Fundamentals of Wind Energy

Alaska Wind Energy Applications Training Symposium
Bethel, Alaska

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TOPICS

Introduction

Energy and Power

Wind Characteristics

Wind Power Potential

Basic Wind Turbine Theory

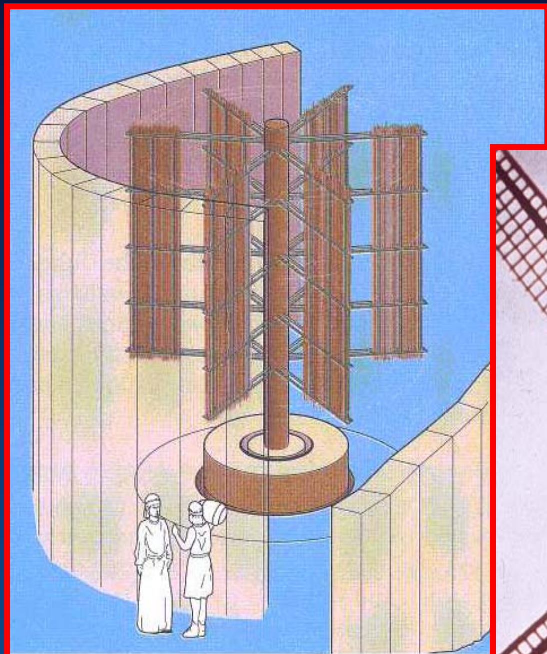
Types of Wind Turbines

Basic Wind Turbine Calculations

Further Information

What is Wind Power

1400-1800 years go,
in the Middle East



800-900 years ago,
in Europe

140 years ago,
water-pumping
wind mills

70 years ago,
electric power

The ability to harness the power available in the wind and put it to useful work.

ENERGY AND POWER

ENERGY: The Ability to do work

ENERGY = FORCE * DISTANCE

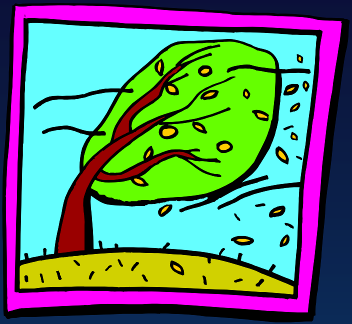
Electrical energy is reported in kWh and may be used to describe a potential, such as in stored energy

POWER: Force without time

POWER = ENERGY / TIME

Generator Size or an instantaneous load which is measured in kW

Power in the Wind



$$P = 0.5\, \rho\, v^3$$

P: power, Watt

ρ: density of air, kg/m^3

V: wind speed, m/s

We call this the **Wind Power Density** (W/m^2)

If we include the area through which the wind flows (m^2), we get the collectable power in Watts.

Power from the Wind

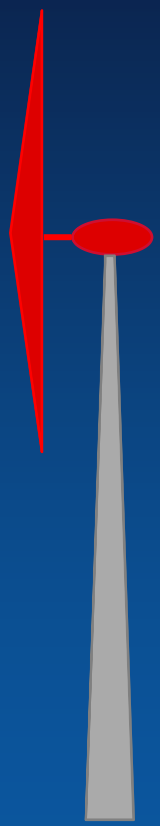
$$P = 0.5\, \rho\, Cp\, v^3\, A_S$$

Cp = Coefficient of Performance
(an efficiency term)

A_S = The swept area of the wind turbine blades

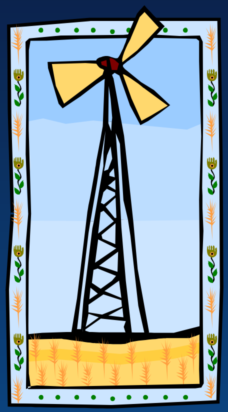
Multiplied by time give you

Energy…

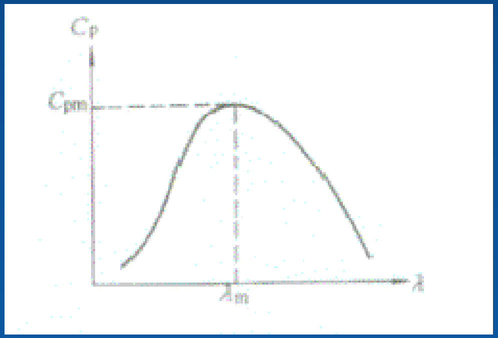


Critical Aspects of Wind Energy

$$P = 0.5\ \rho\ Cp\ v^3\ A_s$$

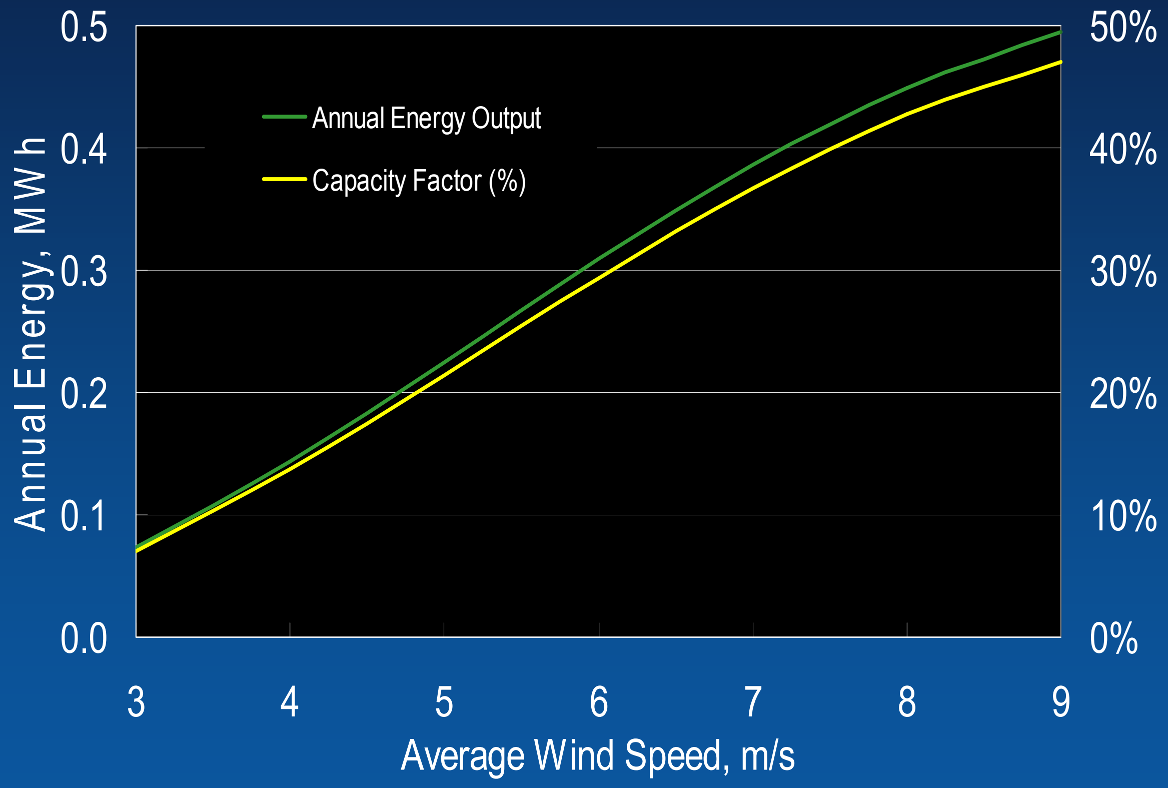


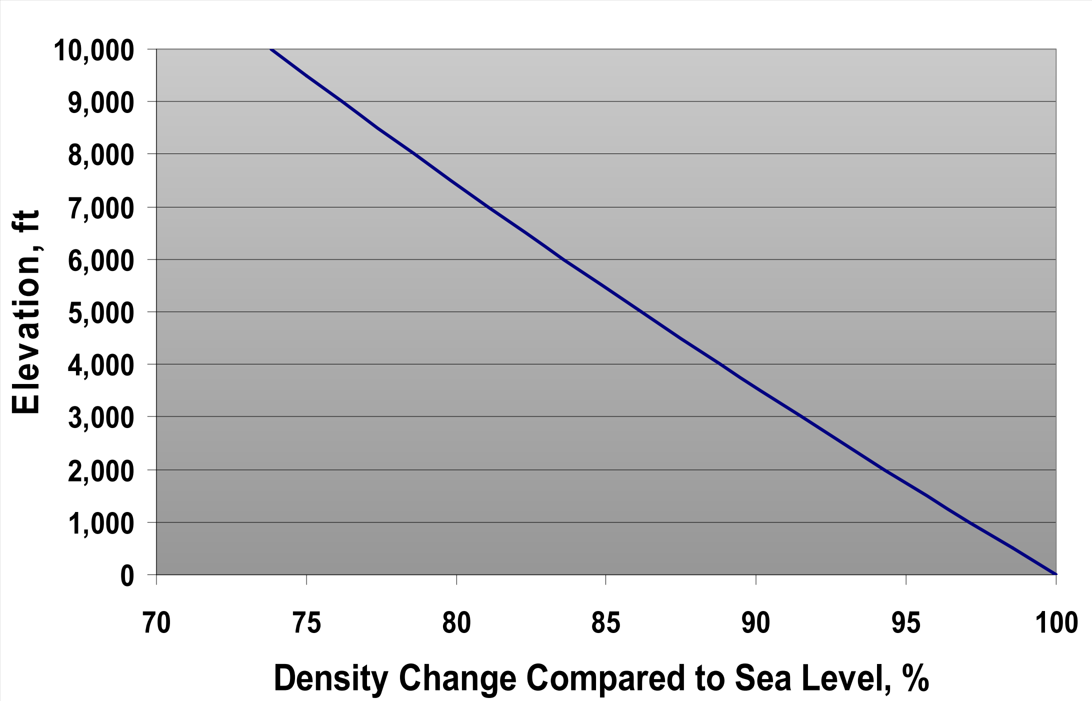
- V^3: Doubling of the wind speed results in an 8 fold increase in power
- ρ: High density air results in more power (altitude and temperature)
- A_s: A slight increase in blade length, increases the area greatly
- Cp: Different types of wind turbines have different maximum theoretical efficiencies (Betz limit $\approx$0.593) but usually between .4 and .5



Impact on Increasing Wind Speed

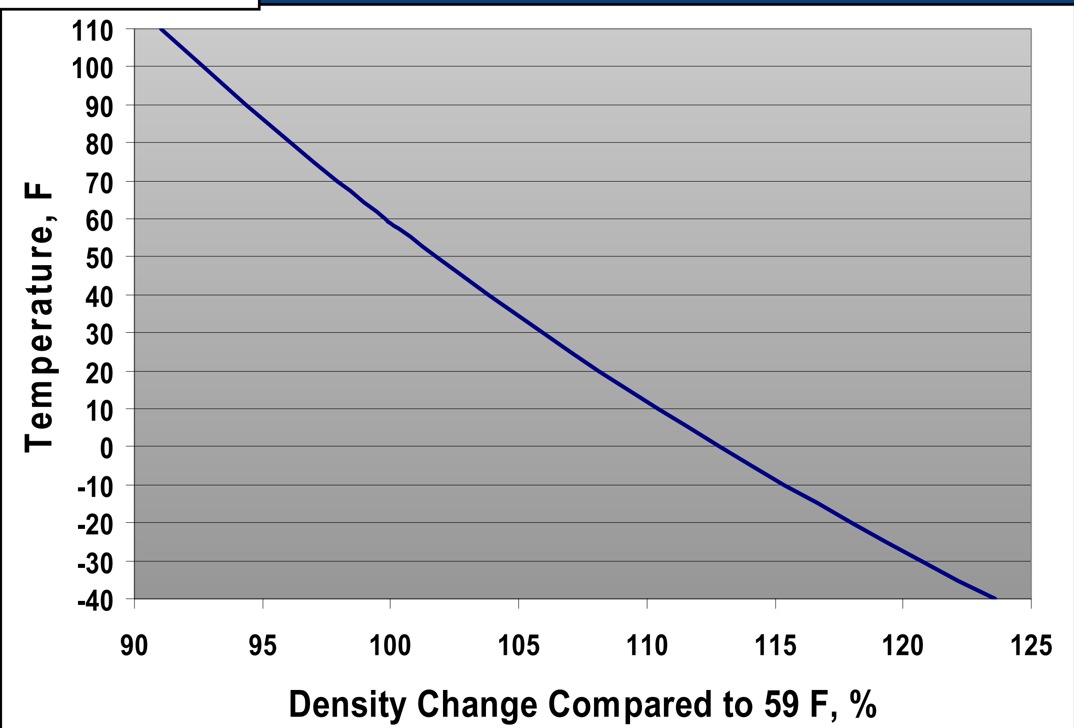
A small increase in wind speed can increase the power greatly

