EPFL

Wind energy

Author: Stefano Moret/Tuong-Van Nguyen

Lecturer: Prof. François Maréchal
EPFL – IPESE

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École polytechnique fédérale de Lausanne

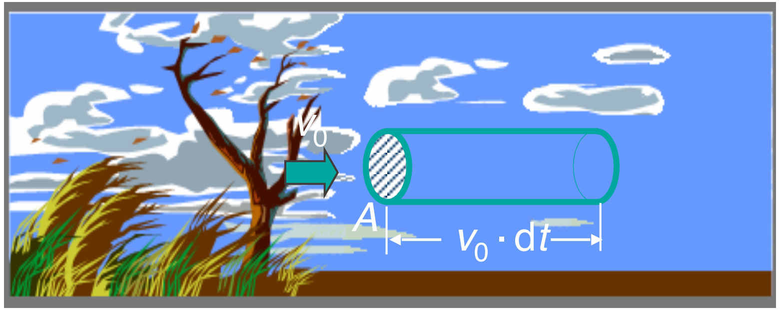
Outline

- 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

What is wind energy?

- Wind can be defined as "air in motion":
  1. Differences in pressure (pressure gradient force), caused by uneven solar heating on the earth surface
  2. Rotation of the Earth: Coriolis force
  3. Friction close to the Earth surface



- Kinetic energy, power, force
  - Air passing through control volume V in dt:
  - Mass flow through an area A:
  - Kinetic energy contained in the moving air:

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

  - Power:

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

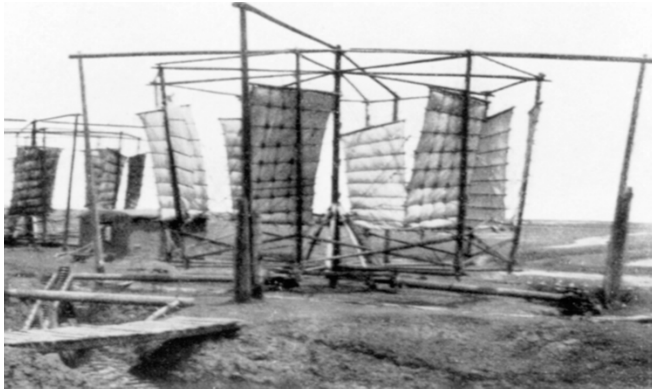
  - Force (drag):

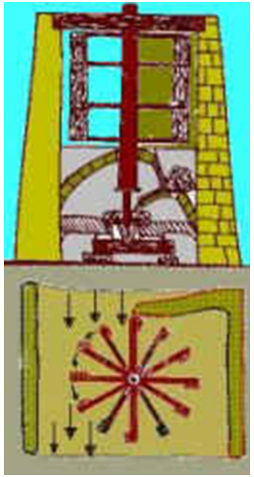
$$F_{air} = \frac{\dot{E}_{k,air}}{v_0} = \frac{1}{2} \rho A v_0^2$$

Tuong-Van Nguyen – tuong-van.nguyen@e

Harvesting wind energy?

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





Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Harvesting wind energy?

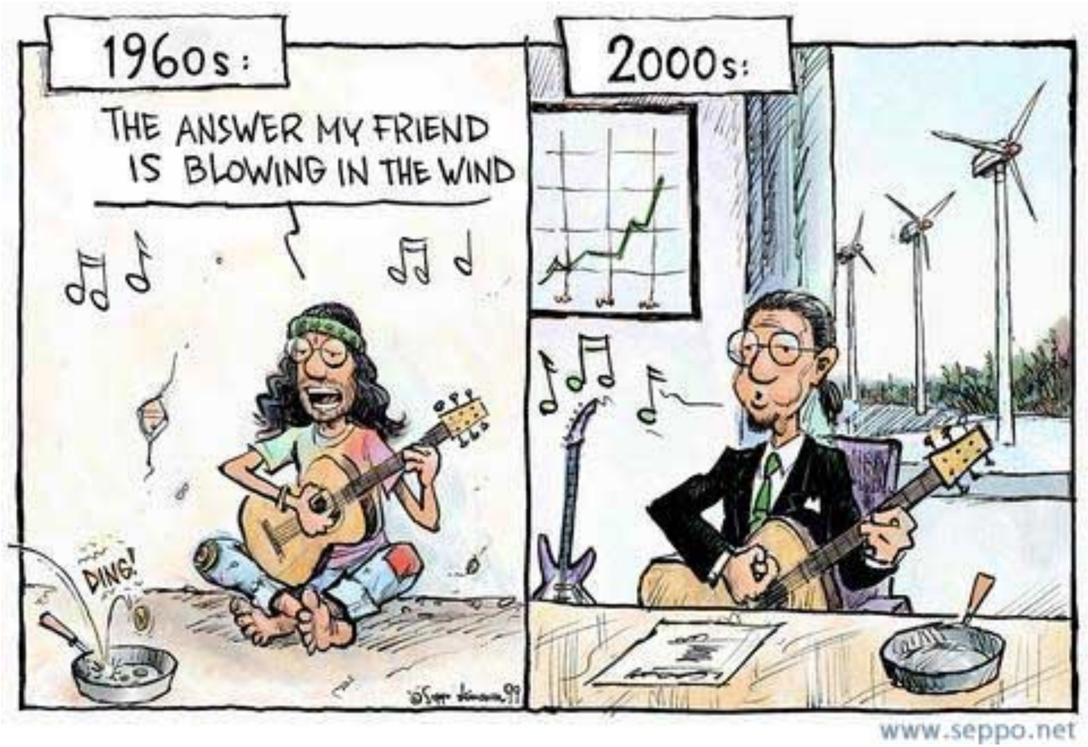
Why wind farms — Search Google

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

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Harvesting wind energy?



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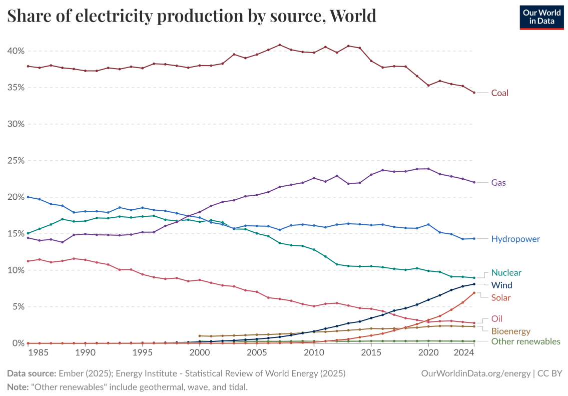
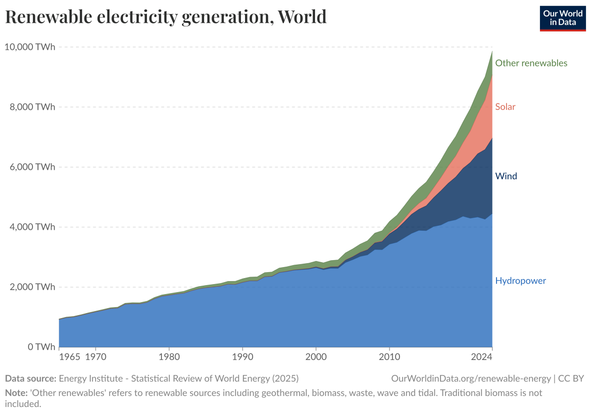
Wind energy today

- World Wind capacity installed (2023): 1021 GW
- Wind production 2311 TWh/y (2023) : capacity factor = 25%)
  - 7.8% of world electricity supply
- IIASA, practical potential (onshore): 20’000-100’000 TWh/y
- IEA: 18% of world electricity supply in 2050
- Potential depends on wind speed…

