Turbulence a Challenging Problem for Wind Energy

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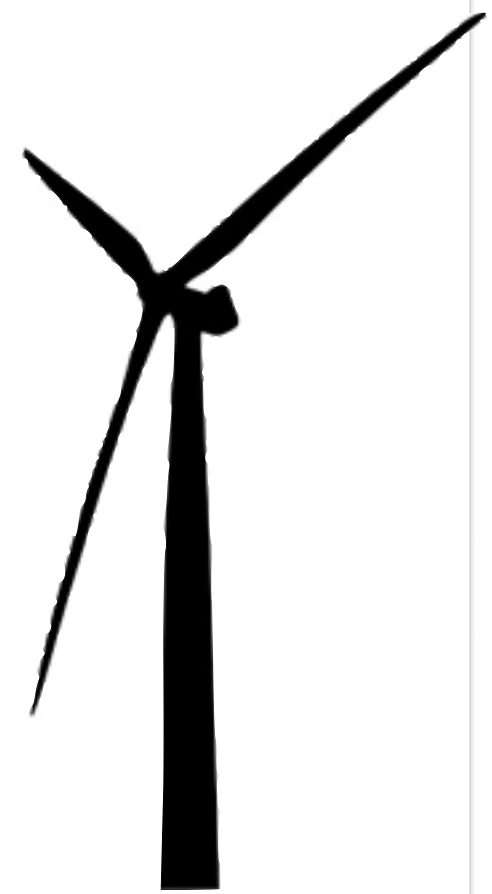
ForWind - Center of Wind Energy Research of Universities Oldenburg, Hannover and Bremen

&

Fraunhofer Institut IWES

content

- basics features of turbulence
- How does a wind turbine work?
- operating conditions for a wind turbine
- research challenges



Turbulence one of 7 millenium problems

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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 millenium problems

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.

