lectures Legi
by Joachim Peinke

1) "Multipoint Statistics of Turbulence and its Stochastic Description"
   Friday 7/12, 10h30-12h:

2) "Nonequilibrium Thermodynamics of Turbulence, Fluctuation Theories and Rare Events as Negative Entropy Events"
   Monday10/12, 10h30-12 h:

3) "Wind Energy Driven by Turbulence (Applied Turbulence)"
   Friday 14/12, 10h30-12 h.

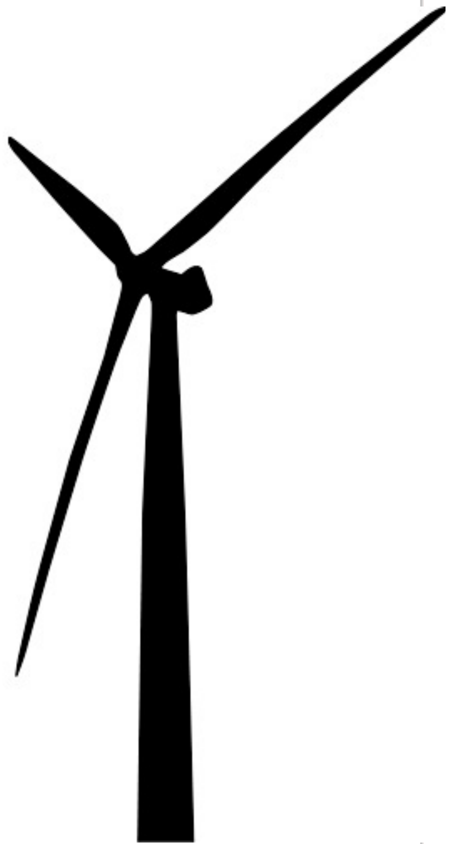
Research Alliance
Wind Energy

Deutsches Zentrum
DLR für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

ForWind
Zentrum für Windenergieforschung

Fraunhofer
IWES

content



Part I: energy and wind

Part II: basics of wind energy conversion

Part III: How much understanding of turbulence do we need?

energy resources - oil

every day

85 million barrel oil per day

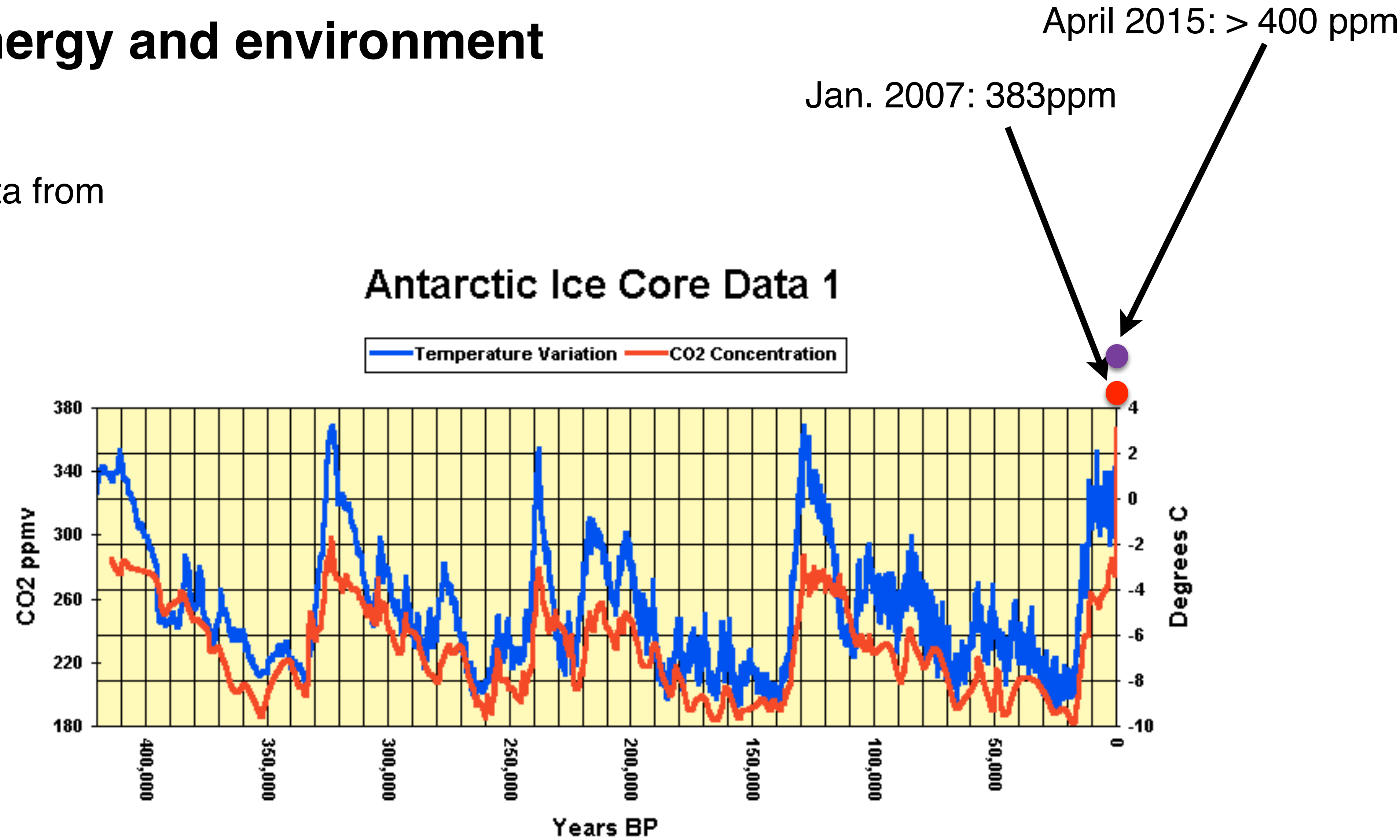
- 400 000 trucks > 7000km (> 4000 Miles)

natural production rate

3- WEC

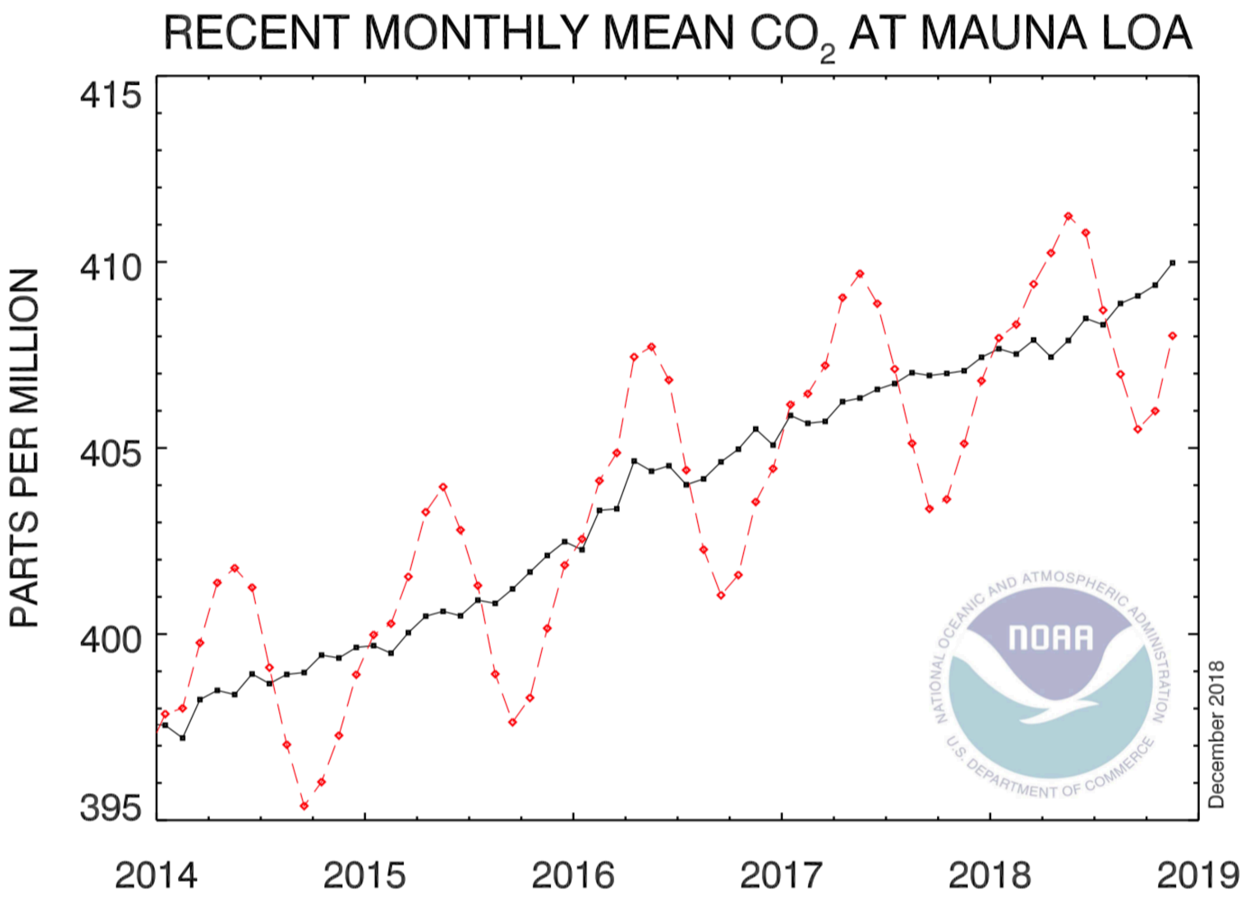
energy and environment

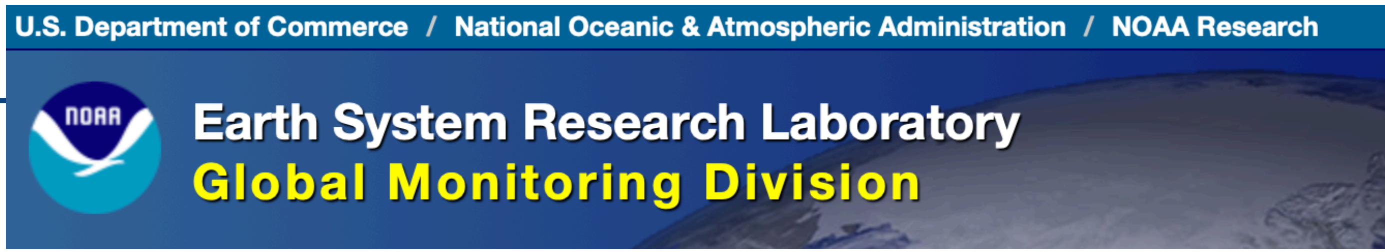
Data from



Nature, 3 June 1999.

energy and environment





Part I: energy and wind - environment

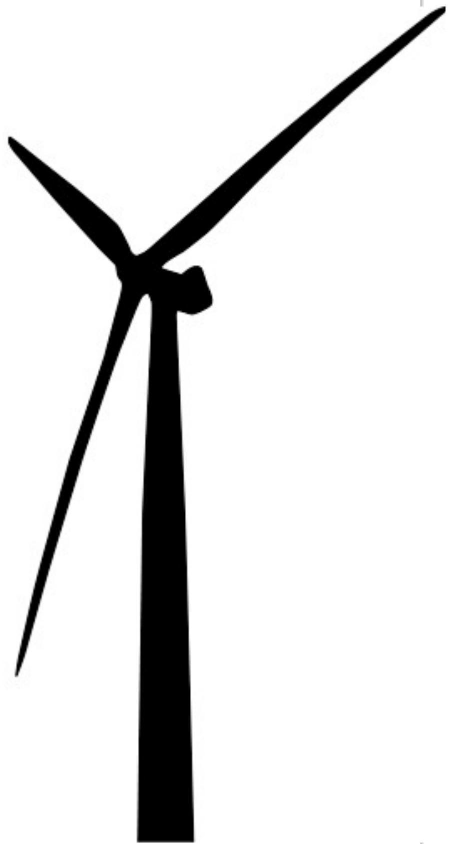
aim 2° or 1.5° limit

in the way we are using energy today we have in 10 years passed the 1.5° limit with our CO_2

-> need new energy concept

MCC
Mercator Research Institute on Global Commons and Climate Change

content



Part I: energy and wind

Part II: basics of wind energy conversion

Part III: How much understanding of turbulence do we need?

