12-Wind Resource

ECEGR 4530

Renewable Energy Systems

Overview

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

Introduction

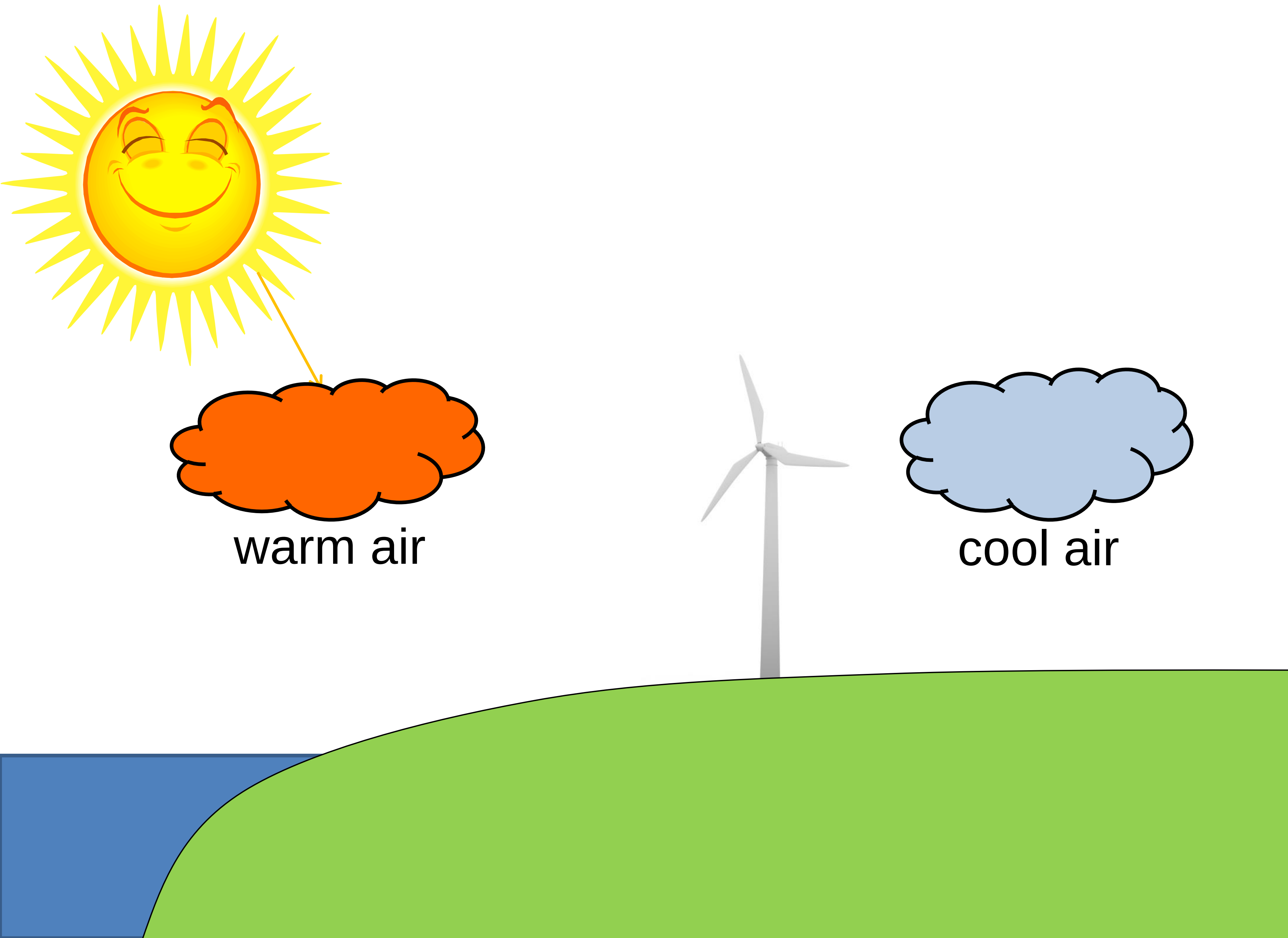
- Energy from wind has been harnessed for thousands of years:
  - Sailing
  - Milling
  - Pumping water
- Wind turbines operate by converting kinetic energy in the air to electrical energy

Introduction

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

Wind Resource

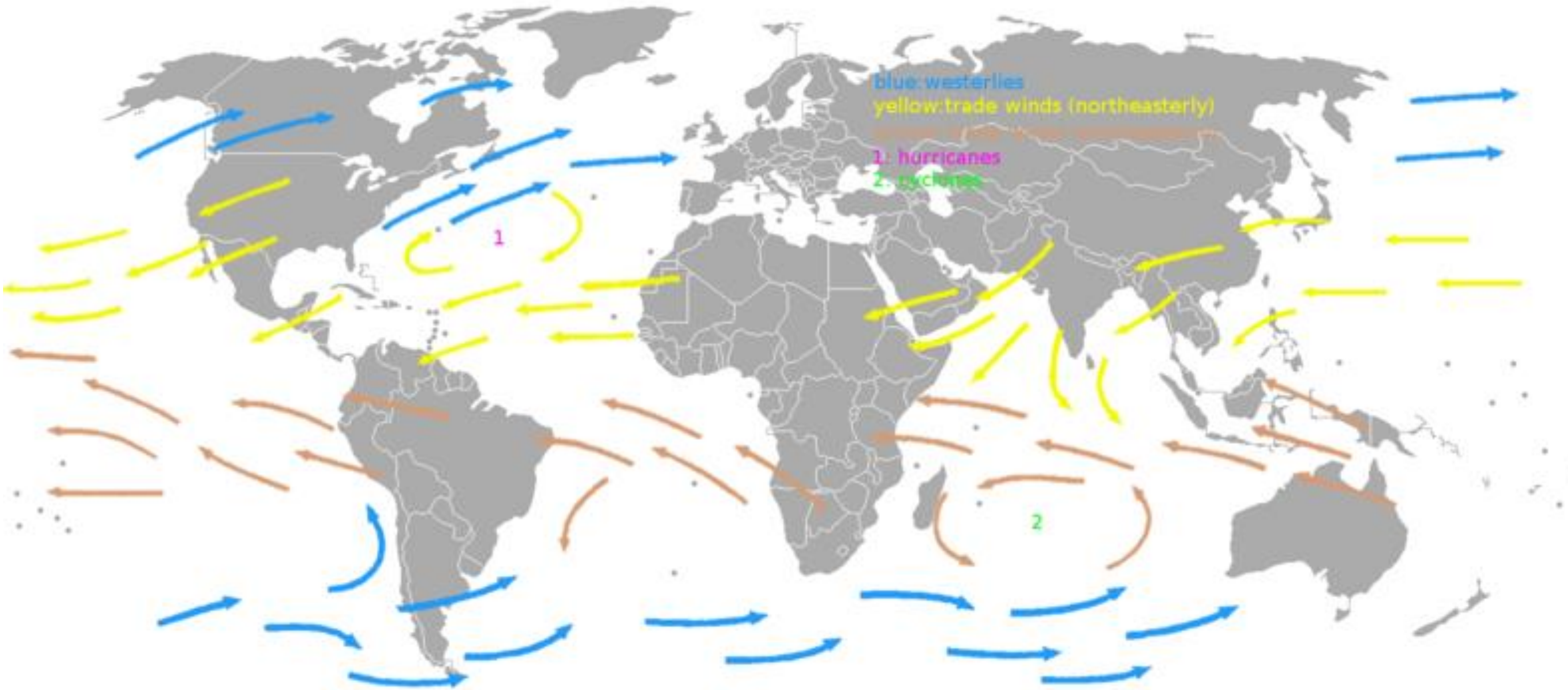
- Movement of air on appreciable scales is caused by temperature differentials
  - Higher temperature air is less dense than cold air
- Temperature differentials (gradients) are predominately caused by uneven solar heating
  - Wind is another form of solar energy


