Fraunhofer IWES

Wind Energy and the Need to Understand Turbulence

Joachim Peinke
ForWind - Uni Oldenburg
&
IWES Fraunhofer

Research Alliance Wind Energy

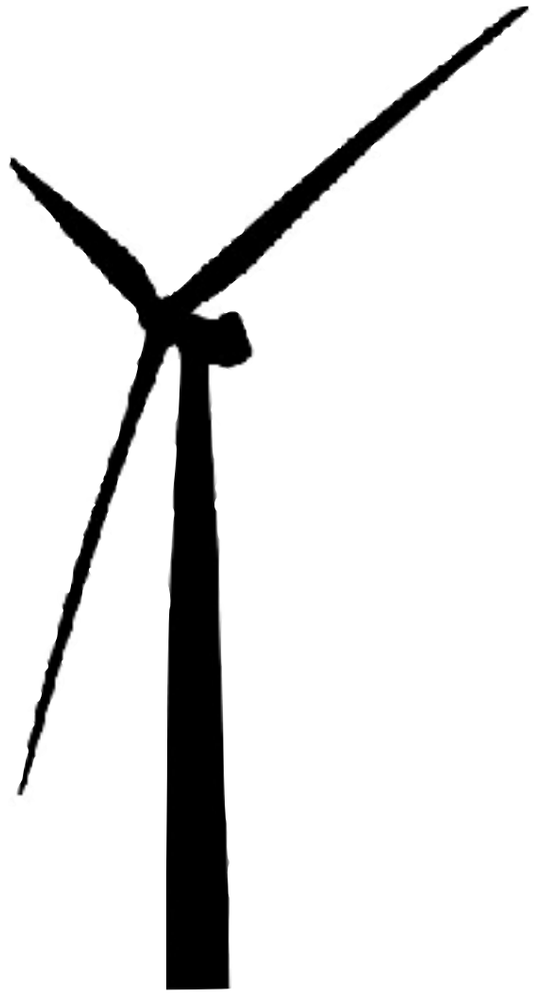
Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

ForWind Zentrum für Windenergieforschung

Fraunhofer IWES

content

- general comments on wind energy
- working conditions for wind turbines
- claim - need to understand turbulence



why wind energy ?

- environment issue CO2
- finite ressources
- costs - wind cheapest way

energy resources

Do you know how much fossil energy we consume worldwide?

IEA : worldwide daily 85 million barrel oil

energy resources - oil

IEA : worldwide daily 85 million barrel oil

truck with 35.000 litre volume

Aral - BP „Alles super“

no problem?

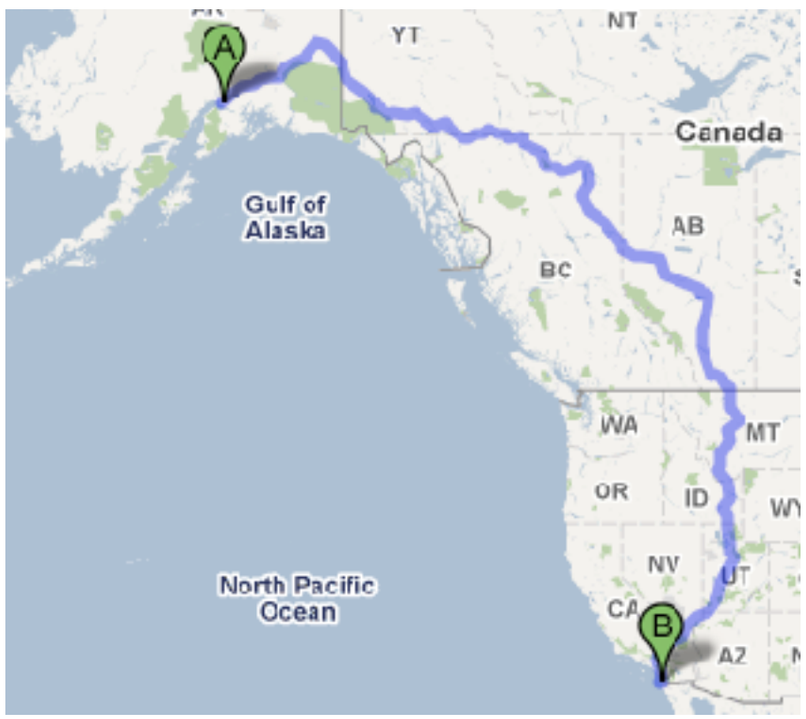
oil consumption

energy consumption

every day

85 million barrel oil per day

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



motivation

energy consumption

every day

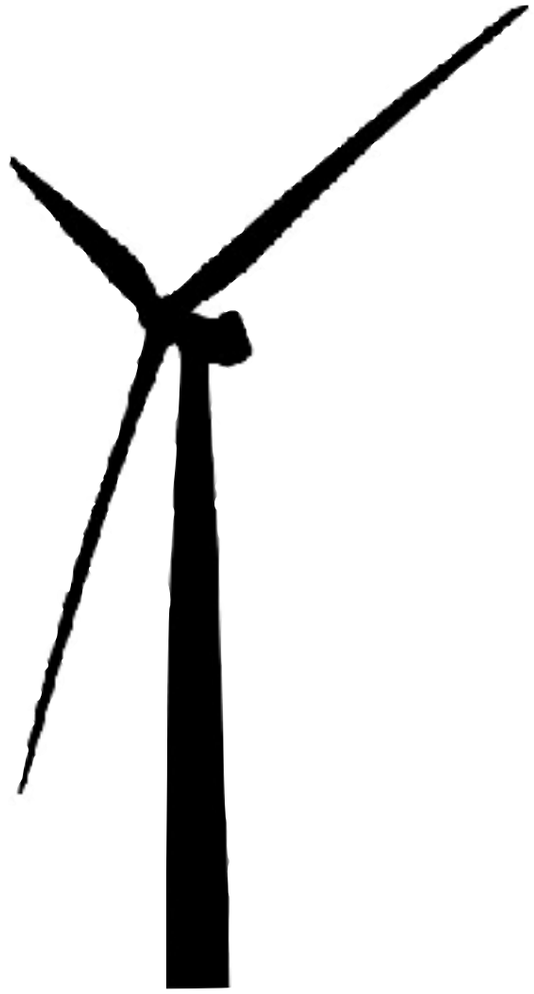
85 million barrel oil per day

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

natural production rate

3- WEC

1st part



- general comments on wind energy

power from wind

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

$$P_{wind} = \dot{E}_{wind} = \frac{1}{2}\dot{m}u^2 \qquad \dot{m} = \rho\dot{V} = \rho A \cdot u$$

