# Wind Energy

**Lacture-1** **Dr.Amani I.**

## Basic of Renewable Energy

**Renewable** are energy sources with unlimited amounts. These natural resources do not need to be burned in order to get energy. Examples include **hydropower, solar power, geothermal power, and wind energy**. Much of the electricity is created using coal and natural gas. These are natural resource found underground and are brought to the surface and burned to produce energy. There is only a limited amount of natural resources available to use for energy.

**Wind** is simply air in motion. It is caused by the uneven heating of the Earth's surface by the sun. Because the Earth's surface is made of very different types of land and water, it absorbs the sun's heat at different rates. Today, wind energy is mainly used to generate electricity. Wind is a renewable energy source because the wind will blow as long as the sun shines.

**Wind power** or (energy) is the conversion of wind energy into a useful form of energy, such as electricity, using wind turbines

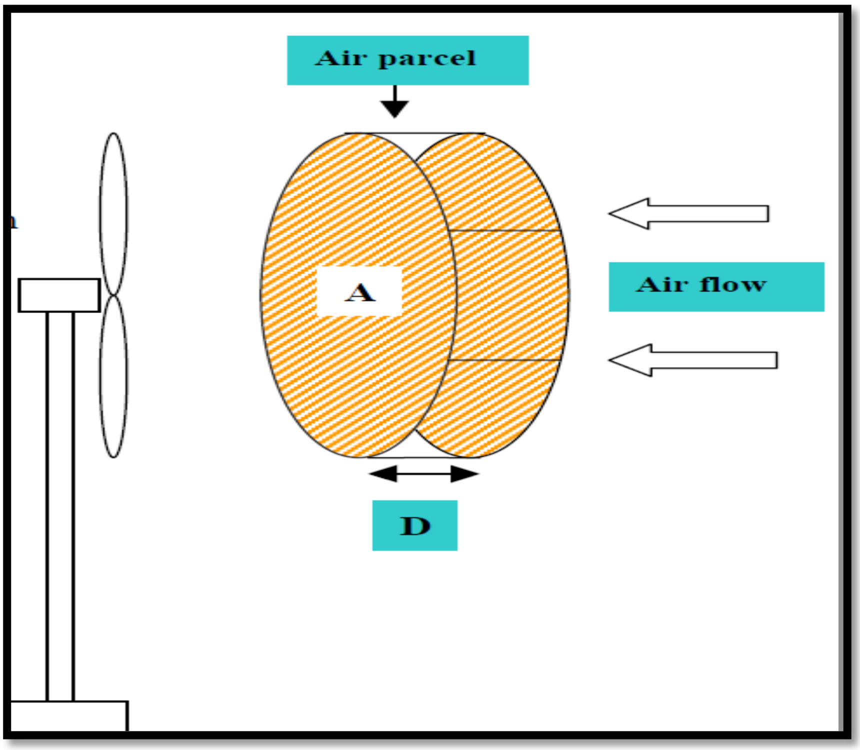
### Calculation of Wind Energy and Power

Calculating the energy (and later power) available in the wind relies on knowledge of basic geometry and the physics behind kinetic energy. The kinetic energy (***KE***) of an object (or collection of objects) with total mass ***M*** and velocity ***V*** is given by the expression:

$$KE = \frac{1}{2} * M * V^2$$

Now, for purposes of finding the kinetic energy of moving air molecules (i.e.: wind), let's say one has a large air parcel with the shape of a huge hockey puck: that is, it has the geometry of a collection of air molecules passing though the plane of a wind turbines blades (which sweep out a cross-sectional area ***A***), with thickness (***D***) passing through the plane over a given time. The volume (***Vol***) of this parcel is determined by the parcel's area multiplied by its thickness:

$$Vol = A * D$$



Let ρ (the greek letter 'rho') represent the density of the air in this parcel. Note that density is mass per volume and is expressed as:

$$\rho = M / Vol$$

And a little algebra gives:

$$M = \rho * Vol$$

Now let's consider how the velocity (***V***) of our air parcel can be expressed. If a time ***T*** is required for this parcel (of thickness ***D***) to move through the plane of the wind turbine blades, then the parcel's velocity can be expressed as