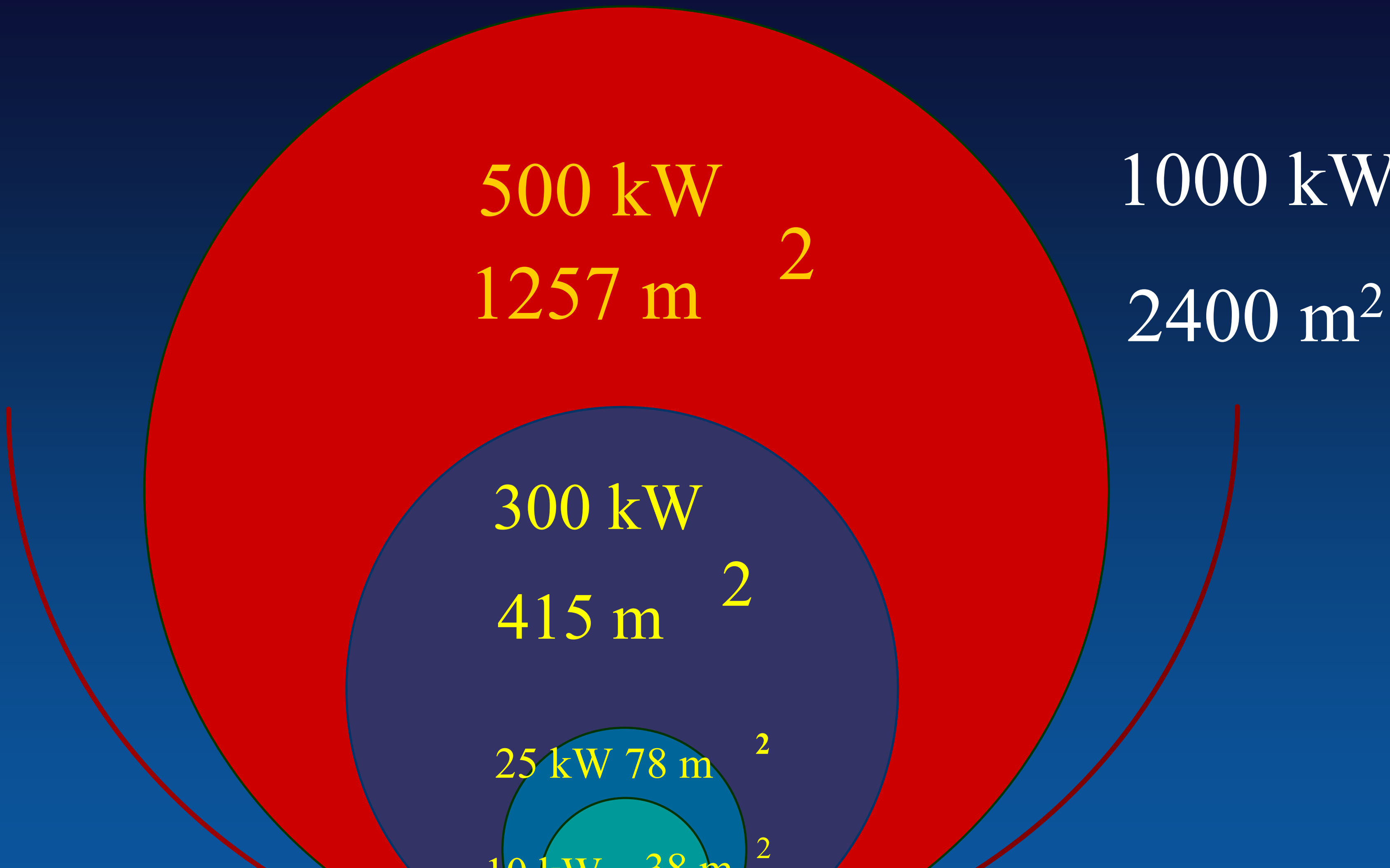




Air Density Changes with Elevation

Air Density Changes with Temperature





1000 kW
2400 m2
500 kW
1257 m 2
300 kW
415 m 2
25 kW 78 m 2
10 kW 38 m 2
1 kW 6 m 2

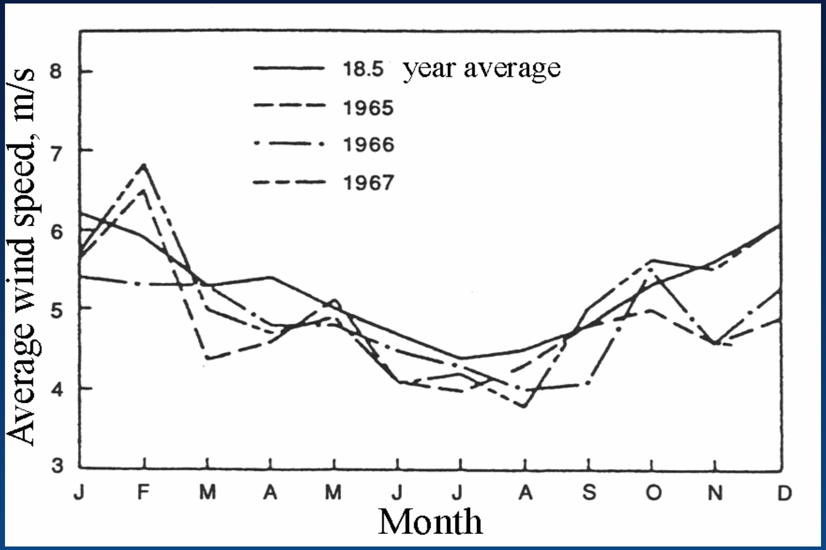
$$A = \frac{(\pi D^2)}{4}$$

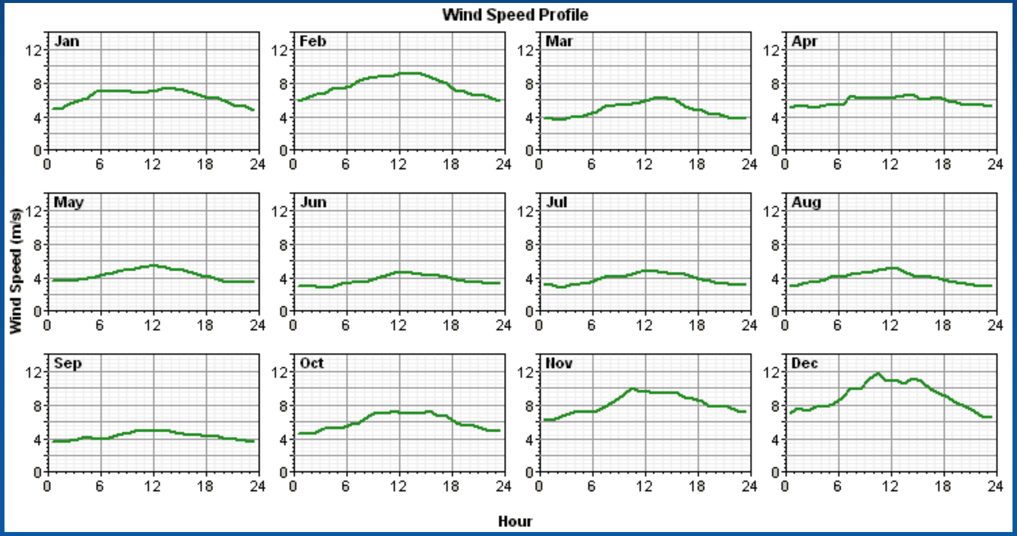
Wind Characteristics and Resources

Understanding the wind resource at your location is critical to understanding the potential for using wind energy

- Wind Speed
  - Wind Profile
  - Wind classes
  - Collection and reporting
- Wind Direction
- Wind speed change with height

Wind Speed





- Measured in m/s or mph
- Varies by the second, hourly, daily, seasonally and year to year
- Turbulence Intensity
- Usually has patterns
  - Diurnal - it always blows in the morning
  - Seasonal – The winter winds are stronger
  - Characteristics – Winds from the sea are always stronger and are storm driven.

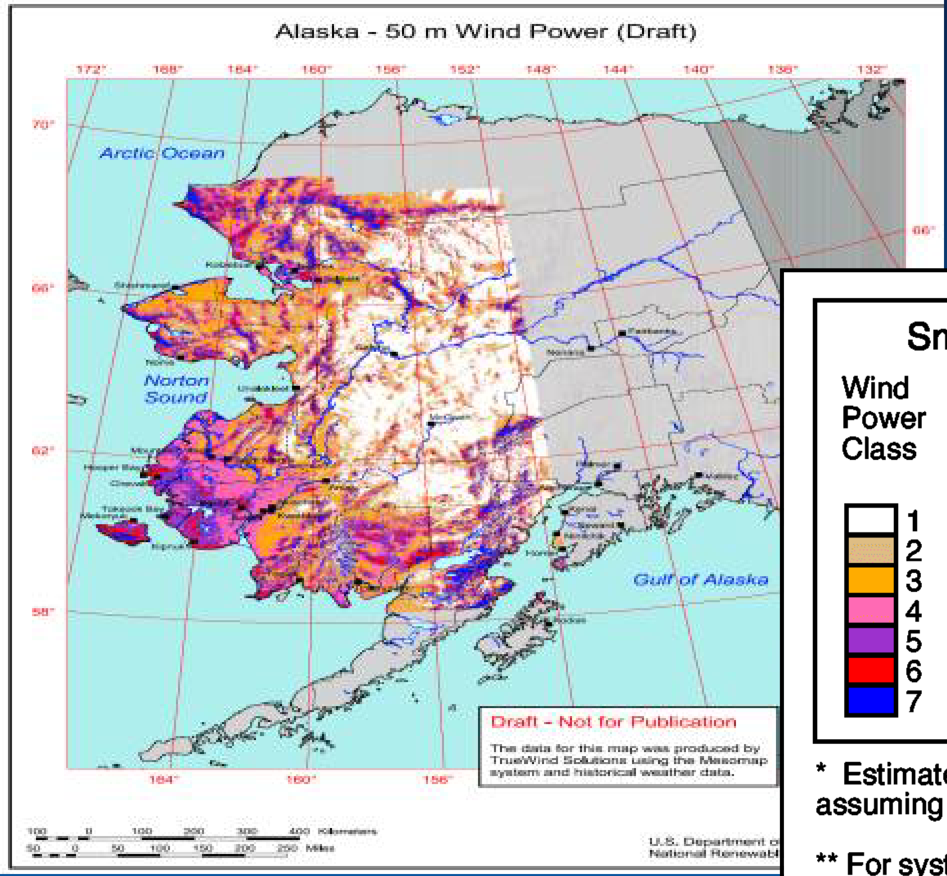
So, which is better…

1. A location where the wind that blows only 50% of the time at 10 m/s but is calm the rest of the time
2. A location where the wind that blows all of the time at 5 m/s

$$P = 0.5\ \rho\ Cp\ v^3\ A_S$$

Both have exactly the same annual average wind speed…

Wind Maps and Class



Careful:
Wind class is defined at a specific height

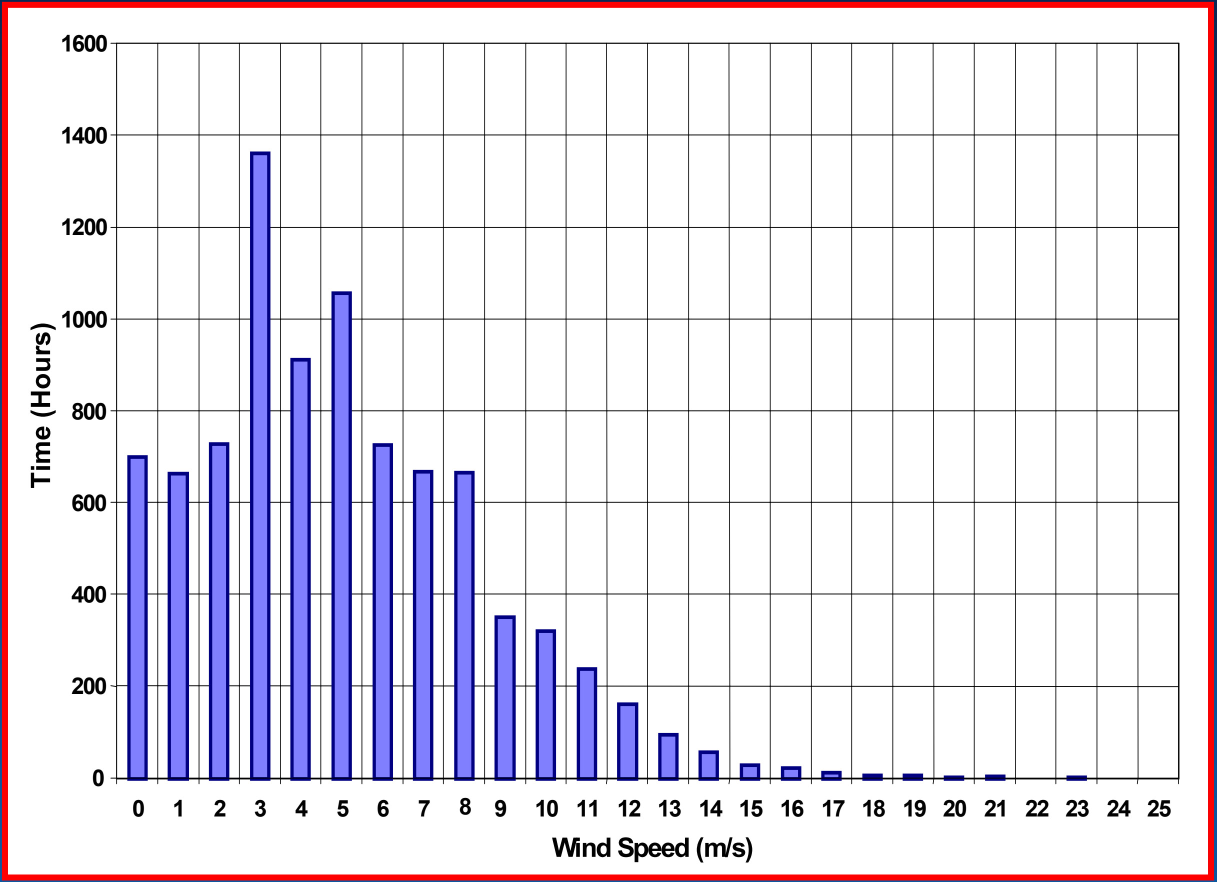
Small Wind Turbine Productivity Estimates*

Wind Power Class	Productivity per m² of swept area** (kWh/year)	Wind Power Density at 33 ft (10 m) (W/m²)	Wind Speed at 33 ft (10 m) (mph)	Wind Speed at 33 ft (10 m) (m/s)
1	< 350	<100	< 9.8	< 4.4
2	350 - 500	100 - 150	9.8 - 11.5	4.4 - 5.1
3	500 - 610	150 - 200	11.5 - 12.5	5.1 - 5.6
4	610 - 690	200 - 250	12.5 - 13.4	5.6 - 6.0
5	690 - 770	250 - 300	13.4 - 14.3	6.0 - 6.4
6	770 - 880	300 - 400	14.3 - 15.7	6.4 - 7.0
7	880 -1170	400 -1000	15.7 - 21.1	7.0 - 9.4

* Estimates are based on different models and sizes of wind turbines assuming a tower height of 80 ft (24 m).

