14-Wind Energy Conversion Systems

ECEGR 4530

Renewable Energy Systems

Overview

- Wind Industry
- Wind Turbine Types
- Tip Speed Ratio
- Power Coefficient
- Wind Turbine Aerodynamics
- Wind Turbine Operation

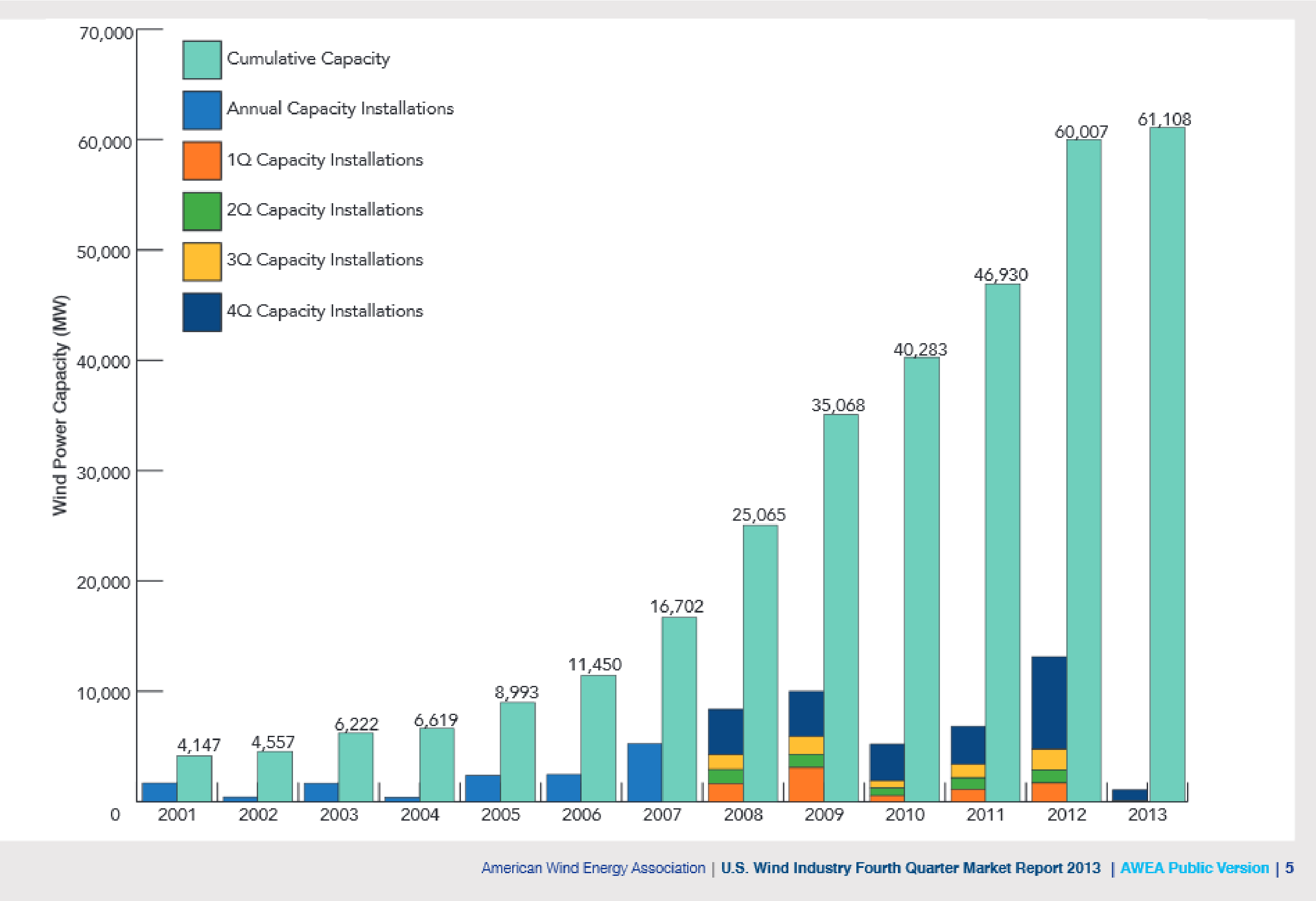
Timeline

- 1887: First wind turbine began producing electricity in Scotland
- 1930s: Small turbines were used in rural areas
- 1931: First grid connected wind turbine
- 1970-1980s :Wind turbines first started being used on an appreciable scale in (due to the energy crisis)
- 1990s (late): Rebirth of wind generation (production tax credit in effect in 1998)
- 2011: 238 GW of capacity worldwide

Global Wind Industry (2015)

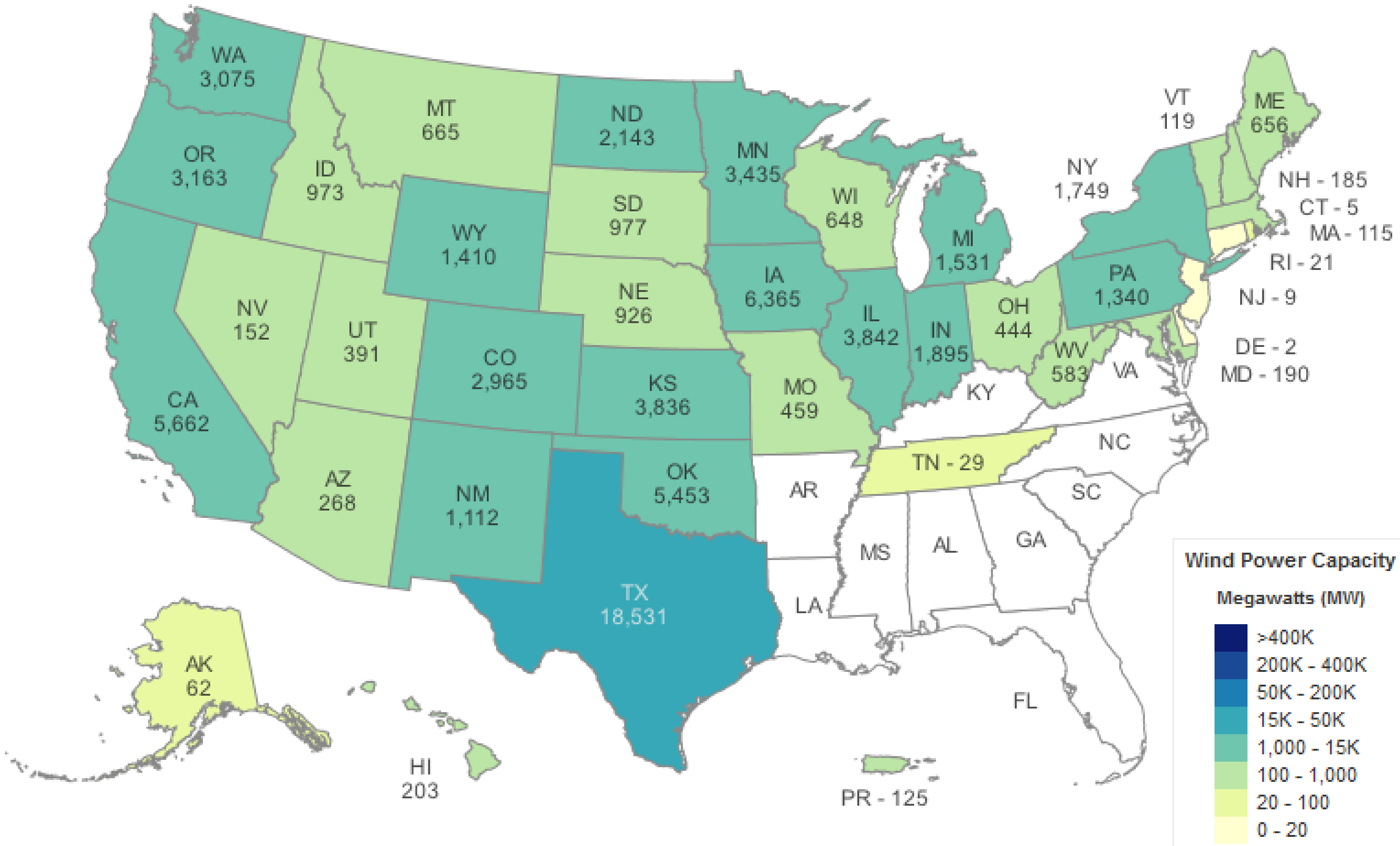
- World total: 433,000 MW
  - +17% increase from 2014
  - 63 GW added in 2014 (30 GW in China)
- 26 countries with +1,000 MW of capacity
  - China: 145GW
  - US: 74 GW
  - Germany: 45 GW
  - India: 25 GW
  - Spain: 23 GW
  - UK: 14 GW

US Wind Industry



Source: AWEA 2013 Q4 Market Report

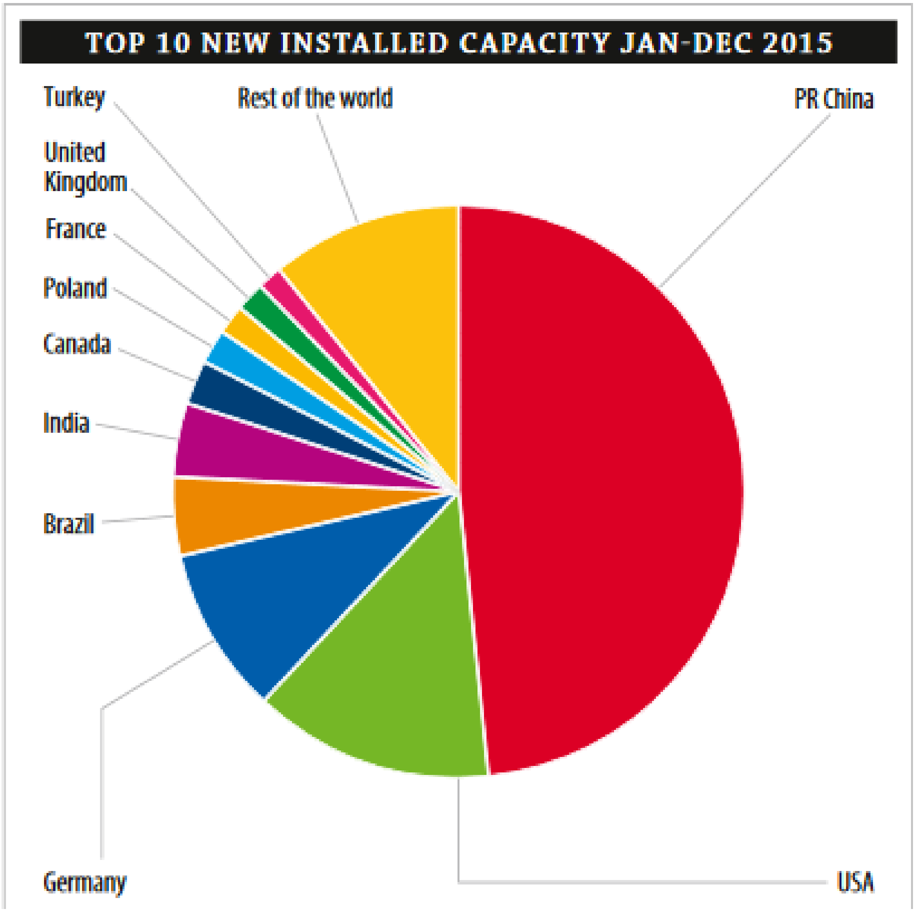
Q3 2016 Installed Wind Power Capacity (MW)