$$V = D / T$$

And a little algebra gives

$$D = V * T$$

Let's make some substitutions in expression no. 1

$$(KE = \tfrac{1}{2} * M * v^2 )$$

Substitute for $M\ (= \rho * Vol\ )$ to obtain:

$$KE = \tfrac{1}{2} * (\rho * Vol) * V^2$$

And $Vol$ can be replaced by $A * D$ to give:

$$KE = \tfrac{1}{2} * (\rho * A * D) * V^2$$

And $D$ can be replaced by $V * T$ to give**:**

$$KE = \tfrac{1}{2} * (\rho * A * V * T) * V^2$$

Leaving us with:

$$KE = \tfrac{1}{2} * \rho * V^3 * A * T$$

Now, power is just energy divided by time, so the power available from our air parcel can be expressed as:

$$Pwr = KE / T = (\tfrac{1}{2} * \rho * V^3 * A * T) / T = \tfrac{1}{2} * \rho\square * V^3 * A$$

And if we divide ***Pwr*** by the cross-sectional area (***A****)* of the parcel, then we are left with the expression:

$$Pwr / A = \frac{1}{2} * \rho * V^3$$

Note two important things about this expression: one is that the power is proportional to the **cube** of the wind speed. The other is that by dividing power by the area, we have an expression on the right that is independent of the size of a wind turbines rotor. In other words, ***Pwr/A*** only depends on (1) the density of the air and (2) the wind speed. In fact, there is no dependence on size, efficiency or other characteristics of wind turbines when determining ***Pwr/A***. The term for the quotient ***Pwr/A*** is called the **"Wind Power Density"** ***(WPD*****)** and has units of watts/m$^2$**.**

We determined this expression for wind power density:

$WPD = ½ * \rho * V^3$

And that air density can be determined to varying degrees of accuracy with the following.

**Methods**

**1.)** $\rho = 1.225\ \mathrm{kg/m^3}$ (constant value based on U.S. Std. Atmosphere, at sea level)

**2.)** $\rho = 1.225 - (1.194 * 10-4) * z$ (z=the location's elevation above sea level in m.)

**3.)** If you have pressure and temperature data:

$\rho = P / RT$ (kg/m$^3$)

Where

$P$ = air pressure (in units of Pascals or Newtons/m$^2$)

$R$ = the specific gas constant (287 J kg$^{-1}$ Kelvin$^{-1}$)

$T$ = air temperature in degrees Kelvin (deg. C + 273)

**4.)** If you have temperature data but not pressure data:

$\rho = (P_o / RT) * \exp(-g*z/RT)\ (\mathrm{kg/m^3})$

Where

$Po$ = std. sea level atmospheric pressure (101,325 Pascal's)
$g$ = the gravitational constant (9.8 m/s$^2$); and
$z$ = the region's elevation above sea level (in meters)

**New lesson:** Note that the expression (1) for *WPD* is a simplification that held for our example in Tutorial 1 because we made the tacit assumption that the wind blew with speed **V** *all the time* .In reality, varying winds mean we must work a little harder to find the true WPD. To get the most accurate estimate for Wind Power Density, one must actually perform a summation using data taken over time, as follows.

$$WPD = 0.5 * 1/n * \sum_{j=1}^{n} (\rho j * V^3 j)$$

Where n is the number of wind speed readings and ρ**j** and **Vj** are the jth (1st, 2nd, 3rd, etc.) readings of the air density and wind speed.

Since air density ρ and wind speed ***V*** will change with every data reading, the most accurate result would entail a calculation for every data interval. For example, to calculate the best possible value for ***WPD*** for Oklahoma Mesonet weather station location for a year, one would need to perform calculations for ρ and ***V*** for 105,120 data intervals! (288 observations per day times 365 days per year). Clearly this must involve running computer programs. Fortunately, there are two ways to get reasonable estimates for ***WPD*** without doing all the calculations described above:

**Method 1.)** The best way to approximate ***WPD*** uses the results of a wind speed frequency distribution (this is like a histogram - a sample table of wind speed frequency occurrence from a Mesonet weather station will be shown in the next tutorial). Using such distribution information, the following summation can be applied:

$$WPD = 0.5 * \sum_{j=1}^{n} [\rho * (\text{median } V^3 \text{ in class } j) * (\text{frequency of occurrence in class } j)]$$

If one uses a value for air density that does not change over time (like values from methods no. 1or 2), then air density can come out of the expression to give:

$$WPD = 0.5 * \rho * \sum_{j=1}^{n} [(\text{median } V^3 \text{ in class } j) * (\text{frequency of occurrence in class } j)]$$

By using wind summary products that are available from the, one can get a reasonable estimate of ***WPD*** that does not involve hundreds of thousands of calculations. In fact, it can be done by summing only about 8 terms in the above expression. This method wills be covered in more detail in the following tutorial (no. 4.)

