

Design and Energy Estimates for Wind Farms

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Abstract- Wind power generation is becoming increasingly common in the portfolio mix of many utilities around the world. Wind turbines are presently available up to 5MW. Smaller turbines may be installed for individual customers and connected to the grid at the distribution level, and larger units are typically combined in a wind “farms” connected to bulk power systems at the transmission level. Turbines ranging from 1 to 3MW are very commonly used in on-shore wind farms and larger units become more practical when installed off-shore. This paper will focus on the procedures used in designing a large scale wind farm and the methods to estimate the expected energy generated.

Index Terms- wind energy, wind power generation, wind farm, renewable energy integration, design of wind farm.

I. INTRODUCTION

Generation of electricity using wind as the source is increasing around the world. Some proponents claim that worldwide investment in wind power is expected to increase from US\$16 billion in 2006 to US\$60 billion by 2016 [1].

In the United States, the growth in wind energy has been primarily motivated by renewable energy portfolios (RPS) which are legislative requirements that require a certain percentage of a state’s energy to be provided by renewable sources. At the present time, wind generation has the lowest cost of all installed renewable generation. For this reason the addition of wind generation has been seen as the easiest method by which utilities can meet legislative mandates.

II. ENERGY OUTPUT OF WIND FARMS

A. Wind Turbine Basics

The amount of power a single wind turbine can generate depends on the design and rating of the turbine and generator combination, the ability of the control system to extract the maximum energy from the wind under varying conditions, and the availability of wind of the proper velocity and sufficient energy to allow generation to occur. Typically a turbine/generator combination has a rated output which is the maximum output of the machine.

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This maximum output will occur at some rated (or minimum) wind velocity, at a standard air density, and will occur for all velocities above the rated wind velocity up to the cut-out velocity.

Each turbine is only designed to operate within a range of wind velocities: “cut-in” velocity is the lowest wind velocity and the “cut-out” velocity is the maximum velocity at which the generator will deliver power. Outside this range the turbine will not be operational.

The energy that is extracted from the wind is kinetic energy (KE). The amount of energy available in any moving mass at constant velocity (air in this case) can be found using Equation (1).

$$KE = \frac{1}{2} m v^2 \quad (1)$$

Where :

m = air mass (kg)

v = wind velocity (m/s)

KE = kinetic energy (Joules)

If a cross sectional area “A” is chosen and assuming the constant velocity, then power contained in a moving column of air can be found by taking the derivative of energy and is shown below.

$$\text{Power} = \frac{dE}{dt} = \frac{1}{2} \frac{dm}{dt} v^2$$

$$\frac{dm}{dt} = \text{density} \times \text{velocity} \times \text{area} = \rho \times v \times A \quad \left[\frac{\text{kg}}{\text{m}^3} \times \frac{\text{m}}{\text{s}} \times \text{m}^2 = \frac{\text{kg}}{\text{s}} \right]$$

Resulting in Equation (2).

$$\text{Power} = P = \frac{1}{2} \rho \times v \times A \times v^2 = \frac{1}{2} \rho A v^3 \quad (2)$$

Where:

P = power in (W)

ρ = air density = 1.225kg/m³ at 15°C and 1 atmosphere.

v = wind velocity in m/s (1m/s = 2.237mi/hr)

A = Area through which the wind flows in (m²).

In a typical horizontal axis wind turbine, the area “A” is the area swept by the blades. This can be found from the blade diameter using Equation (3) where D is the blade diameter in meters and A is the swept area in m².

$$A = \frac{\pi}{4} \times D^2 \quad (3)$$

Another commonly used quantity is called the power density. This is the amount of power per unit area available from the wind, and is routinely utilized in the designing the wind sites that are normally given in (W/m²) at some reference blade height, altitude, and temperature. It is defined by:

$$\text{Power Density} = \frac{P}{A} = \frac{1}{2} \rho v^3 \quad (4)$$

Wind velocity over a certain period of time is usually measured at a prospective wind farm site at a certain height above ground, typically 10m or 50m, and then corrected for the actual tower height of the turbines that will be installed. The wind velocity increases as the distance above ground increases. The semi-empirical Equation (5) is most commonly used to correct wind velocity for height above ground [2].

