) intended for remote power, battery charging, or net metering type generation. The small turbines can be used in conjunction with solar photovoltaics, batteries, and inverters to provide constant power at remote locations where installation of a distribution line is not possible or is more expensive.

Discussion of utility-scale turbines is the primary focus of the NYSERDA Wind Energy Toolkit; however, information about industrial-scale and residential-scale turbines is also provided in this paper for use in planning activities.

The Technology

In North America, all commercially available, utility-scale wind turbines from established turbine manufacturers utilize the 'Danish concept' turbine configuration. This configuration uses a horizontal axis, three-bladed rotor, an upwind orientation, and an active yaw system to keep the rotor oriented into the wind. The drive train consists of a low-speed shaft connecting the rotor to the gearbox, a 2- or 3-stage speed-increasing gearbox, and a high-speed shaft connecting the gearbox to the generator. Generators are typically asynchronous, induction, and operate at 550-690 V (AC). Some turbines are equipped with an additional small generator to improve production in low wind speeds. The second generator can be separate or integrated into the main generator. Each turbine for utility-scale applications is equipped with a transformer to step up the voltage to the on-site collection system voltage. The on-site collection system typically is operated at medium voltages of 25 to 35 kV. Figure 1 shows the major turbine components for a wind turbine.

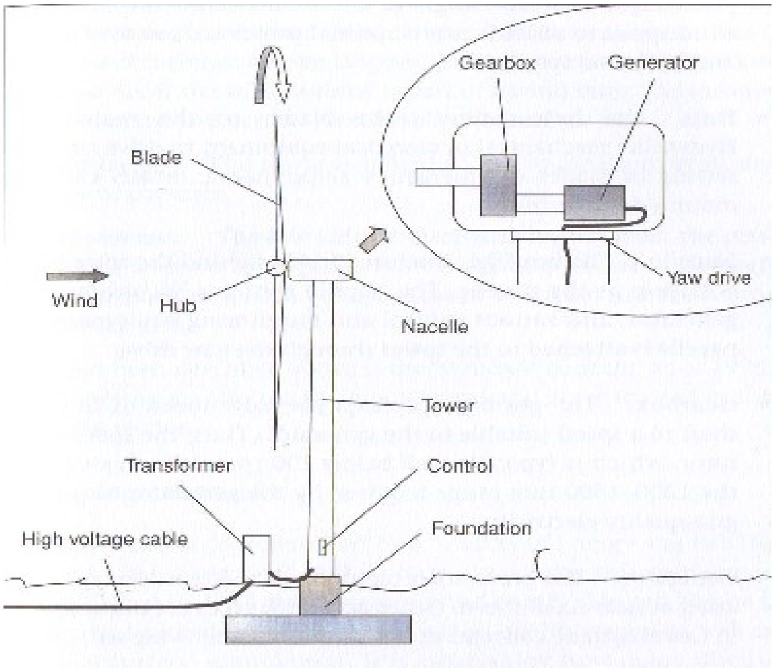

Figure 1. Major Turbine Components

As shown in Figure 2, power production from a wind turbine is a function of wind speed. The relationship between wind speed and power is defined by a power curve, which is unique to each turbine model and, in some cases, unique to site-specific settings. In general, most wind turbines begin to produce power at wind speeds of about 4 m/s (9 mph), achieve rated power at approximately 13 m/s (29 mph), and stop power production at 25 m/s (56 mph). Variability in the wind resource results in the turbine operating at continually changing power levels. At good wind energy sites, this variability results in the turbine operating at approximately 35% of its total possible capacity when averaged over a year.