**Method 2.)** For the rest of this tutorial, we will focus on a simpler method by which you can estimate the WPD in your area of interest. If one makes an assumption about how wind speeds are distributed in the wind speed frequency diagram, one can approximate *WPD* with the following:

$$WPD = 0.5 * k * \rho * (\text{mean wind speed})^3$$

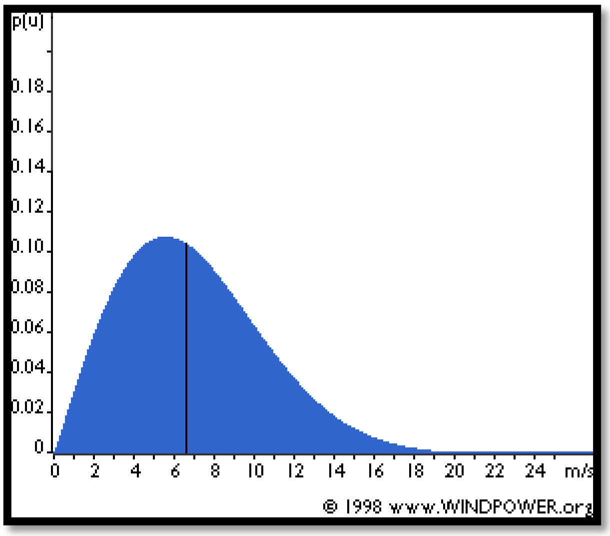
Where

$k$= a value determined by the shape of the distribution pattern that the wind speeds follow.

## Describing Wind Variations: Weibull Distribution

### The General Pattern of Wind Speed Variations

It is very important for the wind industry to be able to describe the variation of wind speeds. Turbine designers need the information to optimize the design of their turbines, so as to minimize generating costs. Turbine investors need the information to estimate their income from electricity generation.



If you measure wind speeds throughout a year, you will notice that in most areas strong gale force winds are rare, while moderate and fresh winds are quite common.

The wind variation for a typical site is usually described using the so-called Weibull distribution, The Weibull distribution is often used in the field of life data analysis due to its flexibility, and it can mimic the behavior of other statistical distributions such as the normal and the exponential. The statistical distribution of wind speeds varies from place to place around the globe, depending upon local climate conditions, the landscape, and its surface. The Weibull distribution may thus vary, both

Weibull distribution can be characterized using the probability density function (PDF) and the cumulative distribution function (CDF) as follows

$$f(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} \exp\left(-\left(\frac{v}{A}\right)^{k}\right)$$

$$F(v) = \int_0^U f(v)\,dv$$

$$F(v) = 1 - e^{-\left(\frac{v}{A}\right)^{k}}$$

Where $f(v) \geq 0,\ v \geq 0;\ k > 0,\ A > 0$

There are more than seven methods to calculate the Weibull parameters such as the Standard Deviation Method (SDM). In this work, the Standard Deviation Method (SDM) was used to find the Weibull parameters. The forms of the Standard Deviation Method (SDM) are

in its shape, and in its mean value. As shown in the image, Weibull distribution depend on two parameter scale($A$) and shape($k$) and we can calculated them by using those equations:

$$k = \left(\frac{S.D}{\bar{X}}\right)^{-1.086}$$

As we shown the above equation depend on Standard Deviation ($S.D$) and the mean of wind speed($\bar{X}$)

$$A = \frac{\bar{X}}{\Gamma\left(1+\frac{1}{k}\right)}$$

While the scale parameter depends on the mean of wind speed and Gamma function $\Gamma$.