velocity increment

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

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

have to understand

$$lim_{r\rightarrow 0}\; u_r$$

Turbulence one of 7 millenium problems

have to understand

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

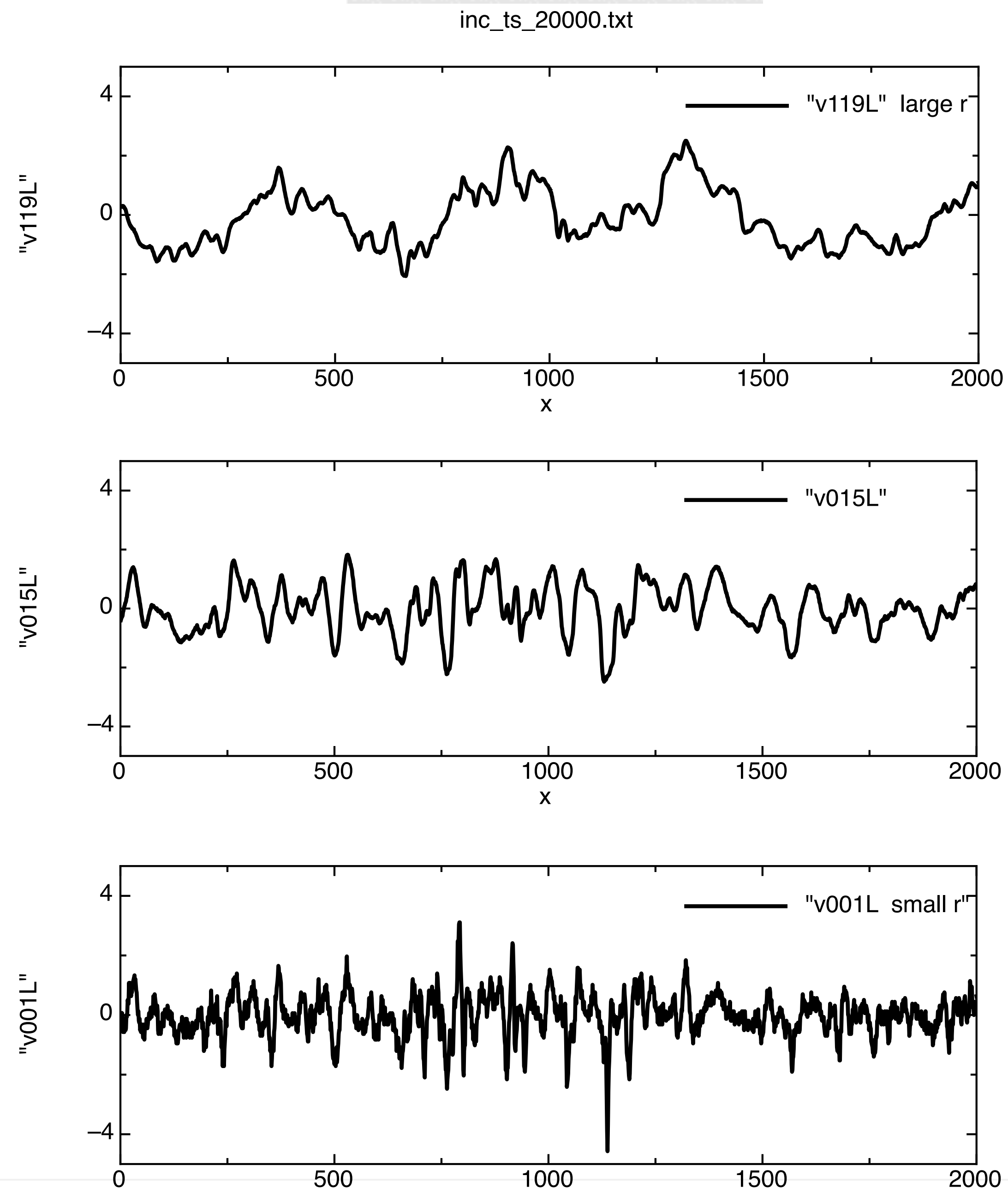
$$u_r = u(x+r) - u(x)$$

Turbulence one of 7 millenium problems

have to understand

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

$$u_r = u(x+r) - u(x)$$



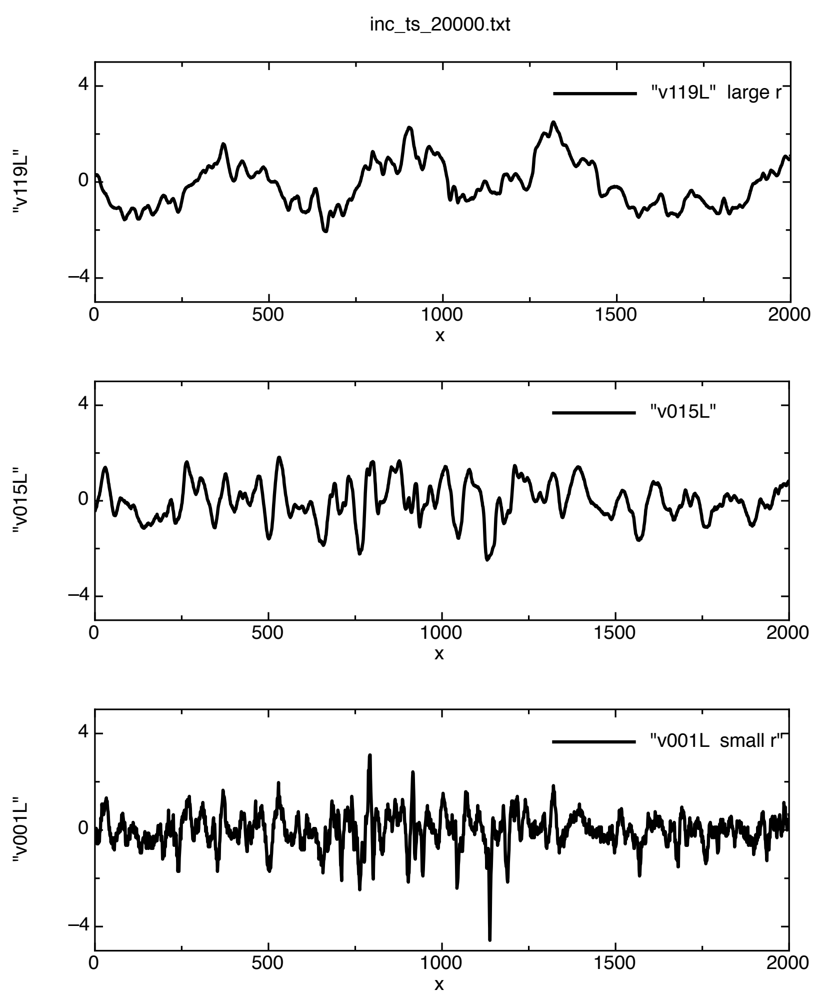
r - large

r - small

homogeneous isotropic turbulence -- hiT

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

- cascade and statistics of increments



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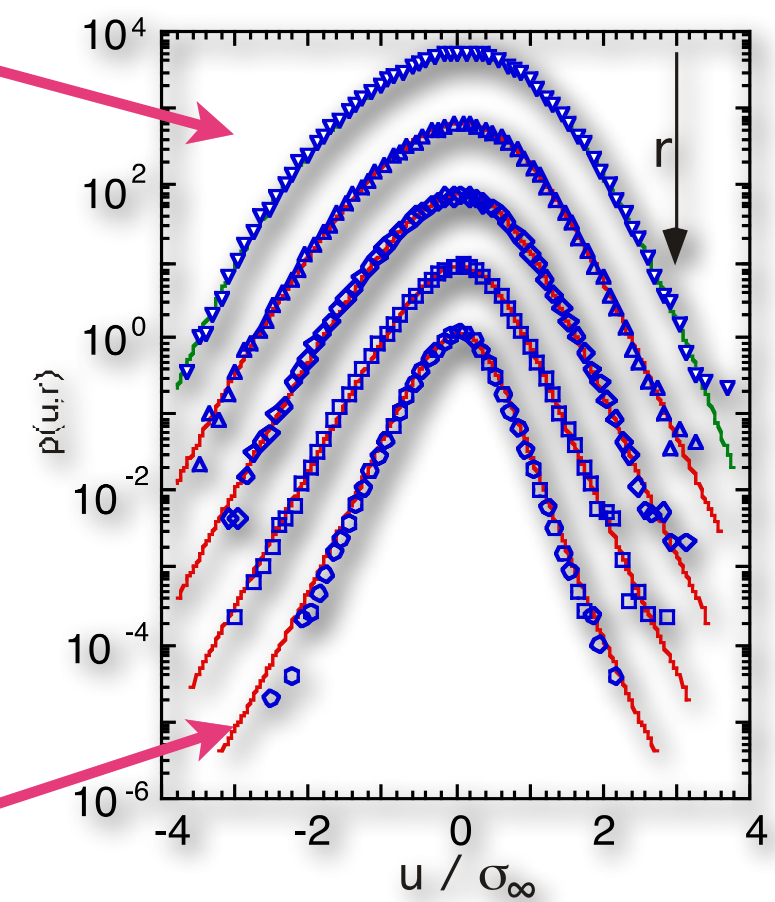
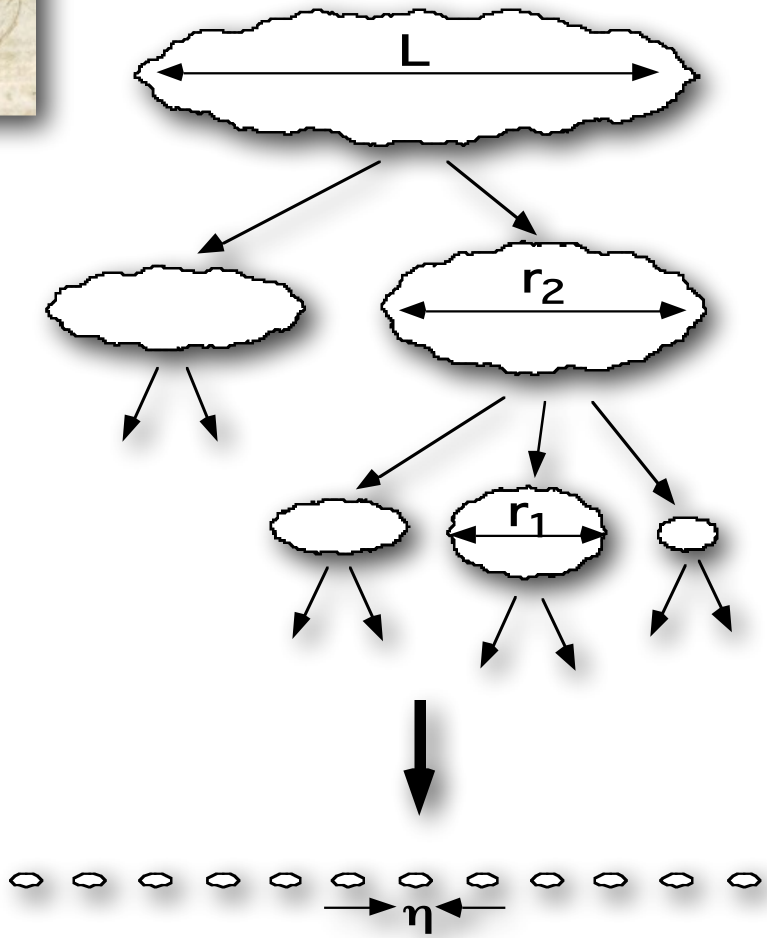
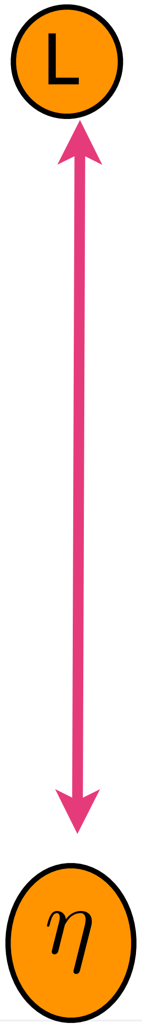


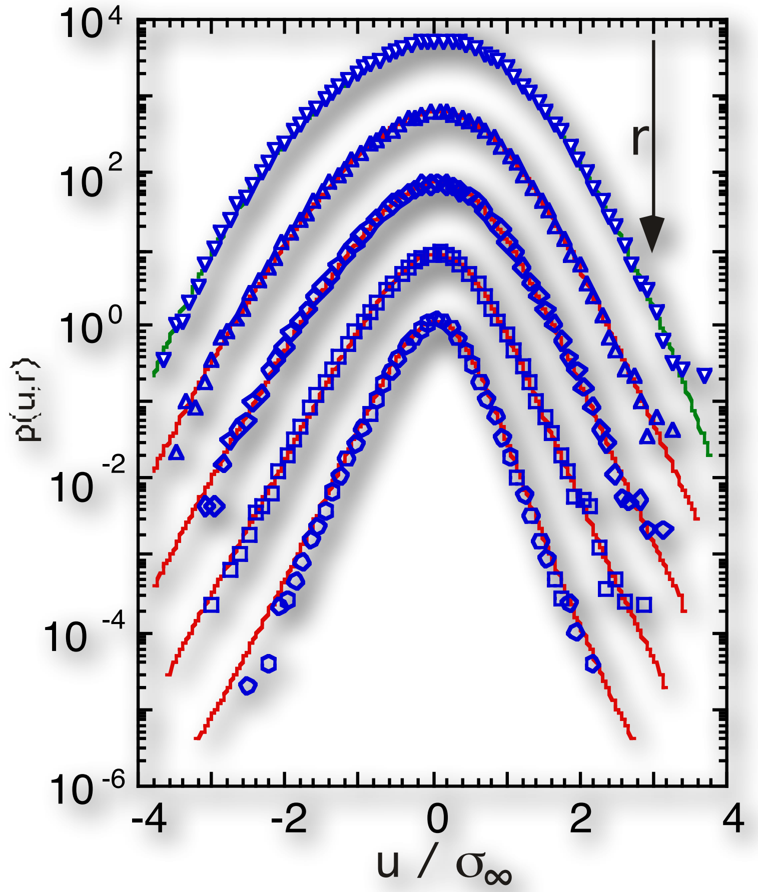
homogeneous isotropic turbulence -- hiT

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

A.N. Kolomogorov





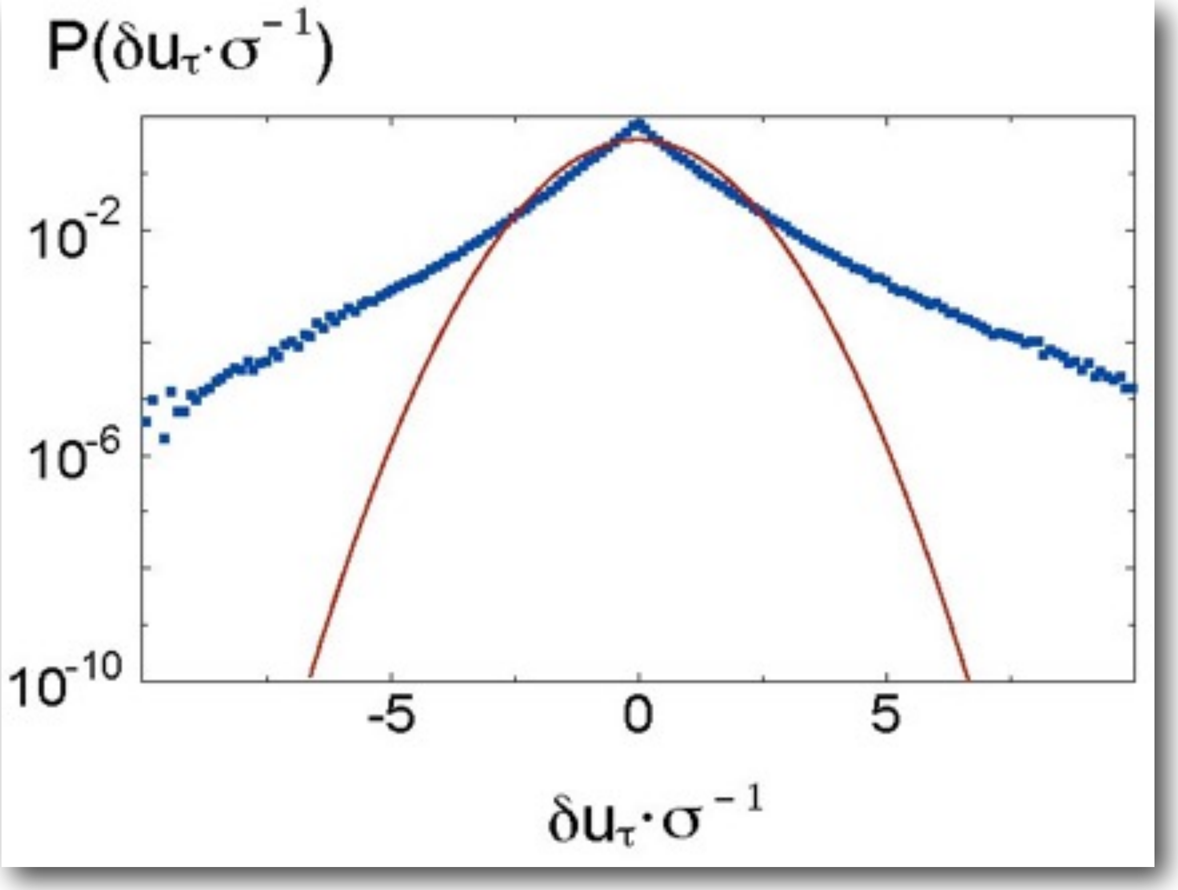


summary turbulence

- cascade and statistics of increments

$$u_r = u(x+r) - u(x)$$

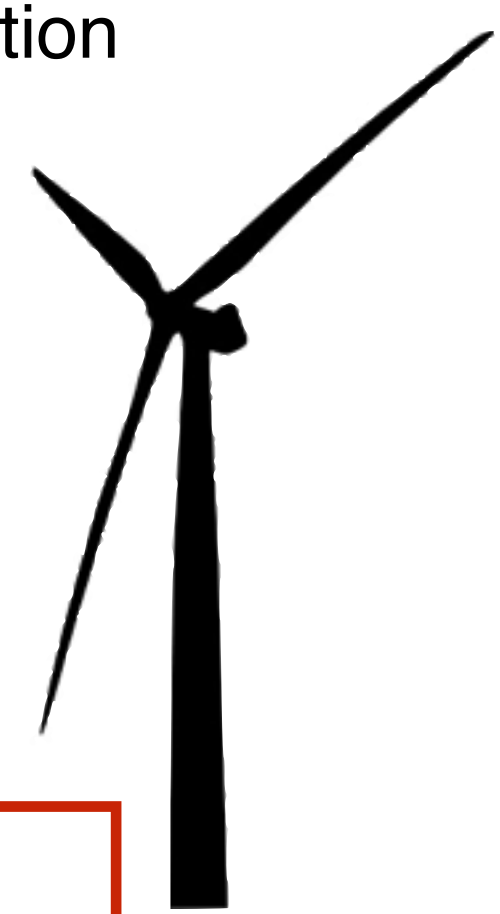
  - non Gaussian statistics for small scales r
  - Intermittency - violent fluctuations on small scales