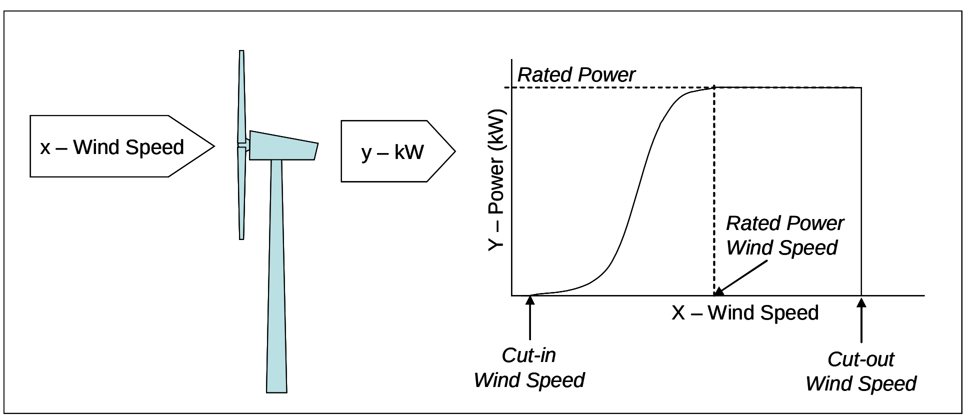

Figure 2. Relationship of Wind Speed to Power Production

Ratings and Rotor Size

The rotor diameters and rated capacities of wind turbines have continually increased in the past 10 years, driven by technology improvements, refined design tools, and the need to improve energy capture and reduce the cost of energy. For comparison, the average turbine rating for turbines installed in the U.S. in 2001 was 908 kW, while turbines installed in 2003 had an average capacity of 1,374 kW. In 2005, turbines with rated capacities of 1.5 MW to 1.8 MW present the vast majority of the turbines sizes installed in North America. Figure 3 compares the height of a large wind turbine with other tall structures.

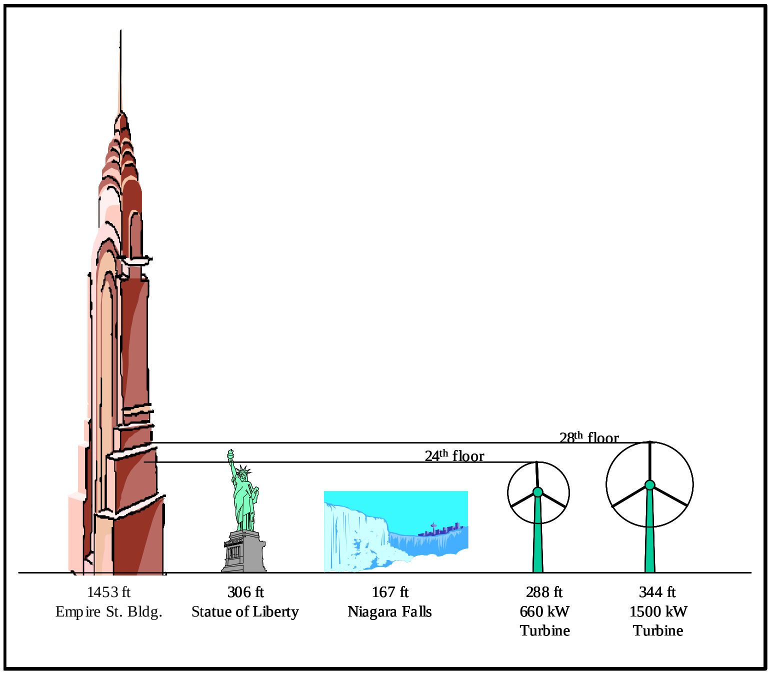

Figure 3. Large Wind Turbine Height Comparisons

Hub and Maximum Tip Heights

As the rotor diameters and rated capacities have increased, so has the hub height of the wind turbines. There is no standard hub height or ratio of hub height to rotor diameter. Wind resource characteristics, terrain, turbine size, availability of cranes, and visual impacts are but a few critical items that are used to determine the most optimum hub height for a given project. Current utility-scale wind turbines can employ hub heights that range from 50 m (164 ft) to 80 m (262 ft). Common hub heights used during 2004-2005 fall in the range of 65 m (213 ft) to 80 m (236 ft).