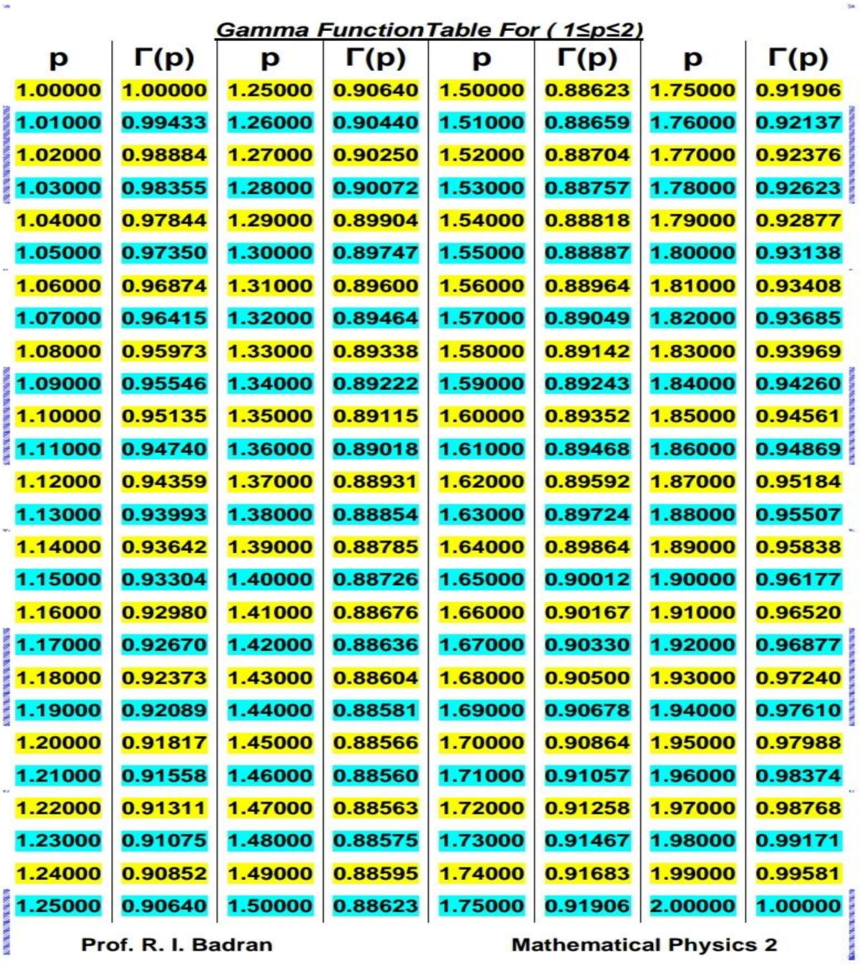
The wind power density based on Weibull distribution can be calculated by

$$WPD_w = \frac{1}{2}\rho A^3 \Gamma\left(1+\frac{3}{k}\right)$$

Where A scale parameter (m/s), $\Gamma$ Gamma function, k shape parameter .It can get the intensity of wind energy WEI ($kWh/m^2$) by multiplying power with times the following

$$\mathrm{WEI} = \mathrm{WPD} * \mathrm{T}$$

Where T Time period (s)