basic problems

problems
of mathematics

application



problems of society:
energy
- **environment CO2**
- **resources**
- **finances**

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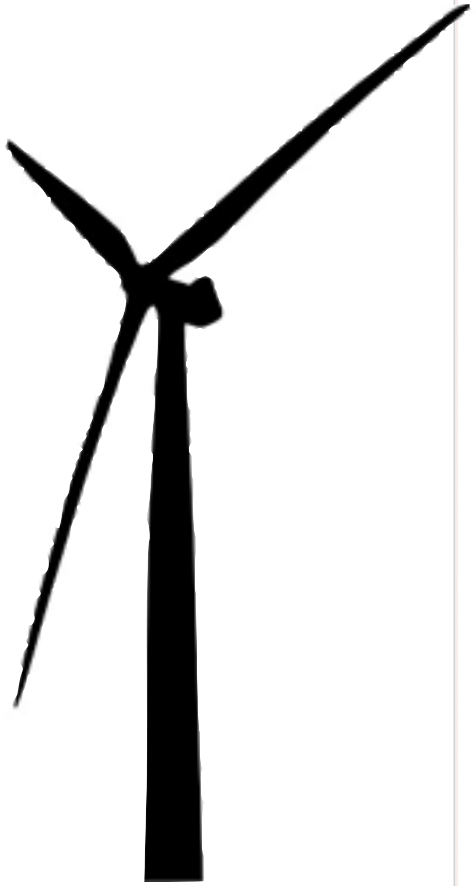