** For systems of different sizes, multiply the estimated productivity by the total swept area of the turbine.

Wind Speed Data Collection and Reporting



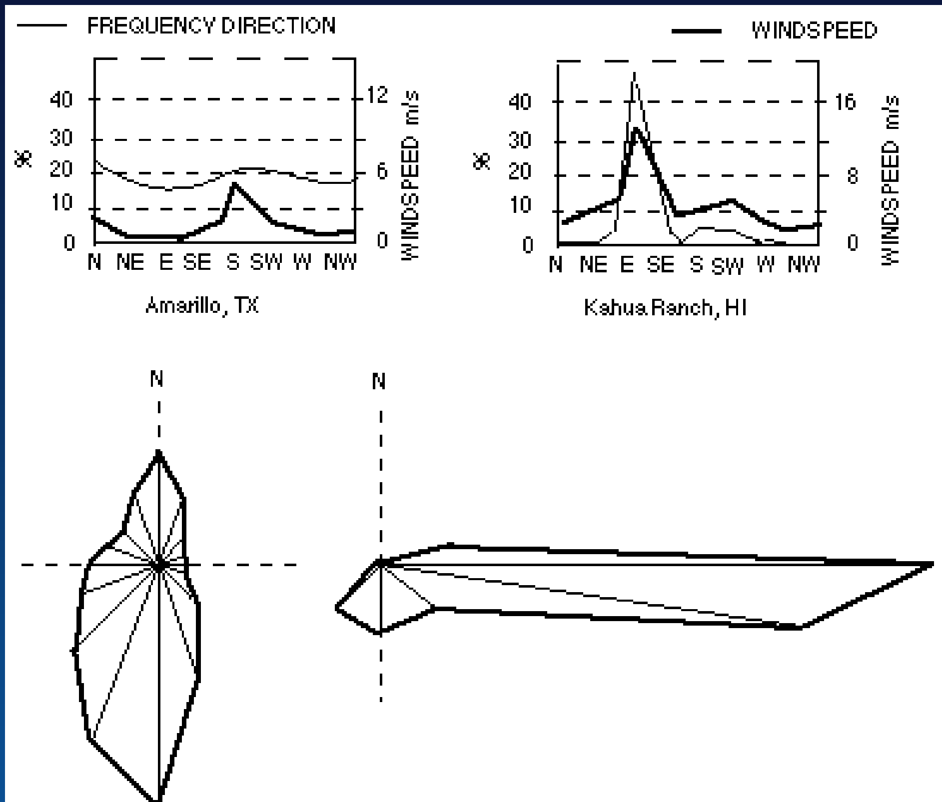
Collection

- Measured every 2 second
- Averaged every 10 minutes
- Reported as hour averages

Wind Speed Frequency of Occurrence Histogram based on hour average data for a year

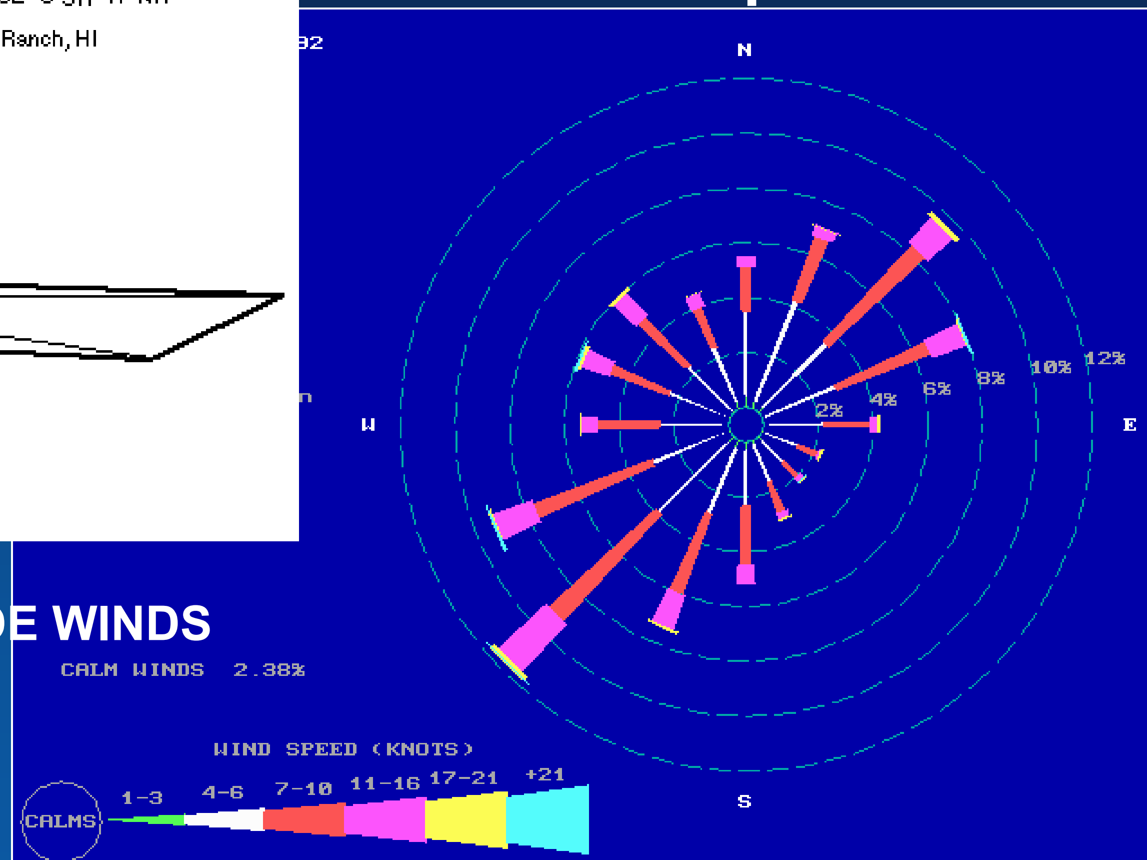
Wind Direction

Wind Rose



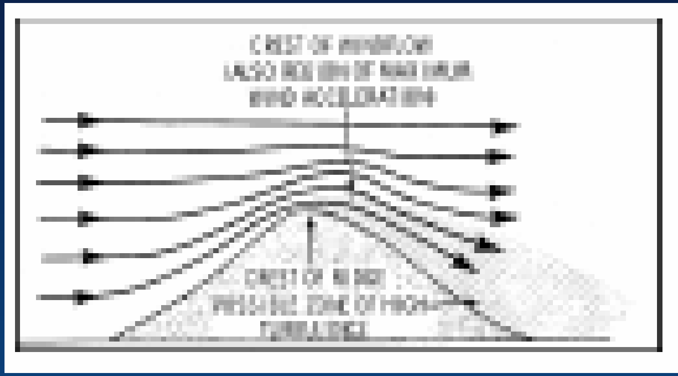
CONTINENTAL TRADE WINDS

Wind Speed Rose



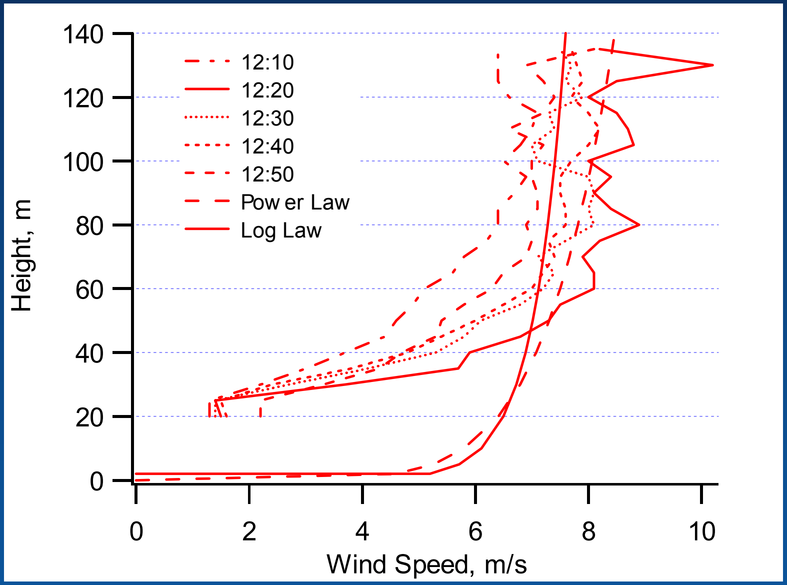
Impacts on Wind Speed

Many things impact the speed and direction of the wind at any specific location, making local measurements important

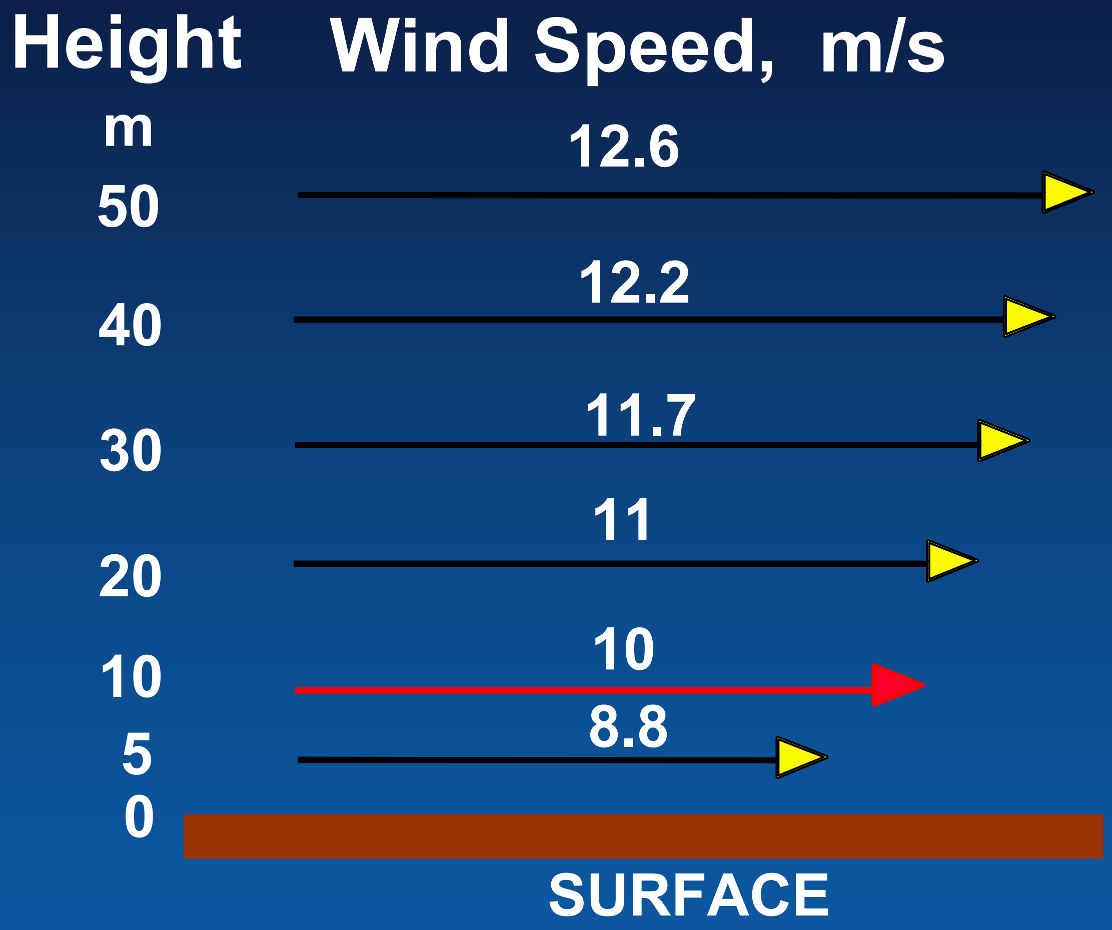


Wind Speed Increases with Height

- Because of friction with the earth, air closer to the surface moves slower
- The farther we get away from the earth (increase in altitude) the higher the wind speed gets until it is no longer effected by the earths surface.



Wind Shear



- The type of surface (grass, trees) impacts the wind shear
- Real vs. apparent height

$$V_N = V_O \left[\frac{h_N}{h_O} \right]^N$$

Factoring in Measurement Height
The Power Law

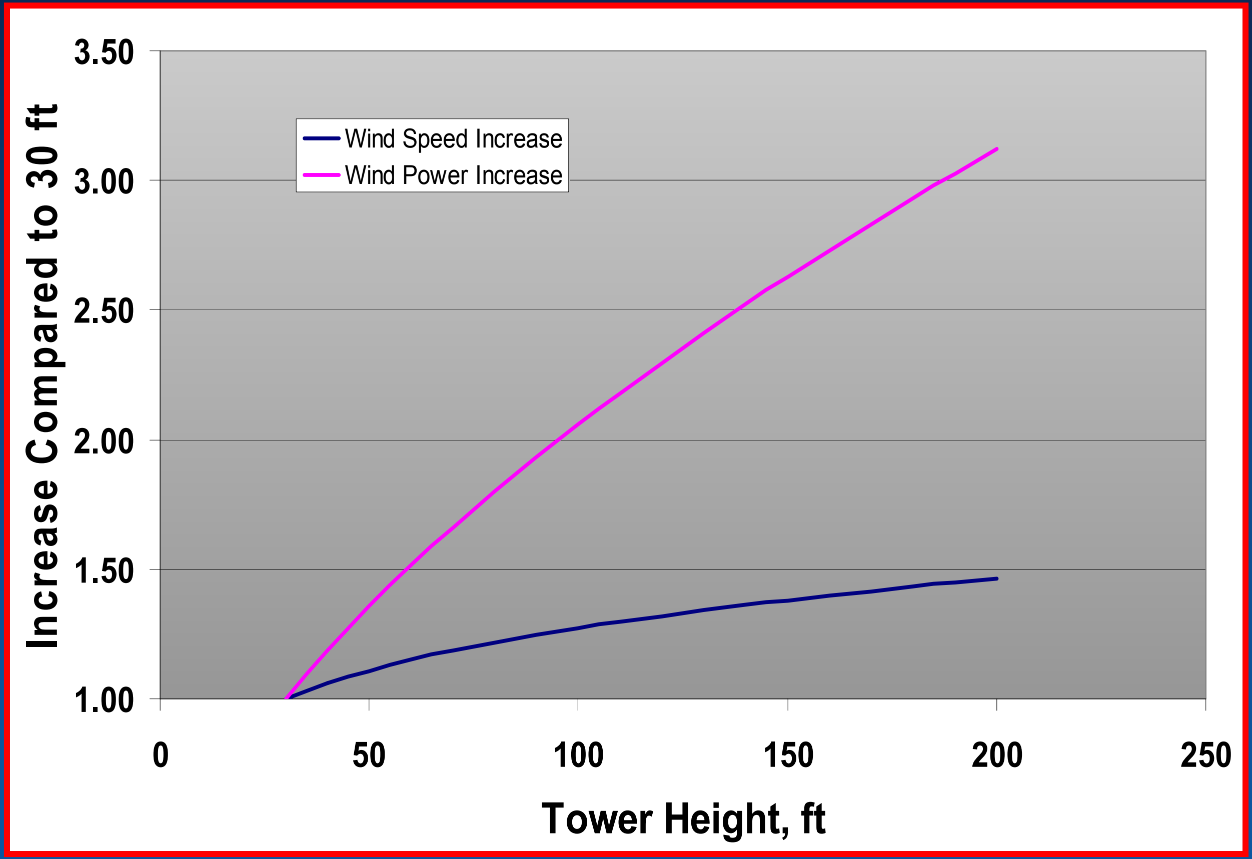
$$V_N = V_O \left[\frac{h_N}{h_O} \right]^N$$

V_N: Wind speed at new height,
V_O: Wind speed at original height,
h_N: New height,
h_O: Original height,
N: Power law exponent.

