Wind energy

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Outline

- **Introduction**
  - What is wind energy?
  - Wind energy today and future potential
  - The resource
- **Physics of wind energy**
  - Physics of wind energy: key equations
  - Betz limit
  - Forces: lift and drag
- **Wind Turbines & energy systems**
  - Types of wind turbines
  - Integration in the energy system
- **Take home message**

Introduction

Introduction

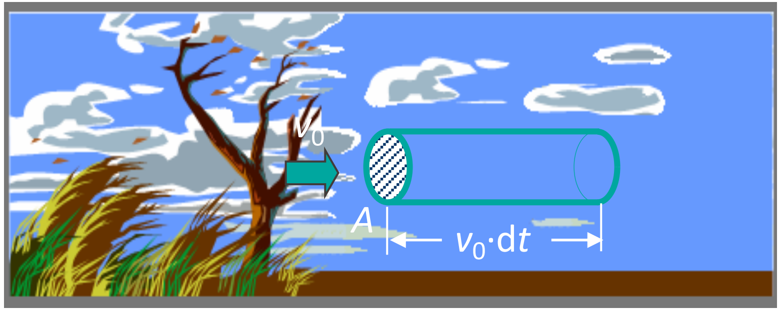
What is wind energy?

- Wind can be defined as "air in motion":

  1. Differences in pressure (pressure gradient force), caused by uneven solar heating → ultimately from the sun
  2. Rotation of the Earth: Coriolis force
  3. Friction close to the Earth surface

$$\dot{E}_{k,air} = \frac{\mathrm{d}E_{k,air}}{\mathrm{d}t} = \frac{1}{2}\rho A v_0^3 \qquad E_{k,air} = \frac{1}{2}m_{air}v_0^2 = \frac{1}{2}\rho A v_0^3 \mathrm{d}t$$

- Kinetic energy, power, force
  - Air passing through control volume V in dt:
  - Mass flow through A:
  - Kinetic energy contained in the air:
  - Power: $F_{air} = \frac{\dot{E}_{k,air}}{v_0} = \frac{1}{2}\rho A v_0^2$
  - Force (drag):



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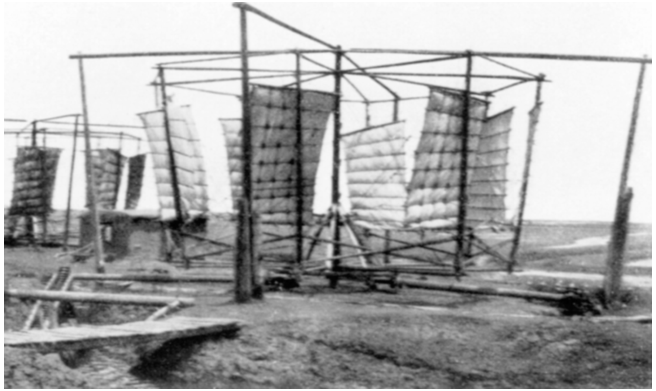
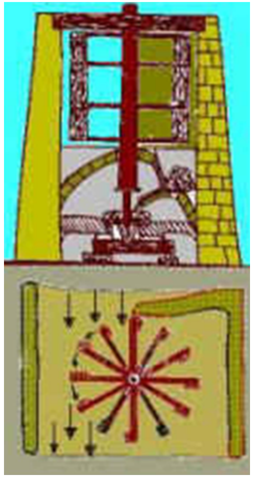
Introduction

What is wind energy?

- Historically, wind has been used for:
  - ~3000BC: sailboats (Babylonians, Egyptians)
  - ~2000BC: pumping water
  - ~1000AD: milling (Europe)
  - Mechanical work





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Introduction

What is wind energy?

Why wind farms — Search Google

Google Suggestions

- Why wind farms
- why wind farms are bad
- why wind farms are good
- why wind farms are important
- why wind farms are a good idea

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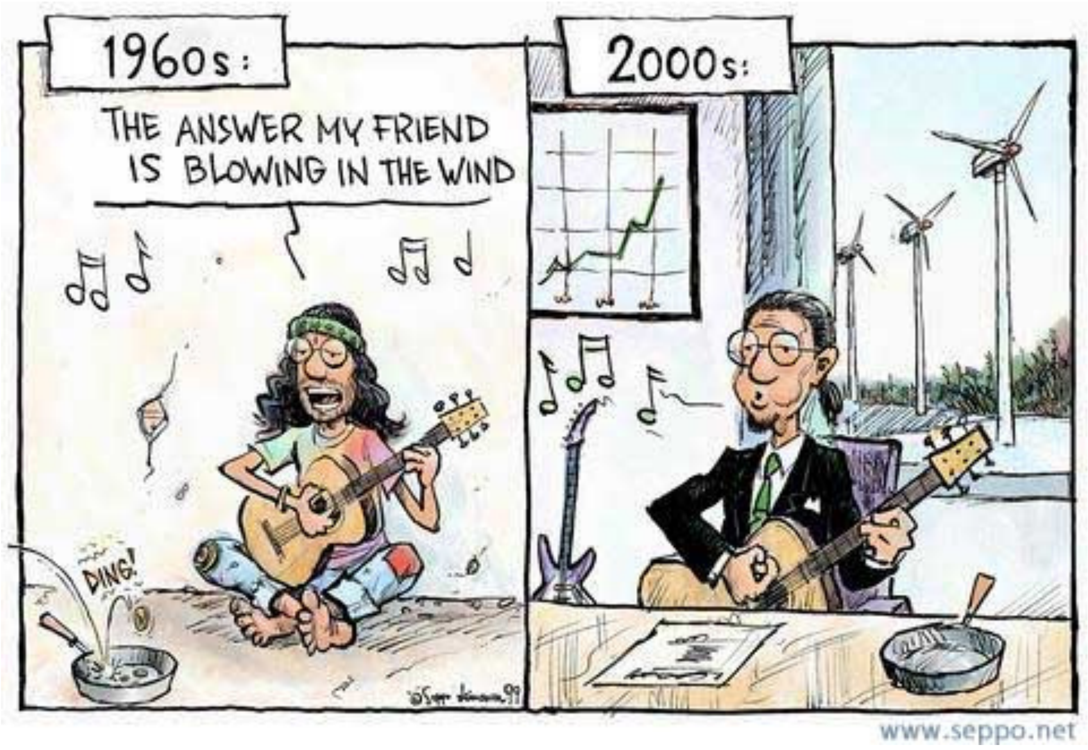
Introduction

What is wind energy?



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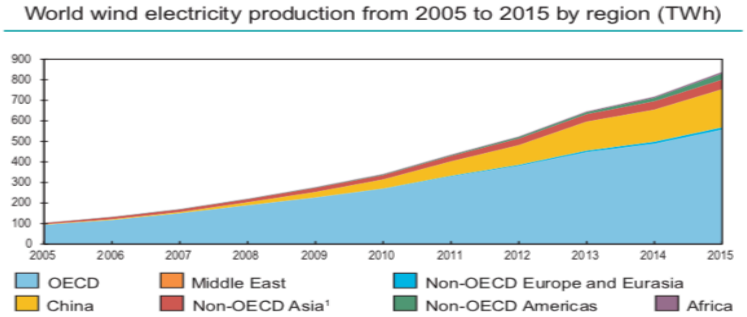
Introduction
Wind energy today

- World primary energy consumption: 158700 TWh/y (2015)[1]
- World final energy consumption: 109100 TWh/y (2015)[1]
- World electricity production: 24255 TWh/y (2015)[1]
- Wind electricity production: **838** TWh/y (2015)[1]

→ 3.5% of global electricity production



Producers	TWh	% of world total
United States	193	23.0
People's Rep. of China	186	22.2
Germany	79	9.5
Spain	49	5.9
India	43	5.1
United Kingdom	40	4.8
Canada	26	3.2
Brazil	22	2.6
France	21	2.5
Sweden	16	1.9
Rest of the world	162	19.3
World	**838**	**100.0**

2015 data

Net installed capacity	GW
People's Rep. of China	129.3
United States	72.6
Germany	44.7
India	25.1
Spain	22.9
United Kingdom	14.3
Canada	11.2
France	10.2
Italy	9.1
Brazil	7.6
Rest of the world	67.0
World	**414.0**

2015 data

Country (top ten producers)	% of wind in total domestic electricity generation
Spain	17.6
Germany	12.2
United Kingdom	11.9
Sweden	10.0
United States	4.5
Canada	3.9
France	3.7
Brazil	3.7
People's Rep. of China	3.2
India	3.1
Rest of the world[1]	2.0
World	**3.4**

2015 data

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Introduction
Wind energy today

- Difference in capacity factors:

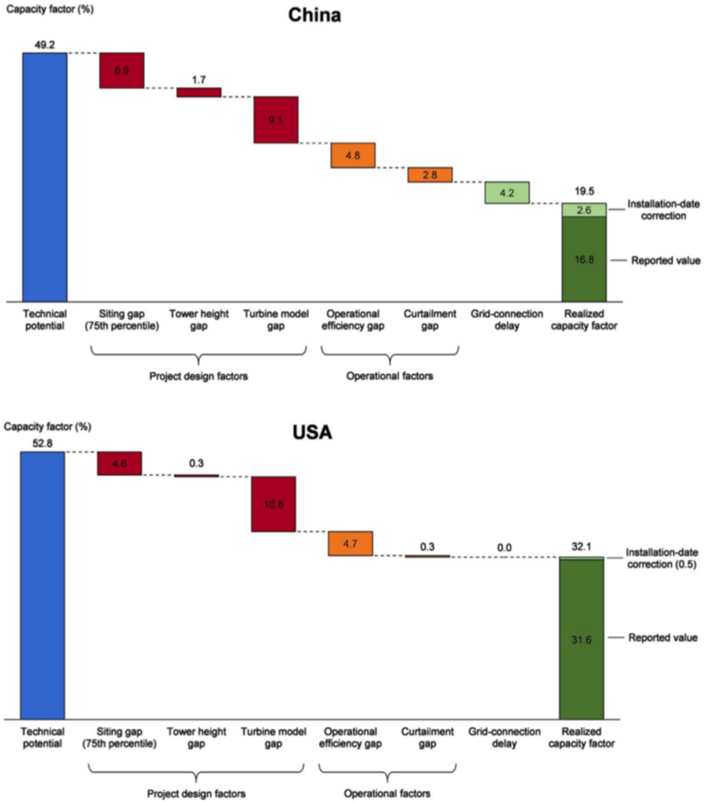

Figure 3. Breakdown of the generation shortfall between reported values and technical potential in China and the United States from their installed capacities in 2013, displayed as percentage points of lost capacity factor.