modern wind turbines

power from wind

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

$$P_{wind} = \dot{E}_{wind} \qquad \dot{m} = \rho \dot{V}$$

$$= \frac{1}{2} \dot{m} u^2 \qquad = \rho A \cdot u$$

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

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

power from wind

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

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

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

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

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

WEC

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

$c_P \leq 0.59$ Betz- Joukowsky limit

size

modern wind turbines

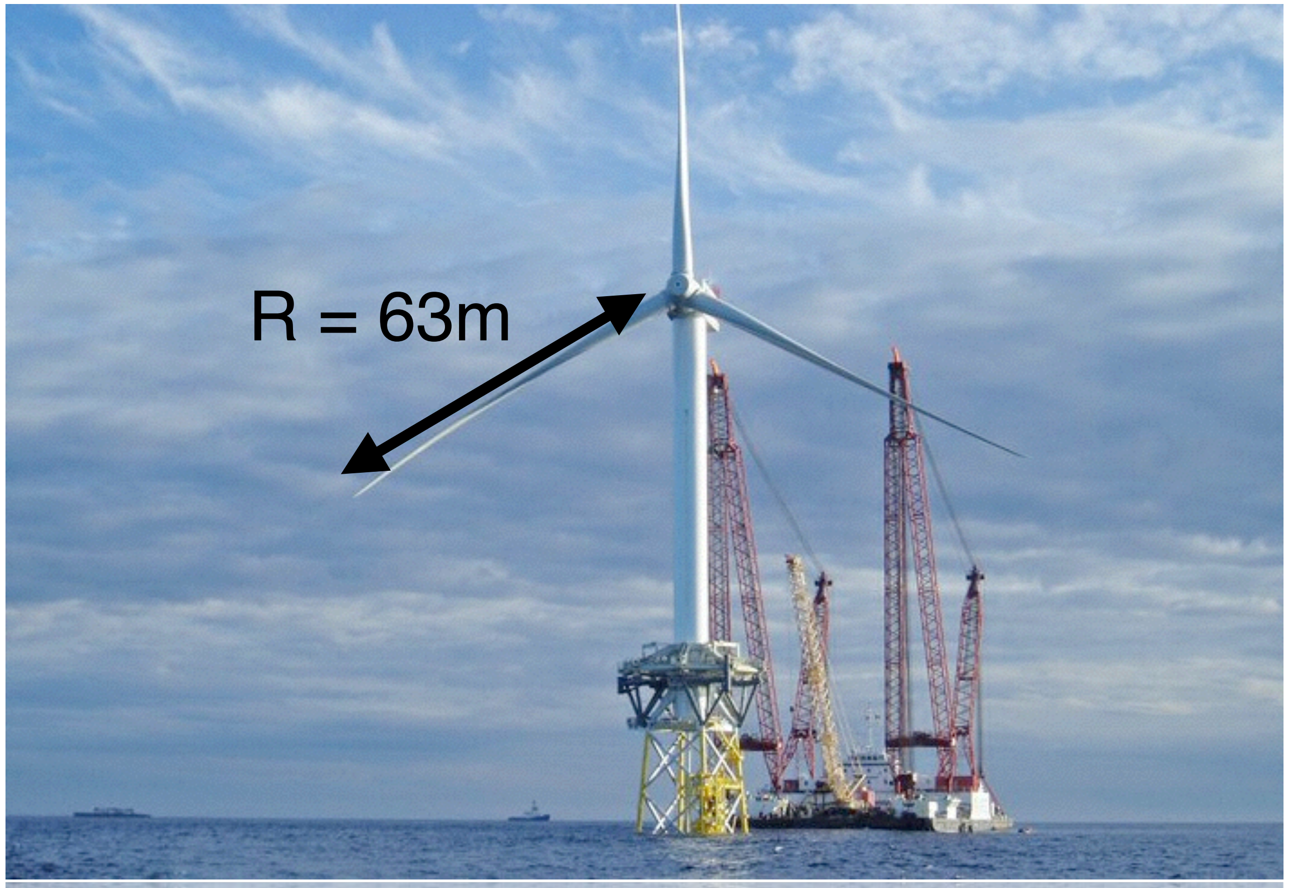
area = 12469 m²

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

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

$$c_P \leq 0.59$$

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



modern wind turbines

WEC >5MW

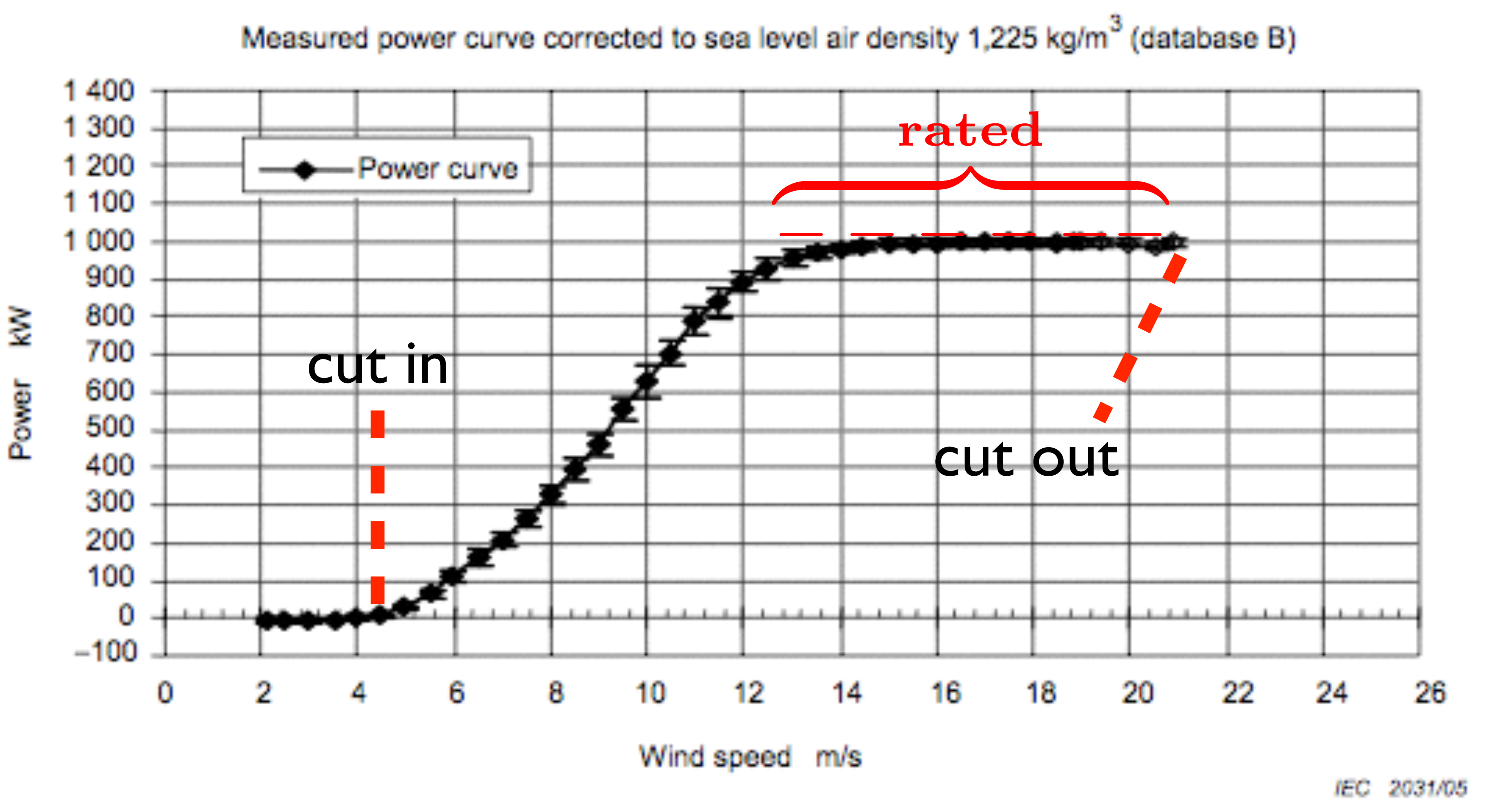
typical engine of a train

3,7 MW

measured power curve

power output of wind turbines

measured power curve



story of success

GLOBAL ANNUAL INSTALLED WIND CAPACITY

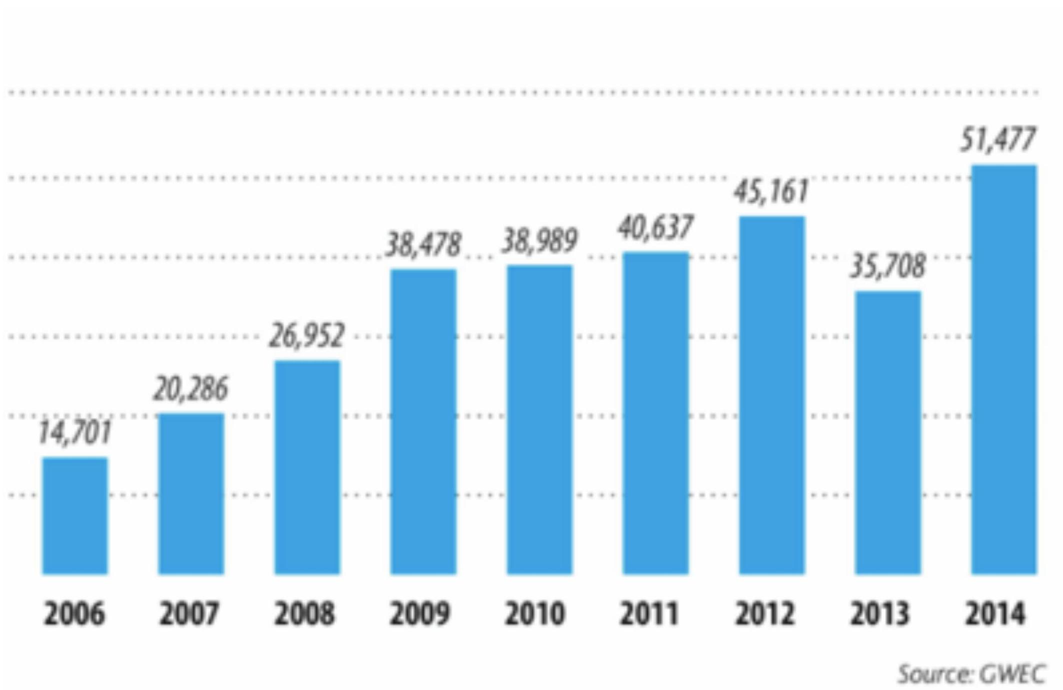
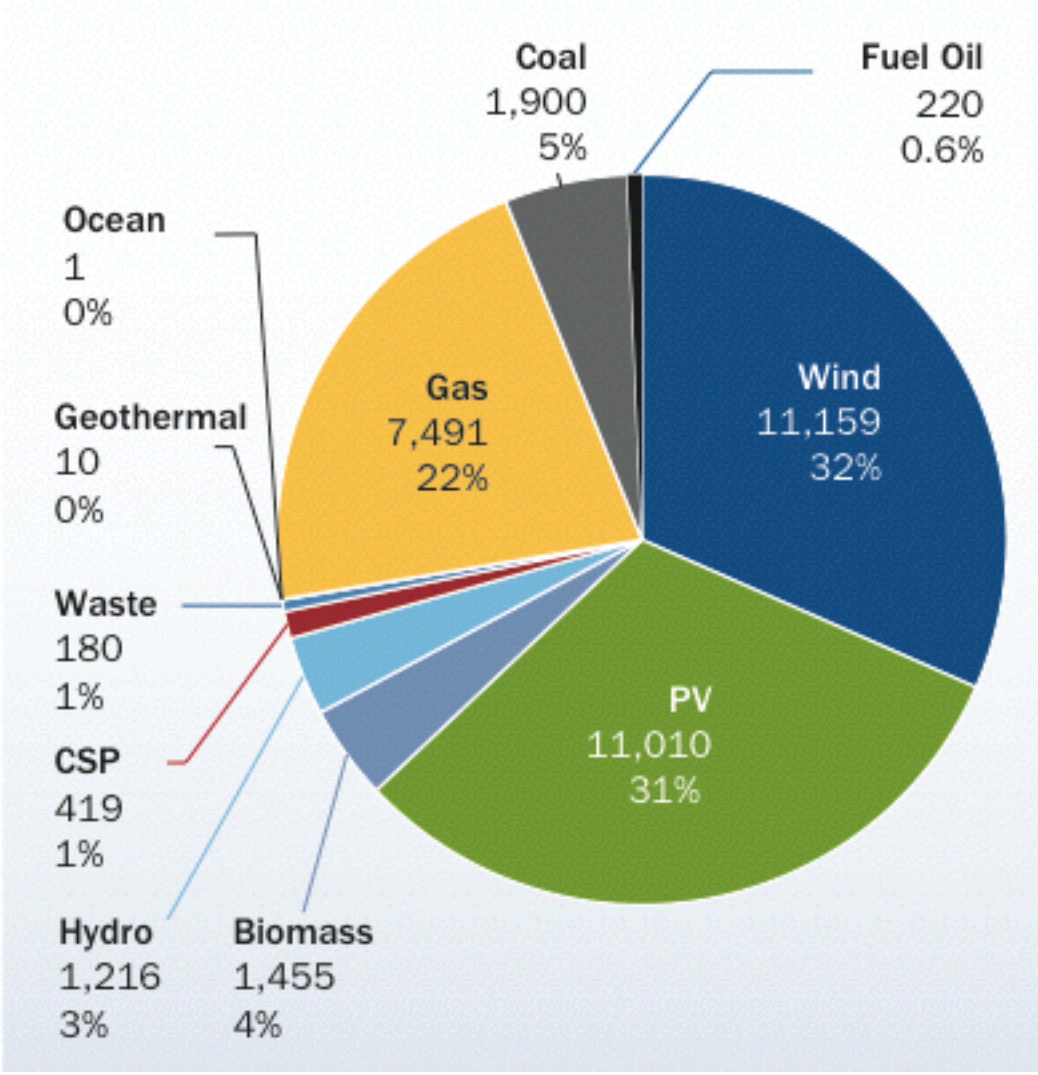
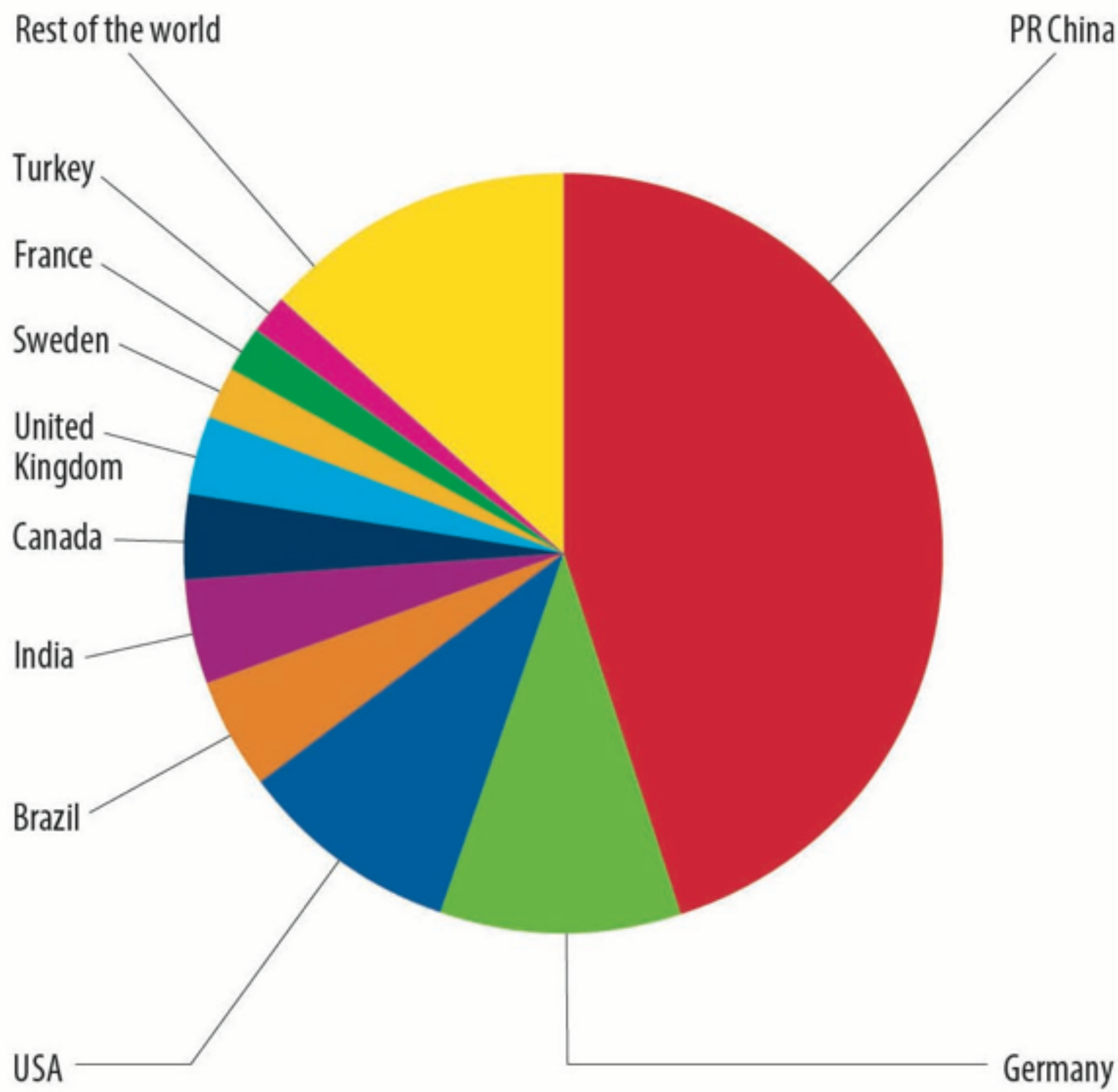


FIGURE 1.2: SHARE OF NEW POWER CAPACITY INSTALLATIONS IN EU, TOTAL 35,181 MW



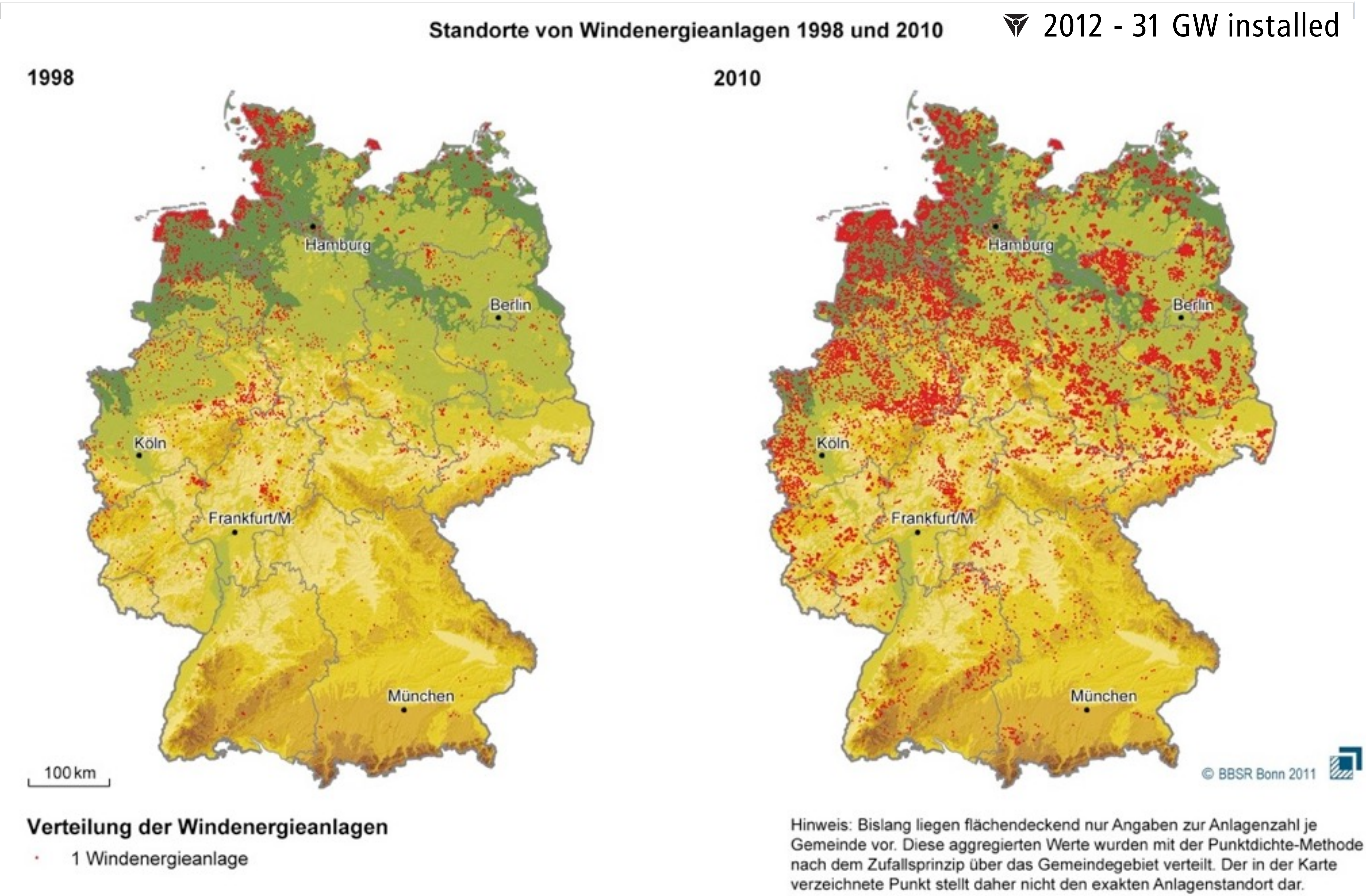
TOP 10 NEW INSTALLED CAPACITY JAN-DEC 2014