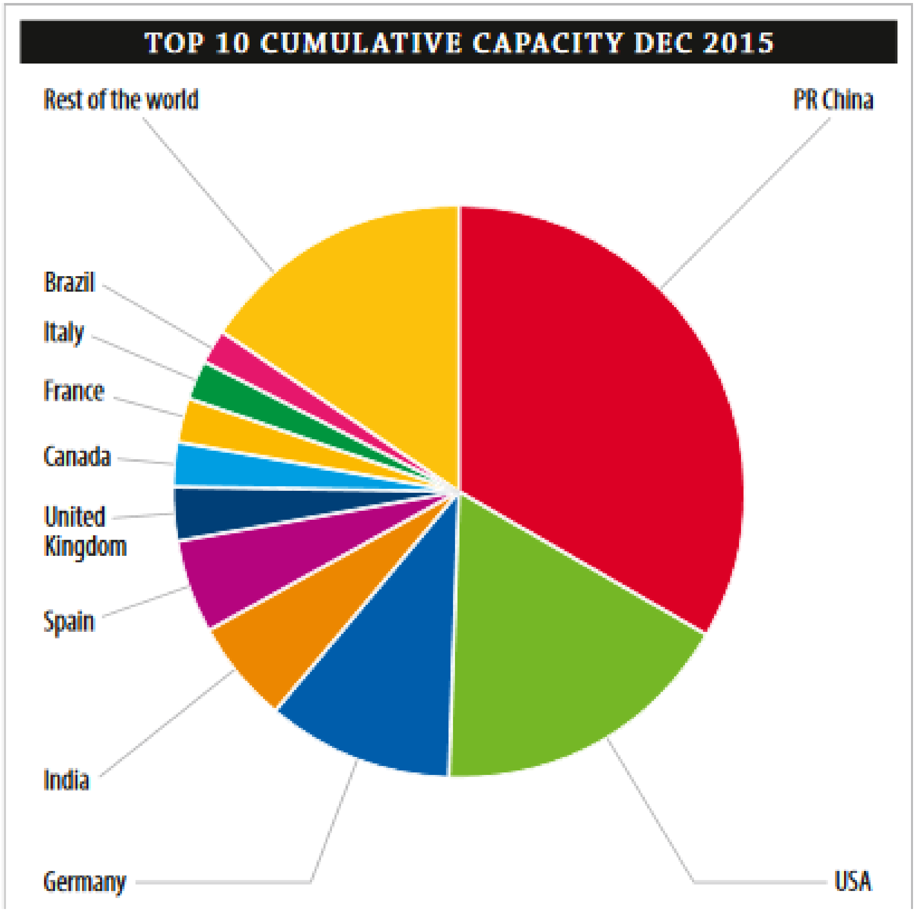


Total Installed Wind Capacity: 75,714 MW

Source: American Wind Energy Association Q3 2016 Market Report

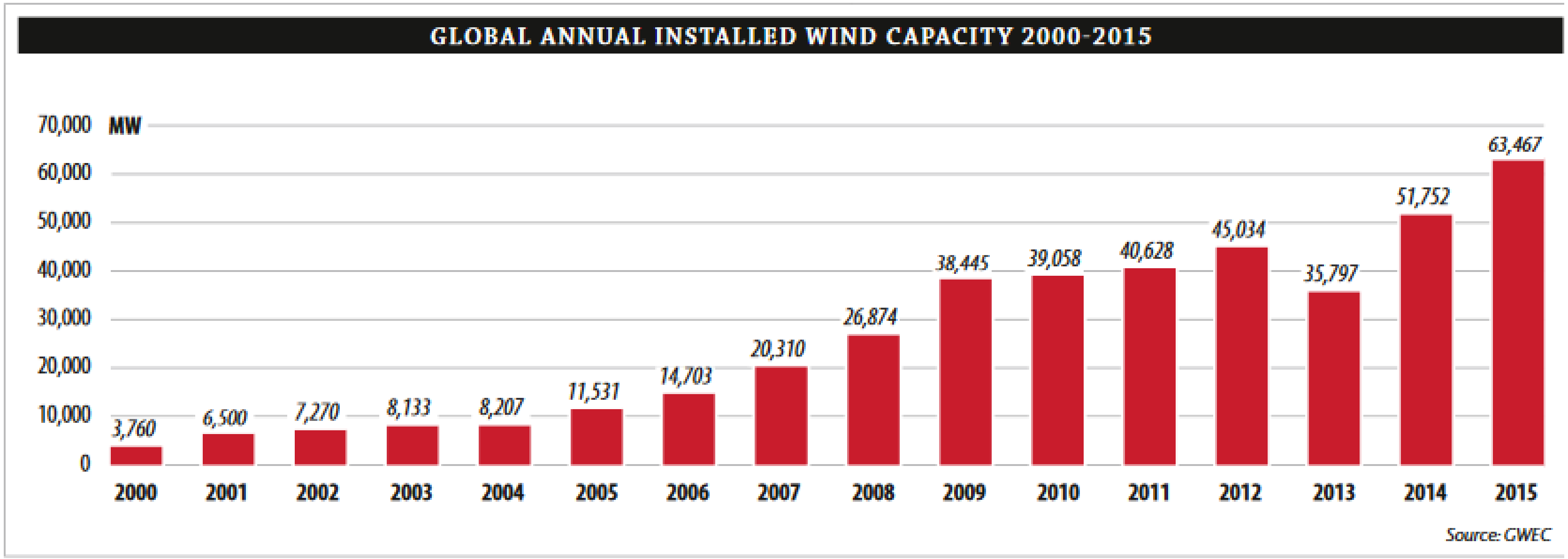
Global Wind Industry





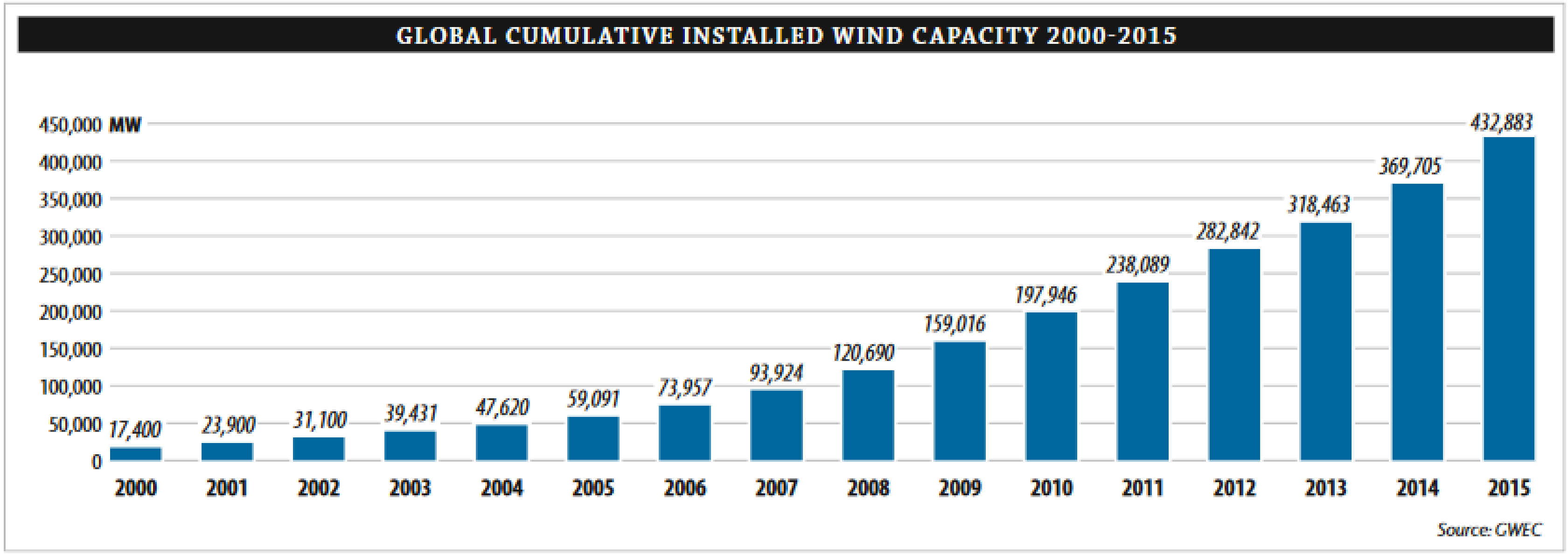
Source: GWEC 2015 Report

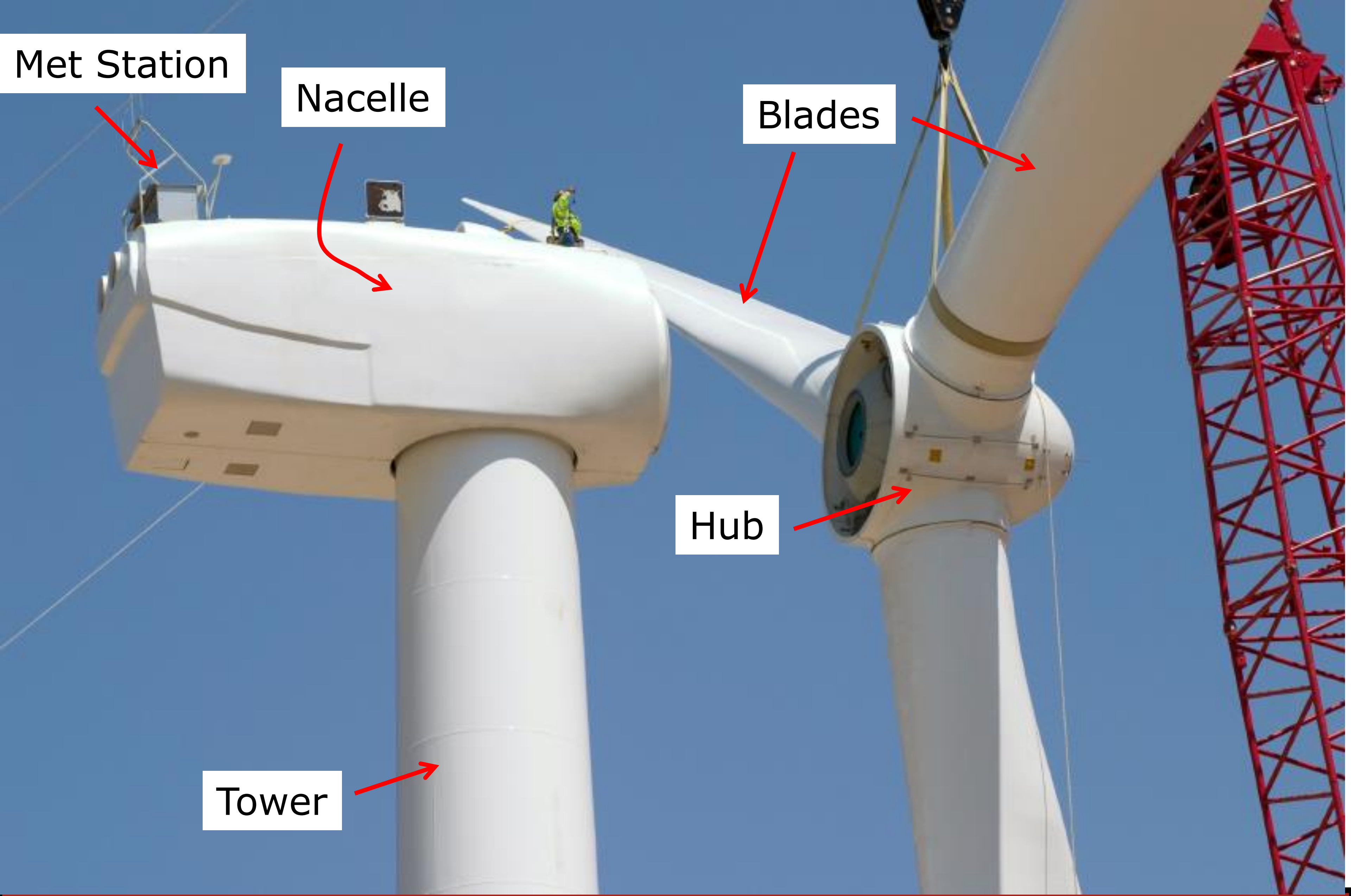
Global Wind Industry

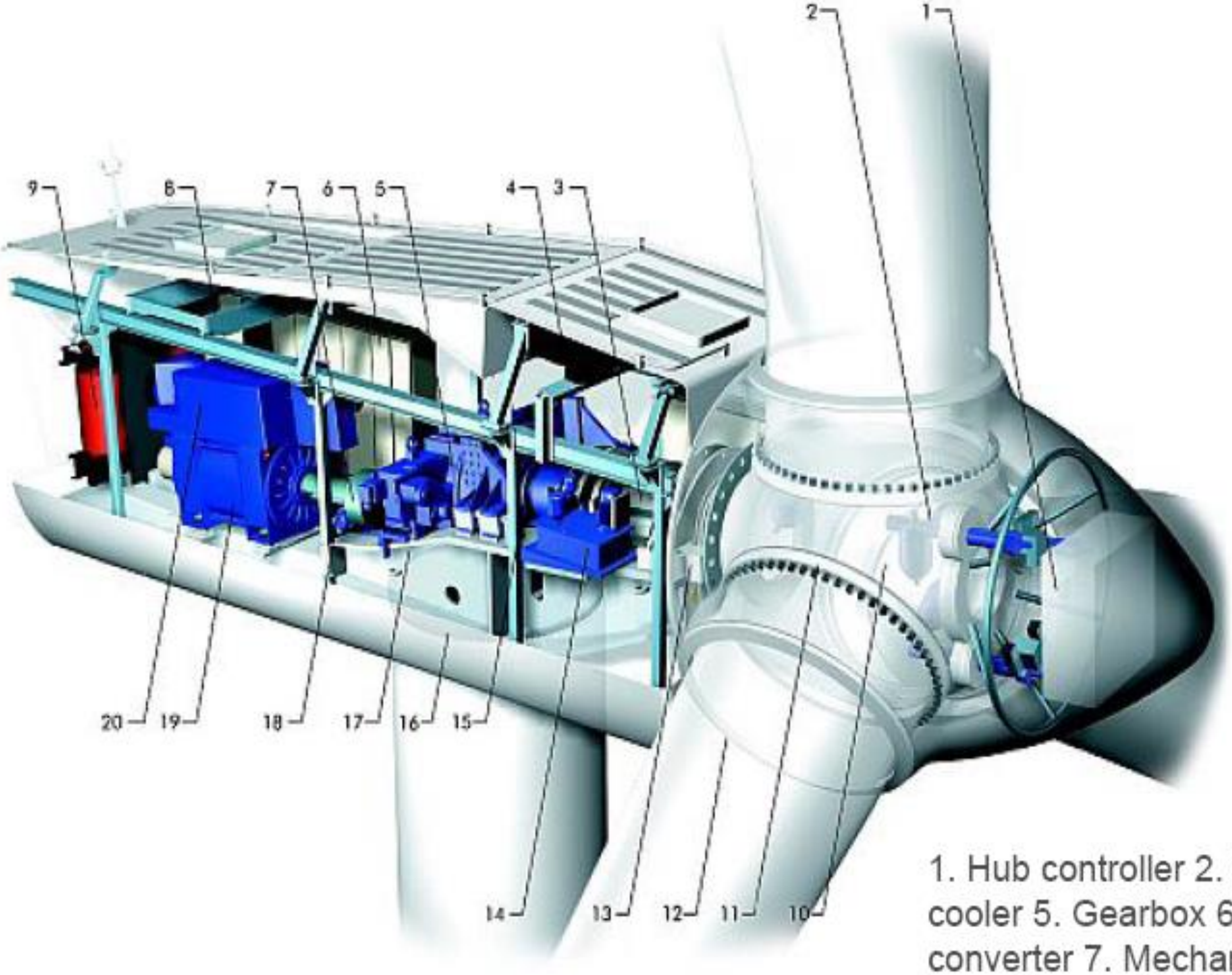


Source: GWEC 2015 Report

Global Wind Industry




Met Station
Nacelle
Blades
Hub
Tower



1. Hub controller 2. Pitch cylinder 3. Main shaft 4. Oil cooler 5. Gearbox 6. VMP-Top controller with converter 7. Mechanical disc brake 8. Service crane 9. Transformer 10. Blade hub 11. Blade bearing 12. Blade 13. Rotor lock system 14. Hydraulic system 15. Hydraulic clamp ring 16. Turntable 17. Machine foundation 18. Yaw gears 19. OptiSpeed™ generator 20. Air cooler for generator

Available Power

- Power extracted from the wind turbine

$$P = \frac{1}{2} C_p A \rho v^3$$

- Where
  - C_p: is wind turbine design and operation-dependent power coefficient, usually between 0.3 and 0.4

Wind Turbine Types