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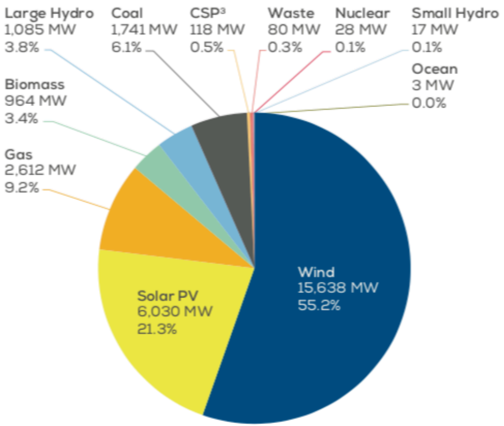
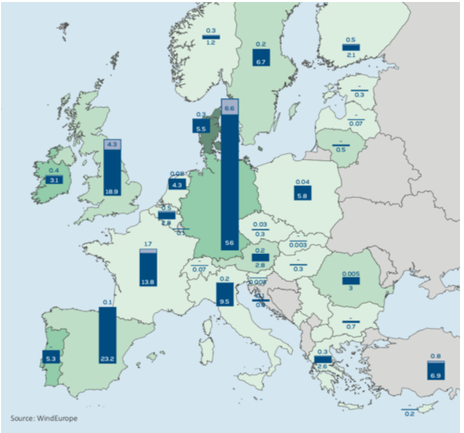
Introduction

Wind energy today

- Total wind capacity in EU: 168.7 GW_e (2017), of which 15.8 GW_e offshore
- +15.6 GW_e installed in 2017
- 18% of EU installed capacity, 11.6% of electricity demand
- 55% of new capacity in 2017

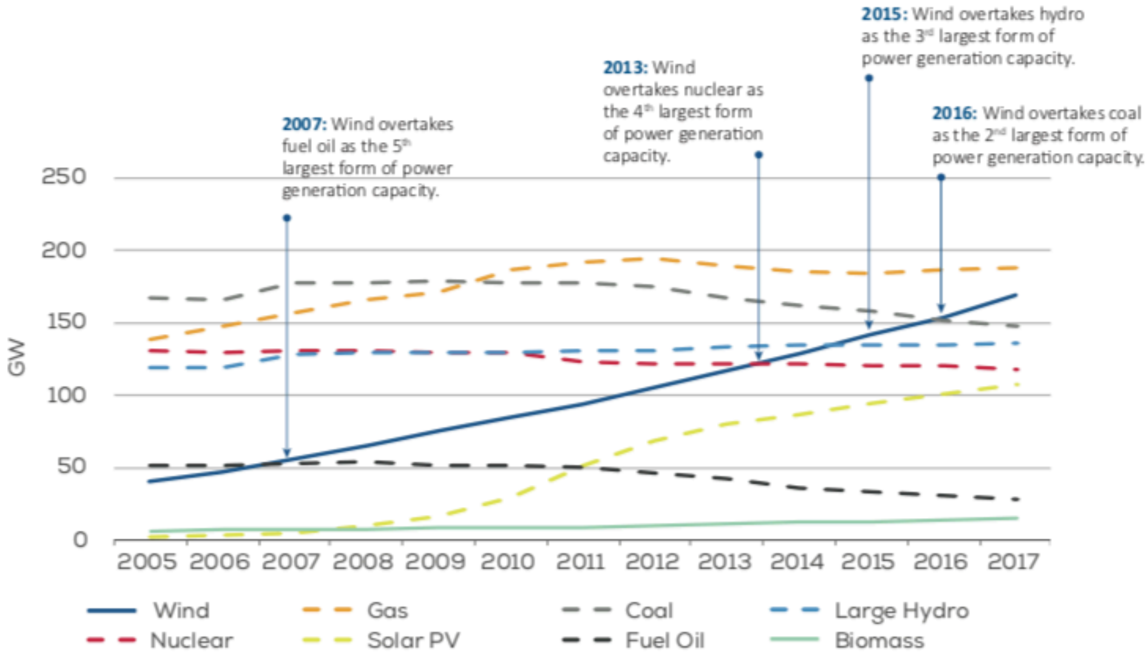
FIGURE 3
Share of new installed capacity. Total 28,316 MW





Introduction
Wind energy today

FIGURE 1
Total power generation capacity in the European Union 2005-2017



Source: WindEurope

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Introduction
Wind energy today

- Swiss final energy consumption: 236 TWh/y (2017)
- Swiss electricity consumption: 58.5 TWh_e/y (2017)
- Wind electricity production: 0.13 TWh_e/y (2017)

→ Only 37 turbines (75 MW_e) installed in CH

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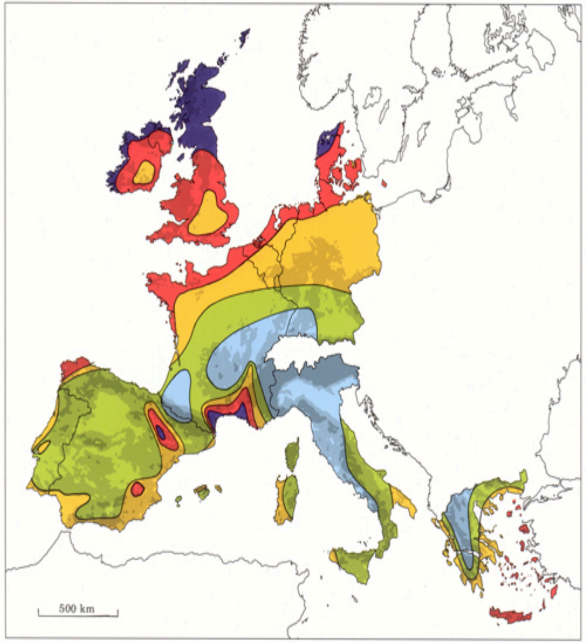
Introduction

Wind energy today

- World electricity production: 24255 TWh/y (2015)
- IIASA, practical potential (onshore): 20000-100000 TWh/y
- IEA: 18% of world electricity supply in 2050
- In Switzerland, technical potential: 10.7 TWh_e/y
- Potential depends on wind speed…



Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Source: Risø DTU National Laboratory, Denmark

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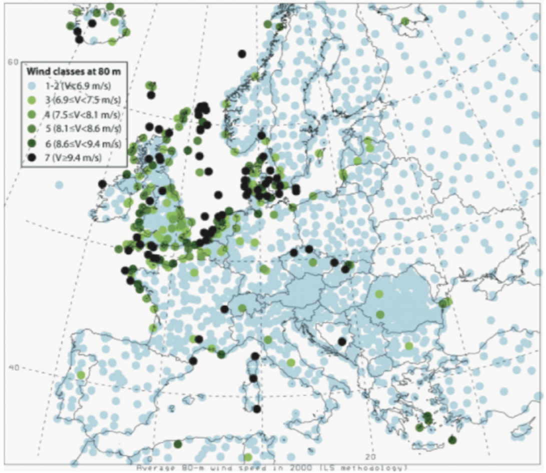
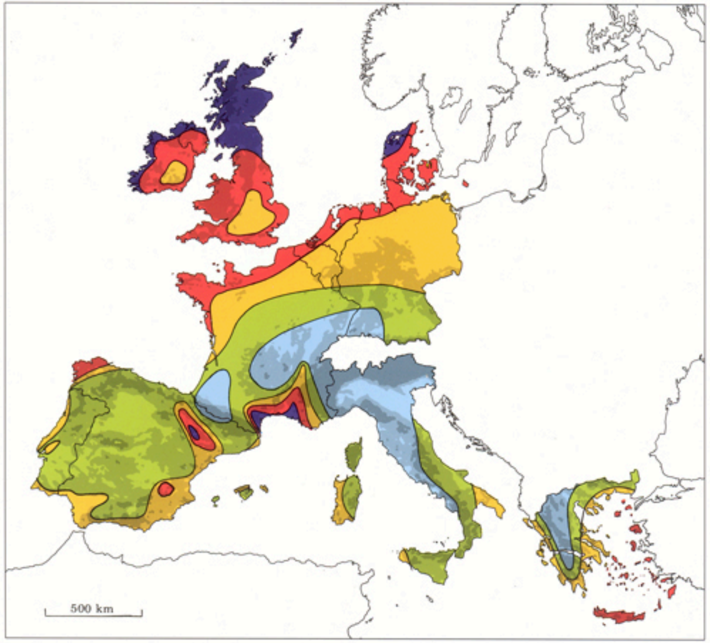
Introduction

The resource

$$\dot{E}_{k,air} = \frac{\mathrm{d}E_{k,air}}{\mathrm{d}t} = \frac{1}{2}\rho A v_0^3$$

- The main factor is the wind speed!





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	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Source: Risø DTU National Laboratory, Denmark

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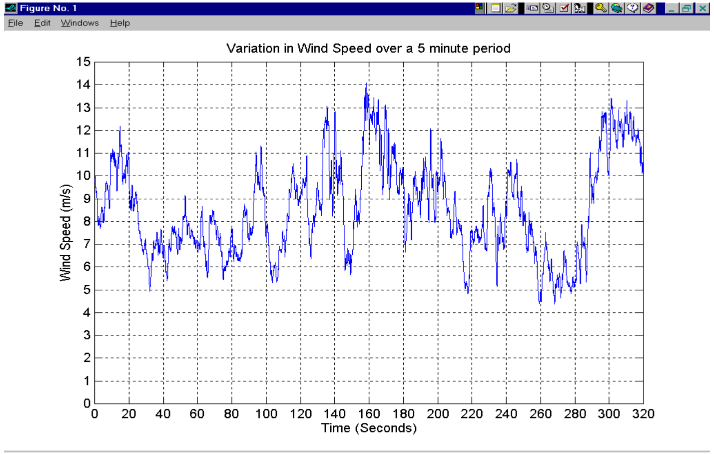
Introduction

The resource

- To be able to predict the performance of a wind turbine at a particular site the developer must know the characteristics (speed and direction) of the resource at the location in question

- Speed variation and time scales:
  1. Yearly
  2. Seasonal
  3. Synoptic (= a passing weather system)
  4. Day
  5. Seconds (turbulence)

Speed [m/s]



- Influences on:
  - Electricity production forecast (1&2)
  - Wind turbine design (all)