Country	MW	% SHARE
PR China	23,196	45.1
Germany	5,279	10.2
USA	4,854	9.4
Brazil*	2,472	4.8
India	2,315	4.5

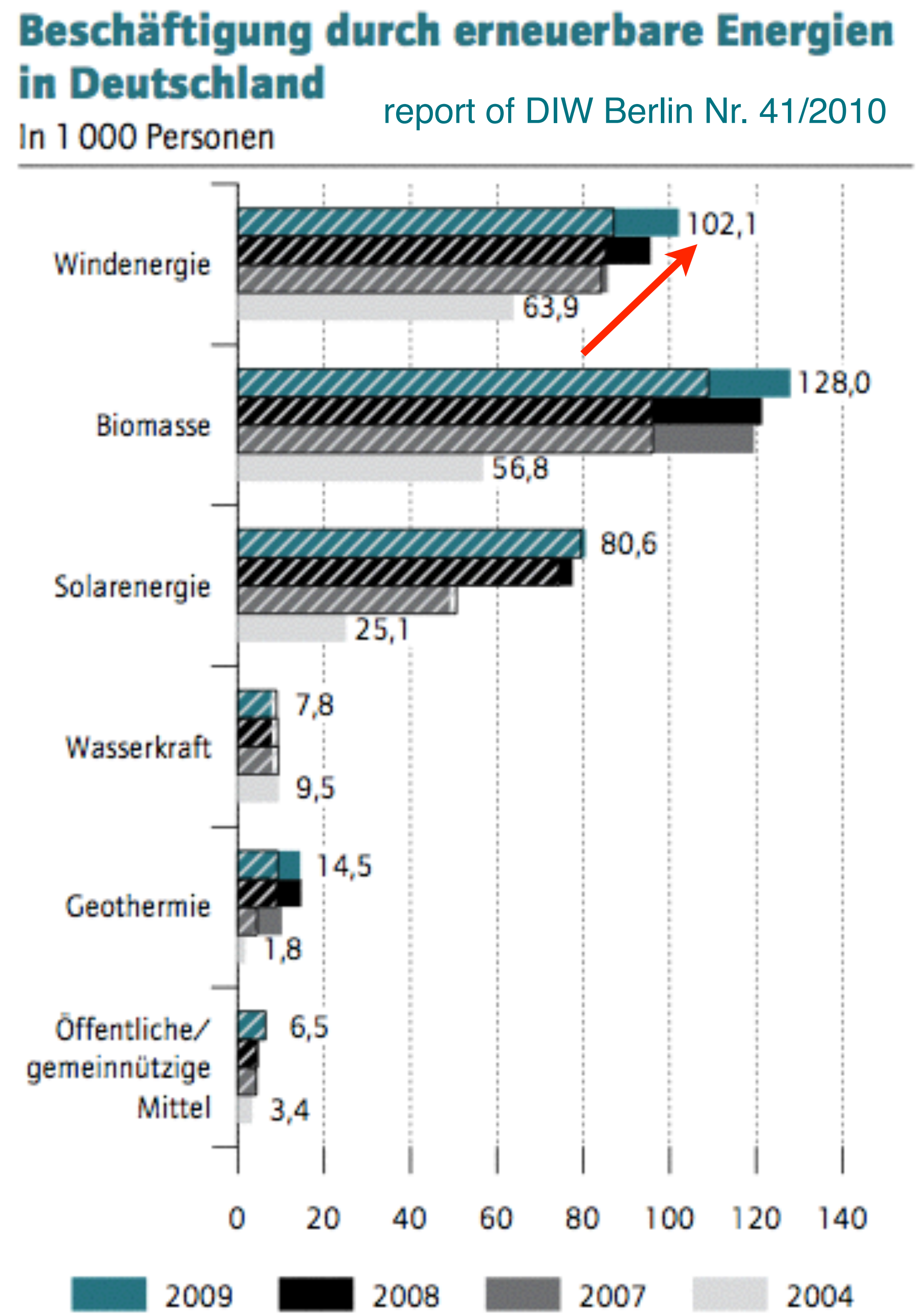
wind turbines in Germany

- 2012 - 31 GW installed

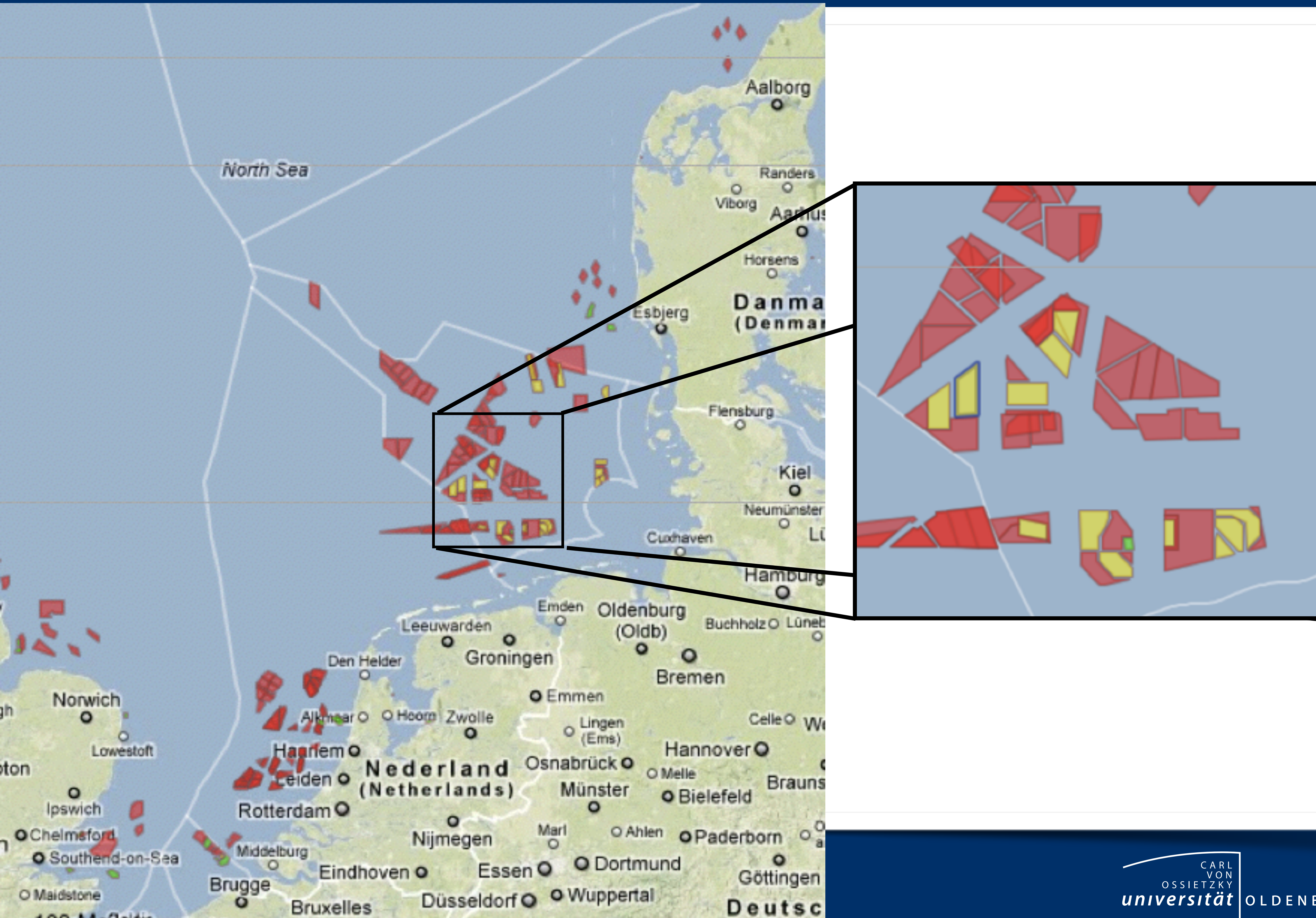


employees

- number of employees even increased during the last year's economic crisis
- 2014 around 130.000 new jobs