- What wind types of wind turbines are there?
- Generally classified as
  - Vertical Axis Wind Turbines (VAWT)
  - Horizontal Axis Wind Turbines (HAWT)

Wind Turbine Types

- Vertical Axis Wind Turbines (VAWT) are less common but have niche applications
- Advantages:
  - do not have to face the wind to harness energy
  - generator is located at the base which has mechanical advantages
- VAWTs are more expensive

Wind Turbine Types

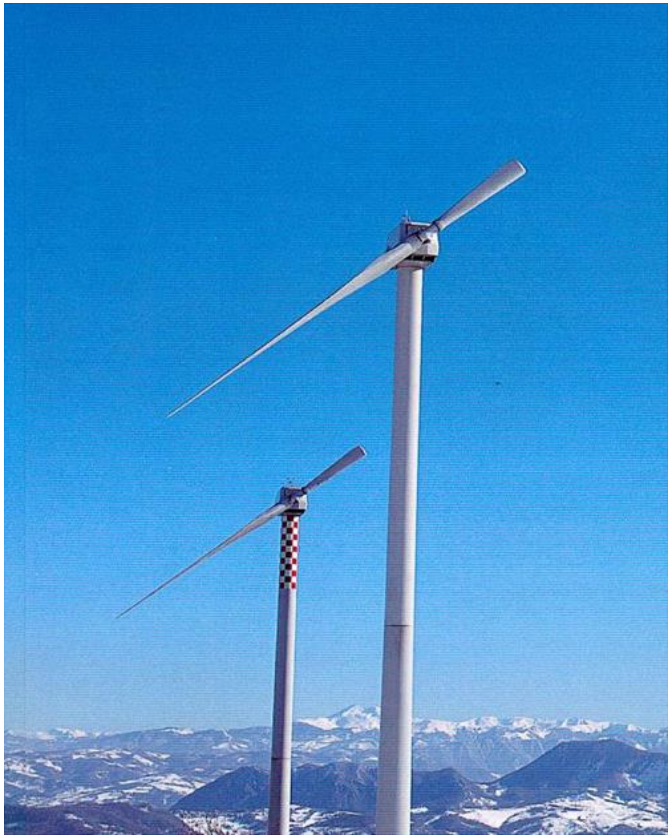
Source: Lysippos, Wikimedia Commons author (GNU Free Documentation License) (Public Domain)

Wind Turbine Types

- Horizontal Axis Wind Turbines are the most common
- Usually 2 or 3 blades

Wind Turbine Types

single blade wind turbine



Source: http://wind-energy-the-facts.org

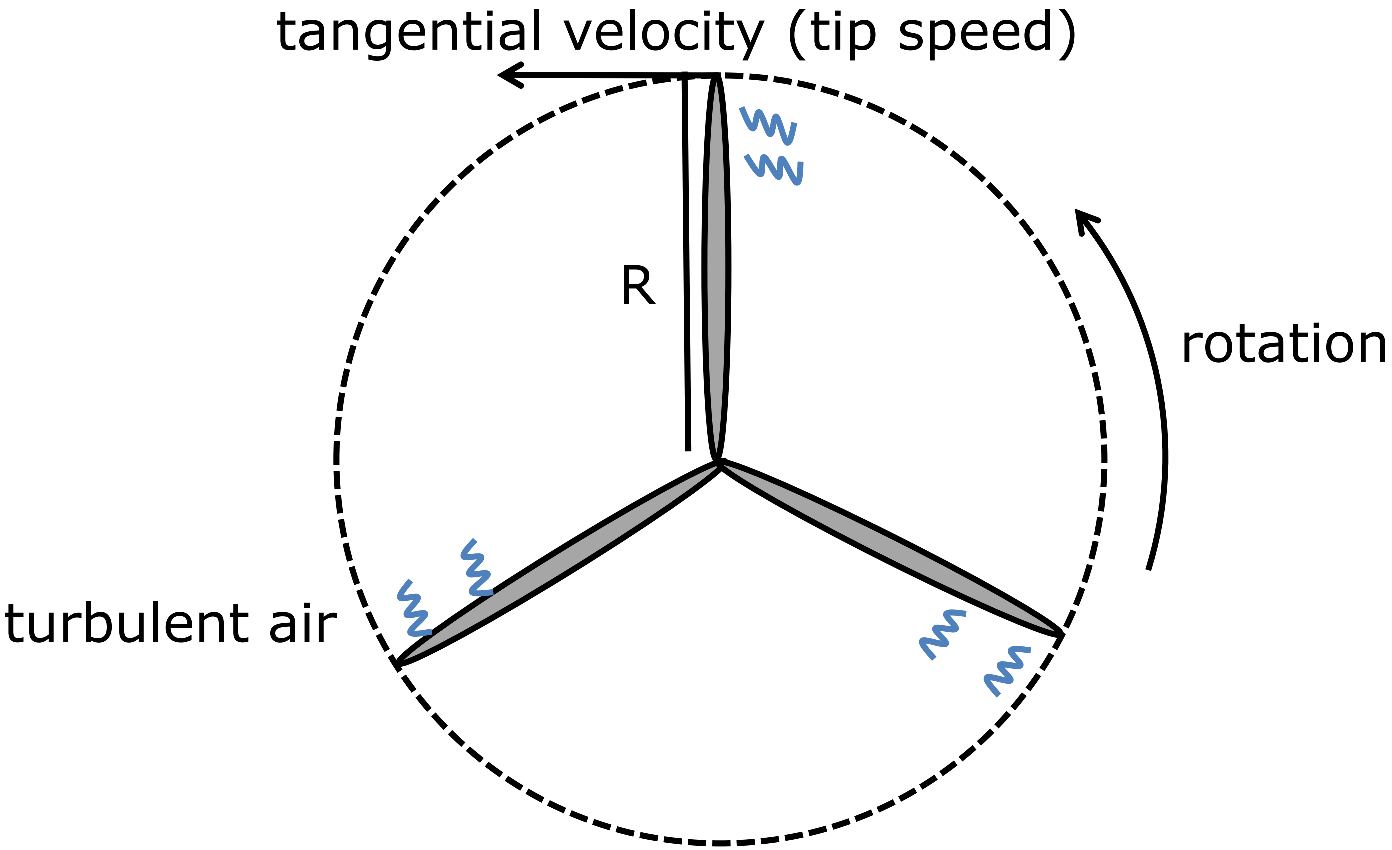
two bladed wind turbine

Source: https://energysavingwales.org.uk

Wind Turbine Operation

- Wind turbines extract energy from the interaction of the rotor blades and the moving air
- Goal: have blades interact with as much air as possible without passing through turbulent wake left by another blade