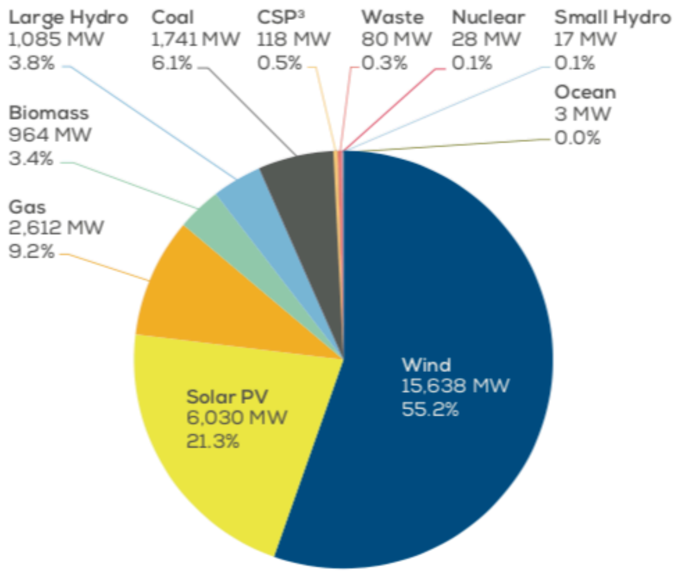


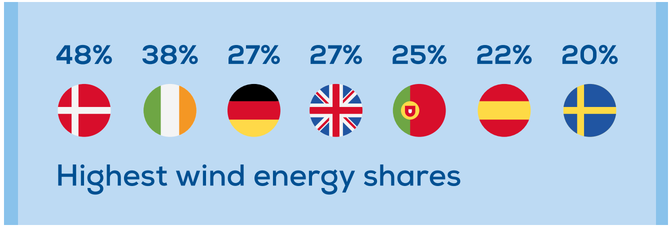


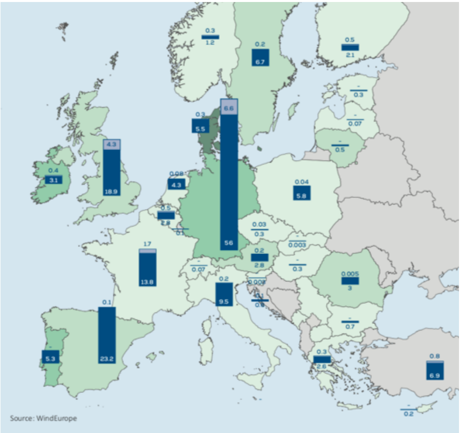
Wind energy in Europe

- Total wind capacity in EU: 220 GW_e (2020), of which 25 GW_e offshore
- +14 GW_e /year installed in 2010-2020
- 16% of electricity demand

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







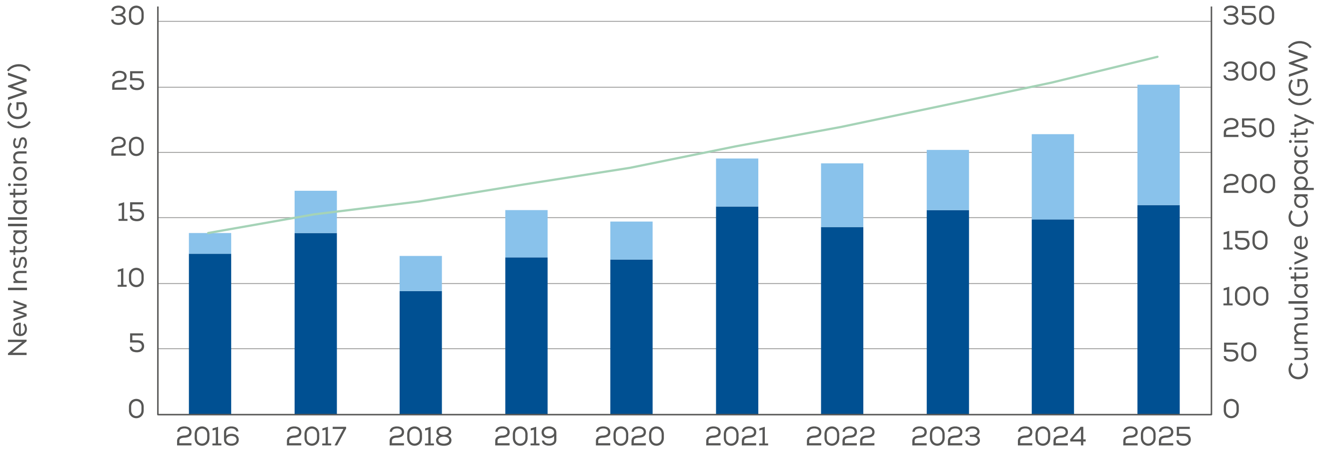
http://windeurope.org

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Wind energy Europe 2021-2025

FIGURE 13

New and total (cumulative) installations in Europe - WindEurope's Realistic Expectations Scenario



	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Offshore	1.6	3.2	2.7	3.6	2.9	3.7	5.1	4.6	6.5	9.2
Onshore	12.3	13.9	9.4	12.0	11.8	15.9	14.1	15.6	14.9	16.0
Cumulative	**162**	**178**	**190**	**205**	**220**	**238**	**256**	**275**	**295**	**318**

Onshore : 72% of new installations

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Swiss Wind energy

- Swiss final energy consumption: 207 TWh/y (2020)
- Swiss electricity consumption: 55.5 TWh_e/y (2020)
- Wind electricity production: 0.17 TWh_e/y (2020)

→ Only 41 turbines (86.5 MW_e) installed in CH

→ Target 2050 : 4.3 TWhe/y (2050)

~ 850 Turbines (2400 MWe)

https://www.bfe.admin.ch/bfe/en/home/supply/renewable-energy/wind-energy.html/

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

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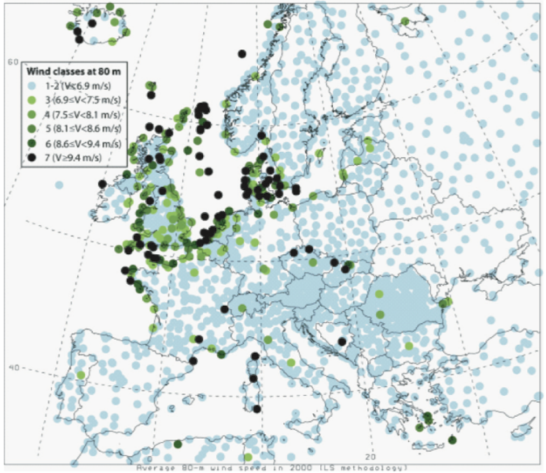
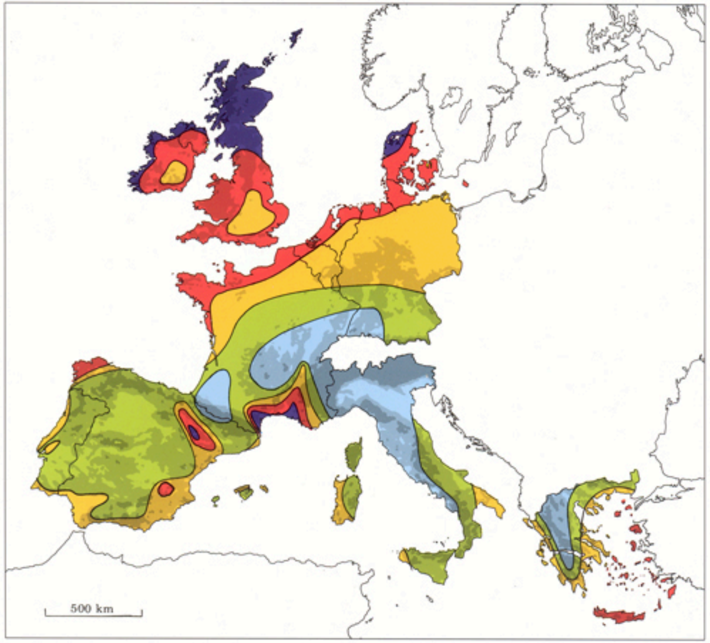
The resource

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

- The main factor is the wind speed!





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}
(purple)	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
(red)	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
(orange)	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
(green)	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
(blue)	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Source: Risø DTU National Laboratory, Denmark

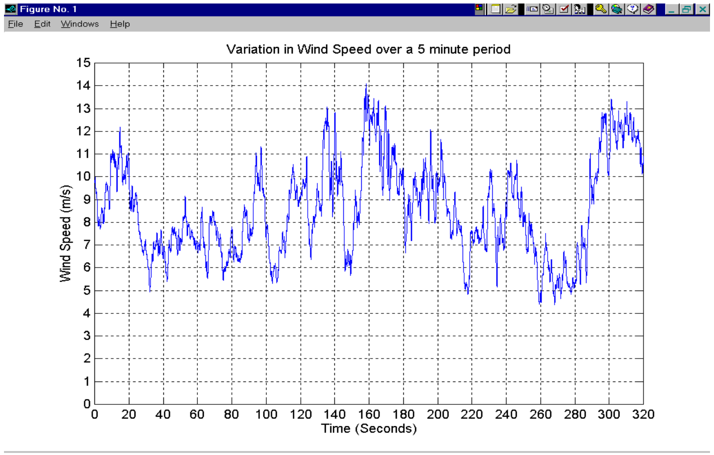
Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

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

Speed [m/s]