offshore activities



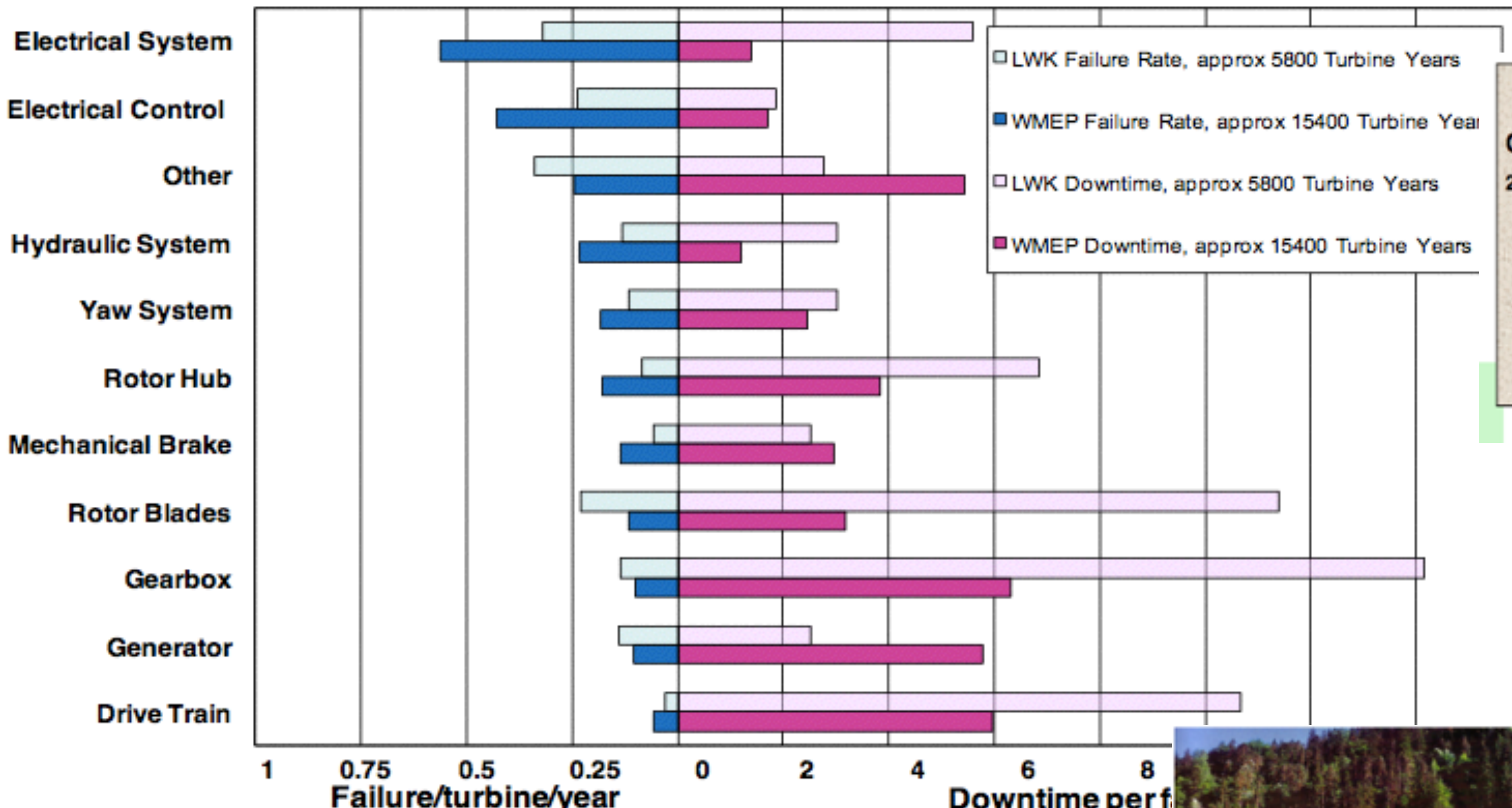
CARL VON OSSIETZKY universität OLDENBURG

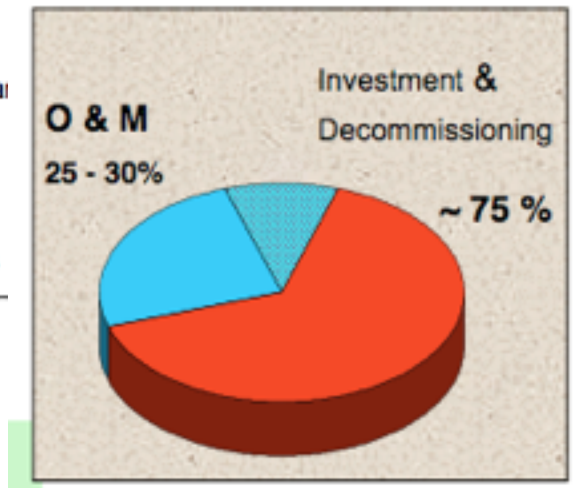
Wind farms under construction [edit]

Wind farm	Cap. (MW)	Turbines	Where	When	Build Cost	Cap. fac.	Depth range (m)	km to shore	Country	Owner	Refs.
DanTysk	288	80 × Siemens SWP-3.6-120	55°8′24″N 7°12′0″E	2015	$900 million		21-31	70	Germany	Vattenfall Stadtwerke München	[w 24][43][44]
Amrumbank West	288	80 × Siemens SWT-3.6-120	54°26′00″N 7°41′0″E	2015				40	Germany		
Borkum Riffgrund I	312	78 × Siemens SWT-4.0-120	53°58′01″N 6°33′14″E	2015	€1.25 billion		23-29	55	Germany	DONG, Kirkbi, Oticon	[w 25]
Butendiek	288	80 × Siemens SWT-3.6	55°01′08″N 7°46′26″E	2015				35	Germany		[w 26]
Eneco Luchterduinen	129	43 × Vestas V112/3000	52°24′18″N 4°09′43″E	2015	€450 million		18-24	24	Netherlands	Eneco, Mitsubishi	[w 27]
Global Tech I	400	80 × Multibrid M5000	54°15′43″N 6°24′38″E	2015				110	Germany		[w 28]
Humber Gateway	219	73 × Vestas V112-3.0	53°38′38″N 0°17′35″E	2015	€900 million		10-18	10	United Kingdom	E.ON	[w 29]
Nordsee Ost	295	48 × Senvion 6.2M126	54°26′00″N 7°41′0″E	2015				55	Germany	RWE Innogy	[w 30]
Trianel Windpark Borkum (phase 1)	200	40 × Areva M5000-116	54°2′30″N 6°28′0″E	2015	€900 million		28-33	45	Germany	Trianel	[w 31]
Westermost Rough	210	35 × Siemens SWT-6.0	53°48′18″N 0°08′56″E	2015	€1 billion		10-25	8	United Kingdom	DONG	[w 32]
Gemini	600	160 × Siemens SWT-4.0	54°2′10″N 5°57′47″E	2017	€2.8 billion			55	Netherlands	Northland Power, Siemens, Van	[w 33]

there are some activities in the North Sea

are there any problems? - Failure statistics





2001 (CA-OWEE)

P. Tavner et.al EWAE 2011

water power plant: Saalach (DB)

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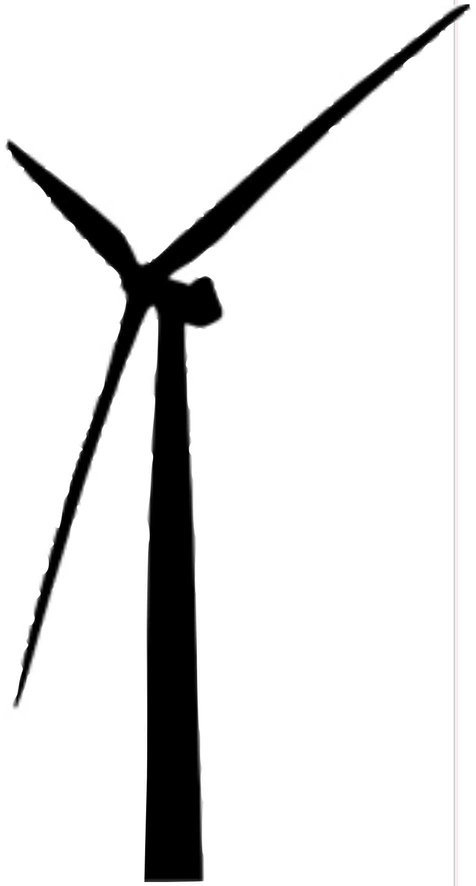