modern wind turbines

power from wind

$$E_{wind} = \frac{1}{2} m u^2$$

$$P_{wind} = \dot{E}_{wind} = \frac{1}{2} \dot{m} u^2$$

$$\dot{m} = \rho \dot{V} = \rho A \cdot u$$

$$P_{wind} = \frac{1}{2} \rho A u^3$$

WEC

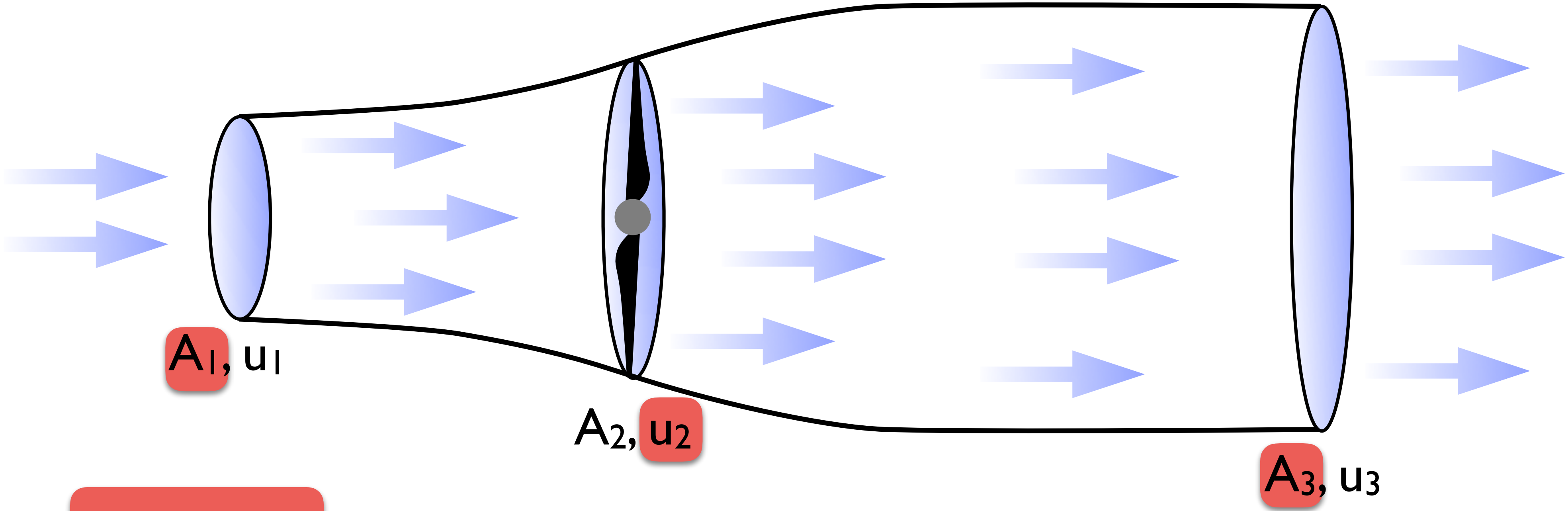
$$P_{WEC} = c_P \frac{1}{2} \rho A u^3$$

$$c_P \leq 0.59$$

Betz- Joukowsky limit

momentum theory and Betz limit

Extracted kinetic energy and extracted power



unknown

known : u1, A2, u3

$$P_{ext} = \frac{1}{2}\dot{m}\left(u_1^2 - u_3^2\right) \quad (2)$$

optimal $\frac{u_3}{u_1}$ for max. P_{ext} ????

momentum theory and Betz limit

Extracted kinetic energy and extracted power

$$P_{WEC} = c_p \frac{1}{2} \rho A_2 u_1^3$$

$$c_p = \frac{P_{WEC}}{1/2 \rho A_2 u_1^3} = \frac{P_{ext}}{1/2 \rho A_2 u_1^3}$$

$$P_{ext} = \frac{1}{2} \dot{m} \left(u_1^2 - u_3^2 \right)$$

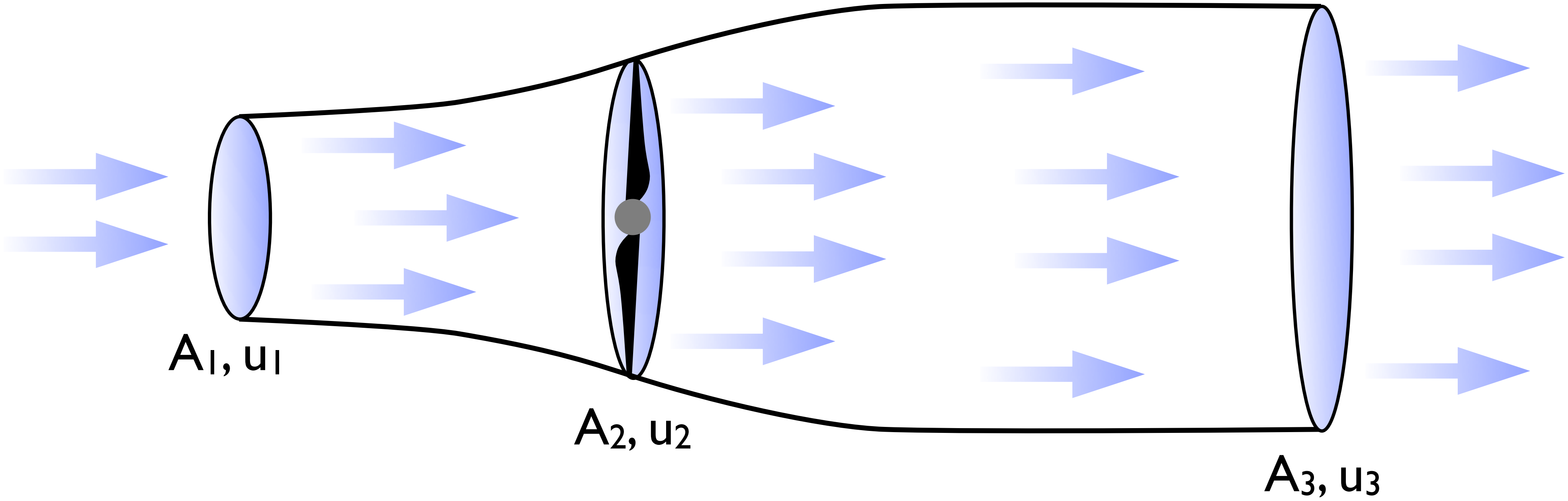
$$\boxed{c_p = \frac{\dot{m}(u_1^2 - u_3^2)}{\rho A_2 u_1^3}}$$

c_p should become maximal

$\dot{m}$ is unknown

momentum theory and Betz limit

Approach: free-stream air flow and conservation of mass flow



$$\Rightarrow \frac{d}{dt} \cdot m = \dot{m} = const.$$

$$\rho \cdot A_1 \cdot u_1 = \quad \rho \cdot A_2 \cdot u_2 = \quad \rho \cdot A_3 \cdot u_3 \qquad (1)$$

momentum theory and Betz limit

Extracted kinetic energy and extracted power

$$P_{WEC} = c_p \frac{1}{2} \rho A_2 u_1^3$$

$$P_{ext} = \frac{1}{2} \dot{m} \left(u_1^2 - u_3^2 \right)$$

$$c_p = \frac{\dot{m}(u_1^2 - u_3^2)}{\rho A_2 u_1^3}$$

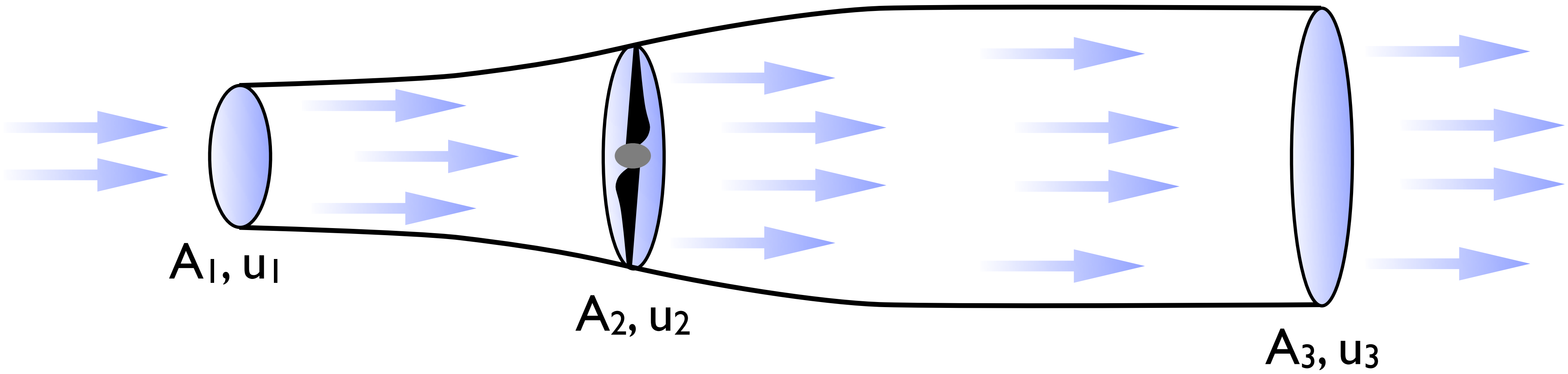
c_p should become maximal

$\dot{m}$ **unknown**

$$\dot{m} = \rho \cdot A_2 \cdot u_2$$

$$c_p = \frac{u_2 (u_1^2 - u_3^2)}{u_1^3}$$

momentum theory and Betz limit



assumed

$$\Rightarrow u_2 = \frac{u_1 + u_3}{2}$$

$$c_p = \frac{(u_1 + u_3)(u_1^2 - u_3^2)}{2u_1^3}$$

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

$$x = \frac{u_3}{u_1}$$

momentum theory and Betz limit

Find the maximum c_p by taking the first derivative

Substitute u_3/u_1 with x:

$$c_p(x) = \frac{1}{2} \cdot \left(1 + x - x^2 - x^3\right)$$

First derivative of $c_p(x)$:

$$c_p'(x) = \frac{1}{2} \cdot \left(1 - 2x - 3x^2\right) \stackrel{!}{=} 0$$

For maximum second derivative of possible solution $x_{1/2}$ must smaller than zero:

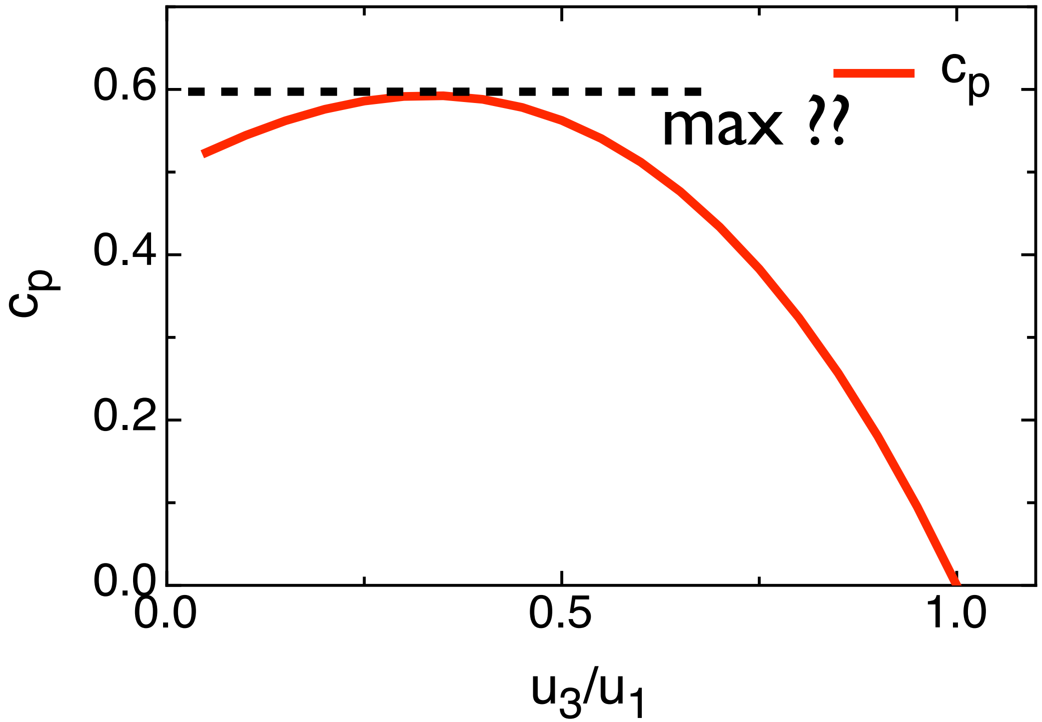
$$c_p''(x_{1/2}) = \frac{1}{2} \cdot (-2 - 6x) < 0$$

Solution: $x = \frac{1}{3} \Rightarrow c_{p_{max.}}(1/3) = \frac{16}{27} \approx 59\%$

momentum theory and Betz limit

Extractable power as function of u_1 and u_3

$$P_{ext} = \underbrace{\frac{1}{2} \cdot \rho \cdot A_2 \cdot u_1^3}_{\text{wind power}} \cdot \underbrace{\left[\frac{1}{2} \cdot \left(1 + \frac{u_3}{u_1} - \frac{u_3^2}{u_1^2} - \frac{u_3^3}{u_1^3}\right)\right]}_{c_p}$$



