Sustainable Energy Transformation Technologies, SH2706

Lecture No 17

Title:
Design and Operation of Wind Power

Henryk Anglart
Nuclear Engineering Division
Department of Physics, School of Engineering Sciences
KTH

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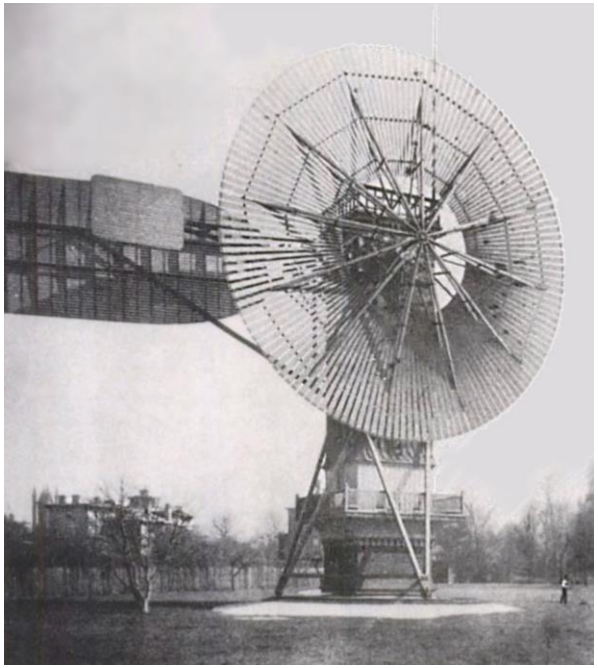
Outline

- Introduction
- Overview of major existing designs
- Principles of operation
- System efficiency
- Current status and future perspectives

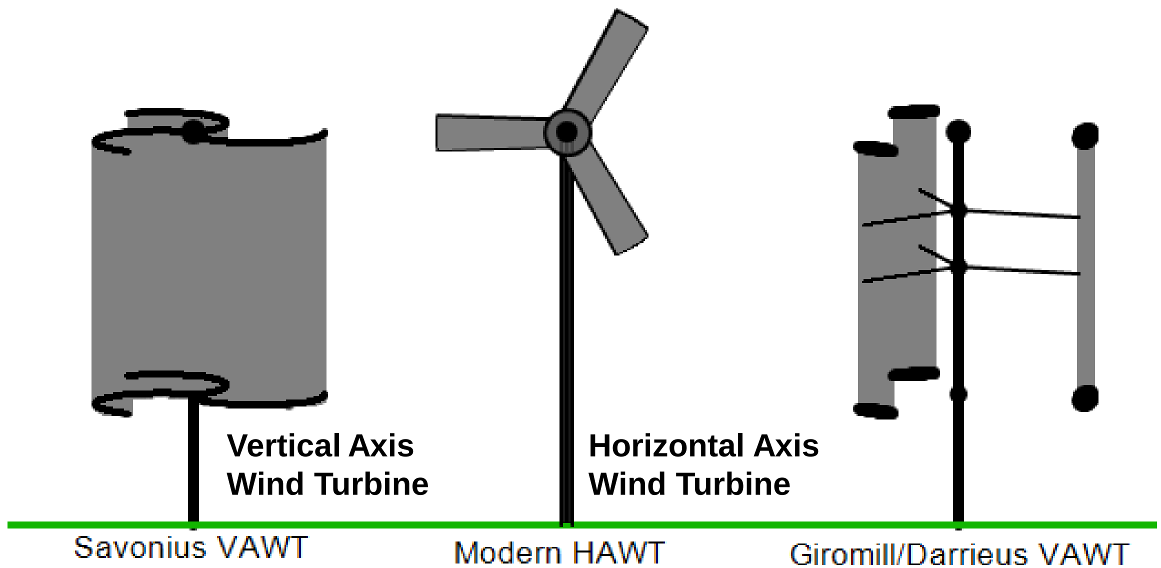
First Windmill for Electricity

- Wind power has been used since sails were invented
- For more than two thousands years wind-powered machines have ground grain and pumped water
- Wind-powered pumps drained the polders of the Netherlands and provided water for livestock in American mid-west or Australian outback
- In 1888 Charles Brush designed windmill to generate electricity



C. Brush's windmill rated at 12kW electrical power

Major Designs – History and Present



Wind Energy Proportional to U^3

- Wind energy is the kinetic energy of air in motion (wind)
- Total wind energy flowing through a surface *A* during time *t* with velocity *U* is:

$$E = \frac{1}{2} m U^2 = \frac{1}{2}(AUt\rho)U^2 = \frac{1}{2}(At\rho)U^3$$

- Thus the corresponding power is

$$N = \frac{E}{t} = \frac{1}{2}(A\rho)U^3$$

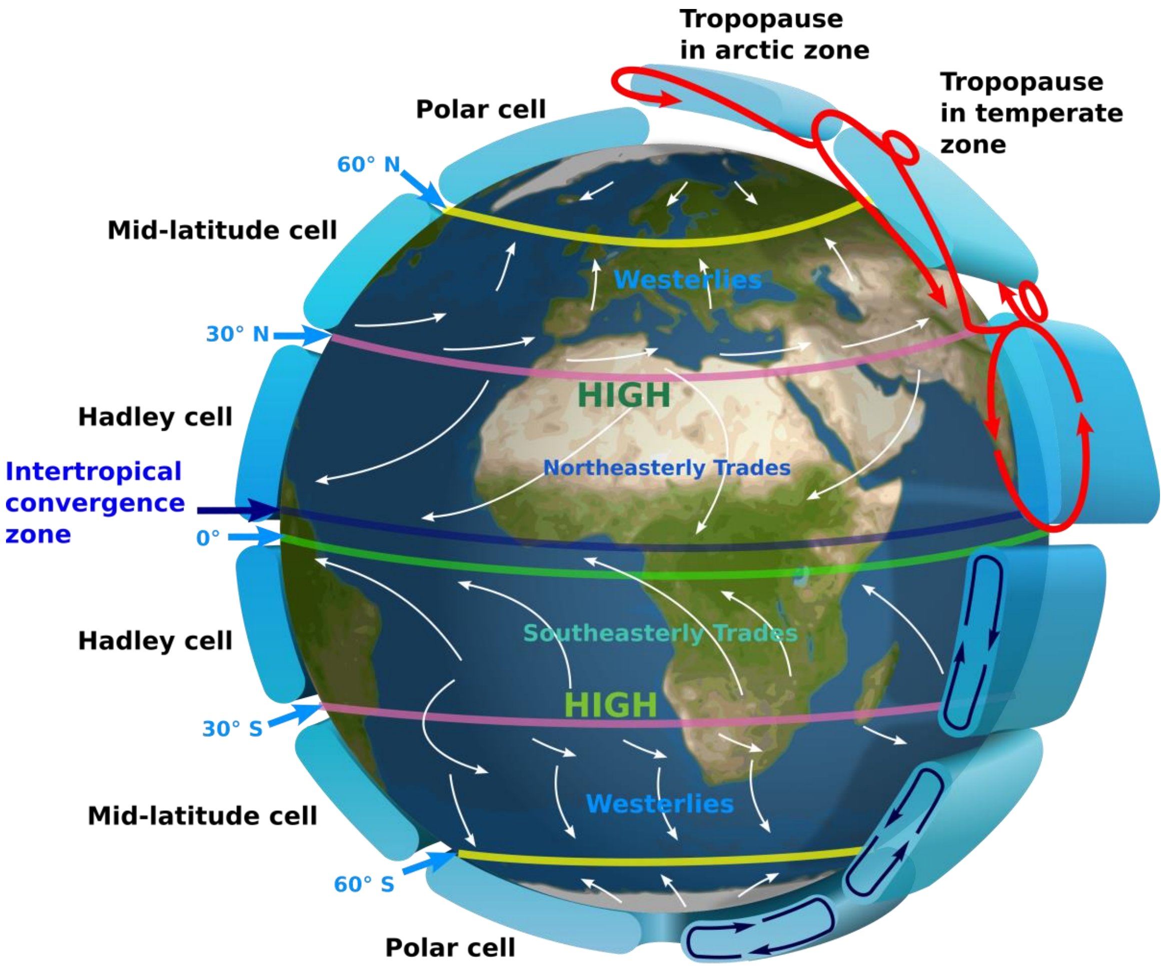
Wind energy and power are proportional to the third power of the wind speed

Global Average Wind Energy

- The global average (over the period from 1979 to 2010) wind kinetic energy is approximately equal to 1.5 MJ/m^2
  - In northern hemisphere this value is 1.31 MJ/m^2
  - In southern hemisphere: 1.70 MJ/m^2

- Note this non-uniform distribution
  - Wind energy depends on location and time
  - Winds are resulting from solar heating and the spherical shape of the Earth
  - Due to that an Earth's atmospheric circulation is developed
  - In addition, local effects are affecting winds:
    - Costal effects
    - Mountains