Wind Turbine Operation



Wind Turbine Operation

- Tip speed of a blade, U (m/s):
  - $U = \Omega R$
- Where:
  - Ω: is the angular velocity rad/sec
  - R: is the radius of the turbine rotor area, in m.
- Using revolutions per minute (RPM)

$$U = \frac{2\pi RN}{60}$$

- Where
  - N: is the RPM

Wind Turbine Operation

- Wind turbines at Wild Horse rotate at a constant velocity (after cut-in) of 16.5 RPM. The rotor blade length is 40 m. How fast is the tip of each blade moving in miles per hour?
  - Hint: there are 1609 m in 1 mile

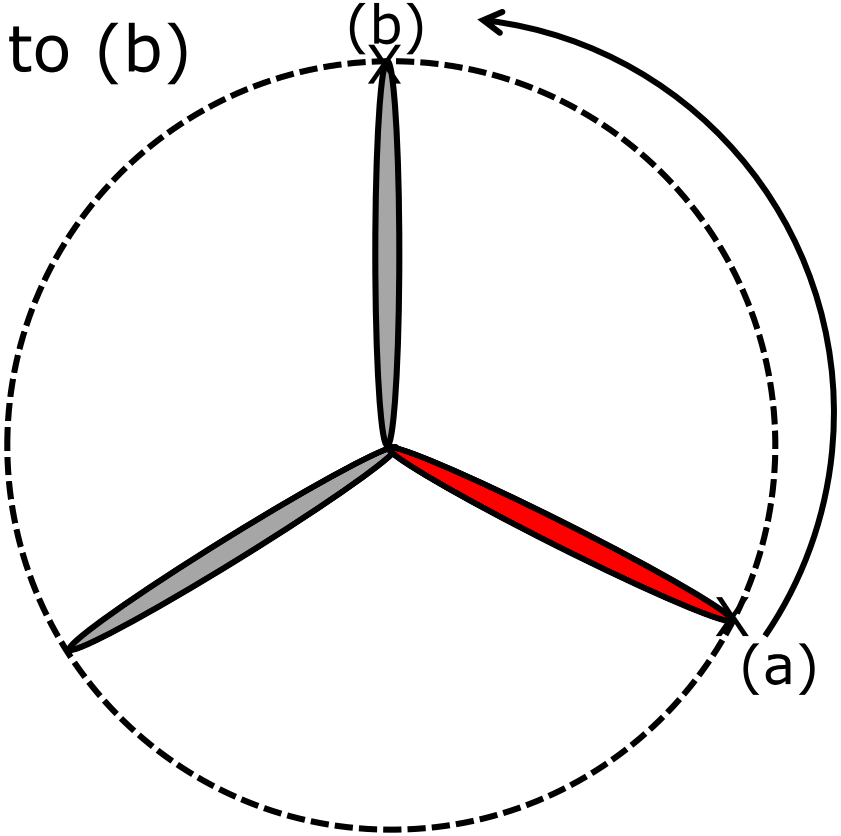
Wind Turbine Operation

- Wind turbines at Wild Horse rotate at a constant velocity (after cut-in) of 16.5 RPM. The rotor blade length is 40 m. How fast is the tip of each blade moving in miles per hour?

$$U = \frac{2\pi RN}{60} = \frac{2\pi \times 16.5 \times 45}{60} = 69 \text{ m/s} = 154 \text{ mph}$$

Wind Turbine Operation

- How long does it take for a blade to reach the space occupied by the preceding blade?
- Length of the arc from (a) to (b)
  - $L_{ab} = 2\pi R/3$
- $t_b = L_{ab}/U$
  - $U = \Omega R$
- $t_b = 2\pi/3\Omega$

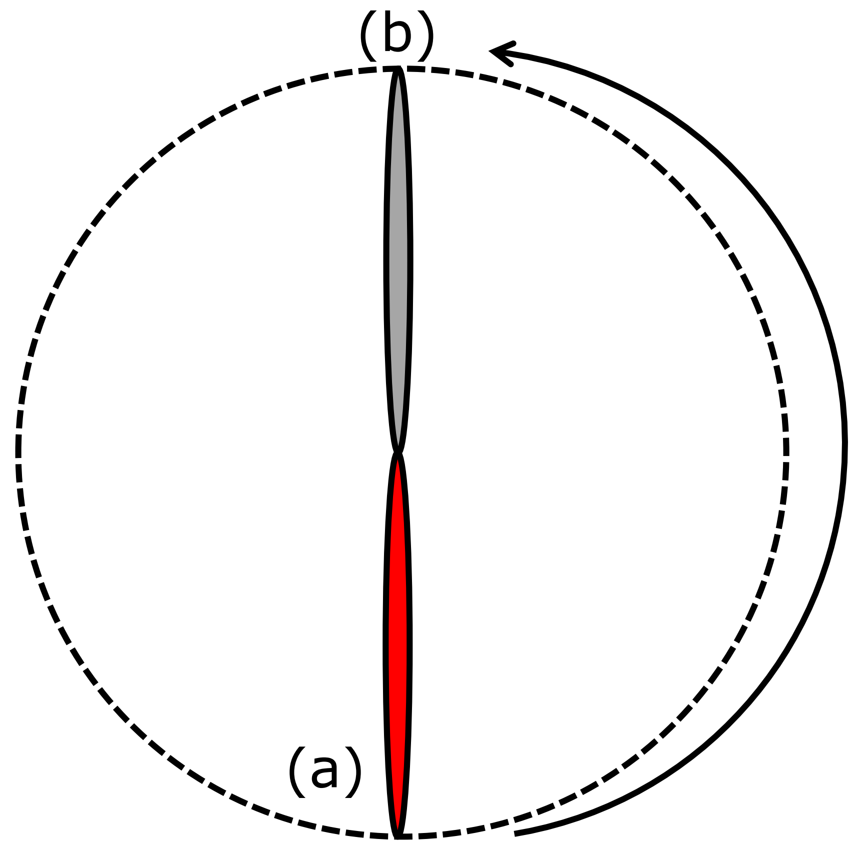


Wind Turbine Operation

- For any number of blades:

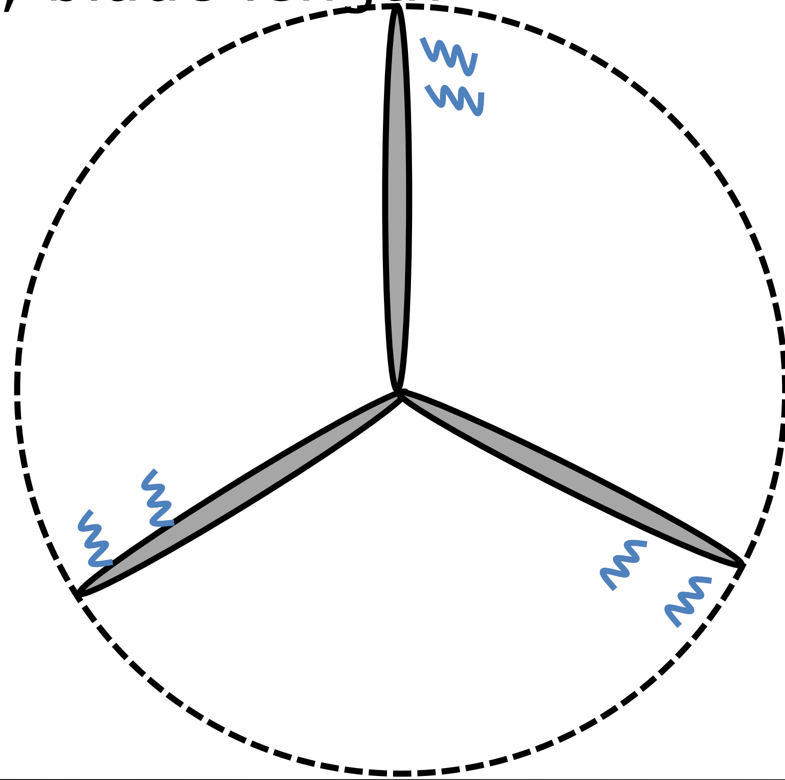
$$t_b = \frac{2\pi}{n\Omega}$$

- Where:
  - n: number of blades



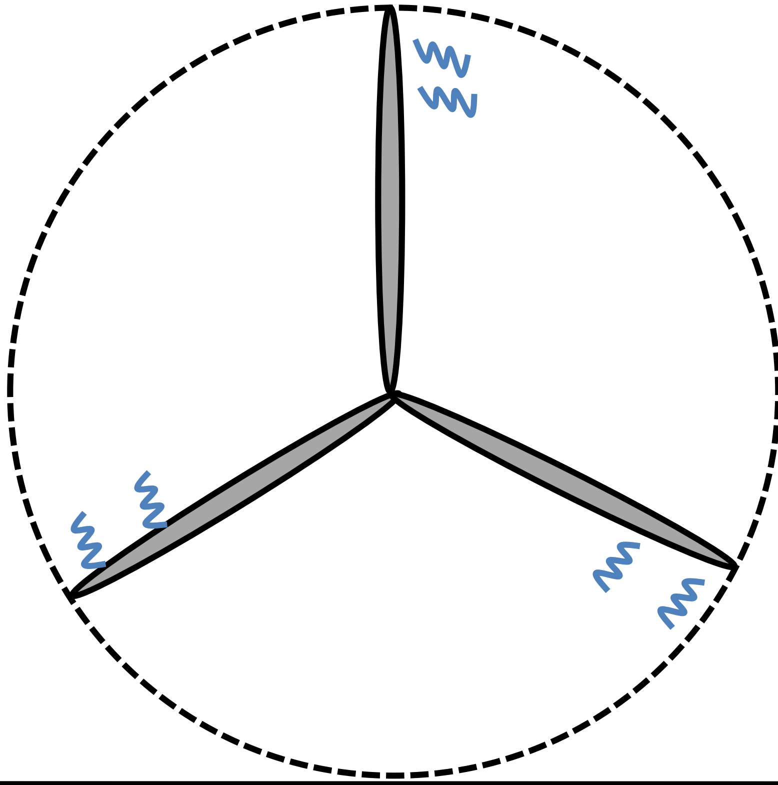
Wind Turbine Operation

- Let the turbulence (wake) for each blade last for t_w seconds
- t_w is a function of wind speed, blade length