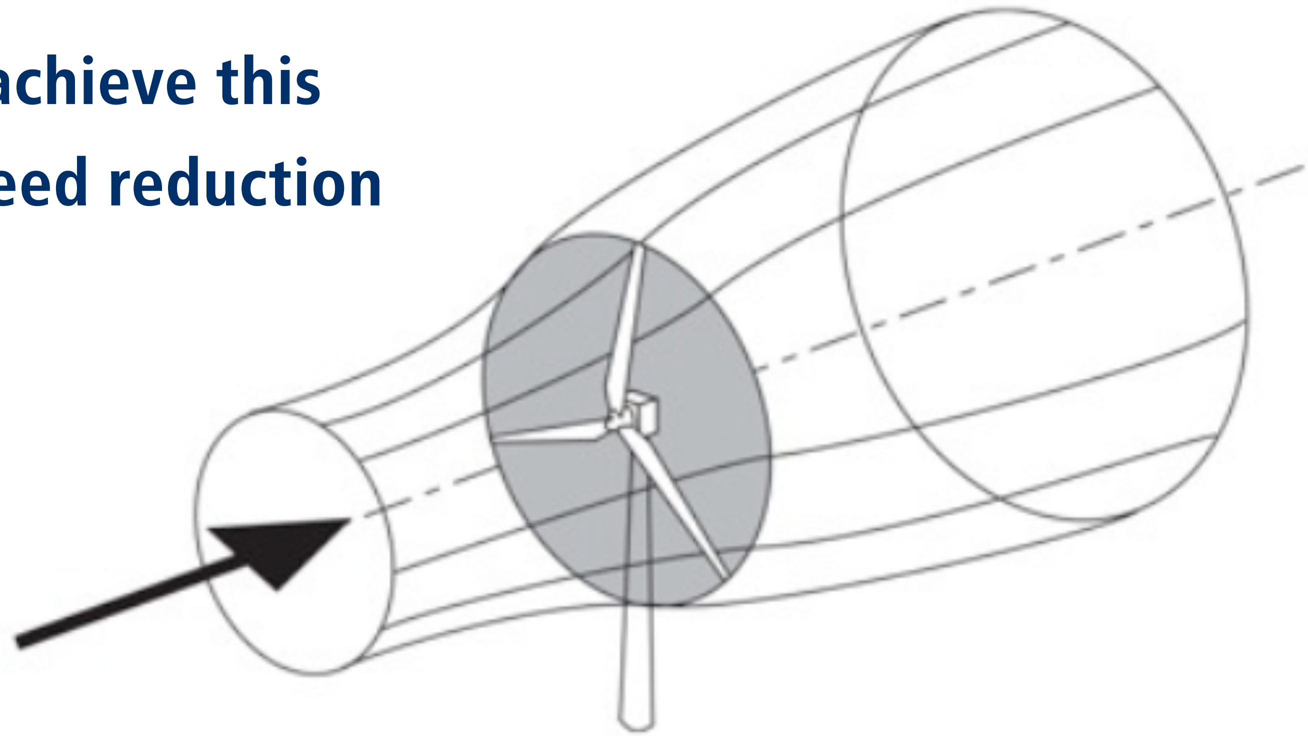
maximun for:

$$\frac{u_3}{u_1} = \frac{1}{3}$$

$$c_p = 0.59$$

momentum theory and Betz limit

how to achieve this
wind speed reduction

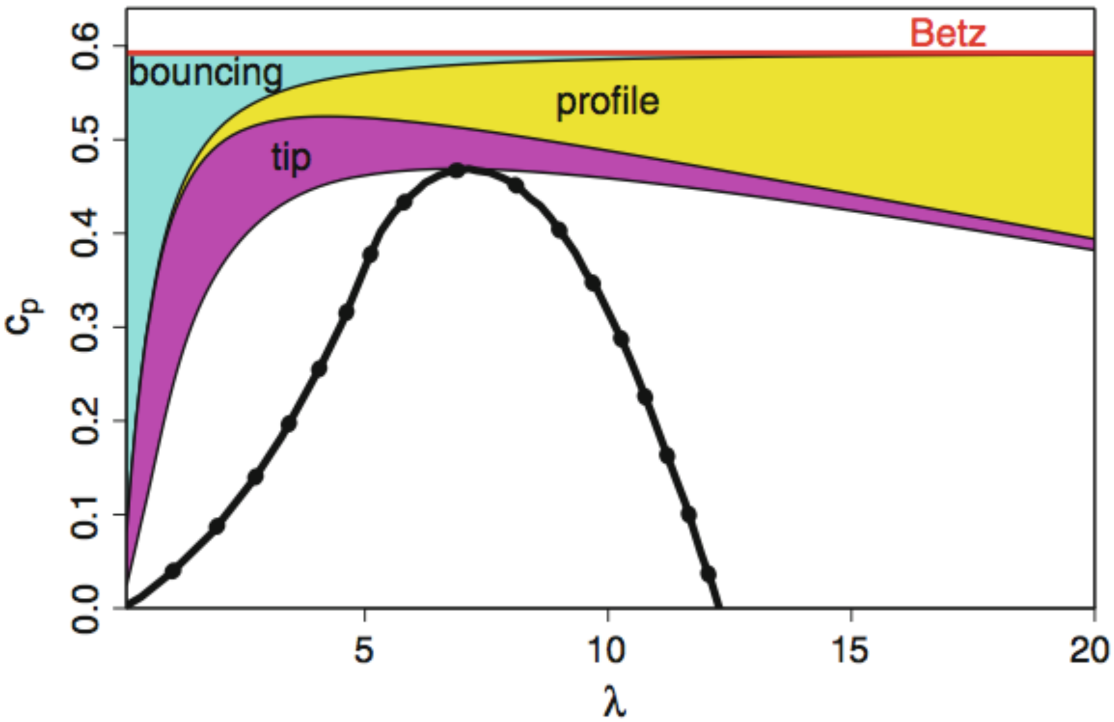


There is an optimal rotational frequency that the blockage results in $\frac{u_3}{u_1} = \frac{1}{3}$ **, characterized by tip speed ratio** $\lambda := \frac{\omega \cdot R}{u_0}$

Limitations of Betz theory - Energy losses

losses:

- Glauert Schmitz theory - rotation if wake, conservation of angular momentum
- tip vortex losses
- drag force on profile