Global Circulation in Atmosphere



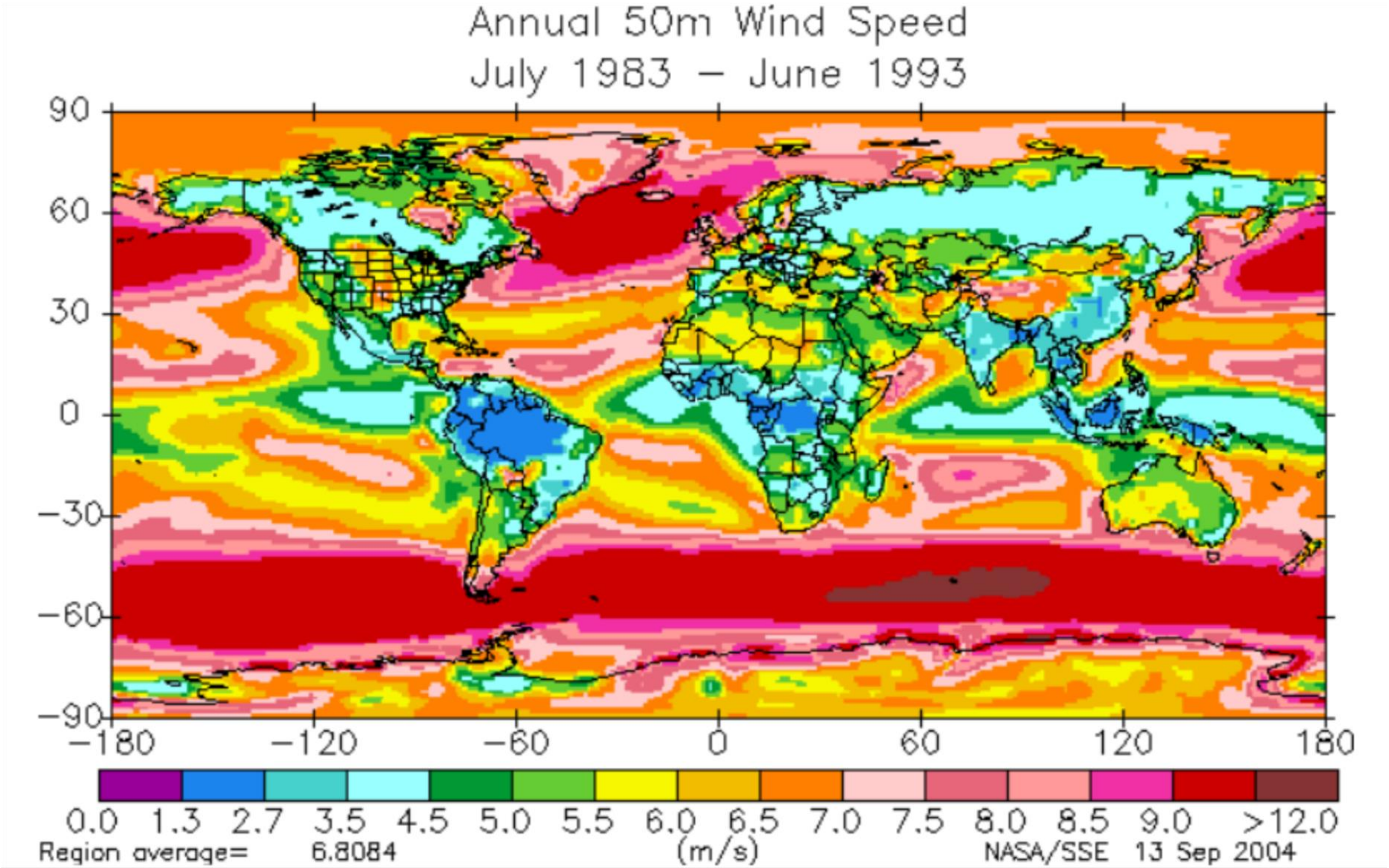
Global circulation of Earth's atmosphere displaying Hadley cell, mid-latitude cell and polar cell.

Winds are generally light and variable near the equator and in the horse latitudes (±30º)

The Hadley and Polar cells produce relatively gentle and reliable winds:

- *trade winds* (0º to ±30º)
- *polar easterlies* (±60º to poles)

Annual Wind Speed



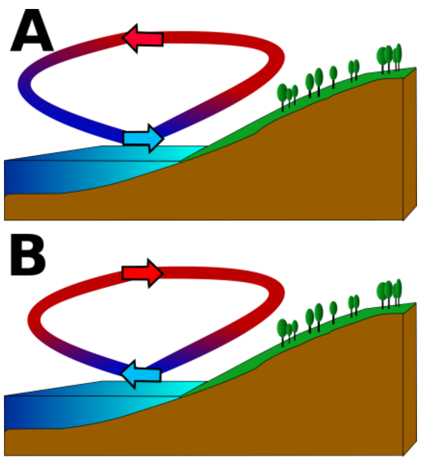
Synoptic Scale Winds

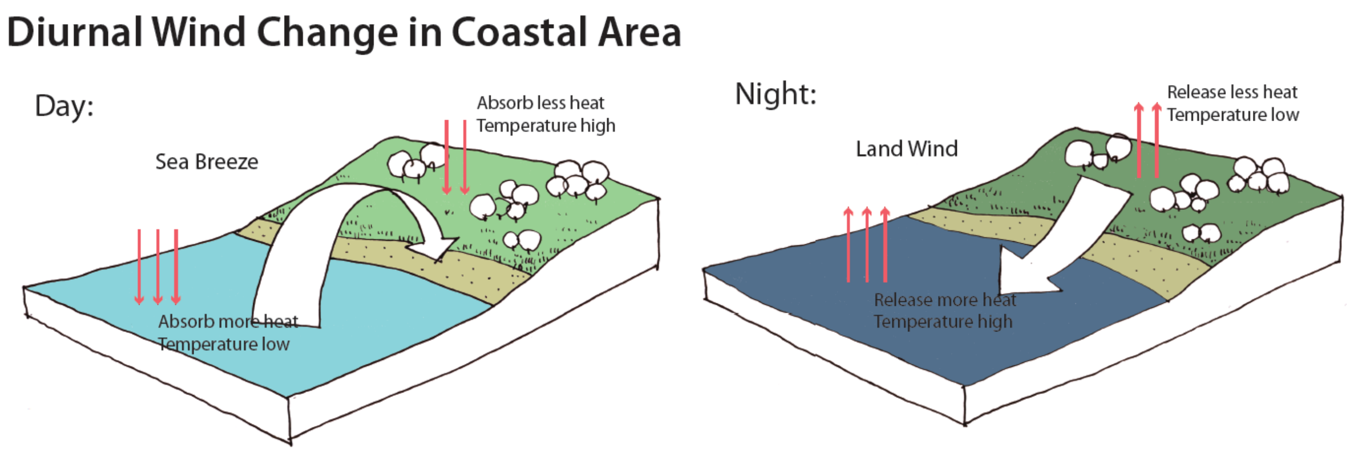
- Winds at the synoptic scale (~1000 km range) are dominated by regions of high and low pressure
  - **cyclones** – with circulation counter-clockwise around regions with low pressure (reversed in the Southern Hemisphere)
  - **anticyclones** - with circulation clockwise around regions with high pressure (reversed in the Southern Hemisphere)
  - monsoons – atmospheric circulation systems that reverse on a seasonal basis as they are driven by land and sea surface temperature difference
  - **tropical cyclones** – (known as hurricanes in West and typhoons in East) – transport vast amounts of thermal energy from tropics into middle latitudes (super-typhoon can have power 30 TW)
    - they are unpredictable and must be treated as a hazard for wind turbines; thus their wind energy is useless

Diurnal Wind Changes

(Diurnal – having a daily cycle)

In areas where the wind flow is light, sea breezes and land breezes are important factors in a location's prevailing winds. The sea is warmed by the sun to a greater depth than the land due to its greater specific heat. The sea therefore has a greater capacity for absorbing heat than the land, so the surface of the sea warms up more slowly than the land's surface.