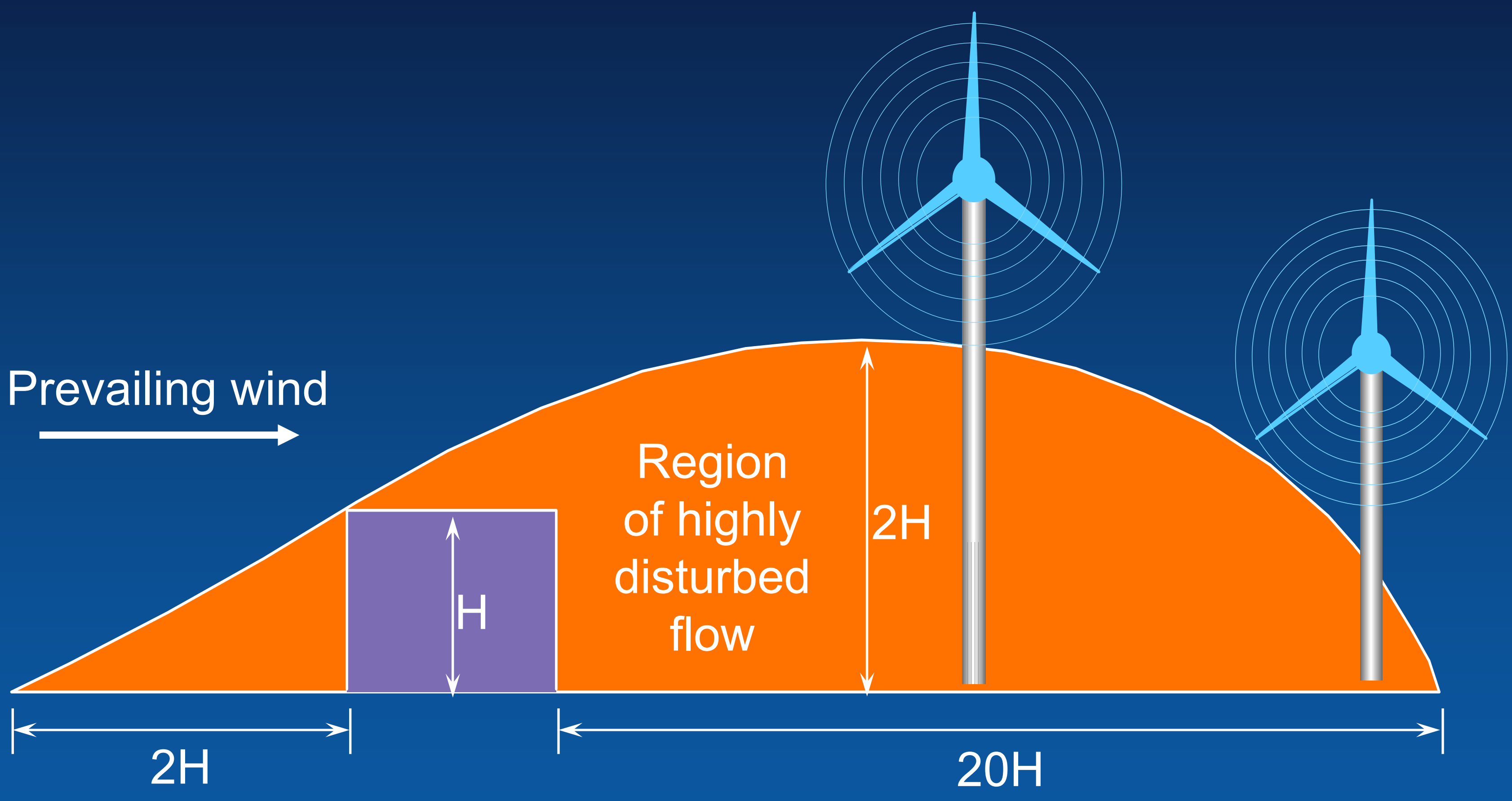
Terrain	Power Law Exponent
Water or ice	0.1
Low grass or steppe	0.14
Rural with obstacles	0.2
Suburb and woodlands	0.25

Source: Paul Gipe, Wind Energy Comes of Age, John Wiley and Sons Inc, 1995, pp 536.

Height Impacts on Power



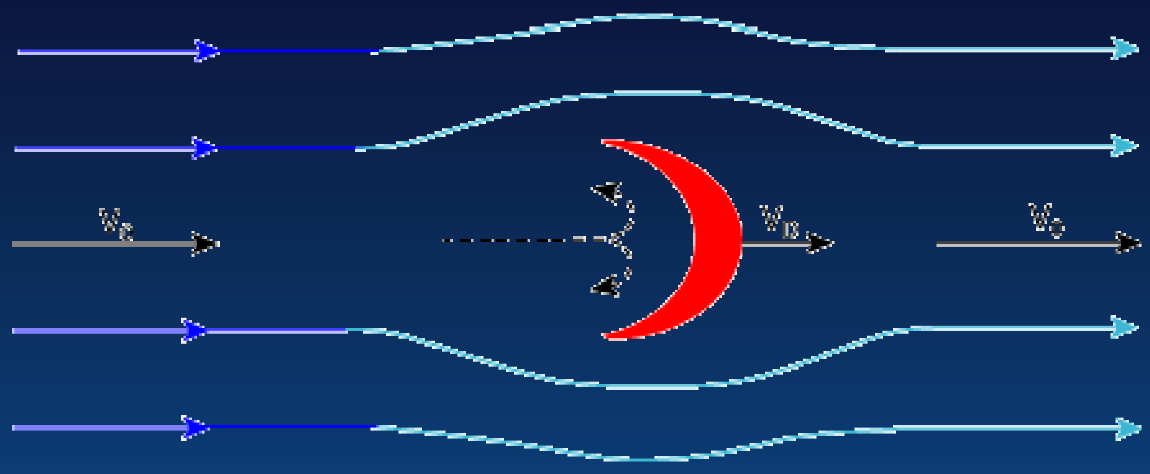
Micro-Siting Example:
Obstruction of the Wind by a Small Building

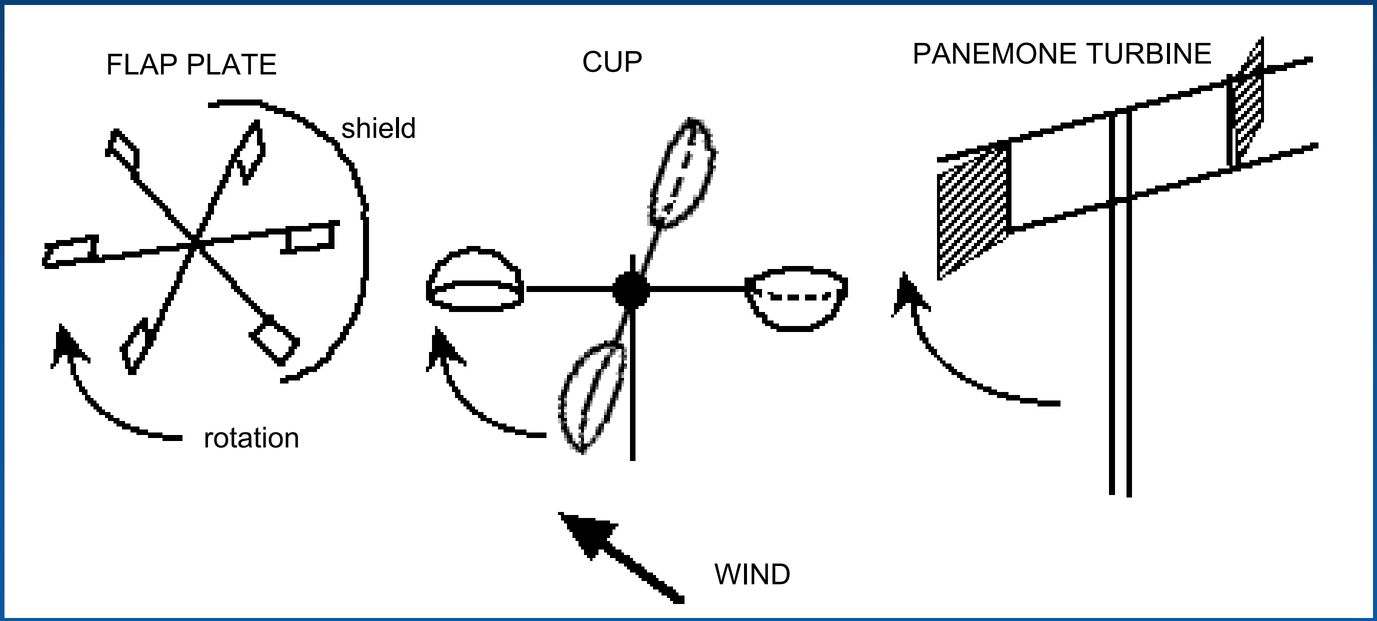


Basic Wind Turbine Theory

- Lift and Drag – The different types of wind turbines
- Aerodynamics – How turbines work
- Power Curves – The performance of wind turbines
- Power Availability - Power your can get from the wind
- Different types of lift turbines