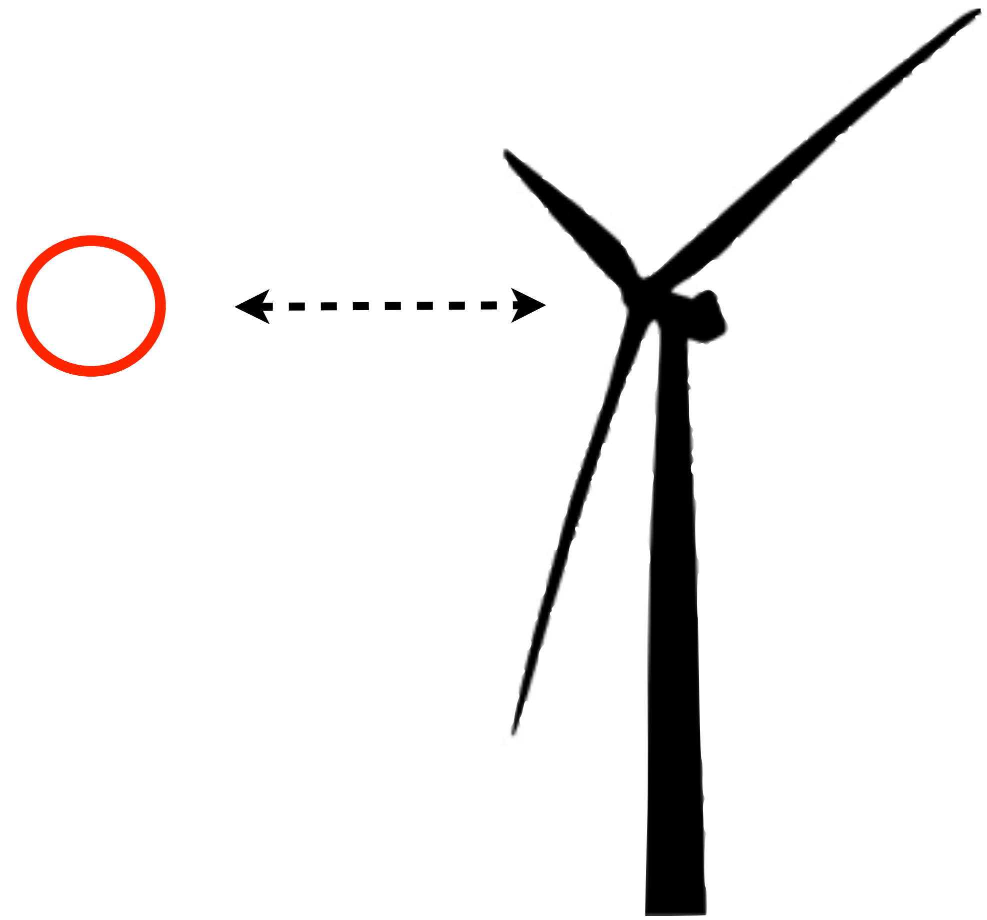
wind measurements and data analysis

INTERNATIONAL STANDARD

IEC 61400-1

Third edition 2005-08

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



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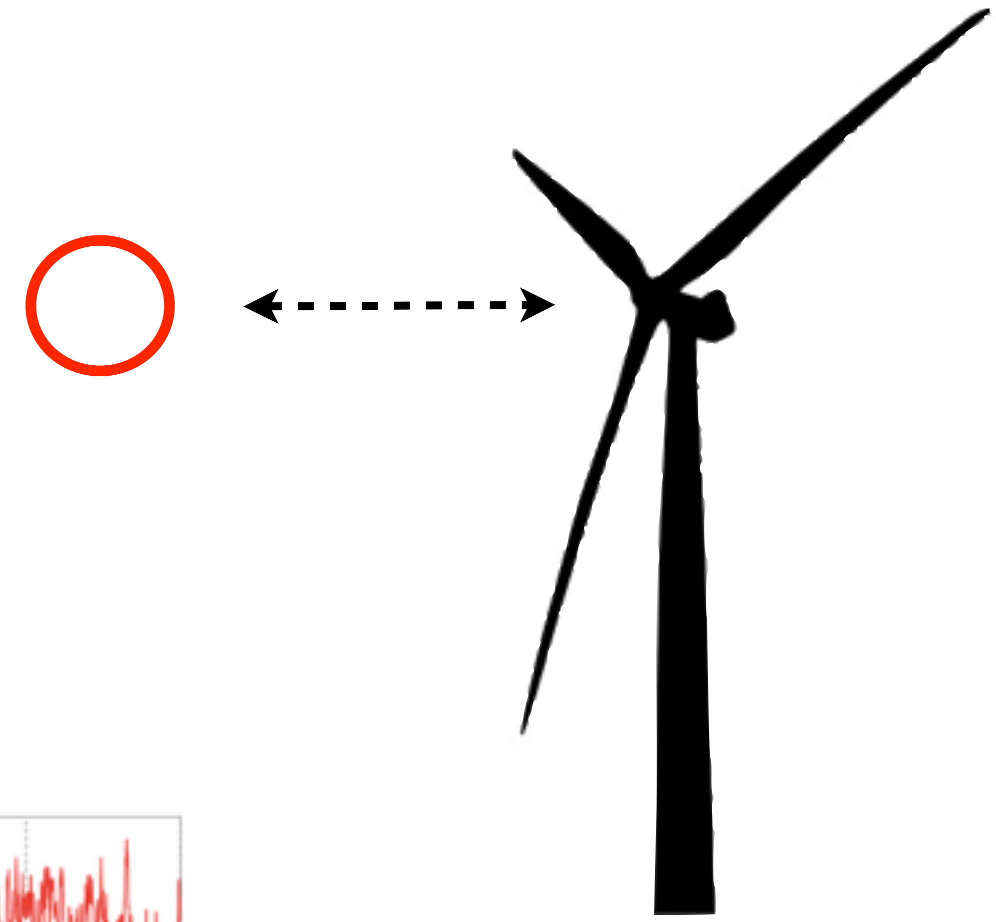
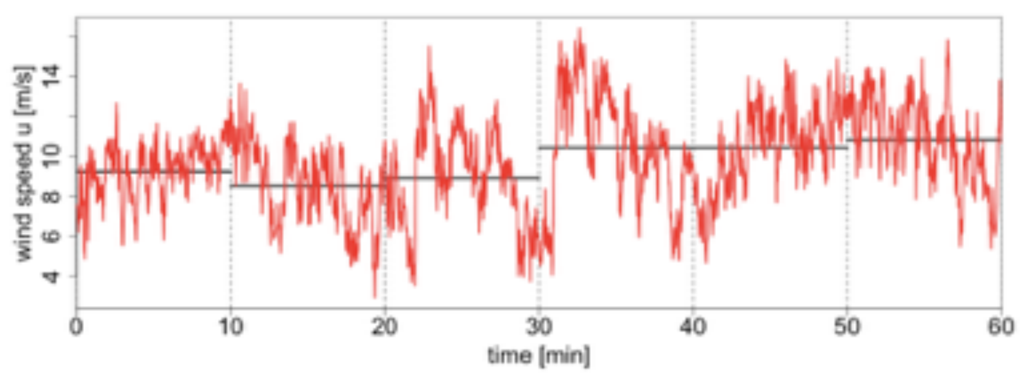


