

14-Wind Resource

ECEGR 452
Renewable Energy Systems



Overview

- Introduction
- Wind Resource Modeling
- Variation with Height
- Power Curve
- Wind Power Modeling



Introduction

- Energy from wind has been harnessed for thousands of years:
 - Sailing
 - Milling
 - Pumping water
- Wind turbines operate by converting kinetic energy in the air to electrical energy



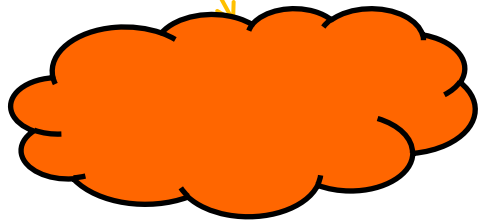
Introduction

- Wind Mill: used to grain mill
- Wind Turbine: used to generate electricity
- Wind Plant (Wind Farm): collection of wind turbines

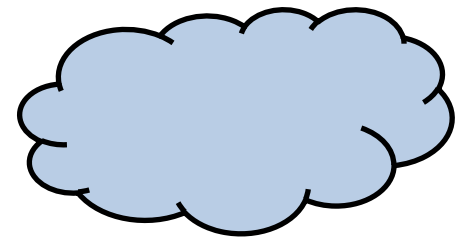


Wind Resource

- Movement of air on appreciable scales is caused by temperature differentials
 - Higher temperature air is less dense than cold air
- Temperature differentials (gradients) are predominately caused by uneven solar heating
 - Wind is another form of solar energy



warm air



cool air

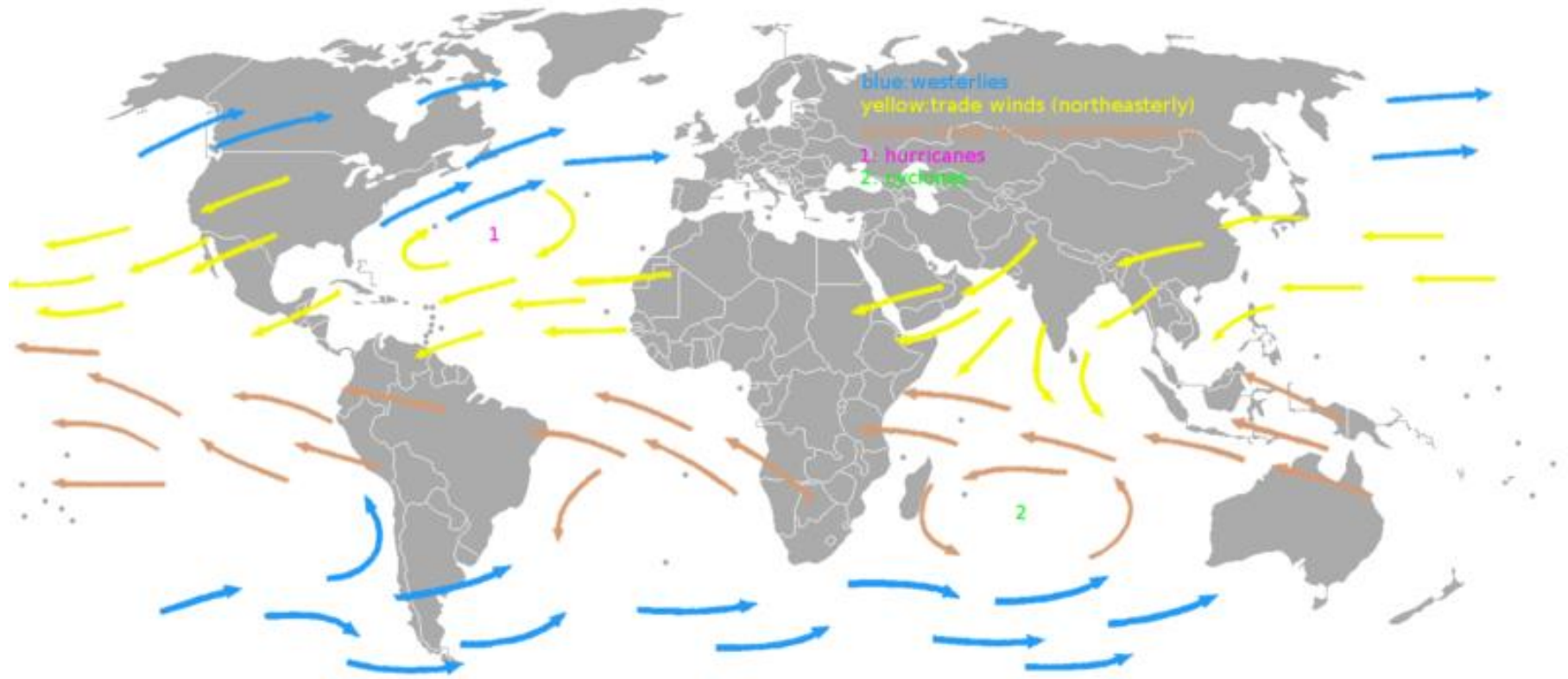


Wind Resource (Northern Hemisphere)

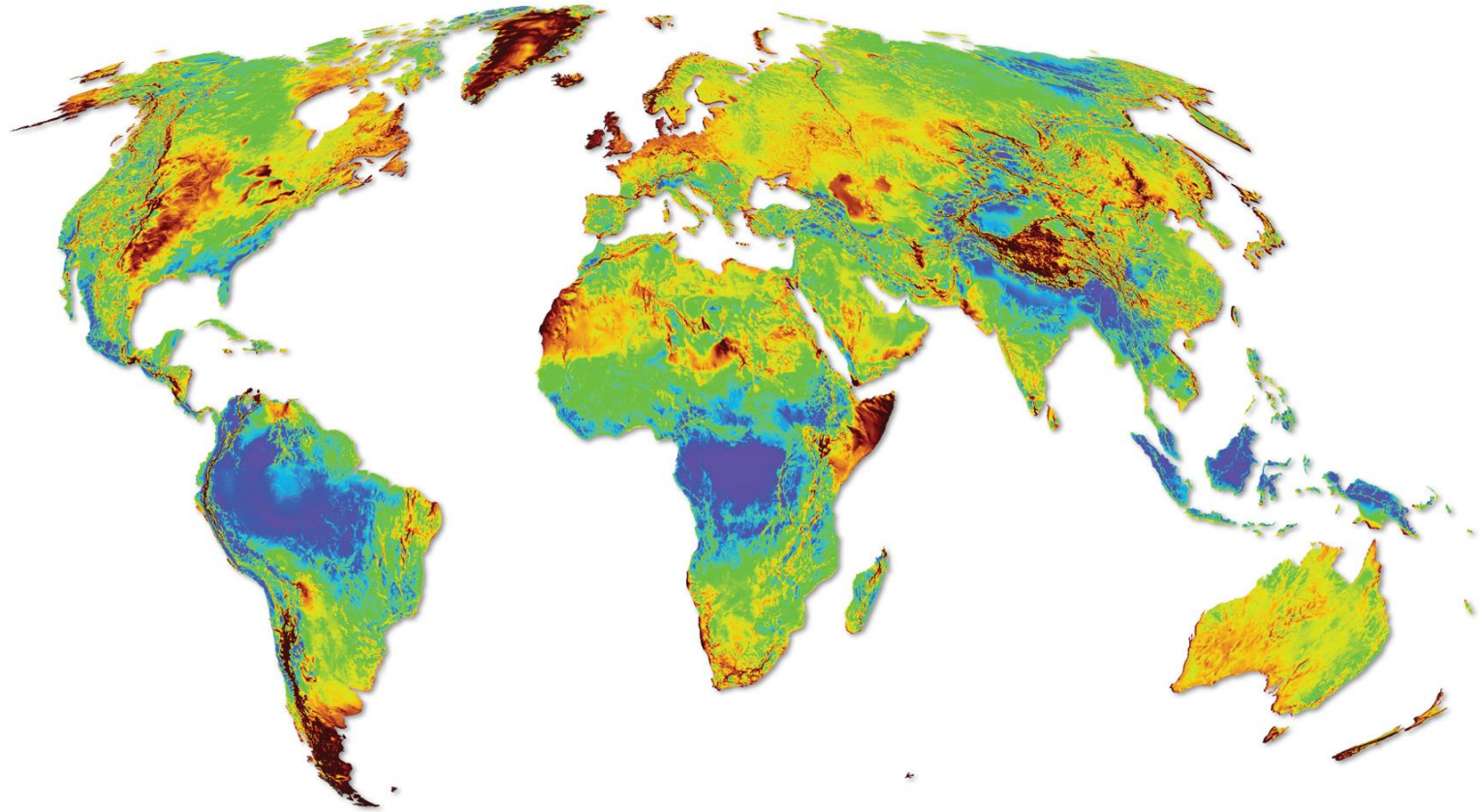
- Equatorial regions receive more solar radiation than polar regions
- Warm air rises and moves toward the north
 - Earth's rotation (Coriolis Effect) imparts an east-west direction (westerlies)
 - Around 30° N the air cools and sinks
- This cooler air returns to equatorial region
 - Direction is south west (trade winds)