Wind Turbine Operation

- Approximate empirical relationship:
  - $t_w \sim (0.5R)/v$
  - v: velocity of the air mass
- Maximum power extraction will occur approximately when $t_b = t_w$



Maximum Power Extraction

- Let $\lambda = \frac{U}{v}$
- Where:
  - λ *:* the tip-speed ratio (sometimes referred to as TSR)
- TSR: the ratio of the speed of the tip of the wind turbine blade to the wind speed of the air before it interacts with the turbine

Maximum Power Extraction

- At maximum power extraction:

$$t_b = t_w$$

$$\frac{2\pi}{n\Omega} = \frac{0.5R}{v} \Rightarrow \frac{2\pi R}{nU} = \frac{0.5R}{v} \Rightarrow \frac{U}{v} = \frac{4\pi}{n}$$

$$\Rightarrow \lambda^* = \frac{U}{v} = \frac{4\pi}{n}$$

- Where λ^* is the optimal TSR

Maximum Power Extraction

$$\lambda^* = \frac{2\pi}{n}\frac{R}{d} = \frac{4\pi}{n}$$

- In real life, this derivation underestimates the TSR by about 30%
  - Optimal TSR ~7-8 for utility scale turbines
- Also note: more blades = lower TSR => slower angular velocity

Maximum Power Extraction

- At a wind speed of 15 m/s, what is the optimum tip speed of a wind turbine with three 40 m blades?

Maximum Power Extraction

- At a wind speed of 15 m/s, what is the optimum tip speed of a wind turbine with three 40 m blades?

$$\lambda^* = \frac{4\pi}{n} = \frac{4\pi}{3} = 4.18$$

$$\Rightarrow U = v\lambda^* = 4.18 \times 15 = 62.83 \text{ m/s} = 141 \text{ mph}$$

Maximum Power Extraction

- At a wind speed of 30 m/s, what is the optimum tip speed of a wind turbine with one 40 m blade?

Maximum Power Extraction

- At a wind speed of 30 m/s, what is the optimum tip speed of a wind turbine with one 40 m blade?

$$\lambda^* = \frac{4\pi}{n} = \frac{4\pi}{1} = 12.56$$

$$\Rightarrow U = v\lambda^* = 12.56 \times 30 = 377 \text{ m/s} = 843 \text{ mph!}$$

Faster than the speed of sound!

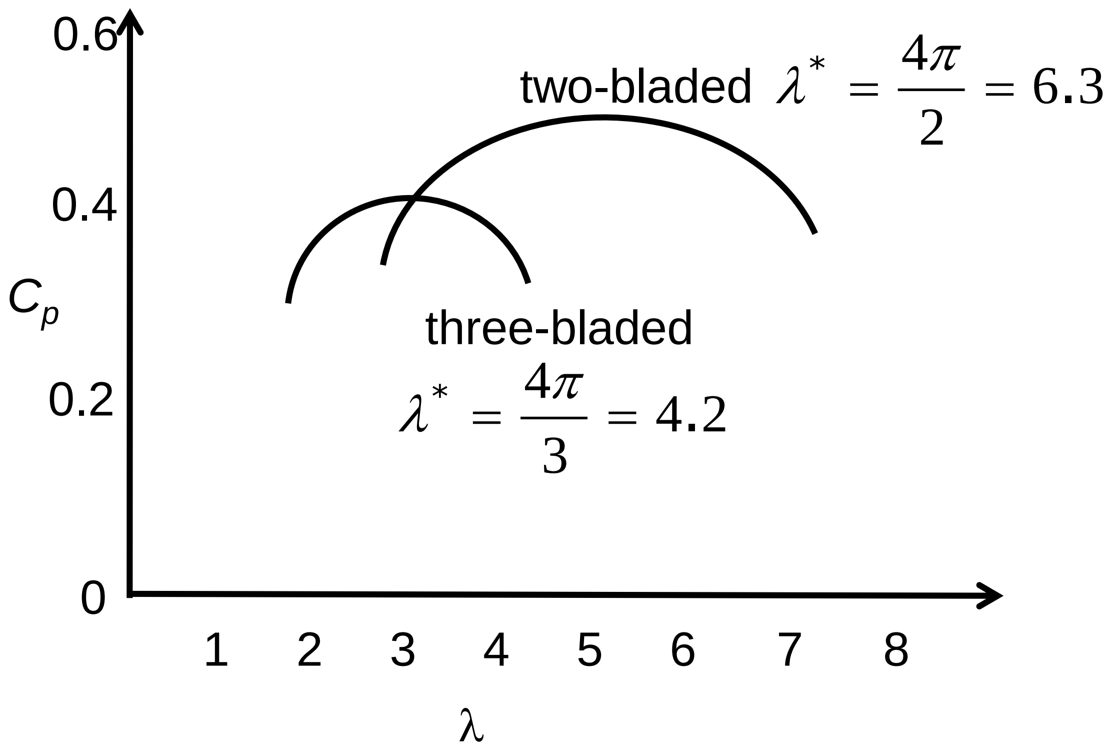
Power Coefficient

- Mechanical power available is:

$$P = \frac{1}{2} C_p A \rho v^3$$

- C_p: is function of
  - TSR
  - Pitch
  - Other variables
- The Betz Limit prevents C_p from being larger than 59%
- C_p is usually in range of 0.3-0.4

Power Coefficient

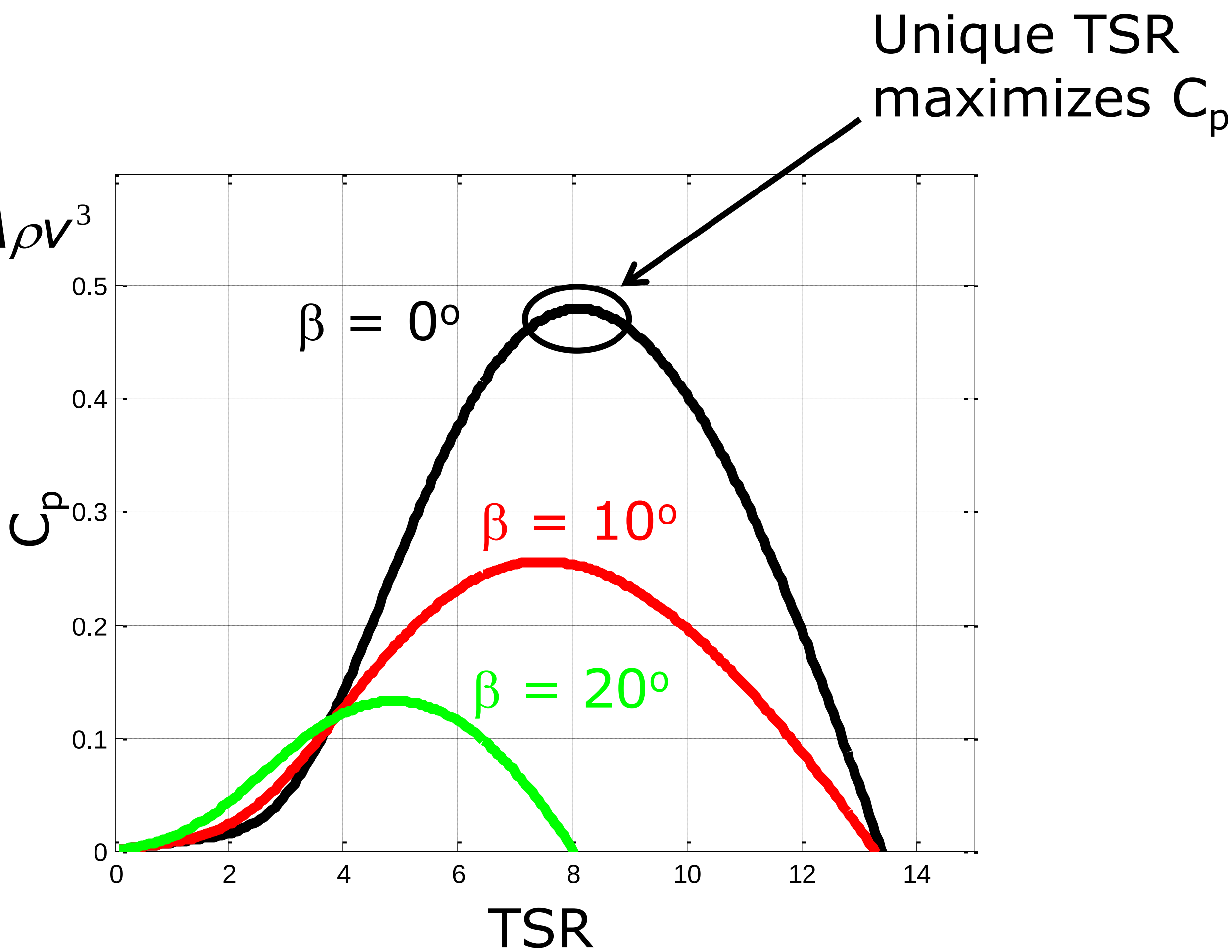


Recall that λ* tends to underestimate the actual optimal TSR

C_p versus TSR

$$P_m = \frac{1}{2} C_p(\lambda, \beta) A \rho v^3$$

β = pitch angle

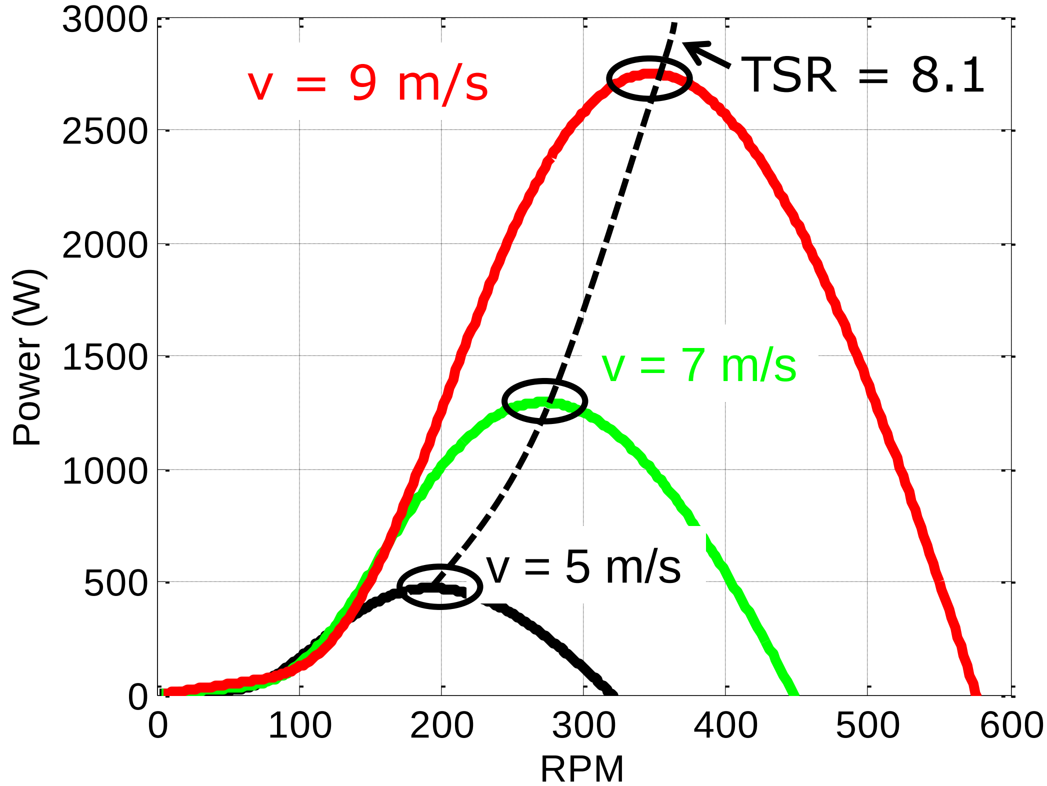


Note: this is for a specific blade design

Power versus RPM

- Variable speed (RPM) operation is desired to maximize rotor power

- Actual RPM depends on generator torque



r = 2m
$\beta = 0^o$

Torque

- Power can be expressed as the product of torque (T) and angular velocity
  - $P = \Omega T$
- Torque is inversely related to the angular speed for a given power