Maximum tip heights (the highest point of the rotor) depend on the hub height and rotor diameter. Table 1 provides an example of the range of tip heights common in 2003. As of

May 2005, the tallest wind turbine in the U.S. utilizes an 80-m (262-ft) hub height and a 82-m (279-ft) rotor diameter with a resulting maximum tip height of 121 m (397 ft). **Figure 4** identifies these key physical features of a wind turbine.

Table 1. Common Dimensions for Utility-Scale Wind Turbines

Dimension	Multi-Megawatt Turbines	Sub-Megawatt Turbines
Hub Height	80 m (230 ft)	65 m (213 ft)
Rotor Diameter	77 m (231 ft)	7 m (154 ft)
Maximum Tip Height	118.5 m (389 ft)	88.5 m (290 ft)

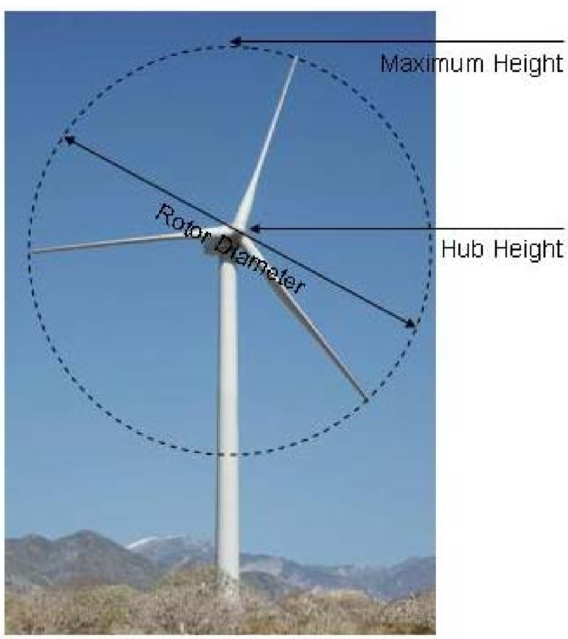

Figure 4. Wind Turbine Features

Optimum turbine size is heavily dependent on site-specific conditions. In general, turbine hub heights are approximately 1 to 1.4 times the rotor diameter. Project analysis conducted to identify the optimum turbine equipment typically results in a compromise between rotor size, hub height, energy production, component handling logistics, and cost.

Specific Rating

The ratio of a turbine's rotor swept area to the rating of the turbine is known as the specific rating. No 'best' relationship between rotor diameter and generator rating exists. Designers of modern turbines appear to have settled on a range of specific ratings from 0.32 to 0.47 kW/m^2, as this range presents the best compromise between energy capture, component loading, and costs. Turbines at sites with lower wind speeds (such as 7.0 to 7.5 m/s annual average at hub height) tend to have larger rotors and lower specific ratings to improve energy capture. Turbines at high-wind-speed sites (exceeding 9 m/s) tend to have smaller rotors and higher specific ratings. The smaller rotor helps to reduce loads on components and thus improves reliability in these aggressive wind sites.

Control Scheme

The control scheme employed to operate the turbine to produce grid-quality electricity varies among turbine manufacturers. No one control scheme is the 'best.' Each has advantages and disadvantages; however, they all successfully deliver energy into utility grids. Variable-speed turbines produce energy at slightly higher efficiencies over a wider operational range of wind speeds than constant-speed turbines. The power electronics necessary in variable-speed turbines to produce grid-quality electricity consume slightly more energy than capacitors used to condition the power from constant-speed turbines. Variable-speed turbines also provide the ability for the turbine to supply reactive power to the grid and dynamically control the reactive power supply (power factor) to the grid. This feature can be advantageous to the operation of the transmission system particularly in remote portions of the transmission system where voltage control can be difficult and costly for the system operator to maintain. Typically, reactive power and its effects are managed through the use of larger conductor sizes, capacitor banks and special reactive power supply equipment. Remote wind energy projects that have the ability to produce or consume reactive power with either a static or dynamic power factor can mitigate costly equipment on the transmission system. Turbines that do not utilize variable-speed technology provide close to unity power factor by using switched capacitors at the turbine and, in some cases, at the project substation. The effect of constant-speed systems on the grid results in the consumption of reactive power. This reactive power must be supplied from other transmission system resources. Transmission system operators are increasingly interested in using remotely located wind energy projects to assist in providing voltage support and control.