Wind Resource

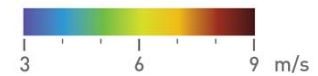


5km Global Wind



5km Wind Map at 80m

Wind speed





Wind Resource

- At lower levels of the atmosphere, wind is also influenced by frictional forces and obstacles (mountains, etc)
 - Very localized
- Result: wide variation in wind speed and direction
- Wind speed depends on
 - Geographic location
 - Climate
 - Height above ground
 - Terrain



Wind Resource

- Localized scale wind regimes
- Examples
 - Shore lines: sea breezes caused by land/water temperature differentials
 - Mountain valleys or gorges: flow channeling
 - Mountain tops/down slope: mountain wave events (Chinook winds)



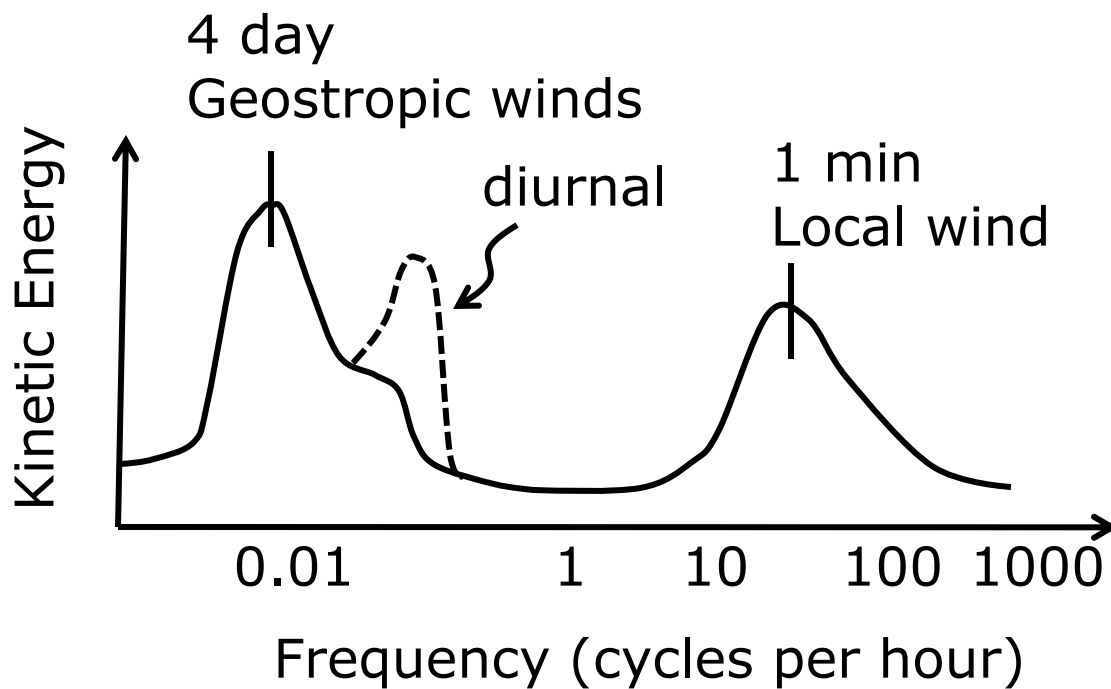
Wind Resource

- Wind speed tends to exhibit patterns:
 - Semi-diurnal
 - Diurnal
 - Seasonal
 - Longer-term



Wind Resource

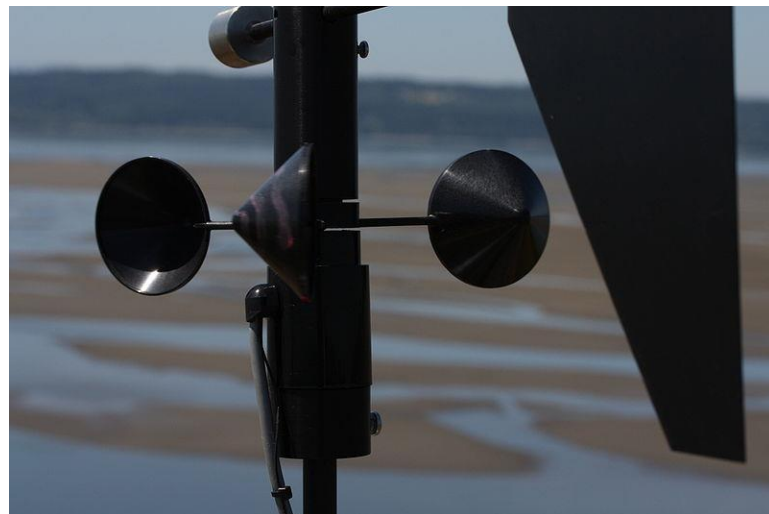
- Van der Hoven spectrum distribution of kinetic energy in the wind in the frequency domain





Wind Measurements

- Meteorological (Met) stations/towers contain weather measurement devices
 - Wind speed (anemometer)
 - Wind direction
 - Pressure
 - Other