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

for u = 12 m/s $P_{wind} = 1kW/m^2$

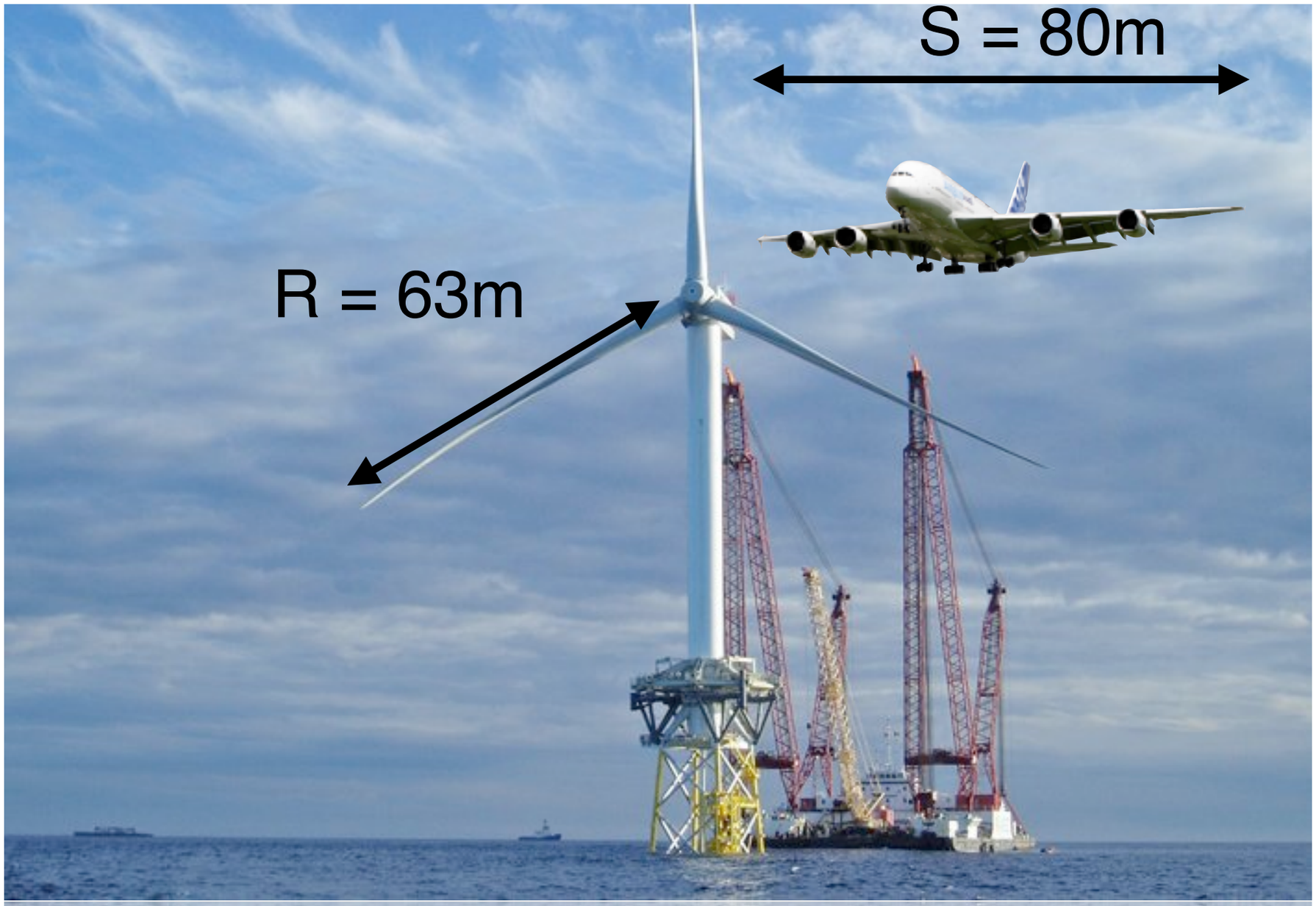
WEC

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

$c_P \leq 0.59$ Betz- Joukowsky limit

modern wind turbines

size



modern wind turbines

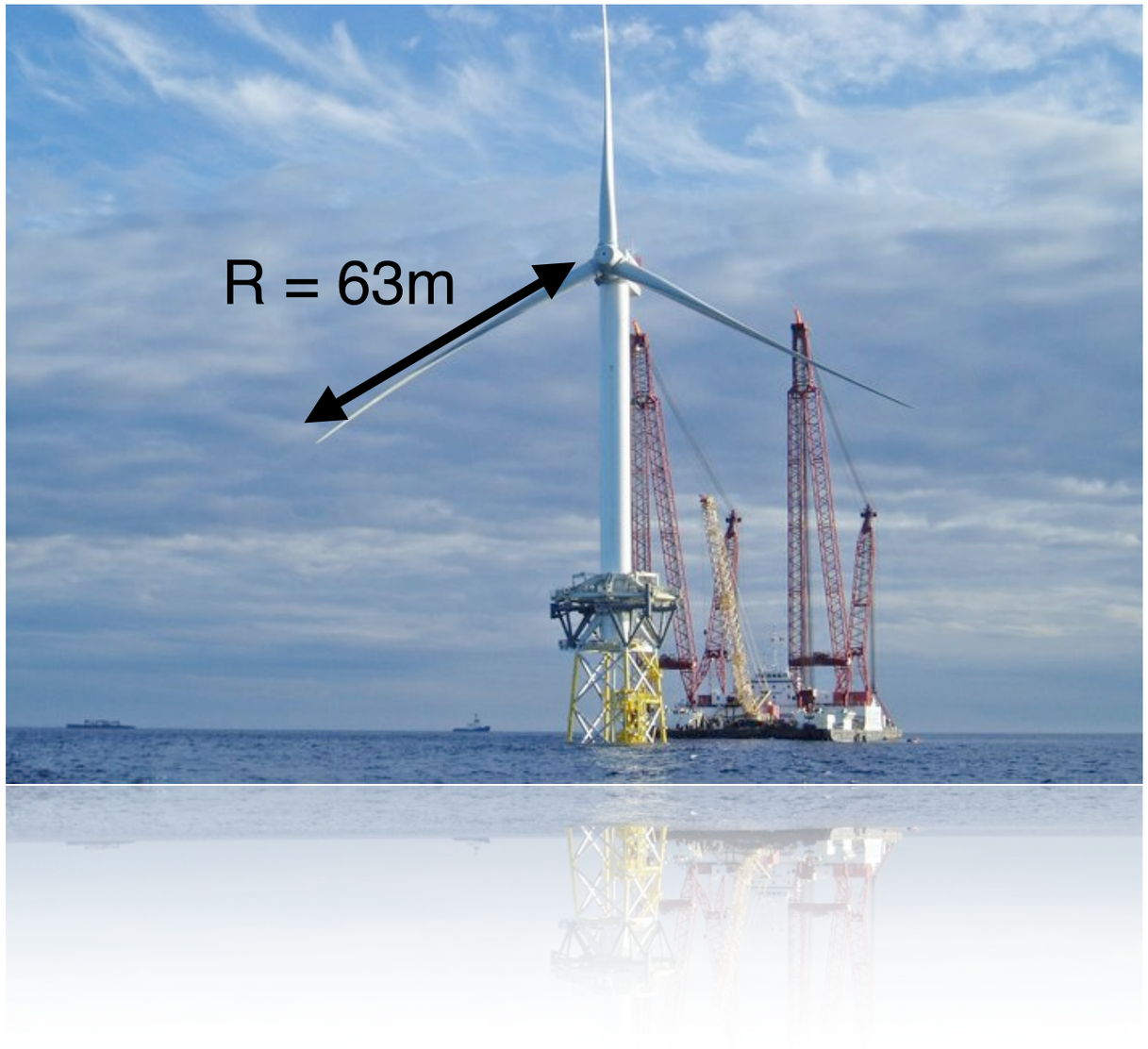
area = 12469 m²

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

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

$$c_P \leq 0.59$$

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



modern wind turbines

WEC >5MW

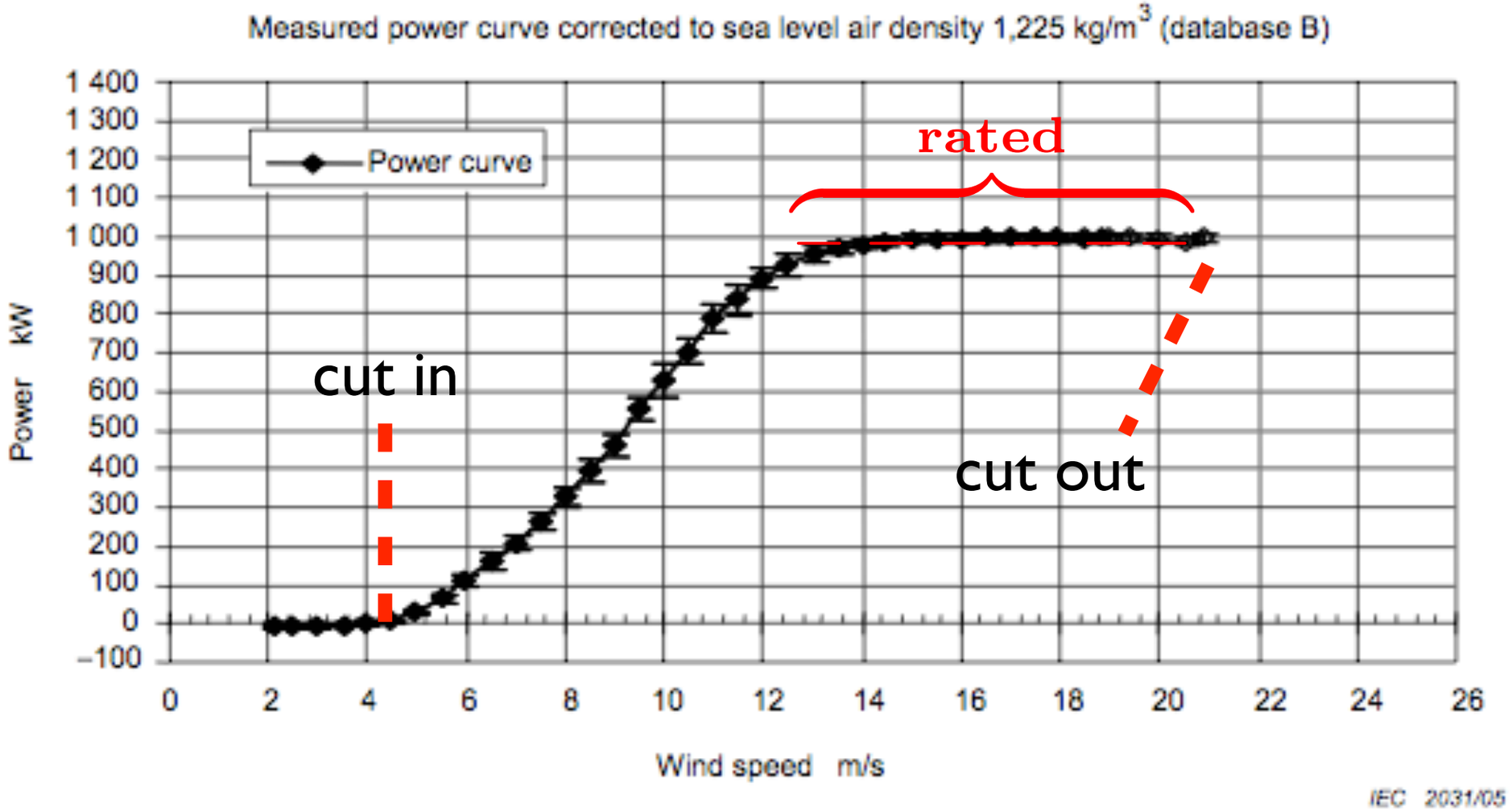
typical engine of a train

3,7 MW

power output of wind turbines

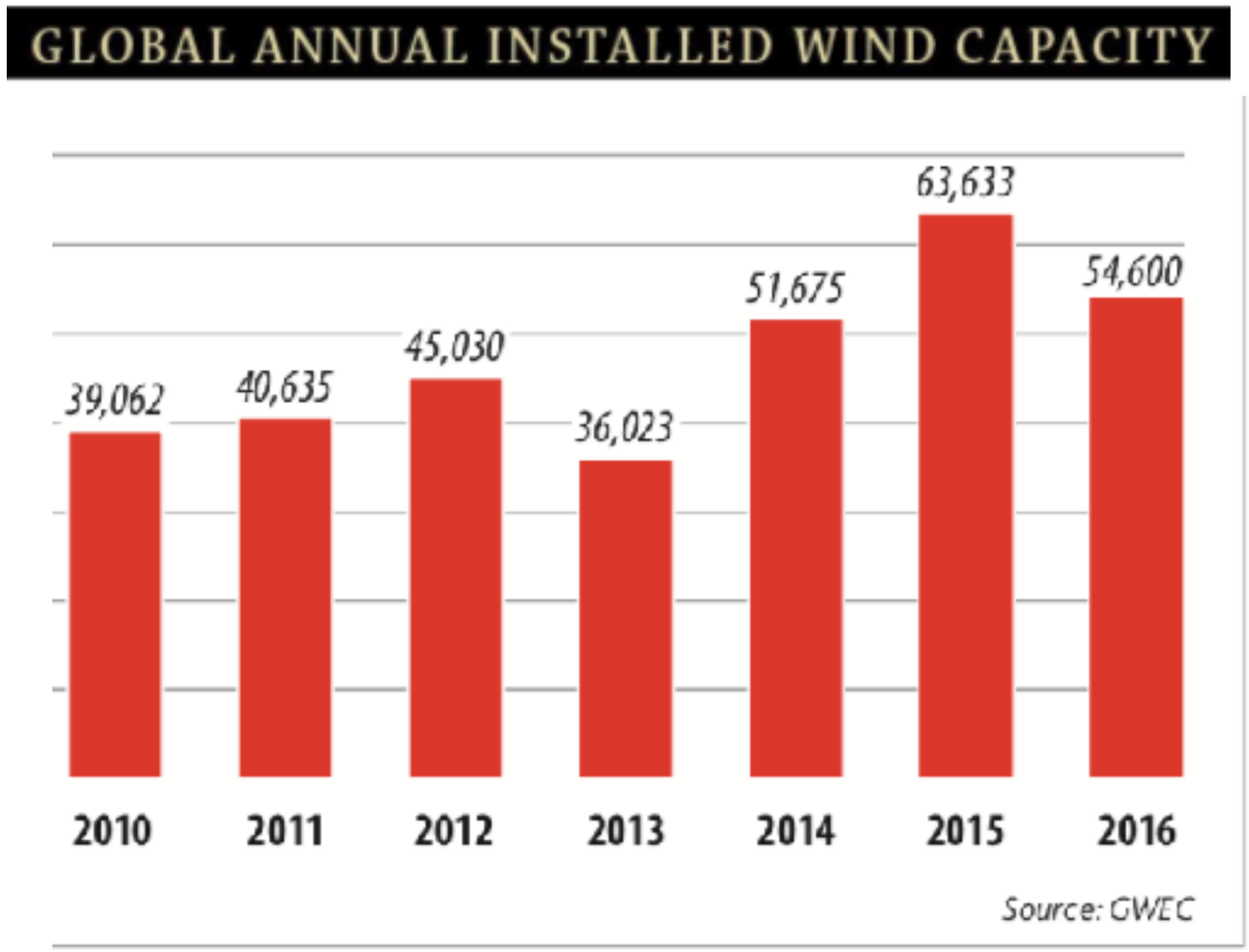
measured power curve

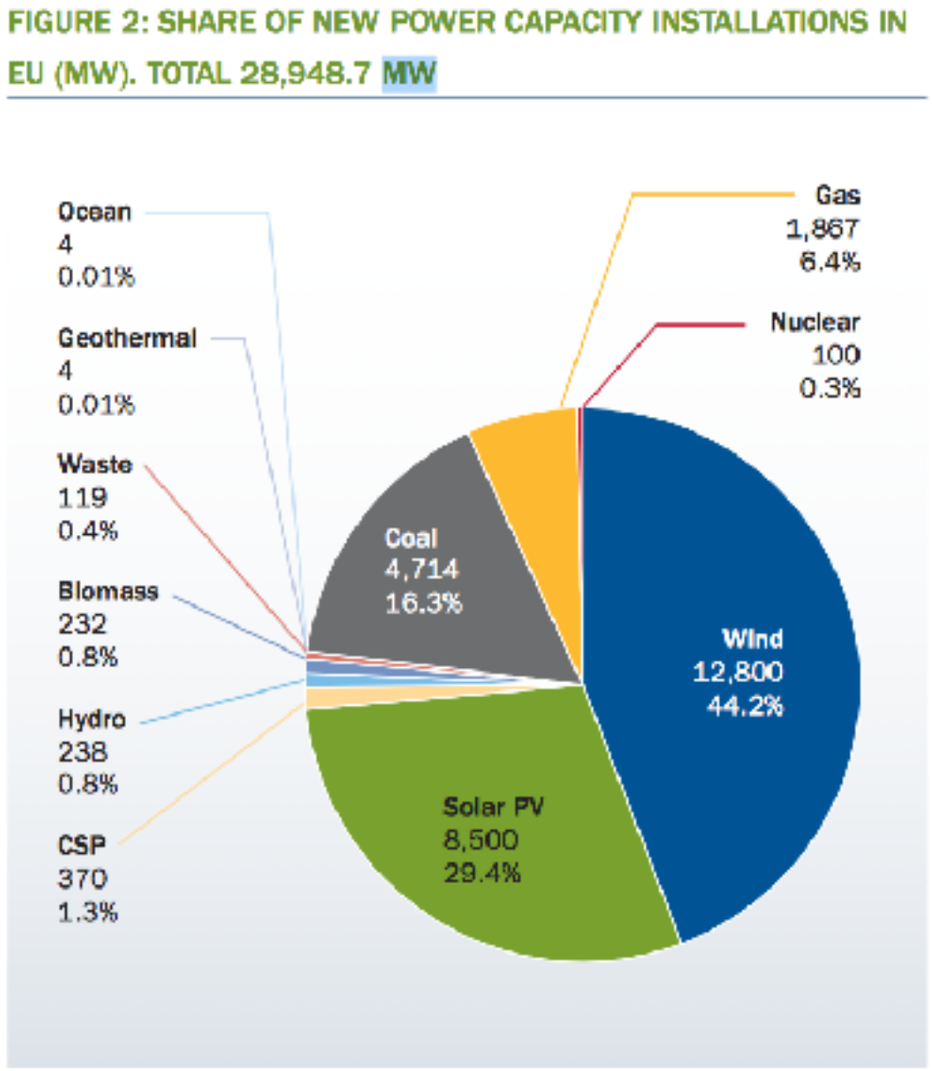
rated power defines the turbine size



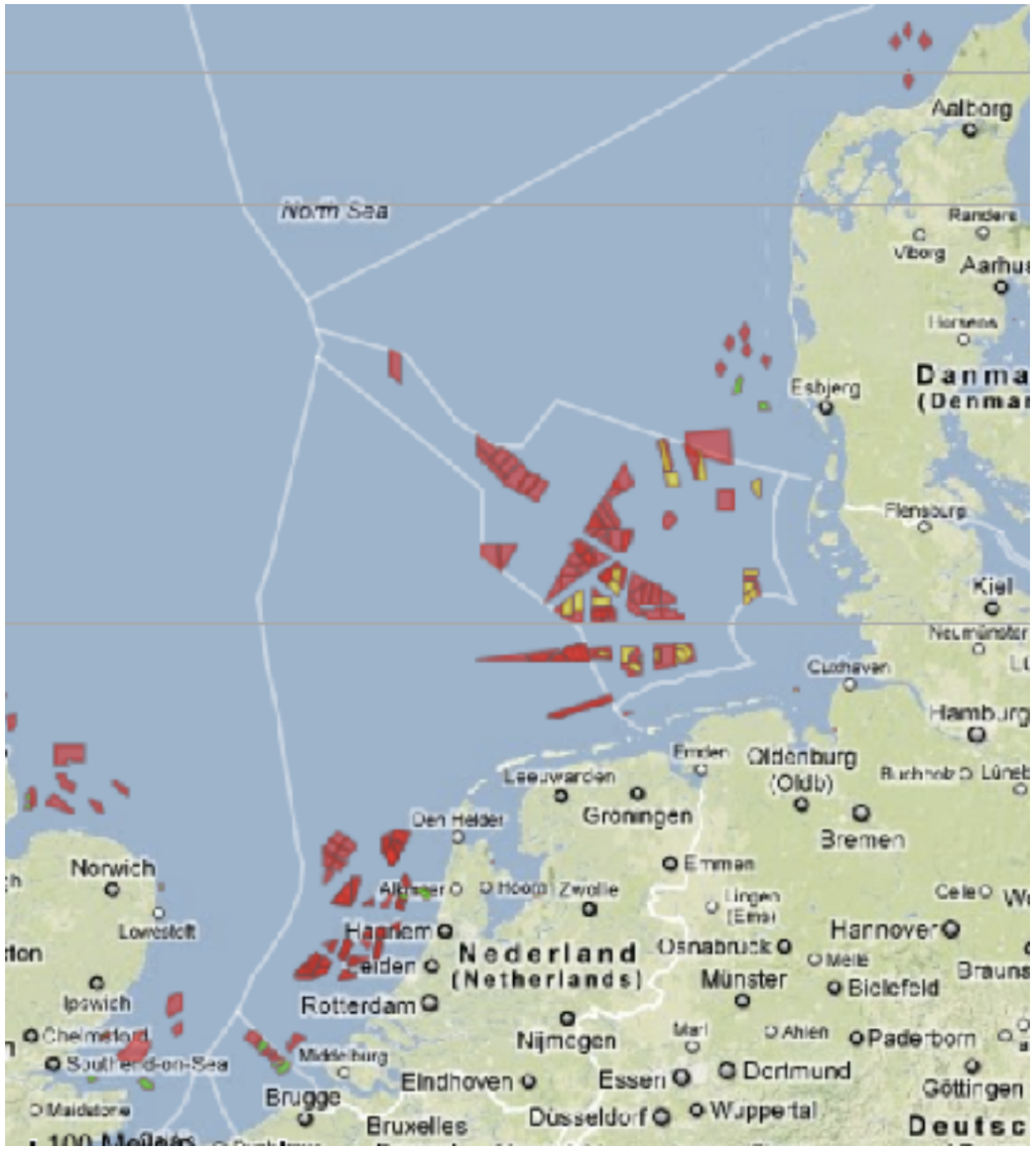
story of success

- wind energy cheapest one
- best C02 balance (return time ◂1 a)
  - one of the best energy return on energy invested ERoEI - relation
- installation Germany:3 GW/a world:50 GW / a





offshore activities



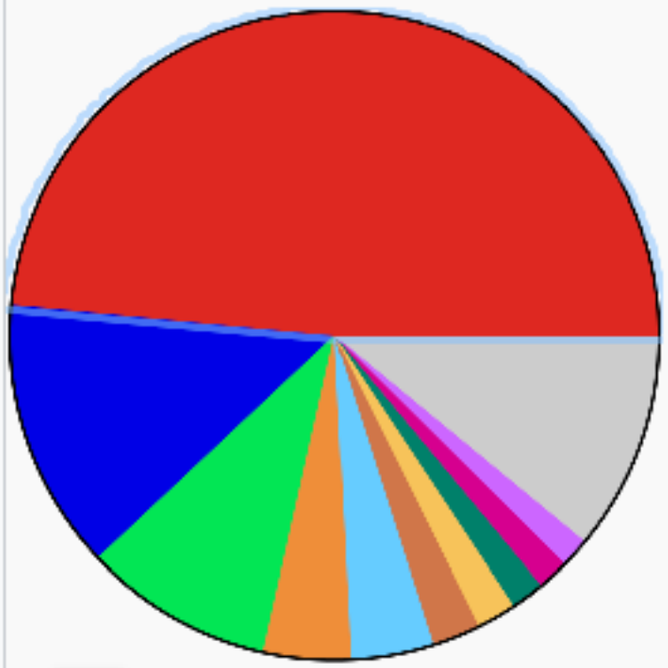
Source: Huisman Equipment

2015 new 2.3 GW offshore / 3,5 GW onshore

leader in wind energy?