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Introduction

The resource

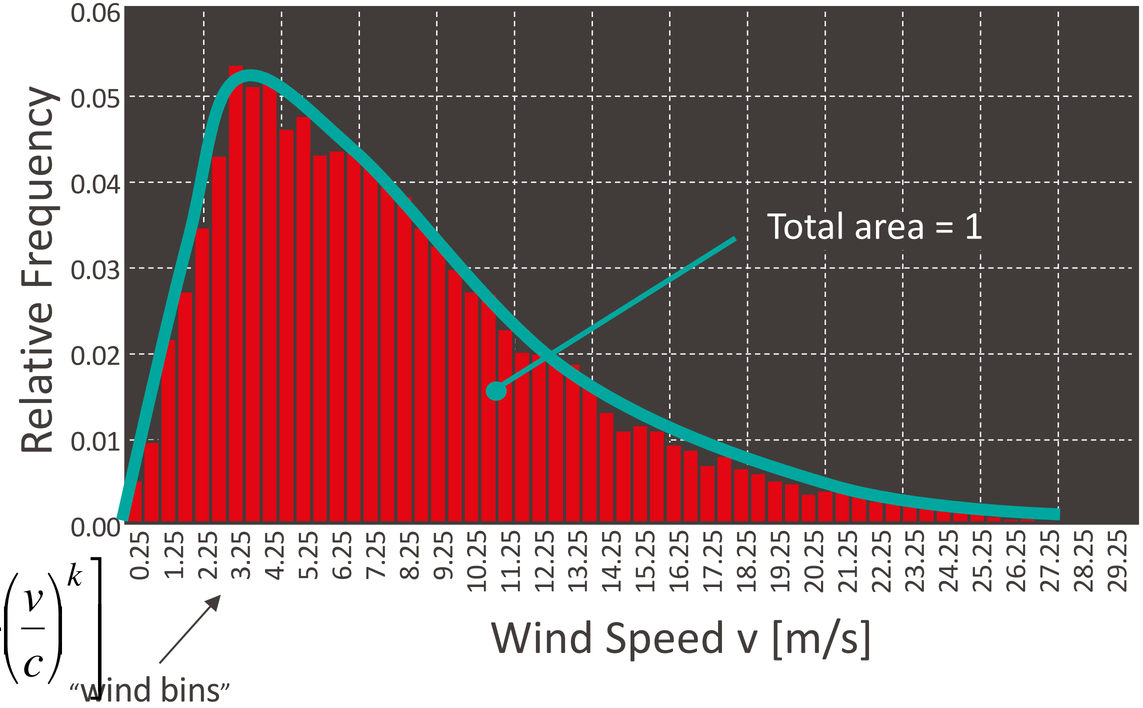
- Wind speed distribution at a given site:

- **Weibull** probability density function:

$$f(v) = \left(\frac{k}{c}\right) \bullet \left(\frac{v}{c}\right)^{k-1} \bullet \exp\left[-\left(\frac{v}{c}\right)^{k}\right]$$

k: shape parameter

c: scale parameter



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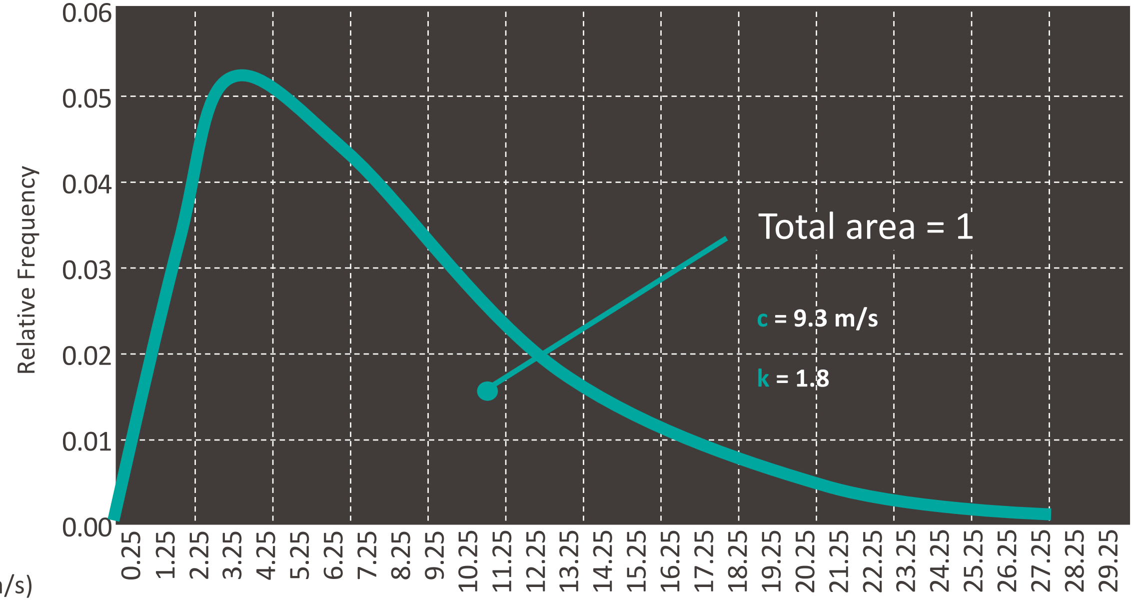
Introduction

The resource

- Wind speed distribution at a given site:



- **Weibull** probability density function:

c: linked to average *v* (63% of speed below 9.3 m/s)

k: linked to variance of v

$$\bar{v} = c \bullet \Gamma\left(1 + \frac{1}{k}\right) \qquad \Gamma(y) = \int_0^\infty \exp(-x).x^{(y-1)}dx$$

$$\sigma^2 = c^2\left[\left(1 + \frac{2}{k}\right) - \left(\Gamma\left(1 + \frac{1}{k}\right)\right)^2\right]$$

Introduction

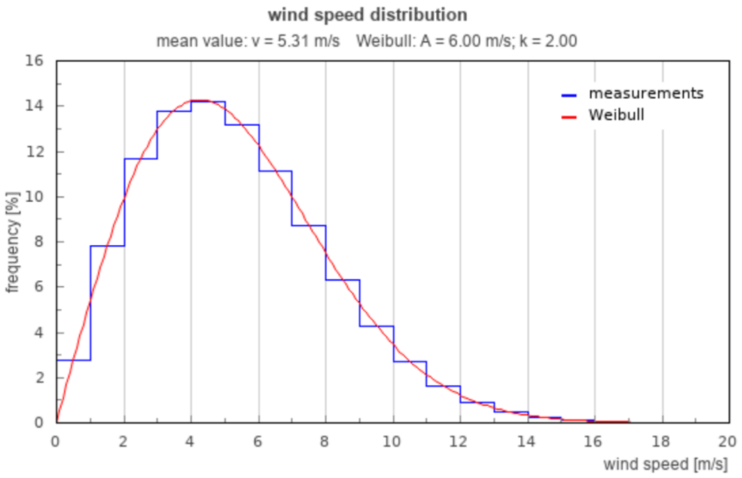
The resource

- Tool to calculate the PDF parameters:

https://wind-data.ch/tools/weibull.php?lng=en

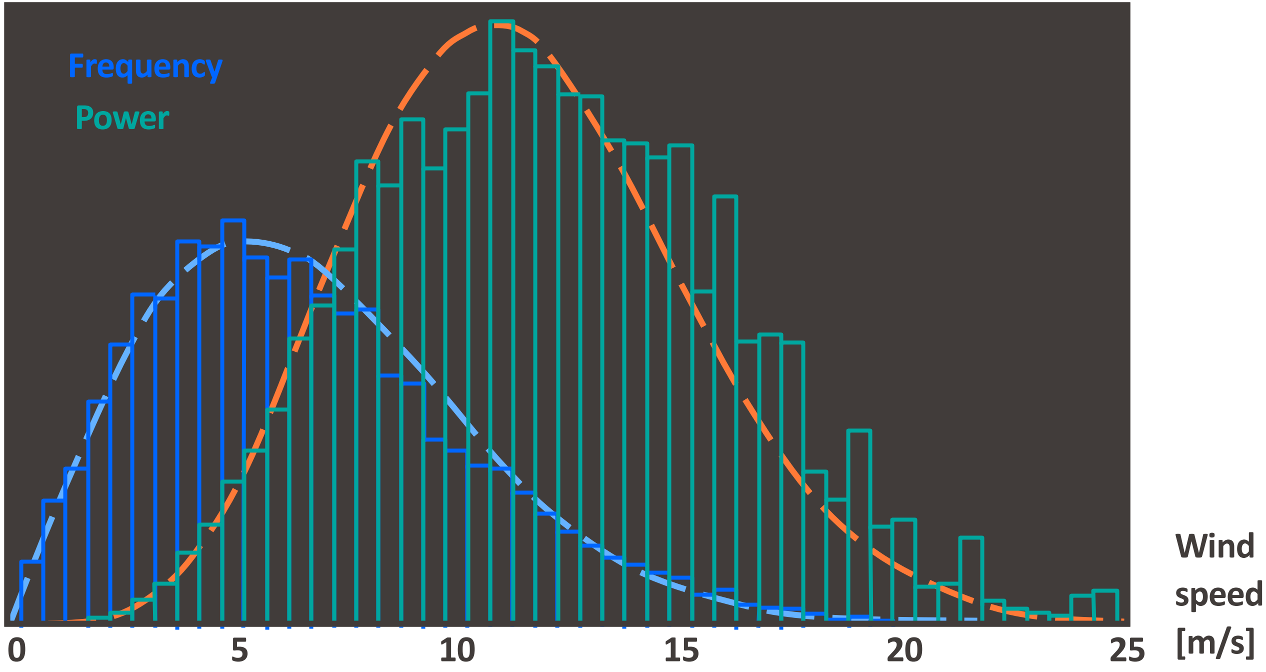
Class	Frequency in %
0 - 1 m/s	2.75
1 - 2 m/s	7.80
2 - 3 m/s	11.64
3 - 4 m/s	13.79
4 - 5 m/s	14.20
5 - 6 m/s	13.15
6 - 7 m/s	11.14
7 - 8 m/s	8.72
8 - 9 m/s	6.34
9 - 10 m/s	4.30
10 - 11 m/s	2.73
11 - 12 m/s	1.62
12 - 13 m/s	0.91
13 - 14 m/s	0.48
14 - 15 m/s	0.24
15 - 16 m/s	0.11
16 - 17 m/s	0.05
17 - 18 m/s	0.02
18 - 19 m/s	0.01
19 - 20 m/s	0.00
Sum	100.00

Result



Introduction
The resource

- Remember that the power is proportional to v^3:



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Physics of wind energy

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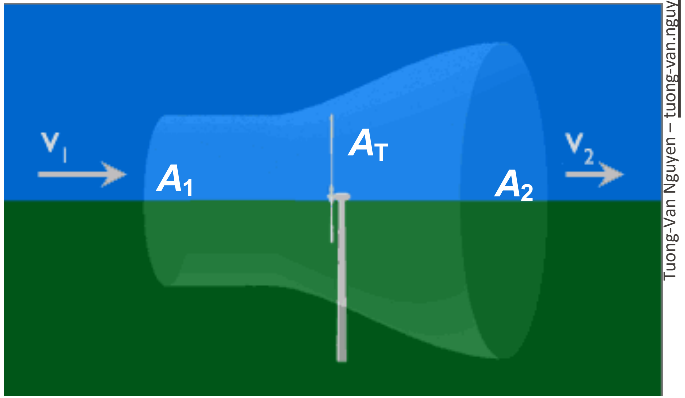
Physics of wind energy

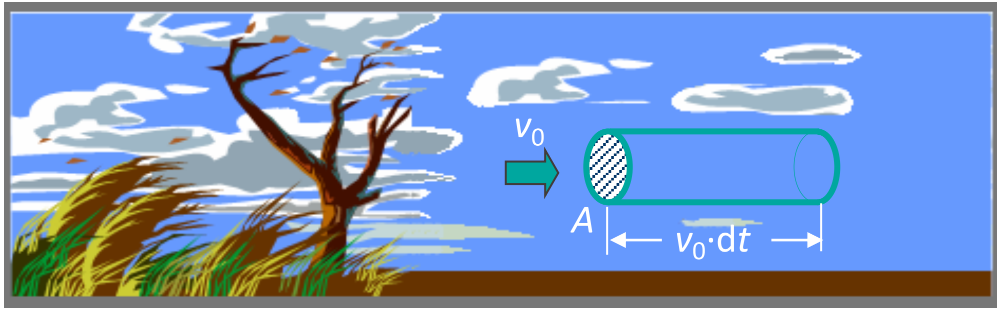
- Additional elements we need:
  - Mass conservation
  - Bernoulli's principle



- Kinetic energy, power, force
  - Air passing through control volume V in dt: $m_{air} = \rho V = \rho A v_0 \mathrm{d}t$
  - Mass flow through A: $\dot{m}_{air} = \rho A v_0$
  - Kinetic energy contained in the air:

$$E_{k,air} = \frac{1}{2} m_{air} v_0^2 = \frac{1}{2}\rho A v_0^3 \mathrm{d}t$$

  - Power: $\boxed{\dot{E}_{k,air} = \frac{\mathrm{d}E_{k,air}}{\mathrm{d}t} = \frac{1}{2}\rho A v_0^3}$
  - Force (drag): $F_{air} = \frac{\dot{E}_{k,air}}{v_0} = \frac{1}{2}\rho A v_0^2$



ME-409 ENERGY CONVERSION AND RENEWABLE ENERGY

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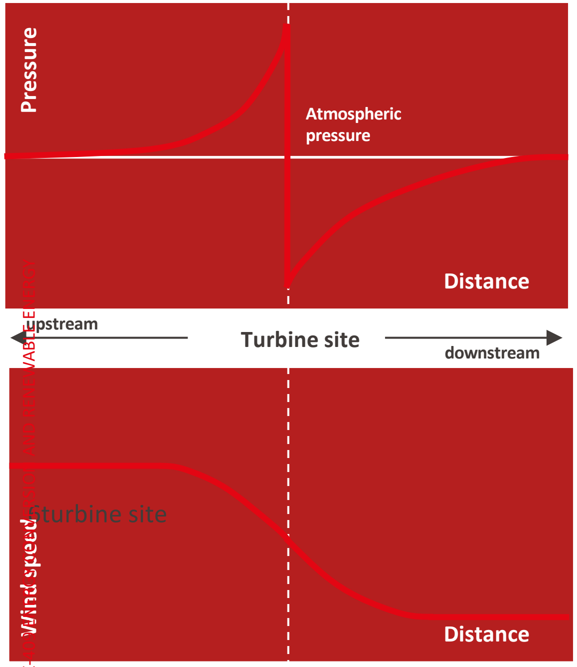
Physics of wind energy

- Wind turbines can (only partly!) extract the kinetic energy from a wind flow
- Pressure and speed fields before and after the turbine



1) The turbine (or *aerogenerator*) first causes the approaching air to slow down gradually, which results in a rise in the static pressure.

2) Across the turbine-swept surface there is a drop in static pressure such that, on leaving, the air is below the atmospheric pressure level.

3) As the air proceeds downstream, the pressure climbs back to the atmospheric value causing a further slowing down of the wind.

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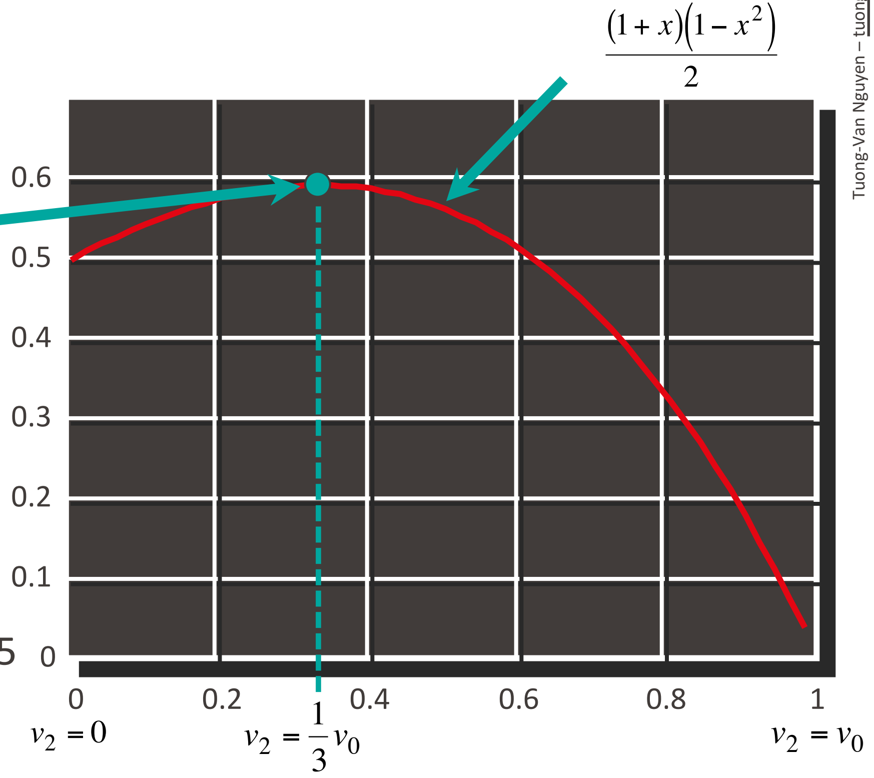
Physics of wind energy

- Betz law gives us a theoretical limit for the efficiency (i.e. conversion of wind kinetic energy into mechanical power) – we can harness **59.3%** of the energy in the wind.
- Effective (real) power coefficient:

$$C_p = \frac{\dot{E}_T}{\dot{E}_W} = \frac{\dot{E}_T}{\frac{1}{2}\rho_{air} A_T v_0^3}$$



- Betz limit: 16/27 = 0.5926…
  - $v_2 = v_0/3$
  - $v_T = 2v_0/3$
  - $A_2 = 3A_1$
  - $A_T = 3A_1/2$
- Practical values in real applications: 0.35-0.5

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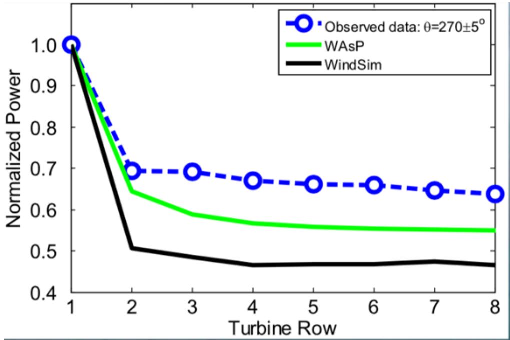
Physics of wind energy

- Why do we get from 59.3% (Betz limit) to around 40% in the practice? Losses:

1. Wake loss: wake is the plume-like region downwind of a wind turbine characterized by reduced wind speed and increased turbulence intensity.
   → predicting performance is still challenging

2. Tip losses: the blade tips themselves also create (‘horseshoe’) vortices. Air ‘overspill’ between the high and low pressures below and above the blade.

3. Drag losses: the blades rotating through air experience a resistance (drag force).



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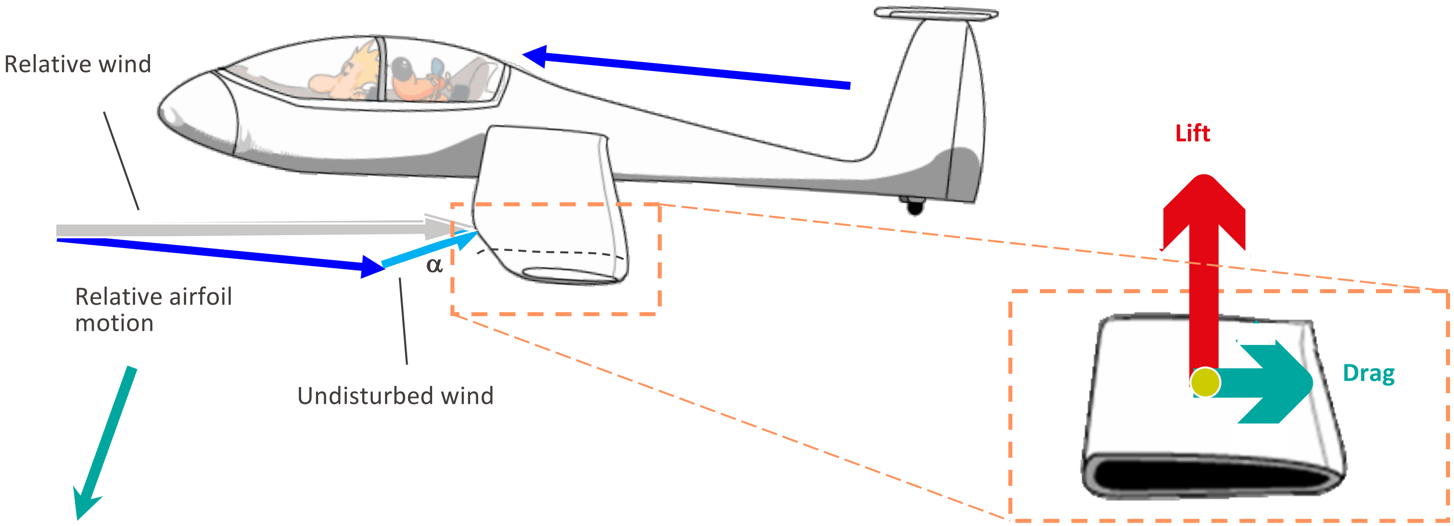
Physics of wind energy

- The forces acting on a turbine blade are lift and drag. Blades are shaped as airfoils: it is very similar to what happens on an airplane.