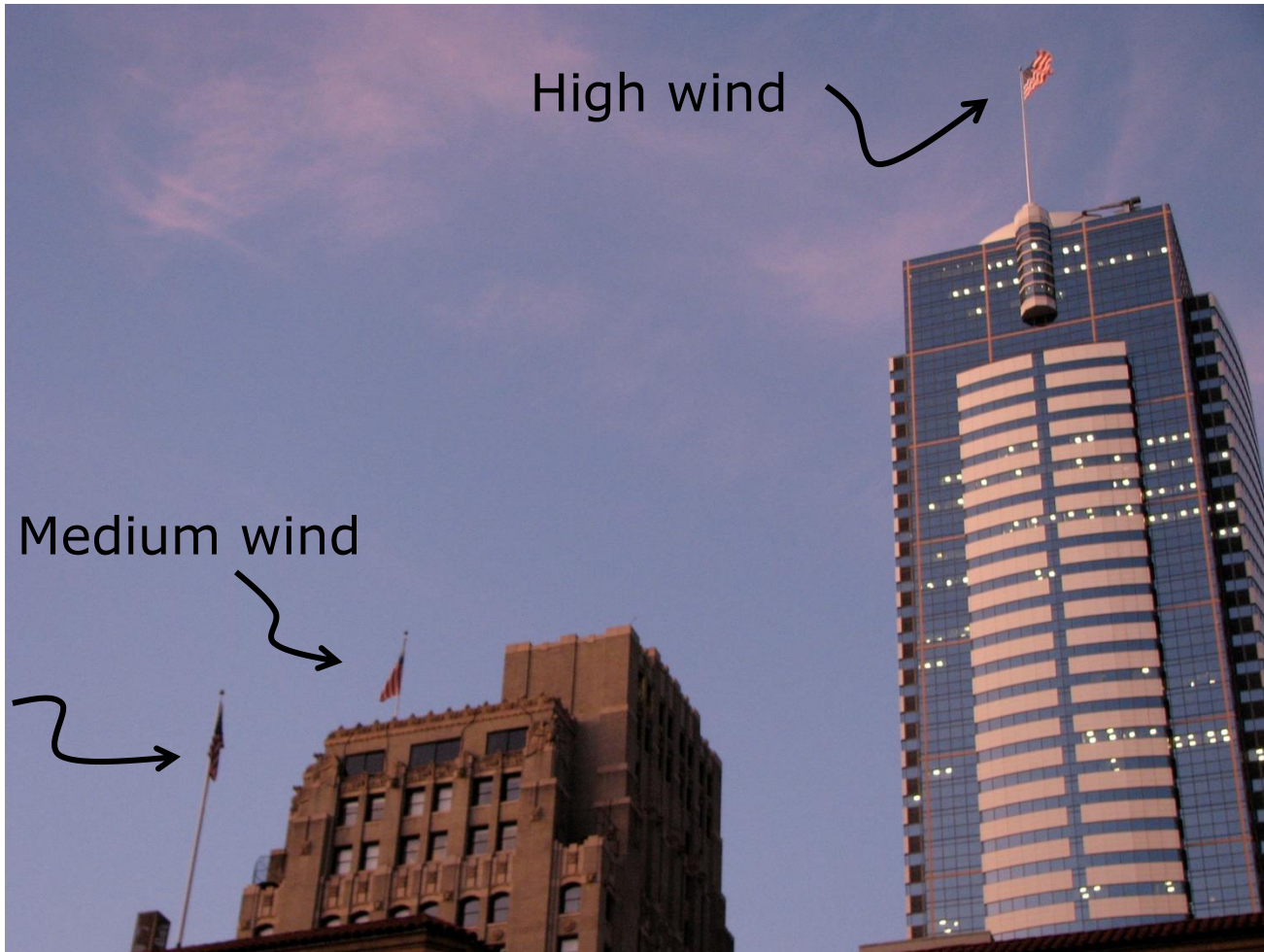


Variation with Height

- Wind speeds at greater distance from ground level tend to be higher
 - Wind shear
 - Less turbulence caused by ground friction
- Important considering wind turbine hub heights are 80 m, but measurements may be taken at much lower heights



Variation with Height



Credit: Danielle Isbell



Variation with Height

$$\frac{V_{hub}}{V_{meas}} = \frac{\ln(z_{hub}/z_0)}{\ln(z_{meas}/z_0)}$$

- Where

V_{hub} : wind speed at hub height (m/s)

V_{meas} : measured wind speed (m/s)

Z_{hub} : height of the wind turbine hub (m)

Z_{meas} : height of measurement (m)

Z_0 : roughness length (m)



Variation with Height

Roughness Length

Very smooth, ice or mud	0.00001 m
Calm open sea	0.0002 m
Blown sea	0.0005 m
Snow surface	0.003 m
Lawn grass	0.008 m
Rough pasture	0.010 m
Fallow field	0.03 m
Crops	0.05 m
Few trees	0.10 m
Many trees, few buildings	0.25 m
Forest and woodlands	0.5 m
Suburbs	1.5 m
City center, tall buildings	3.0 m



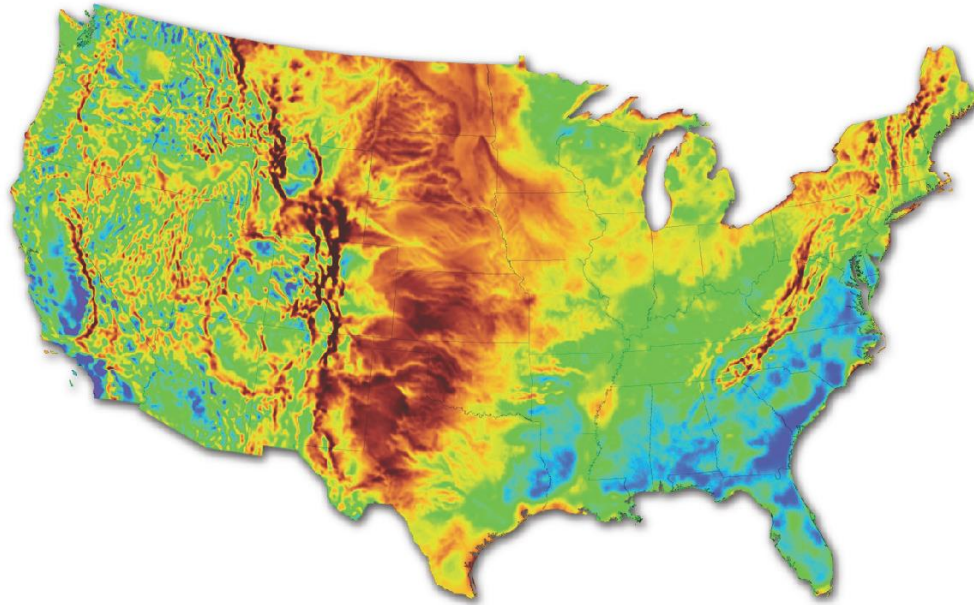
Variation with Height

- Compute the wind speed at a hub height of 90 m if the measurement from a 10 m anemometer is 3 m/s, given the terrain is:
 1. Few trees
 2. City center



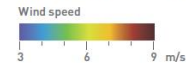
Wind Resource in the US

U.S. Wind Map at 80m



© Copyright 2008 3TIER, Inc.