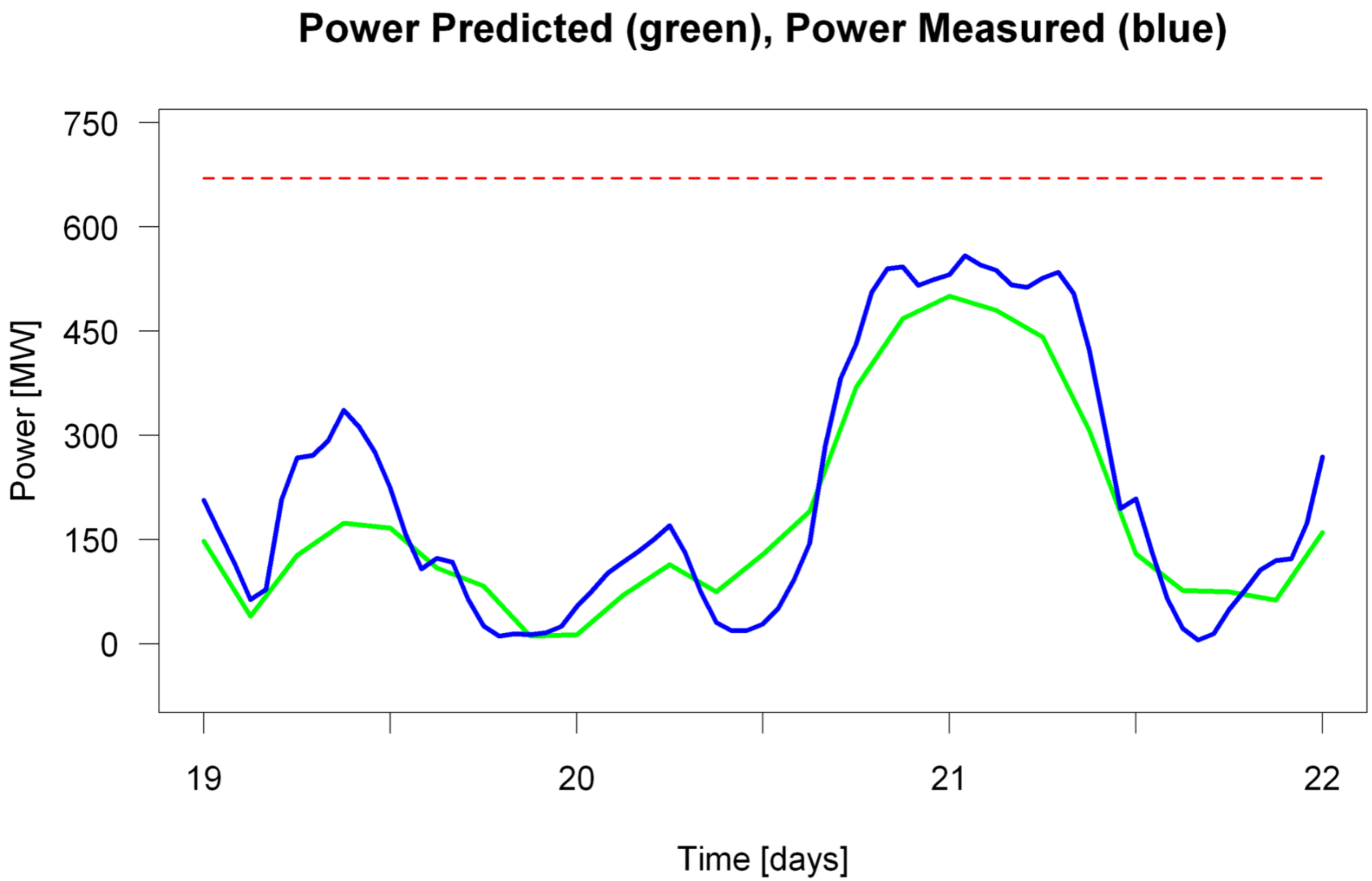


When in-land surface temperature increases, the land heats the air, which rises and the colder air above sea flows toward the land (cooler breeze)

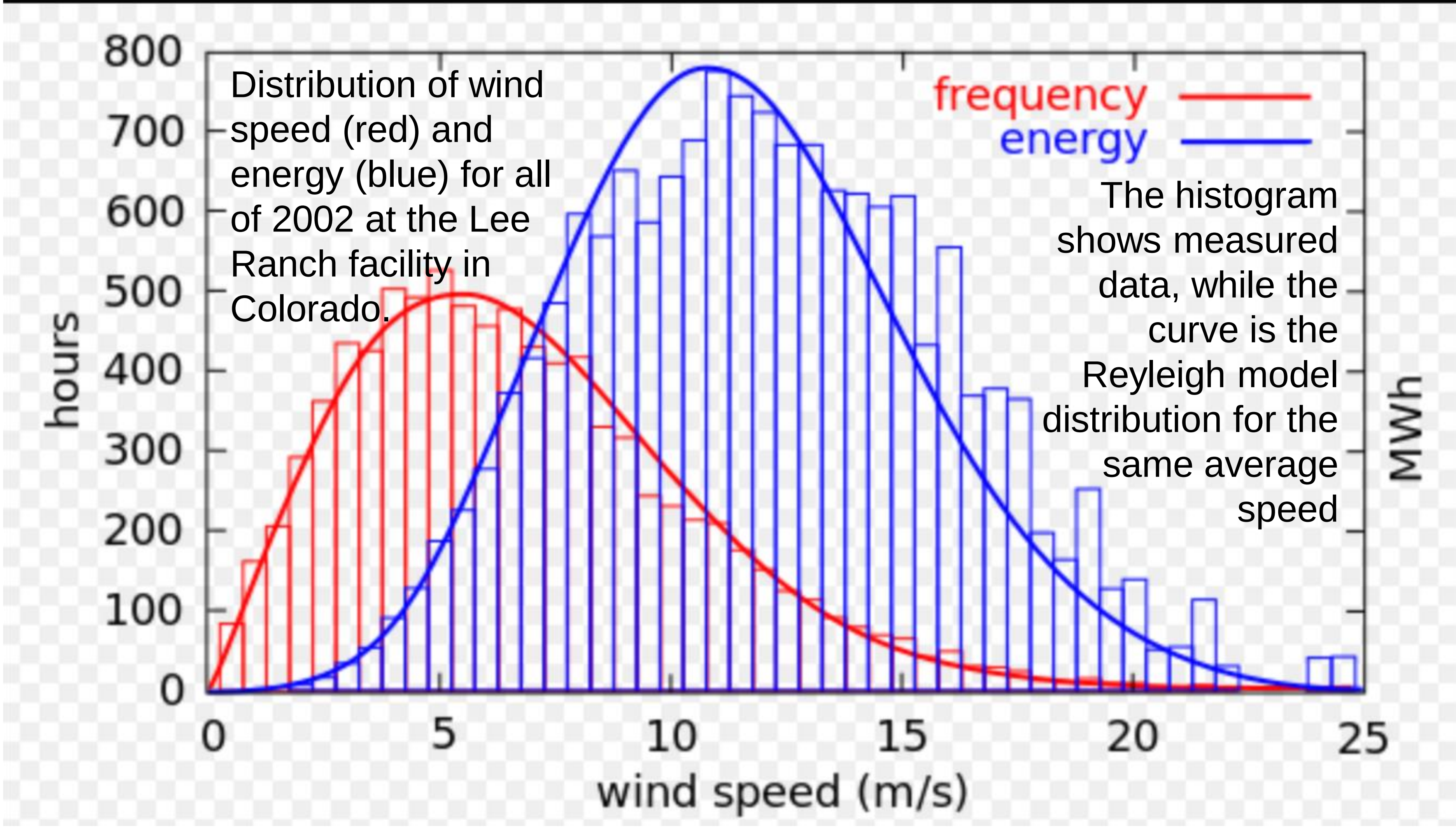
Variable Wind Power (1)

- The strength of wind at any location varies with time
- Thus an average local wind speed does not alone indicate the amount of energy a wind turbine could produce there
- To asses local wind power resources a probability distribution is often fit to the observed wind speed data
- Different locations will have different wind speed distributions
- The Weibull model closely describes the actual distribution of hourly/ten-minutes wind speeds
- Rayleigh distribution can be used as simpler, but less accurate, model

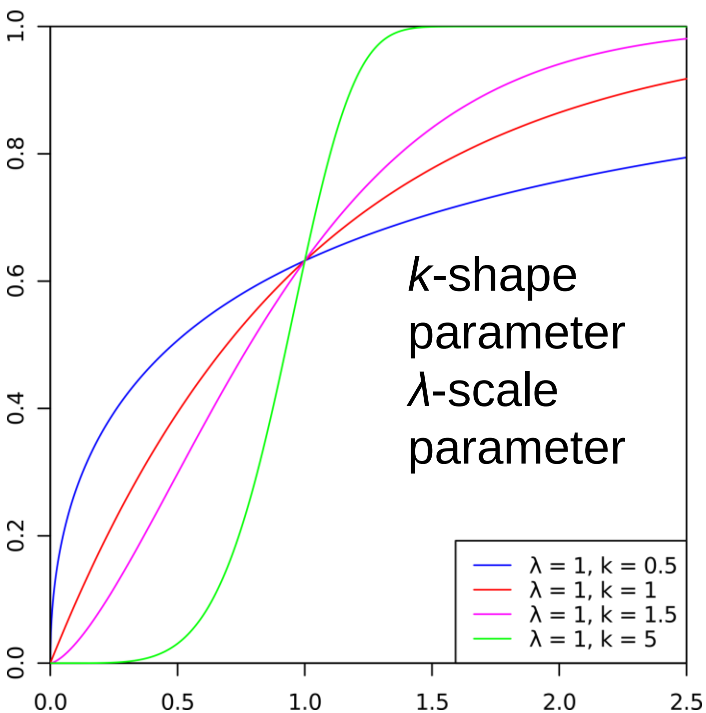
Variable Wind Power (2)