Torque

- For a given power output, as the number of blades increases, does the torque developed at the optimal TSR increase or decrease?

Torque

- For a given power output, as the number of blades increases, does the torque developed at the optimal TSR increase or decrease?
- Recall

$$\lambda = \frac{U}{v};\ \lambda^* = \frac{4\pi}{n}$$

- then

$$\Omega = \frac{U}{R} = \frac{v\lambda^*}{R} = \frac{v}{R}\frac{4\pi}{n}$$

$$P = \Omega T = T\frac{v}{R}\frac{4\pi}{n} \Rightarrow T = P\frac{nR}{4\pi v}$$

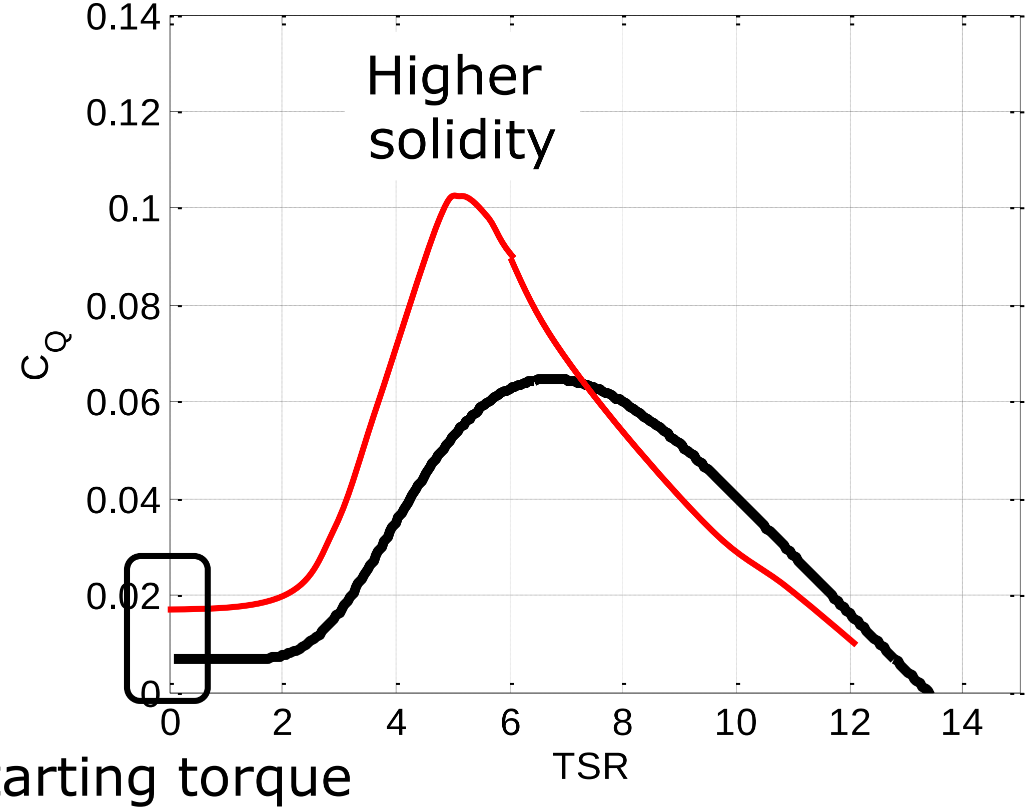
More blades: lower optimal TSR
Lower TSR: higher torque
(for a given power)

Torque

- The more solid the rotor area (number of blades), the higher the starting torque
- The "Little House on the Prairie" style wind turbines are highly solid and used for pumping water

Torque

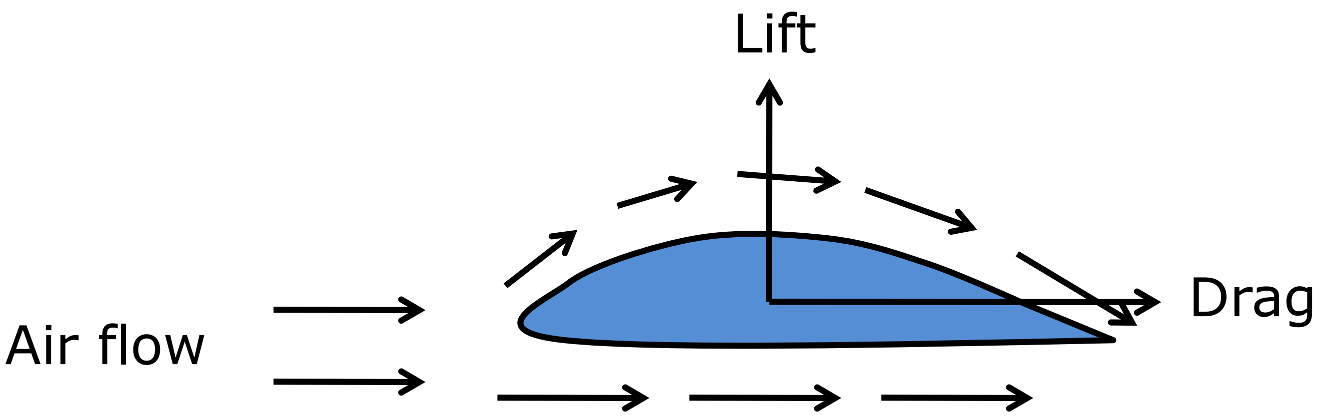
- Torque coefficient (C_Q/TSR) varies with TSR
- Unique maximum point



Blade Aerodynamics

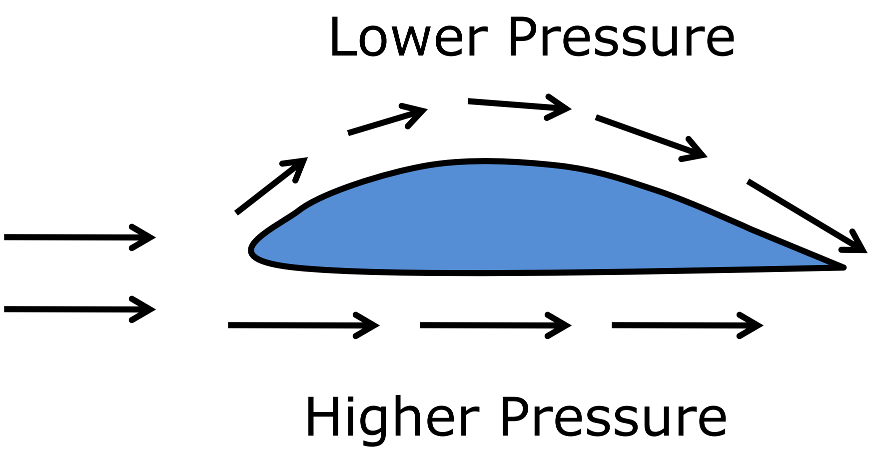
- Wind turbine blade design is an active area of research
- We will only discuss the very basics as it relates to wind turbine operation

Blade Aerodynamics



Blade cross section

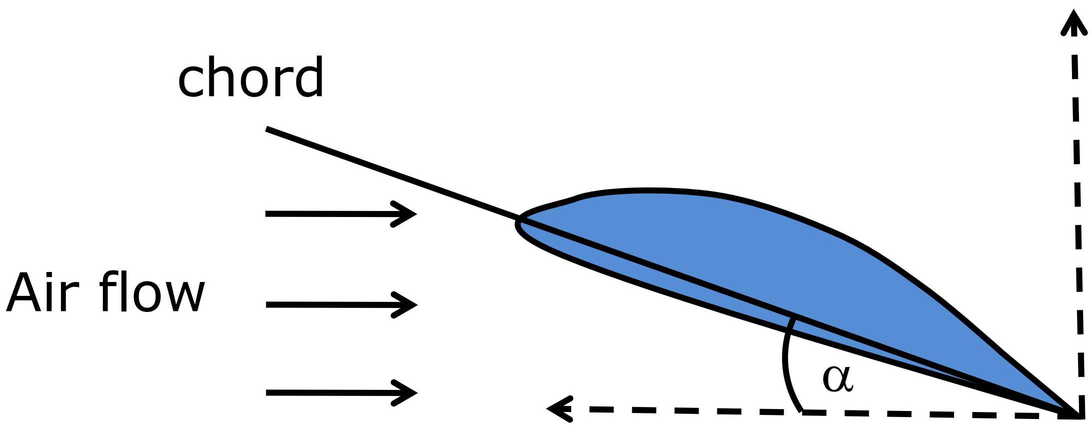
Blade Aerodynamics



Lift force rotates turbine blades

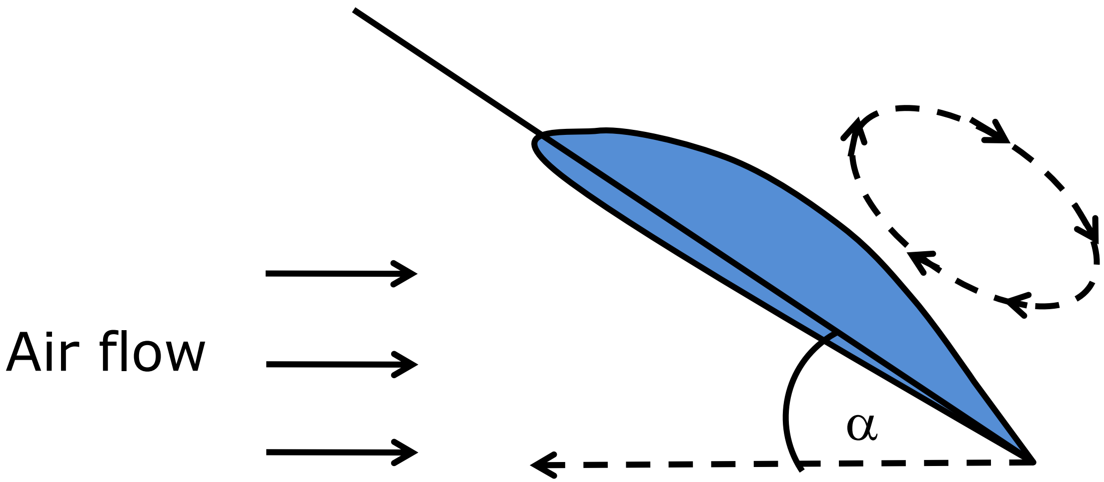
Blade Aerodynamics

- Angle of attack: angle between airflow and the chord line of the airfoil
- Increasing angle of attack tends to increase lift
- Some wind turbines adjust their pitch (β) to affect the angle of attack and increase lift