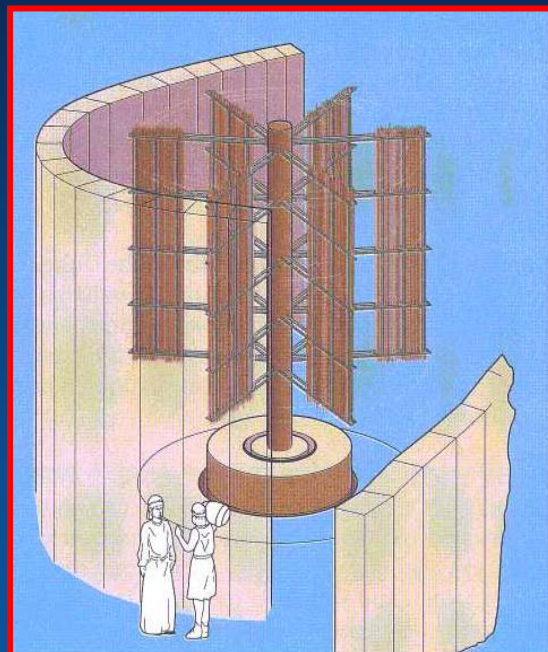
Aerodynamic Drag



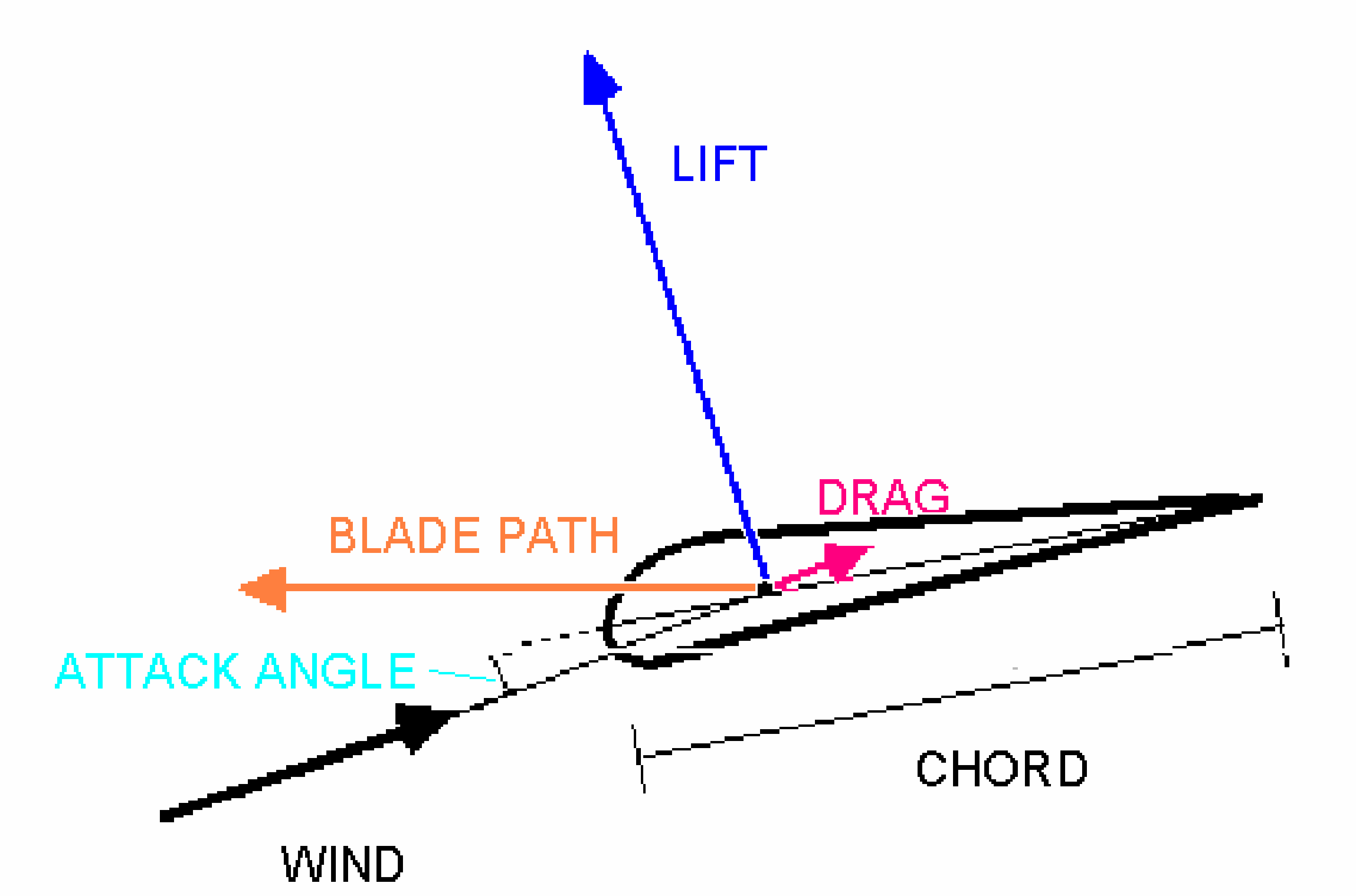


Classic Drag Devices

Some Modified Drag Devices

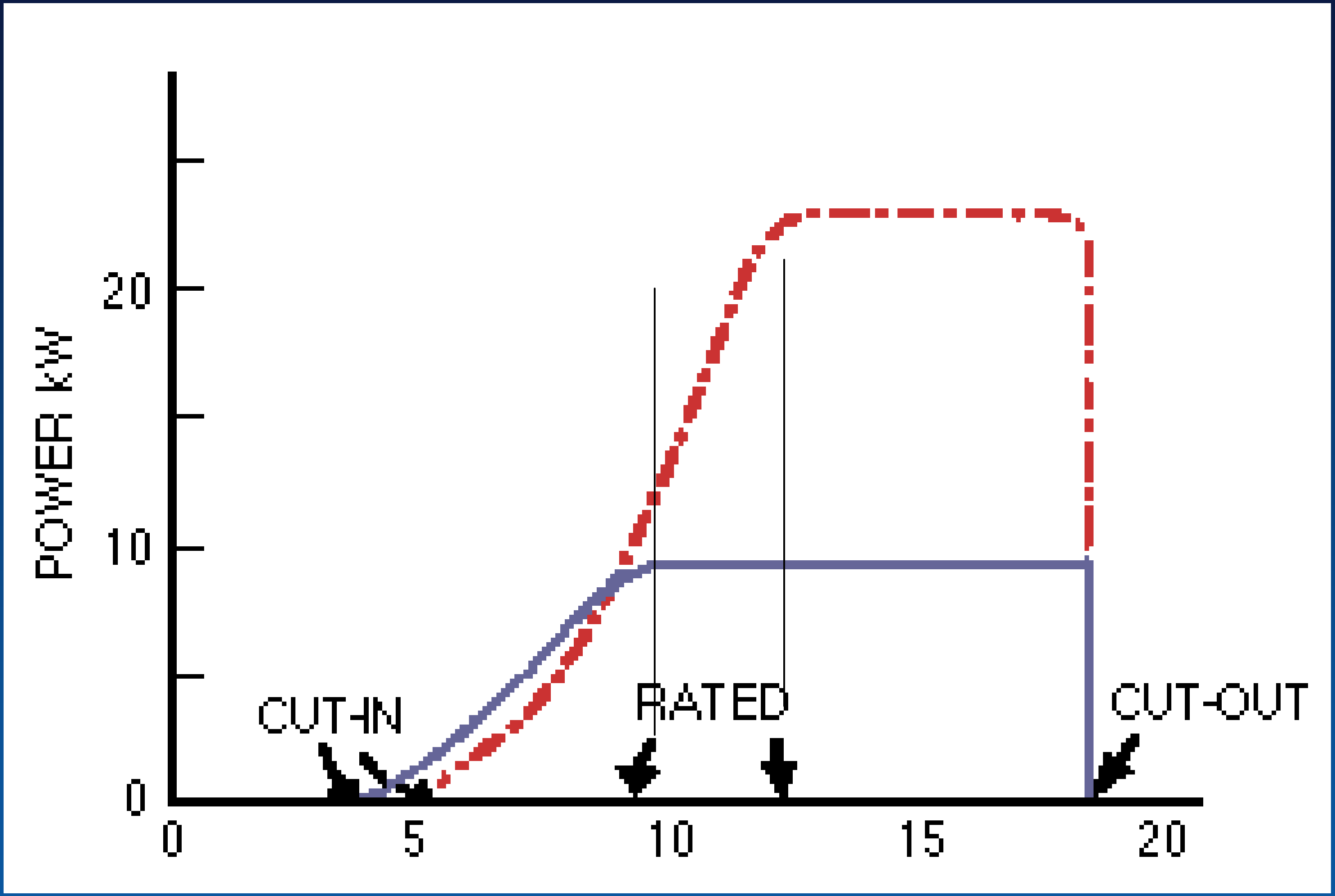


Aerodynamic Lift



Lift Wind Turbines

WTG Power Curve

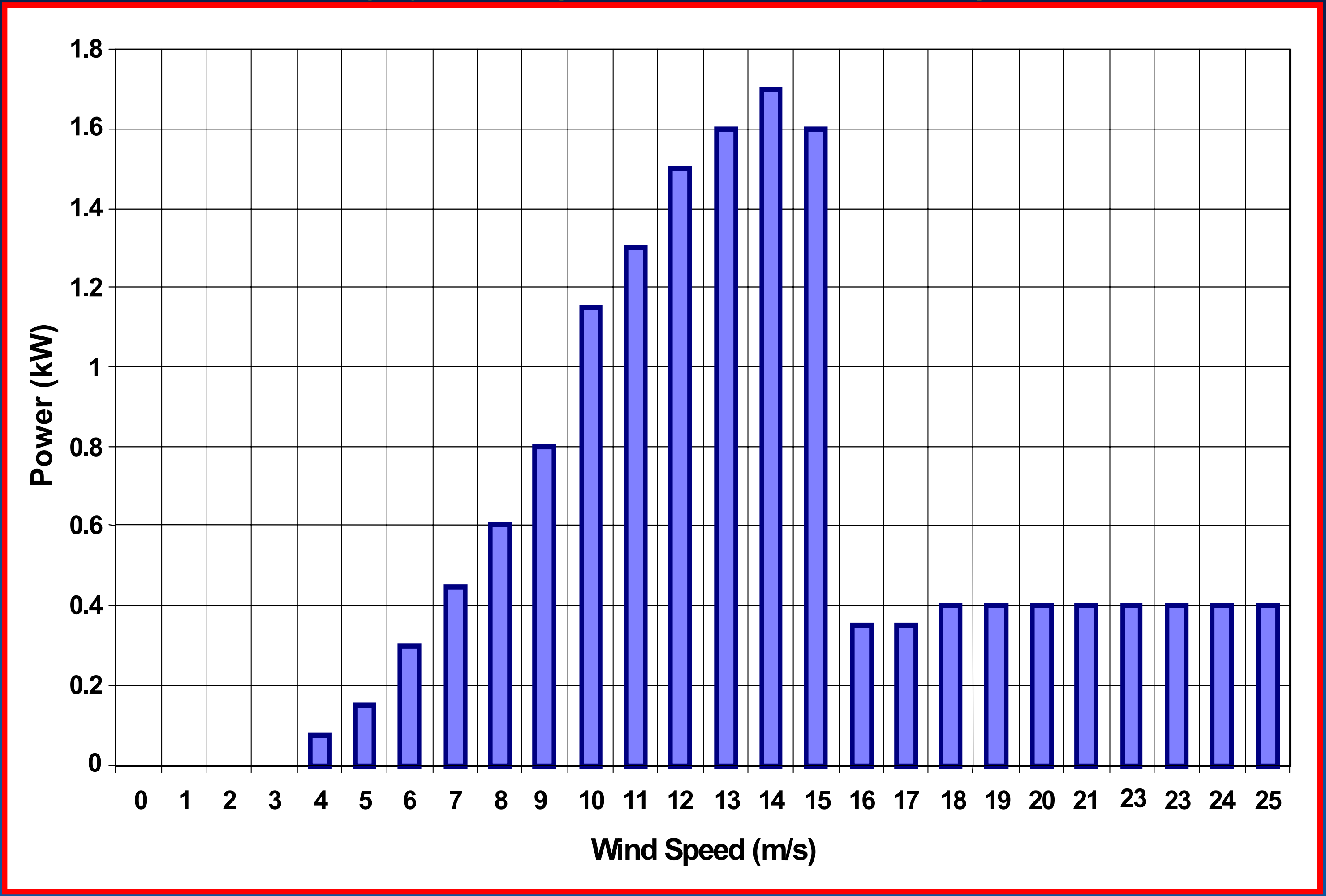


Important Terms

- Cut in wind speed: The wind speed that the turbine starts producing power (may be different than the speed at which the turbine starts spinning)
- Rated Wind Speed: The wind speed at which the turbine is producing “rated power” – though “rated power” is defined by the manufacture
- Cut out wind speed: The wind speed at which the turbine stops producing power
- Shut down wind speed: The wind speed at which the turbine stops to prevent damage
- Survival wind speed: Wind speed that the turbine is designed to withstand without falling over

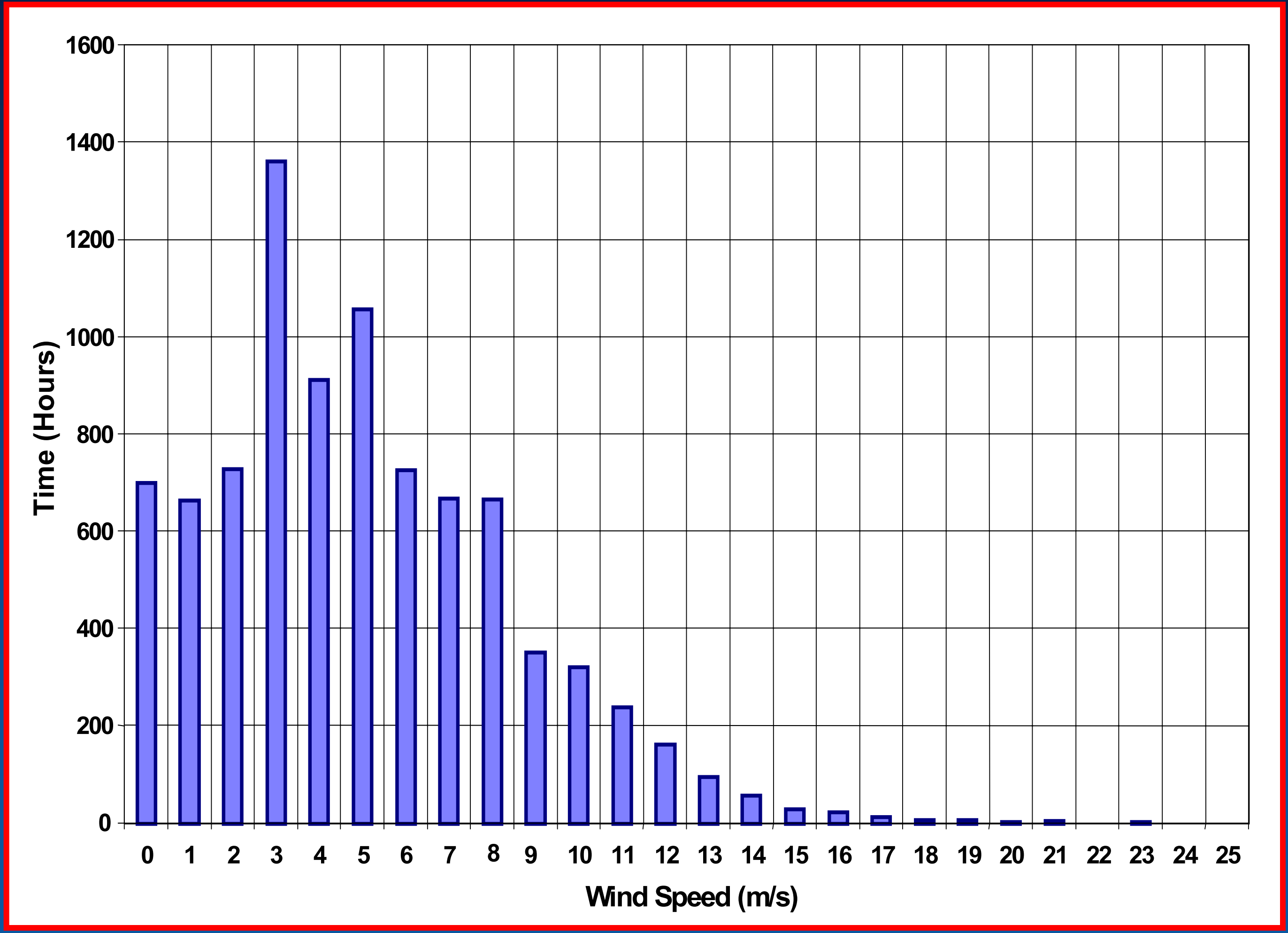
Wind Turbine Power Curve

Bergey 1500 (manufacturer's data)



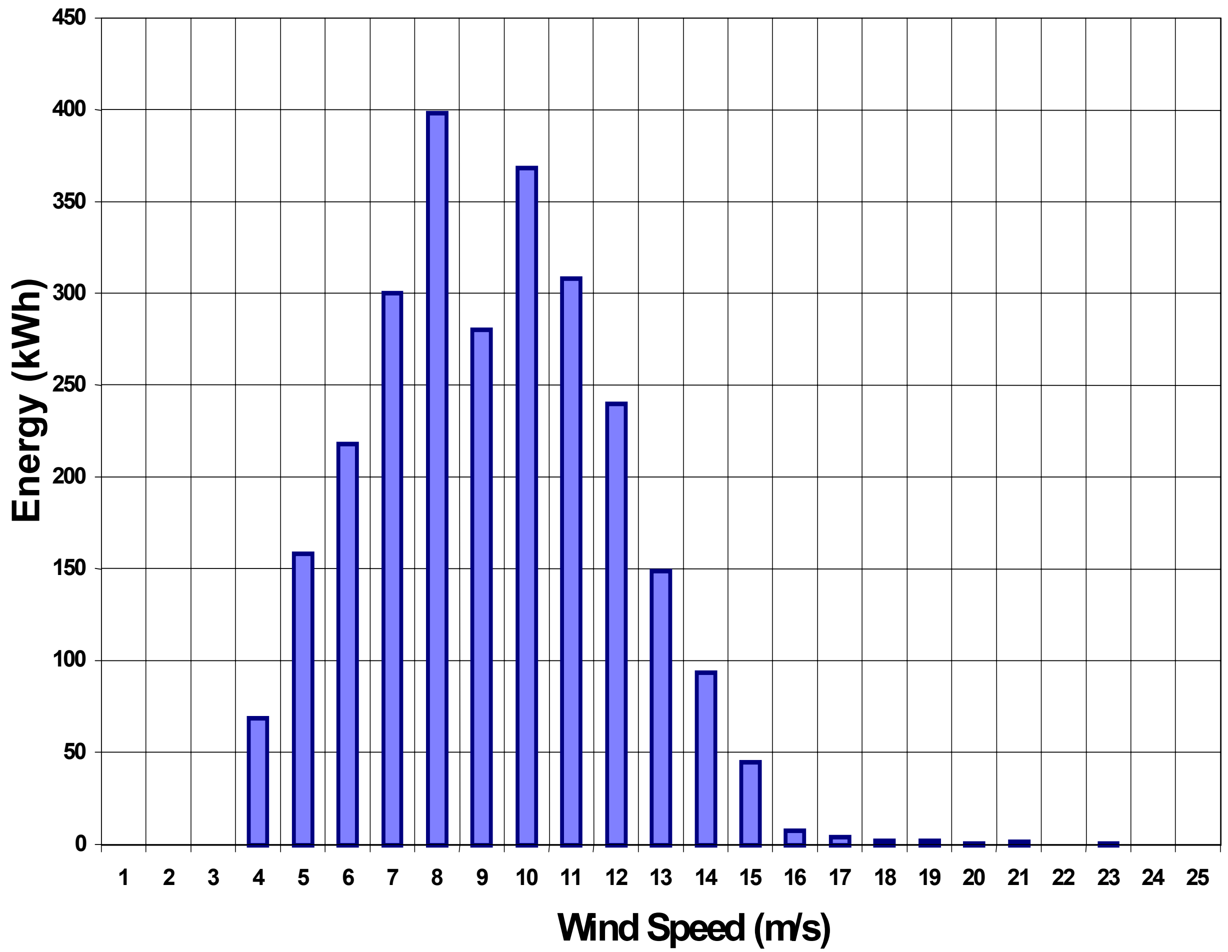
Wind Speed Frequency of Occurrence

Average Wind Speed: 5 m/s (11 mph)