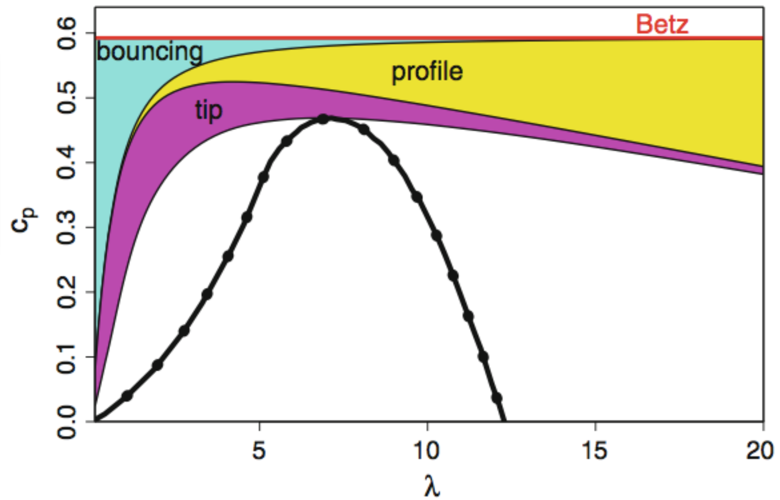
summary of conversion

power of Wind turbine $P_{WEC} = c_P \frac{1}{2} \rho A u^3$

Betz power coefficient $c_{P_max} < \frac{16}{27} \approx 0.59$

tip speed ratio determines the blockage

$$\lambda; \quad c_P(\lambda)$$



modern wind turbines

power from wind

WEC

$$P_{WEC} = c_P \frac{1}{2} \rho A u^3$$

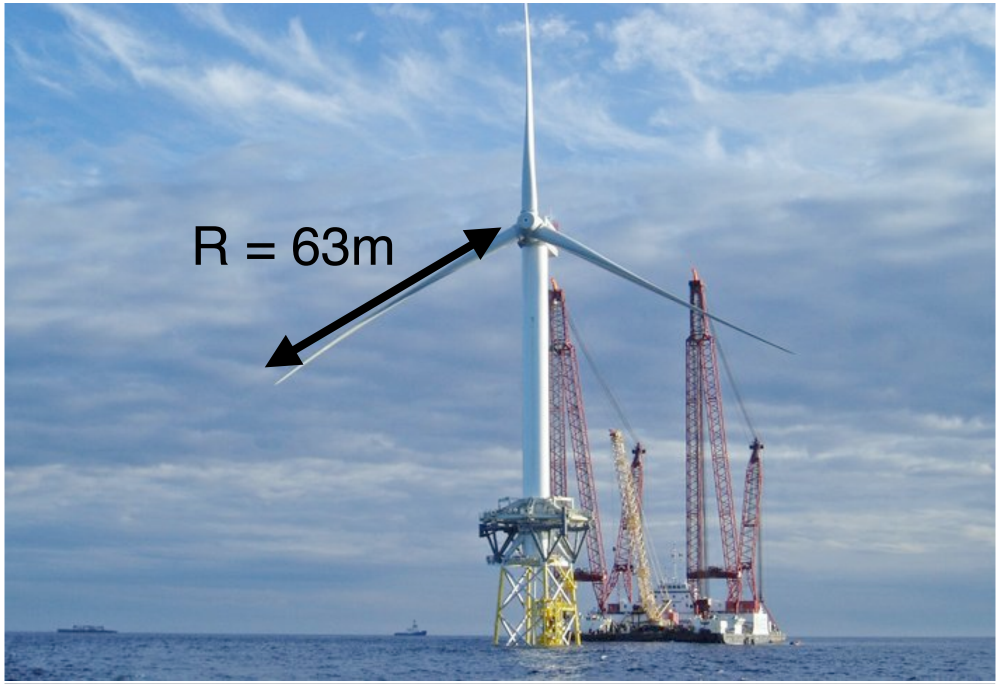
for u = 12 m/s $\quad c_P \leq 0.59$

$$P_{wind} = 1kW/m^2$$

modern wind turbines

area = 12469 m²

$$P_{wind} \leq 12MW$$



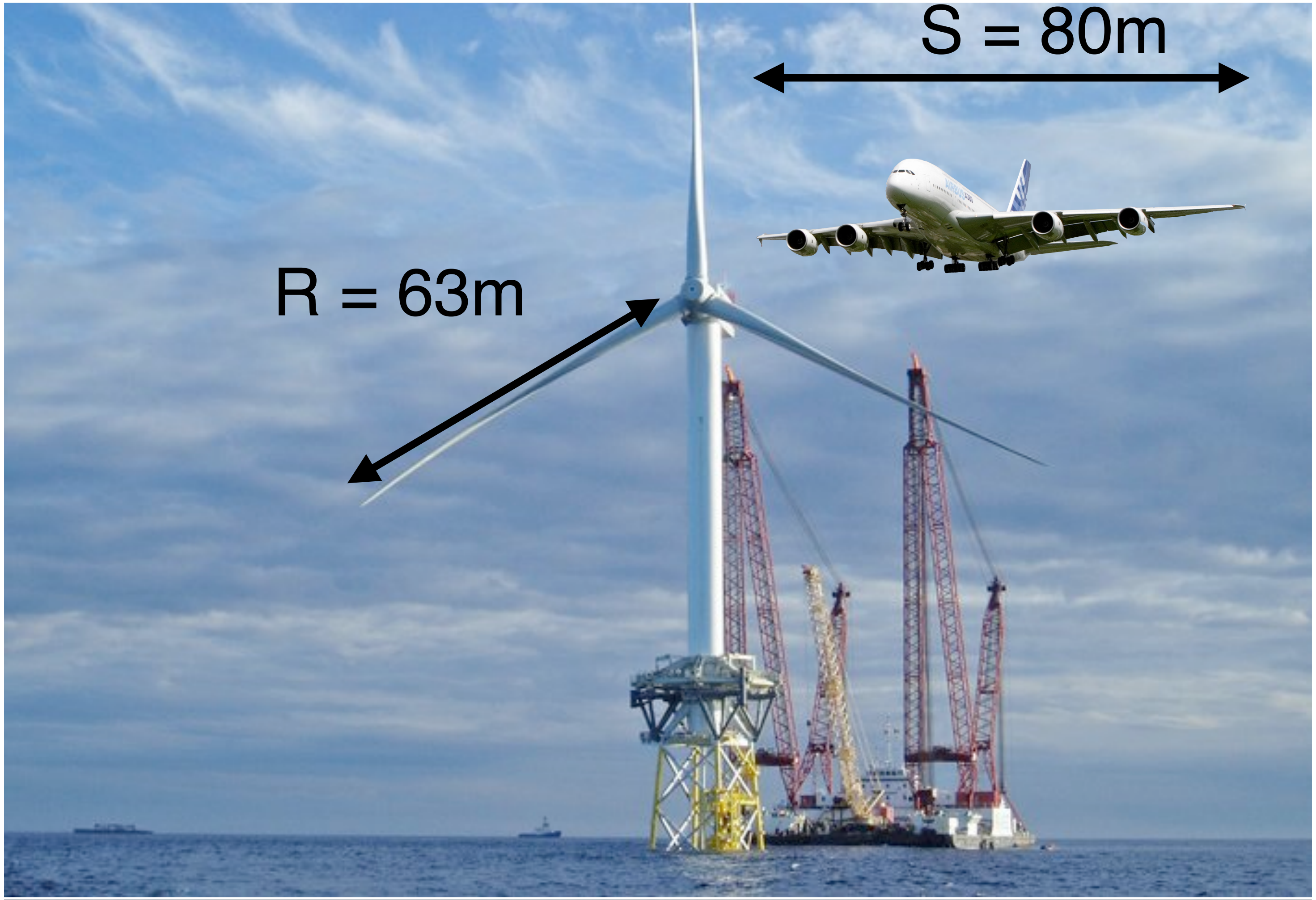
$$P_{WEC} = c_p \cdot P_{wind}$$

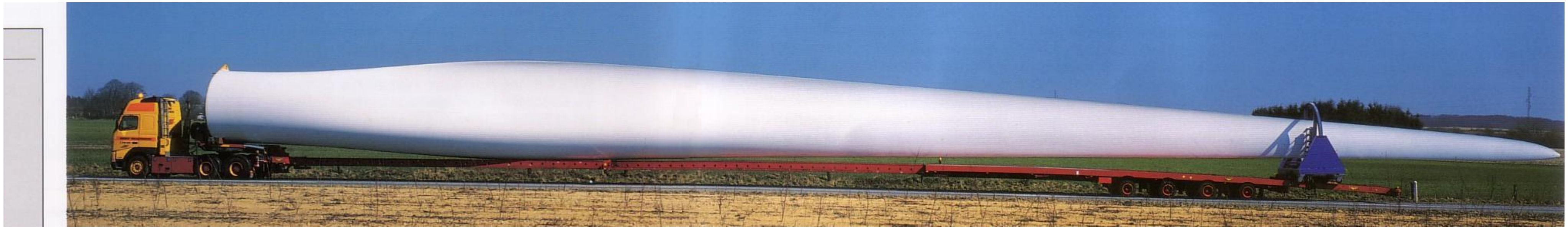
$$c_P \leq 0.59$$

$$P_{WEC} \approx 5 - 6MW$$

modern wind turbines

size





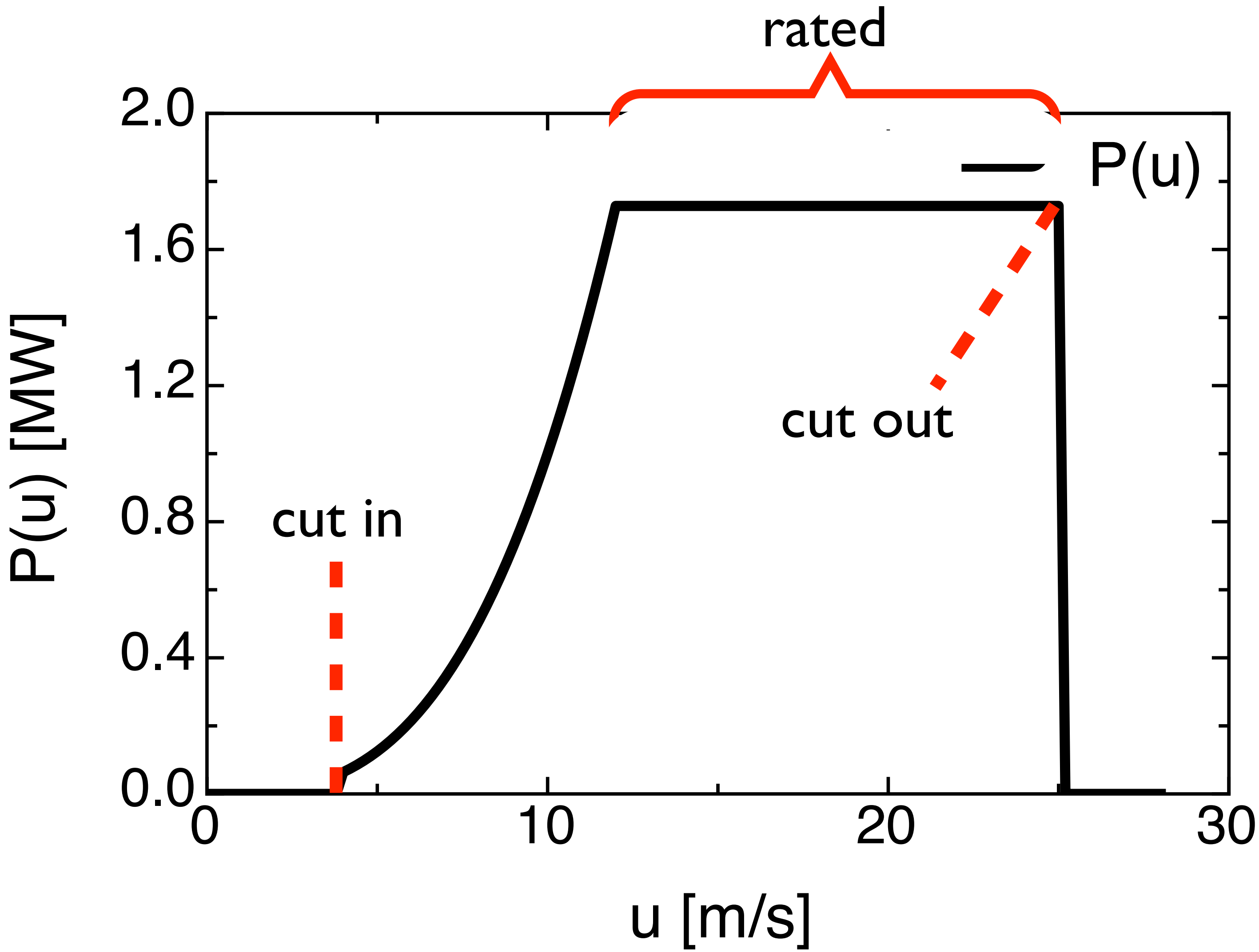
largest turbines - close to 10MW

Vestas V164 - 9.5MW - for 8.8MW 24GW installed

Siemens 167 8 MW

Goldwind 6.7 MW

power curve of a wind turbine



ForWind Zentrum für Windenergieforschung Bremen Hannover Oldenburg

Solar / Wind

	sun	wind
power	1 kW/m²	1 kW/m²
efficiency	15 %	40 %
rated power	150 W/m²	400 W/m²
rated power/year (germ.)	1000h	2000h - 3000h
averaged power production	17 W/m²	100 - 150 W/m²

per person

	sun	wind
el. power 200W	10 m²	2 m²
total power 5 kW	300 m²	50 m²

Photovoltaic Power Plant, Tucson Electric Power Co., Arizona
Nominal Power (August 2002): 2.4 MW
Photovoltaics: Multi-crystalline Silicon (ASE), CdTe (BP-Solar), amorphous Silicon

Abbildung: www.globalsolar.com

2.4 MW PV power plant
25.000 m²

2.3 MW WEC (E70)
3.800 m²
energy pay back few months

cost of energy

Costs for turbine 1 - 2 € / installed Watt (MW 1-2 Million €)

income due to power production: 1 MW-WEC * 2000 h = 2* 10^6 kWh

5-10 cent/kWh 100,000 - 200,000 €

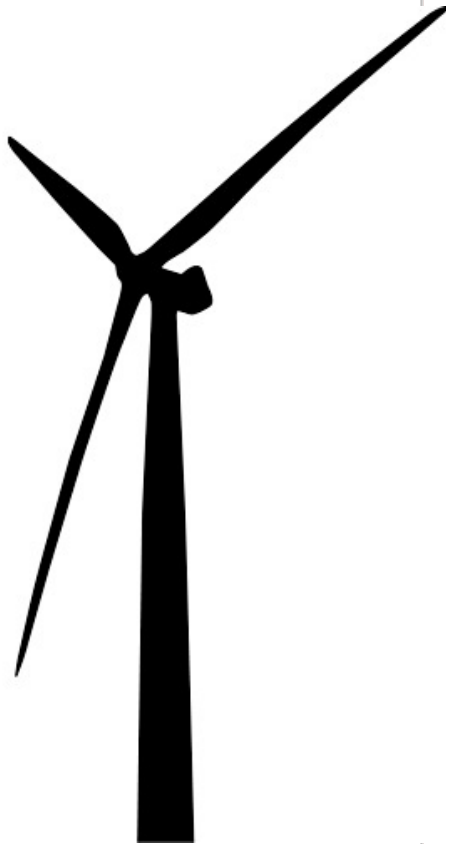
cost estimation depend crucially on wind speed.

which consequence has an 5% error in the estimated wind speed?

$$P_{wind} = \frac{1}{2}\rho A u^3$$

Propagation of uncertainty: $$\frac{\delta P_{WEC}}{P_{WEC}} = 3\frac{\delta u}{u}$$

➡ **nee to know well the inflow conditions**



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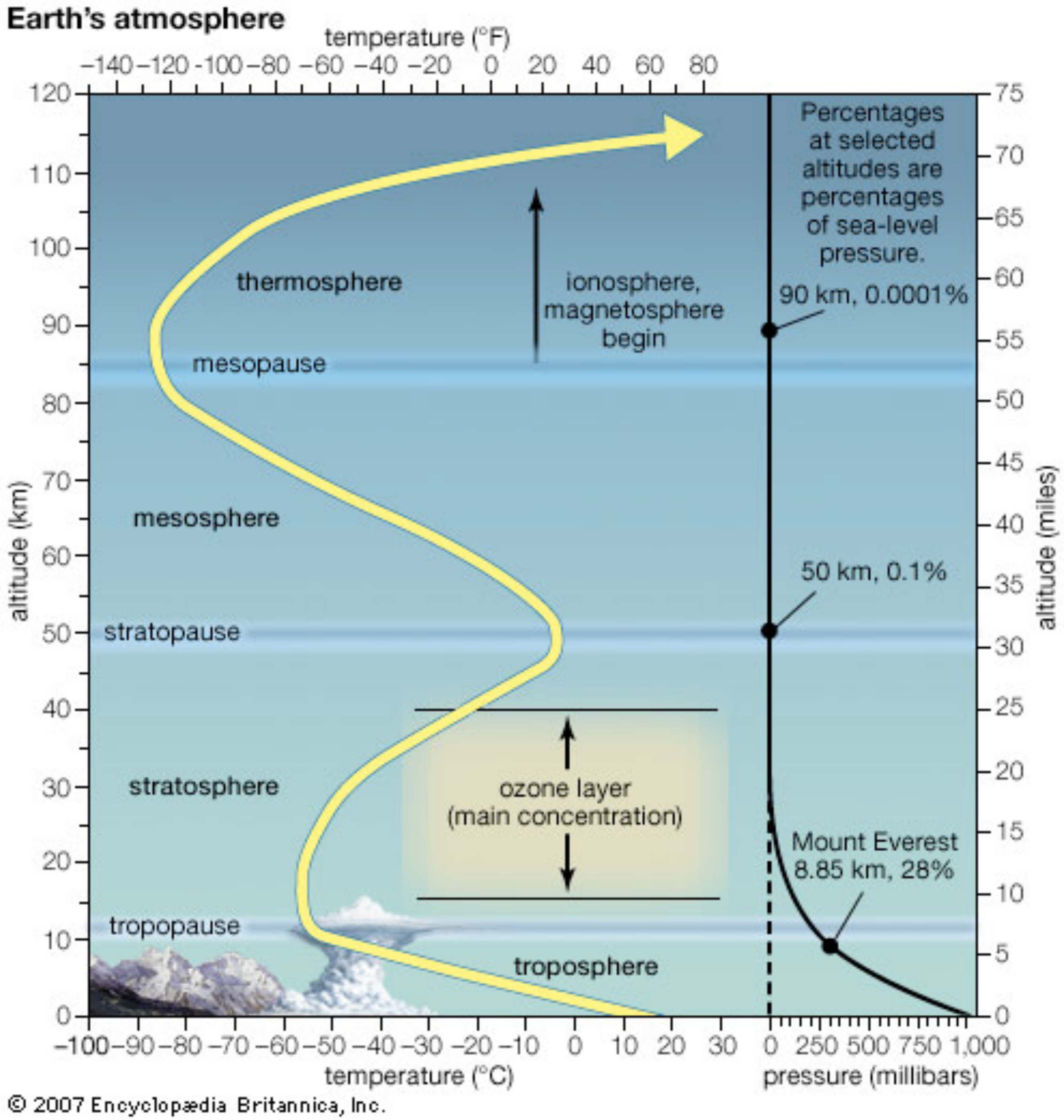
boundary layer (AML - atmospheric boundary layer)



wind resource boundary layer

wind characterisation after common procedure

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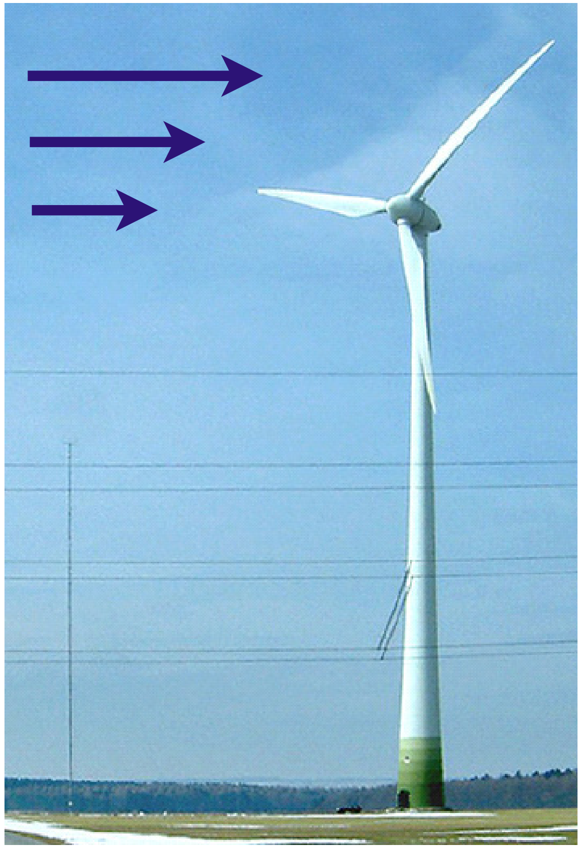


- annual mean wind speed
- how often which wind speed

on hub height

$$Prob(u) = \left(\frac{k}{A}\right) \cdot \left(\frac{u}{A}\right)^{k-1} \cdot e^{-\left(\frac{u}{A}\right)^{k}}$$