new

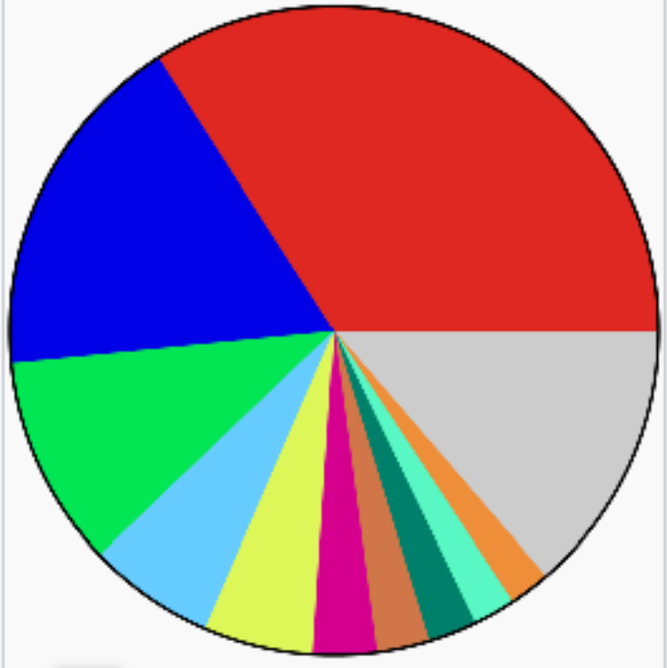
New Installed capacity by country in 2015 (MW)[2]



- China: 30,753 MW (48.5%)
- United States: 8,598 MW (13.5%)
- Germany: 6,013 MW (9.5%)
- Brazil: 2,754 MW (4.3%)
- India: 2,623 MW (4.1%)
- Canada: 1,506 MW (2.4%)
- Poland: 1,266 MW (2.0%)
- France: 1,073 MW (1.7%)
- United Kingdom: 975 MW (1.5%)
- Turkey: 956 MW (1.5%)
- Rest of the world: 6,950 MW (11.0%)

total

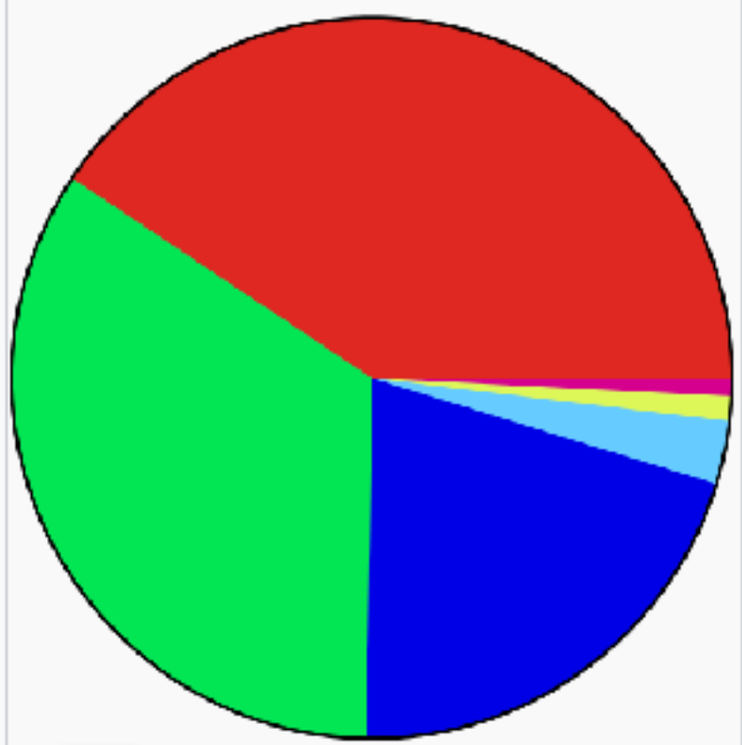
Installed capacity by country in 2015 (MW)[2]



- China: 145,362 MW (34.1%)
- United States: 74,471 MW (17.5%)
- Germany: 44,947 MW (10.5%)
- India: 27,151 MW (6.4%)
- Spain: 23,025 MW (5.4%)
- United Kingdom: 13,603 MW (3.2%)
- Canada: 11,205 MW (2.6%)
- France: 10,358 MW (2.4%)
- Italy: 8,958 MW (2.1%)
- Brazil: 8,715 MW (2.0%)
- Rest of the world: 58,275 MW (13.7%)

total

Installed capacity by regions in 2015 (MW)[2]



- Asia (excluding Middle East): 175,831 MW (40.6%)
- Europe: 147,771 MW (34.1%)
- North America: 88,749 MW (20.5%)
- Latin America and Caribbean: 12,220 MW (2.8%)
- Pacific Region: 4,823 MW (1.1%)
- Africa and Middle East: 3,489 MW (0.8%)

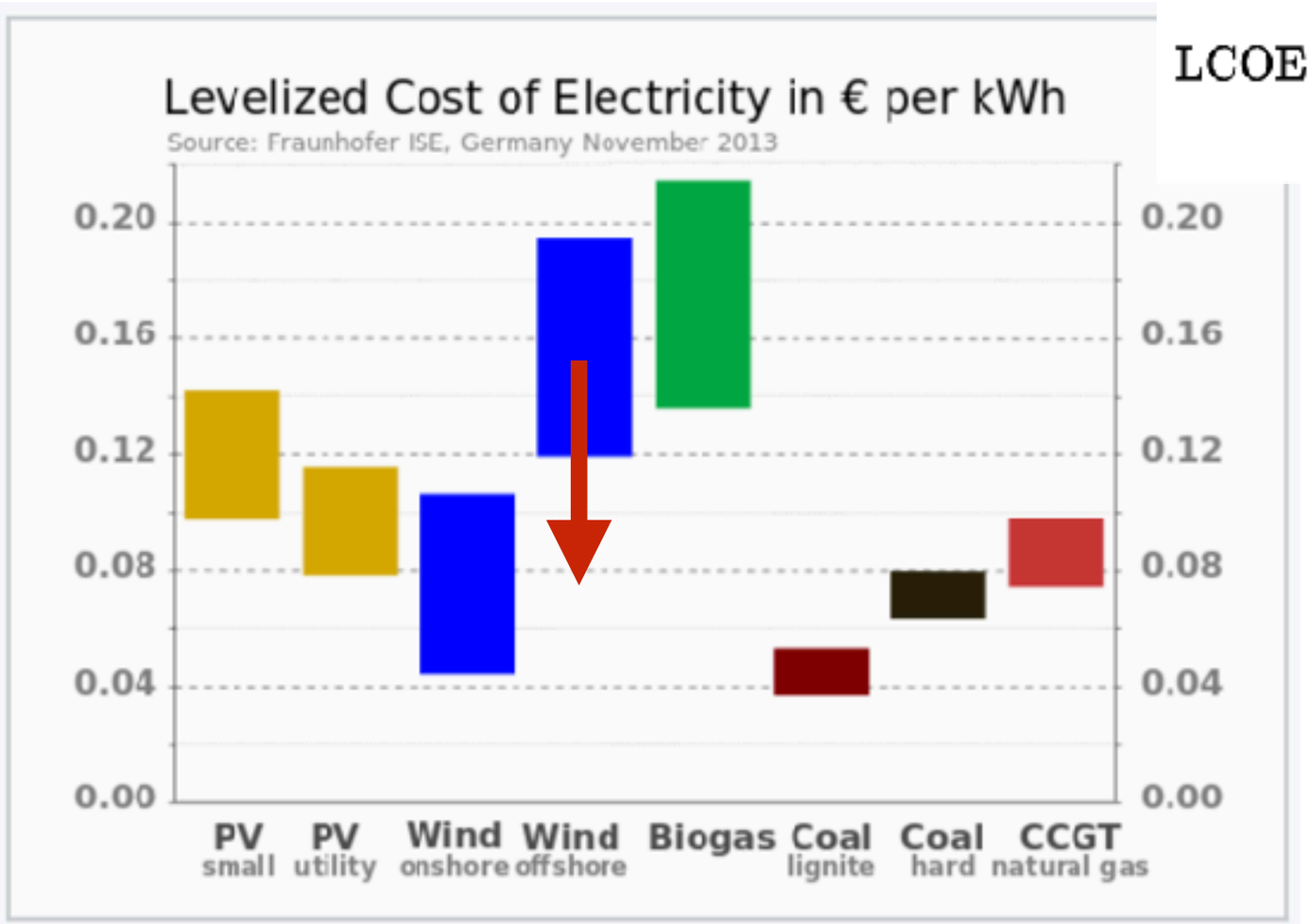
who like wind energy

Opinion on increase in number of wind farms (2010)

	US %	UK %	France %	Italy %	Spain %	Germany %
Strongly oppose	3	6	6	2	2	4
Oppose more than favour	9	12	16	11	9	14
Favour more than oppose	37	44	44	38	37	42
Strongly favour	50	38	33	49	53	40

Source: Harris Poll, 2010. Base: All EU and U.S. adults.[55] *Note*: Percentages may not add up to 100% due to rounding

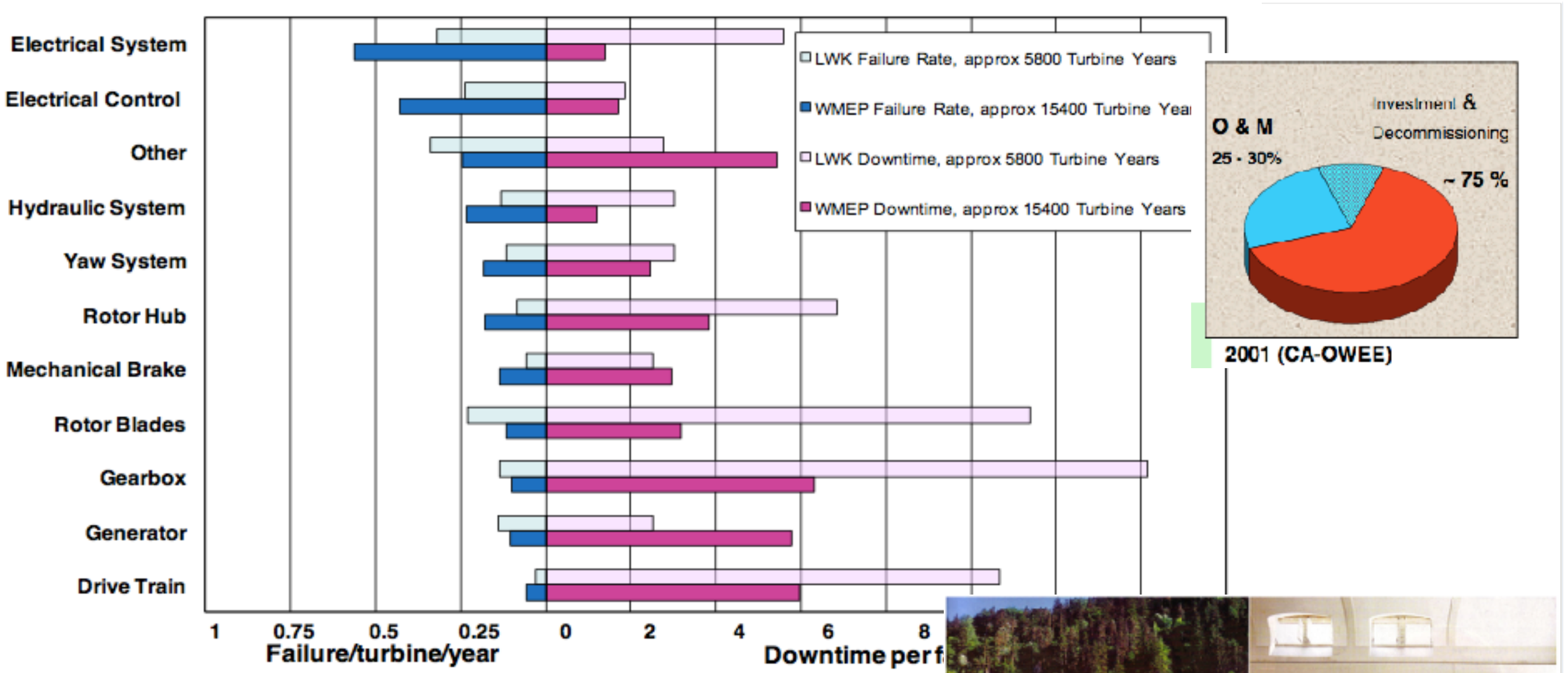
cost of energy



Comparison of the levelized cost of electricity for some newly built renewable and fossil-fuel based power stations in euro per kWh (Germany, 2013)
Note: employed technologies and LCOE differ by country and change over time.

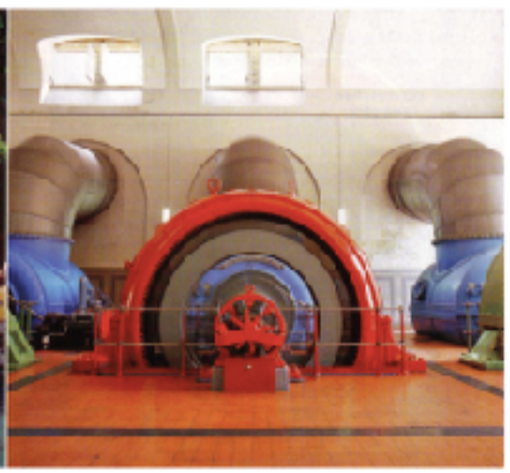
$$\mathrm{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}}$$

are there any problems? - Failure statistics



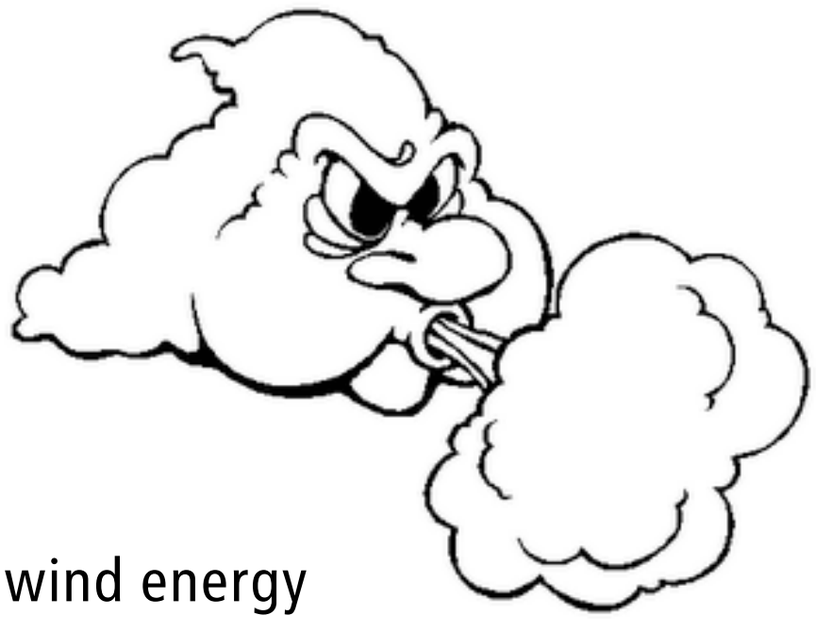
2001 (CA-OWEE)

P.Tavner et.al EWAE 2011



water power plant: Saalach (DB)

content



- general comments on wind energy
- working conditions for wind turbines
  - wind conditions

who knows fluid dynamics ?