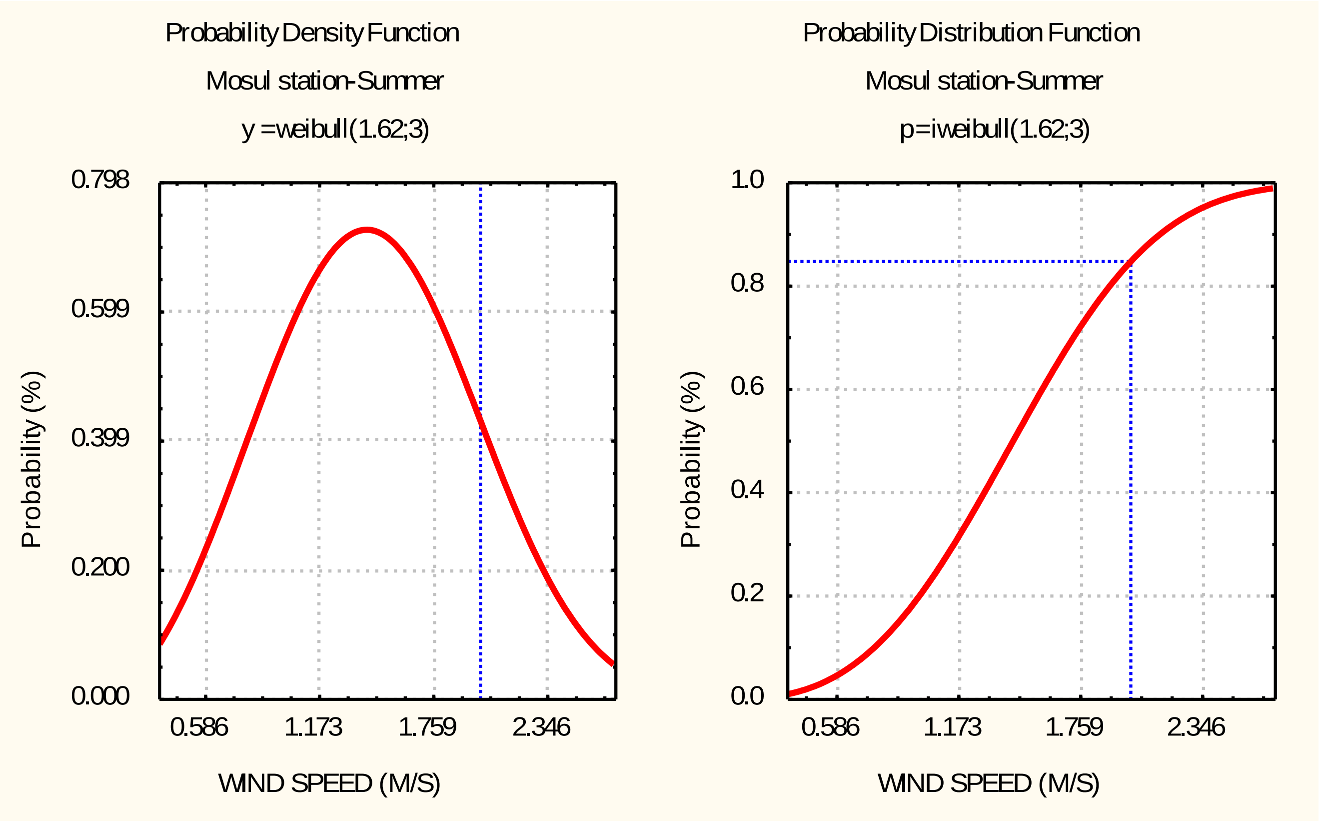


*Gamma FunctionTable For ( $1 \le p \le 2$)*

| p | Γ(p) | p | Γ(p) | p | Γ(p) | p | Γ(p) |
|---|---|---|---|---|---|---|---|
| 1.00000 | 1.00000 | 1.25000 | 0.90640 | 1.50000 | 0.88623 | 1.75000 | 0.91906 |
| 1.01000 | 0.99433 | 1.26000 | 0.90440 | 1.51000 | 0.88659 | 1.76000 | 0.92137 |
| 1.02000 | 0.98884 | 1.27000 | 0.90250 | 1.52000 | 0.88704 | 1.77000 | 0.92376 |
| 1.03000 | 0.98355 | 1.28000 | 0.90072 | 1.53000 | 0.88757 | 1.78000 | 0.92623 |
| 1.04000 | 0.97844 | 1.29000 | 0.89904 | 1.54000 | 0.88818 | 1.79000 | 0.92877 |
| 1.05000 | 0.97350 | 1.30000 | 0.89747 | 1.55000 | 0.88887 | 1.80000 | 0.93138 |
| 1.06000 | 0.96874 | 1.31000 | 0.89600 | 1.56000 | 0.88964 | 1.81000 | 0.93408 |
| 1.07000 | 0.96415 | 1.32000 | 0.89464 | 1.57000 | 0.89049 | 1.82000 | 0.93685 |
| 1.08000 | 0.95973 | 1.33000 | 0.89338 | 1.58000 | 0.89142 | 1.83000 | 0.93969 |
| 1.09000 | 0.95546 | 1.34000 | 0.89222 | 1.59000 | 0.89243 | 1.84000 | 0.94260 |
| 1.10000 | 0.95135 | 1.35000 | 0.89115 | 1.60000 | 0.89352 | 1.85000 | 0.94561 |
| 1.11000 | 0.94740 | 1.36000 | 0.89018 | 1.61000 | 0.89468 | 1.86000 | 0.94869 |
| 1.12000 | 0.94359 | 1.37000 | 0.88931 | 1.62000 | 0.89592 | 1.87000 | 0.95184 |
| 1.13000 | 0.93993 | 1.38000 | 0.88854 | 1.63000 | 0.89724 | 1.88000 | 0.95507 |
| 1.14000 | 0.93642 | 1.39000 | 0.88785 | 1.64000 | 0.89864 | 1.89000 | 0.95838 |
| 1.15000 | 0.93304 | 1.40000 | 0.88726 | 1.65000 | 0.90012 | 1.90000 | 0.96177 |
| 1.16000 | 0.92980 | 1.41000 | 0.88676 | 1.66000 | 0.90167 | 1.91000 | 0.96520 |
| 1.17000 | 0.92670 | 1.42000 | 0.88636 | 1.67000 | 0.90330 | 1.92000 | 0.96877 |
| 1.18000 | 0.92373 | 1.43000 | 0.88604 | 1.68000 | 0.90500 | 1.93000 | 0.97240 |
| 1.19000 | 0.92089 | 1.44000 | 0.88581 | 1.69000 | 0.90678 | 1.94000 | 0.97610 |
| 1.20000 | 0.91817 | 1.45000 | 0.88566 | 1.70000 | 0.90864 | 1.95000 | 0.97988 |
| 1.21000 | 0.91558 | 1.46000 | 0.88560 | 1.71000 | 0.91057 | 1.96000 | 0.98374 |
| 1.22000 | 0.91311 | 1.47000 | 0.88563 | 1.72000 | 0.91258 | 1.97000 | 0.98768 |
| 1.23000 | 0.91075 | 1.48000 | 0.88575 | 1.73000 | 0.91467 | 1.98000 | 0.99171 |
| 1.24000 | 0.90852 | 1.49000 | 0.88595 | 1.74000 | 0.91683 | 1.99000 | 0.99581 |