Blade Aerodynamics

- Increasing angle of attack too greatly induces a stall
- Lift dramatically decreases
- This can happen in airplanes



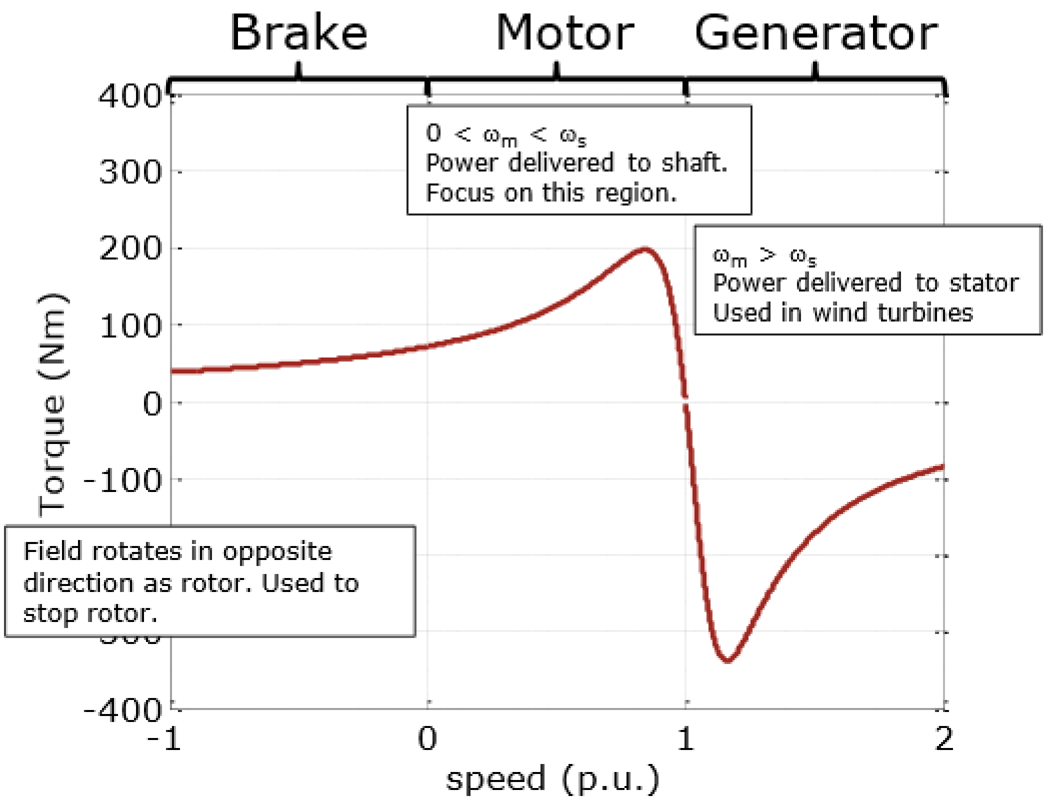
Wind Turbine Operational Speeds

- Two classes of wind turbines
  - Constant Speed
  - Variable Speed
- Technology and performance (efficiency) differs for each class

Constant Speed Wind Turbine

- Rotor rotates at nearly constant speed
  - may vary by a few percent or less, depending on wind speed
  - assumes wind is sufficient for rotation to start (different from cut-in speed)
- Uses <u>induction generator</u> to produce electricity
- Rotational speed determined by the generator design (number of poles), grid frequency, gearbox ratio

Constant Speed Wind Turbine

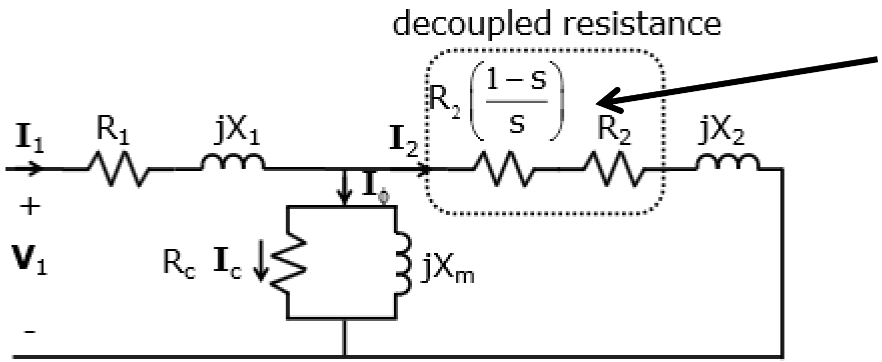


Constant Speed Wind Turbine

Slip of a motor is:

$$s = \frac{\omega_r}{\omega_s} = \frac{\omega_s - \omega_m}{\omega_s} = \frac{N_s - N_m}{N_s}$$

For wind turbines, s is negative as the generator's rotor rotates faster than the synchronous speed



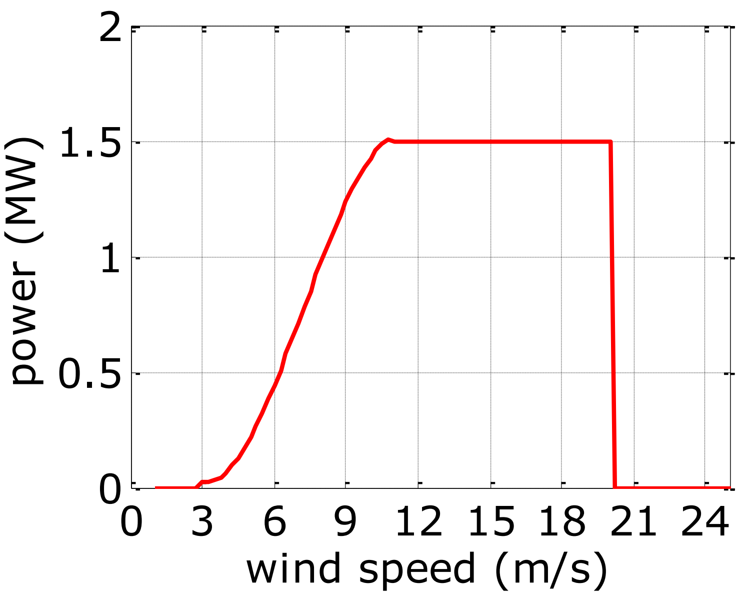
Negative resistance, power is generated

Constant Speed Wind Turbine

- Advantages:
  - Inexpensive electrical system
  - Simple design
  - No harmonics
- Disadvantages:
  - Optimal TSR is only achieved for one wind speed
  - Mechanical stresses
  - Requires grid connection
  - Noisy

Constant Speed Wind Turbine

- Wind turbine must be capable of maintaining nearly rated power for wind speeds between rated and cut-out
  - avoid generator overloading



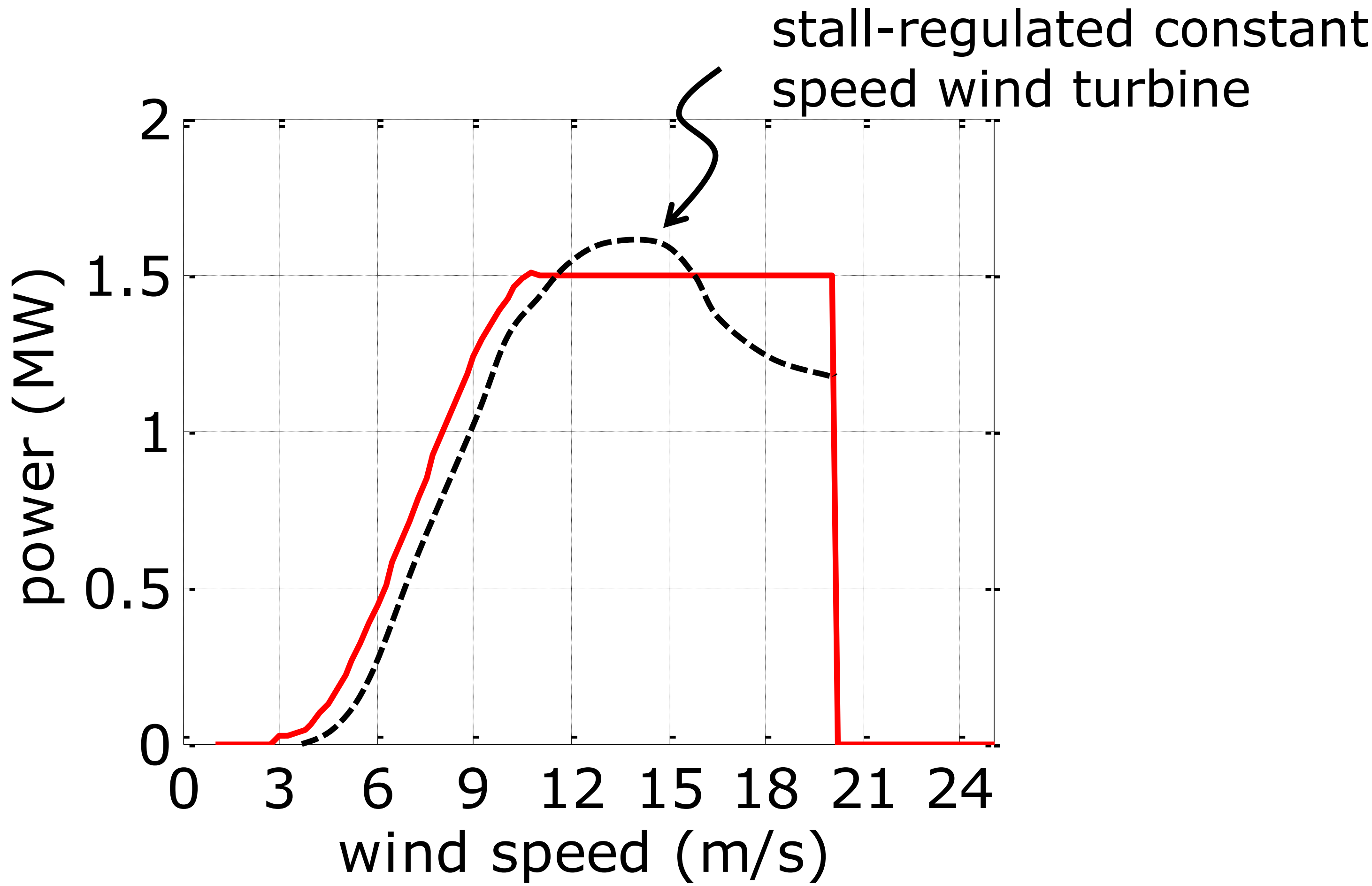
Constant Speed Wind Turbine

- Since torque (and hence mechanical power) on a constant speed wind turbine increases with wind speed, need to make the turbine less aerodynamically efficient to maintain nearly constant electrical power output
  - Need to regulate the power
- Two types of constant speed wind turbines:
  - Stall regulated (passive)
  - Pitch regulated