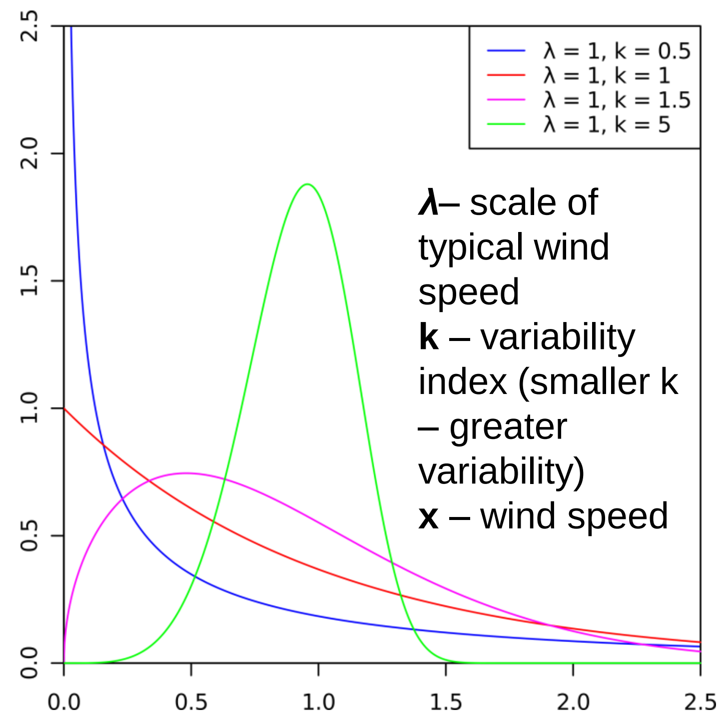


Wind Speed Distributions



Weibull Distribution





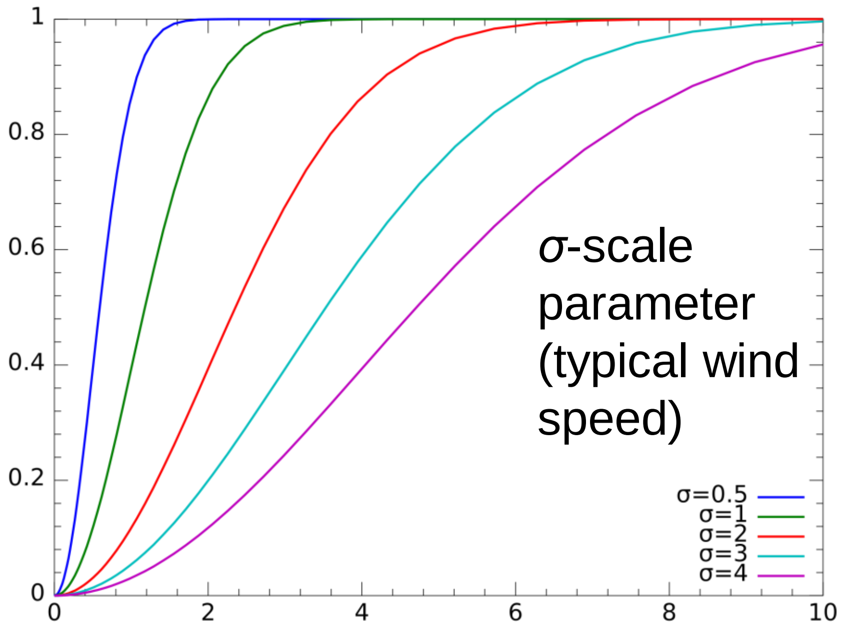
$$F(x;\lambda,k)=\begin{cases}1-e^{-(x/\lambda)^k} & x\geq 0\\ 0 & x<0\end{cases}$$

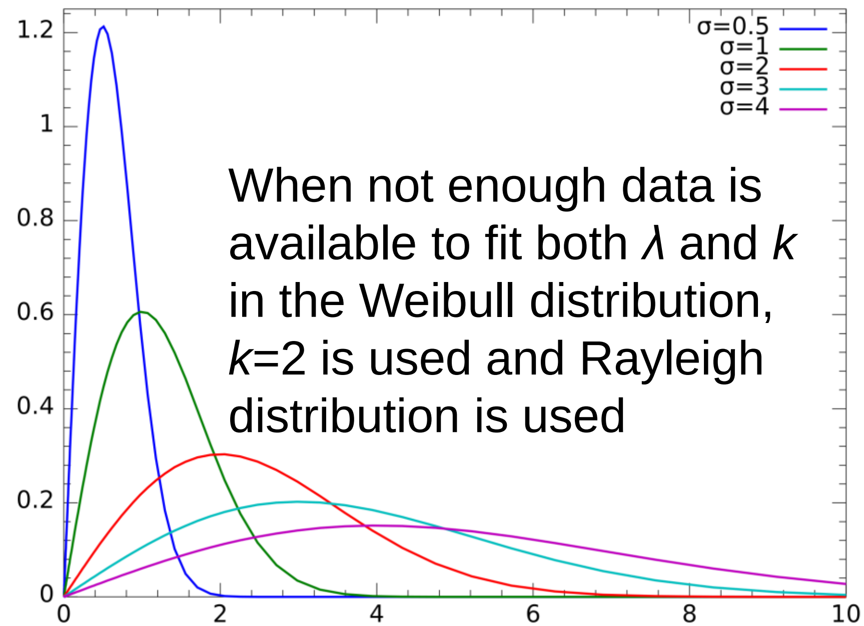
Cumulative density function

$$f(x;\lambda,k)=\begin{cases}\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}e^{-(x/\lambda)^k} & x\geq 0\\ 0 & x<0\end{cases}$$

Probabilistic density function

Rayleigh Distribution





When not enough data is available to fit both λ and k in the Weibull distribution, k=2 is used and Rayleigh distribution is used

$$F(x;\sigma)=\begin{cases} 1-e^{-x^2/\left(2\sigma^2\right)} & x\geq 0 \\ 0 & x<0 \end{cases}$$

Cumulative density function

$$f(x;\sigma)=\begin{cases} \frac{x}{\sigma^2}e^{-x^2/\left(2\sigma^2\right)} & x\geq 0 \\ 0 & x<0 \end{cases}$$

Probabilistic density function

Wind Speed Variation with Height

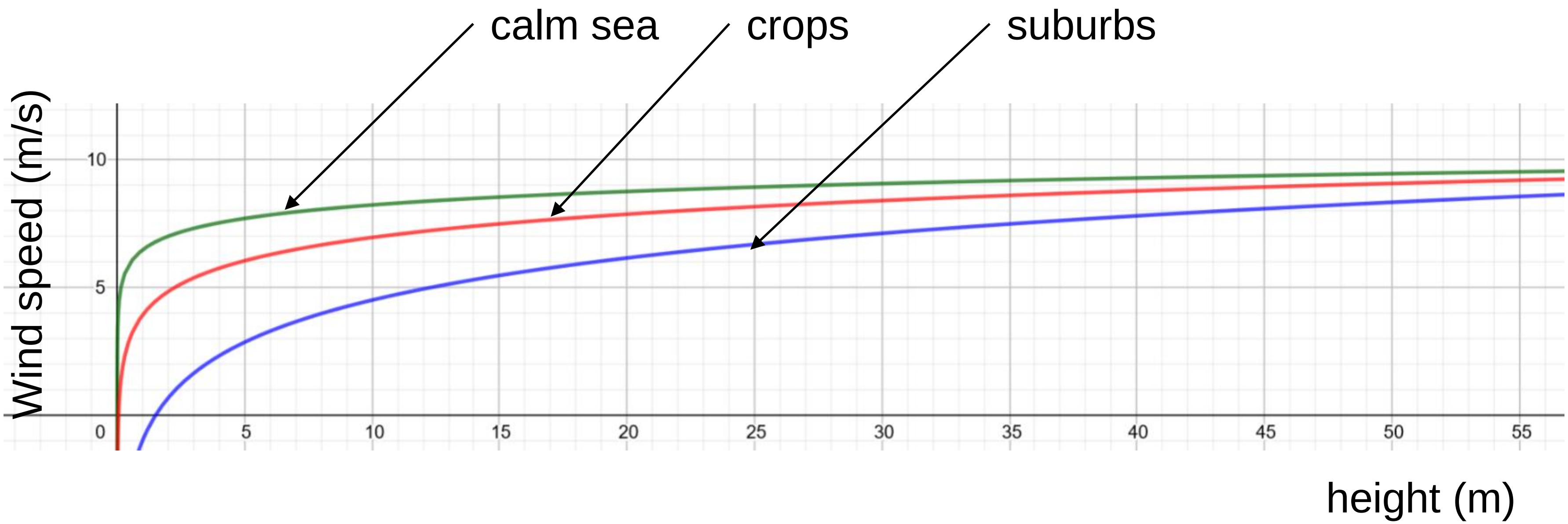
- Wind speed increases with height through the surface layer of the atmosphere as

$$v(z) = v_{ref} \frac{\ln(z/z_0)}{\ln(z_{ref}/z_0)}$$

where z_0 is the roughness length – depending on landscape type; v_{ref} – reference speed at the reference height z_{ref}