warm air
cool air

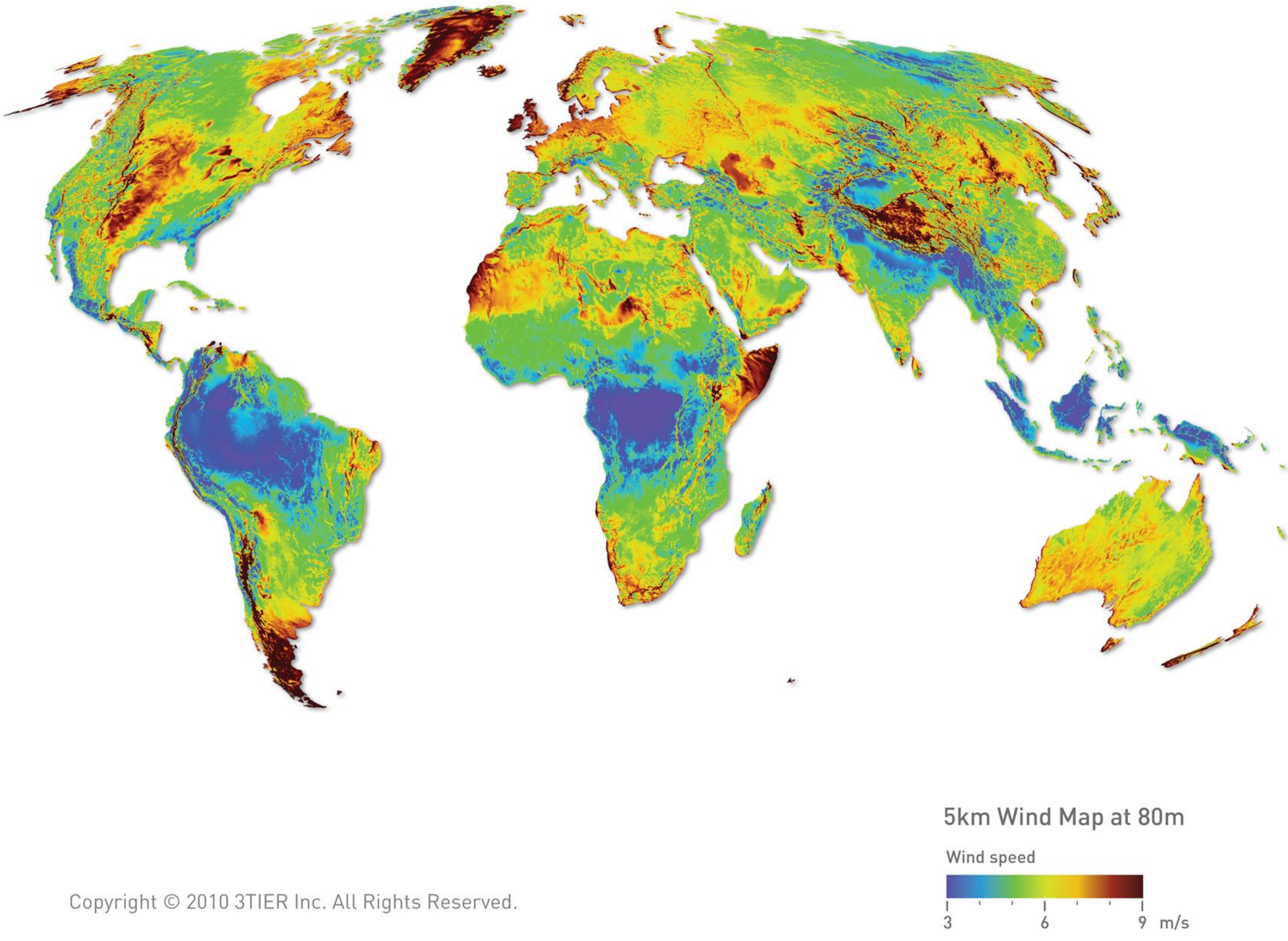
Wind Resource (Northern Hemisphere)

- 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^{o} N the air cools and sinks
- This cooler air returns to equatorial region
  - Direction is south west (trade winds)

Wind Resource



5km Global Wind



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

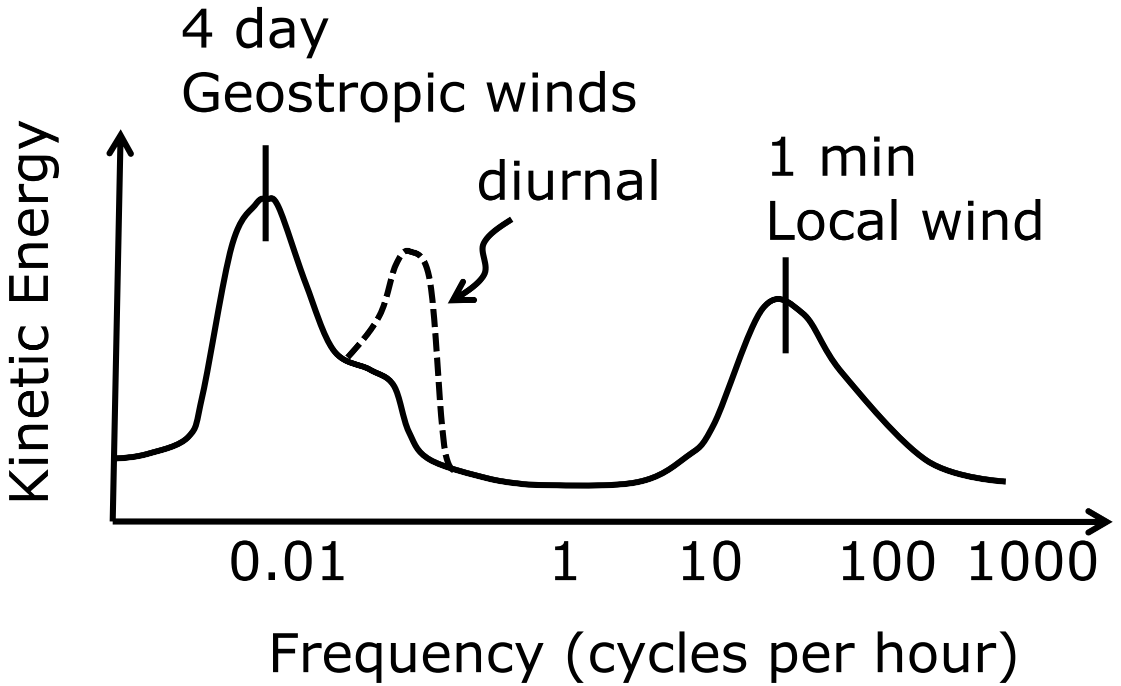
- Localized scale wind regimes
- Examples
  - Shore lines: sea breezes caused by land/water temperature differentials
  - Mountain valleys or gorges: flow channeling
  - Mountain tops/down slope: mountain wave events (Chinook winds)