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Introduction
The resource

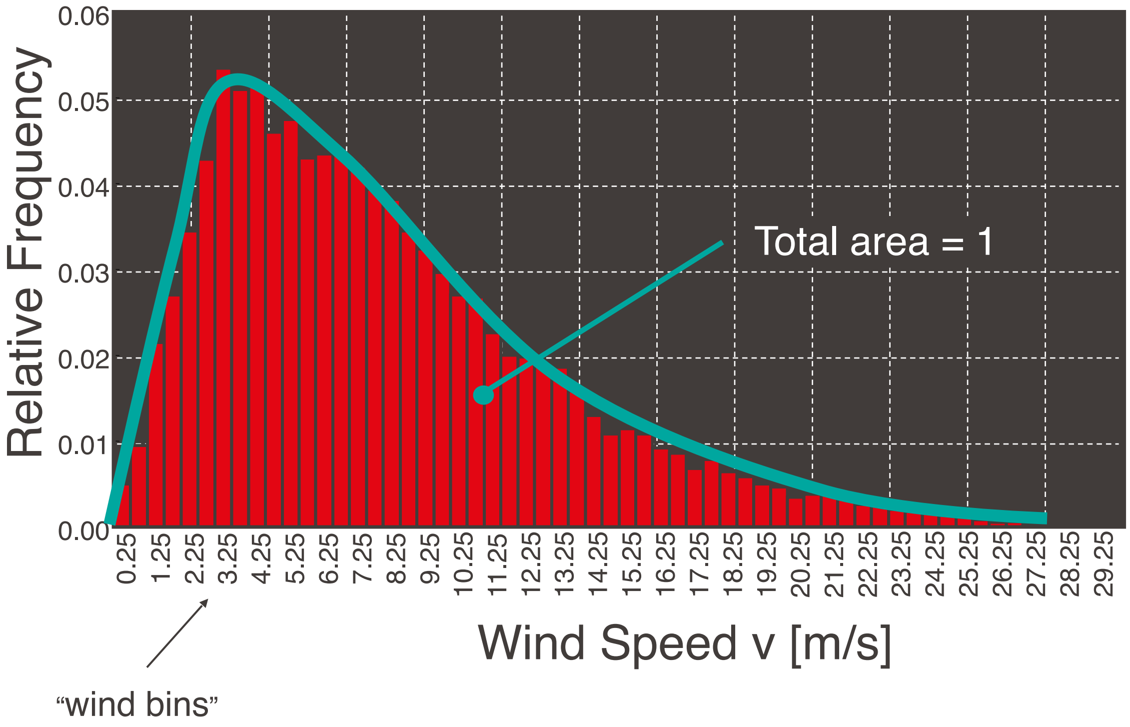
- Wind speed distribution at a given site:

- **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



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

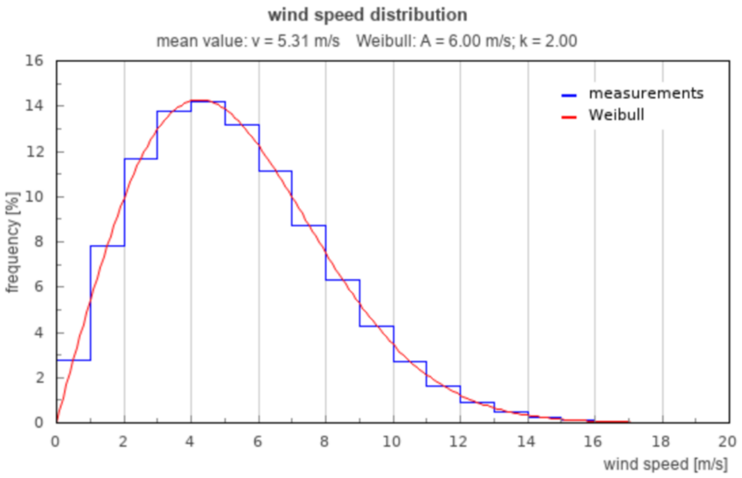
Introduction
The resource

- Data base of the Probability distribution function parameters:

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

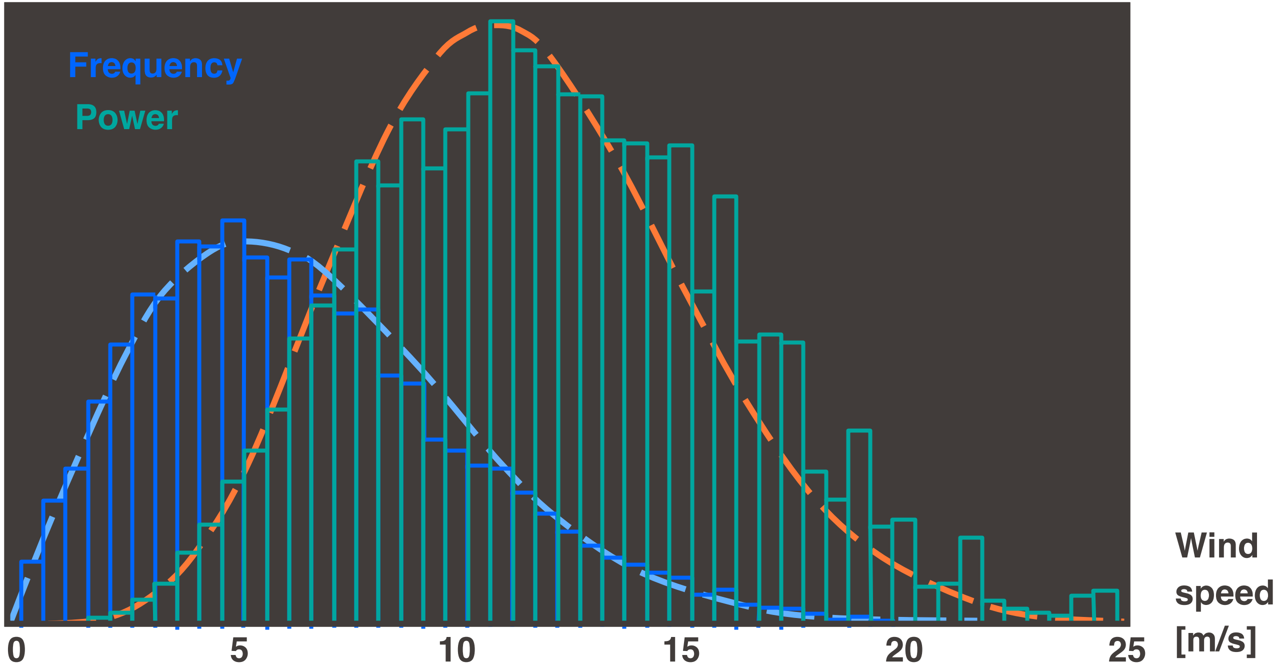
Class	Frequency in %
0 - 1 m/s	2.75
1 - 2 m/s	7.80
2 - 3 m/s	11.64
3 - 4 m/s	13.79
4 - 5 m/s	14.20
5 - 6 m/s	13.15
6 - 7 m/s	11.14
7 - 8 m/s	8.72
8 - 9 m/s	6.34
9 - 10 m/s	4.30
10 - 11 m/s	2.73
11 - 12 m/s	1.62
12 - 13 m/s	0.91
13 - 14 m/s	0.48
14 - 15 m/s	0.24
15 - 16 m/s	0.11
16 - 17 m/s	0.05
17 -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



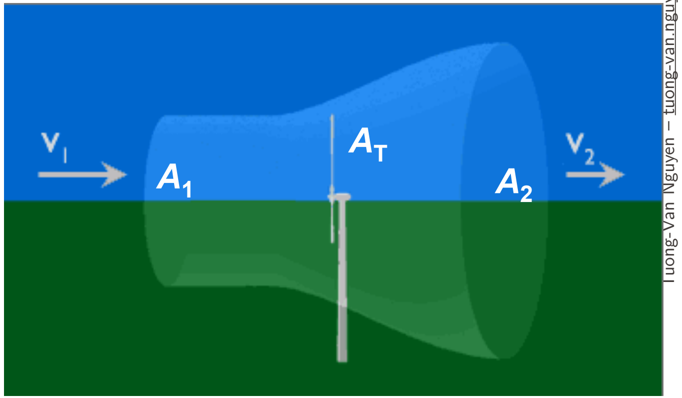
Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Physics of wind energy

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Physics of wind energy

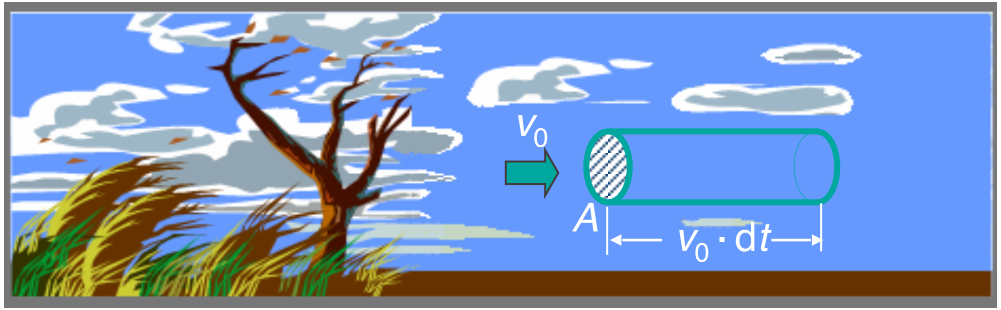
- Additional elements we need:
  - Mass conservation
  - Bernoulli's principle