Annual Energy Production: 2643 kWh/year

Bergey 1500 @ 5 m/s (11 mph) average wind speed



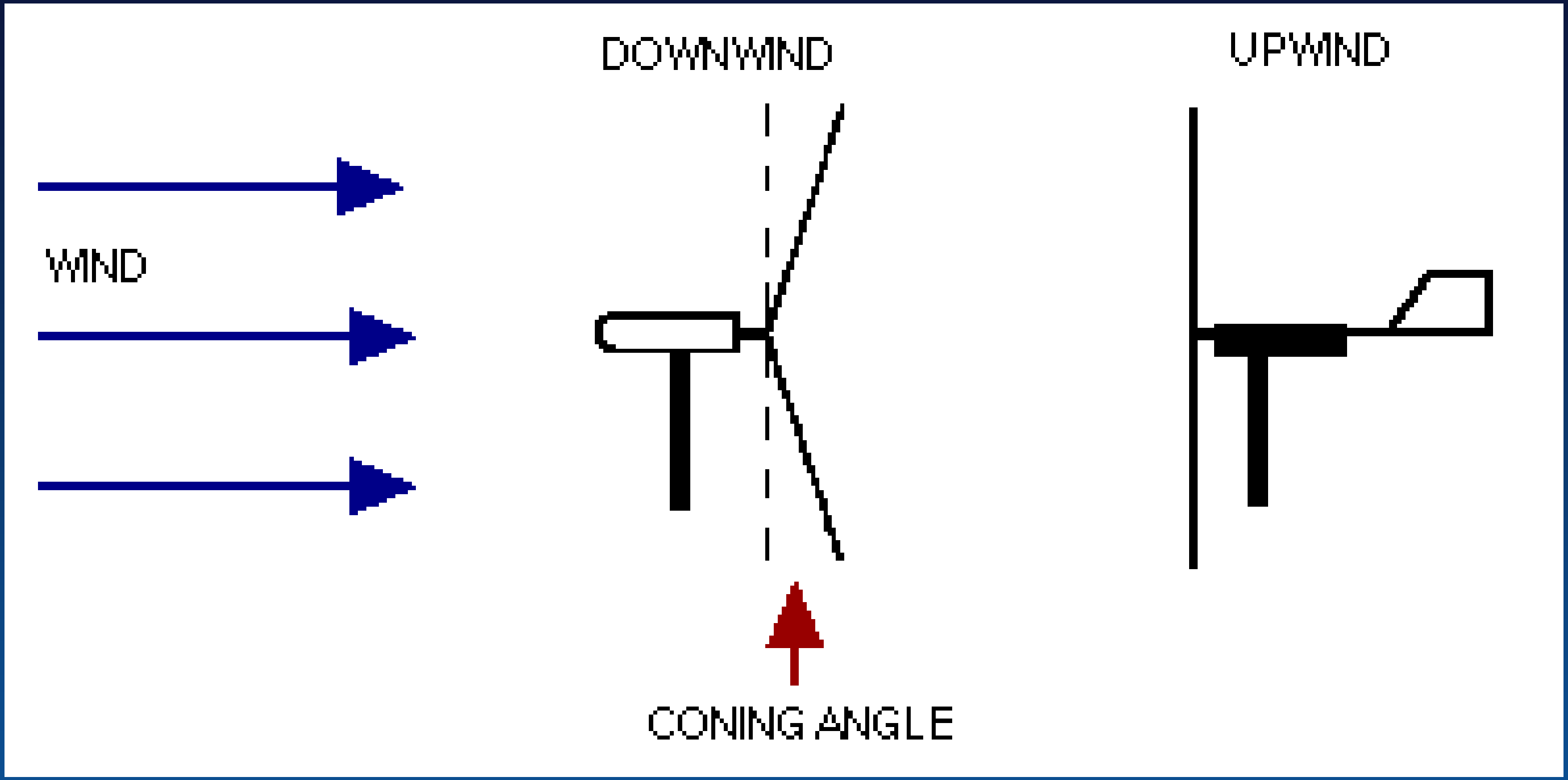
All available energy may not be captured

Types of Lift Turbines

HAWT VAWT

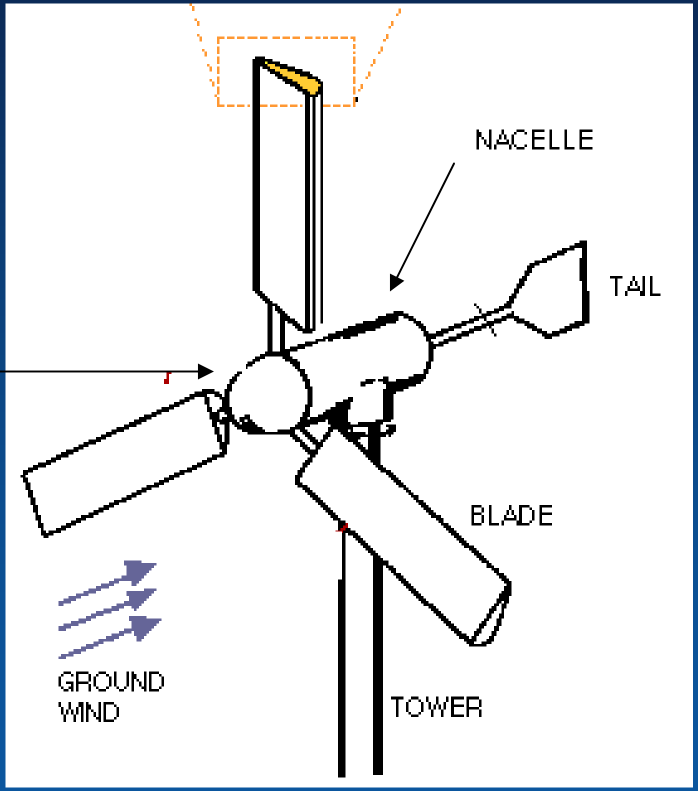
Basic Properties of HAWT

- Basics of a horizontal axis wind turbine
- Types of turbines
- Small distributed turbines
- Large grid connected turbines

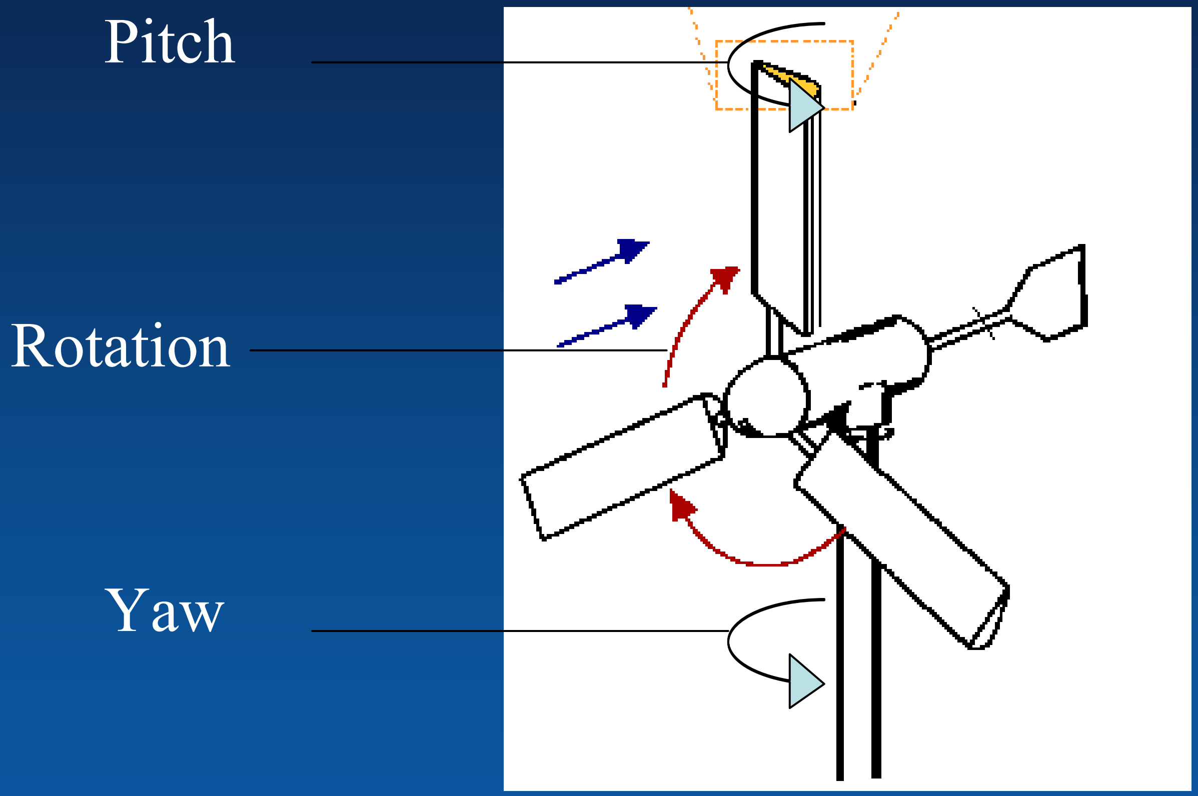

DOWNWIND
UPWIND
WIND
CONING ANGLE

Parts of a Wind Turbine

Rotor

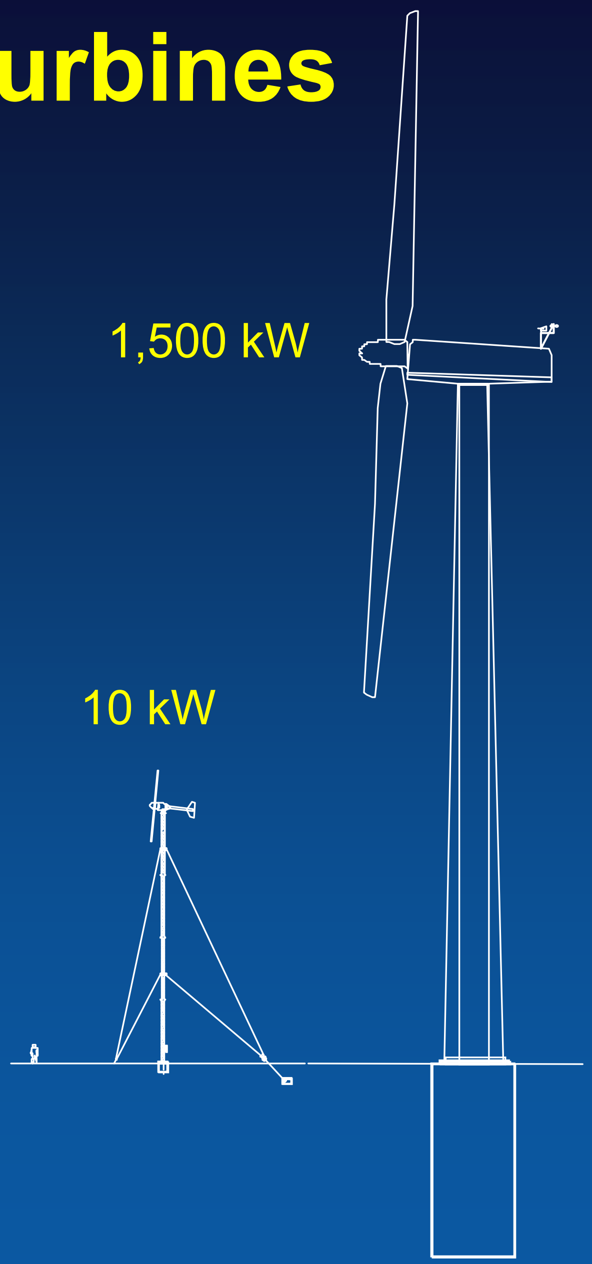


Basic Motion of a Wind Turbine



Different Types of Wind Turbines

- Utility-Scale Wind Power
  600 - 5,000 kW wind turbines
  - Installed on wind farms, 10 – 300 MW
  - Professional maintenance crews
  - Classes 5 and 6 (> 6 m/s average)
- Distributed Wind Power
  300 W - 600 kW wind turbines
  - Installed at individual homes, farms, businesses, schools, etc.
  - On the "customer side" of the meter
  - High reliability, low maintenance
  - Classes 2 and 3 (5 m/s average)



Sizes and Applications

Small (≤10 kW)

Homes

Farms

Remote Applications
(e.g. water pumping, telecom sites, icemaking)

Intermediate

(10-250 kW)