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

$$\frac{v_{hub}}{v_{meas}} = \frac{\ln\left({}^{z_{hub}}\!/_{z_0} \right)}{\ln\left({}^{z_{meas}}\!/_{z_0} \right)}$$

- 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

Variation with Height

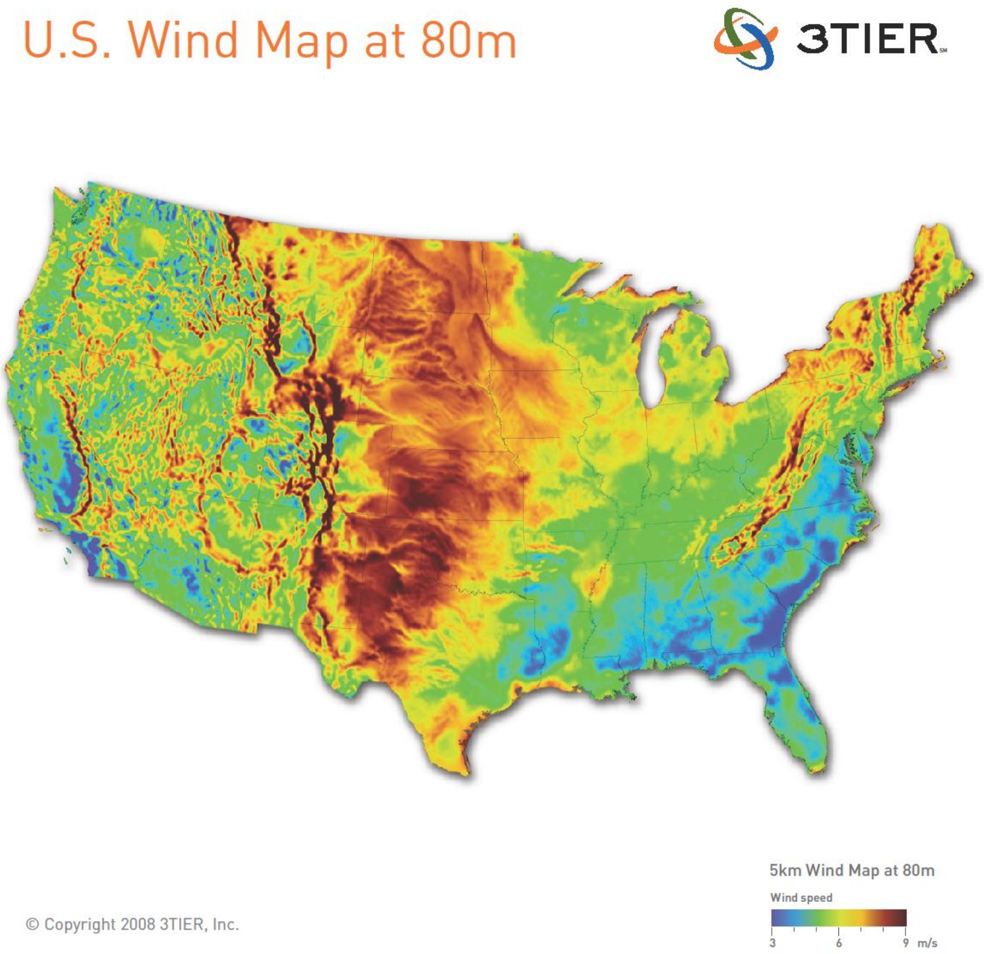
- Few trees:

$$\frac{v_{hub}}{v_{meas}} = \frac{\ln\left(\frac{z_{hub}}{z_0}\right)}{\ln\left(\frac{z_{meas}}{z_0}\right)} \Rightarrow v_{hub} = 3 \times \frac{\ln\left(\frac{90}{0.1}\right)}{\ln\left(\frac{10}{0.1}\right)} = 4.43\text{m/s}$$

- City Center:

$$\frac{v_{hub}}{v_{meas}} = \frac{\ln\left(\frac{z_{hub}}{z_0}\right)}{\ln\left(\frac{z_{meas}}{z_0}\right)} \Rightarrow v_{hub} = 3 \times \frac{\ln\left(\frac{90}{3}\right)}{\ln\left(\frac{10}{3}\right)} = 8.48\text{m/s}$$

Wind Resource in the US



Wind Resource Classes

Class	**Mean Wind Speed (m/s)** at 50m	**Wind Power Density (W/m^2)** 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

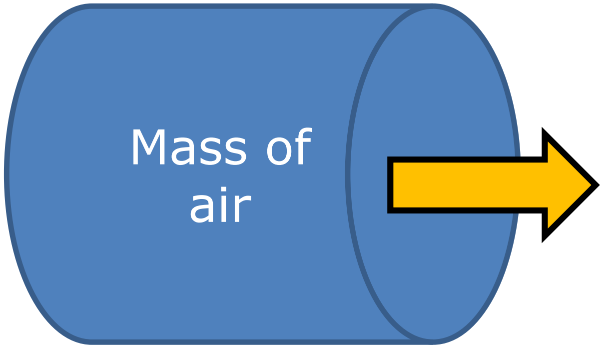
suitable for large-scale development (classes 4–7)

How do these density values compare with irradiance?