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



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Physics of wind energy

- Let's consider the "**control volume**" V: If the surface A_T is swept by the blades of an horizontal-axis wind turbine of diameter D, the disturbed air flux affects a volume (control volume) having a cross-section **significantly larger** than A_T

1. **Force** acting on the turbine (v_0 = "free" wind speed; recalling that

$$\boldsymbol{F}\cdot\cancel{dt} = m\,dv = \rho\cdot A_T\cdot v_T\cdot\cancel{dt}\cdot(v_1 - v_2) = \rho\cdot A_T\cdot v_T\cdot\cancel{dt}(v_0 - v_2)$$

2. We have also that: $\boldsymbol{F} = A_T\cdot(P_{in} - P_{out})$

$$\boxed{A_T\cdot(P_{in} - P_{out}) = \rho\cdot A_T\cdot v_T\cdot(v_0 - v_2)} \quad (3)$$

3. And from Bernoulli's principle:

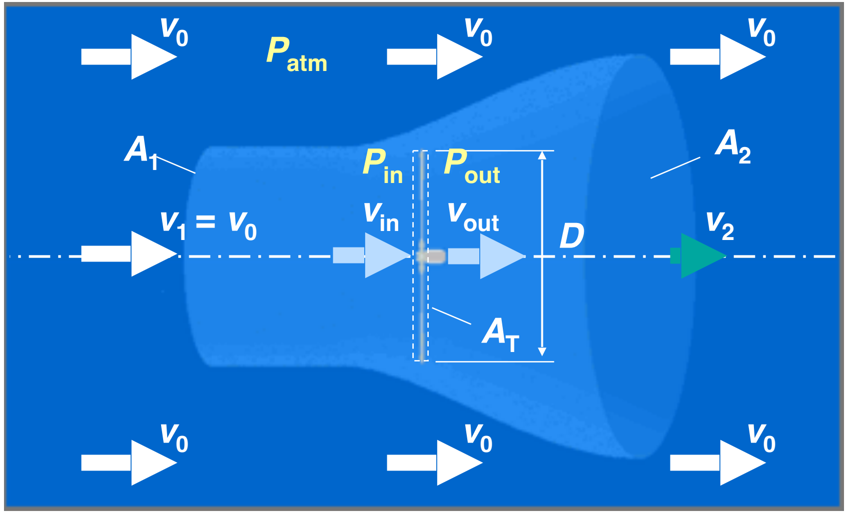
upstream: $P_{in} - P_{atm} = \rho\,\dfrac{v_0^2 - v_T^2}{2}$

downstream: $P_{atm} - P_{out} = \rho\,\dfrac{v_T^2 - v_2^2}{2}$

$\tfrac{1}{2}\cdot\rho\cdot v^2 + P =$ cst

$$\boxed{P_{in} - P_{out} = \frac{1}{2}\rho\left(v_0^2 - v_2^2\right)} \quad (4)$$

$v_{in} = v_{out} = v_T$



Physics of wind energy

- Let's consider the "**control volume**" V: If the surface A_T is swept by the blades of an horizontal-axis wind turbine of diameter *D*, the disturbed air flux affects a volume (control volume) having a cross-section **significantly larger** than A_T
- Let's now look at the **kinetic energy**:

$$E_T = E_{kin,air}^{in} - E_{kin,air}^{out} = \frac{1}{2} m_{air}\left(v_0^2 - v_2^2\right) \quad (1)$$

$$\dot{E}_T = \frac{1}{2}\dot{m}_{air}\left(v_0^2 - v_2^2\right) = \frac{1}{2}\rho_{air} \underbrace{A_T v_T}_{=A_2 \cdot v_2 \text{ (mass conservation)}} \left(v_0^2 - v_2^2\right) \quad (2)$$

$$A_T \cdot (P_{in} - P_{out}) = \rho \cdot A_2 \cdot v_2 \cdot (v_0 - v_2) \quad (3)$$

$$P_{in} - P_{out} = \frac{1}{2}\rho\left(v_0^2 - v_2^2\right) \quad (4)$$

$v_{in} = v_{out} = v_T$

$$\frac{A_2}{A_T} = \frac{\left(1 + \frac{v_2}{v_0}\right)}{2\frac{v_2}{v_0}}$$

$$\dot{E}_T = \frac{1}{2}\rho_{air} A_T \frac{A_2}{A_T} v_2 \left(v_0^2 - v_2^2\right)$$ (multiply by v_0/v_0)

$$\dot{E}_T = \underbrace{\frac{1}{2}\rho_{air} A_T v_0^3}_{\text{Power in the wind}} \underbrace{\frac{A_2}{A_T}\frac{v_2}{v_0}\left[1 - \left(\frac{v_2}{v_0}\right)^2\right]}_{C_p\text{: Power coefficient}} \quad (5)$$

$$\dot{E}_T = C_p \dot{E}_{Wind}$$

$$if \quad x = \frac{v_2}{v_0} \quad then \quad C_P = \frac{(1+x)(1-x^2)}{2}K$$

Power coefficient : max for x= v2/v0

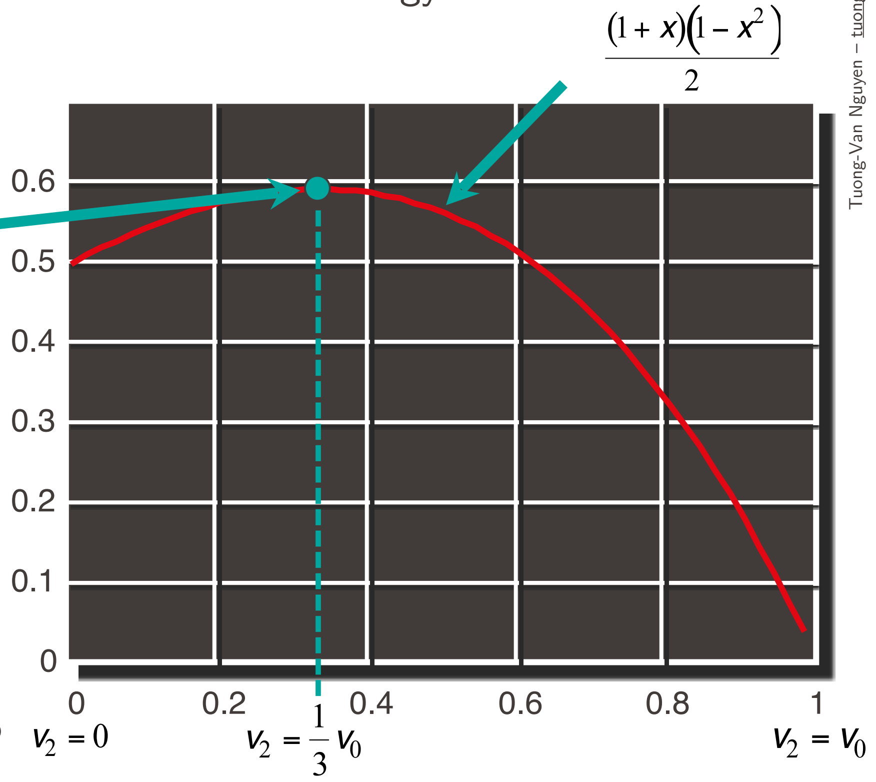
- Betz law gives us a theoretical limit for the efficiency (i.e. conversion of wind kinetic energy into mechanical power) – we can harness 59.3% of the energy in the wind.
- Effective (real) power coefficient:

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

$$\max_x C_P(x) = \frac{(1+x)(1-x^2)}{2}$$

- 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

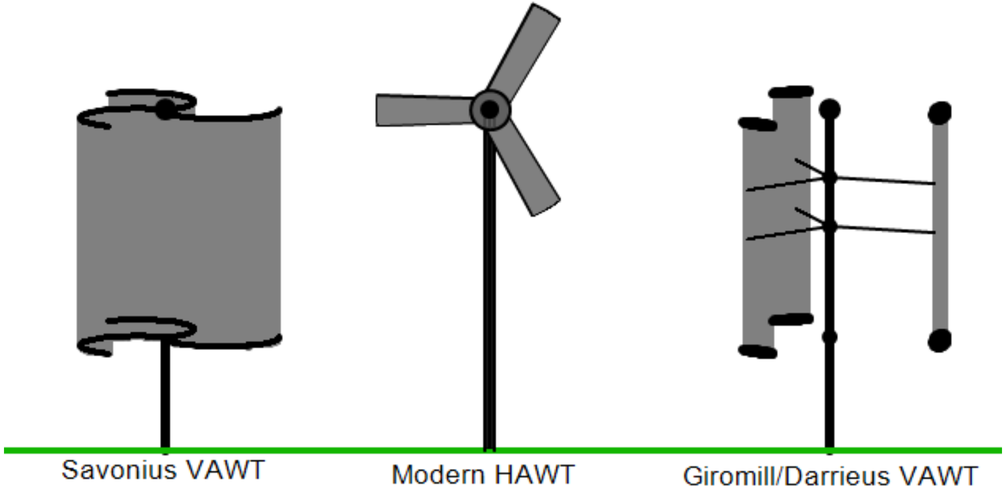


Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Wind turbines & energy systems

Wind turbines

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



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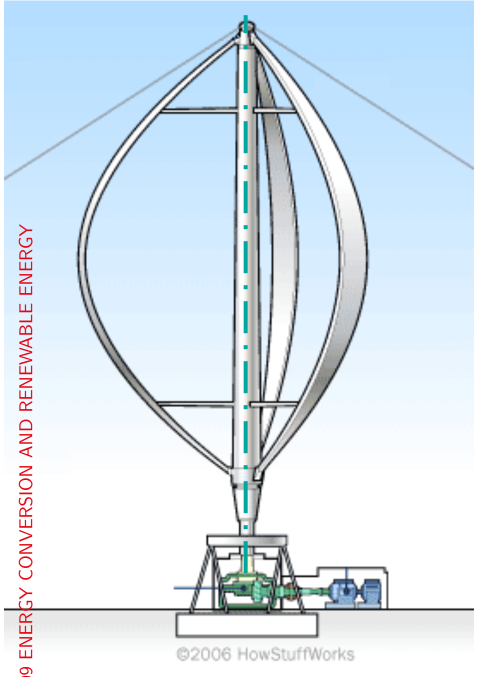
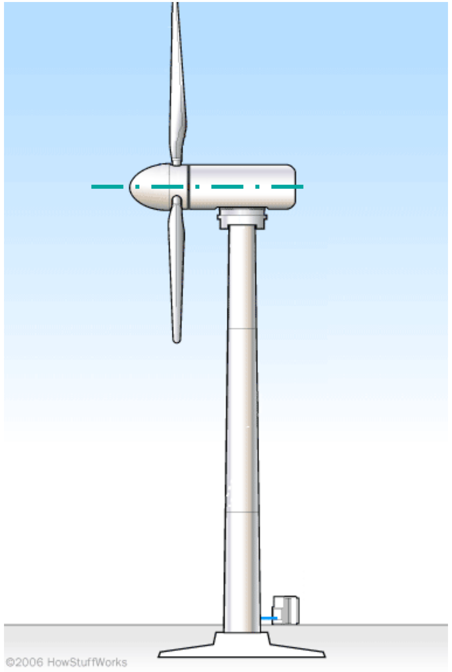
Types of wind turbines

- Key classification: vertical vs. horizontal axis



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



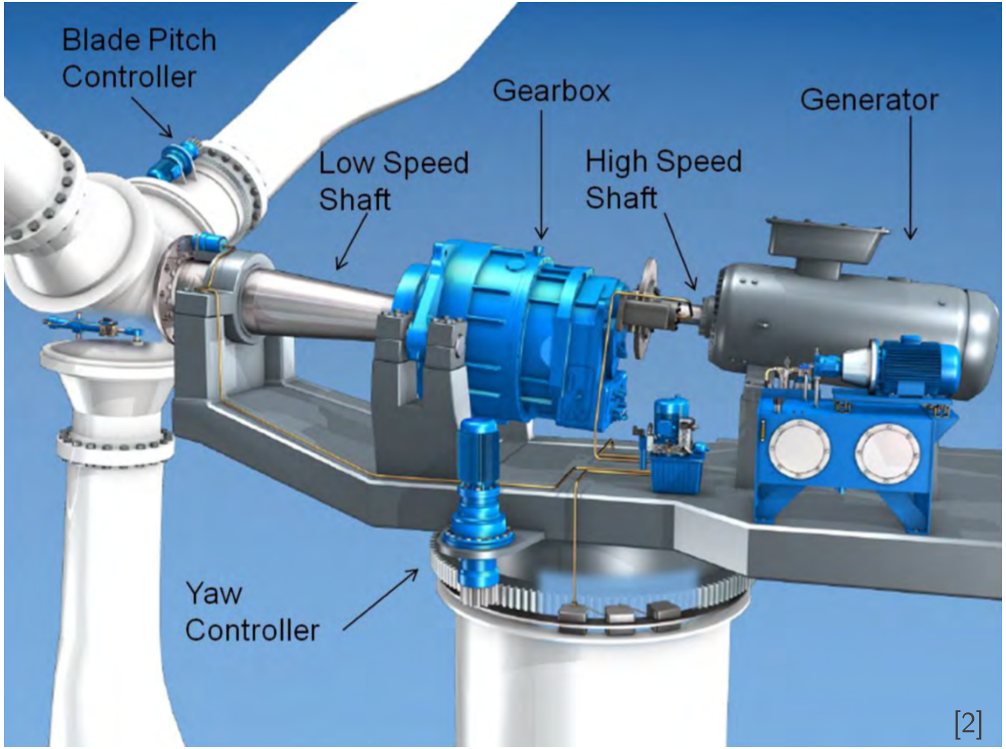
HAWT: Horizontal axis wind turbines. Most used and efficient configurations, normally with 1-3 blades.