5km Wind Map at 80m





Wind Resource Classes

Class	Mean Wind Speed (m/s) at 50m	Wind Power Density (W/m²) at 50m
1	<5.6	<200
2	5.6-6.4	200-300
3	6.4-7.0	300-400
4	7.0-7.5	400-500
5	7.5-8.0	500-600
6	8.0-8.8	600-800
7	>8.8	>800

suitable for
large-scale
development

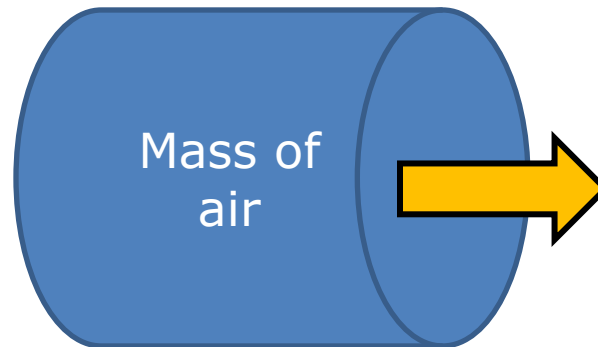
How do these density values compare with irradiance?



Available Power

Kinetic energy in moving air:

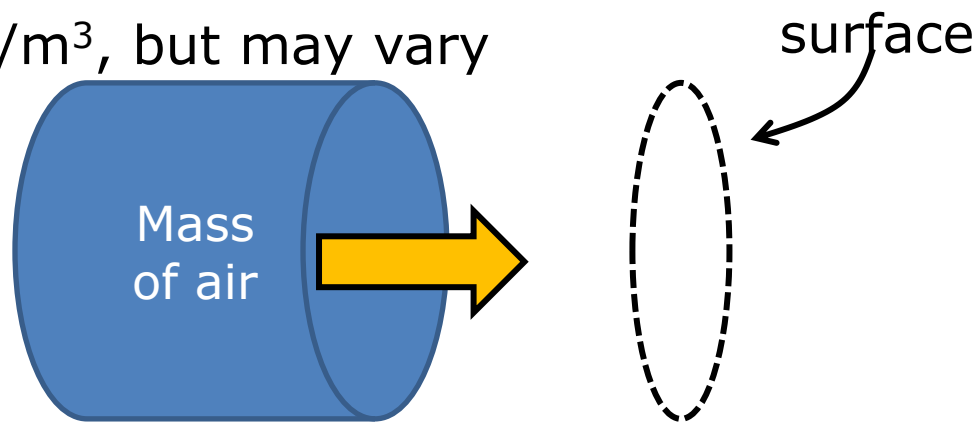
$$E_{\text{air}} = \frac{1}{2} mv^2$$





Available Power

- Let the mass of air ℓ meters in length pass through a surface each second
- Mass of air that has passed through a circular cross section 1 m^2 each second
 - $m = \ell\rho$
- Where:
 - ρ : is the density of air kg/m^3
 - Usually $1.23 \text{ kg}/\text{m}^3$, but may vary





Available Power

- Substituting:
 - $m = \ell\rho$ into
 - $E_{\text{air}} = \frac{1}{2} mv^2 = \frac{1}{2}\ell\rho v^2$
- Computing power
 - $P_{\text{air}} = E_{\text{air}}/s = \frac{1}{2}\ell\rho v^2/s$ Note: s is seconds
 - Substituting $\ell/s = v$ yields:
 - $P_{\text{air}} = \frac{1}{2}\rho v^3$



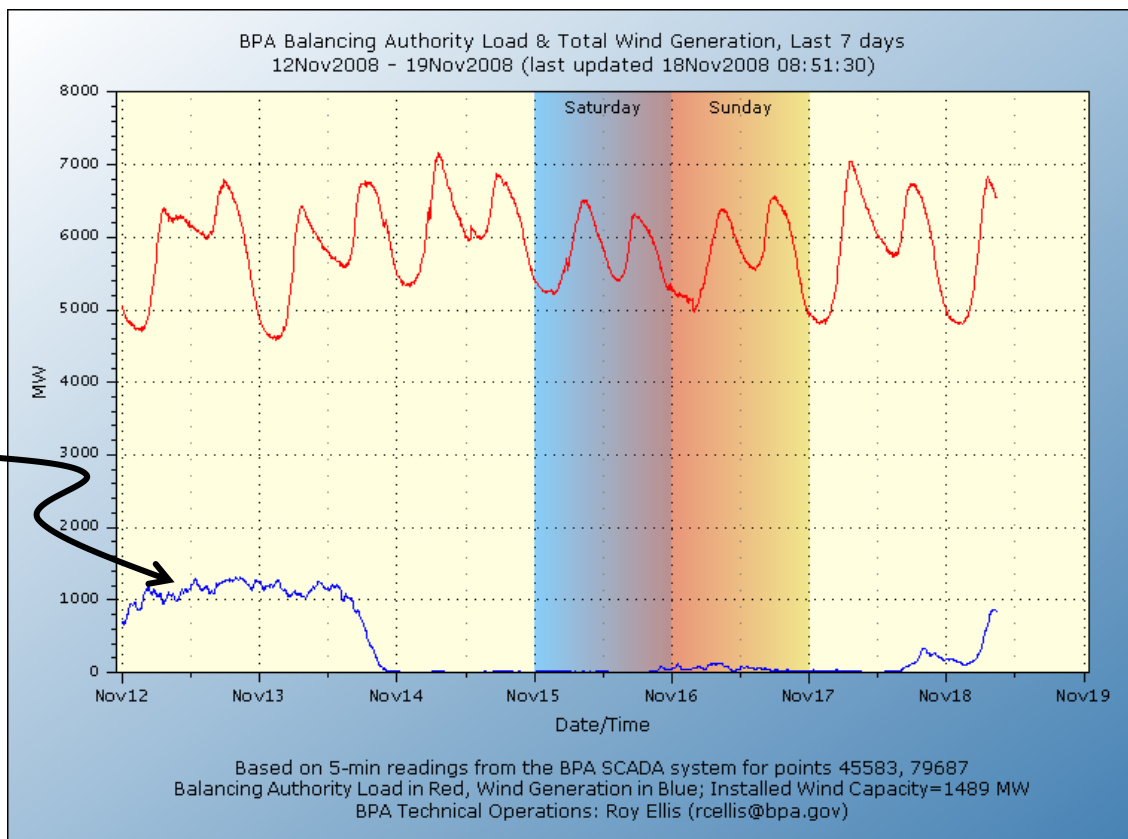
Available Power

- Cubic relationship between wind speed and power
 - $P_{\text{air}} = \frac{1}{2}\rho v^3$
- Very important to place wind turbines in high wind speed locations



Wind Resource

- Wind speeds (and power) tend to exhibit more variability and uncertainty than solar irradiance





Wind Resource

- To determine if a location is suitable for development (i.e. will be profitable) developers rely on probabilistic models of wind speed
- This usually involves installing temporary anemometers for a period of 6 months – 2years
- Models can be formed based upon the data



Probability Density Functions

- Wind speed can be considered a random variable \mathbf{v}
- We can describe the likelihood that \mathbf{v} will be within a particular range through its Probability Density Function (PDF), $f(\mathbf{v})$