Air movement when regarding the wing (airfoil, blade) as *static*

An **angle of attack** α is needed to produce lift.

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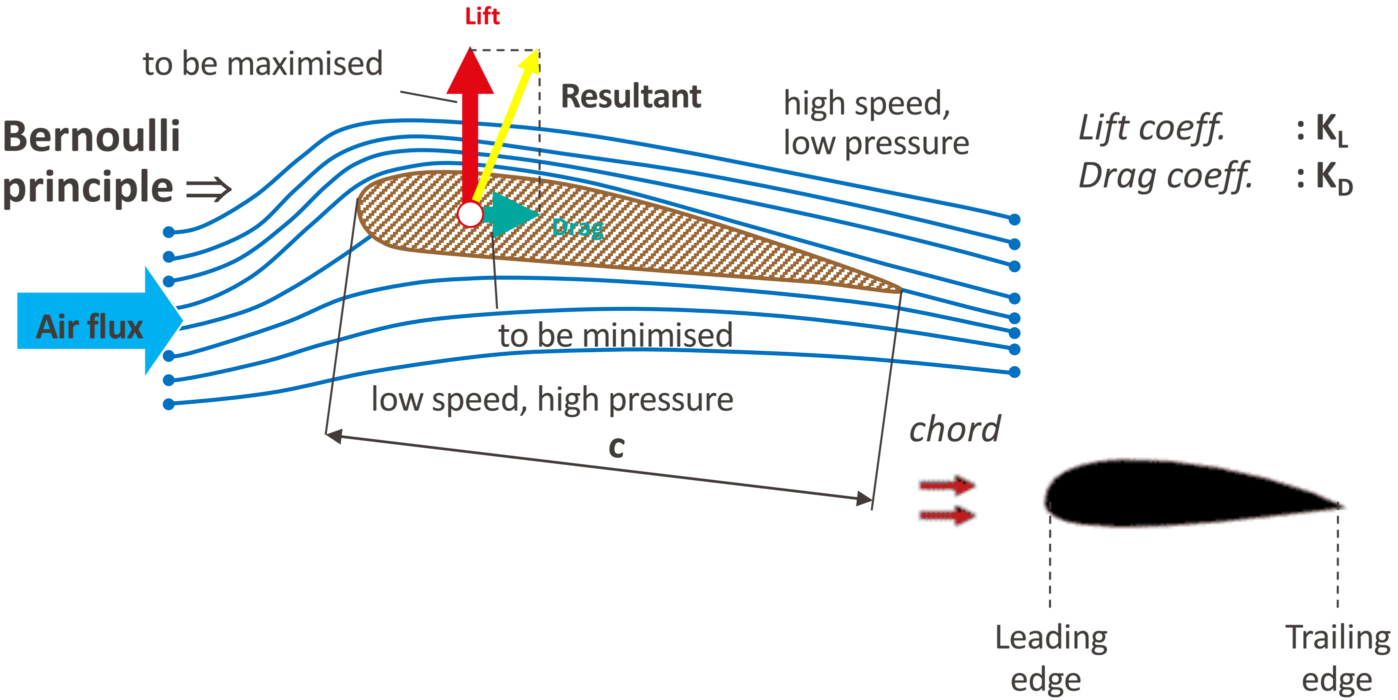
Physics of wind energy



Lift coeff. : K_L

Drag coeff. : K_D

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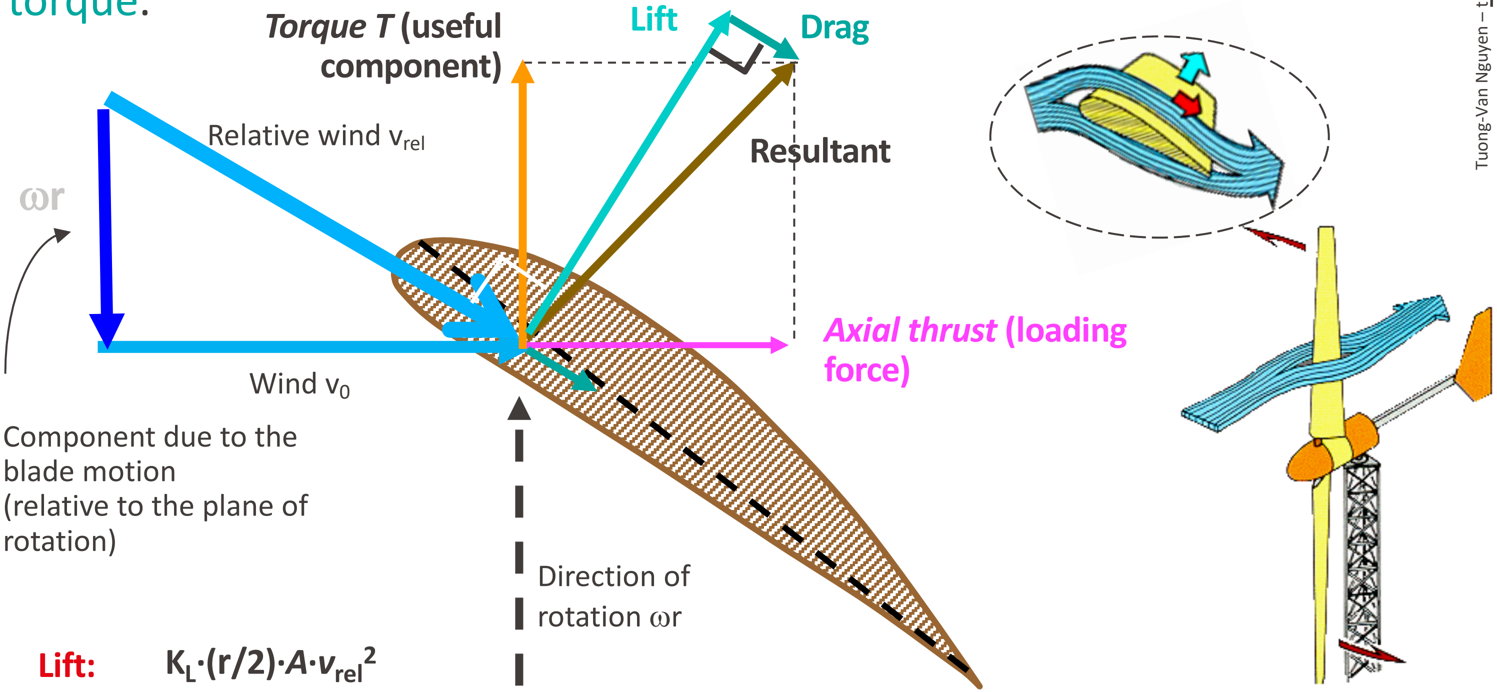
Physics of wind energy

- The forces acting on a turbine blade are lift and drag. In the case of a vertical-axis wind turbine the ratio lift/drag needs to be maximized to increase the useful torque.



Lift: $K_L \cdot (r/2) \cdot A \cdot v_{rel}^2$
Drag: $K_D \cdot (r/2) \cdot A \cdot v_{rel}^2$

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Wind turbines & energy systems

Wind turbines

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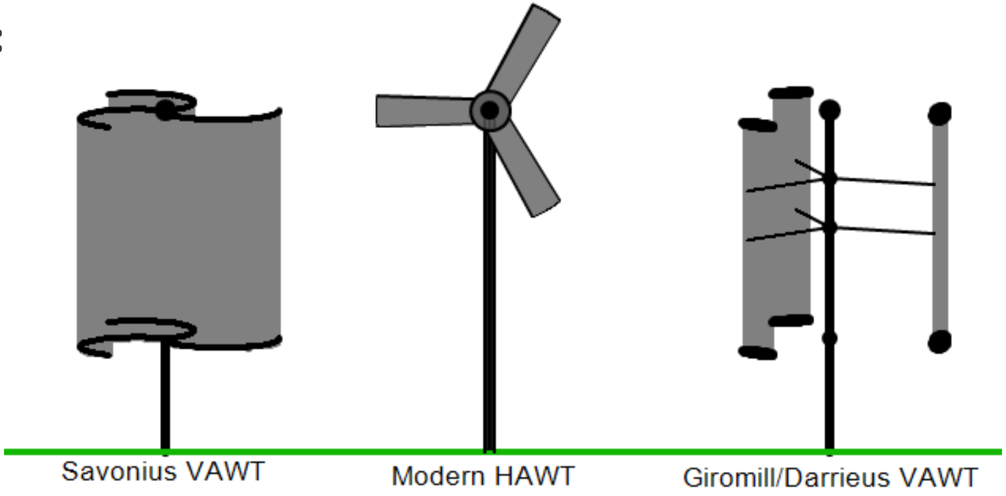
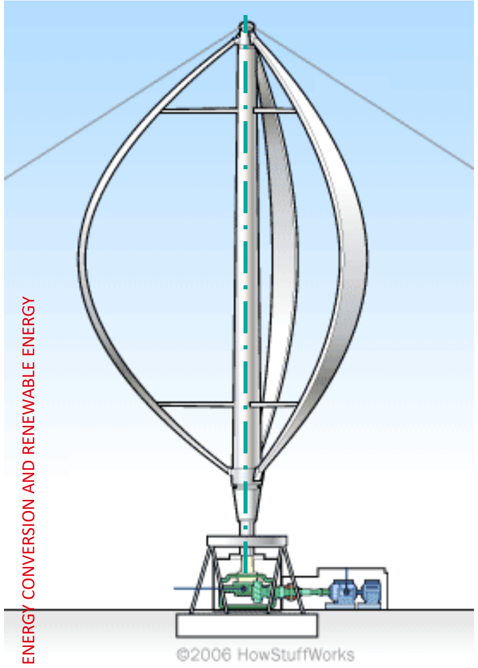
- Types of wind turbines
- Key components
- Design parameters (HAWT):
- Operating ranges
- Growing in size
- Wind farms