$$\frac{v}{v_0} = \left(\frac{H}{H_0} \right)^\alpha \quad (5)$$

Where:

v = wind velocity at height H

v_0 = wind velocity at the reference height H_0

α = ground roughness (empirical) coefficient:

- = 0.10 for smooth ground or water
- 0.15 tall grass on level ground
- 0.20 high crops or hedges
- 0.25 wooded country side
- 0.30 small town with trees and shrubs
- 0.40 large city with tall buildings.

To determine the power density and the power output, the air density (or mass) must also be known. Air density will vary with both altitude and temperature. At sea level at 60°F air density is 1.225kg/m³. At higher altitudes, air density can be considerably less significantly reducing the power available in the wind. Since temperature decreases at a standard rate with altitude, the following equation with one variable a single equation is used to correct the air density for altitude.

$$\rho = \rho_0 e^{-\left(\frac{0.297 H_m}{3,048}\right)} \quad (6)$$

Where:

ρ = air density at any elevation

ρ_0 = air density at sea level

H_m = site elevation in (m)

Wind turbine blade efficiency (C_p) is maximum for any wind velocity (v) at only one blade speed (RPM). So, to maintain maximum blade efficiency the generator (and rotor) speed (RPM) must vary as the wind speed varies. Modern variable speed turbines coupled to doubly-fed-induction-generators (DFIG) endeavor to operate the blade RPM at its optimal value for every wind velocity. The usual way to show this concept is to present rotor efficiency as a function of “Tip Speed Ratio (TSR).” TSR is the ratio of the tip of the blade speed over the wind velocity and is defined in Equation (7).

$$\text{Tip Speed Ratio (TSR)} = \frac{\text{Rotor Tip Speed}}{\text{Wind Speed}} = \frac{(\text{RPM}) \times \pi \times D}{60 v} \quad (7)$$

Where:

D = rotor diameter in (m)

RPM = rotor speed in revolutions per minute

v = wind velocity in (m/s)

If the overall plant control system varies the turbine speed (RPM) as the wind speed varies so that the TSR remains at its ideal value (or close to it), then the turbine efficiency will be at its maximum possible level [2]. It can be shown that the maximum theoretical limit of turbine efficiency is 59.3% (known as the “Betz” limit), and modern turbines can achieve approximately 80% of this value under ideal wind conditions.

B. Selection of Wind Site, Data Collection and Measurement

Wind resource maps are available from various sources which classify wind sites according to the expected wind power density (W/m²). These maps are useful to make simple and preliminary estimates for the amount of energy a wind farm can deliver at a certain site. Sites are classified at a certain altitude and at a certain height above ground. To use the data they contain data to estimate energy output at a site. However, the values given on the map must be corrected for altitude and height above the ground.

Additionally, it is extremely important and must be understood that these maps usually assume the wind velocity takes on a Weibull type probability distribution of a special kind known as a Rayleigh distribution. Making this assumption allows these maps to measure only mean annual wind velocity at a site and then calculate power density from this measurement and the assumed probability distribution.

Even though the Rayleigh distribution is often assumed, the probability density function describing the annual wind velocity at a site may vary somewhat from the Rayleigh distribution, so using the values shown on wind maps may result in some error. Wind site classification values are shown in Table 1.

Table 1: Site Classifications for Wind Sites.