Fixed-pitch turbines generally have fewer moving parts and are less complex than variable-pitch turbines, resulting in lower manufacturing costs. Variable-pitch turbines are able to optimize blade pitch and adjust it for changes in air density or blade contamination. For these and other reasons, the energy output from variable-pitch turbines is somewhat higher than fixed-pitch turbines, thus offsetting the higher system costs. In locations with large variations in temperature, and thus air density, fixed-pitch turbines can experience difficulties with excessive power production during periods of high air density if the blades are pitched in a manner that optimizes production throughout the year. The specific wind and climate characteristics at a given site ultimately determine which type of control scheme generates energy most cost effectively.

Small Turbines

Most small turbines are much less sophisticated. Several resources on small wind turbines covering both technical and non-technical information are readily available on the Internet. A few of these resources include the following:

- New York Public Service Commission Website – interconnection requirements for distributed generation systems between 15 and 300 kW. This document includes technical requirements as well as non-technical requirements such as fees, forms, and insurance.
- California Energy Commission (2002) – Buying a Small Wind Energy System. This document discusses grid intertied small systems.
- Mick Segrillo (2002) – Choosing a home-sized Wind Generator. He reviews most wind generators sold and supported in the U.S. and includes technical descriptions of each.
- U.S. Department of Energy, EERE – Small Wind Electric Systems: A U.S. Consumer's Guide. This document includes information on sizing, zoning issues, technical information, how to choose a turbine, connecting a turbine to the grid, insurance, and off-grid applications.

Figure 5 presents a comparison of small wind turbines with common structures.