Available Power

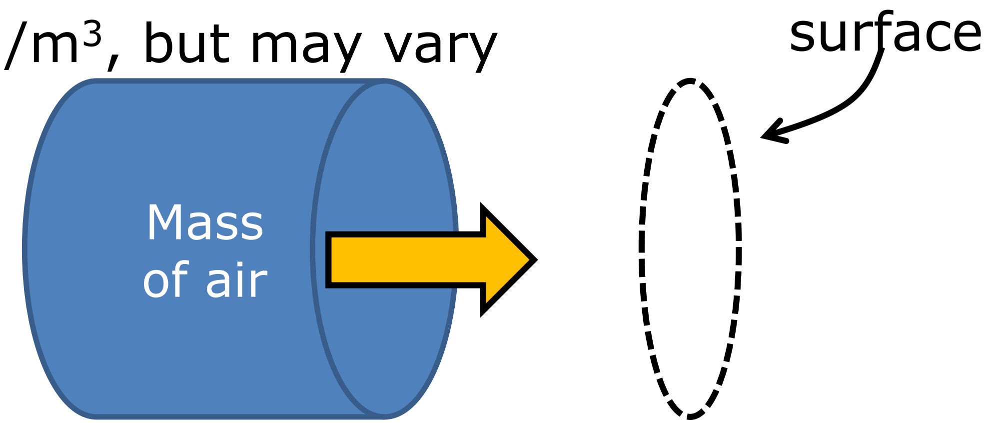
Kinetic energy in moving air:

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



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
  - $m = 1\ell\rho$
- Where:
  - ρ: is the density of air kg/m^3
    - Usually 1.23 kg/m^3, but may vary



Available Power

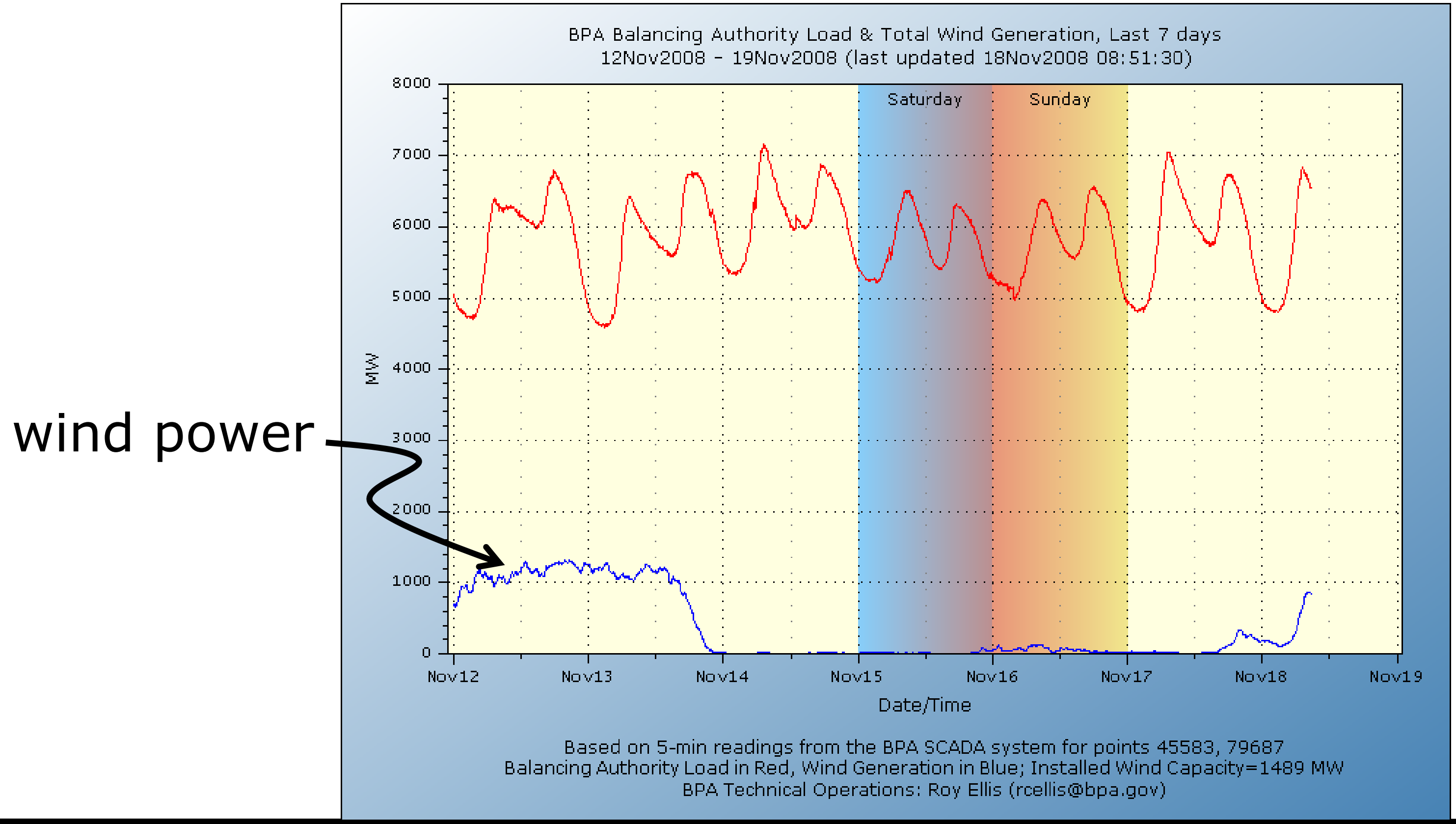
- Substituting:
  - $m = \ell\rho$ into
  - $E_{air} = ½\ mv^2 = ½\ell\rho v^2$
- Computing power
  - $P_{air} = E_{air}/s = ½\ell\rho v^2/s$ Note: s is seconds
  - Substituting $\ell/s = v$ yields:
    - $P_{air} = ½\rho v^3$

Available Power

- Cubic relationship between wind speed and power
  - $P_{air} = \frac{1}{2}\rho v^3$
- 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 **v**
- We can describe the likelihood that **v** will be within a particular range through its Probability Density Function (PDF), f(**v**)

Probability Density Functions

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

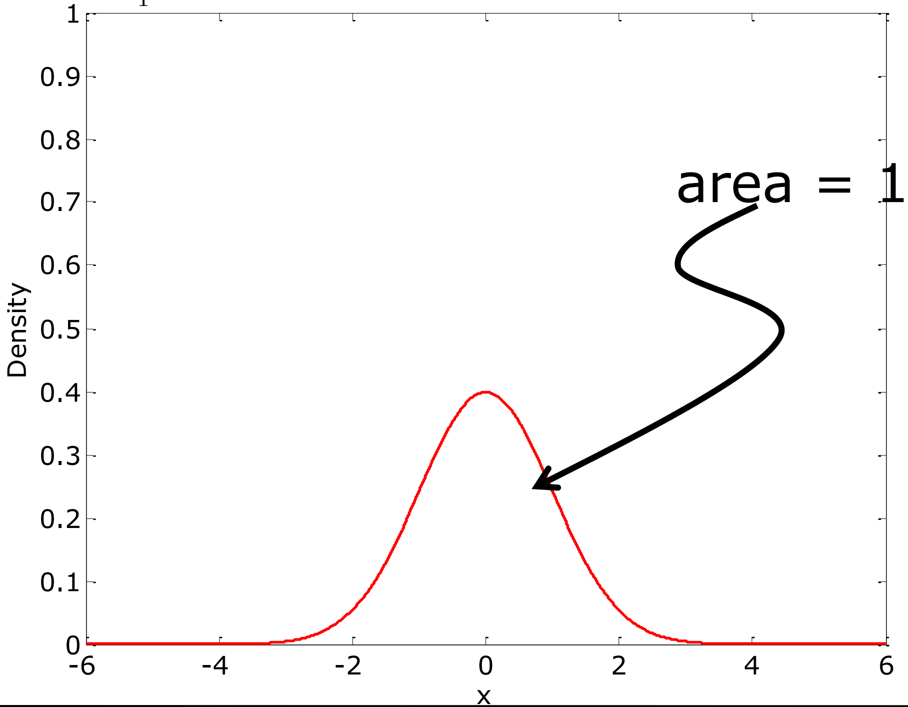
$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