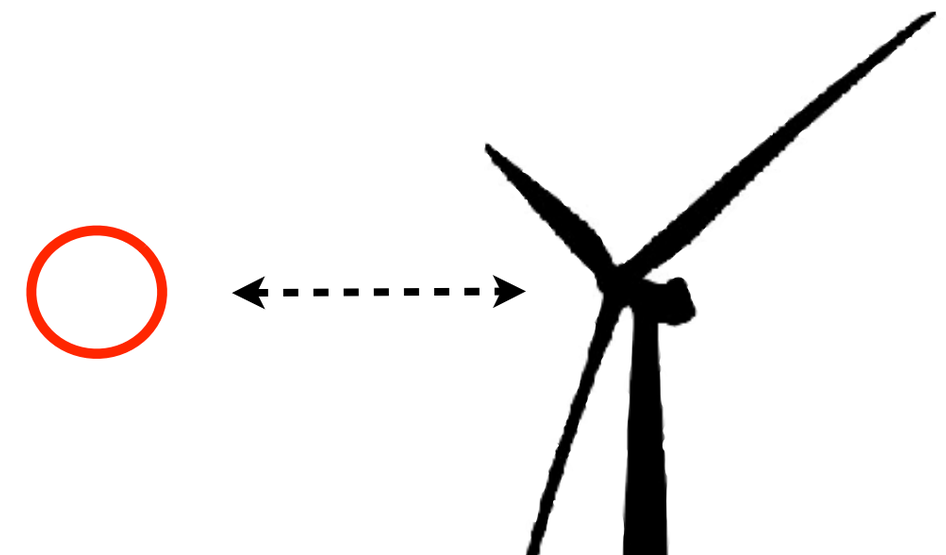
who knows Navier Stokes equation ?