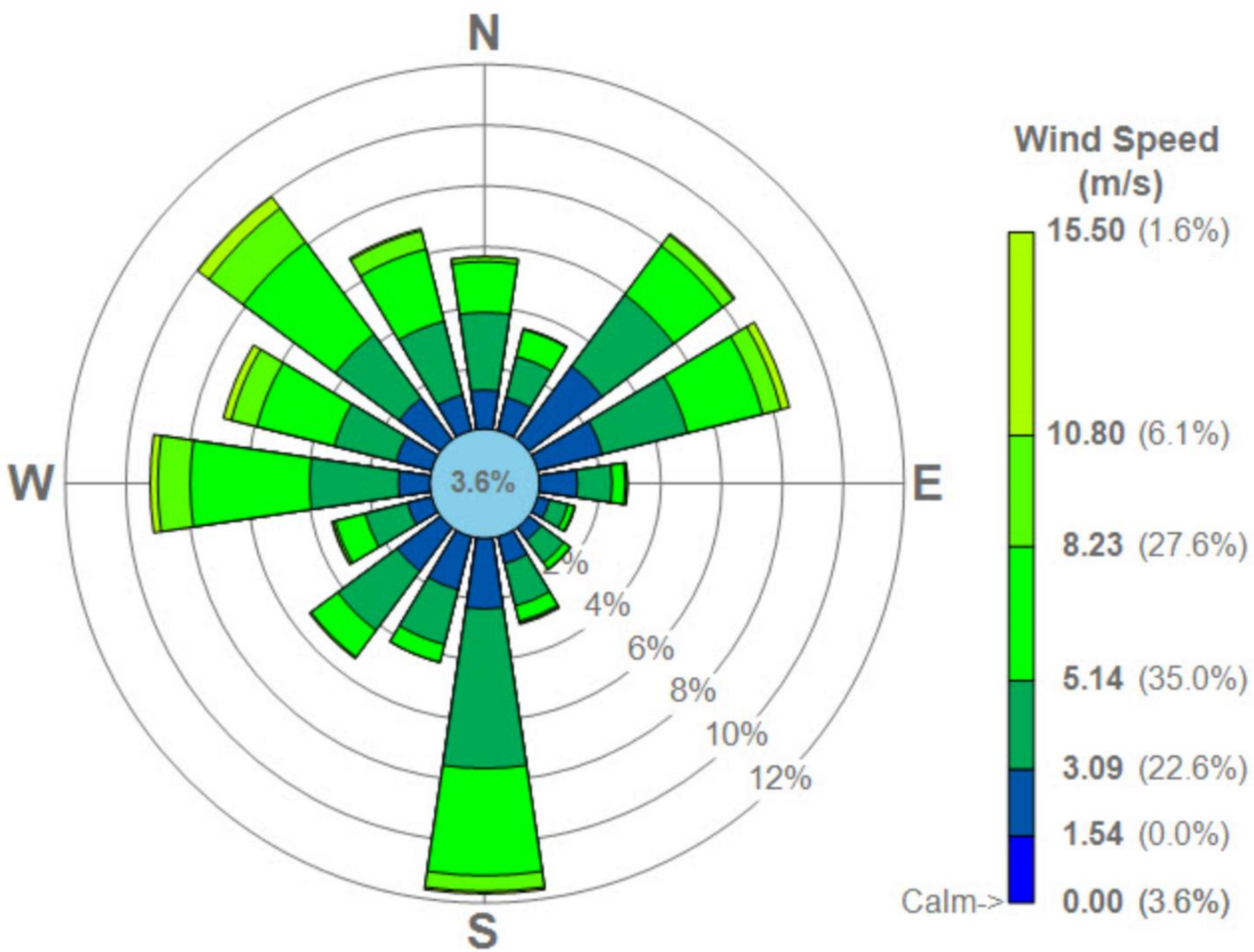
Landscape	z_0 (m)
calm open sea	0.0002
snow surface	0.003
rough pasture	0.01
crops	0.05
few trees	0.1
forest	0.5
suburbs	1.5

Wind Speed Variation with Height



Velocity profiles over various landscapes with reference speed 10 m/s at the reference height 100 m

Wind Direction and Intensity- Wind Rose



Wind rose gives a view of how wind speed and direction are typically distributed at a particular location

Wind Turbine Aerodynamics

- Aerodynamics plays important role in a theory of wind turbines
- One of the main goals is to determine the power extracted from a wind turbine, according to the governing equation

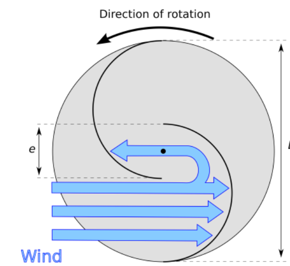
$$N = \mathbf{F} \cdot \mathbf{v}$$

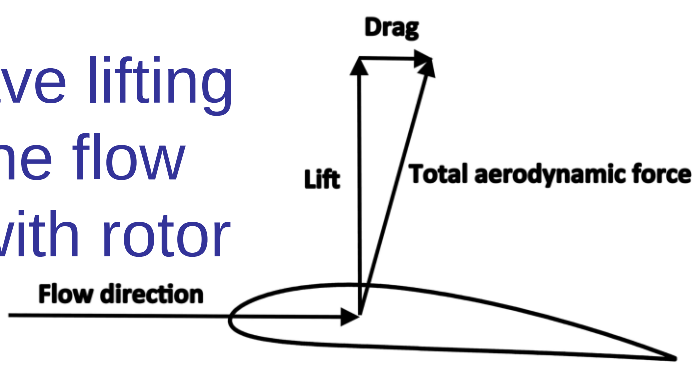
N – power, **F** – force vector, **v** – velocity vector

- To extract power, the turbine working element must move in the direction of net force

Wind Turbine Aerodynamics

- In the case of drag force based wind turbines, the relative wind speed decreases, which causes a decrease of the drag force
- The reduction of the drag force with the relative speed limits the maximum power that can be extracted
- Lift-based wind turbines typically have lifting surface moving perpendicularly to the flow and the relative velocity increases with rotor speed
- The power limit is thus much higher for this type of system





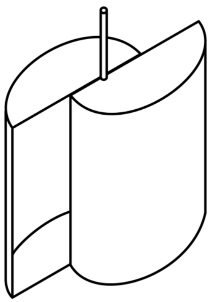
Wind Turbine Aerodynamics

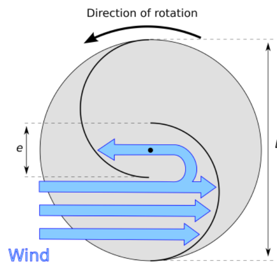
- **Characteristic parameters** of a wind turbine are defined as follows
  - Speed ratio $$\lambda = \frac{u}{U}$$
  - Coefficient of power $$C_P = \frac{N}{\rho A U^3 / 2}$$
  - Thrust Coefficient $$C_T = \frac{T}{\rho A U^2 / 2}$$
  - Lift coefficient $$C_L = \frac{L}{\rho A w^2 / 2}$$
  - Drag coefficient $$C_D = \frac{D}{\rho A w^2 / 2}$$

u – working element speed (e.g. at the tip of the blade) found as ***u*** = ***ω R***; here ,
ω – rotational velocity (rad/s)
R – radius of the working element
U – wind speed
w = ***U***-***u*** is the relative velocity of the working element
A – area (can be different in each definition and has to be clarified each time)
ρ – air density

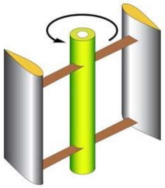
Wind Turbine Aerodynamics

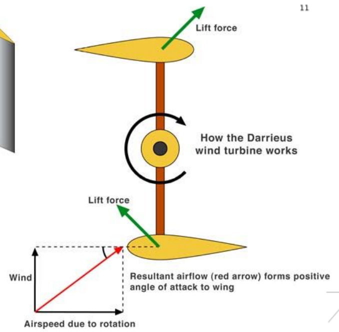
- Wind turbines extract energy from the wind through aerodynamic forces, drag and lift
- Savonius wind turbine is a drag-based machine

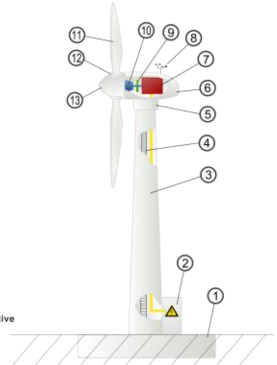




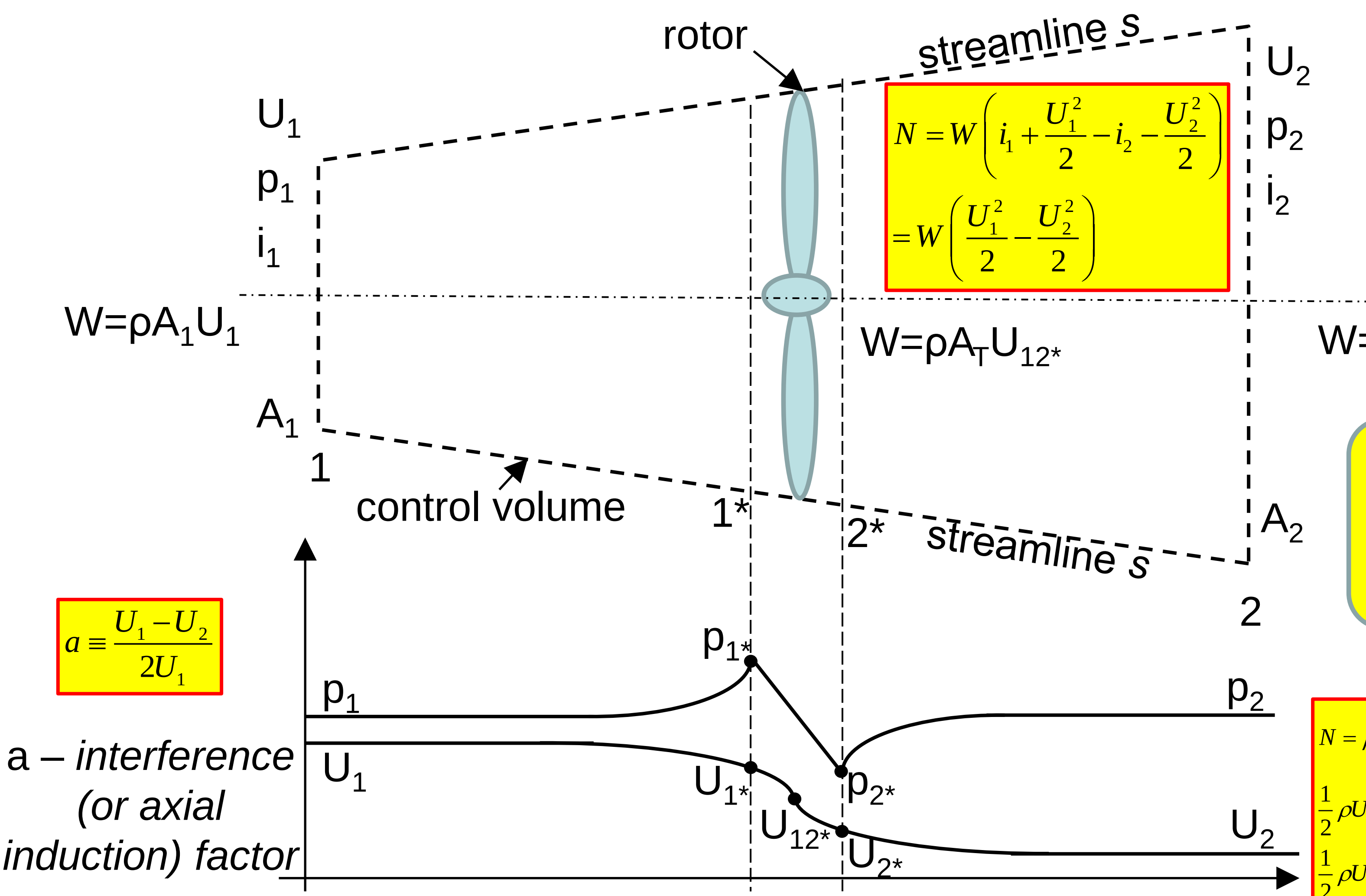
- Darrieus wind turbine and conventional horizontal axis wind turbines are lift-based machines