Wind Power Class	Avg. Annual Wind Velocity (m/s) at 10m	Average Annual Wind Power Density (W/m ²) at 10m
1	0-4.4	0-100
2	4.4-5.1	100-150
3	5.1-5.6	150-200
4	5.6-6.0	200-250
5	6.0-6.4	250-300
6	6.4-7.0	300-400
7	7.0-9.5	400-1000

The values shown in Table 1 are annual average values. If a wind power density map shows a site to be Class 5, it can be determined quickly and approximately how much energy a particular wind turbine may deliver at this site. As an example, assuming a power density of 250W/m² is available on average from a wind, this can be multiplied by the number of hours per year (8,760hrs./yr.) to get the energy in Watt-hours that are available at this site. This is shown below:

$$\frac{250 \times 8,760}{1,000} = 2,190 \text{ kWh/m}^2$$

The wind map indicates that every (m²) of area swept by the turbine blades should produce 2,190kWh of energy/year at 10m height. If a turbine with a blade 80m in diameter is used, (with an area of 5,026 m²) the amount of energy flowing in the wind through the turbine would be:

$$2,190 \times 5,026 = 11,006,940 \text{ kWh/year}$$

Also it is an interesting observation, that the power rating of the generator would be approx. 250 x 5,026W or 1.26MW.

If the wind farm could extract 30% of the energy in the wind (assuming the efficiency of the complete system is 30%, a typical value) then the energy the wind farm would deliver from each turbine-generator set at this site would be approximately 3,302,082 kWh/year.

C. Turbine and Generator Sizing

To extract the maximum amount of energy from a site the turbine size (blade diameter) needs to be matched with the generator size and the site average wind velocity. To understand this concept, we must first define *Capacity Factor*.

$$\text{Capacity Factor (CF)} = \frac{\text{Amount of energy a generator produces in a year}}{\text{Amount of energy it would produce at 100\% output 8,760 hrs/year}} \quad (8)$$

If we match a large blade to a smaller generator at a particular site, we may cause the generator to produce greater output much of the year so the capacity factor is high. However, since the generator cannot utilize the full output from the turbine, the total amount of energy produced is far less than could be produced if the generator were larger and utilized more of the energy available from the turbine.

If the blade is made small and the generator made large, during high wind speeds the turbine may be capable of producing enough energy so the generator can produce its full output, but at slower wind speeds the generator will probably be running far below its ratings since the turbine cannot produce sufficient power for most of the year. So the capacity factor will be small and the total energy output will be less than optimal.

For each site, with a particular average wind velocity, it is possible to calculate a single best match (or optimal) between the turbine blade diameter and generator rating.

To approximate the capacity factor at a particular site using a single blade diameter, generator rating, Equation (9) may be used [2].

$$CF \approx 0.087v_{\text{avg}} - \frac{P_r}{D^2} \quad (9)$$

Where:

P_r = generator rated power in (kW)
 v_{avg} = average wind velocity in (m/s)
 D = rotor diameter in (m)
 CF = expected capacity factor

Equation (9) assumes the wind takes on a Rayleigh density function for the probability of wind velocity to provide an estimate for the best match between the generator

and turbine diameter at a particular site where the average annual wind velocity is known.

Using Equation (8), where P_r is the rating of the generator:

$$\text{Annual Energy Output (E)} = CF(8,760)P_r \quad (10)$$

Substituting Equation (9) into Equation (10):

$$E = \left(0.087v_{\text{avg}} - \frac{P_r}{D^2} \right) (8,760)P_r = 762P_r v_{\text{avg}} - 8,760 \frac{P_r^2}{D^2}$$

Taking the derivative of the energy with respect to generator size results in:

$$\frac{dE}{dP_r} = 762v_{\text{avg}} - (2)(8,760) \frac{P_r}{D^2} = 762v_{\text{avg}} - 17,520 \frac{P_r}{D^2}$$

To find the maximum energy this equation is set to zero and solved for P_r resulting in Equation (11)

$$P_r = 0.0435D^2v_{\text{avg}} \quad (11)$$

D. Example Problem

Let's examine a case to determine the expected energy output and best match for blade and turbine for a wind farm which a wind map states is Class 5 site with $v_{\text{avg}} = 6\text{m/s}$ measured at a height of 10 meters. The proposed hub height of the machines will be 80 meters and the proposed generator rating is 1,500kW.