wind measurements and data analysis

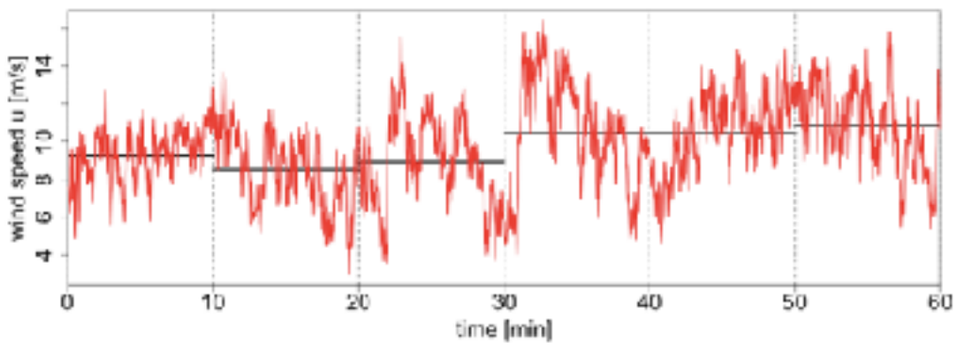
INTERNATIONAL STANDARD **IEC 61400-1**

Third edition 2005-08

- wind conditions after IEC
  - measurement at hub height in front of a turbine

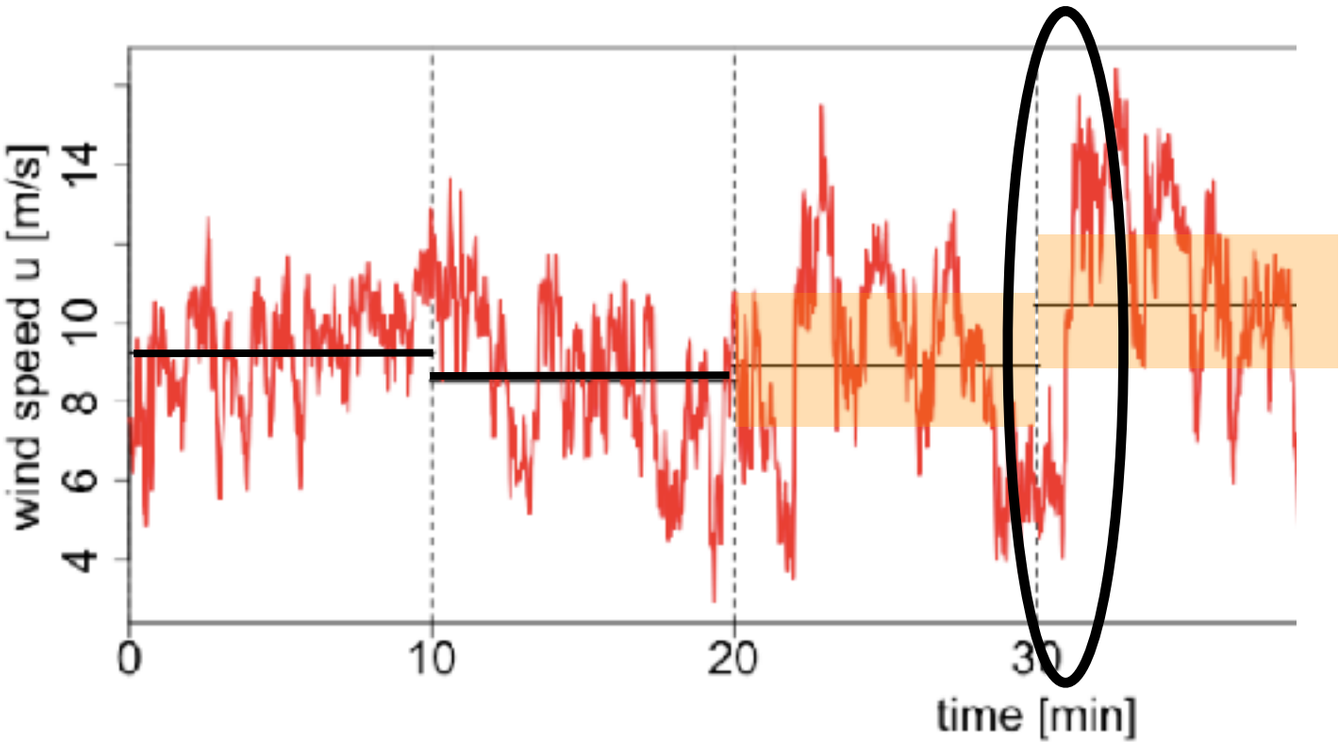


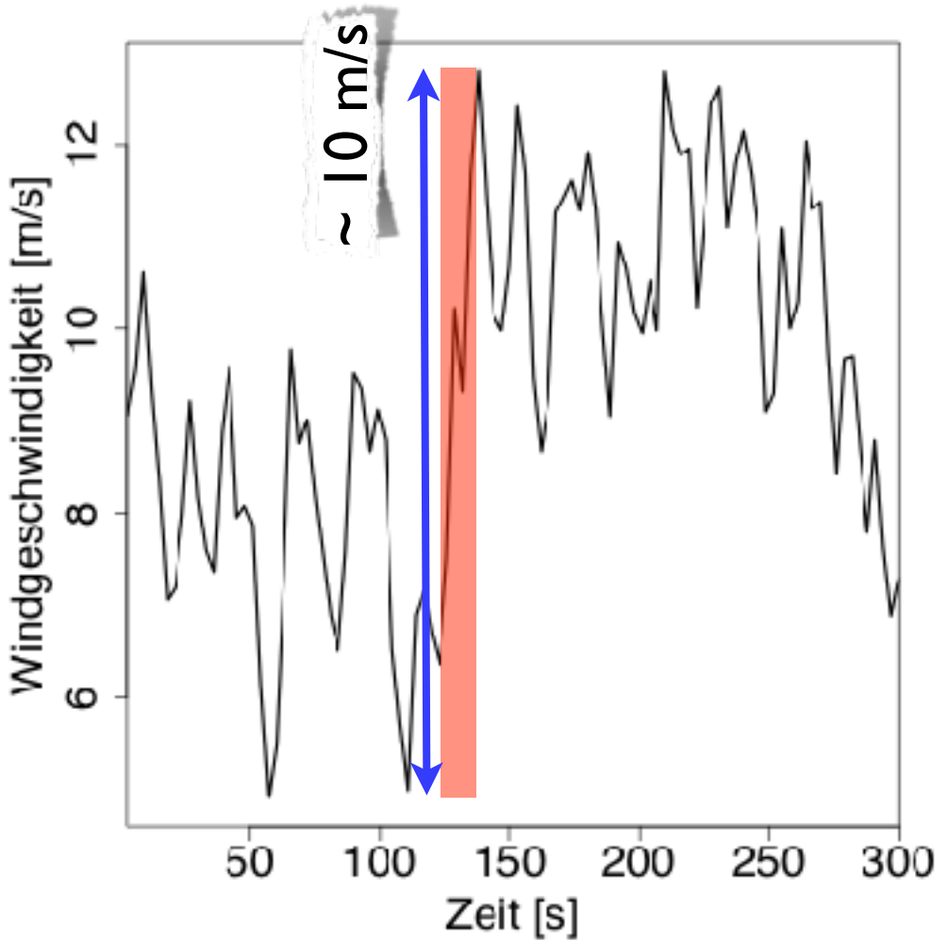
measured time series



wind measurements and data analysis

- characterization after IEC norm

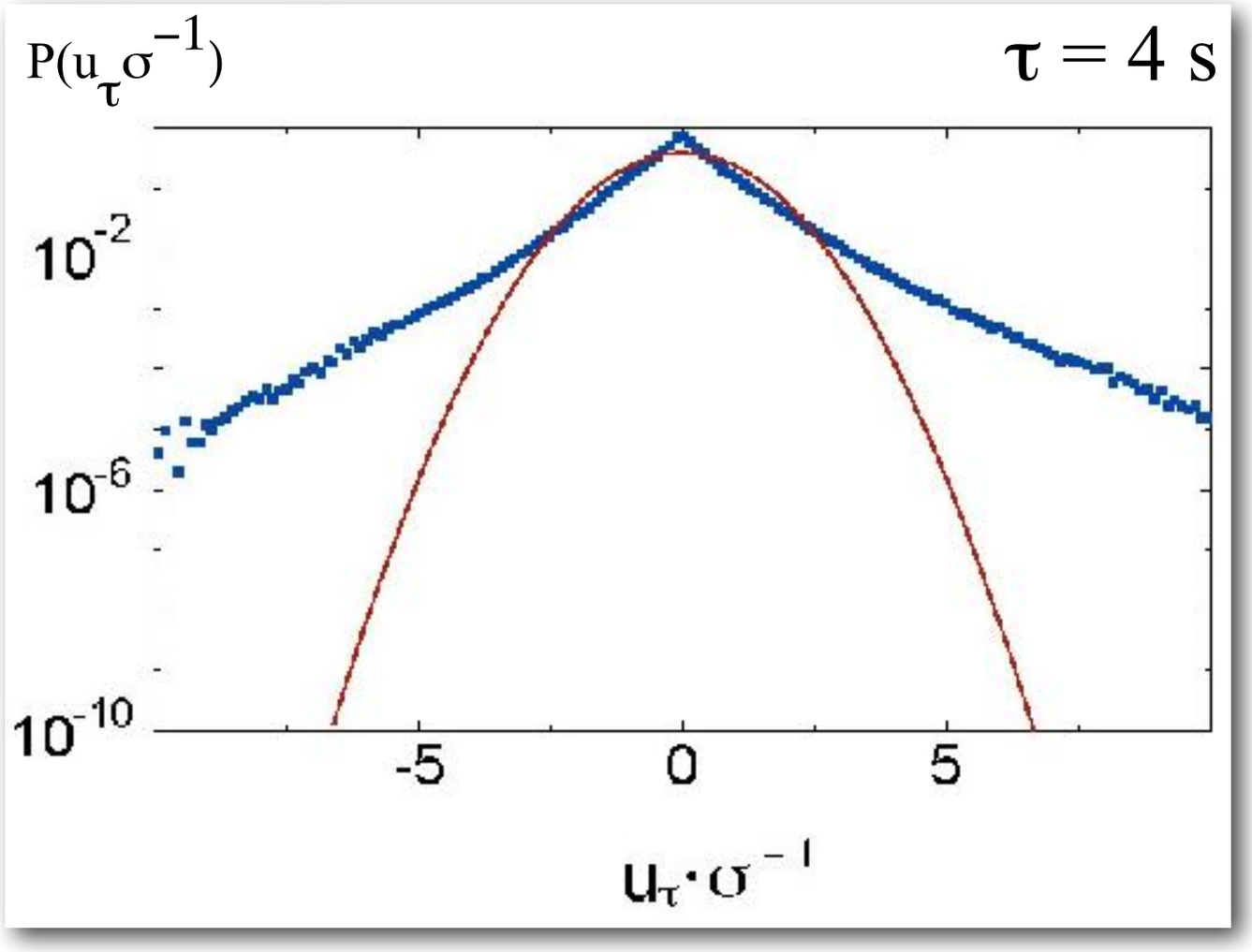




statistics of gusts

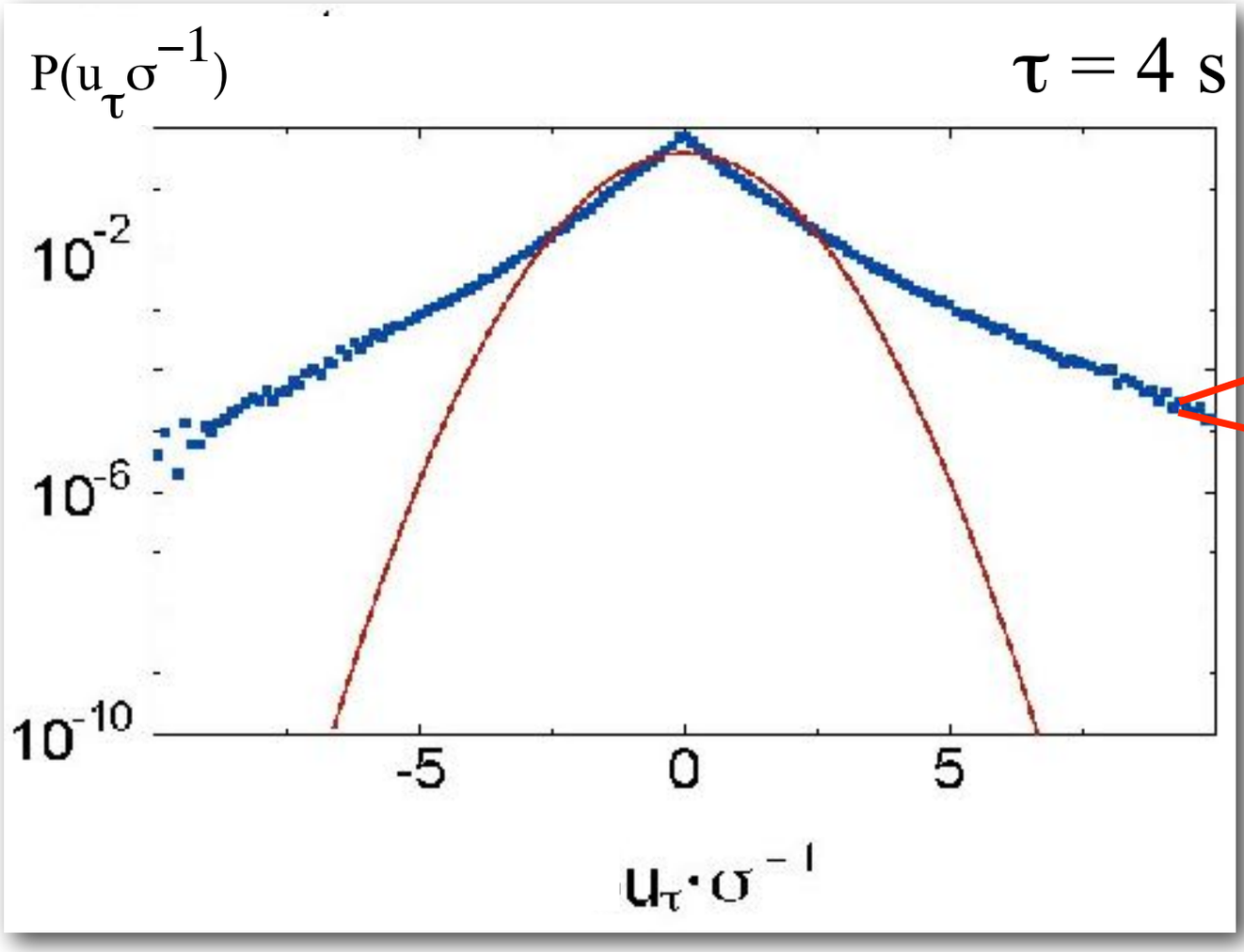
- wind fluctuations can be measured by velocity increments

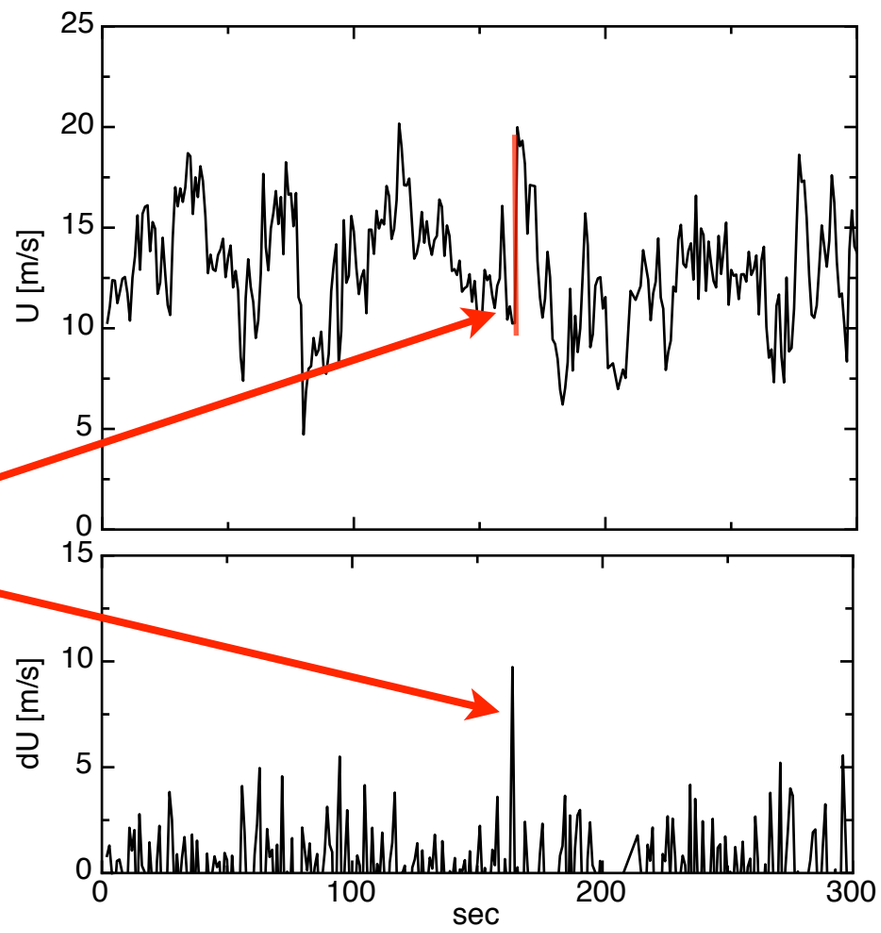
$$u_\tau = u(t+\tau) - u(t)$$



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

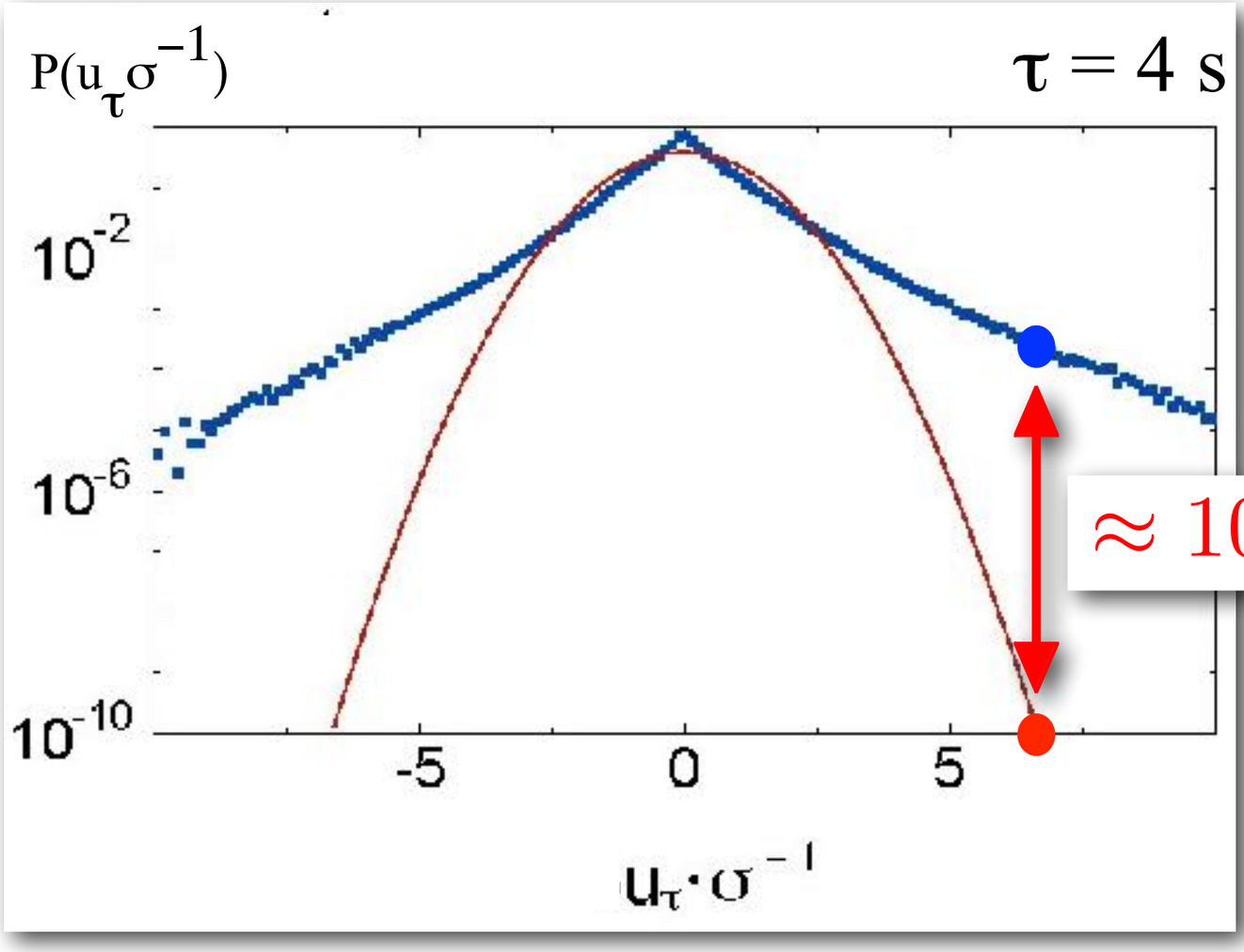
statistics of gusts





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

statistics of gusts



$\approx 10^6$

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

1/day

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

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

1/3000 years

content - 3rd part

- general comments on wind energy
- working conditions for wind turbines
- claim - need to understand turbulence

content - 3rd part

who knows fluid dynamics ?

who knows Navier Stokes equation ?

who knows the solution of the Navier Stokes equation ?

Turbulence one of 7 millennium problems

EXISTENCE AND SMOOTHNESS OF THE NAVIER–STOKES EQUATION

CHARLES L. FEFFERMAN

The *Navier–Stokes* equations are then given by

$$\frac{\partial}{\partial t}u_i + \sum_{j=1}^{n} u_j \frac{\partial u_i}{\partial x_j} = \nu \Delta u_i - \frac{\partial p}{\partial x_i} + f_i(x,t) \qquad (x \in \mathbb{R}^n, t \geq 0), \tag{1}$$

$$\operatorname{div} u = \sum_{i=1}^{n} \frac{\partial u_i}{\partial x_i} = 0 \qquad (x \in \mathbb{R}^n, t \geq 0) \tag{2}$$

$$p, u \in C^\infty(\mathbb{R}^n \times [0, \infty)). \tag{11}$$

A fundamental problem in analysis is to decide whether such smooth, physically reasonable solutions exist for the Navier–Stokes equations. To give reasonable leeway to solvers while retaining the heart of the problem, we ask for a proof of one of the following four statements.

Turbulence one of 7 millennium problems

Clay Mathematics Institute

Dedicated to increasing and disseminating mathematical knowledge

HOME | ABOUT CMI | PROGRAMS | NEWS & EVENTS | AWARDS | SCHOLARS | PUBLICATIONS

A fundamental problem in analysis is to decide whether such smooth, physically reasonable solutions exist for the Navier–Stokes equations. To give reasonable leeway to solvers while retaining the heart of the problem, we ask for a proof of one of the following four statements.

u_r → velocity increment

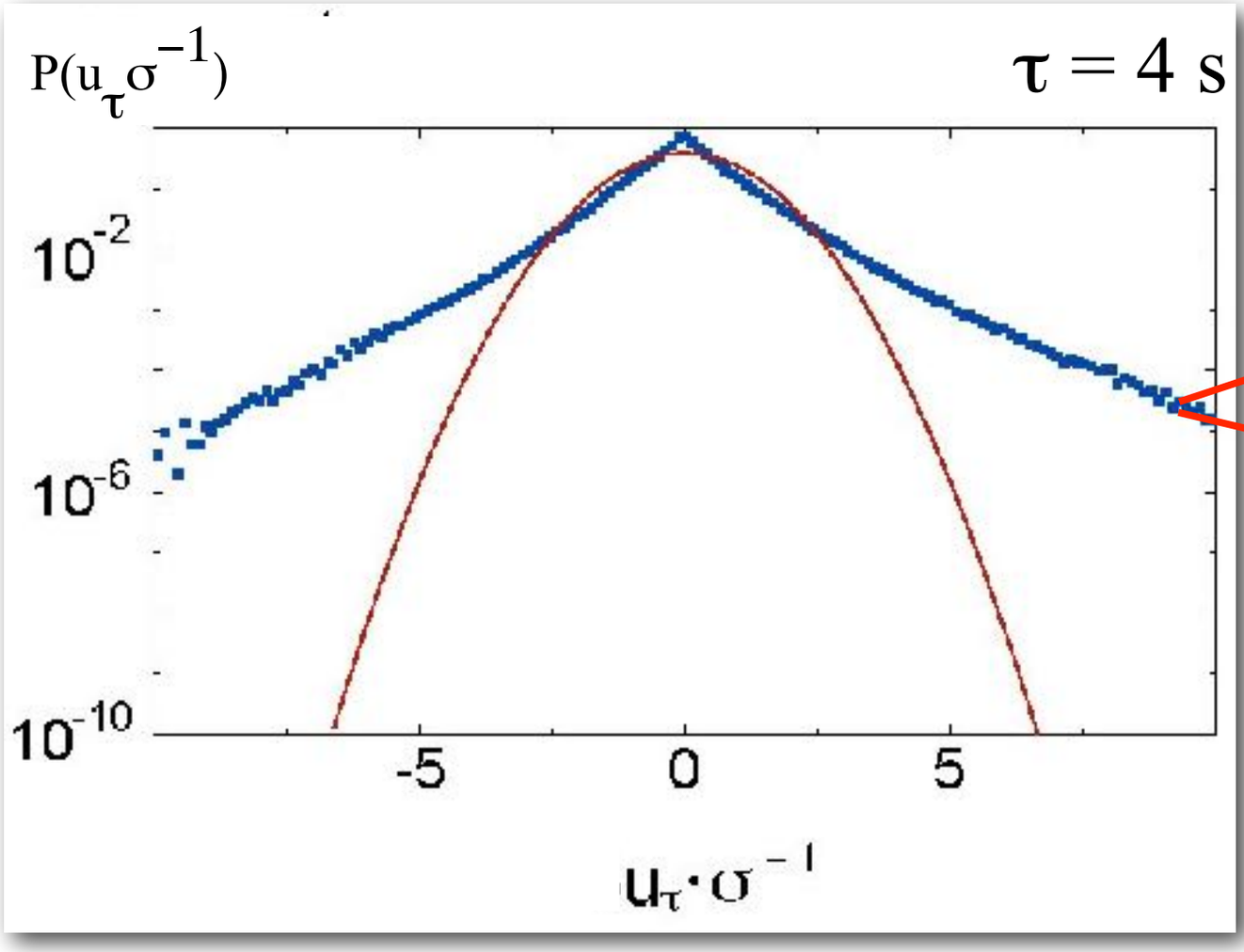
$$\frac{\partial}{\partial x}u(x) = lim_{r\to 0}\frac{\overbrace{u(x+r)-u(x)}}{r}$$