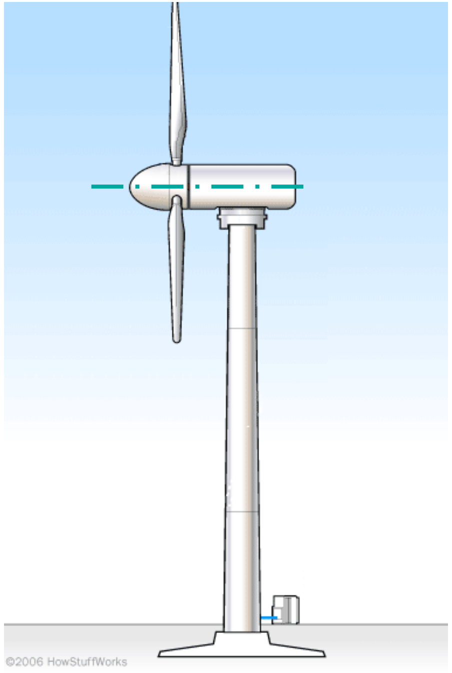


Types of wind turbines

- Key classification: vertical vs. horizontal axis



VAWT: Vertical axis wind turbines. Can be drag (Savonius rotor) or lift based (Darrieus rotor)

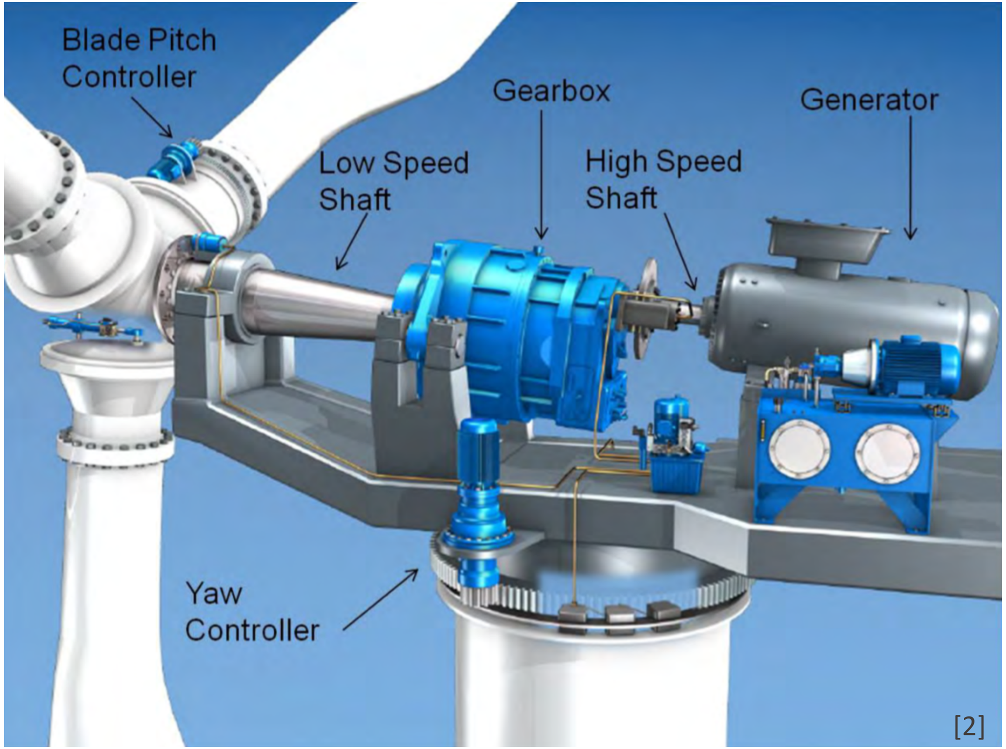


HAWT: Horizontal axis wind turbines. Most used and efficient configurations, normally with 1-3 blades.

Key components

Key components of a horizontal axis wind turbine.

- The drivetrain consists of a gearbox connected
  to the rotor by a low-speed shaft
- The generator converts mechanical work to electricity..
- Mechanical brakes needed to completely
  stop the turbine



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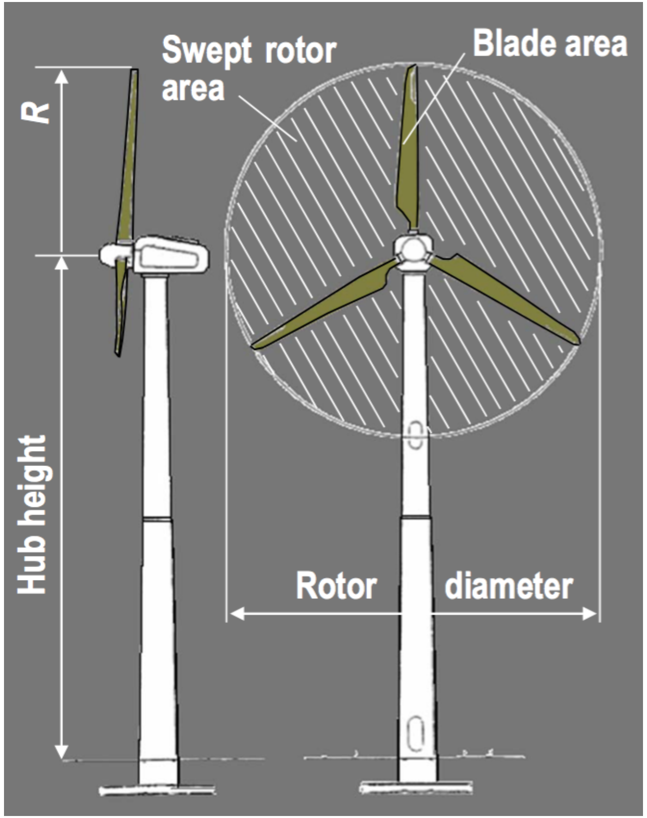
Design parameters of HAWT

Key parameters of a HAWT:

- Number of blades
- Rated power
- Hub height (directly proportional to diameter)
- Swept area
- Solidity = blade area / swept area
  - High: high starting torque, low speed of rotation ω
  - Low: low starting torque, high speed of rotation ω



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Design parameters of HAWT

- **Number of blades:** it does not influence the power. In theory, the most efficient design comes with infinite number of infinitely narrow blades
- Real design criteria: aesthetics, structural, financial

1 blade

2 blades

- **Same power**
- Low torque
- High RPM
- More noise
- **Cheap**
- +6% efficiency vs 1-blade[2]

3 blades

- **Same power**
- Higher torque
- Lower RPM
- Less noise
- +3% efficiency vs 2-blades[2]

Multiple blades

- **Same power**
- **High** torque
- Low RPM
- No noise
- Expensive rotor
- Negligible better efficiency[2]

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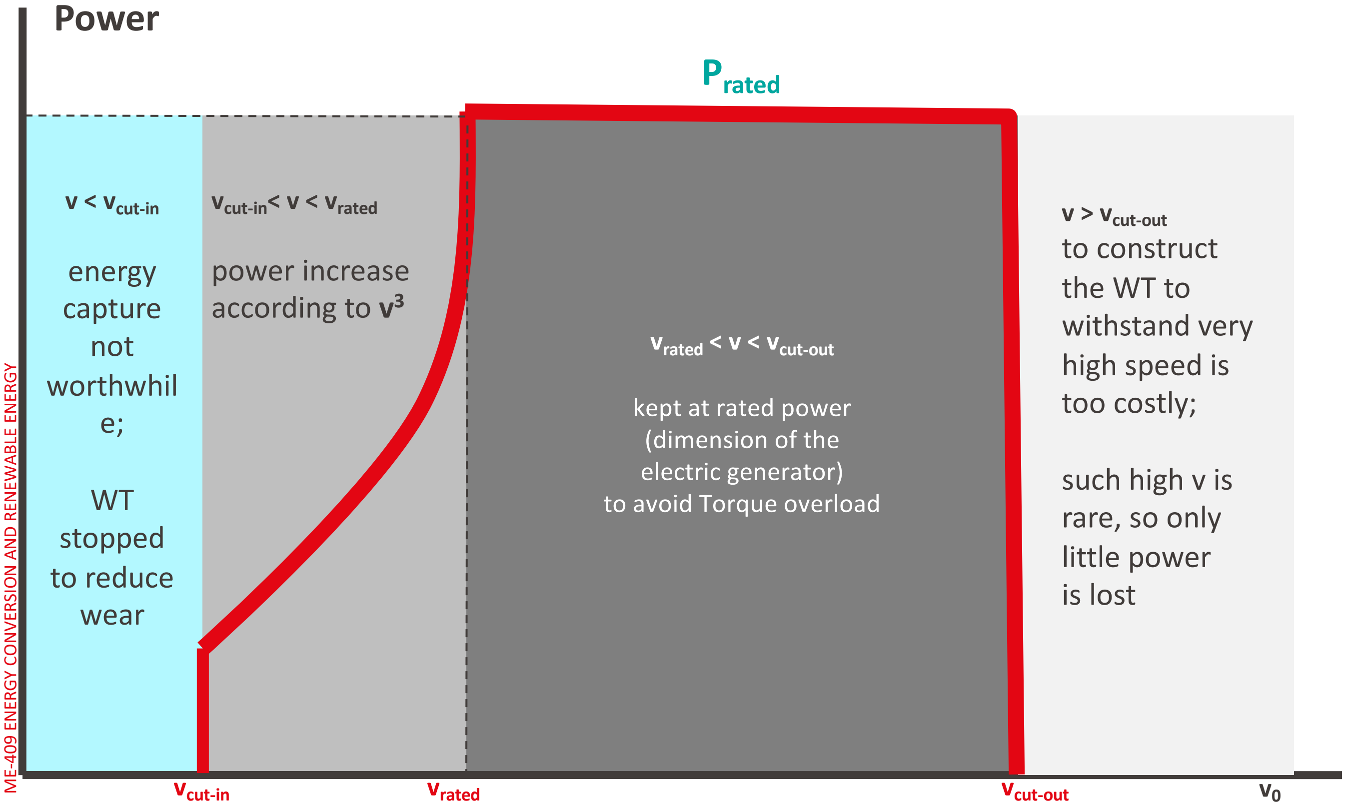
Operating ranges



Aerodynamic power limiting regulation by:

1. Variable pitch
2. Yaw
3. Stall

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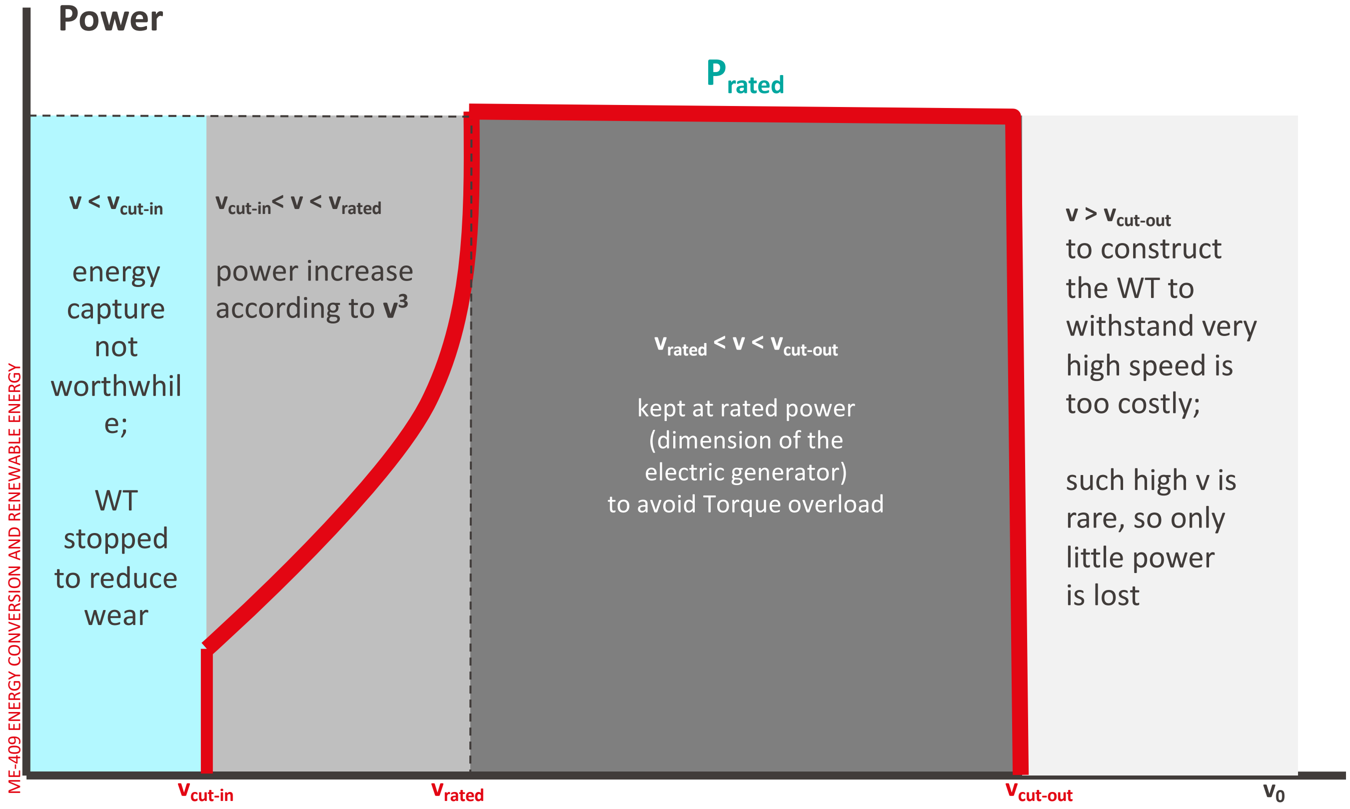
Operating ranges



Aerodynamic power limiting regulation by:

1. Variable pitch
2. Yaw
3. Stall

WT can be run at:

- **One fixed ω**
- Two fixed ω
- Variable ω

Variable speed:

+ 7% energy
+ less power fluctuations
- higher cost
- less reliability

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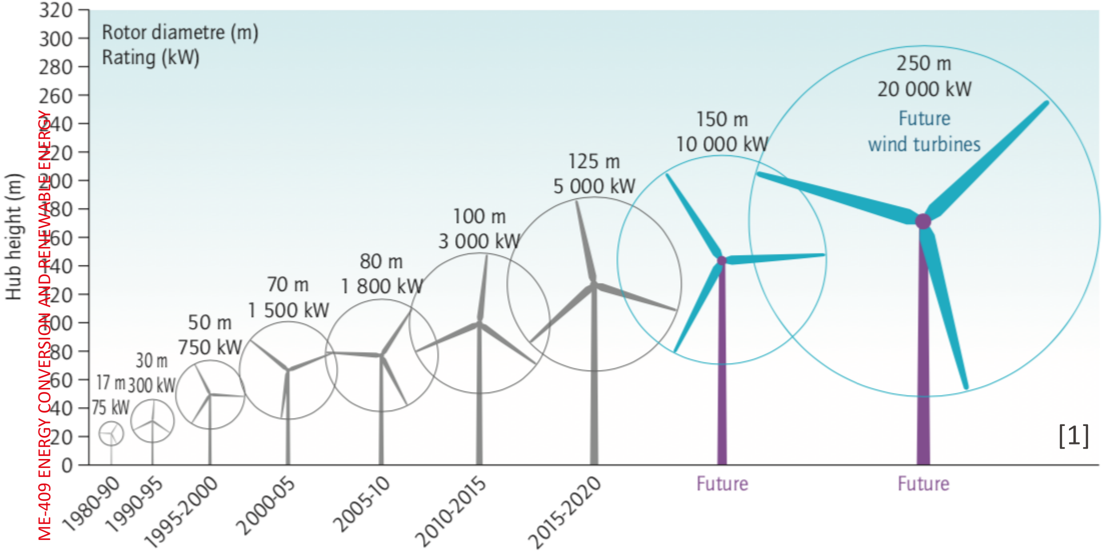
Growing in size

$$\dot{E}_{k,air} = \frac{\mathrm{d}E_{k,air}}{\mathrm{d}t} = \frac{1}{2}\rho A v_0^3$$

- The power is proportional to A → D^2



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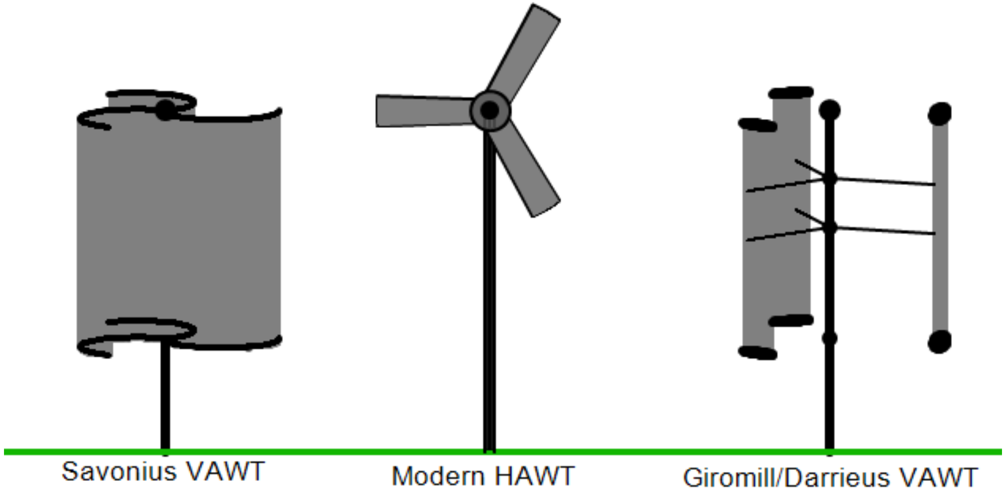
Wind farms

- Wind turbines are commonly used in wind farms:
  - Usually 10-30 turbines
  - Spacing: 7-8*Diameters
  - 1 grid transformer for the whole site
  - Timing: construction (1y); operation (20y); decommissioning (0.5y)

- Horns Rev offshore wind farm (DK):
  - 80 turbines
  - 160 MW_e
  - Offshore:
    - Higher capacity factors
    - Higher and more regular wind speed (120 m/s)
    - More noise (lower solidity)

Wind in the energy system

- Capacity factors
- Cost
- Intermittency
- Risks and impacts



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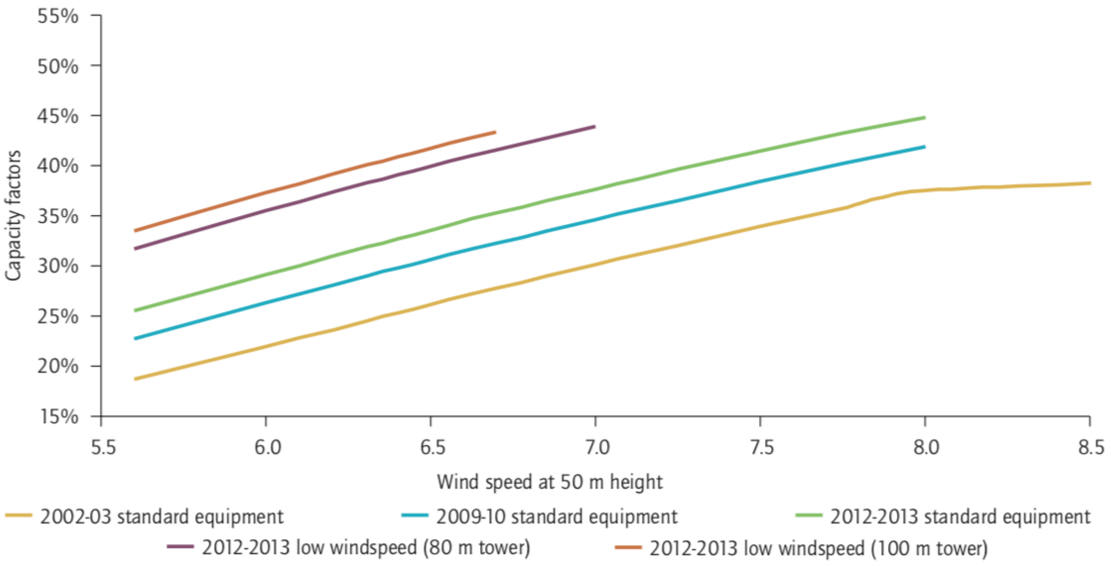
Capacity factors

- Capacity factor c_p, typical values:
  - Onshore: 26% (2013) → 31% (2050)
  - Offshore: 36% (2013) → 42% (2050)
  - In Switzerland: 19% (today) → 23% (future)

Figure 3: Capacity factors of selected turbine types



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Costs

- Cost is decreasing!
  - IEA projection for 2035: 1600 USD_{2012}/KW_e
  - 2017 data by Wind Europe:
    - 22.3 B€ announced investments
    - 11.5 GW_e

    → 1939 €/kW_e
  - LCOE in 2020: 50 €/MWh onshore, 60 €/MWh offshore

Figure 5.3 Total installed costs of onshore wind projects and global weighted average, 1983-2017