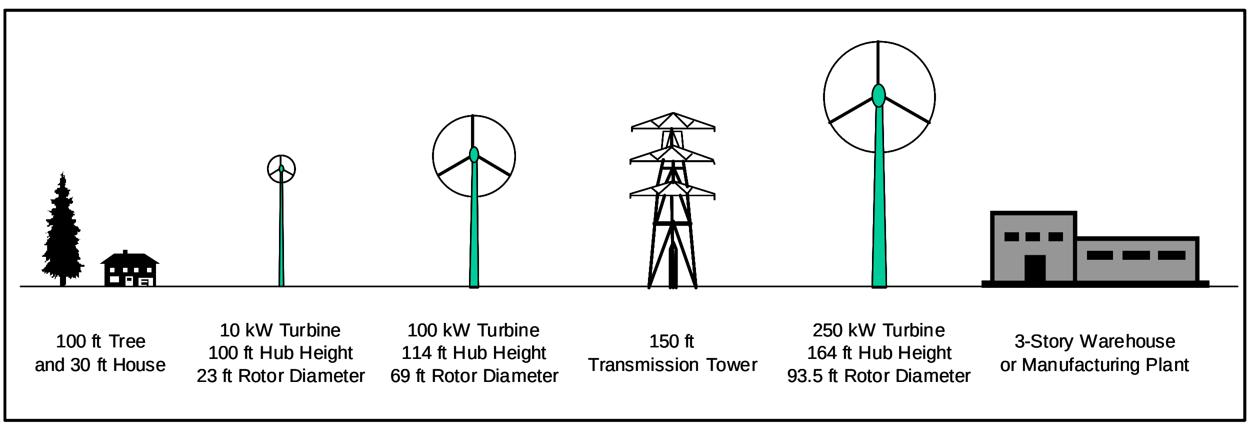

Figure 5. Small Wind Turbine Height Comparisons

Applications

Distributed Generation

Residential

Small wind turbines can be grid-connected for residential generation or they can be used in off-grid applications such as water pumping or battery charging. Small turbines are typically installed as a single unit or in small numbers. The smallest turbines (with power ratings less than 1 kW) are normally used to charge batteries for sailboats, cabins, and small homes. Turbines with power ratings between 1 kW to 20 kW are normally used for water pumping, small businesses, residential power, farm applications, remote communication stations, and government facilities. They are often found as part of a hybrid system that can include photovoltaic cells, grid power connections, storage batteries, and possibly back-up diesel generator sets. Small turbines with power ratings between 1 kW and 20 kW can be connected to single-phase electrical service that is typical in almost every home.

Turbines less than 1 kW are usually customer installed on short pole-type masts which can be located on roofs or boats. For turbines over 1 kW, tower heights can range from 12 m (40 ft) to 36 m (120 ft). Rotor diameters range from 1.1 m (3.5 ft) for a 400 W turbine to 15 m (49 ft) for a 50 kW turbine. For towers that use guy wires, the guy anchors are typically spaced one half to three quarters of the tower height from the base. A steel base plate or concrete foundation is necessary to adequately support the tower, depending on the turbine and tower size. Monolith-type concrete foundations are approximately 3 to 6 ft square. Free-standing towers can require construction of more elaborate concrete piles for each tower leg. Tilt-down towers are also available to facilitate easier access for maintenance.

Grid connected systems may be practical if the following conditions exist:

- The wind resource averages at least 10 mph over the course of the year.
- Local electrical rates are high – ranging from 10 to 15 cents per kilowatt hour (¢/kWh).
- The local utility requirements for connecting a small wind turbine are not prohibitively expensive.
- Good incentives for the sale of excess electricity or for the purchase of a small wind turbine exist.

Industrial

Industrial-scale wind turbines can range in size from 50 kW to 250 kW and are typically used in light commercial/industrial and village power applications. Industrial turbines typically utilize rotor diameters between 15 m (50 ft) and 30 m (100 ft) and hub heights between 25 m (80 ft) and 40 m (131 ft). Resulting maximum tip heights can vary from 30 m (100 ft) to 55 m (180 ft). Industrial-scale turbines require connection to three-phase electrical power found more typically in commercial and village power applications, as opposed to residential locations. These turbines are installed by construction crews with the guidance of the turbine manufacturer. Electrical interconnection would be guided by the local utility.

Harbec Plastics Inc. in Ontario, New York, installed a 250 kW wind turbine to help offset electric purchases. This particular turbine is on a 130-ft (39.5-m) tower and has a rotor diameter of 98 ft (30 m). More information on the Harbec wind turbine is available on the internet at http://www.northerndevelopment.com/renewableenergy.html.

Community

Though large wind turbines are most commonly deployed in large arrays of multiple turbines, they are also installed in distributed generation applications that consist of a single or a few turbines connected directly to a distribution line. Common examples include installing one large turbine to offset electric purchases at a school, or a municipality or electric cooperative may wish to install a few large wind turbines to offset electric needs at municipal buildings or to supplement the bulk energy purchases of a cooperative on behalf of its customer-owners.

Bulk Power Delivery

Most wind energy projects in the U.S. are commercial facilities that generate electrical energy for delivery and sale on the bulk power system (the grid). Most current commercial wind power plants range in size between 20 and 300 MW. The type of turbine utilized in the project determines the number of turbines installed at a site.

The three existing wind power plants in New York State are typical examples of medium- to small-sized wind energy projects in terms of the number of turbines and the installed MW capacity. Larger wind projects (100 MW or more) have been installed in several locations in the western U.S. The Maple Ridge Wind Farm in Lewis County that will be operational in 2005 is considered a large, utility-scale project.