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

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

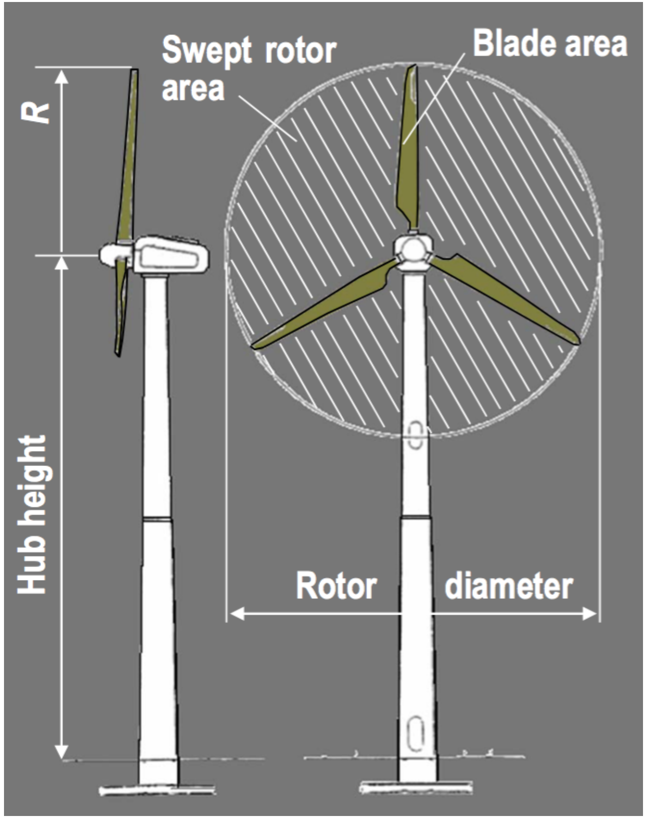


Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

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



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

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

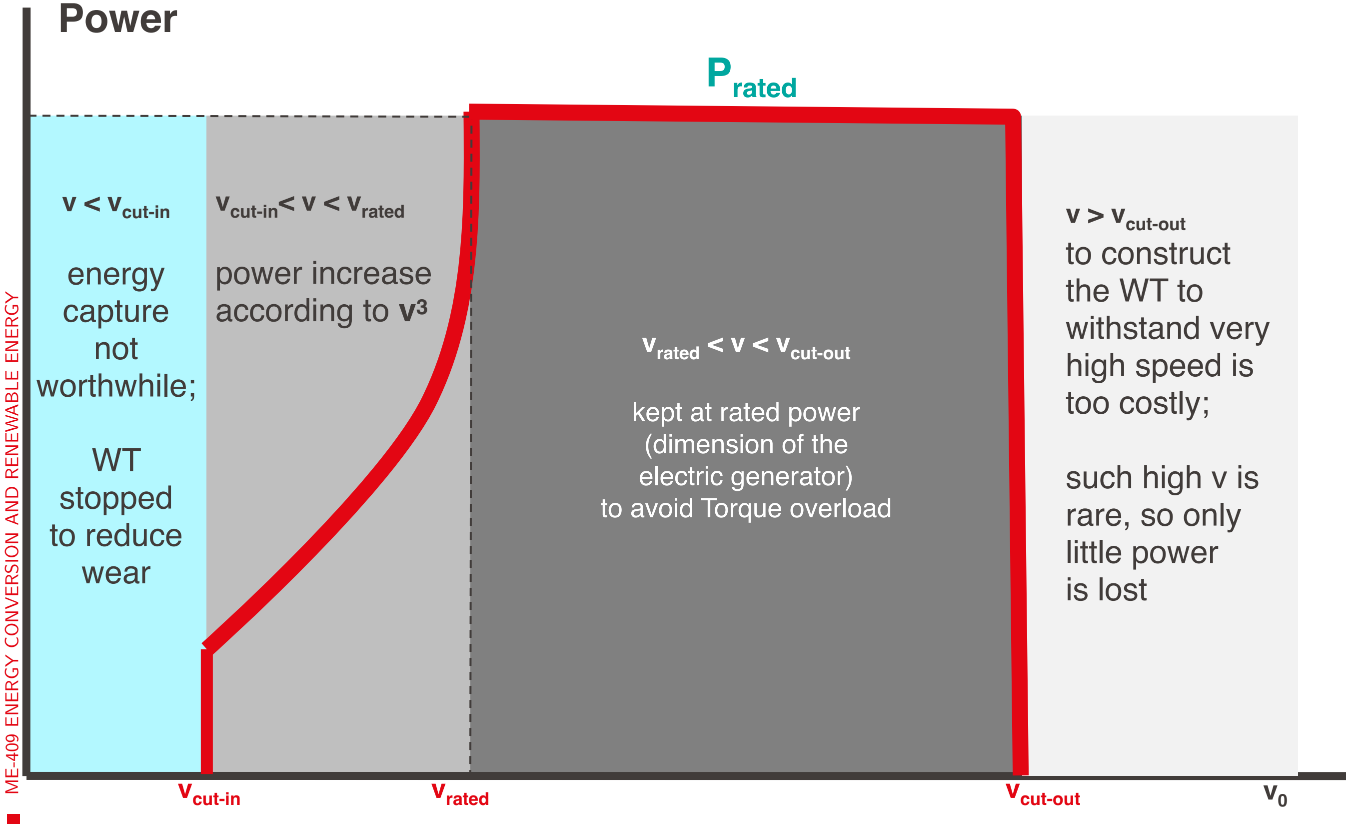
- **Same power**
- Higher torque
- Lower RPM
- Less noise
- +3% efficiency vs 2-blades[2]

Multiple blades

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

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

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:

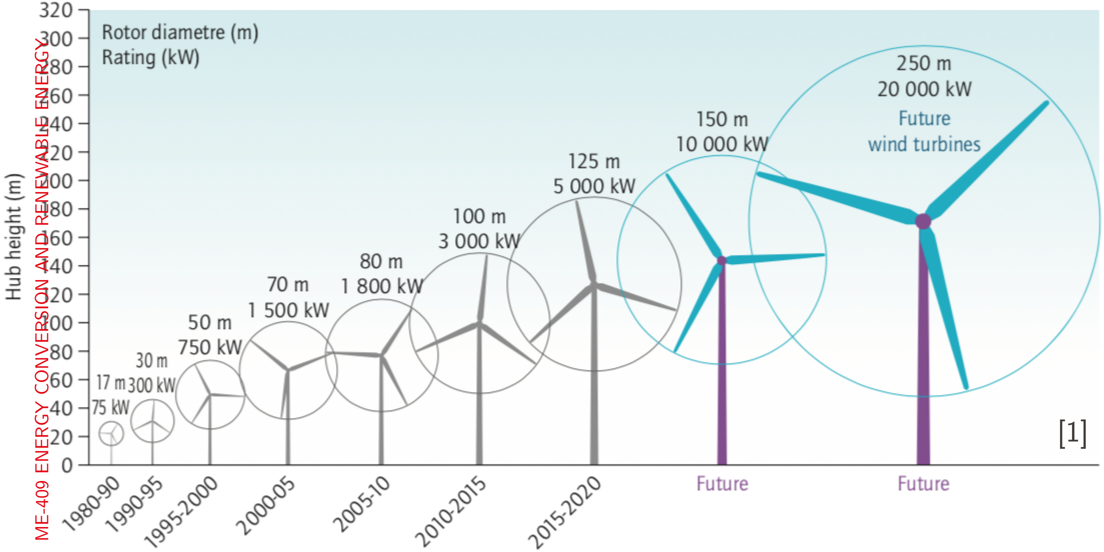
+ 7% energy
+ less power fluctuations
- higher cost
- less reliability

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

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 → D²



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Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

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)

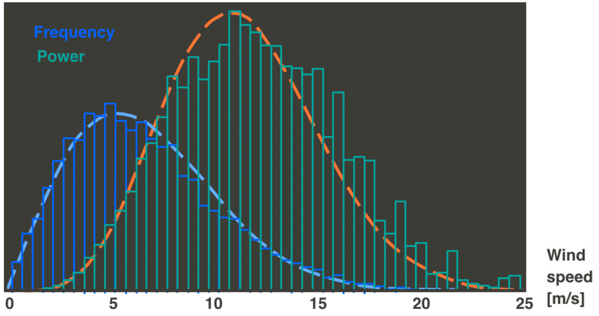
- Horns Rev offshore wind farm (DK):
  - 80 turbines
  - 160 MW_e
  - Offshore:
    - Higher capacity factors
    - Higher and more regular wind speed (120 m/s)
    - More noise (lower solidity)

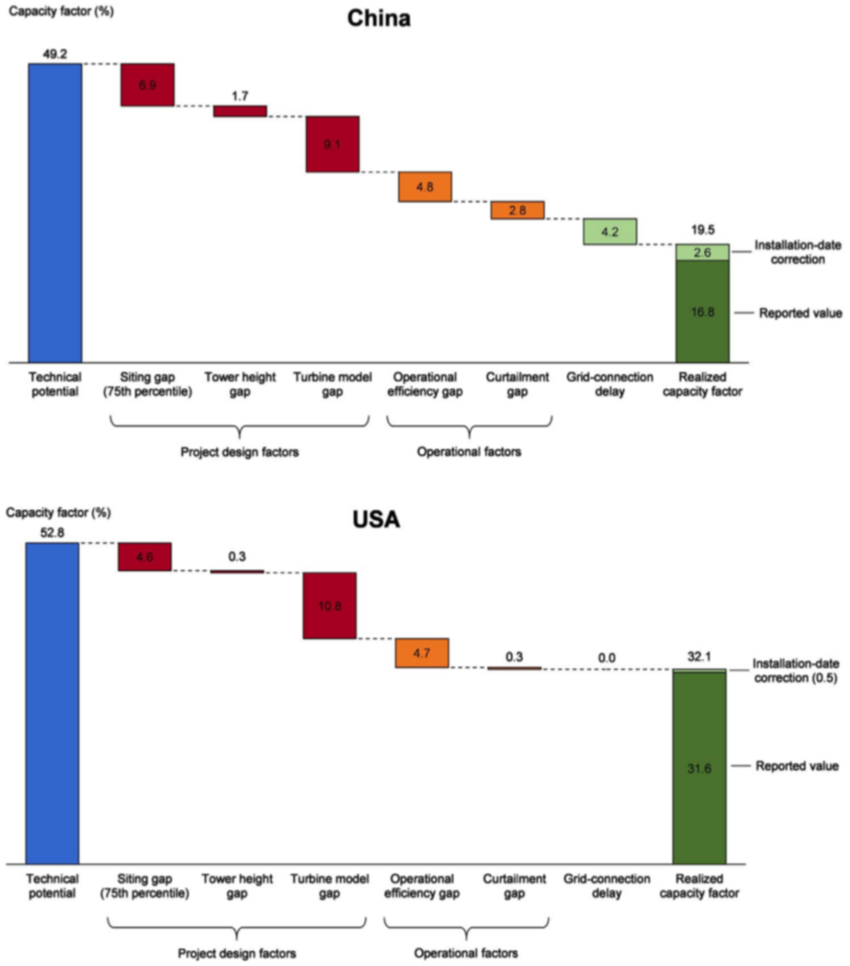
Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Capacity factor

$$CapacityFactor = \frac{\int_{year} \dot{E}(t)dt}{\dot{E}_{rated} \cdot 8760}$$

Location is critical (wind speed distribution)