Weibull distribution - parameters for different orography

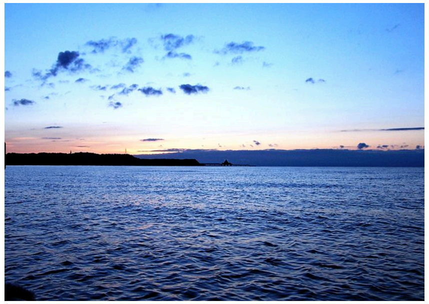
A scaling and k form parameter

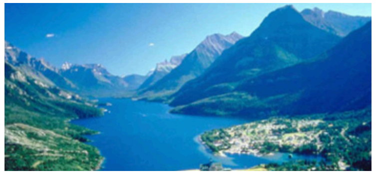
$$Prob(u) = \left(\frac{k}{A}\right) \cdot \left(\frac{u}{A}\right)^{k-1} \cdot e^{-\left(\frac{u}{A}\right)^k}$$

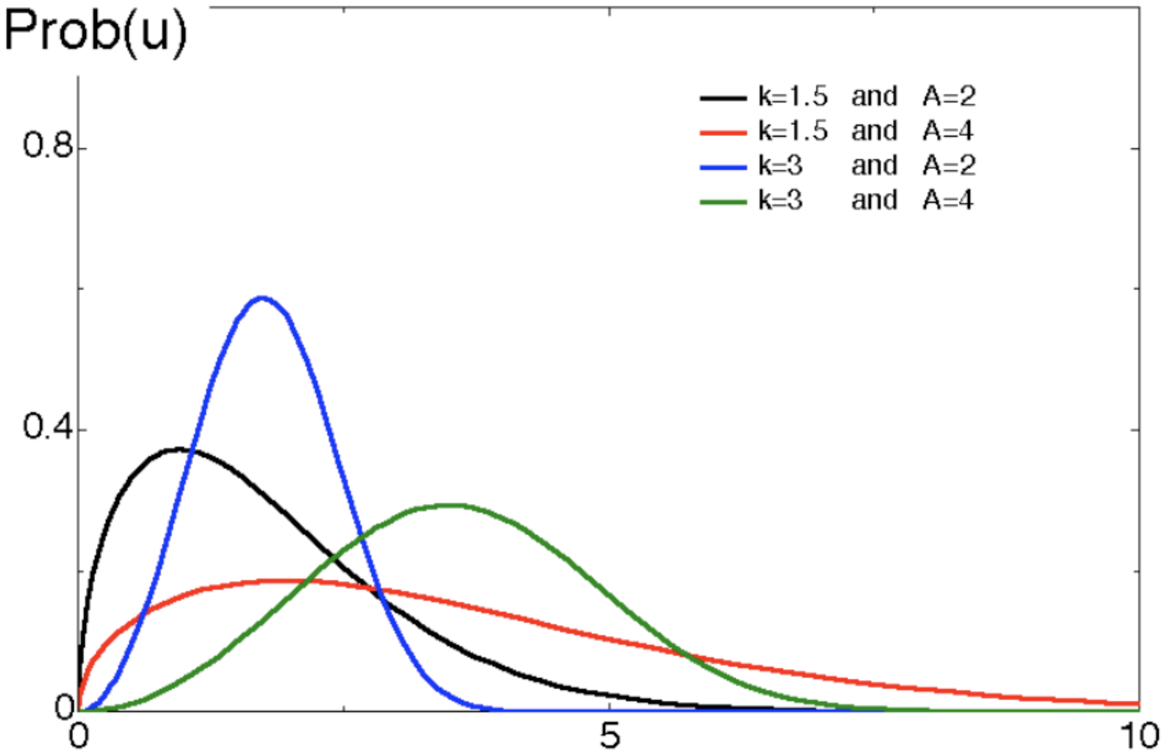
k=2 Rayleigh

$$Prob(u) = C \cdot u \cdot e^{-\frac{u^2}{A^2}}$$

flat -> Gaussian complex -> exp(-x)





wind resource boundary layer

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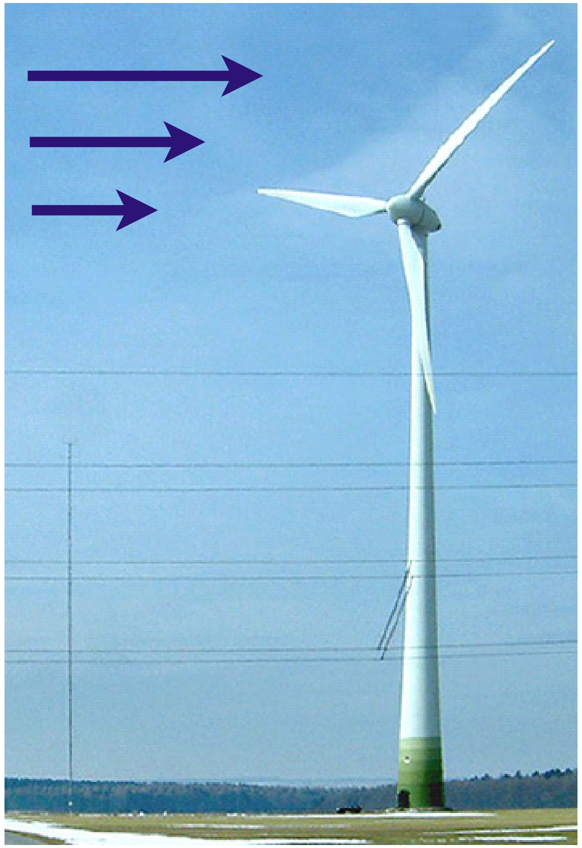
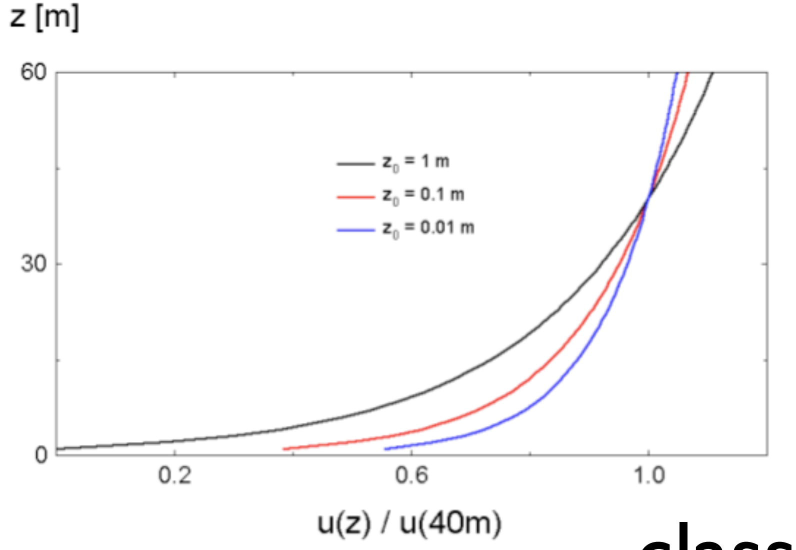


- annual mean wind speed
- how often which wind speed on hub height
- height profile

boundary layer (AML - atmospheric boundary layer)

- log law - z_0 is the roughness coefficient

$$u(z) = \frac{u^*}{k} ln\left(\frac{z}{z_0}\right)$$



- classes 0 to 3
  - 0 smooth, sand ..
  - 3 rough, suburbs ..

Table 2.1 Typical Surface Roughness Lengths

Type of terrain	Roughness length z_0(m)
Cities, forests	0.7
Suburbs, wooded countryside	0.3
Villages, countryside with trees and hedges	0.1
Open farmland, few trees and buildings	0.03
Flat grassy plains	0.01
Flat desert, rough sea	0.001

classes
3
2
1
0

=> summary: standard wind speed characterisation

annual mean - first estimation of wind potential

10 min means at hub height - improved estimation

with power curve - estimation of annual power production

Weibull distribution

- no extrem value statistics - 1 D of 2 D Gauß
- orographic parameters

$$Prob(u) = \left(\frac{k}{A}\right) \cdot \left(\frac{u}{A}\right)^{k-1} \cdot e^{-\left(\frac{u}{A}\right)^k}$$

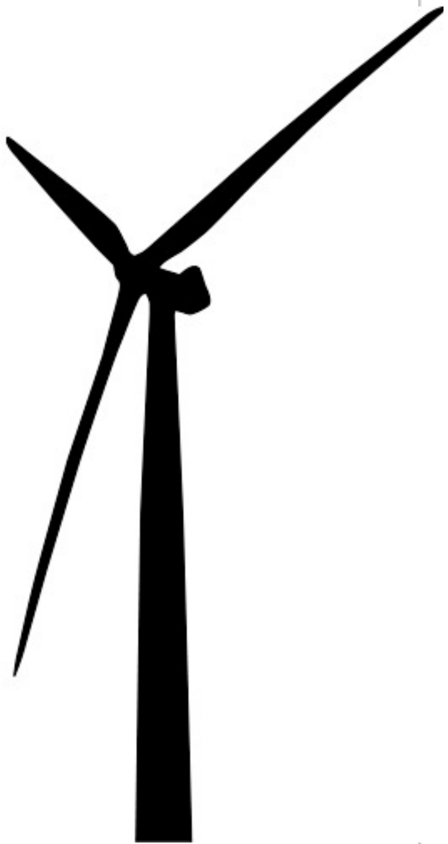
height profiles

dependence on roughness

$$\frac{u(z_2)}{u(z_1)} = \left(\frac{z_2}{z_1}\right)^\alpha$$

$$u(z) = \frac{u^*}{k} ln\left(\frac{z}{z_0}\right)$$

content



Part I: energy and wind

Part II: basics of wind energy conversion

Part III: Inflow: How much understanding of turbulence do we need?