Figure 6 provides an illustration of the components that comprise a typical wind energy project. Groups or rows of wind turbines are positioned for optimum exposure to the prevailing winds while accounting for terrain variations. Inter-turbine spacing is selected to maximize production while minimizing exposure to damaging rotor turbulence. Inter-turbine and inter-row spacing vary as a function of the rotor diameter and the wind resource characteristics. Because wide spacing between wind turbines generally maximizes energy production but increases infrastructure costs (e.g., land, cabling, and road building), costs must also be considered when creating a project layout. A trade-off exists between optimizing the turbine location for energy production (through wider spacing) and maintaining reasonable turbine interconnection costs, which increase with wider spacing. Experience, mathematical analysis, and cost considerations are employed to determine the optimum configuration given all of the existing site conditions and proposed turbine equipment[1].

The majority of civil and electrical work required to design and construct a wind power plant is similar to the same activities for other power plants. In addition to the wind turbines and towers, wind power plants contain other components that are necessary for proper operation:

- Electrical Power Collection System – Energy produced from the turbines is collected in a medium-voltage (approximately 25-35 kV) power collection system consisting of below-ground cabling within the turbine rows and above-ground power lines from the turbine rows to the main substation (see figure 6). The interconnection point to the utility line can be co-located in the substation or it can be physically separated and located adjacent to the utility line. In general, wind energy projects are positioned within 1 to 10 miles from the high-voltage transmission line to minimize costs associated with the interconnection. However, greater distances may be economically feasible if the wind resource is sufficiently high. Pad-mounted transformers, generally located immediately adjacent to the base of each tower, are used to transform the low-voltage power produced by the turbine to the higher voltage of the on-site electrical collection system.
- Substation and Interconnection – For most wind energy projects, electrical energy produced by the turbines passes through a substation where it is metered and the voltage is increased to match the voltage of the utility grid. Plant isolation breakers, power quality monitors, and protective equipment are also present in the substation to protect both the electrical grid and the wind turbines. A system of switches and overhead infrastructure is used to connect the substation to the utility's power lines.

[1] For more information on land requirements and multiple land uses, see the Land Requirements section of the NYSERDA Wind Energy Toolkit.