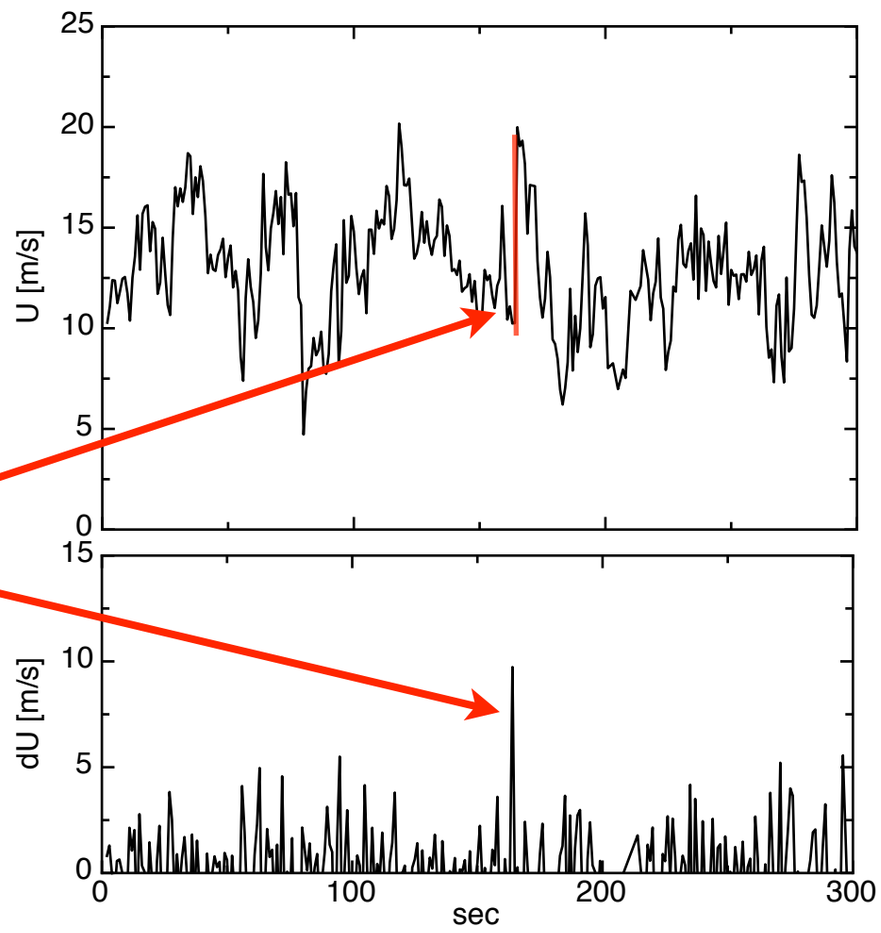
$$= lim_{r\to 0}\frac{u_r}{r}$$

have to understand

$$lim_{r\to 0}\ u_r$$

statistics of gusts

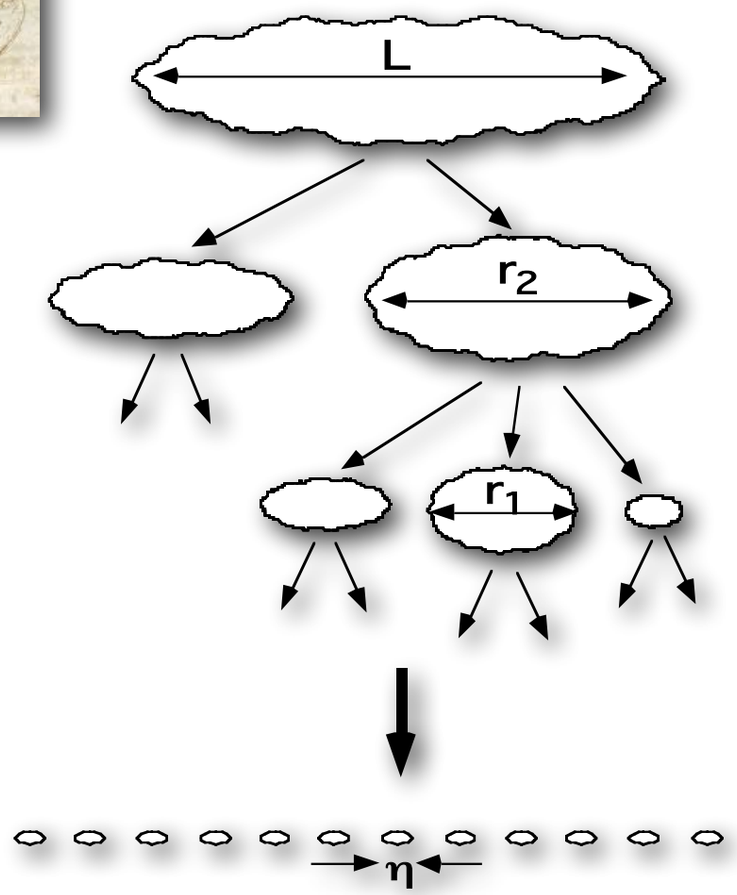




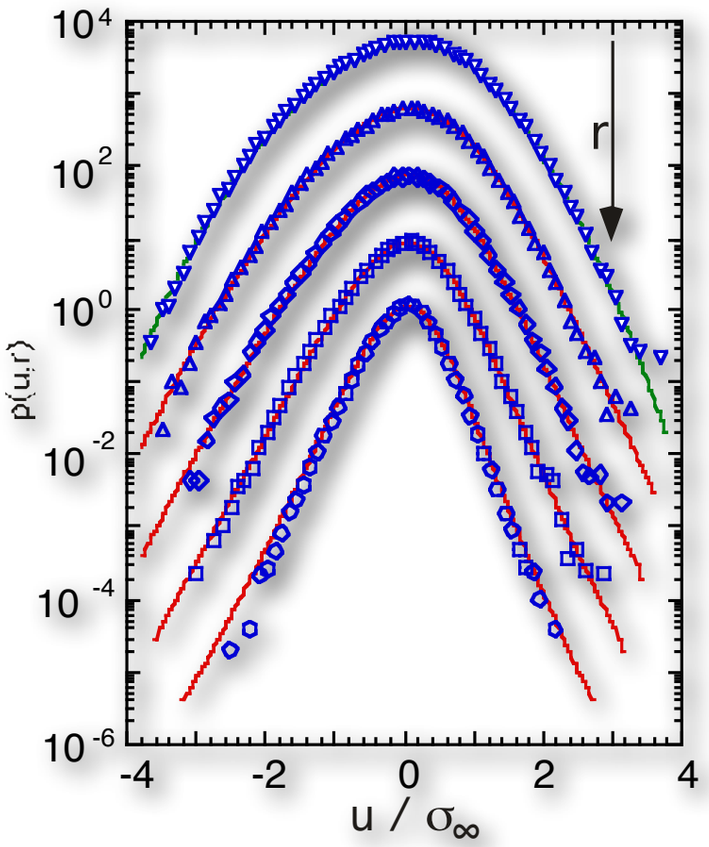
Boundary-Layer Meteorology **108** (2003)

homogeneous isotropic turbulence -- hiT

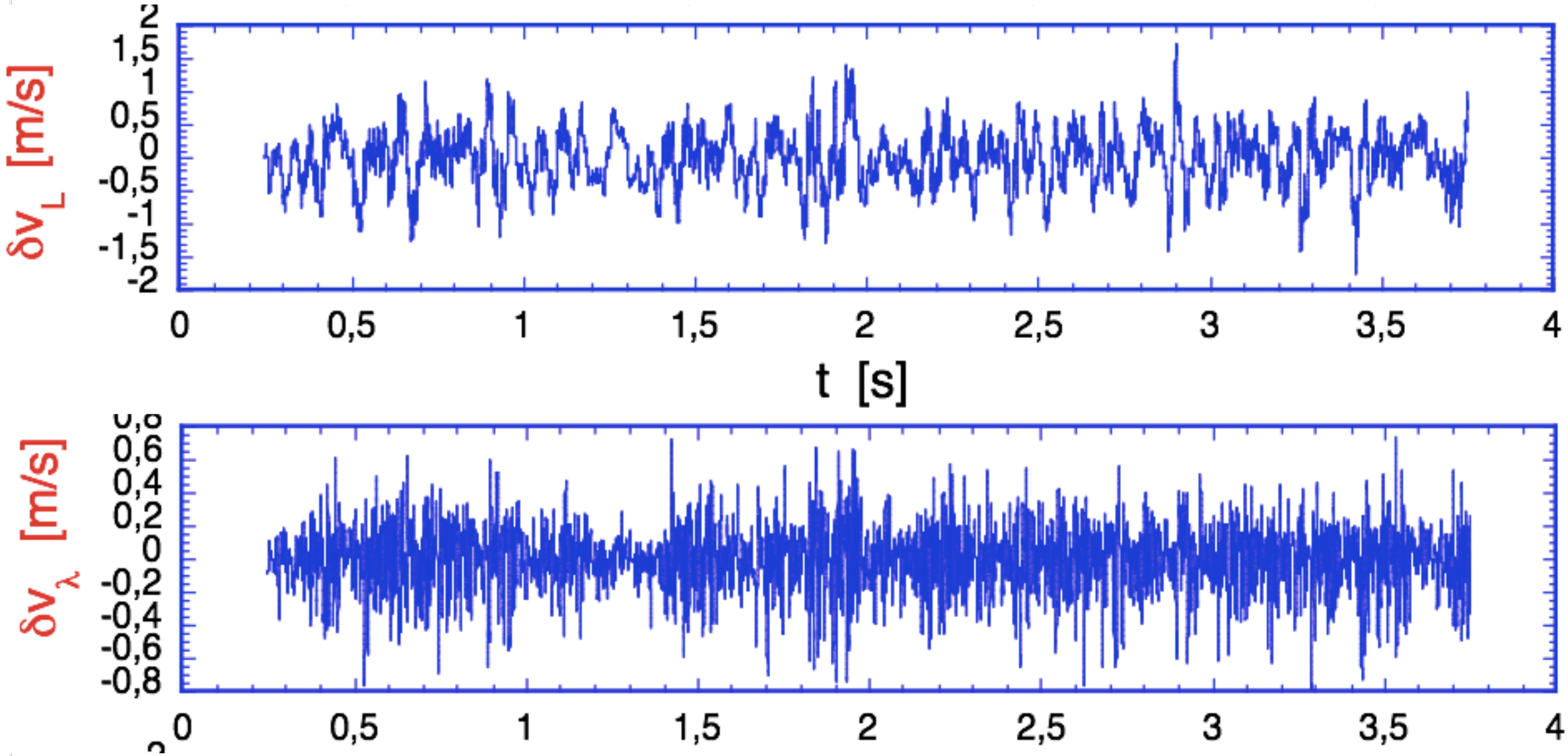
- r - depend of velocity increments: $u_r = u(x+r) - u(x)$
- cascade and statistics of increments



A.N. Kolomogorov

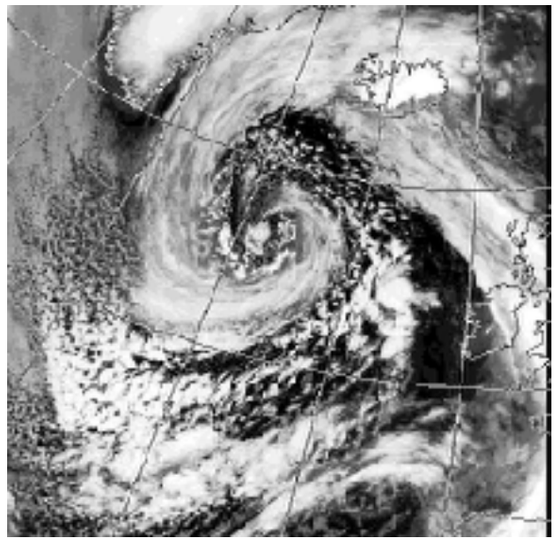


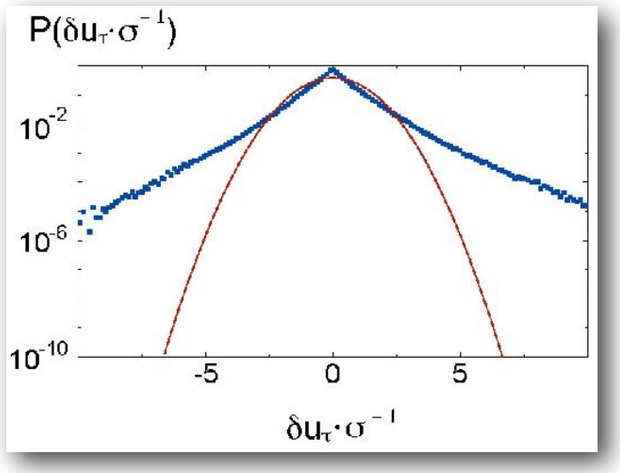
- fluctuations on small scales are more violent than on large scales



claim - need to understand turbulence

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



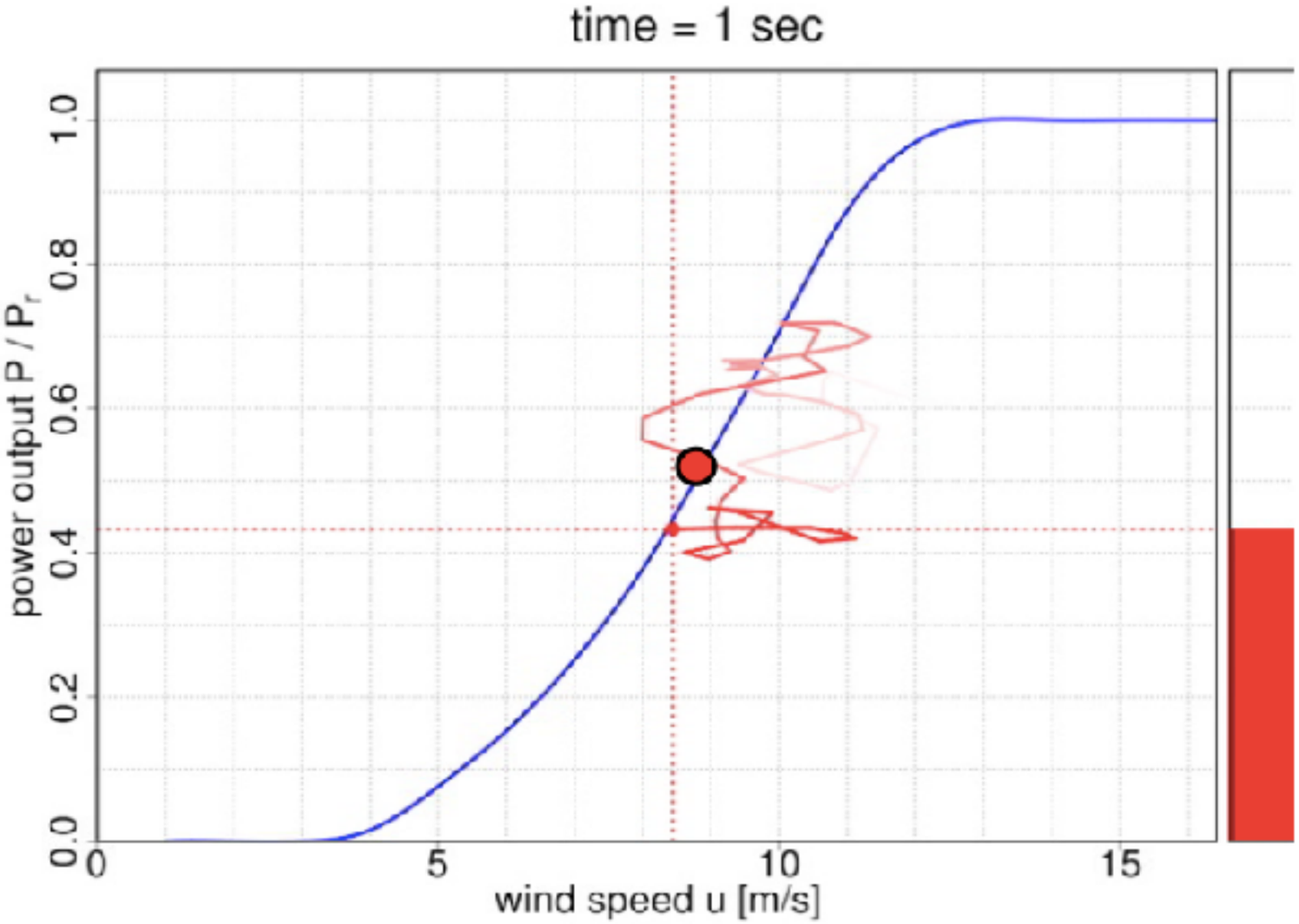


claim - need to understand turbulence

- Wind characterization —-
- impact on turbine
  - blade aerodynamics
  - power output
    - **but turbine is large**