- Where
  - μ: mean
  - σ^2: variance

Probability Density Functions

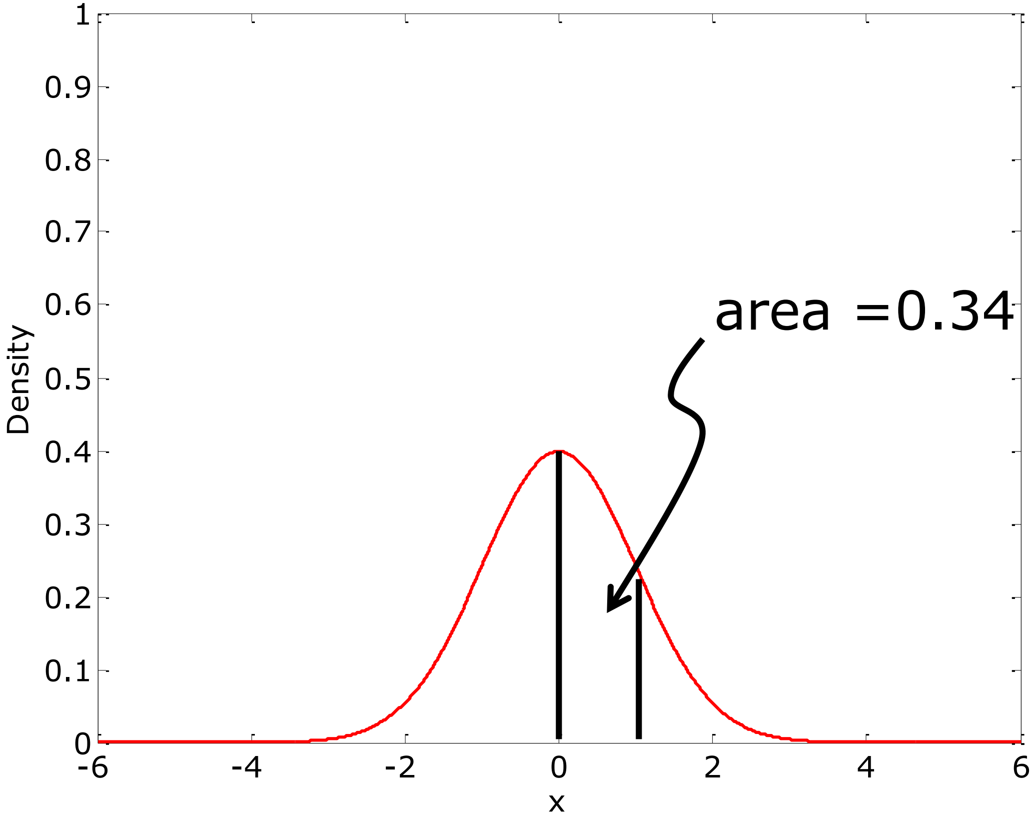
- Probability that x will be between x_1 and x_2 is found through integration

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



Probability Density Functions

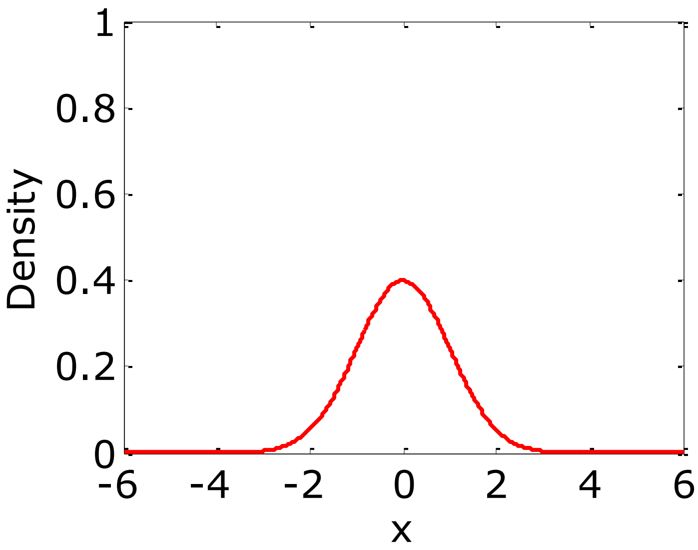
- Probability that x will be between 0 and 1 is found through integration