| 1.25000 | 0.90640 | 1.50000 | 0.88623 | 1.75000 | 0.91906 | 2.00000 | 1.00000 |

Prof. R. I. Badran Mathematical Physics 2

The figure down about ( PDF) Probability Density function to Mosul station



**Exercises:**

1. For a wind turbine with rotor diameter 43 meters (a typical size for a 600 kW turbine), calculate the volume and mass of a 1 meter thick parcel of air passing through the plane of the turbine blades (for this exercise, assume a value for the air density of 1.225 kg/m3).

2. Imagine that you have just 2 readings of wind speed: 5 m/s and 15 m/s. Calculate the WPD over the interval of these readings (assume ρ = 1.0 kg/m3 to make the math easier).

**3**-If you were responsible for calculating the annual average WPD for a potential wind farm to go offshore in the Gulf of Mexico, but weather data was scarce, which method would you use to estimate air density? Why?

The ratio of the total power available in the wind to the power corresponding to the mean wind speed is called the Energy pattern factor method (EPF)

$$\mathrm{EPF} = \frac{1/n \sum_{i=1}^{n} {v_i}^3}{\left(1/n \sum_{i=1}^{n} v_i\right)^3}$$

$$k = 3.957\mathrm{EPF} - 0.898$$

Usually, the data of wind speed are available in most cases on a high of 10m above the ground level. Since the wind, speed tends to increase with height in most locations. The height of the hub in the energy generation systems is more than 10m, therefore it's necessary to estimate the wind speed at the range of elevations that corresponding for the wind turbine which possible to install in the selected site. In order to transfer the anemometer height to the standard level or other desired heights, it should use the power law equation as follows

$$v_2 = v_1 \left(\frac{z_2}{z_1}\right)^{\alpha}$$

Where v1wind speed at a height $(Z_1)$,$v_2$ wind speed at a height$(Z_2)$, $\alpha$ ground surface friction coefficient.

The scale and shape parameters of Weibull distribution will change as a function of height as the following expressions

Q1-The monthly wind speed for Baghdad station 3 m/s at height 10m and S.D is equal o.75, Calculate the wind power density at height 50m