Using Equation (5) and assuming that the terrain is farmland, the corrected average velocity at 80 meters will be:

$$\frac{v_{\text{avg}}}{6} = \left(\frac{80}{10} \right)^{0.2}$$

$$v_{\text{avg}} = 9 \text{ m/s}$$

Using this value in Equation (11) and solving for blade diameter shows that the blade diameter to give the largest amount of energy would be:

$$1,500 = 0.0435D^2(9)$$

$$D \approx 62 \text{ meters}$$

Assuming a blade 60 meters in diameter can be purchased for this generator, the expected capacity factor of this machine at this site would be found using Equation (9).

$$CF \approx 0.087(9) - \frac{1500}{62^2} = 0.39$$

And the amount of energy this machine would be expected to produce at this site would be approximately:

$$E = 0.39(8760) (1500) = 5,125 \text{ MWh/year}$$

E. Measured Data and Better Estimate

A far more exact estimate of the extracted energy that a particular turbine-generator set can deliver per year at any particular site can be arrived at using measured data. Site data is commonly measured for a year or more at a proposed wind farm site. Typically, 10 minute measurements of wind speed are taken, along with temperature and other data.

Measured wind generator data is also provided by the manufacturer. This usually consists of actual power output of the generator at each wind speed and the corresponding air density. This data, corrected for expected tower height and altitude, is used to estimate the exact output of a wind generator.

To illustrate this method, the following data was compiled from measured wind velocity at an actual proposed wind site, and combined with manufacturer's data on a 3MW wind turbine with a cut-in wind velocity of 4m/s and a cut-out wind velocity of 26m/s. This data was used to estimate the amount of energy this particular turbine would produce at this site. The results of this calculation are shown in Table 2.

It may be seen that this particular generator should produce approximately 8,420 MWh/year at this site. This would give this 3MW generator a capacity factor of:

$$CF = \frac{8420}{3(8760)} = 0.32$$

Table 2: Estimated Generator Output from Measured Data

Measured Wind Velocity m/s (corrected for hub height)	Hours per year at this velocity	Generator Output at this Velocity kW (corrected for hub height)	Energy Output (kWh)
4	732.87	61	44,705.07
5	816.09	259	211,367.31
6	850.28	300	255,084.00
7	839.46	497	417,211.62
8	791.27	760	601,365.20
9	715.57	1093	782,118.01
10	622.92	1471	916,315.32
11	523.23	1849	967,452.27
12	424.81	2201	935,006.81
13	333.82	2525	842,895.50
14	254.15	2790	709,078.50
15	187.63	2939	551,444.57
16	134.41	2988	401,617.08
17	93.47	2998	280,223.06
18	63.14	3000	189,420.00
19	41.44	3000	124,320.00
20	26.43	3000	79,290.00
21	16.39	3000	49,170.00
22	9.89	3000	29,670.00
23	5.8	3000	17,400.00
24	3.31	3000	9,930.00
25	1.84	3000	5,520.00
TOTAL			8,420,604

F. Array Efficiency

A single isolated wind generator can be expected to deliver the amount of energy calculated by the methods shown above. However, when generators are arranged in arrays the array will not deliver the amount of energy that can be expected by simply multiplying the energy shown by the number of machines. This is due to the fact that wind turbines placed closely together interfere with each other's air flow.

At the minimum, wind turbines must be placed 3 blade diameters apart between columns and 5 blade diameters apart between rows. If there is no prevailing wind direction these values must be increased and 10 blade diameters is often used as a basic approximation for the required distance between machines.

Even when spaced apart by 10 blade diameters, interference still occurs and becomes more pronounced when more machines are in the array. The concept of array efficiency defined below [2] quantifies this effect:

$$\text{Array Efficiency} = \frac{\text{Array Output}}{\text{Array Output if No Interference Occurred}}$$

Array efficiency can vary from 95% with a 2x2 array of turbines with 10 blade diameters between each tower to 85% when a 10x10 array is used, to less than 50% if the 10x10 array has only 4 blade diameters between towers [2].