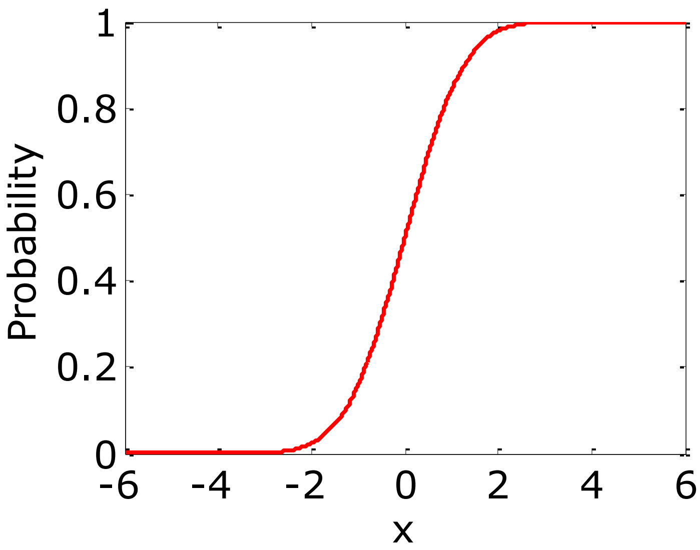


Cumulative Distribution Function

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

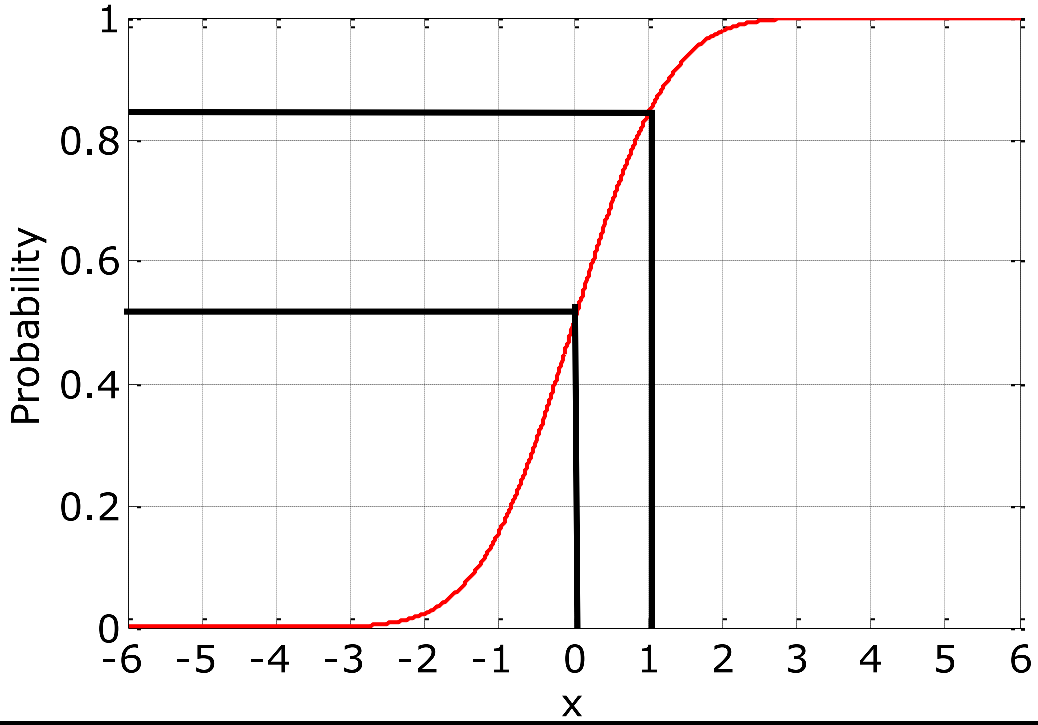
$$F(x_1) = p[x \le x_1] = \int_{-\infty}^{x_1} f(x)dx$$





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

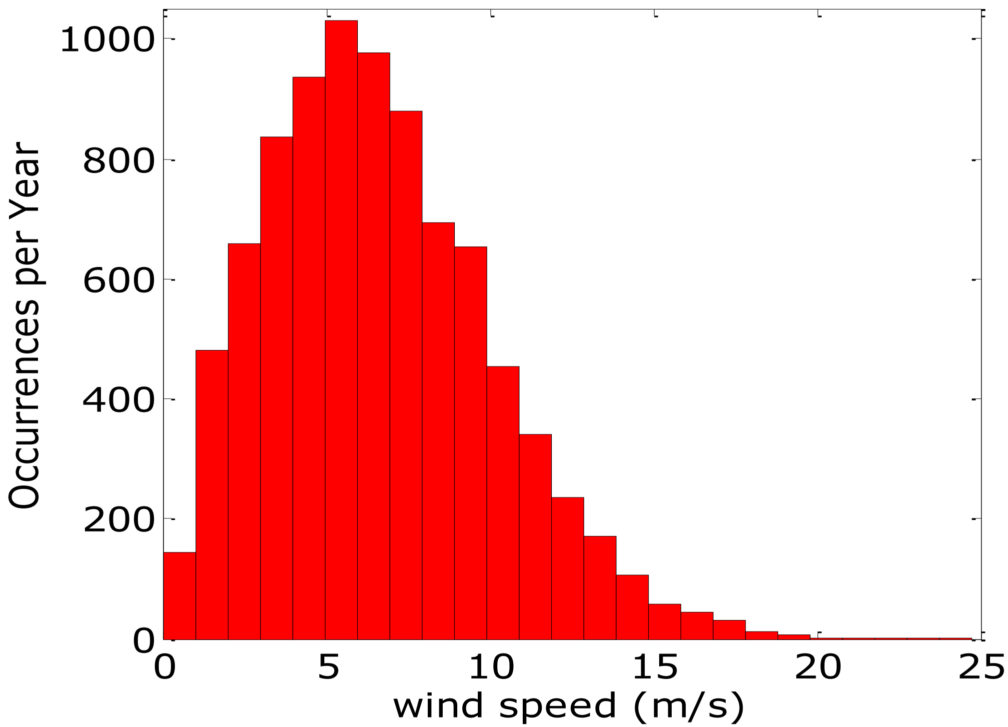


Wind Speed Modeling

- 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

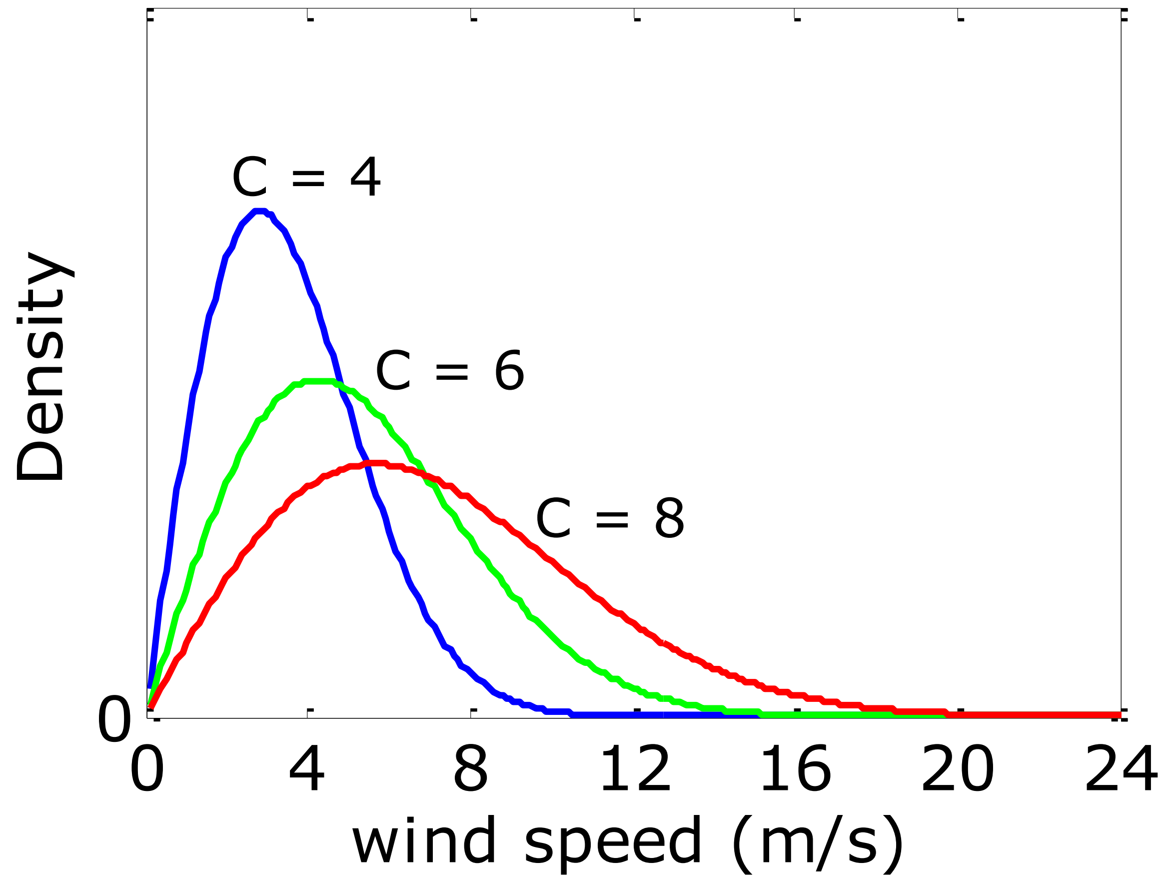
$$f(v) = \frac{2v}{c^2} e^{\frac{-v^2}{c^2}}$$