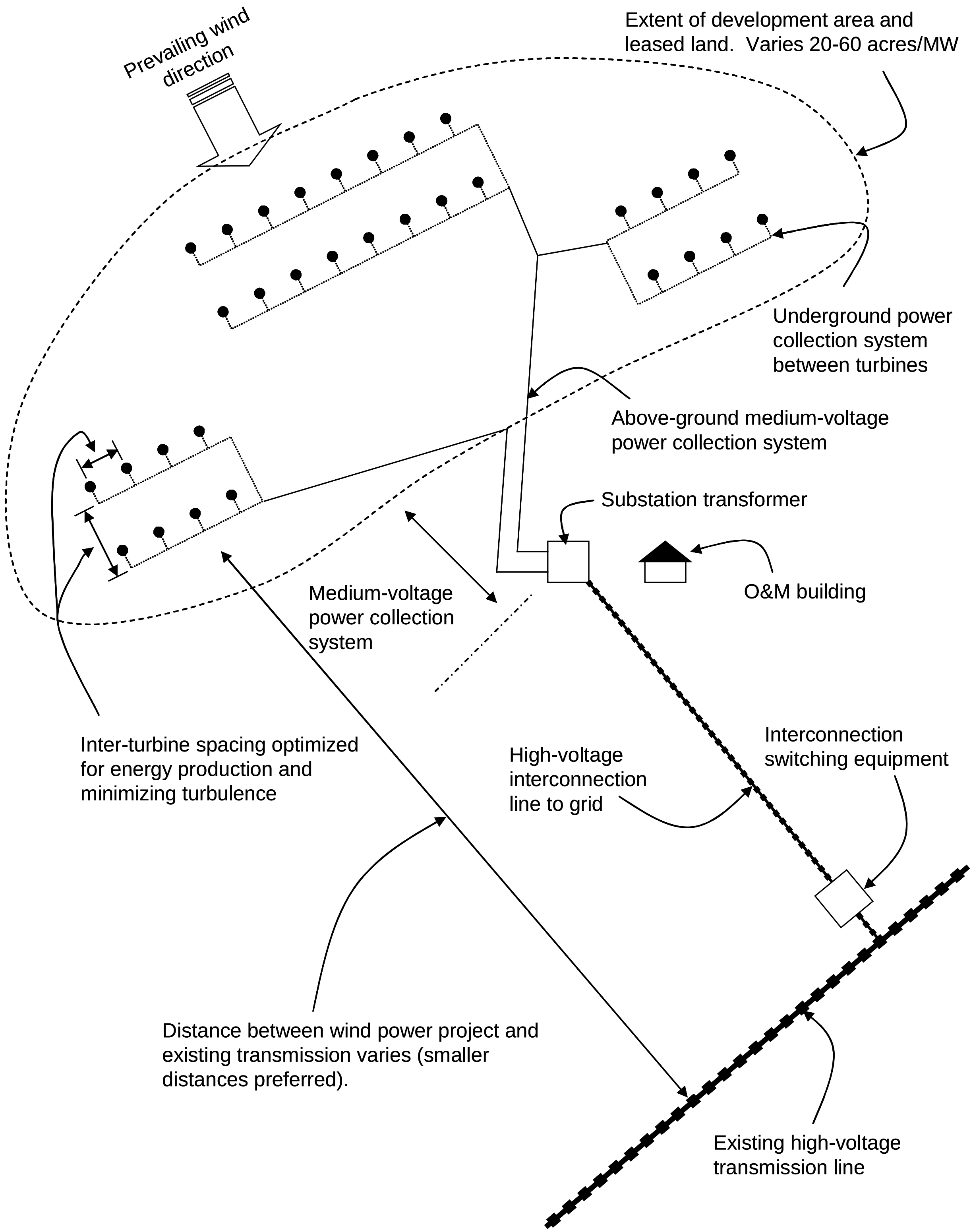

Figure 6. Typical Wind Energy Project Components and Layout

- Foundations – In general, the foundation design is based on the weight and configuration of the proposed turbine, the expected maximum wind speeds, and the soil characteristics at the site. Typical foundation approaches include an inverted "T" slab design and the patented concrete cylinder design (Figure 7 and Figure 8, respectively).