Village Power

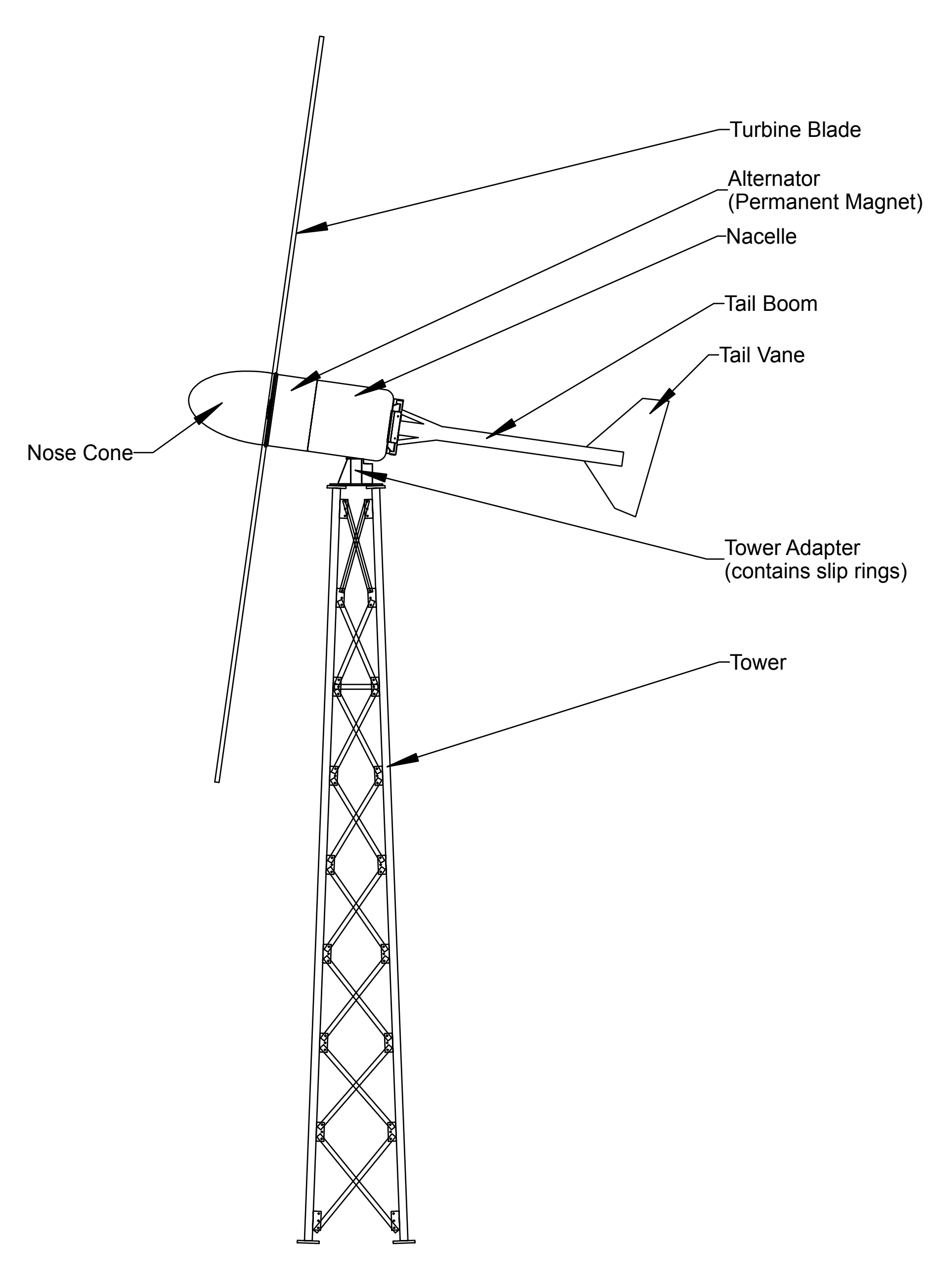
Hybrid Systems

Distributed Power

Large (250 kW – 2+ MW)

Central Station Wind Farms

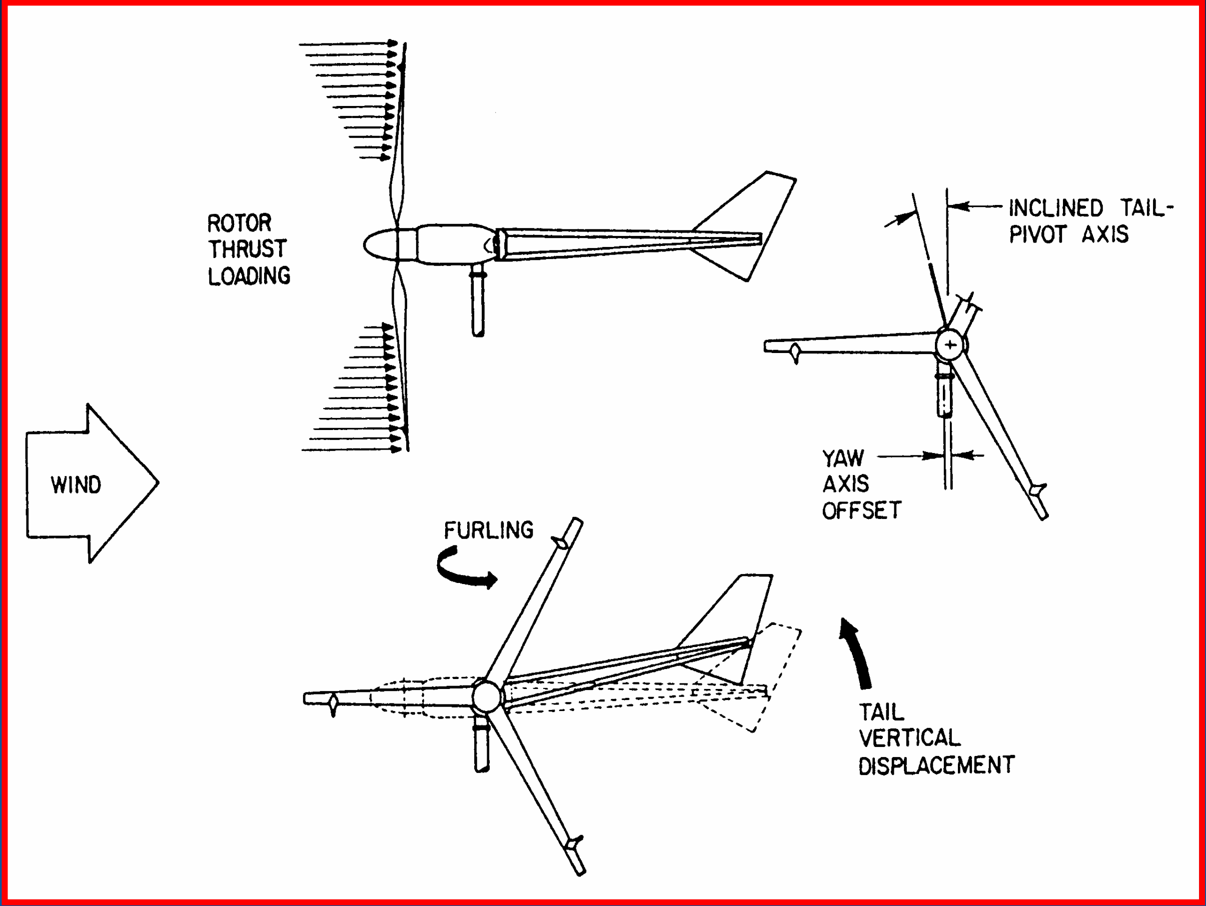
Distributed Power



Permanent Magnet WTG

- Permanent magnet alternator
- Generates wild AC (variable voltage and frequency) power that must be treated.
- Can provide AC or DC power
- Passively controlled

Overspeed Protection of Small WTG During High Winds

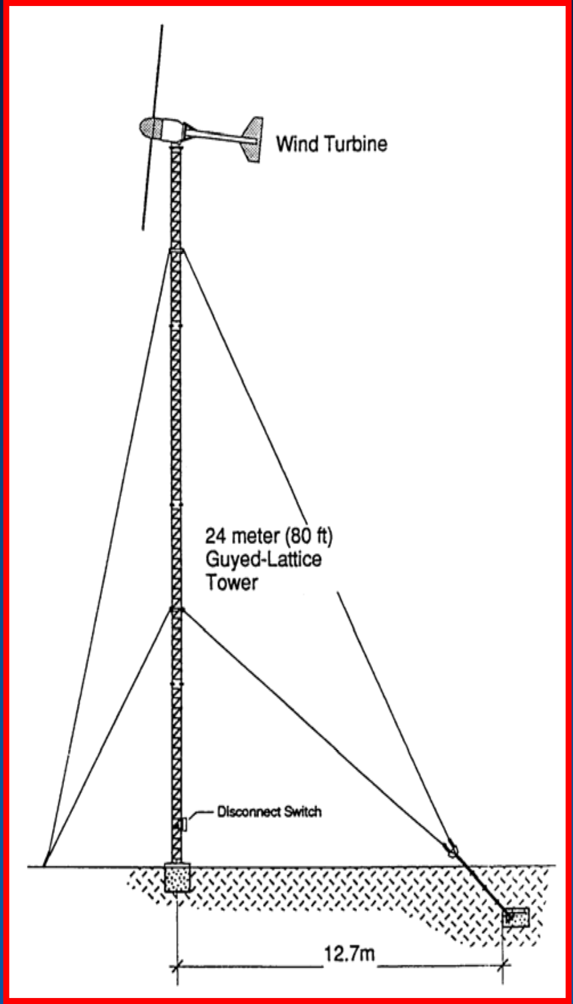


Furling: The rotor turns up or too one side under high winds

- Used to control rotor speed and power output
- Dynamic activity

Small Wind Turbine Towers

- Guyed lattice and tube towers are the least expensive and most commonly used towers for small wind turbines
- Adequate space is needed for the guy wires and their anchors
- Free-standing towers are used where space is limited

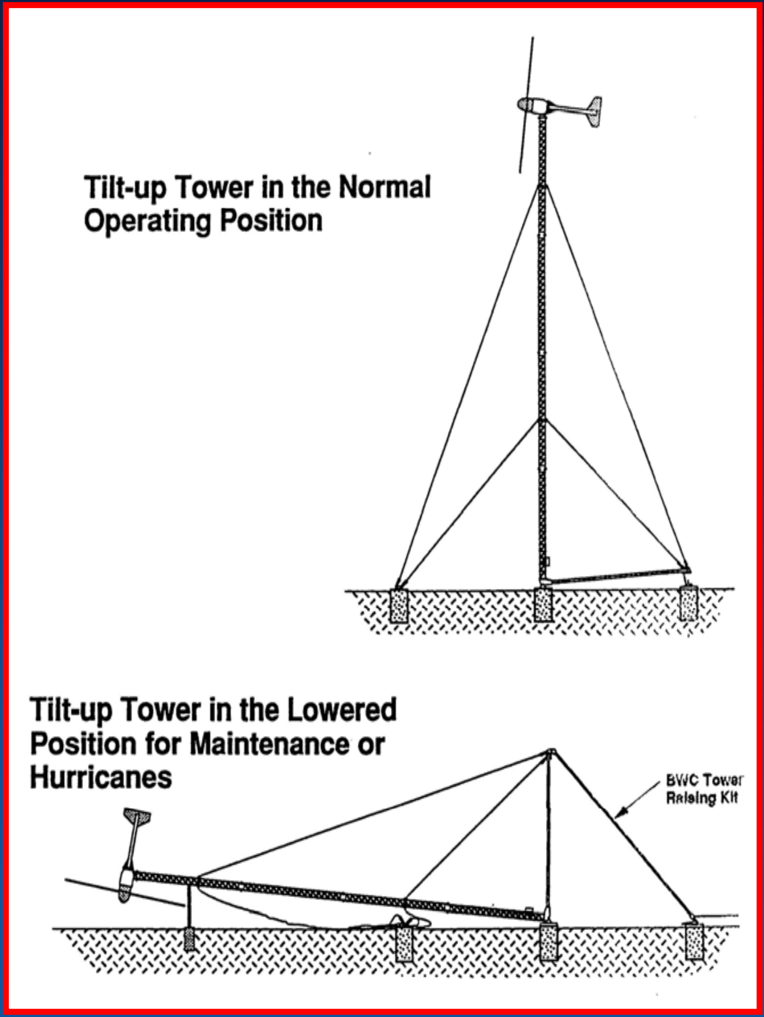


Tilt-Up Towers

Turbine installation in remote areas can be a problem.