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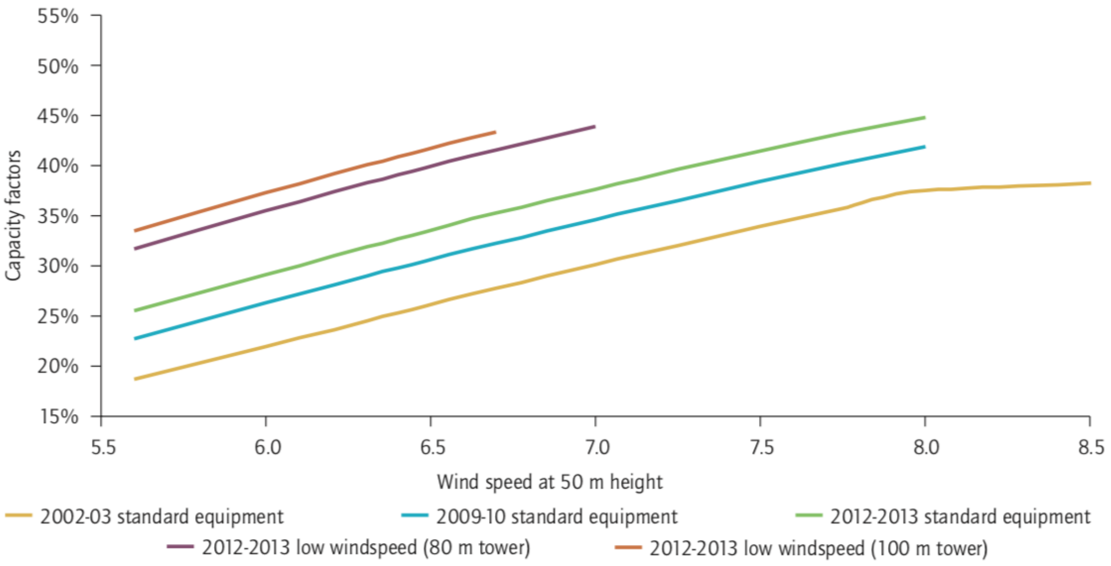
Capacity factors

- Capacity factor c_f, 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



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

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 2023: 35-80 €/MWh onshore, 70-120 €/MWh offshore

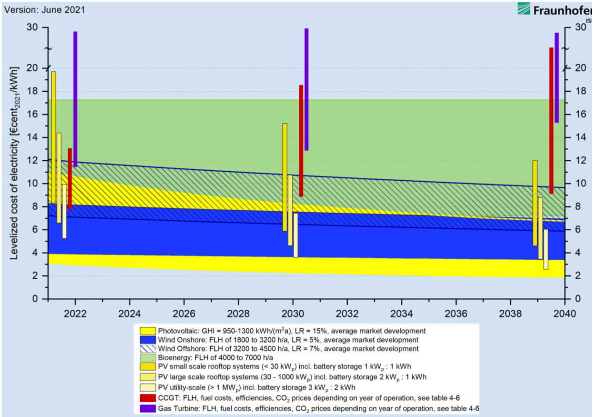


Figure 5.3 Total installed costs of onshore wind projects and global weighted average, 1983-2017

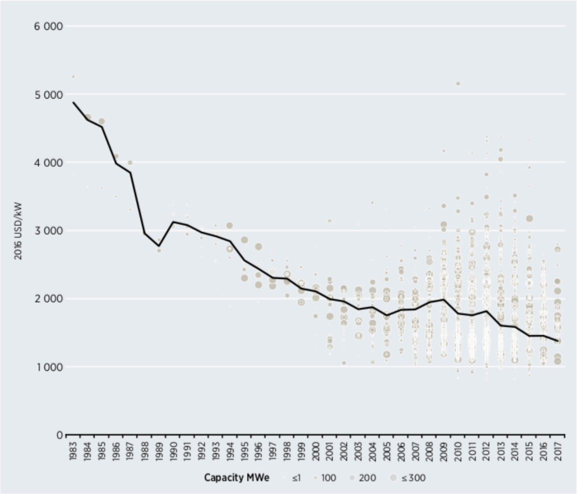
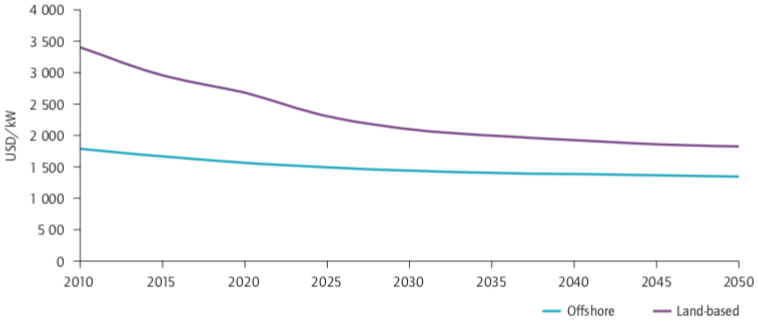
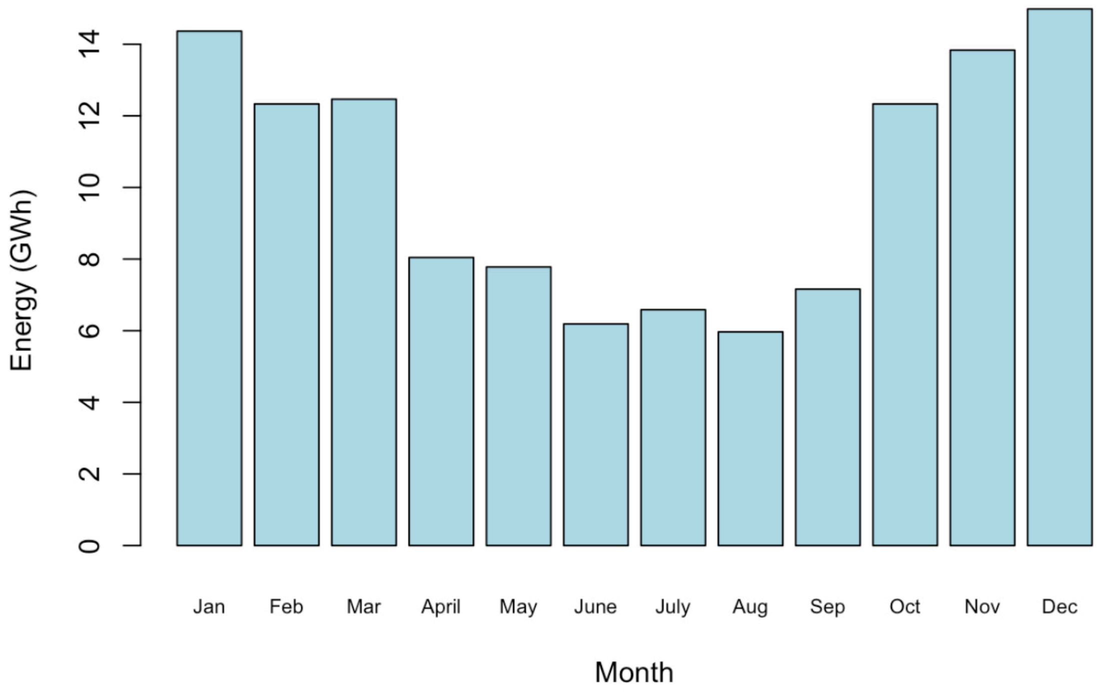