Figure 7. Inverted "T" Slab Foundation

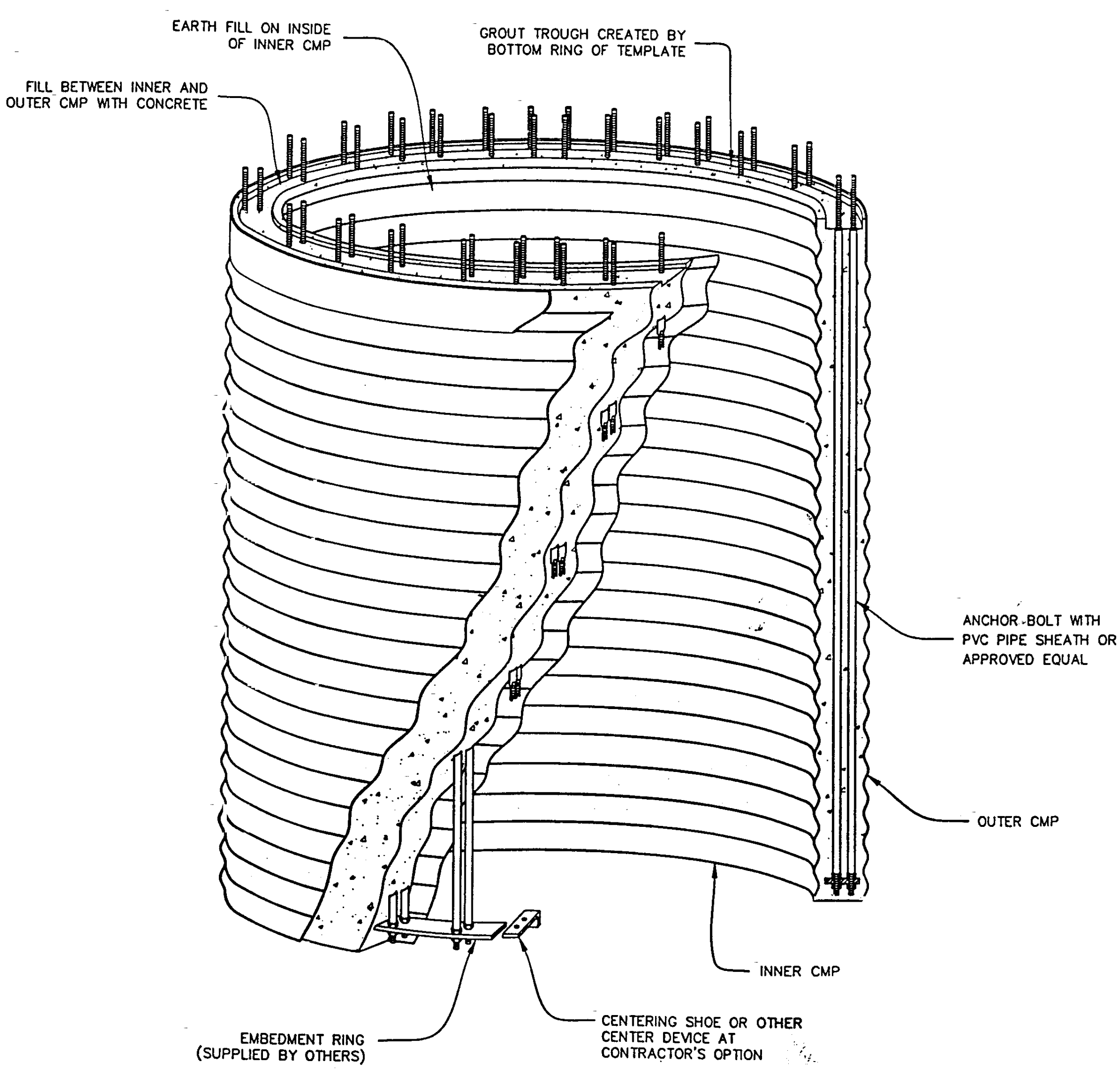

Figure 8. Concrete Cylinder Foundation

- Control and Communications System – In addition to individual turbine control systems on each machine, a wind project typically includes a Supervisory Control and Data Acquisition System (SCADA). SCADA systems consist of a central computer with control capabilities for individual turbines and the ability to collect, analyze, and archive time-series data. Communication cables connecting the central computer with the individual turbine controllers are commonly buried in the same trenches as the electrical collection system.
- Access Roads – Access roads to each turbine location are typically 18 to 20 ft wide and consist of compacted crushed rock. In hilly or complex terrain, access roads are constructed to specified slopes and turning radii that are necessary to allow delivery of large components such as blades and tower sections. During the construction

phase of a project, 'crane pads' (flat, well graded and compacted areas constructed of crushed rock) are installed along the access road and adjacent to the tower foundations. During project operation, the crane pads remain in place in the event that a crane is required to replace large components that cannot be handled by the service crane in the turbine.

- Operation and Maintenance (O&M) Facility – O&M facilities for wind power plants generally consist of an office and maintenance shop. These spaces can be located on site or off site and in some cases may be in separate locations. An office is necessary for plant management staff, control computers, and communication systems. The maintenance shop is used to store vehicles and spare parts, and provides a work space for the repair of turbine components.