A 60MW array of the 3MW machines (20 machines total) shown in Table 2 which were located so as to have 10 blade diameters between towers would be expected to have an array efficiency of approximately 90%. So 20 of these machines would produce $(20)(8,420)(0.9) = 151,560$ MWh/year, which would be a site capacity factor of approximately 29% ($=0.32 \times 0.9$).

G. Wind Farm Land Area

Besides higher capital cost, the most important drawback of many types of renewable sources is that the source of energy is very diffused. This inherent problem in the production of large amounts of energy from wind require large land to produce amounts of power useful to a utility.

It is useful and essential to have a method to quickly estimate the amount of land a wind farm will occupy. This is somewhat problematic since wind turbines are often sited to follow ridge lines, and actually estimating the amount of land they use may be difficult. Even though they may require a site many square miles in area, the land between turbines can often still be useful for other functions such as farming.

To derive a method of quick estimating the land use it will be assumed a rectangular type array with equal spacing between each turbine and its neighbor.

If we make the assumptions that the spacing between turbines is 8x8 rotor diameters, the average year around machine efficiency is 30% and the array efficiency is 85% a simple approximation for the average annual power output per m² of land area for a site with a known power density can be estimated.

Following Equation (4), Equation (12) is the average power density of a site as a function of average of the cubes of the site wind velocity [2][3].

$$P_{\text{density}} = \frac{1}{2} \rho (v^3)_{\text{avg}} \quad (12)$$

Using the stated assumptions, and making (A) equal to the area swept by the turbine blade, the average annual power available to the turbine should be:

$$P_{\text{avg}} = (0.85)(0.3) \frac{1}{2} \rho (v^3)_{\text{avg}} A$$

Combining with Equation (12) results in:

$$P_{\text{avg}} = (0.85)(0.3) P_{\text{density}} (A) \quad (13)$$

Substituting Equation (3) into Equation (13) results in:

$$P_{\text{avg}} = (0.85)(0.3) (P_{\text{density}}) \frac{\pi}{4} D^2 \quad (14)$$

With an (8 x 8) rotor diameter spacing, each turbine would require a spacing of (8D) x (8D) = 64D² rotor diameters of land area (L_{area}). So the needed land area is given by equation (15).

$$D^2 = \frac{L_{\text{area}}}{64} \quad (15)$$

Substituting into Equation (14) yields:

$$P_{\text{avg}} = (0.85)(0.3) (P_{\text{density}}) \frac{\pi}{4} \frac{L_{\text{area}}}{64}$$

Simplifying, the above equation yields to Equation (16)

$$P_{\text{avg}} \approx (P_{\text{density}}) \frac{L_{\text{area}}}{320} \quad (16)$$

$$\text{Or, } P_{\text{avg}} / L_{\text{area}} \approx \frac{P_{\text{density}}}{320}$$

An approximation for the average annual power available per square meter of land area at a site with a known annual average power density is then given by Equation (17).

$$P_{\text{avg}/m^2} \approx \frac{P_{\text{density}}}{320} \quad (17)$$

For example if the wind site under consideration has an annual average power density of 400W/year/m² at the turbine hub height (approximately a Class 4 wind site if the hub height is 50m) then each square meter of land area would produce an average power of 400/320=1.25 Watts/m². The amount of energy that could be produced would be 1.25(8,760hours/year) = 10.95kWh/year/m².

A typical 100MW wind farm with a capacity factor of 35% would produce 306,600 MWh/year. A wind farm capable of producing this amount of energy (it may not be able to deliver 35% capacity factor depending upon the

machines chosen) on this class of site would need an estimated area of:

$$\frac{306,600,000}{10.95} = 28,128,440 \text{ m}^2$$

This is equivalent to 10.2 square miles.