Stall Regulated, Constant Speed Turbines

- No control necessary
- Blades are aerodynamically designed to become less efficient at high wind speeds
- Angle of attack is increased as wind speed increases, after rated wind speed, the blades stall and the lift force is reduced
- Entirely passive

Stall Regulated, Constant Speed Turbines



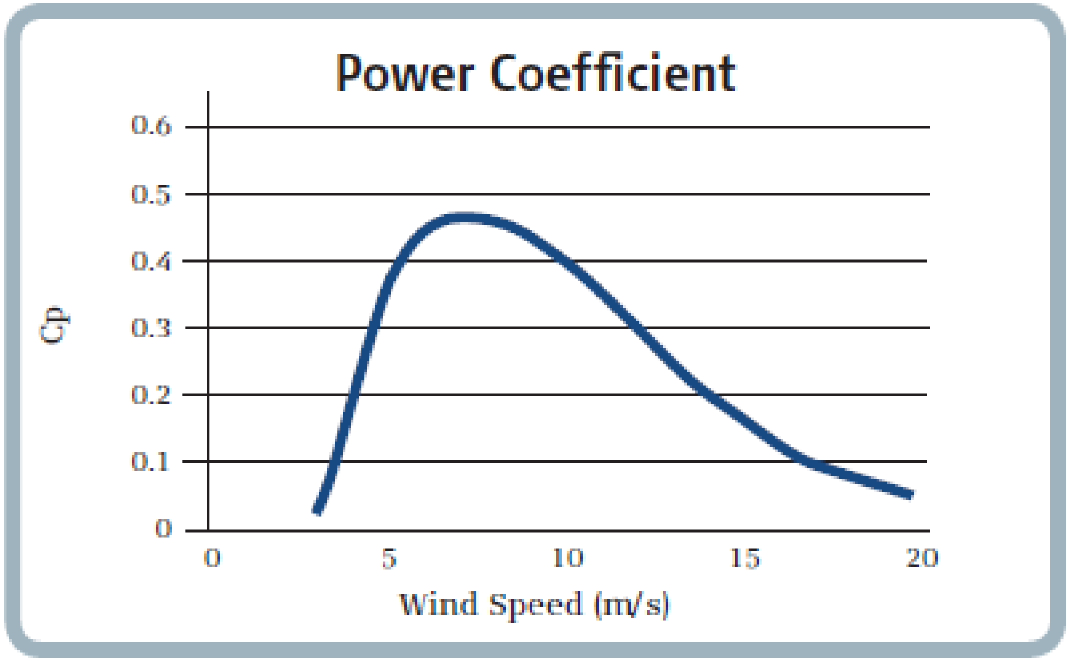
Pitch Regulated, Constant Speed Turbines

- Blades rotate along longitudinal axis
- Pitching blades can increase or decrease angle of attack
  - increase angle of attack at start-up
  - decrease angle of attack at wind speeds above rated
    - lift decreases, less power

Variable Speed Turbines

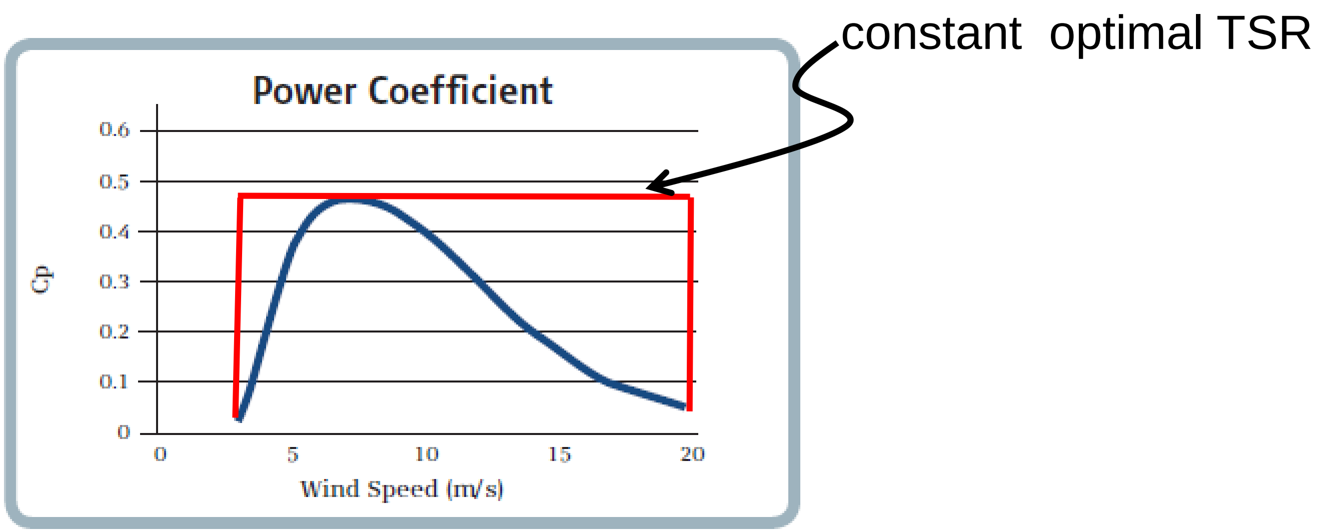
- Rotor can rotate over a range of speeds
- Generator:
  - Wound rotor induction
  - Doubly fed induction
  - Variable frequency
- Generator can be controlled for different torque/speed relationships
- Wind turbine blades can be pitch regulated

Constant Speed Wind Turbine



Source: Vestas V82-1.65 MW

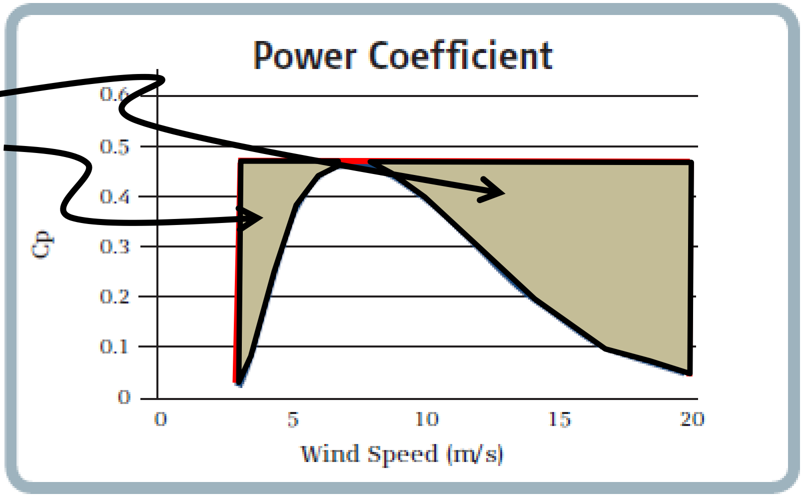
Constant Speed Wind Turbine



Source: Vestas V82-1.65 MW

Constant Speed Wind Turbine

Penalty for not operating at optimal TSR



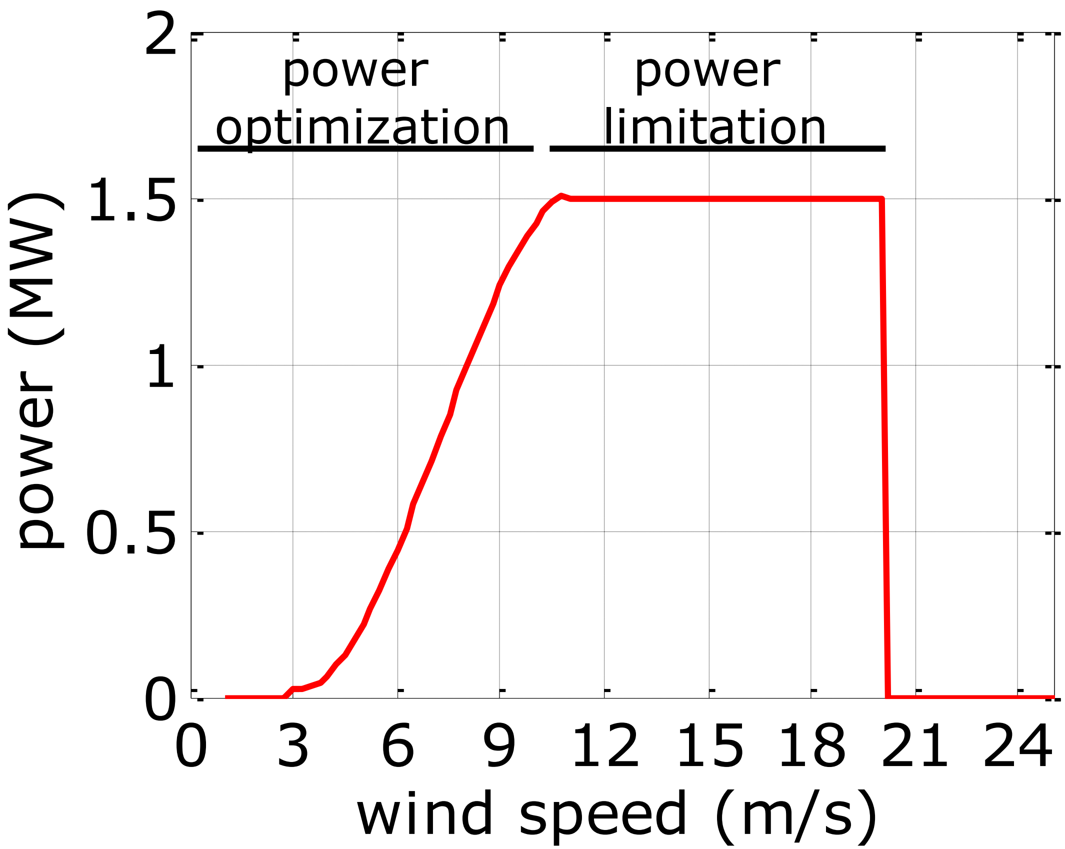
Source: Vestas V82-1.65 MW

Ignoring effects of other components on C_p

Variable Speed Turbines

- Low wind speeds: generator torque control used to optimize power
- High wind speeds (above rated): pitch control used

Variable Speed Turbines



Variable Speed Wind Turbine

- Most new wind turbines are variable speed
- Advantages:
  - Greater energy conversion (5-15%)
  - Lower cut-in speed
  - Aerodynamically efficient
- Disadvantages:
  - Expensive
  - Less electrically efficient
  - Complex control

Reading

E. DeMeo, W. Grant, M. Milligan and M. Schuerger, “Wind Plant Integration”, Power and Energy Magazine, vol. 3, no. 6, Dec. 2005.