Maximum Power of WT



$$N = W\left(i_1 + \frac{U_1^2}{2} - i_2 - \frac{U_2^2}{2}\right) = W\left(\frac{U_1^2}{2} - \frac{U_2^2}{2}\right)$$

$$a \equiv \frac{U_1 - U_2}{2U_1}$$

a – *interference (or axial induction) factor*

Assumptions

$U_{12*} = U_1(1-a)$

$U_2 = U_1(1-2a)$

$$N = \rho U_{12*} A_T \left(\frac{U_1^2}{2} - \frac{U_2^2}{2}\right) = \frac{1}{2}\rho U_1^3 A_T (1-a)\left[1-(1-2a)^2\right] = \frac{1}{2}\rho U_1^3 A_T 4a(1-a)^2$$

Maximum Power of WT

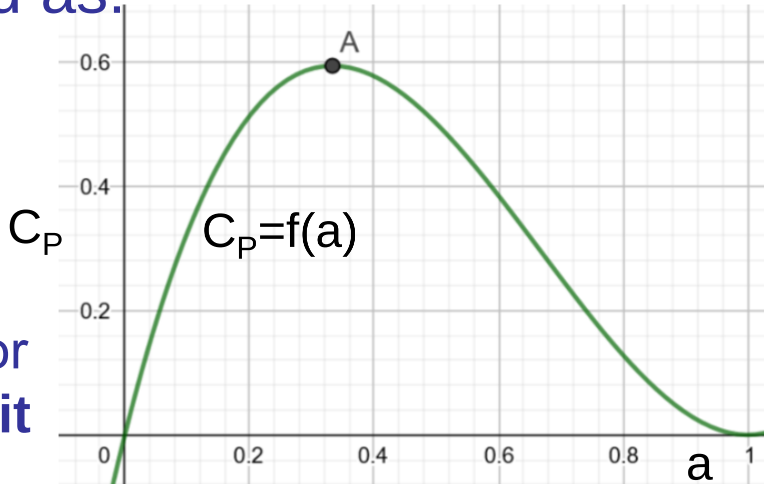
- Thus the turbine power, for given U_1, A_T and ρ, is the following function of *a*:

$$N(a) = \frac{1}{2}\rho U_1^3 A_T 4a(1-a)^2$$

- The power coefficient is defined as:

$$C_P \equiv \frac{N(a)}{1/2\rho U_1^3 A_T} = 4a(1-a)^2$$

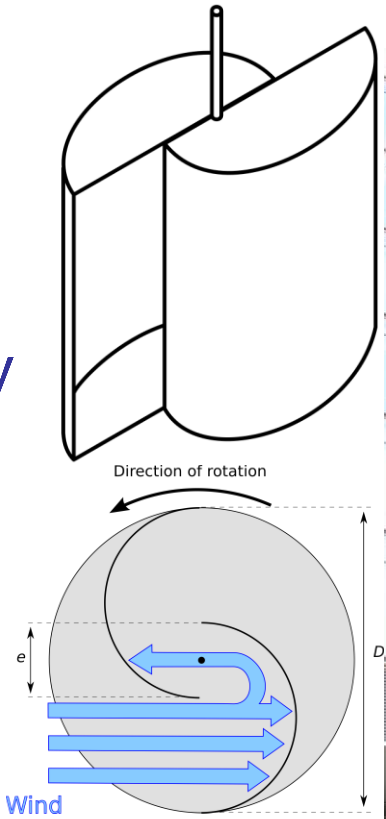
  - with maximum C_P = 16/27≈0.59 for a = 1/3. This is so called **Betz limit**



Savonius Vertical-Axis WT

- These are drag-type devices with two (or more) scoops that are used in anemometers and some high-reliability low efficiency power turbines

- They are always self-starting if there are at least three scoops



Two-scoop design

Savonius Vertical-Axis WT

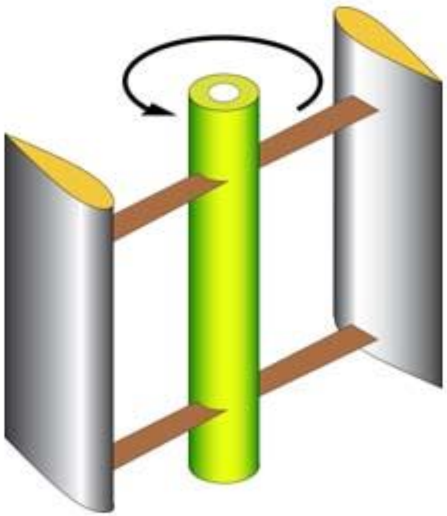
- According to Betz's law, the maximum power that can be extracted from a rotor is N_{max}, where ρ is density of air, *h* and *r* are the height and radius of the rotor and *U* is the wind speed.
- The angular frequency of a rotor is ω, where λ is a dimensionless factor (tip-speed ratio)≈1

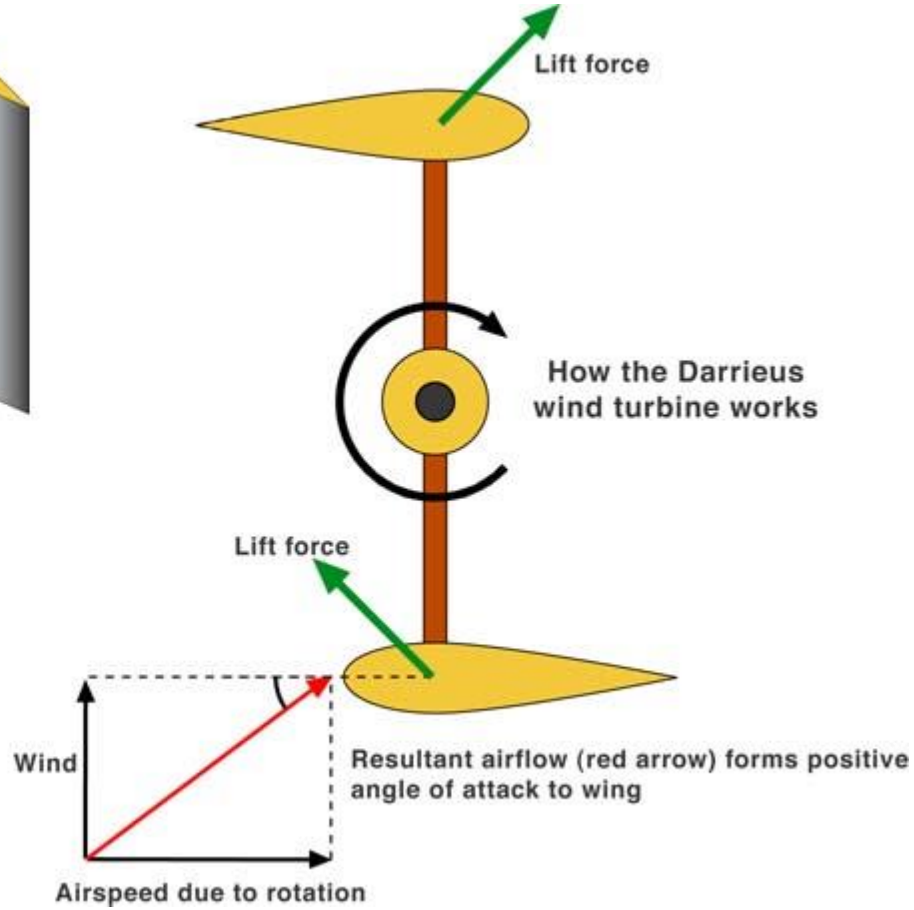
$$N_{\max} = \frac{16}{27}\rho \cdot r \cdot h \cdot U^3$$

$$\omega = \frac{\lambda \cdot U}{r}$$

For example, the maximum power generated by the Savonius rotor with height h=1m and radius r=0.5m, when U=10m/s, is about 180 W, and the angular speed is 20 rad/s