Probability Density Functions

- For a random variable x with a Normal (Gaussian) Distribution

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

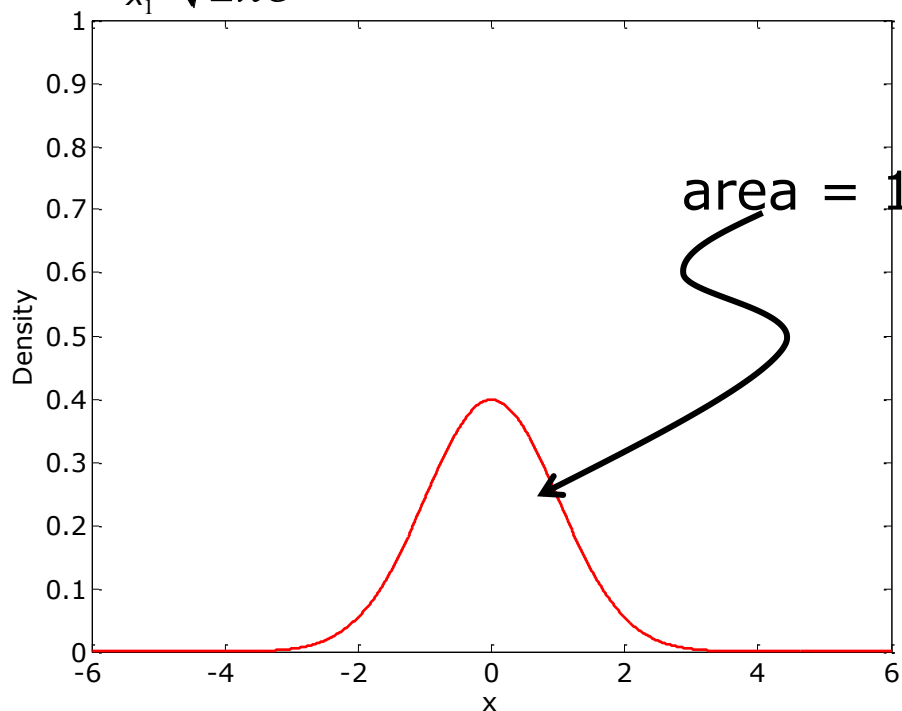
- Where
 - μ : mean
 - σ^2 : variance



Probability Density Functions

- Probability that x will be between x_1 and x_2 is found through integration

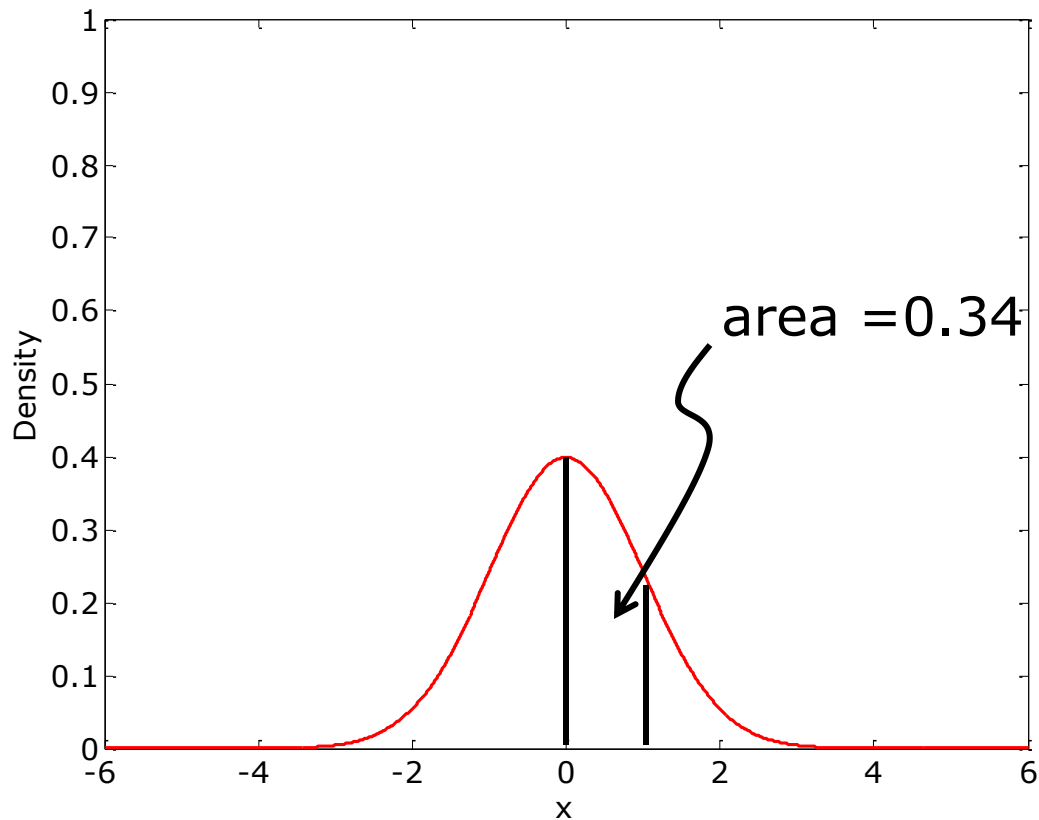
$$p[x_1 \leq x \leq x_2] = \int_{x_1}^{x_2} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx$$





Probability Density Functions

- Probability that x will be between 0 and 1 is found through integration

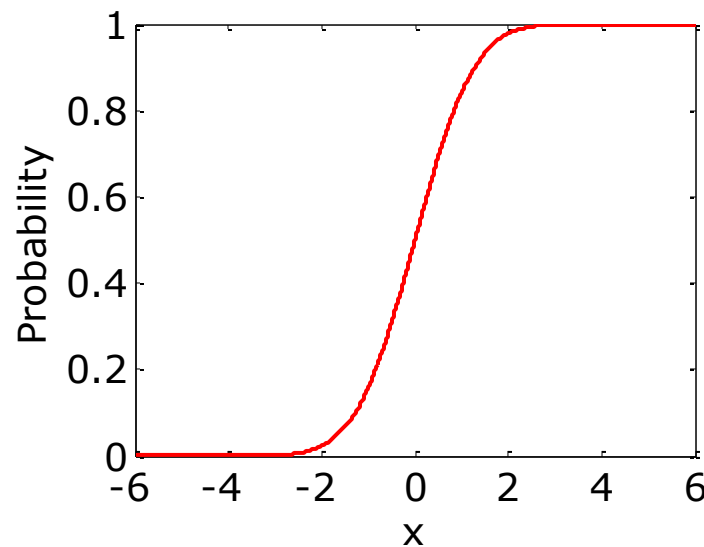
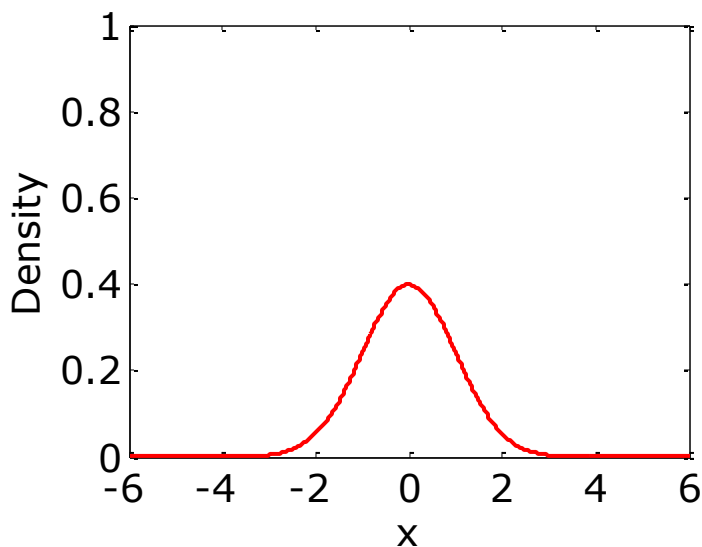