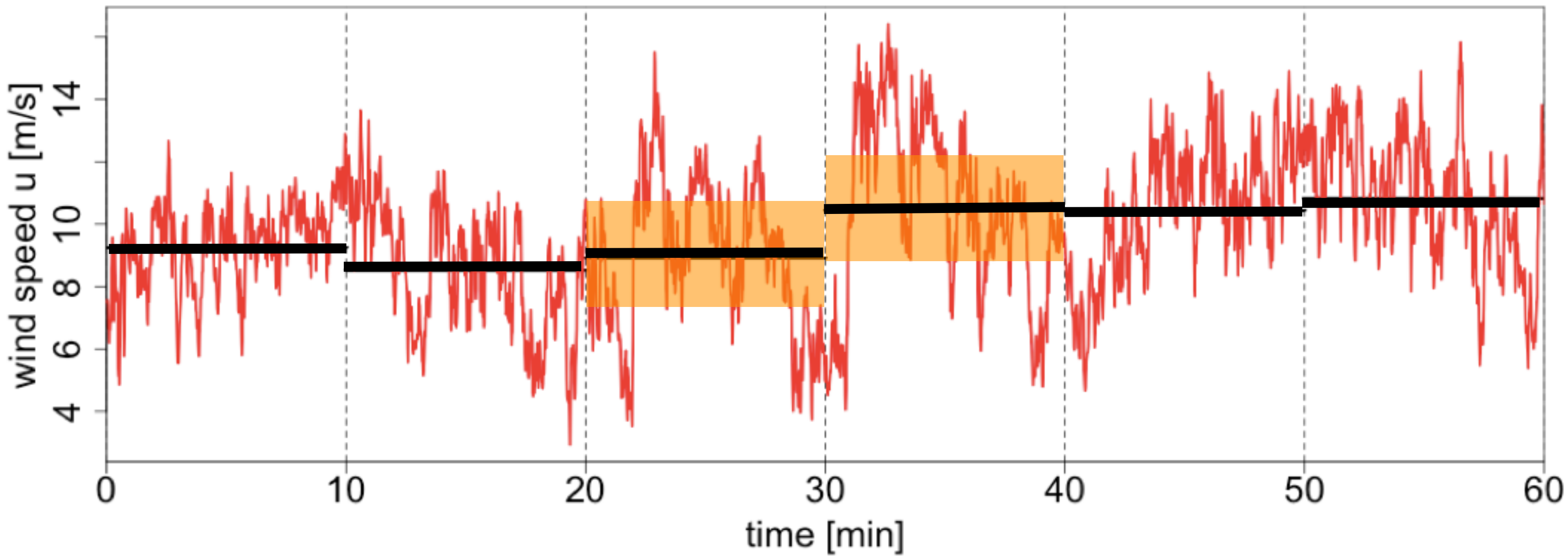
— critics on standard characterisation

wind measurements and data analysis

- characterisation after IEC norm

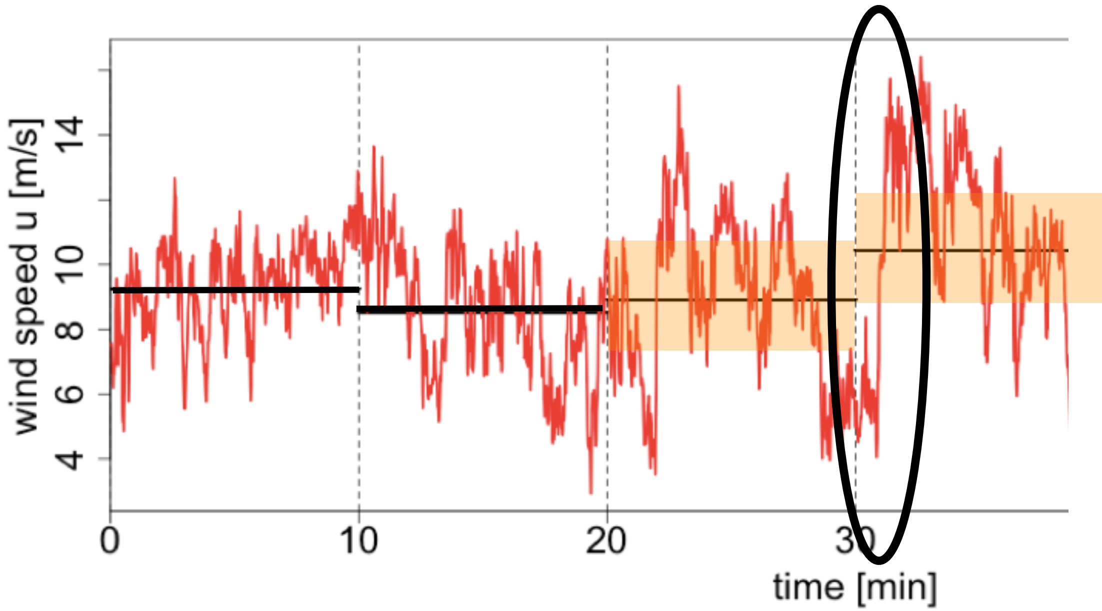
• 10 min mean value

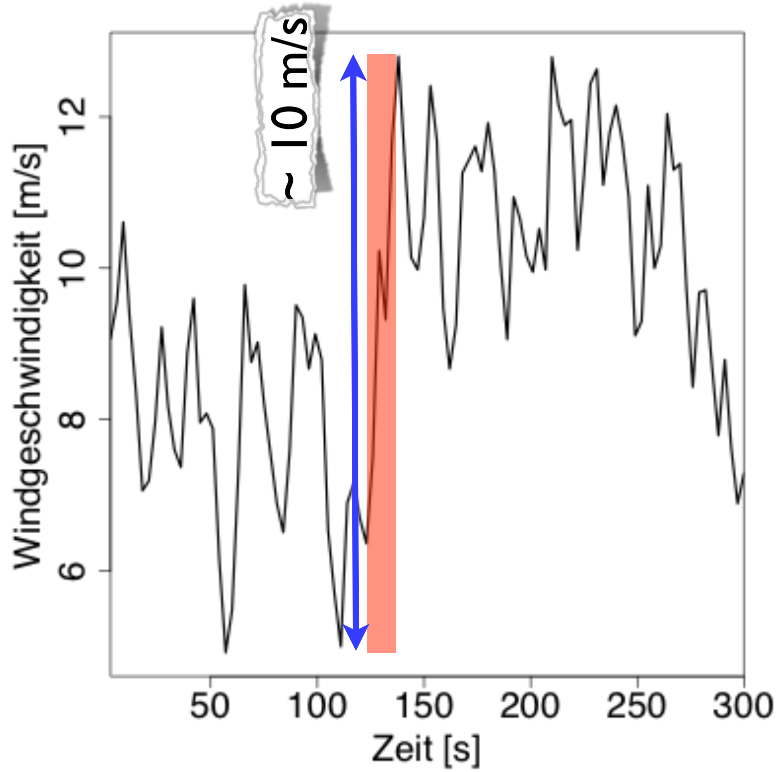
• turbulence intensity



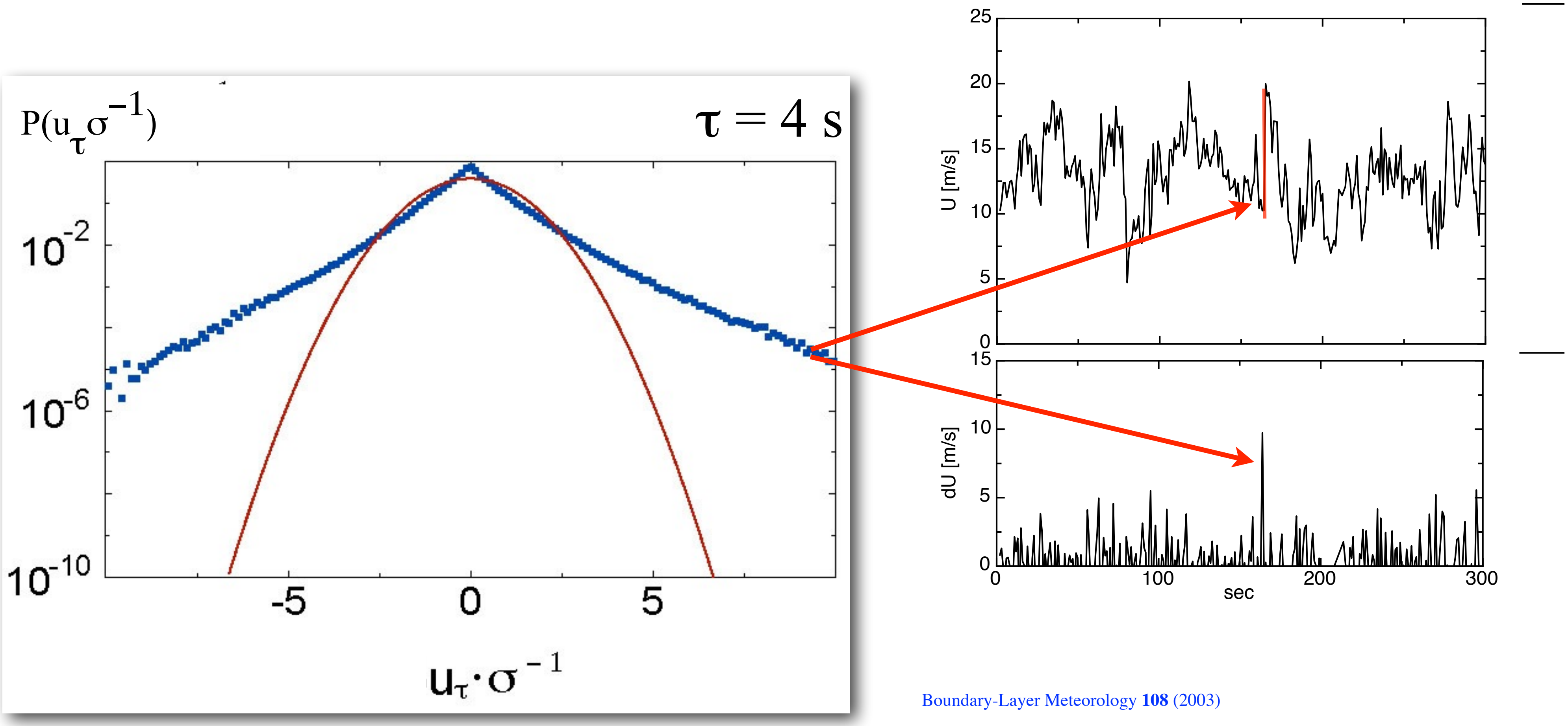
wind measurements and data analysis

- characterisation after IEC norm



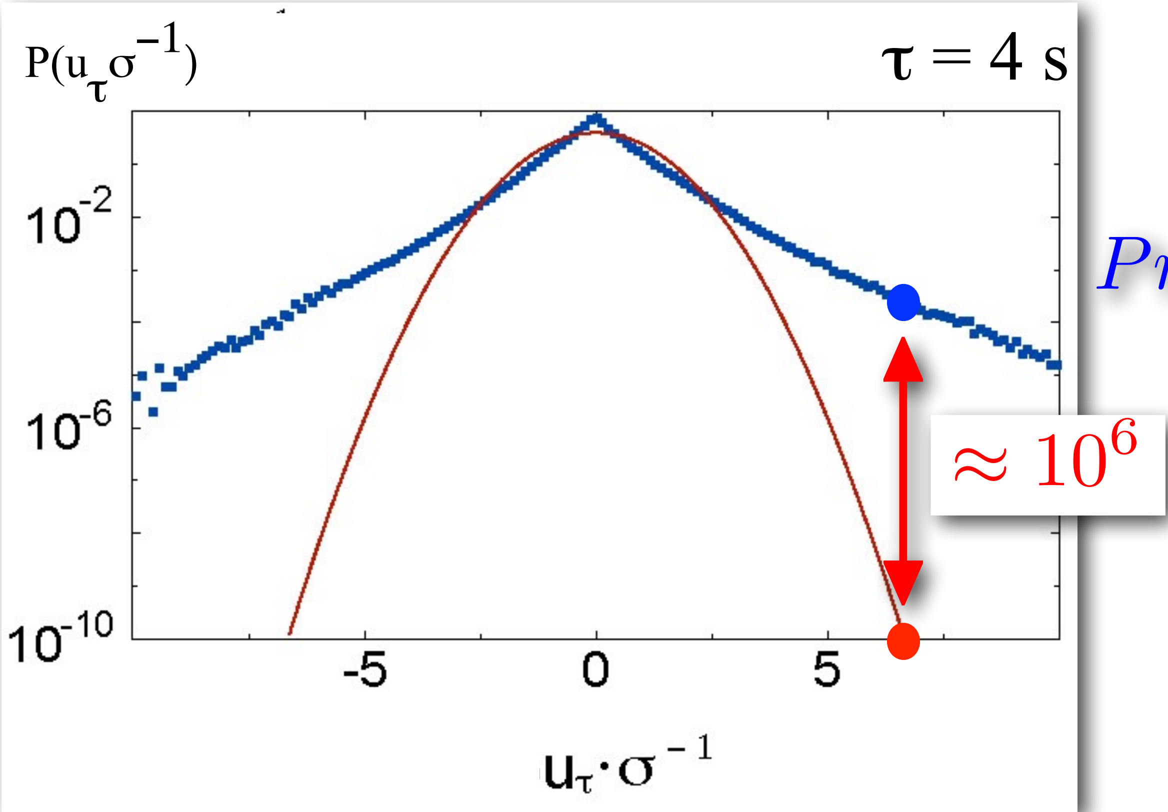


statistics of gusts



Boundary-Layer Meteorology **108** (2003)

statistics of gusts



$$Prob(u_\tau > 6\sigma) \approx 10^{-4}$$

1/day

Boundary-Layer Meteorology **108** (2003)

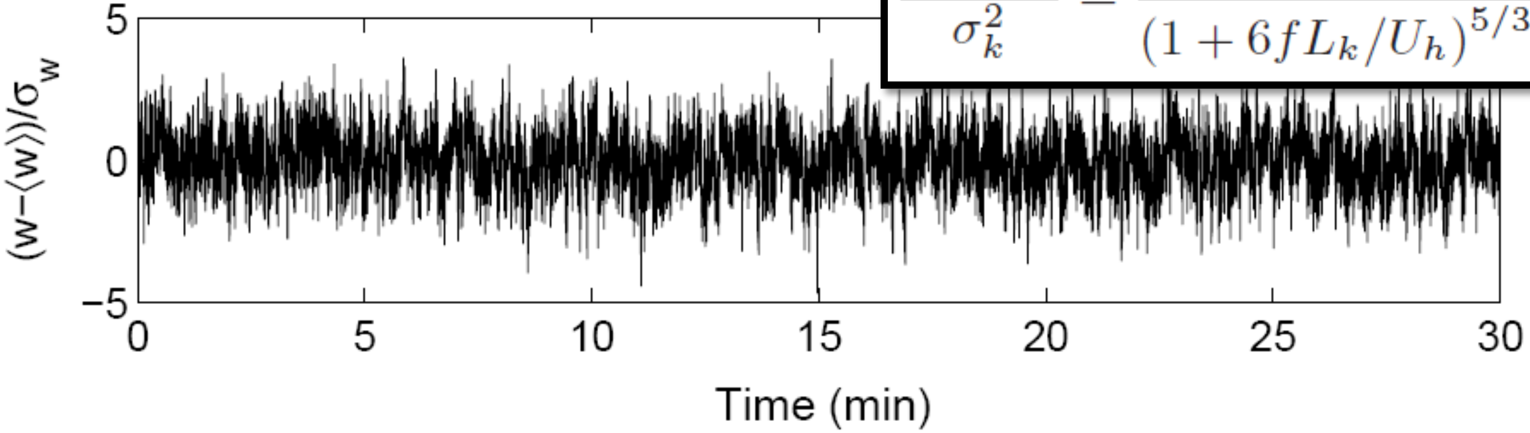
$$Prob(u_\tau > 6\sigma) \approx 10^{-10}$$