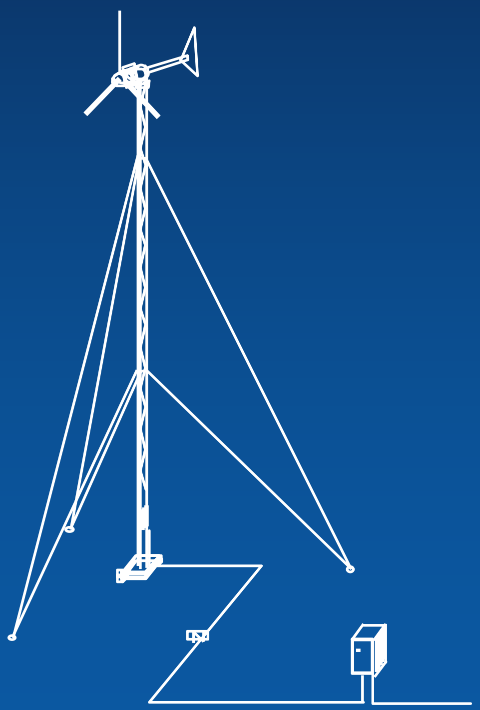
To solve this problem:

- Tilt-up versions of guyed towers are available for easier installation and maintenance.
- Self erecting technology also used wisely



The Wind Turbine Controller

- Battery-Charging
  - Converts AC power to DC for battery-charging
  - Regulates the battery voltage to prevent over-charging
  - When the battery is fully charged:
    - Power is diverted to another load, or …
    - The rotor is unloaded and allowed to "freewheel"
- Grid Interconnection
  - "Inverter," converts the power to constant frequency 60 Hz AC
- Water Pumping
  - Direct connection to the pump



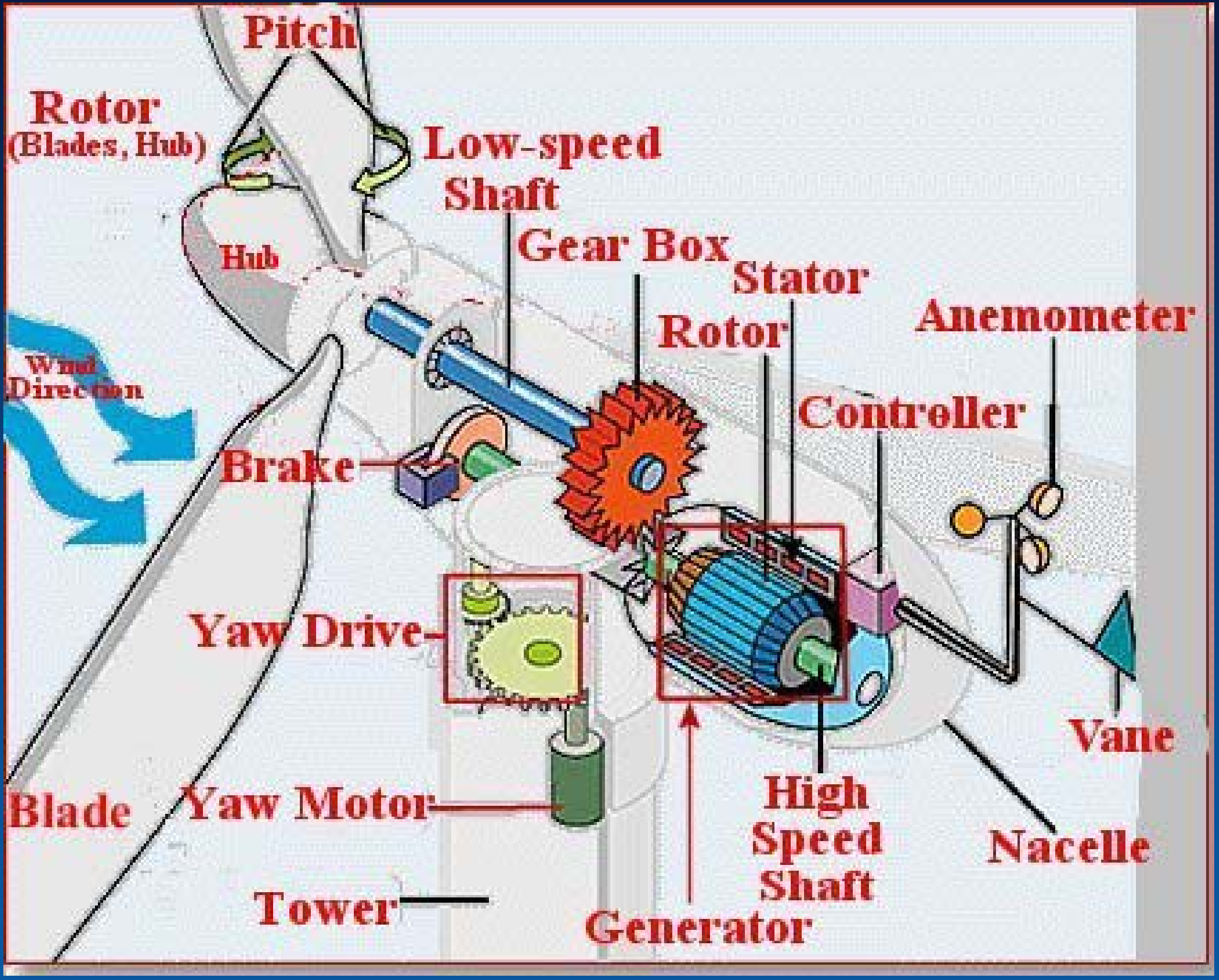
Small Wind Turbine Maintenance and Lifetime

- **“Low maintenance” not “no maintenance”**
  - Inspection and maintenance every year: tightening bolts and electrical connections, inspecting slip ring brushes, checking for corrosion, etc.
  - Between 2 and 4 years: blade leading edge tape may need replacement
  - Beyond 5-10 years: blade or bearing replacement may be needed
- **Lifetimes of 10 to 20 years are possible**
  - Some Jacobs wind turbines have been operating for more than 60 years with periodic maintenance!

"Hot Tips" on Small Wind Energy

- "Buy Reliability"
  "Based on experience, I side with the 'school of heavy metal,' those who believe that beefiness of components is directly related to the longevity of the equipment." M. Sagrillo, small wind turbine expert
- "Taller is Better"
  Taller towers give better performance due to smoother wind and higher wind speeds
- "Micro-Siting"
  For best performance, locate wind turbines above and away from obstructions to the wind

AC WTG



- Induction or variable speed generator
- Create AC power supplied to the grid
- Actively controlled

Control of Large WTG

Fixed Pitch (Stall regulated): The shape of the blade varies over its length so that as wind speed increase parts of the blade stop producing lift and limit power.

Variable Pitch: The rotation (pitch) of each blade is individually controlled to control lift

Yaw: Motors control yaw behavior based on a wind direction vain, used to shut down wind turbine in high winds but can also be a source of problems.

Brake: All wind turbines are required to have two of them but there are several types:

- Aerodynamic: Flaps on the blades that cause drag.
- Mechanical: Disks or calipers, like your car.
- Electrical: using the generator to cause electrical resistance.

Characteristics of Large WTG

Power Types

- Induction (Constant speed)
- Variable Speed (uses power electronics)

Power System Efficiencies

- Aerodynamic
- Rotor
- Drive train / gear box
- Generator
- Power Conversion (if applicable)

1MW WTG Nacelle

A 27 m Blade

Rotor Area = 2460 m^2 for a 1MW wind turbine

- 1.5 MW turbine is now “standard”
- 5 MW Turbines in prototype

Other Large (and Small) Turbines Considerations

- Policy
- Siting
- Transmission
- External Conditions
- Intermittency

Policy

- Encourage economic development and use of local resources
- facilitate “green” markets
- Federal, state and local incentives (Production Tax Credit (PTC) and Renewable Portfolio Standards (RPS)

Siting

- Avian and other wildlife
- Noise
- Visual Impact
- Land Ownership

Transmission

- Grid Access
- System studies
- Allocation of available capacity
- Scheduling and costs for usage
  - firm
  - non-firm

External Conditions

- Lightening
- Extreme Winds
- Corrosion
- Extreme temperatures

Intermittency

- Operational Impacts (ancillary services)
  - voltage/VAR control, load following, etc.
- 10-20% of system capacity is reasonable

Other General Wind Terms

- Availability: The amount of time that the wind turbine is available to produce power (Maintenance parameter)
- Capacity Factor: The annual energy production of a wind turbine divided by the theoretical production if it ran at full rated power all of the time (Resource parameter)
  - The stronger the resource the higher the availability
  - 25-40% is typical, up to 60% has been reported
  - Reason for the “only works 1/3 of the time” quote.

Basic WTG Calculations

Back of the envelope calculations for wind turbine sizing

1. Turbine size or energy production
2. Cost of energy
3. Turbine capital cost

Note: Designing a power system that includes wind turbines is not a simple issue and should not be taken lightly.

Determining Turbine Size

There is a direct tradeoff between the size of the generator and the amount of power that it will produce. If you know one, you can get the other.

$$AKWH = CF * AV * GS * 8760$$

AKWH Annual energy production, kWh/yr

CF Capacity Factor (25 to 50%)

AV Turbine Availability (~95 to 98%)

GS Generator Size (rated power), kW

8760# of hours in a year

Example – What Sized Turbine?

Your community/home/building/business uses 11,250 kWh / year and you want ~ 25% of that to come from wind.

AEP = CF * GS * AV * 8760

CF	30% = 0.30 (~ 6 mps annual average)
AV	97% = .97
AEP	11,250 kWh
8760	# of hours in a year

GS = 11250 / (0.30 * .97 * 8760)

GS = 4.5 kW

Of course there are many other factors…

Quick calculation of Annual Energy Production using density

$$AKWH = CF * Ar * WM * 8.76$$

AKWH	Annual energy production, kWh/yr
CF	Capacity factor (efficiency factor)
Ar	Rotor Area, m^2
WM	Wind Map Power, W/m^2
8.76	1000 hours in a year converts W to kW

Levelized Cost of Energy

$$COE = \frac{(FCR * ICC) + LRC + AOM}{AEP}$$

COE = LEVELIZED COST OF ENERGY, $/kWh

LRC = LEVELIZED REPLACEMENT COST, $/yr (major repairs)

ICC = INITIAL CAPITAL COST, $

FCR = FIXED CHARGE RATE, per year

AEP = ANNUAL ENERGY PRODUCTION, kWh

A0M = ANNUAL OPERATION & MAINTENANCE, $/kWh

Turbine Capital Cost

Hardware Cost		$670/kW
turbine	$550/kW	
tower	$120/kW	
Installation Cost		$100/kW
foundation, erection, interconnection		
Shipping		$70/kW
Other		$100/kW
ROUND NUMBER		**$1000/kW**

Costs however are impacted by the market. In 2005 the cost of installed wind turbines has increased to between $1300 and $1400 per kW due to high steel prices and demand caused by the Production Tax Incentive

COE Example

1 MW TURBINE

FCR = 10% = 0.10

ICC = $1000/kW = $1,000,000

LRC = $5,500

AOM = $0.01/kWh availability elevation

AEP = 2,600,000 98% 1000 m

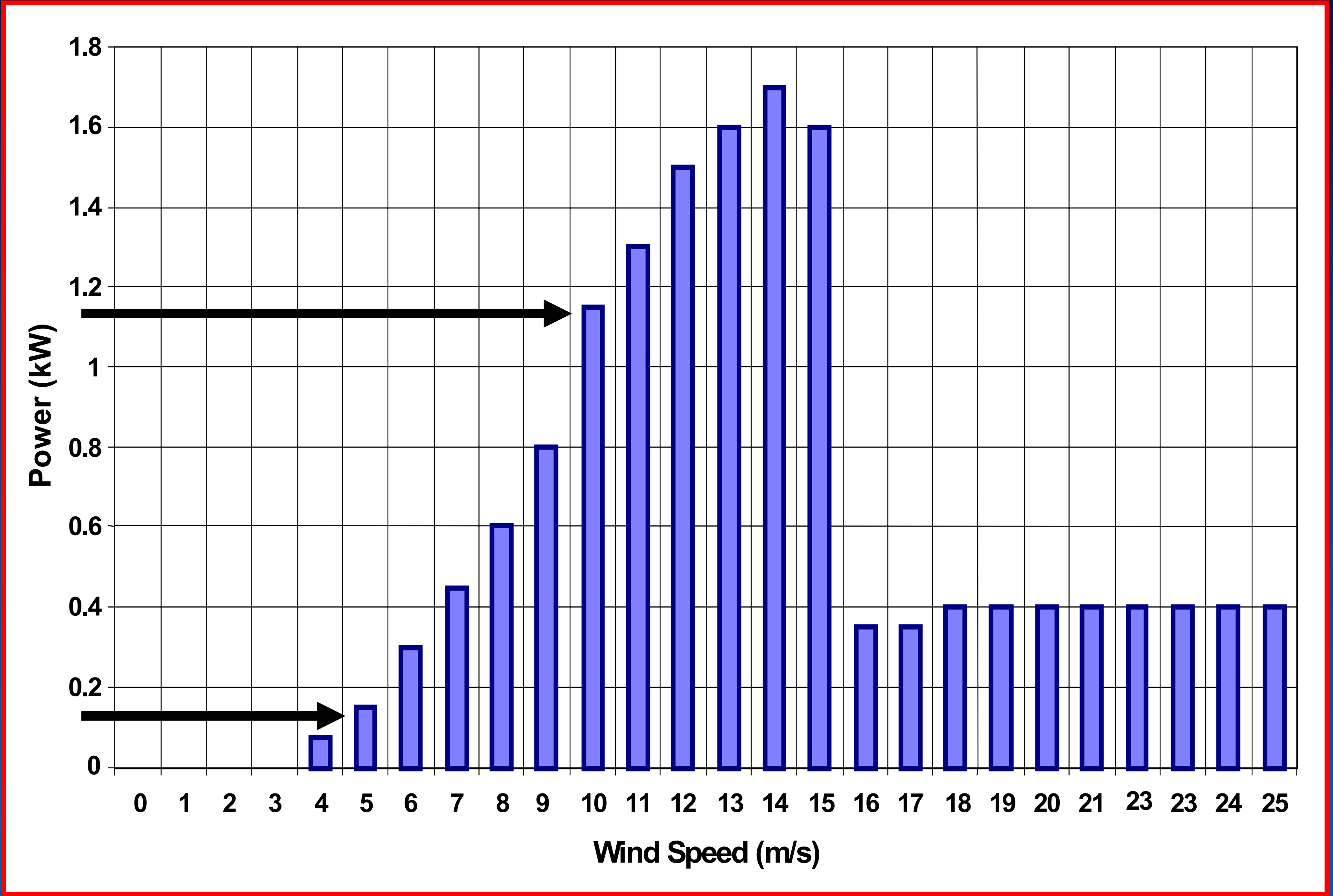
$$COE = \frac{(0.1 * 1,000,000) + 10,000 + 0.01}{2,700,000}$$

COE = $0.051 / kWh

So, which is better…

1. A location where the wind that blows only 50% of the time at 10 m/s but is calm the rest of the time
2. A location where the wind that blows all of the time at 5 m/s

Bergey 1500 (manufacturer's data)



Make the calculation

AEP = expected power * availability * time

Case 1: 10 m/s 50% of the time

AEP = 1.15 kW * 0.97 * (8760 *0.5)

= 4,886 kWh / year

Case 2: 5 m/s all of the time

AEP = 0.15 kW * 0.97 * (8760 * 1.0)

= 1,275 kWh / year

Further Information / References

Web Based:

- American Wind Energy Association http://www.awea.org/
- Wind Powering America http://www.eere.energy.gov/windpoweringamerica/
- European Commission's Atlas Project: http://europa.eu.int/comm/energy_transport/atlas/homeu.html
- Solar Access: http://www.solaraccess.com

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- Ackermann, T. (Ed’s): (2005), *Wind Power in Power Systems*, John Wiley and Sons, west Sussex, England, p299-330 (2005).
- Hunter, R., Elliot, G. (Ed’s) (1994) *Wind-Diesel Systems*. Cambridge, UK: Cambridge University Press, 1994.
- Paul Gipe, Wind Energy Comes of Age, John Wiley and Sons Inc, 1995.
- AWS Scientific Inc. “Wind Resource Assessment Handbook” produced by for the National Renewable Energy Laboratory, Subcontract number TAT-5-15283-01, 1997