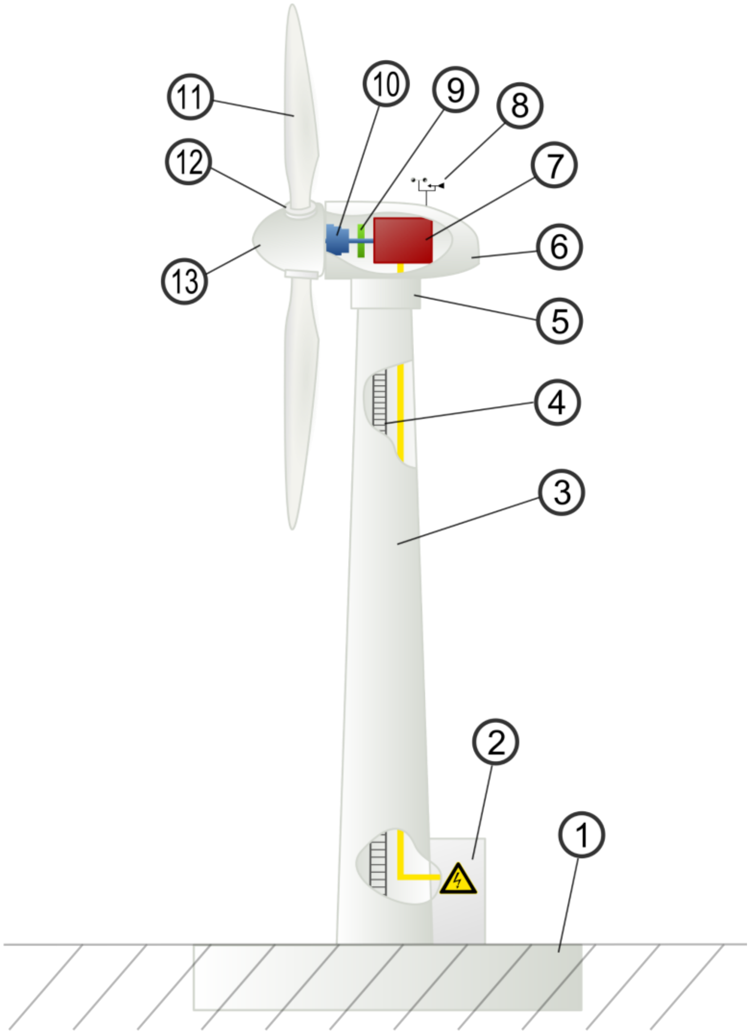
Darrieus Turbine Design





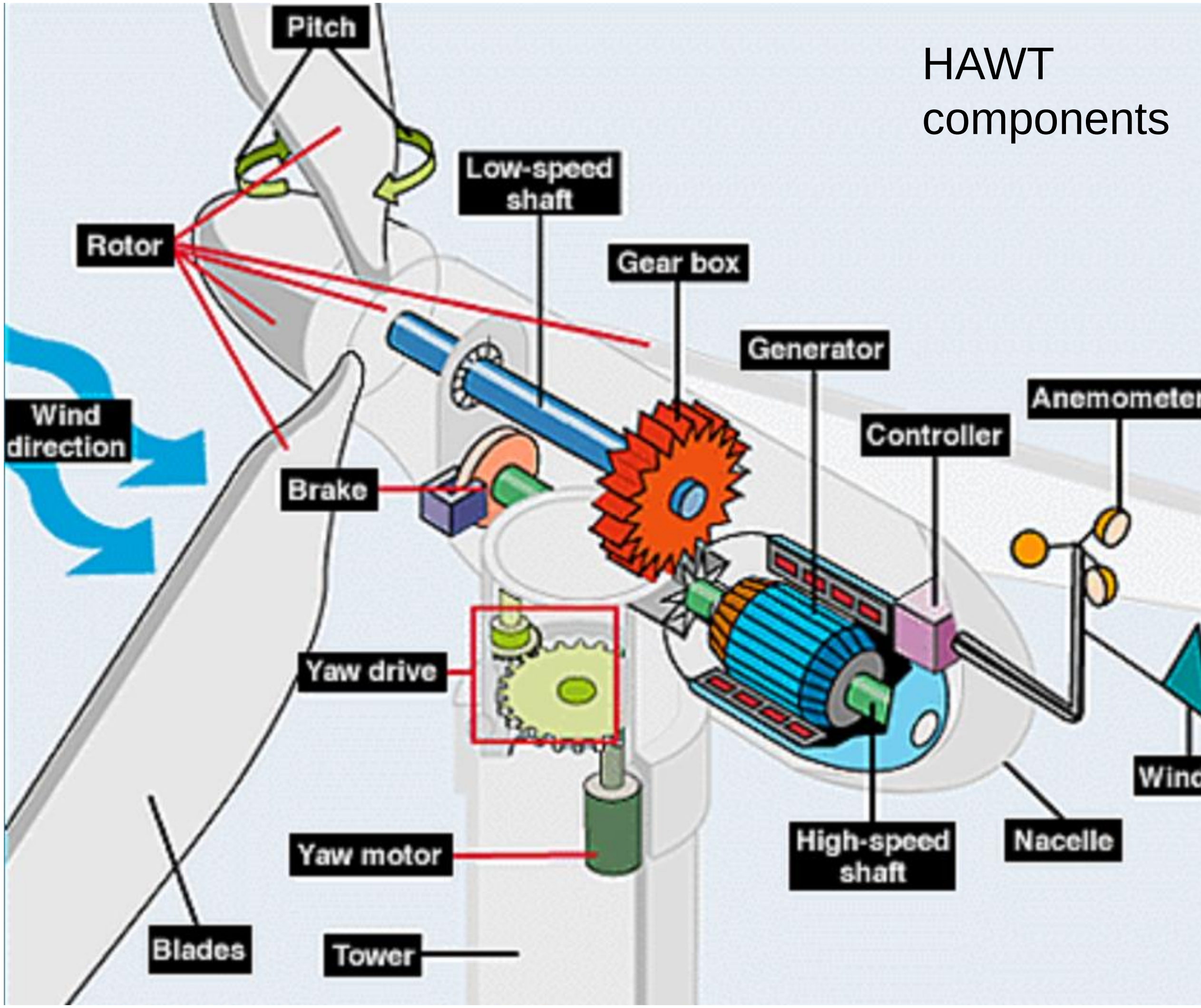
Horizontal Axis WT Design

- The majority of commercial turbines use the horizontal axis wind turbine (HAWT) design[11]



Wind turbine components : 1-Foundation, 2-Connection to the electric grid, 3-Tower, 4-Access ladder, 5-Wind orientation control (Yaw control), 6-Nacelle, 7-Generator, 8-Anemometer, 9-Electric or Mechanical Brake, 10-Gearbox, 11-Rotor blade, 12-Blade pitch control, 13-Rotor hub.

Horizontal Axis WT Design



Wind turbine gearbox

Wind turbine blades

Wind Turbine Efficiency

- Betz limit provides an upper bound on the power that a single planar device with fixed area can extract from free flowing fluid

- Betz limit is often referred to as the efficiency limit

- The real power coefficient depends on the wind turbine design and is approximately:
  - ~15% for American farm windmill
  - ~ 30% for Savonius wind turbine
  - ~ 40% for Darrieus wind turbine
  - ~ 50% for high speed 2 or 3 blade wind turbine

Future Perspectives – Design Challenges

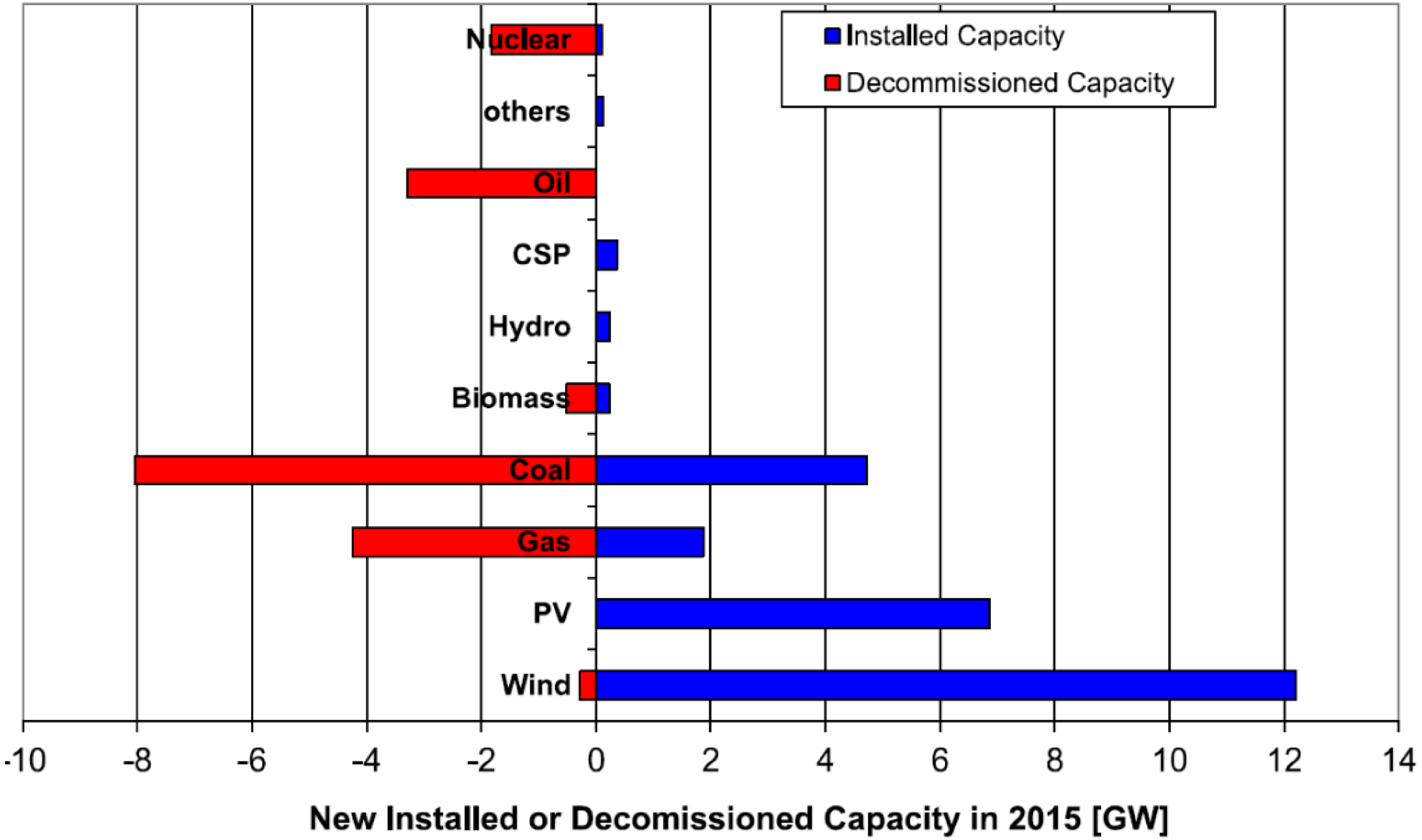
- The design and manufacture of wind turbines is a sophisticated branch of mechanical engineering