III. WIND FARM ECONOMICS

A wide range of cost estimates is available for the wind farms. One source gives an average cost of approximately \$1,750/kW of installed capacity [5]. Other sources give the price in dollars/MWh which often begs the question of whether these costs are subsidized (by the tax payer and/or rate payer).

To arrive at a simple calculation for the minimum cost an owner must receive a quote for power generated by a wind turbine. A cost of \$1,750/kW installed will be used here, and profit, maintenance, land costs, and any other widely variable costs associated with a wind farm will be ignored for this simple example.

If we use the example of the 3MW wind turbine on the wind site whose data is shown in Table 2, and further assume this turbine is installed in a typical array where the array efficiency is 85%, how much would electricity have to be sold for assuming the wind turbine has an expected life of 20 years and the cost of borrowing money is 6%/year?

Each 3MW turbine would cost (3,000)(1,750)=\$5.25 million. It would be expected to generate (8,420,605)(0.85) = 7,157,513 kWh/year.

The annual cost of \$5.25 million at 6% interest spread over 20 years would be \$457,718.00. So the cost of electricity to pay only for the equipment would be (457,718/7,157,513) = \$0.065/kWh (or 6.5¢/kWh).

So to just break even on the equipment and installation costs (and ignoring O&M and land cost), an owner must get at least 6.5¢/kWh for the power generated. This is higher than the average wholesale costs of electricity sold in the United States [6]. This simplified calculation does not include the additional costs on ancillary power needed to supplement the large variability in a wind derived source. As wind energy comes to make up a larger percentage of the generation portfolio, these ancillary costs can be expected to increase as reliability requirements for the power system make necessary the installation of additional equipment to handle the intermittent and unpredictable characteristics of large amounts of wind derived power.

To make wind and other renewable sources financially attractive many states have resorted to the use of renewable energy mandates which force utilities into installing certain amounts of wind and other renewable sources. Inadequate transmission facility required to transmit large amount of wind power from wind farm is also a very expensive proposition. The additional costs for generation and transmission are then passed on to the rate payers. This has come to the forefront of current discussions nationwide.

Another method being used to make renewable sources more attractive from an economic point of view is the implementation of carbon taxes or carbon caps. The

institution of carbon taxes or carbon caps will have the result of increasing the costs for cheaper conventional sources of electricity generation, perhaps to the point where wind and other renewable sources become competitive.

IV. CONCLUSION

Due to the continued pressure from different spheres of life to install renewable generation, wind farms have become one of the fastest growing (as a percentage of existing installed capacity) types of generation. Many utilities are being required (Renewable Portfolio Standards) to install additional renewable generation by legislative actions at all levels even though their energy projections would not otherwise require them to install new generation of any type. Wind power is the forerunner alternative in this advancement.

This paper has provided a basic understanding of wind as a resource for electric power generation. It has also provided simple methods and analytical tools to quickly estimate the amount of energy available at a particular wind site. It has also provided a practical and simplified approach to determine the amount of land needed to generate the certain amount of energy required by the wind farm designer.

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VI. BIOGRAPHIES



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Keith Malmedal (Member IEEE) received his BSEET degree from Metropolitan State College of Denver in 1995, a MSEE degree (Power), a MSCE degree (Structures) from the University of Colorado at Denver in 1998 and 2002, respectively. In 2008 he received his PhD at Colorado School of Mines, Golden, CO in Engineering Systems (Electrical Specialty) focussing on Electric Power/Renewable Energy Applications. He has over 20yrs of combined experience in electrical power system design and system study, teaching, and research, and is presently the President of NEI Electric Power Engineering, Arvada, Colorado, a consulting firm specializing in all aspects of power system engineering and design. He has published over a dozen "peer reviewed" technical papers in archival journal and taught university courses (both undergraduate and graduate level) and short courses related to power systems, machines, protection, renewable energy, and energy policy issues. Dr. Malmedal is also a member of the American Society of Civil Engineers (ASCE) and a registered professional engineer in 17 states and Alberta, Canada.