Cumulative Distribution Function

- Cumulative Distribution Function (CDF) provides information on the probability that $x \leq x_1$
- Integral of the PDF

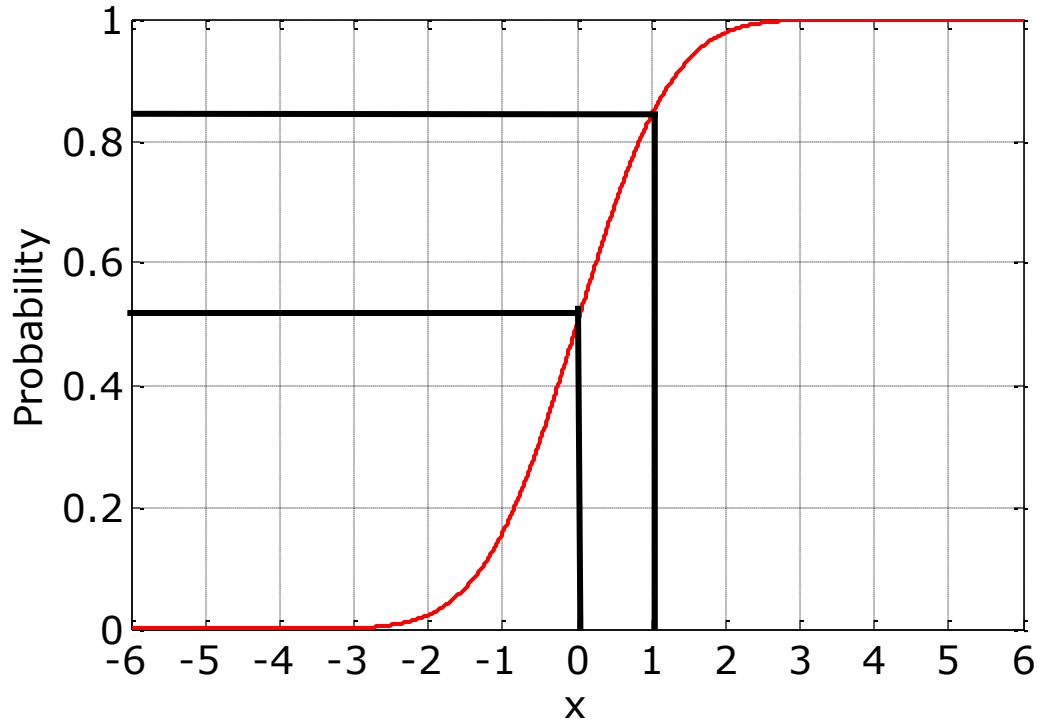
$$F(x_1) = p[x \leq x_1] = \int_{-\infty}^{x_1} f(x) dx$$





Cumulative Distribution Function

- Probability that x will be between 0 and 1 is found by subtracting $F(1) - F(0)$
 - $0.84 - 0.5 = 0.34$





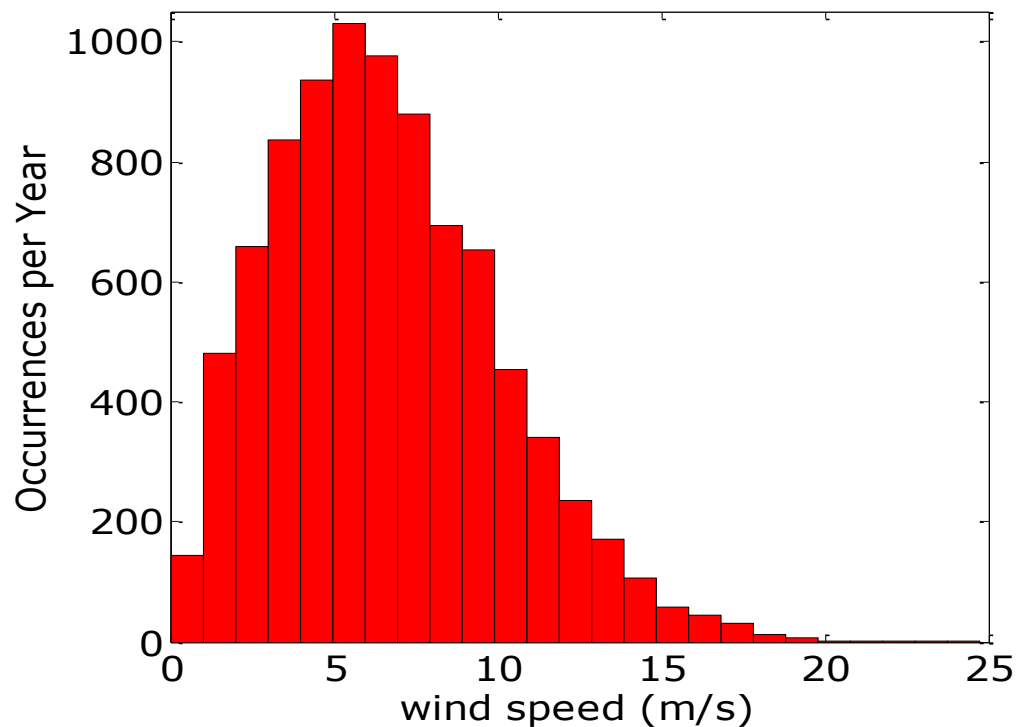
Wind Speed Modeling

- PDF of the wind resource can be modeled by collecting a number of samples from a met tower
- Normalized histogram of those samples will resemble (hopefully) a common PDF



Wind Speed Modeling

- Histogram of wind speed measurements
- Observations
 - Values > 0
 - Peaked
 - Long tail





Wind Speed Modeling

- Based on empirical observations, wind speed tends to follow a Rayleigh (or Weibull) distribution

$$f(v) = \frac{2v}{c^2} e^{-\frac{v^2}{c^2}}$$

- Where:

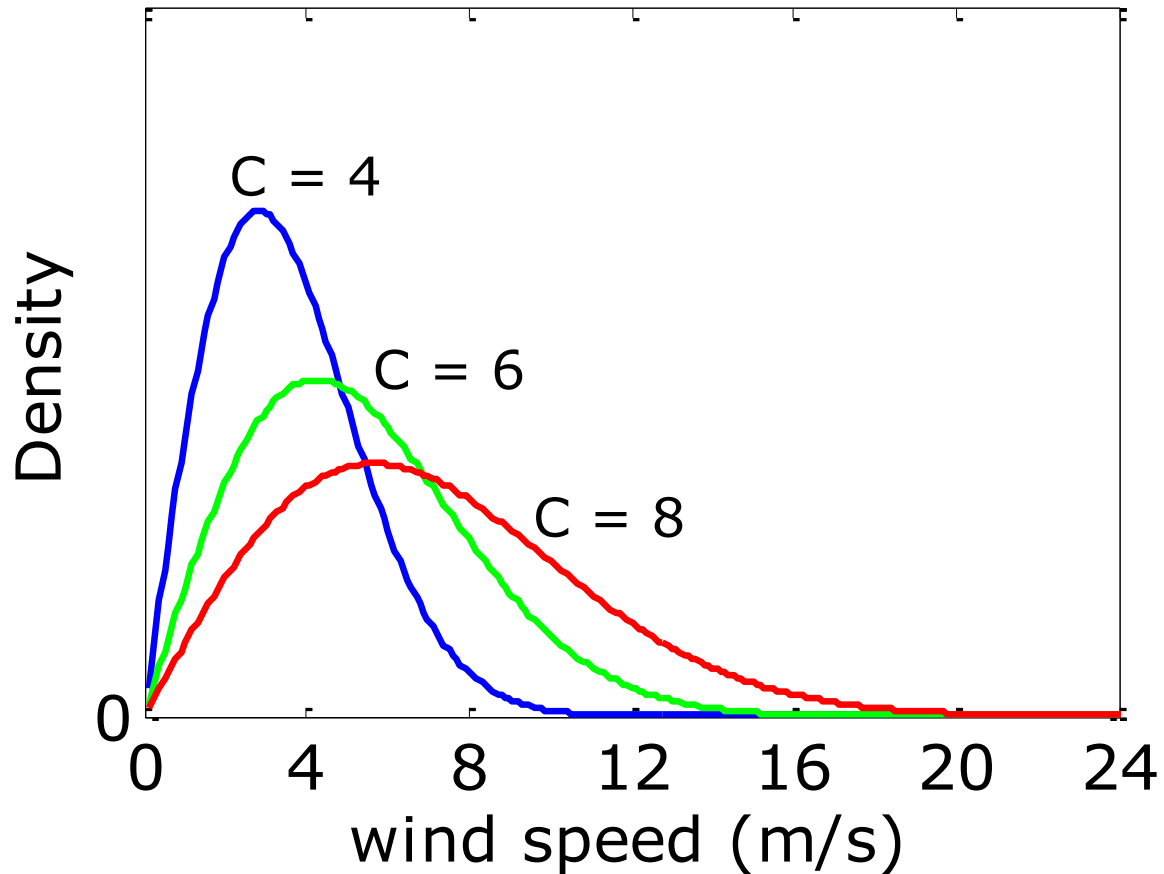
- c : a parameter of the distribution

$$c = \frac{2\bar{v}}{\sqrt{\pi}}$$

- \bar{v} : is the mean wind speed of the sample



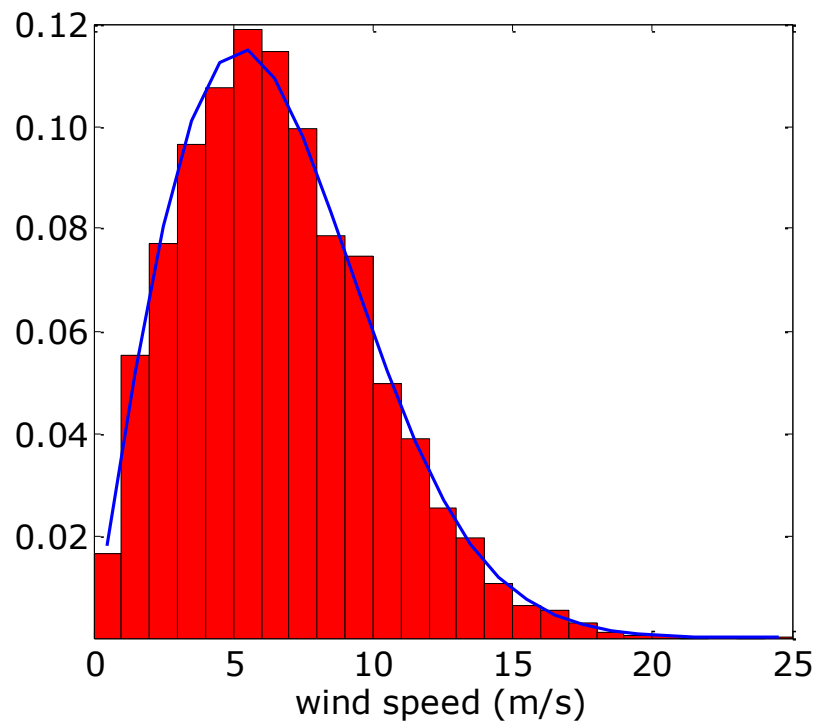
Wind Speed Modeling





Wind Speed Modeling

- Mean wind speed is NOT the most probable
- Most probable wind speed occurs at $0.8\bar{v}$ (if it perfectly follows a Rayleigh Distribution)

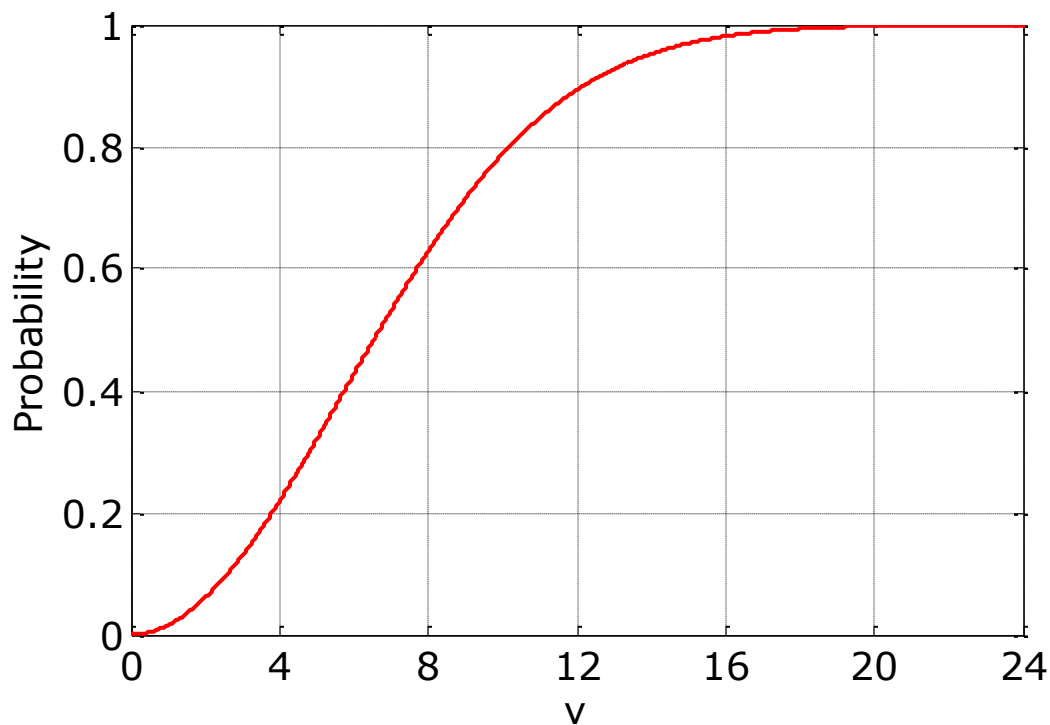




Wind Speed Modeling

- CDF of Rayleigh is:

$$F(v_1) = \int_0^{v_1} \frac{2v}{c^2} e^{-\frac{v^2}{c^2}} dv = 1 - e^{-\frac{v_1^2}{c^2}}$$



mean speed
is 7.1 m/s



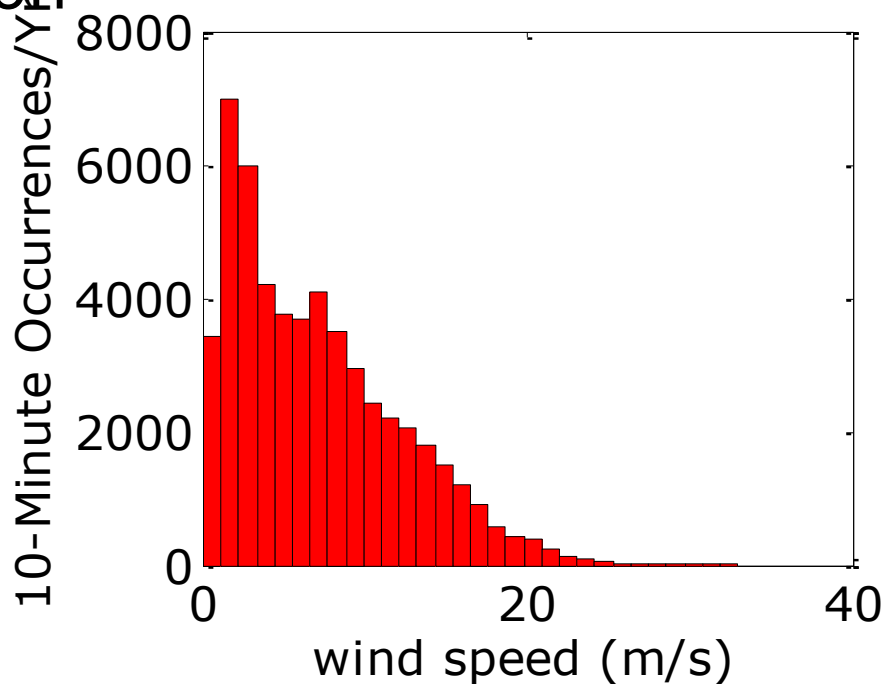
Wind Speed Modeling

- We can judge how well the fitted Rayleigh distribution approximates the measurements in several ways
 - χ^2 goodness-of-fit test (parametric)
 - probability plots (non-parametric)
 - Other
- We can refine the model by month, hour, wind direction



Wind Speed Modeling

- Data from a 80 m met tower is shown
- Mean wind speed is computed to be: 7.1 m/s
- Write the equation of the best-fit Rayleigh Distribution





Wind Speed Modeling

Compute the probability that the wind speed will be less than 3 m/s



Wind Speed Modeling

- Compute the probability that the wind speed will be less than 3 m/s

$$F(3) = 1 - e^{\frac{-3^2}{8.03^2}} = 0.13$$

$$F(0) = 1 - e^{\frac{-0^2}{8.03^2}} = 0$$

- 13% of the time the wind will be <3 m/s

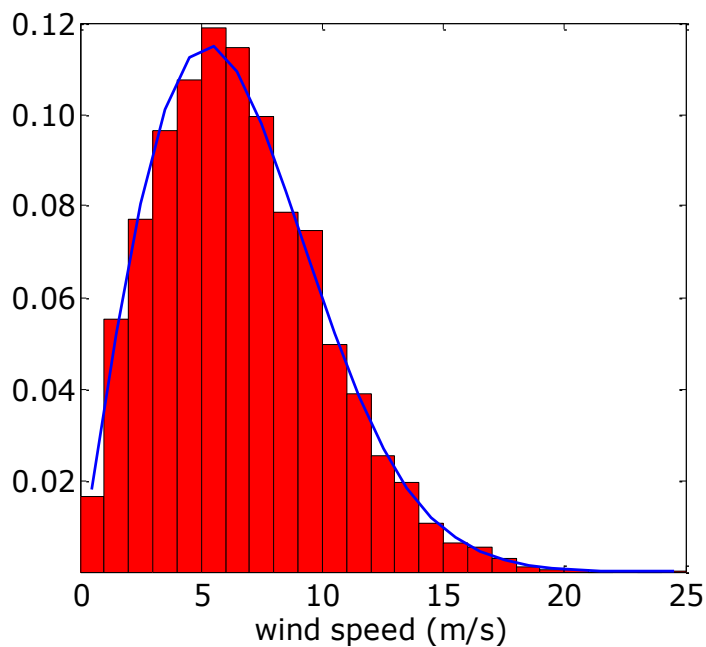


Wind Power Modeling

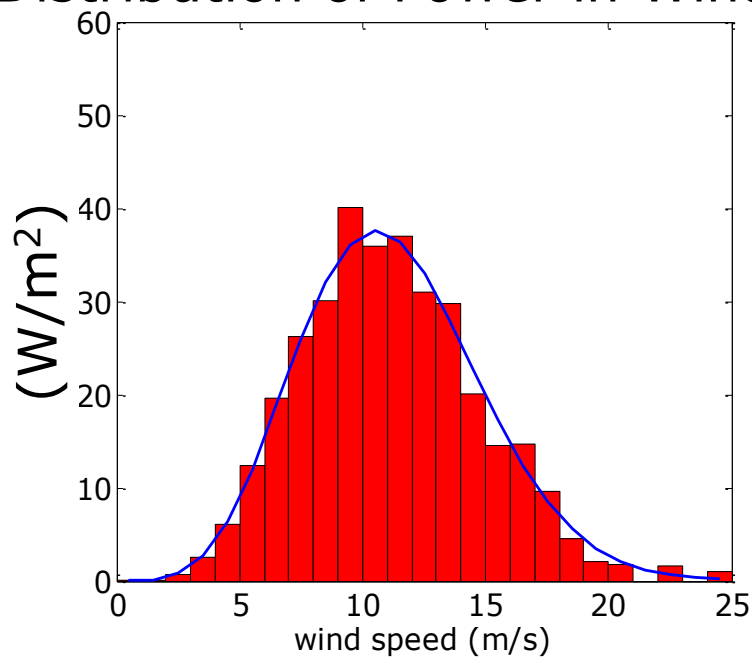
- Now that we have our wind resource modeled, we need to determine how much energy a wind turbine will produce
- Capacity Factor is an appropriate metric
- CF by:
 - Hour
 - Month
 - Direction



Wind Power Modeling



Distribution of Power in Wind



Cubic relationship between
wind speed and wind power