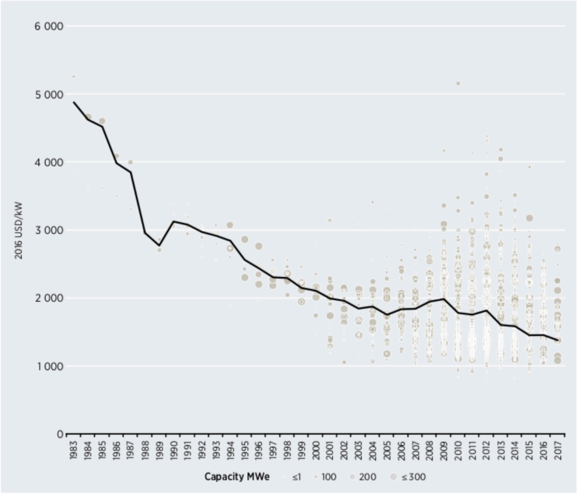
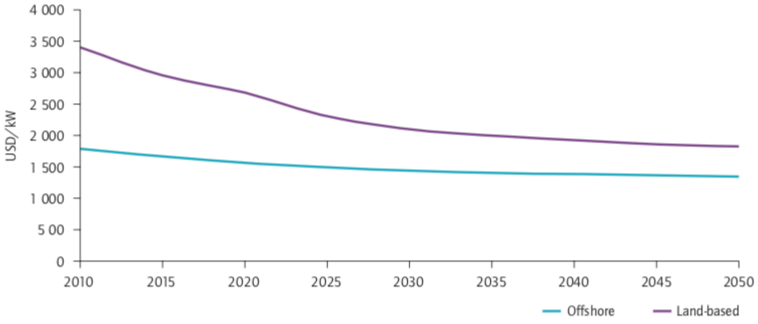


Figure 13: 2DS projections for investment costs of wind turbines



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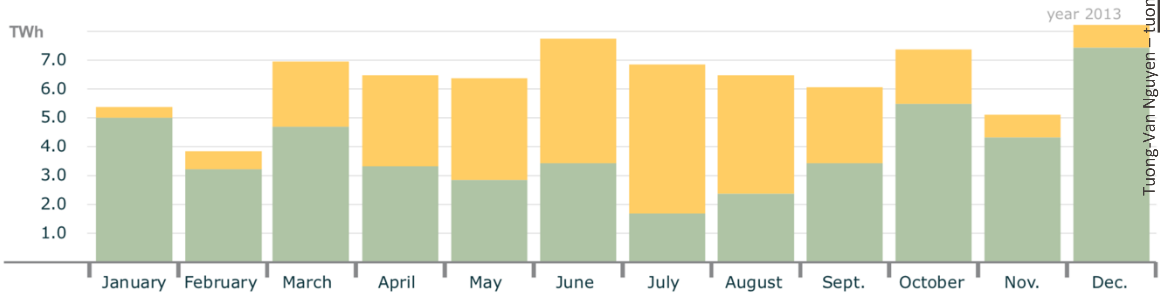
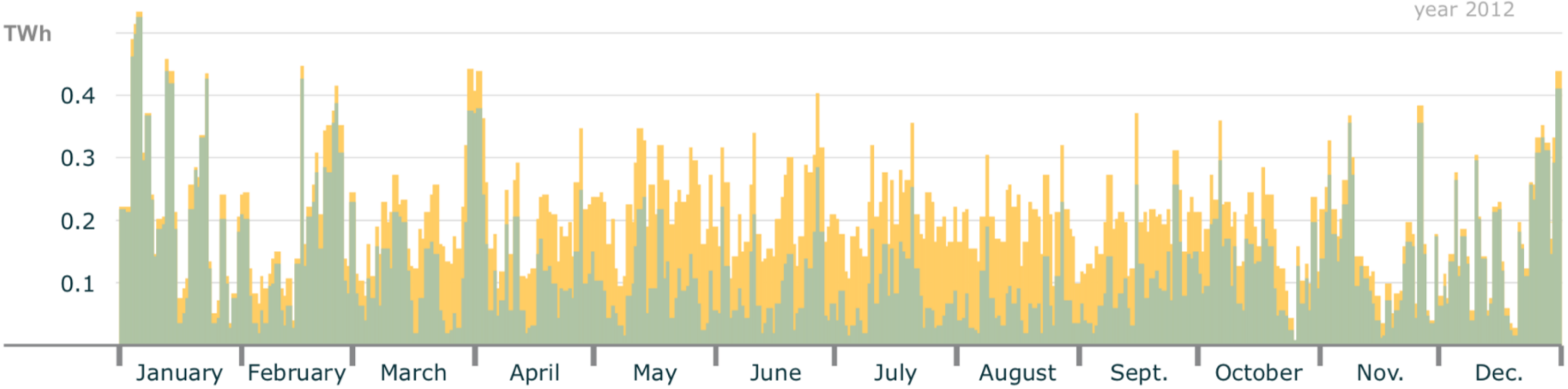
Intermittency

- Different time scales:
  - Hourly
  - Daily
  - Weekly
  - Seasonal
- Can complement solar

Monthly Production Solar and Wind



Daily production Solar and Wind



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Risks and impacts

- Machinery maintenance accidents
- Blade failures
- Falling ice
- Paragliders and small aircraft crashing into support structures
- Turbine's brake fails → the turbine can spin freely until it disintegrates
- Turbine blades may fall off due to manufacturing flaws
- Lightning strikes → rotor blade damage and fires

A turbine on fire after an oil leak

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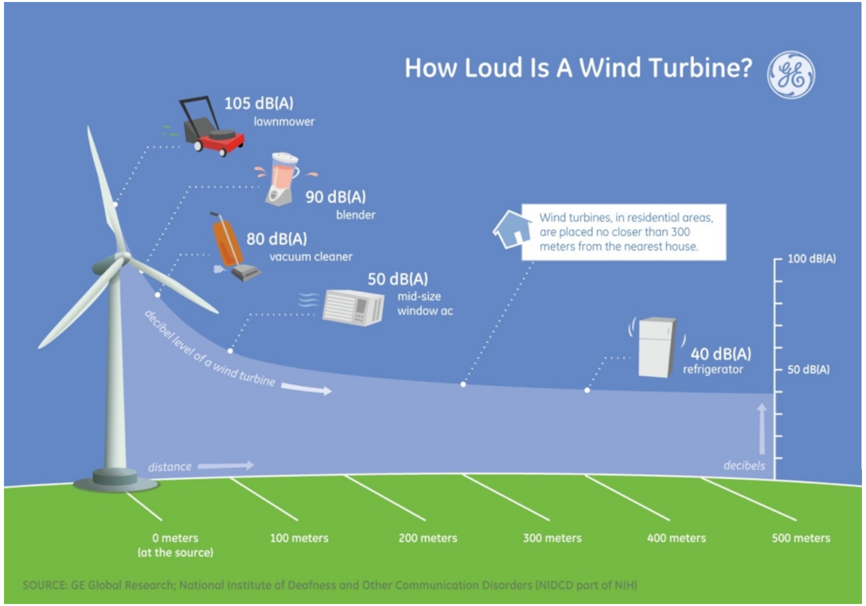
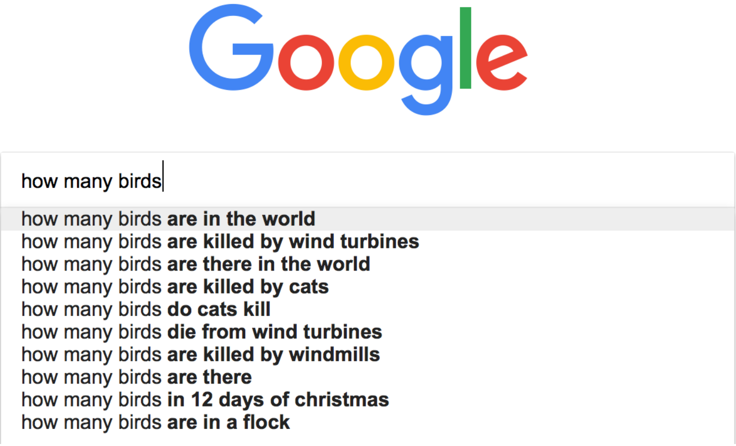
Perceived risks

- Other perceived problems are: visual impact, noise and killing birds





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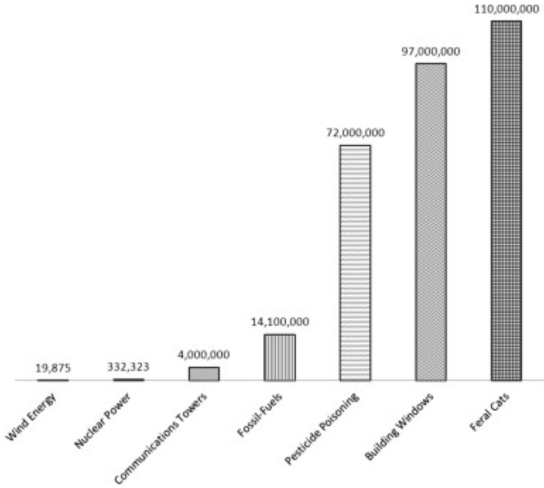
Risks and impacts

- Other perceived problems are: visual impact, noise and killing birds



Annual avian deaths in 2009 in the US

Some controversy about
- Orders of magnitude are clear
- Relatively small danger for birds
- Climate change likely to be a more severe risk for birds

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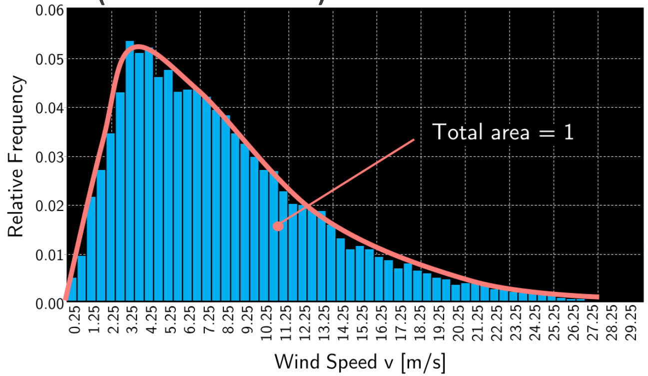
Take-home message

Take-home message

- **Key concepts**
  - Wind is growing fast → key player for climate change
  - Resource: power goes with v³, location dependent (Weibull PDF)
  - Betz limit: theoretical limit is 59.3% efficiency
  - Forces: maximise lift/drag

$$\dot{E}_{k,air} = \frac{\mathrm{d}E_{k,air}}{\mathrm{d}t} = \frac{1}{2}\rho A v_0^3$$



$$\dot{E}_{T,max} = \frac{1}{2}\rho_{air} A_T v_0^3 \left[\frac{16}{27}\right] = 0.593\dot{E}_{Wind}$$

- **Wind Turbines**
  - Classified in vertical vs horizontal axes
  - Growing is size
  - Wind farms

- **Wind in the energy system**
  - Costs are quickly reducing → wind is alredy competitive!
  - Capacity factors: 25-30% onshore, 35-40% offshore
  - Wind can be a good complement of solar

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Questions?

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