- The design challenges are as follows:
  - control at high wind speeds – to protect turbine from damage
  - blade number – affecting the efficiency
  - tip vortices – causing significant aerodynamic losses

Future Challenges

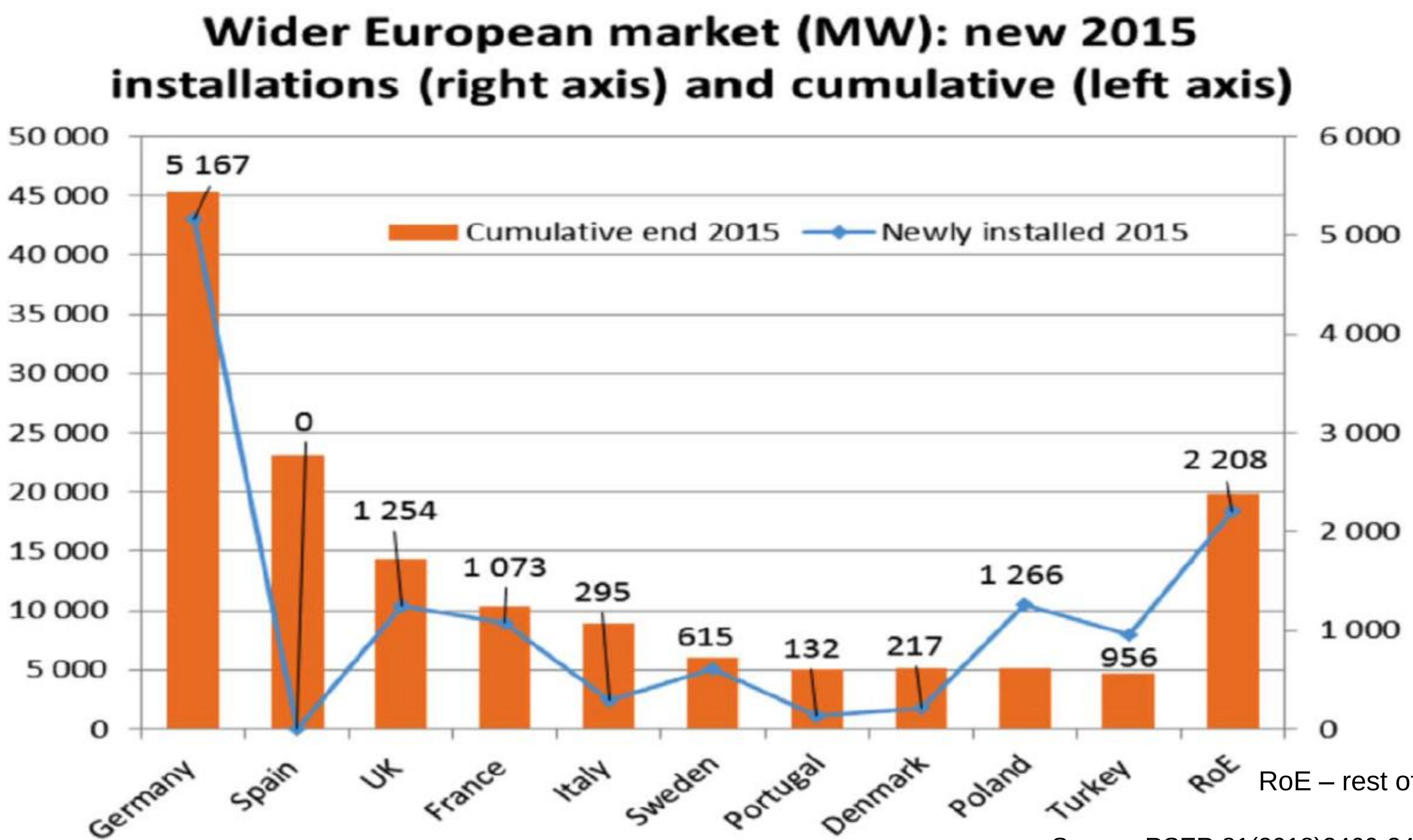
- Wind power development will require a change of a number of national and international regulations
- The electricity grid needs modernisation to allow for the integration of increasing volumes of electricity produced from variable sources
- Key issues include grid balancing, grid flexibility with distributed production and managing strategic and efficient storage facilities
- Grid needs to be more interconnected
  - connect large wind farms with hydropower storage and large demand centers

Installed&Decomissioned Capacity in EU



Source: RSER 81(2018)2460-2471

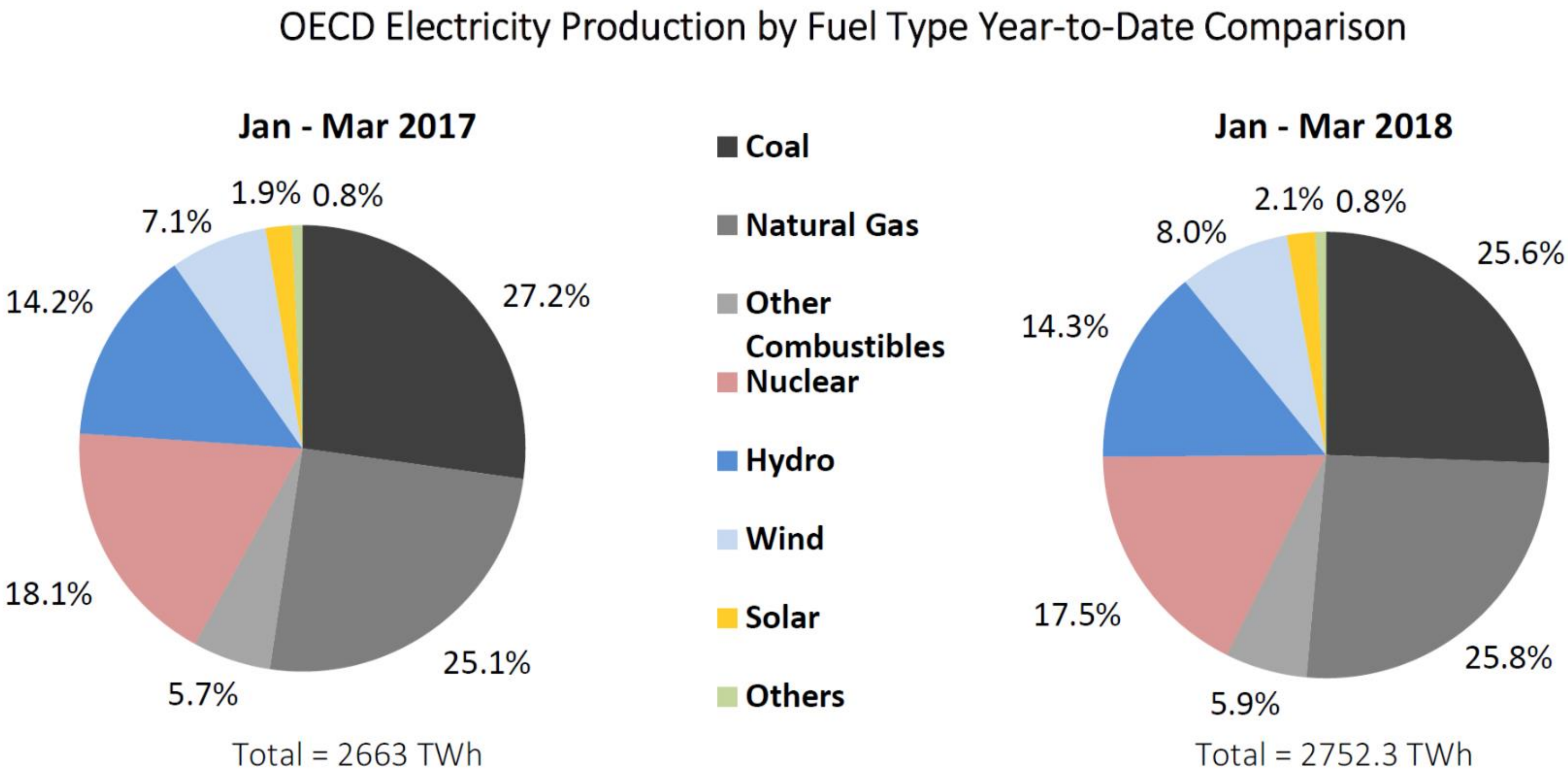
Wind Power Installation in EU 2015



RoE – rest of EU

Source: RSER 81(2018)2460-2471

OECD Electricity Production Data



Wind electricity production in OECD countries increased from 7.1% to 8% during the first quarters of years 2017 and 2018

Source: IEA