- Where:
  - c: a parameter of the distribution

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

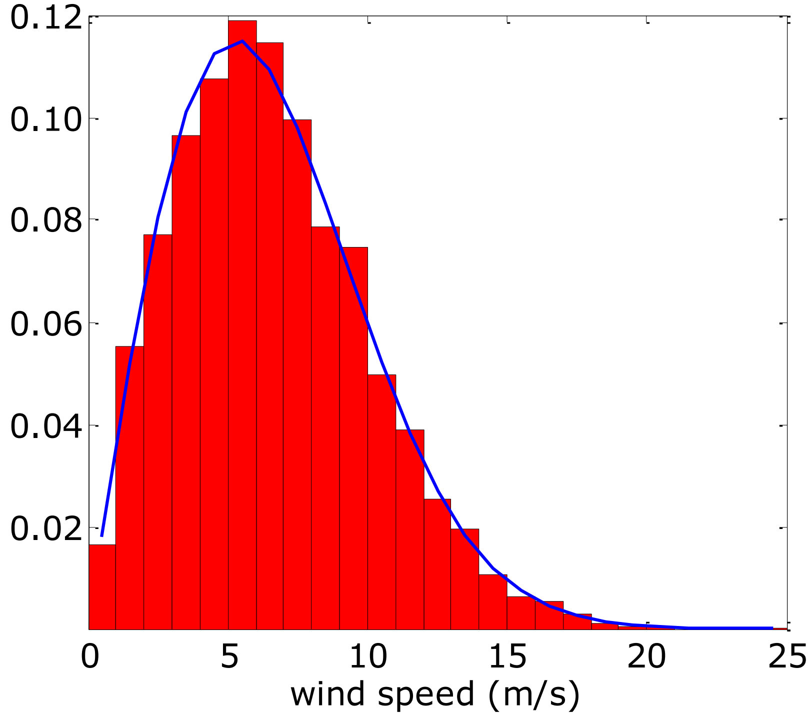
  - $\overline{v}$: is the mean wind speed of the sample

Wind Speed Modeling



Wind Speed Modeling

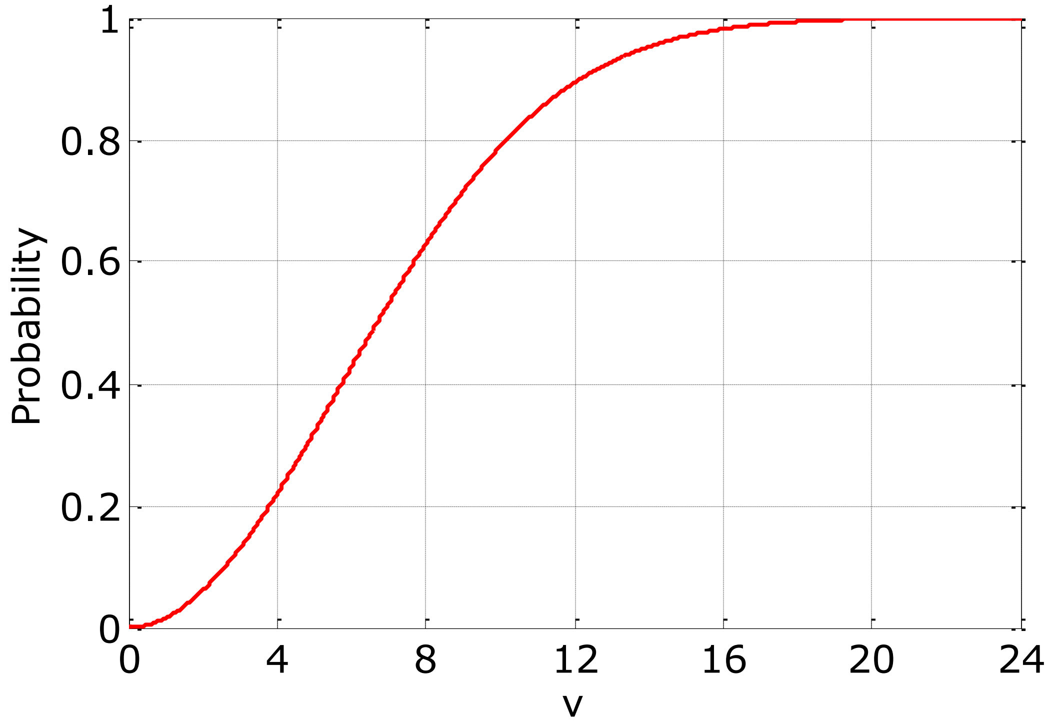
- Mean wind speed is NOT the most probable
- Most probable wind speed occurs at $0.8\bar{v}$ (if it perfectly follows a Rayleigh Distribution)



Wind Speed Modeling

- CDF of Rayleigh is:

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



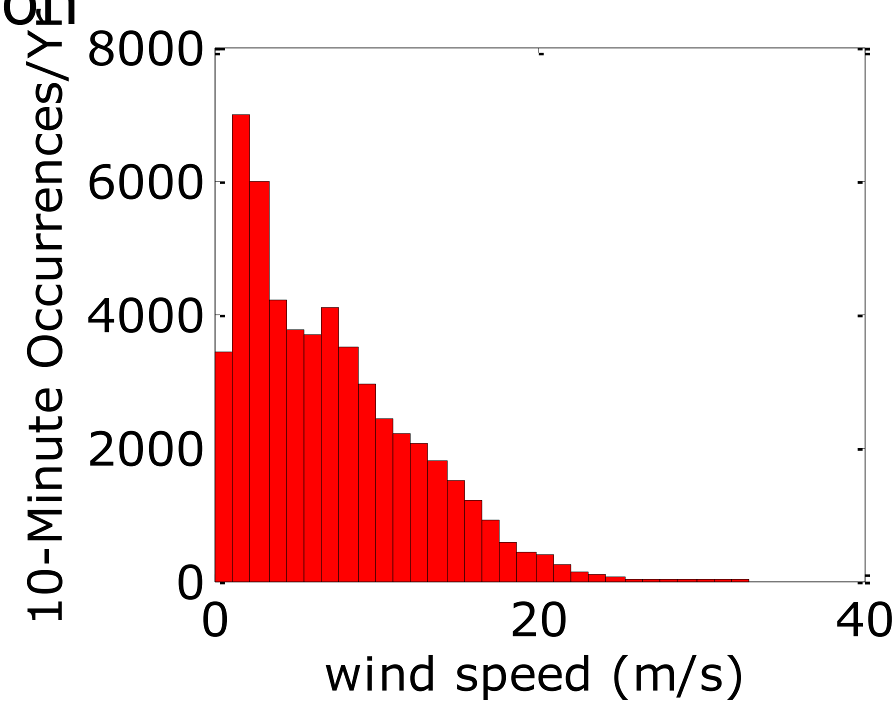
mean speed is 7.1 m/s

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

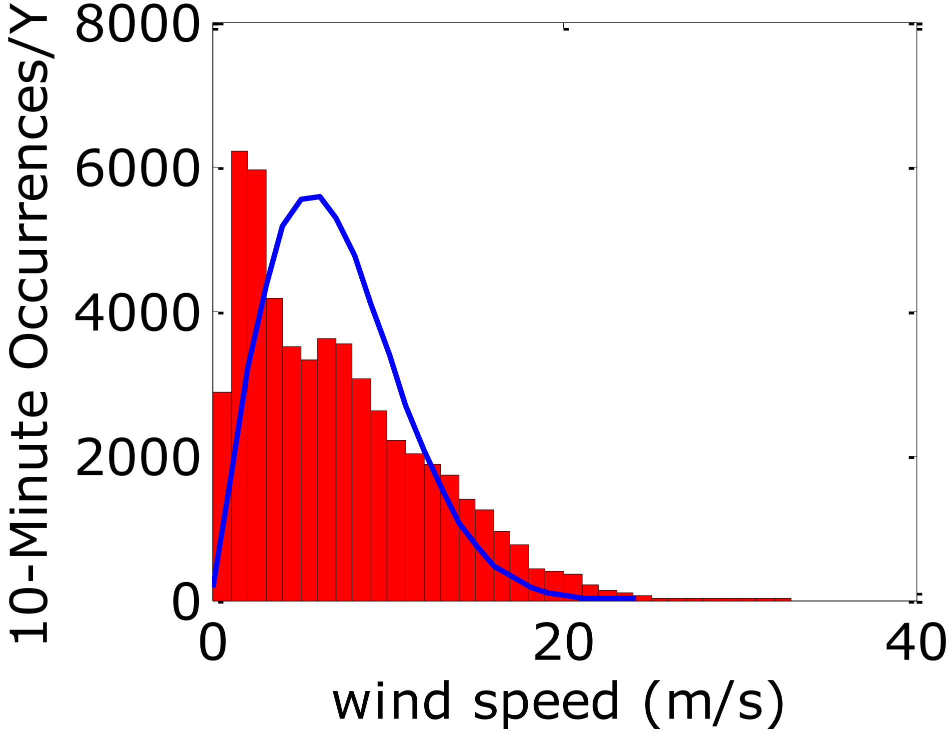
- Data from a 80 m met tower is shown
- Mean wind speed is computed to be: 7.1 m/s
- Write the equation of the best-fit Rayleigh Distribution



Wind Speed Modeling

$$c = \frac{2\bar{v}}{\sqrt{\pi}} = 8.03$$

$$f(v) = \frac{2v}{8.03^2} e^{\frac{-v^2}{8.03^2}}$$



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

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

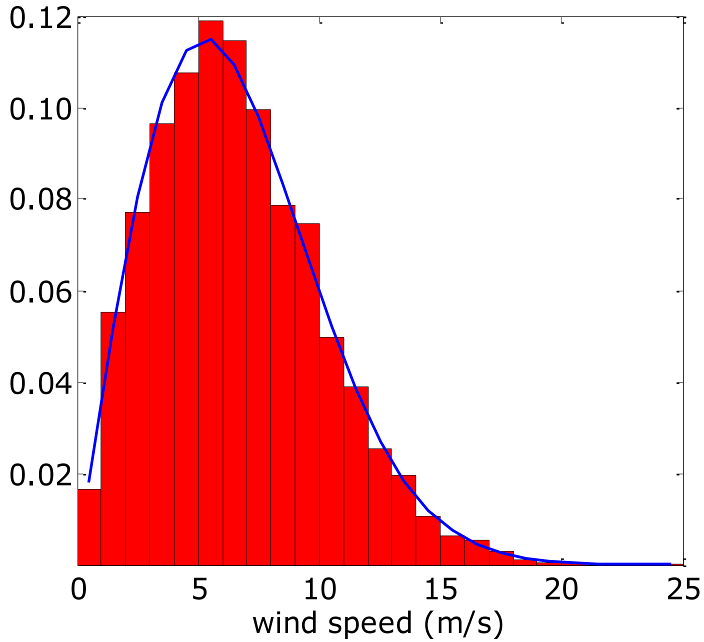
$$F(0) = 1 - e^{\frac{-0^2}{8.03^2}} = 0$$

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

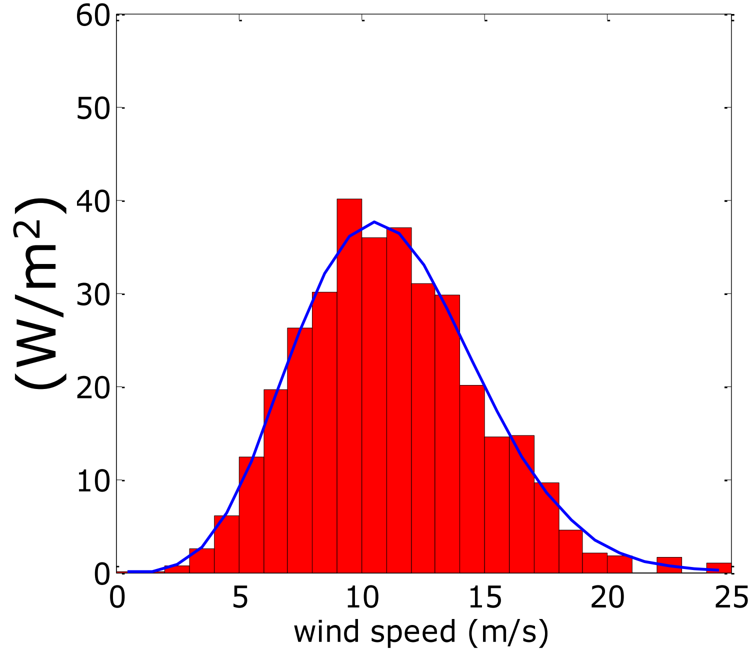
Wind Power Modeling

- 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