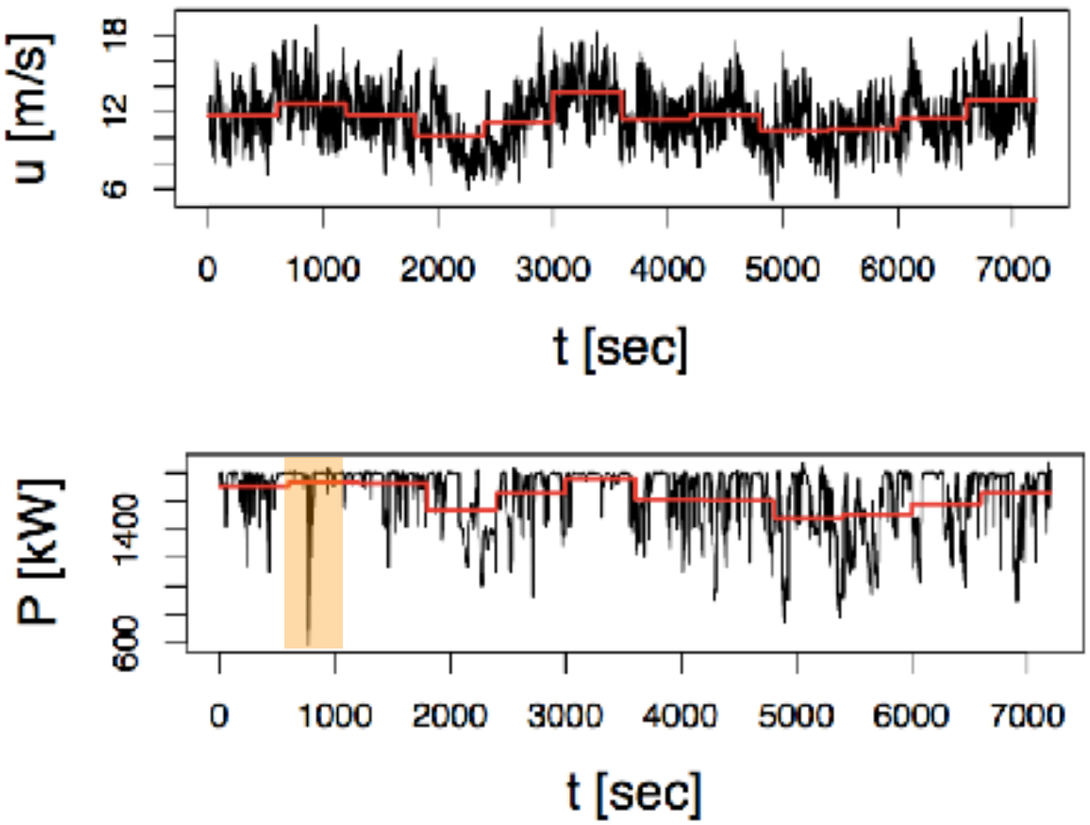
dynamics of power conversion

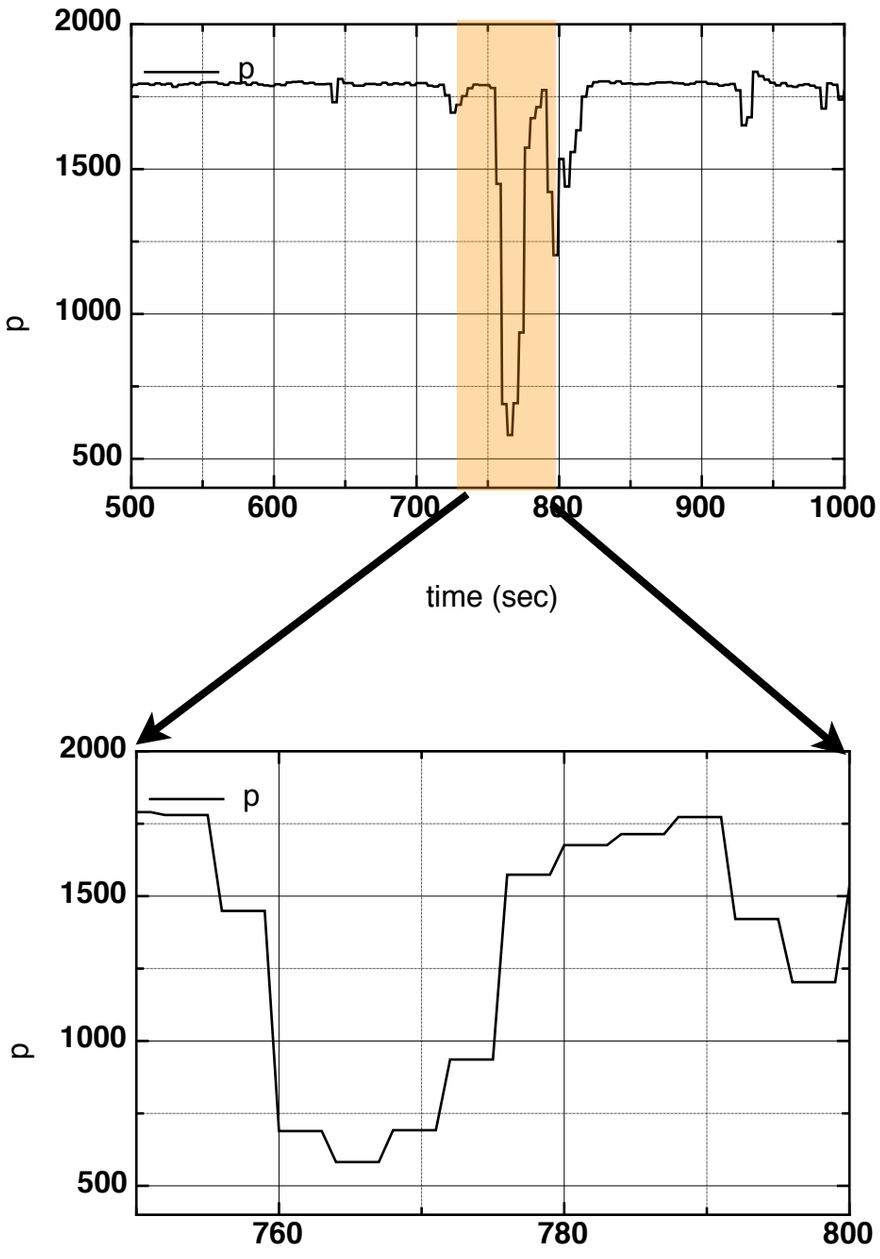
$$P_{WT} = \frac{1}{2} c_p(\lambda)\ \rho\ u_{wind}^3 \cdot A$$



time series of power production

rot 10 min Mittelwerte

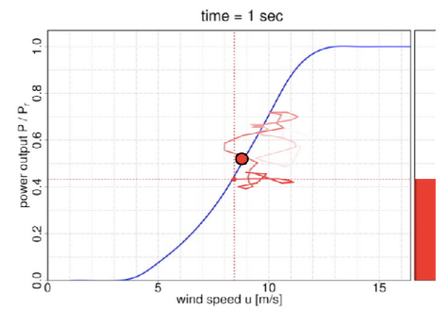


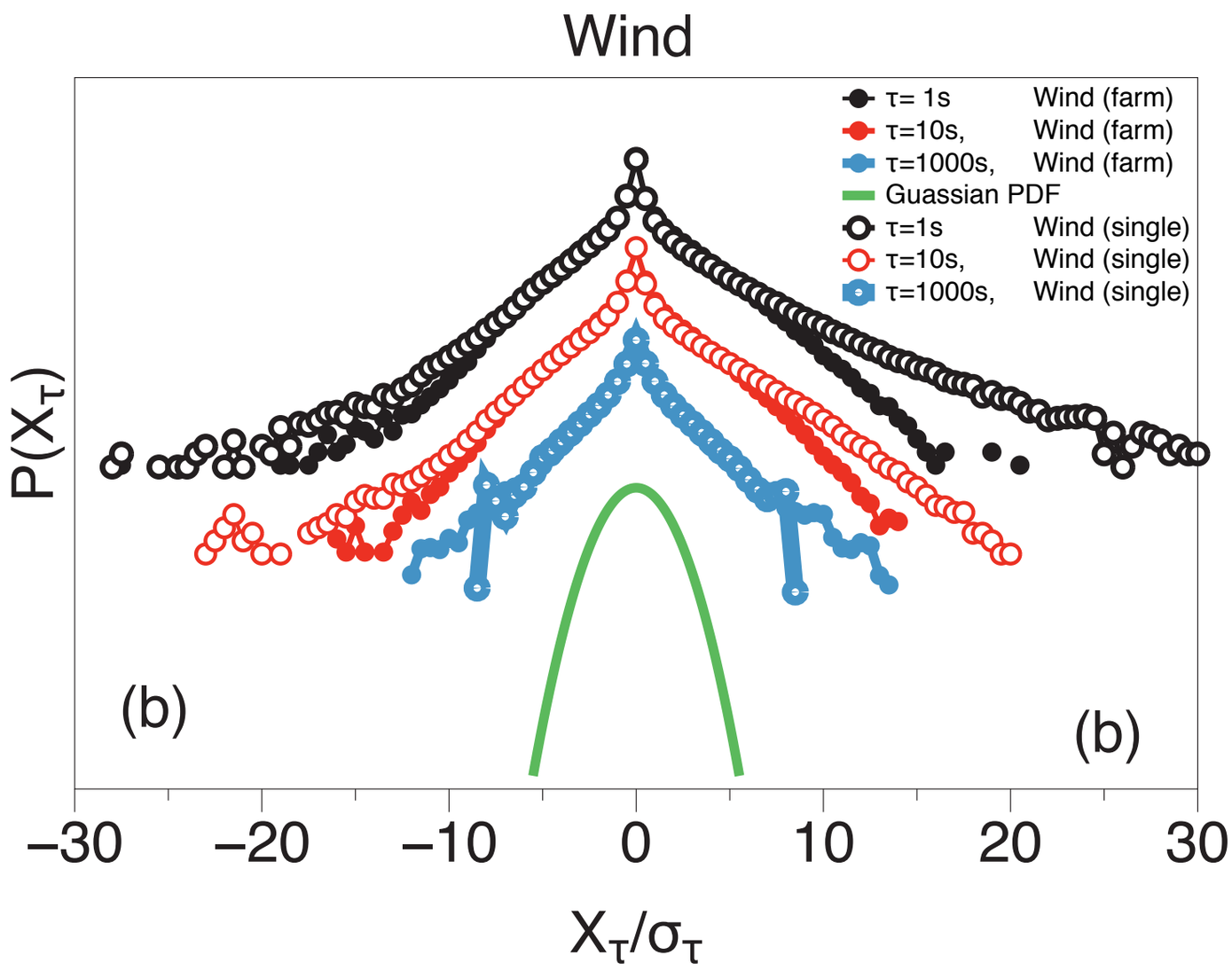


working condition

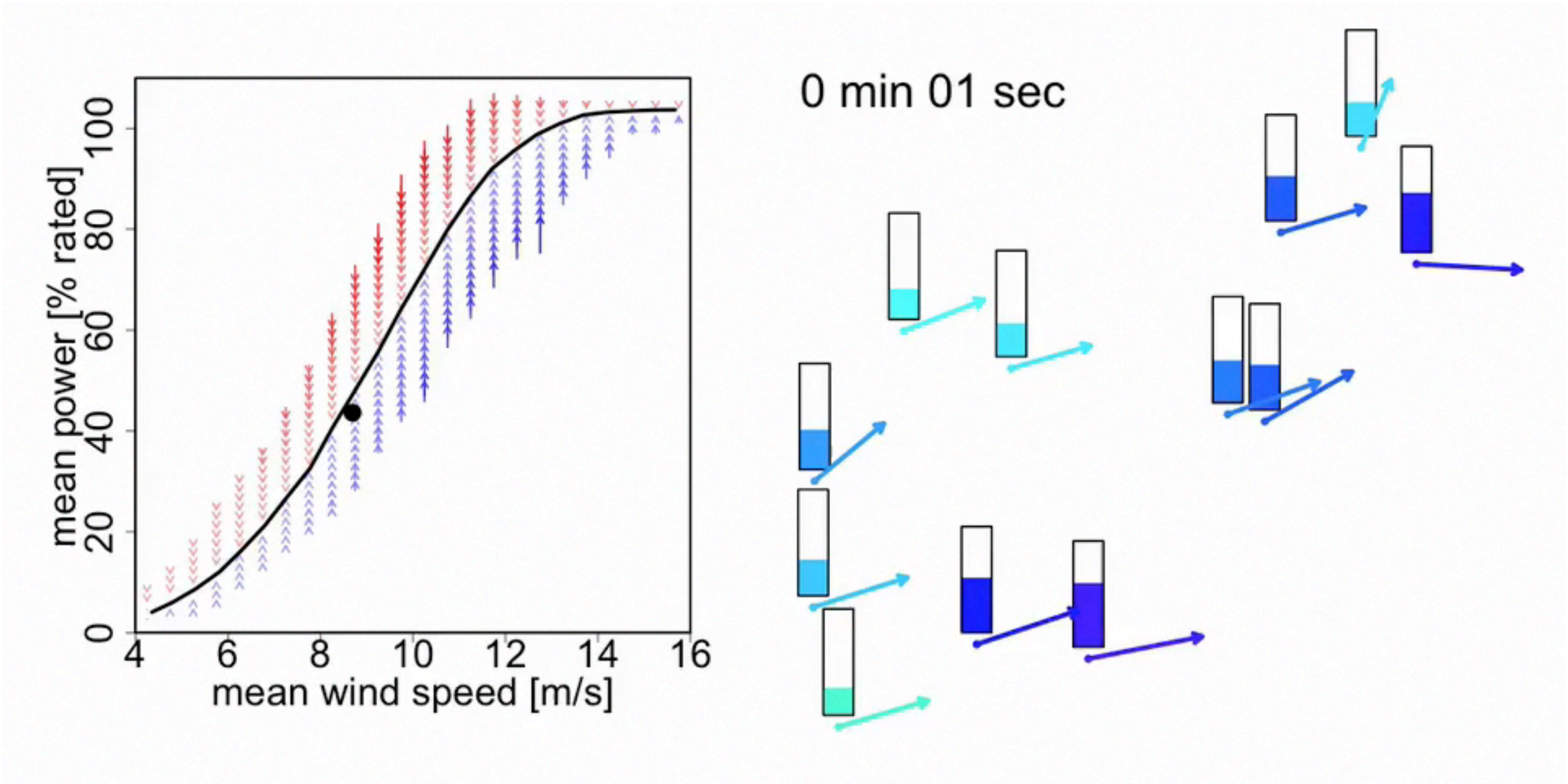
increment statistics of power fluctuations

highly intermittent and turbulent power dynamics from wind turbines and wind farms