Figure 13: 2DS projections for investment costs of wind turbines



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

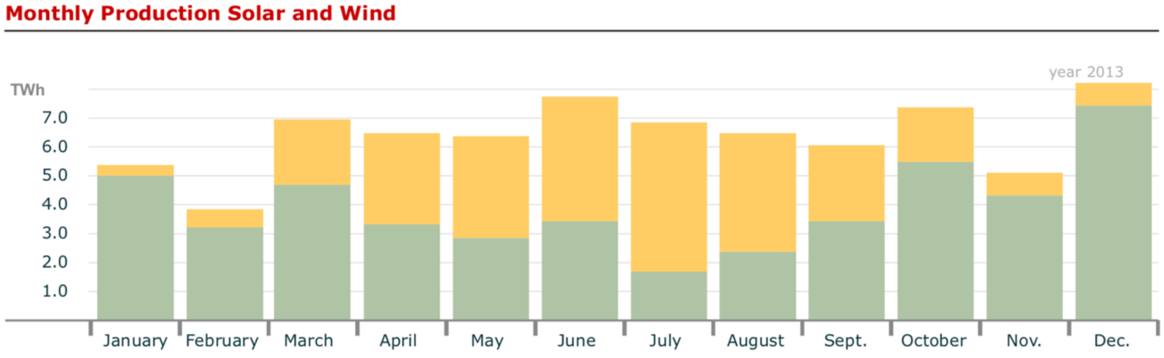
Monthly profiles

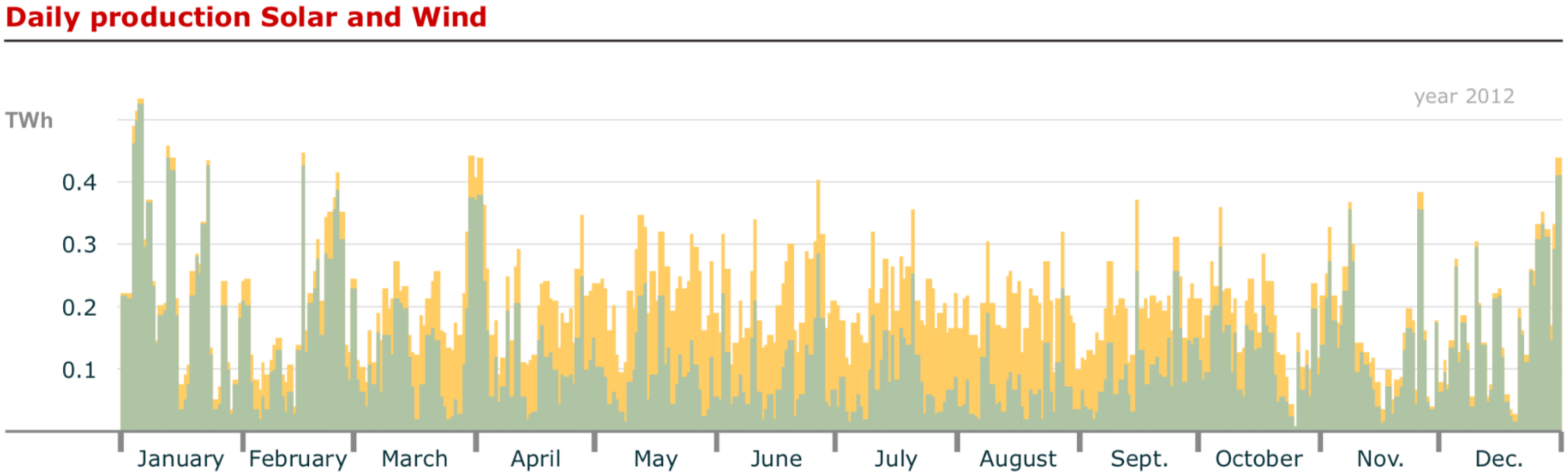


Monthly wind energy in Switzerland, 2018 [3]

Intermittency

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





Risks and impacts

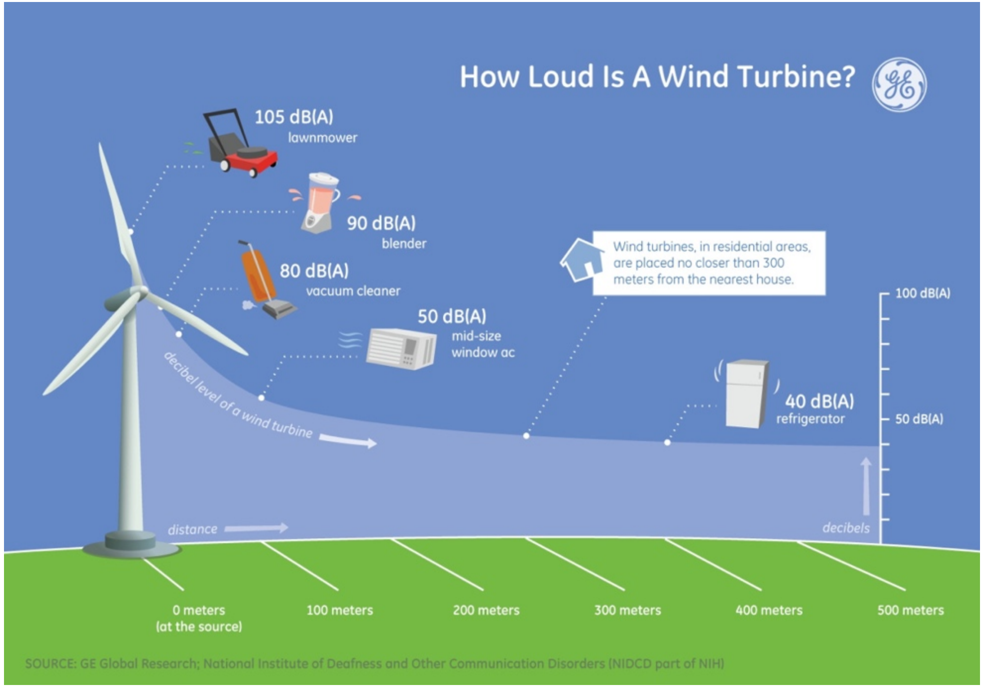
- Machinery maintenance accidents
- Blade failures
- Falling ice
- Paragliders and small aircraft crashing into support structures
- Turbine's brake fails → the turbine can spin freely until it disintegrates
- Turbine blades may fall off due to manufacturing flaws
- Lightning strikes → rotor blade damage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

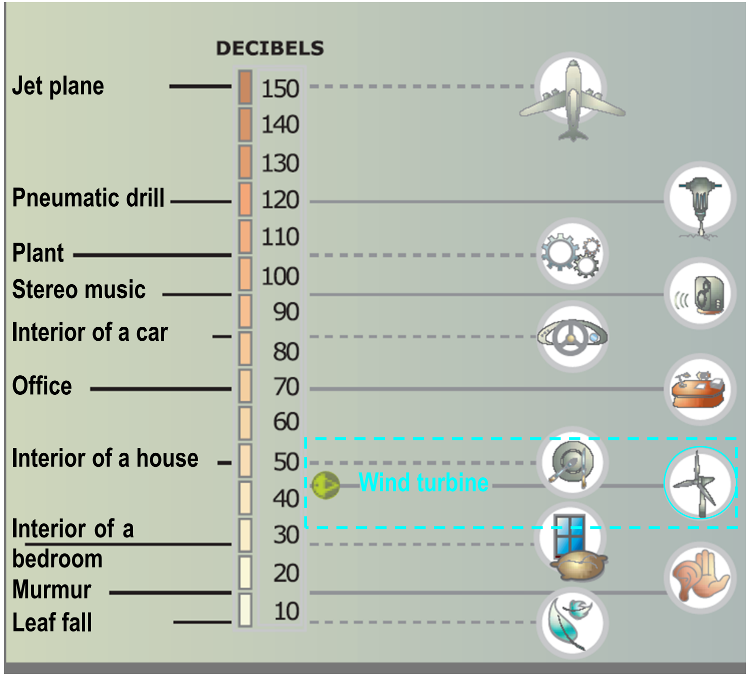
A turbine on fire after an oil leak

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Perceived risks : noise

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





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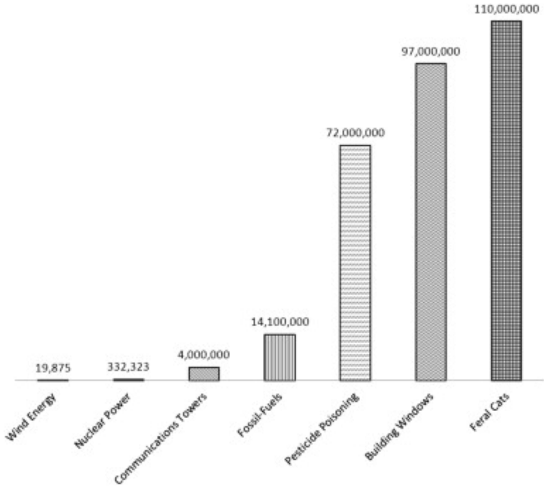
Risks and impacts: Killing birds

- 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

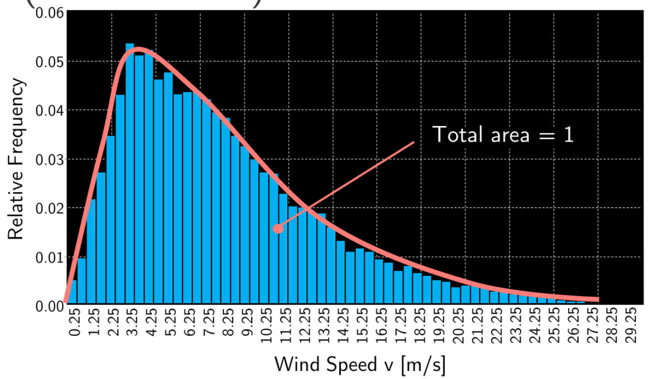
Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Take-home message

Take-home message

- Key concepts
  - Wind is growing fast → key player for climate change
  - Resource: power goes with v^3, 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 competitive!
  - Capacity factors: 25-30% onshore, 35-40% offshore
  - Wind can be a good complement of solar

$$CapacityFactor = \frac{\int_{year} \dot{E}(t)dt}{\dot{E}_{rated} \cdot 8760}$$

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

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Questions?

Prof. François Maréchal