1/3000 years

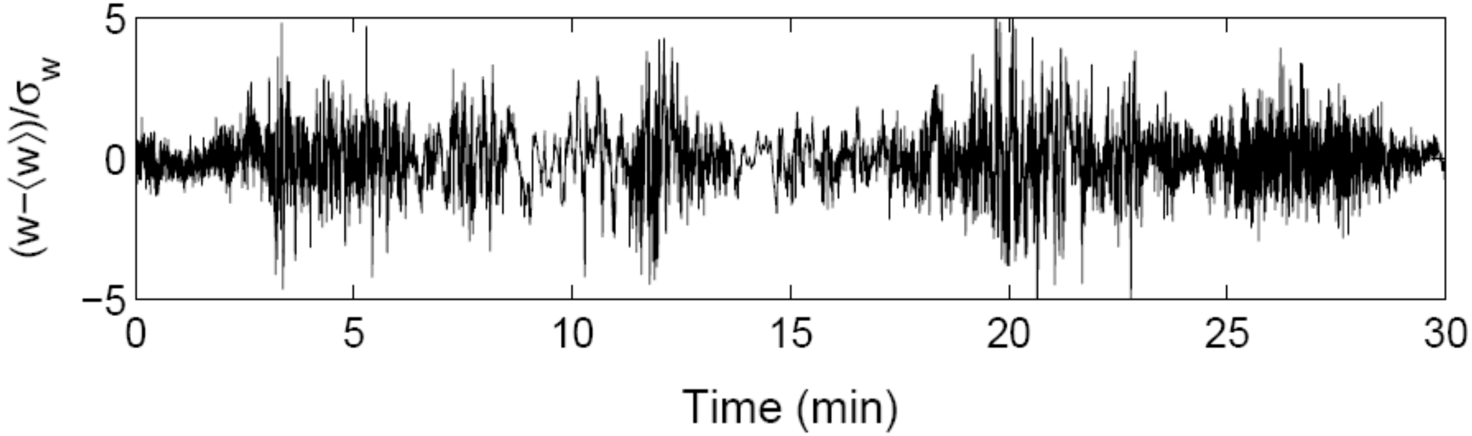
IEC Wind and measured

IEC Code

$$\frac{fS_k(f)}{\sigma_k^2} = \frac{4fL_k/U_h}{(1+6fL_k/U_h)^{5/3}}$$



Observation

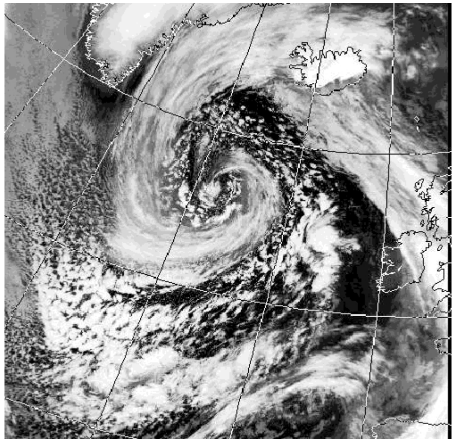


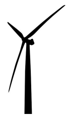
EUROMECH 528, *S. Basu Uni Texas,*

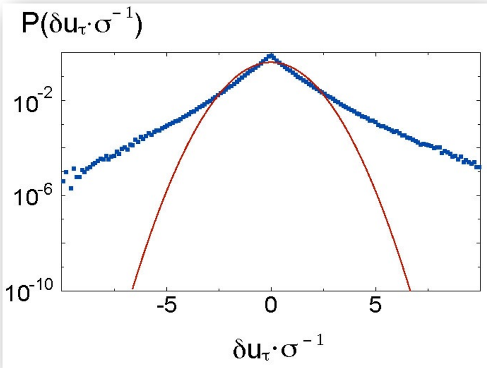
claim - need to understand turbulence

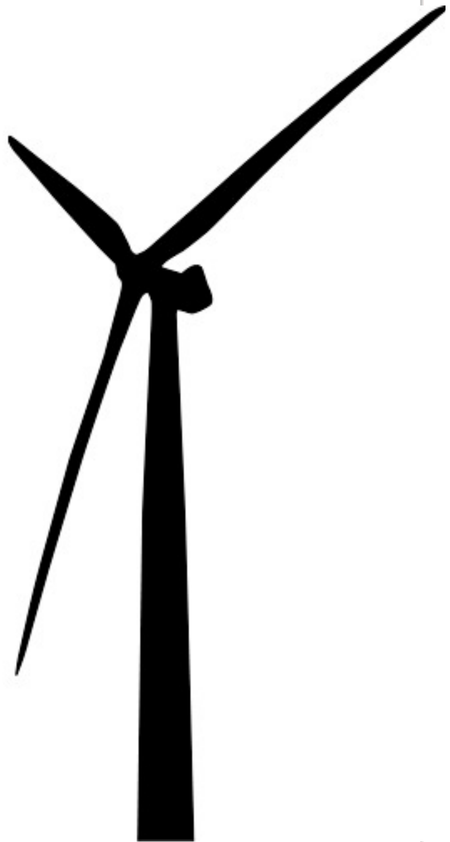
Wind characterisation —-

- wind has intermittent statistics - not taken into account by IEC norm
- wind turbine is a small scale structure - strong intermittency









Part I: energy and wind

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Part III: Inflow: How much understanding of turbulence do we need?

— critics on standard characterisation

— does turbulence effect a wind turbine ?

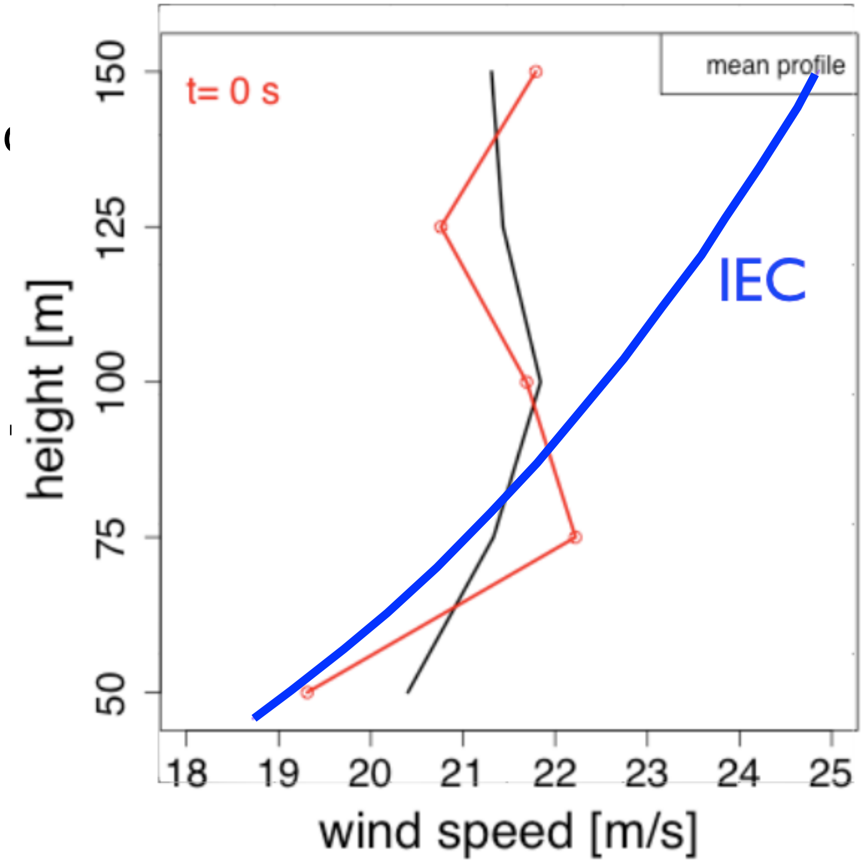
modern wind turbines

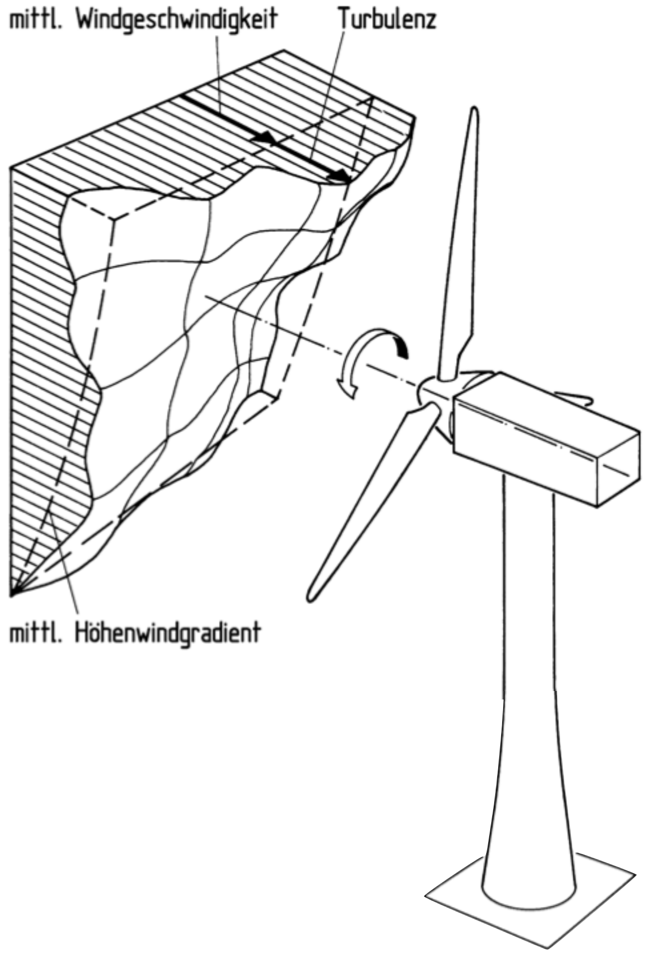
size averages how much of turbulence??

incident wind field

wel

entral für





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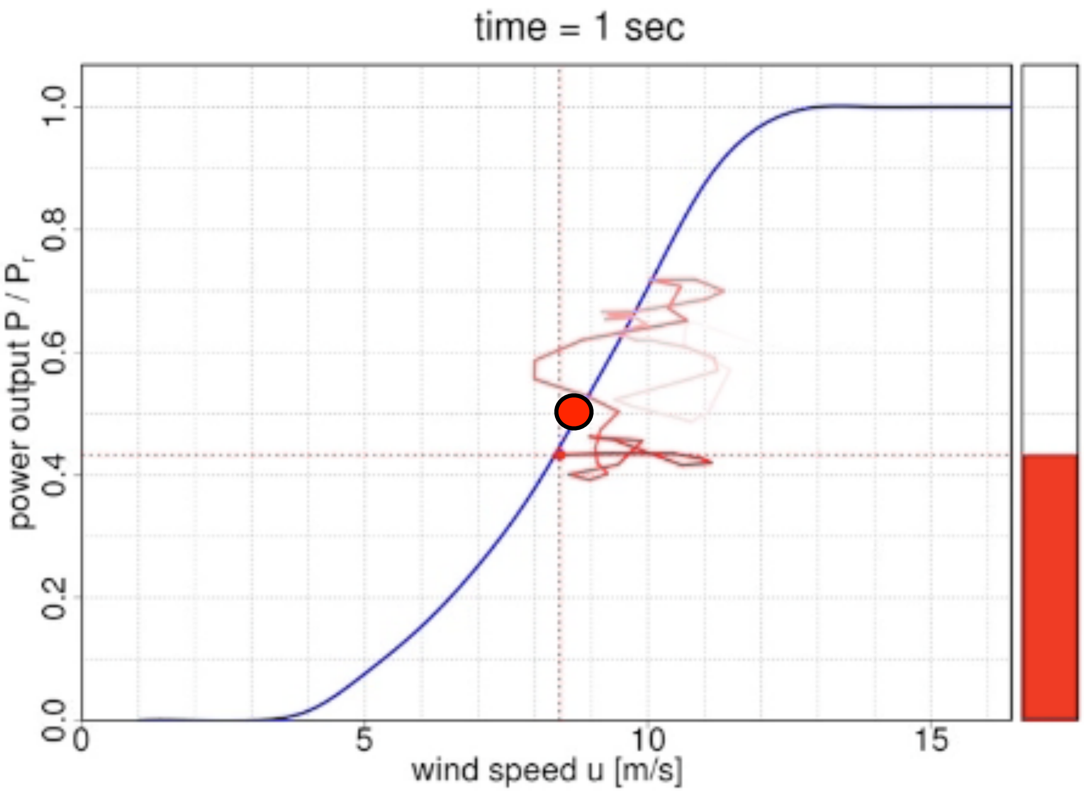
Part 2
motivation : dynamics of power conversion

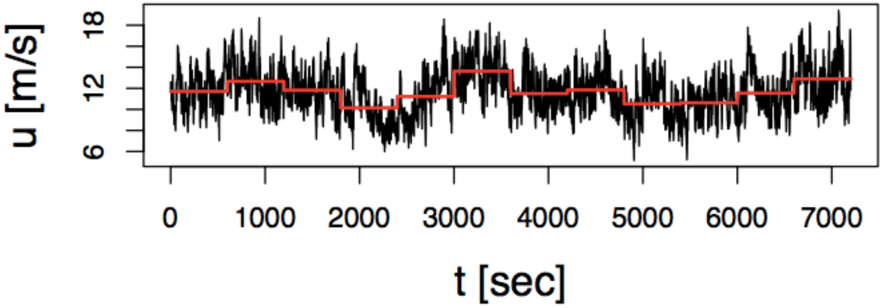
$$P_{WT} = \frac{1}{2} c_p(\lambda)\, \rho\, u_{wind}^3 \cdot A$$