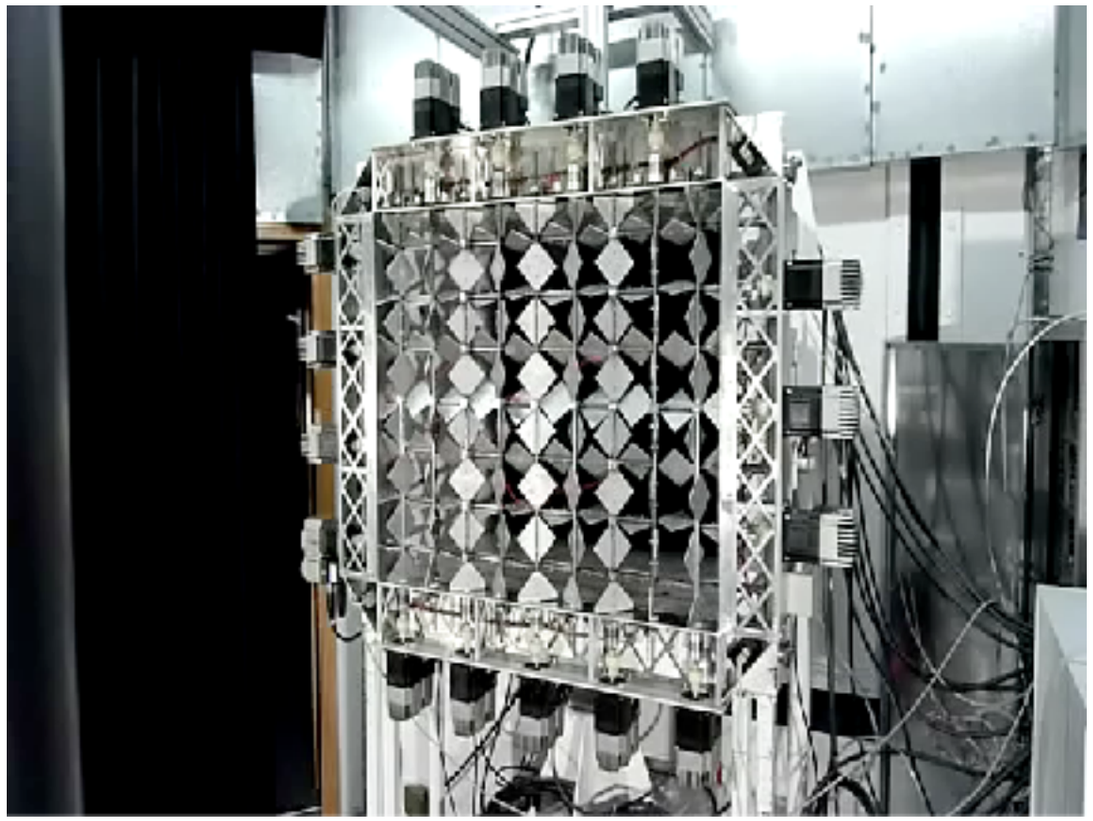


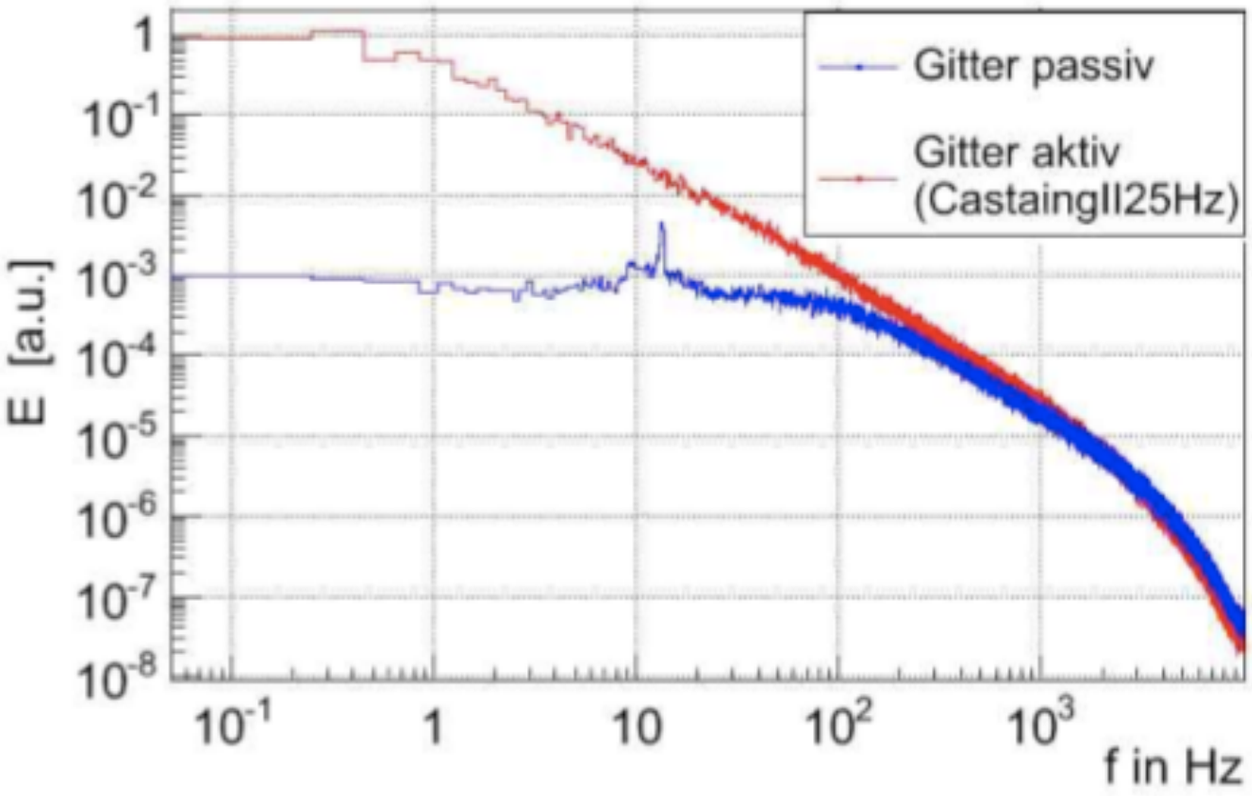


Windpark power dynamics



reproduction of wind fields with active grid





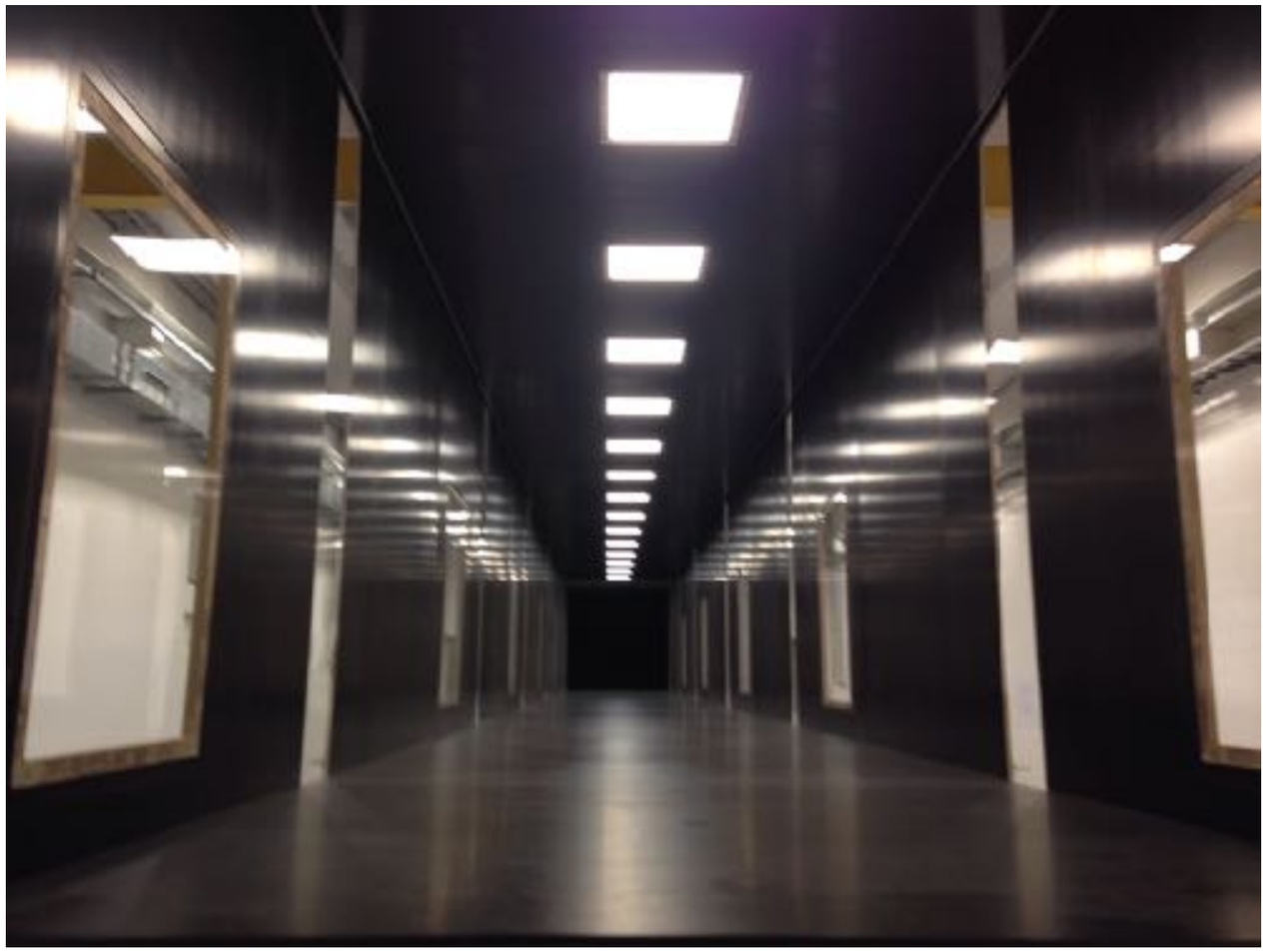
Facility WindLab

—

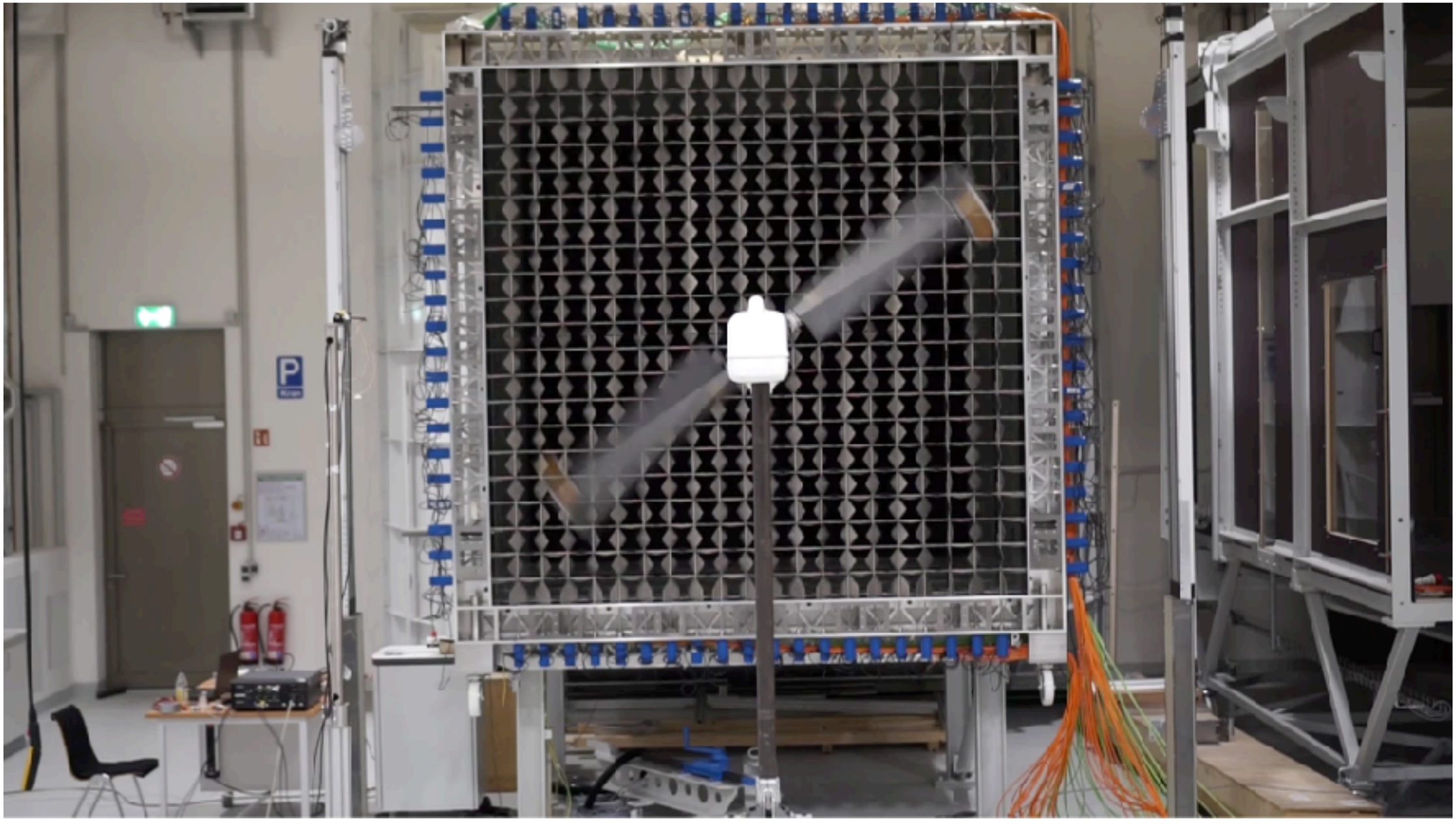
Wind tunnel with active grid

Exp - Big wind tunnel

- 3m x 3m outlet
- open and closed test section
- 30m measurement section
- about 32m/s max. vel. in open
- about 41m/s max. vel. in closed configuration



Exp - Active grid in big wind tunnel



wind physics is challenging and makes fun