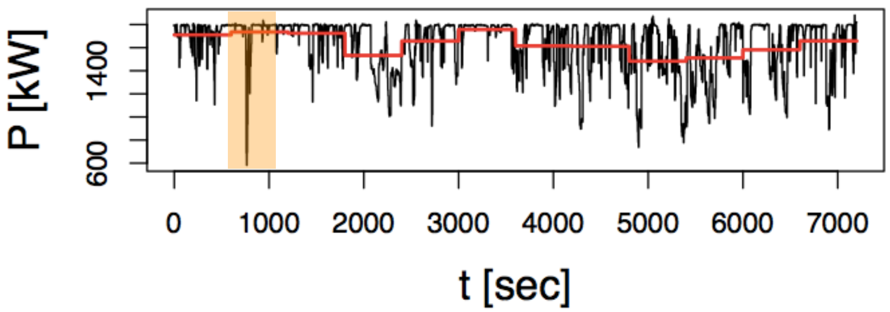


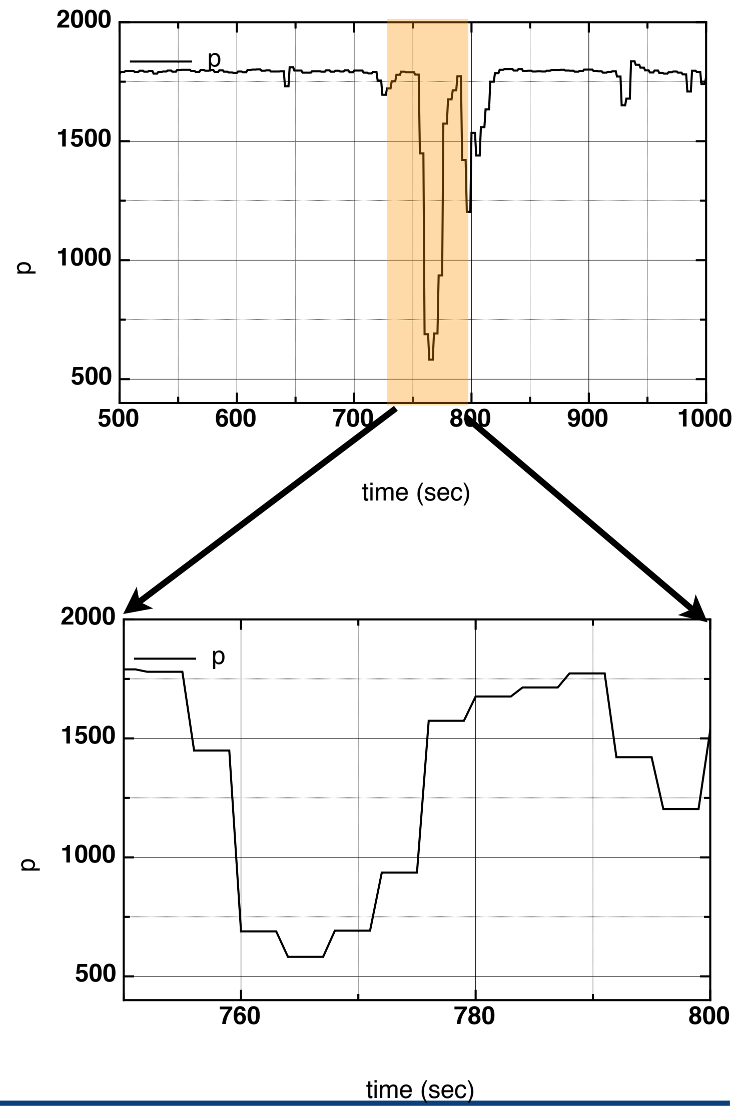
http://phys.org/news/2013-04-turbines-great-turbulence-consequences-grid.html

time series of power production

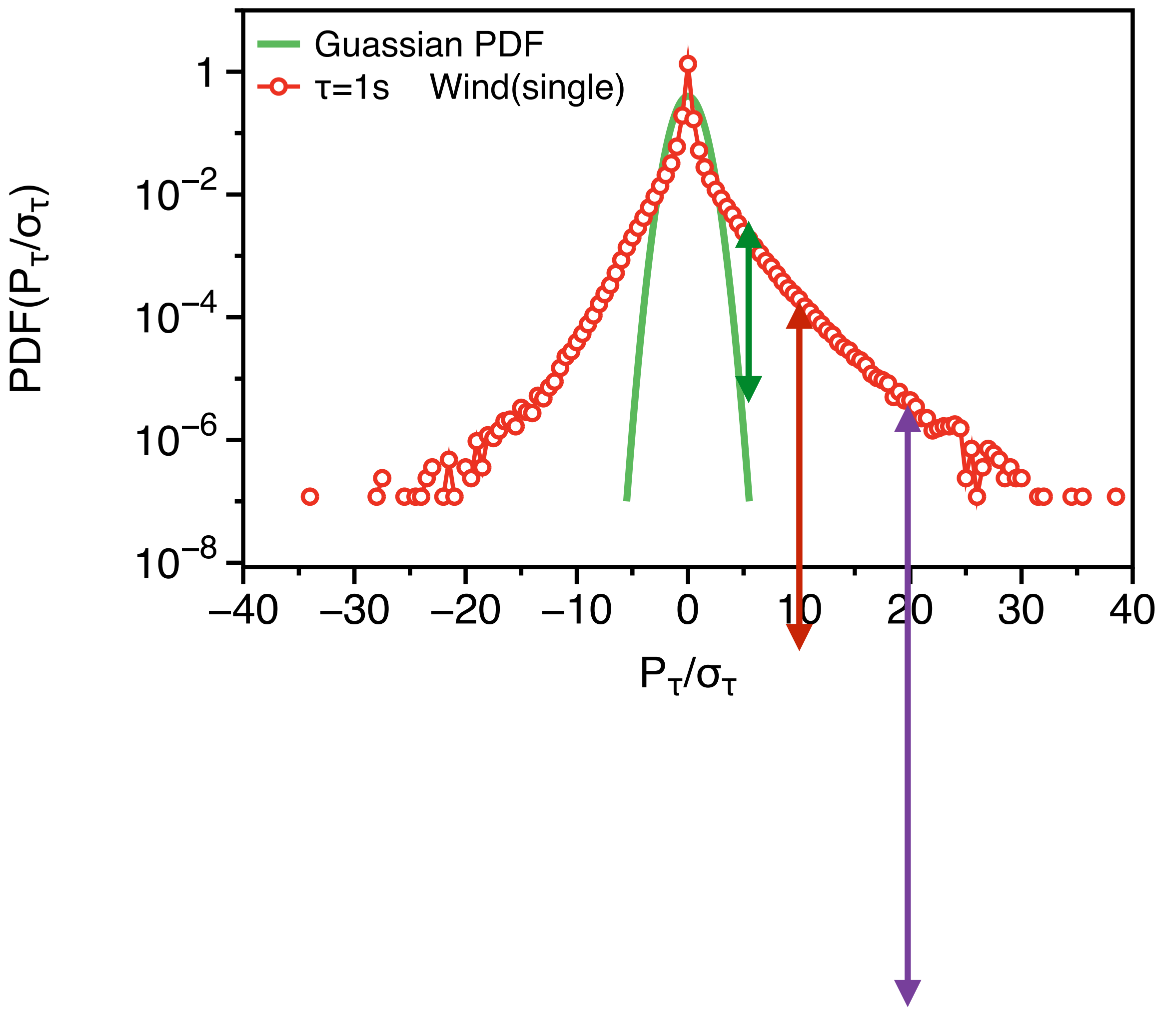
rot 10 min Mittelwerte







statistics of power fluctuations

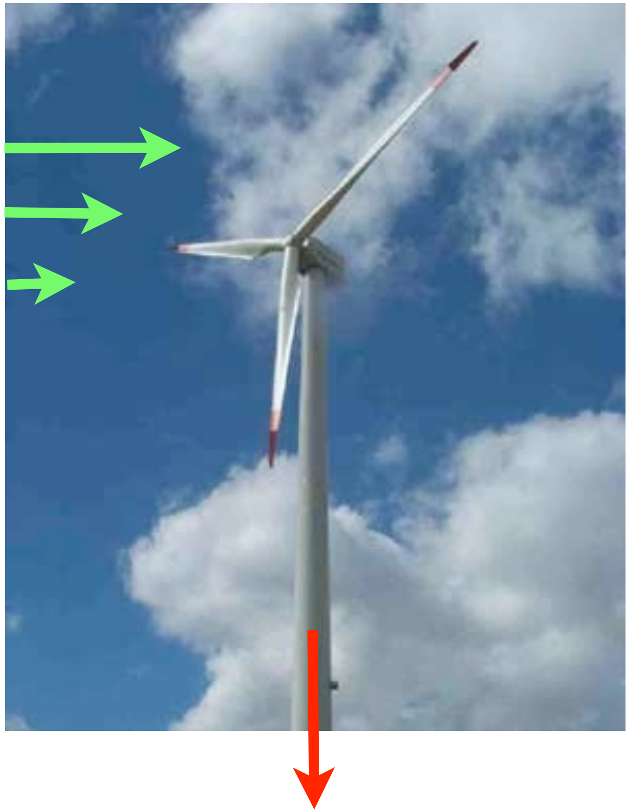


waiting time	5 σ	10 σ	20 σ
wind (τ = 1 sec)	~ 10 min	~ 4 hours	~1 month
Gauss	~ 3 days	~ 5 years	~ 3 million years

wind turbine input: turbulent, noisy wind

dynamic power curve

wind speed
u(t)



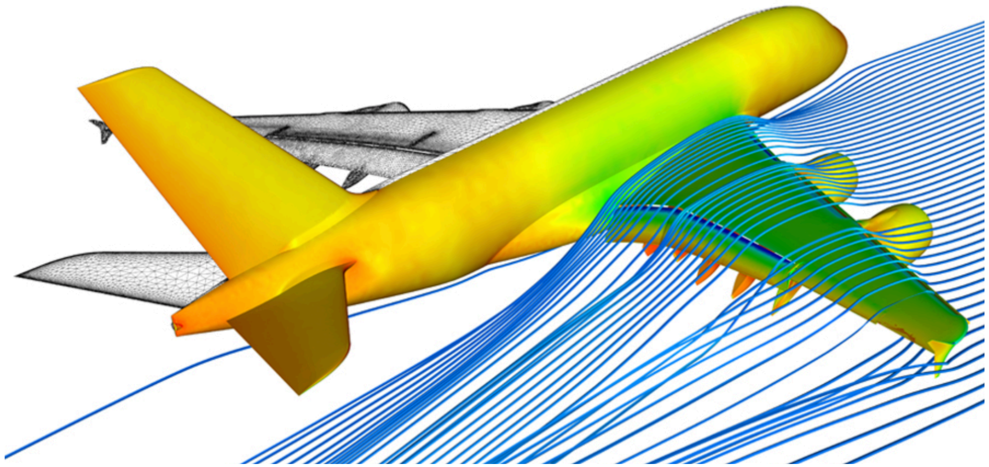
power *P(t)*

power increment statistics
(intermittent like wind speed)

response of a noisy driven
system — stochastic analysis

output - power into the grid

challenge - new aerodynamics for turbulent inflow

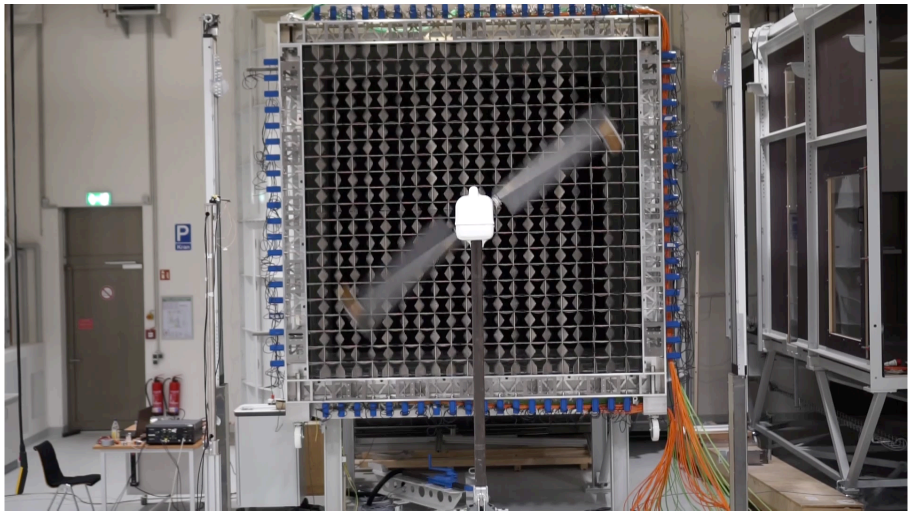


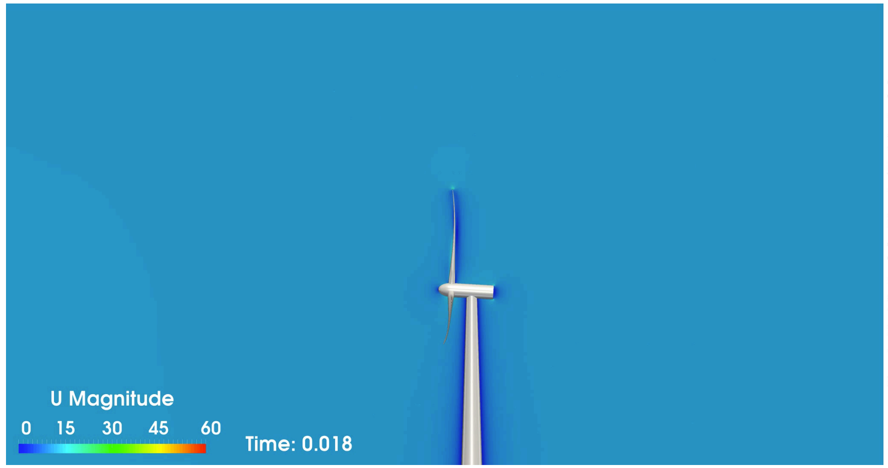
aviation

- optimised flight in laminar surrounding

wind energy

- operation in fully developed small scale turbulence





free field offshore

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ForWind Center for Wind Energy Research

Bremen Hannover Oldenburg

new research building WindLab in Oldenburg

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