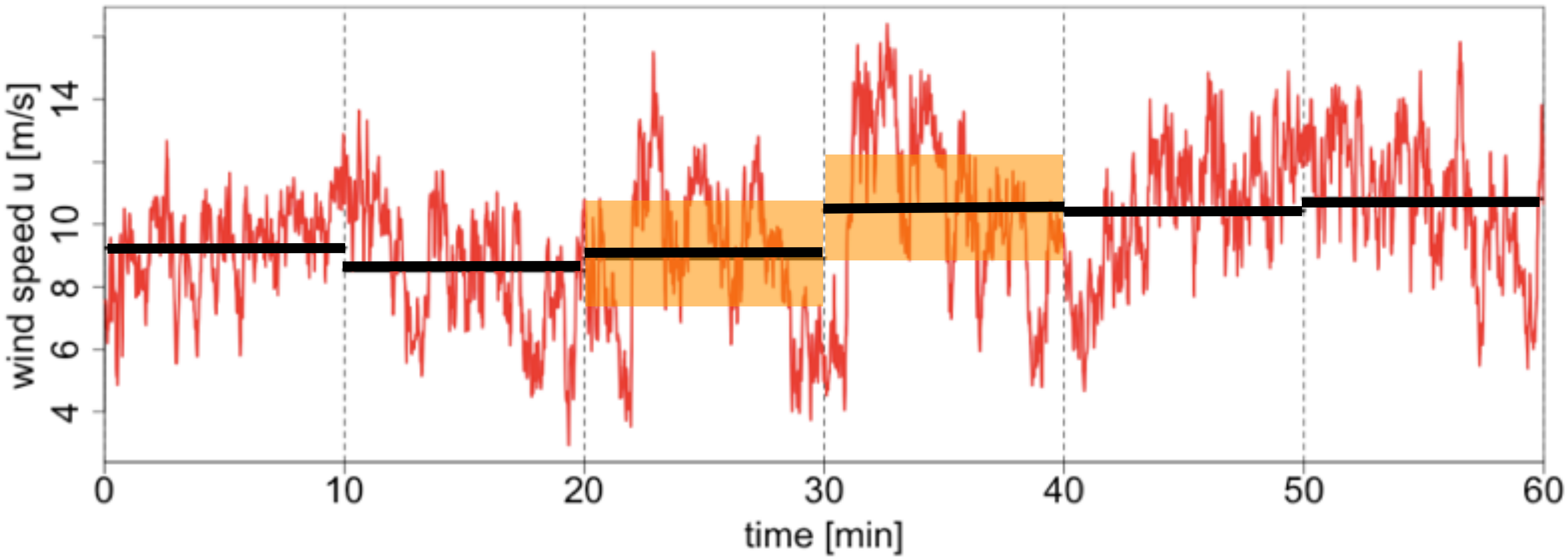
measured time series



wind measurements and data analysis

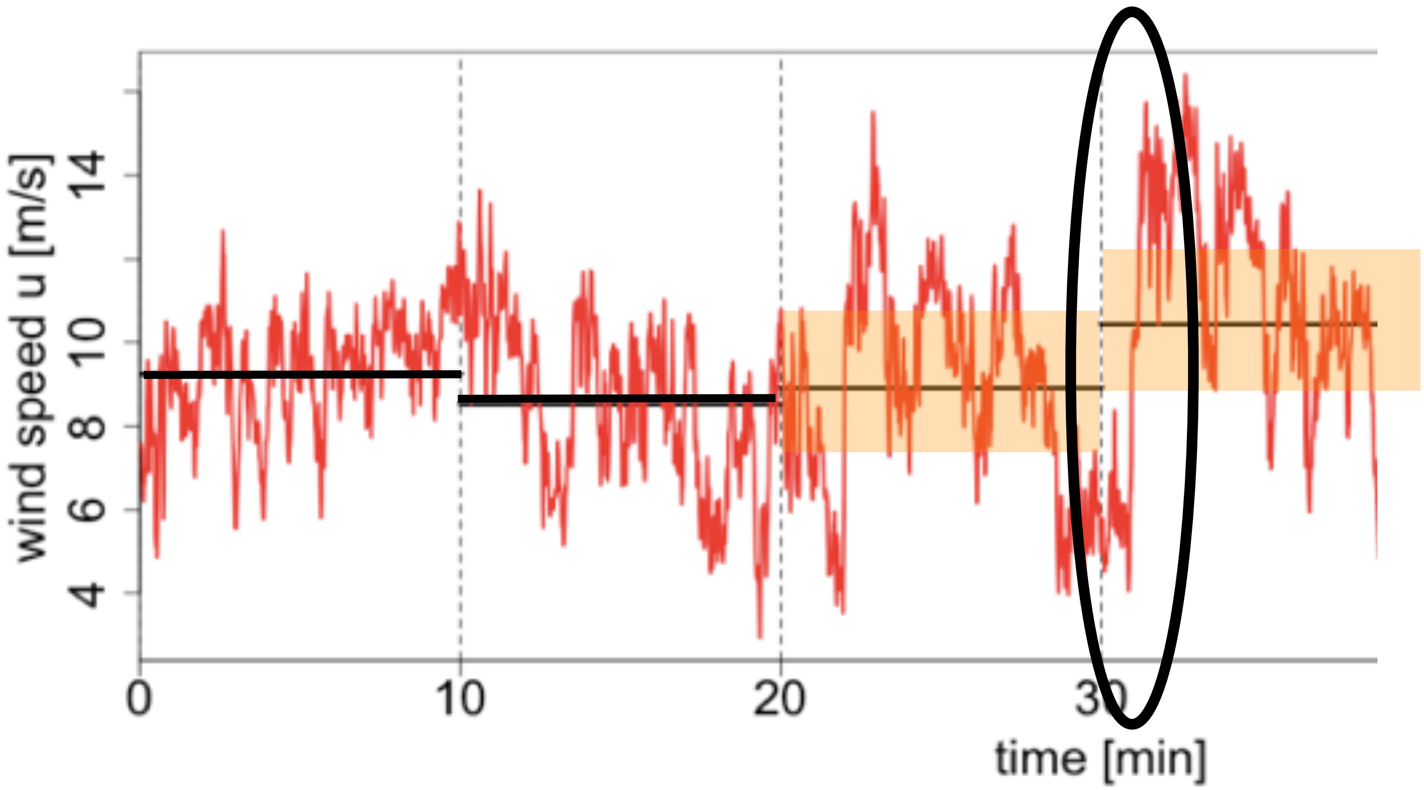
characterization after IEC norm

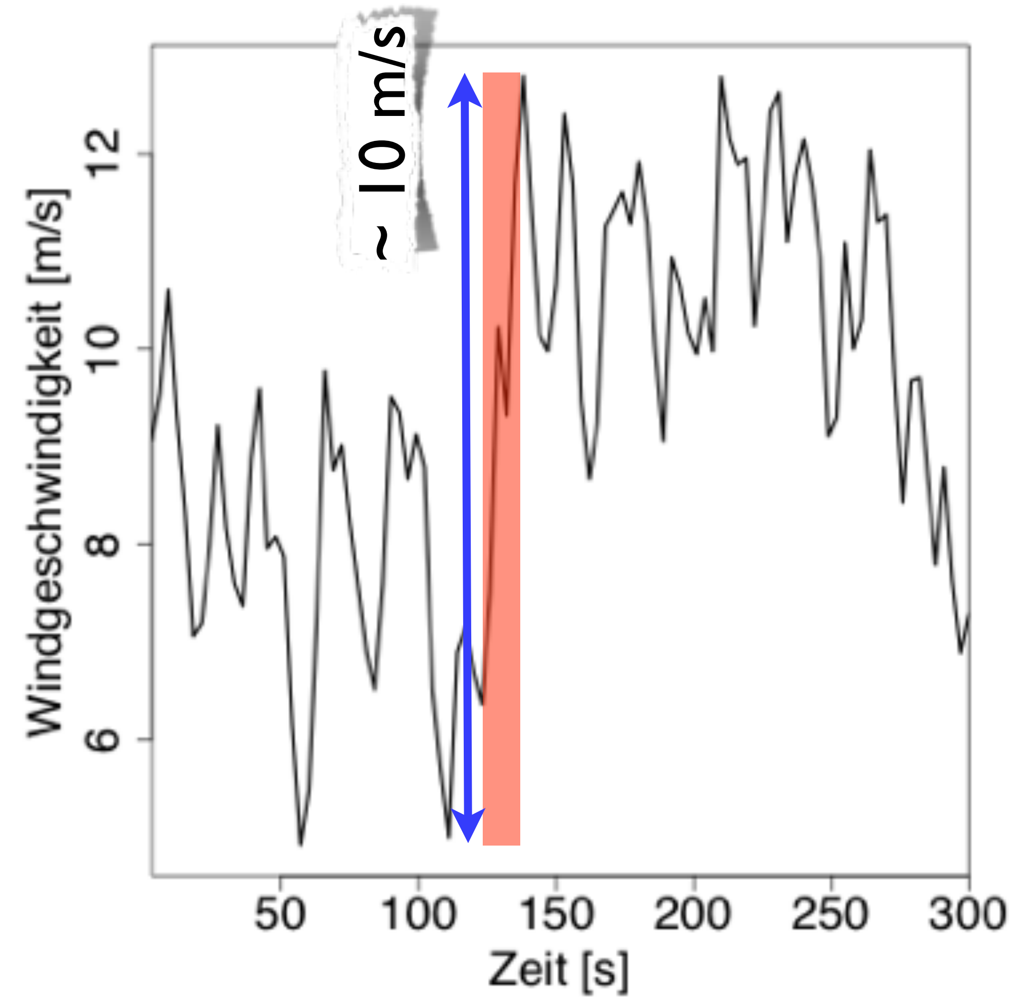
- 10 min mean value
- turbulence intensity



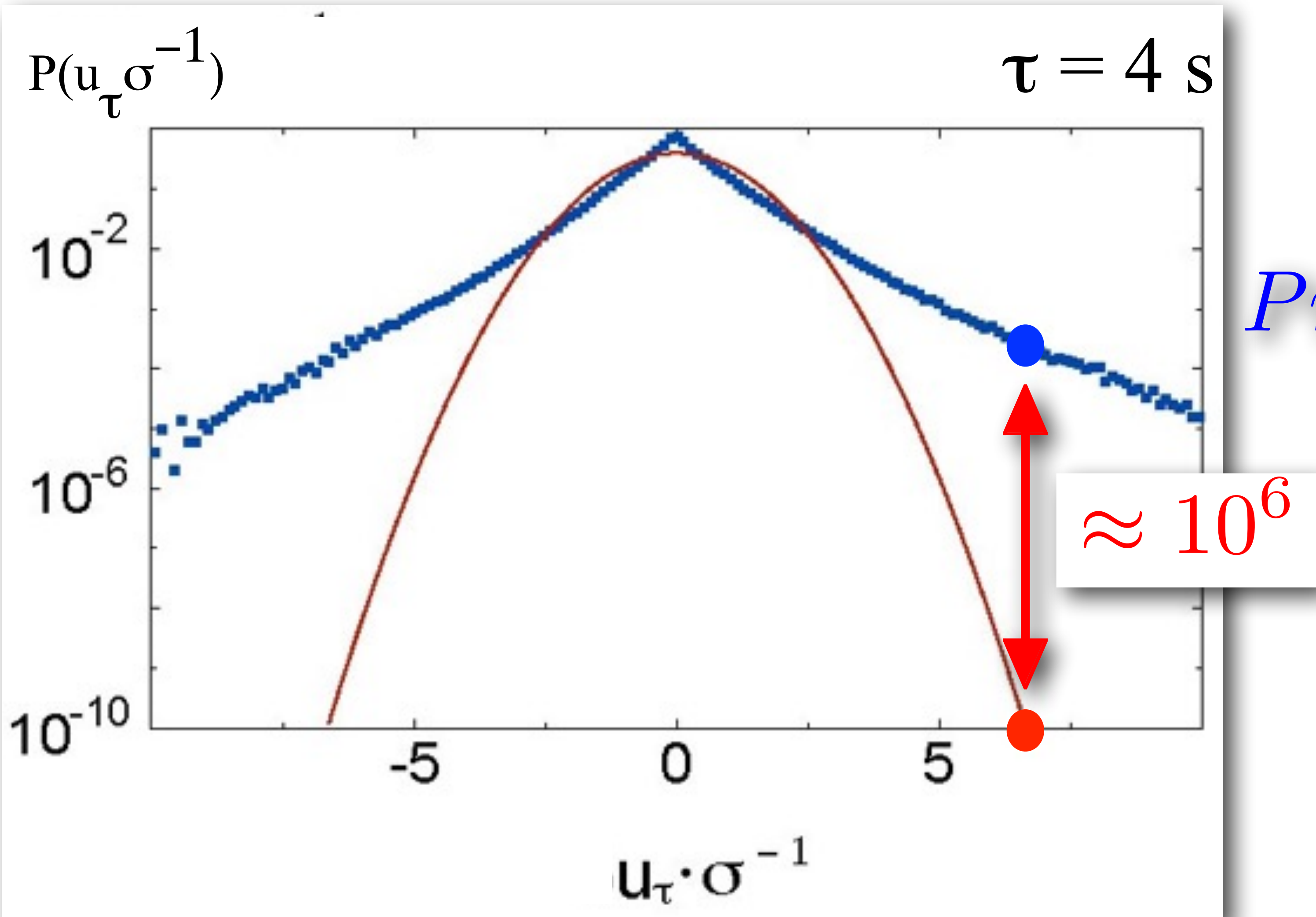
wind measurements and data analysis

- characterization after IEC norm





statistics of gusts



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

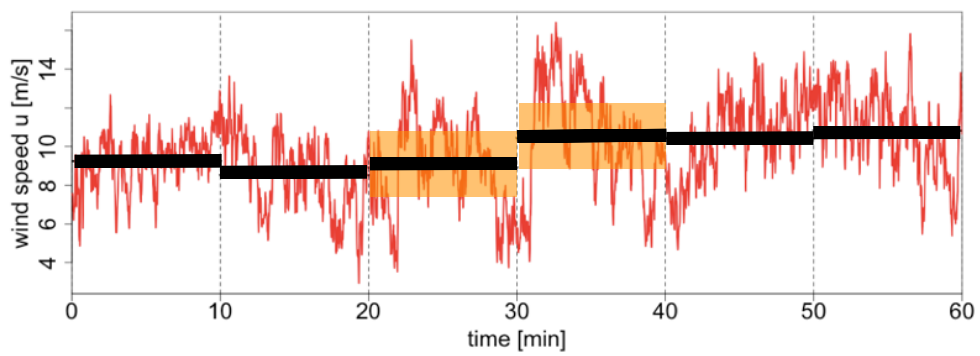
1/day

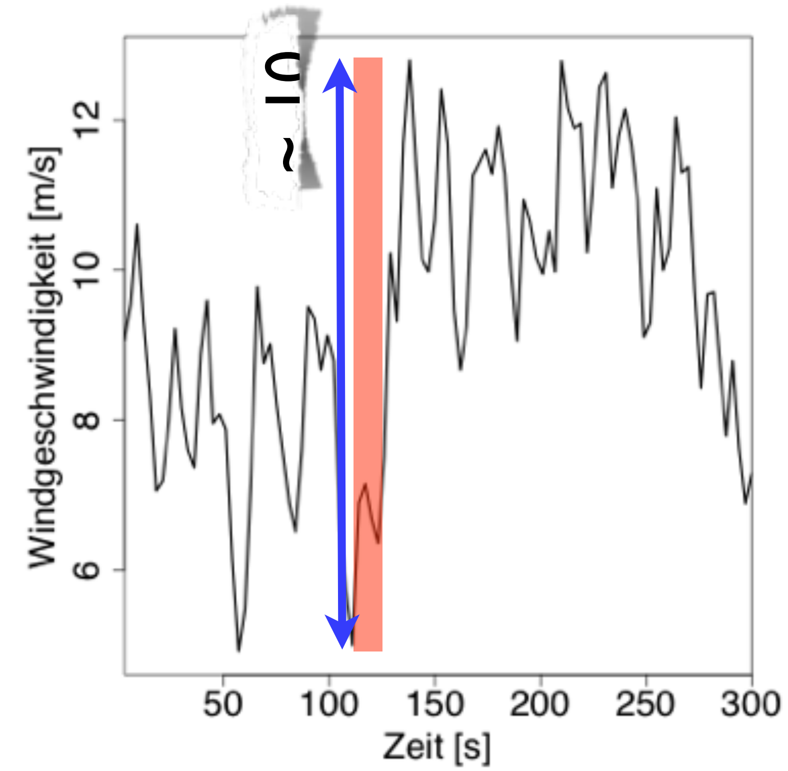
Boundary-Layer Meteorology **108** (2003)

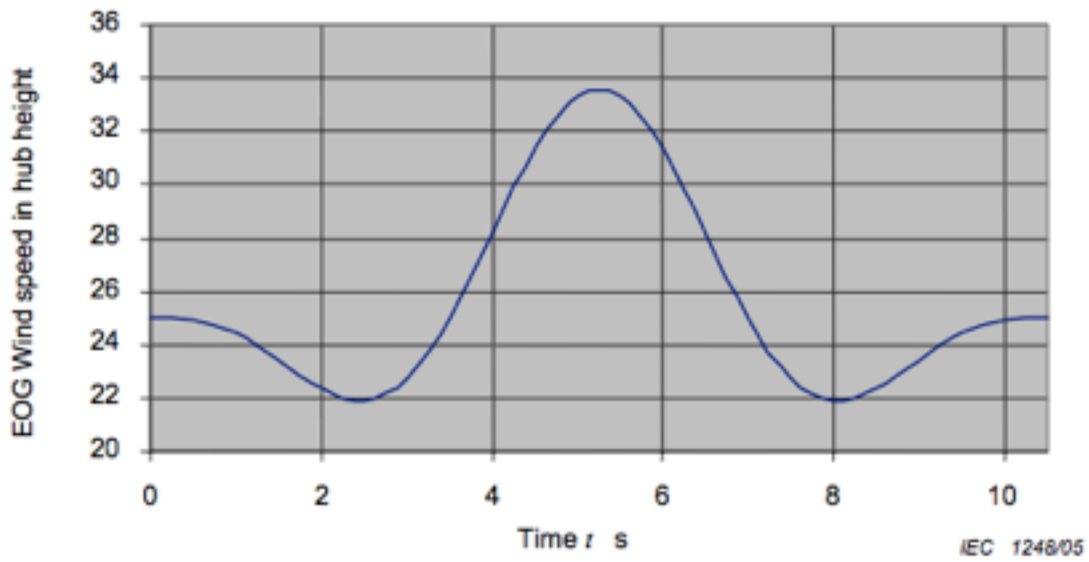
$$Prob(u_\tau > 6\sigma) \approx 10^{-10}$$

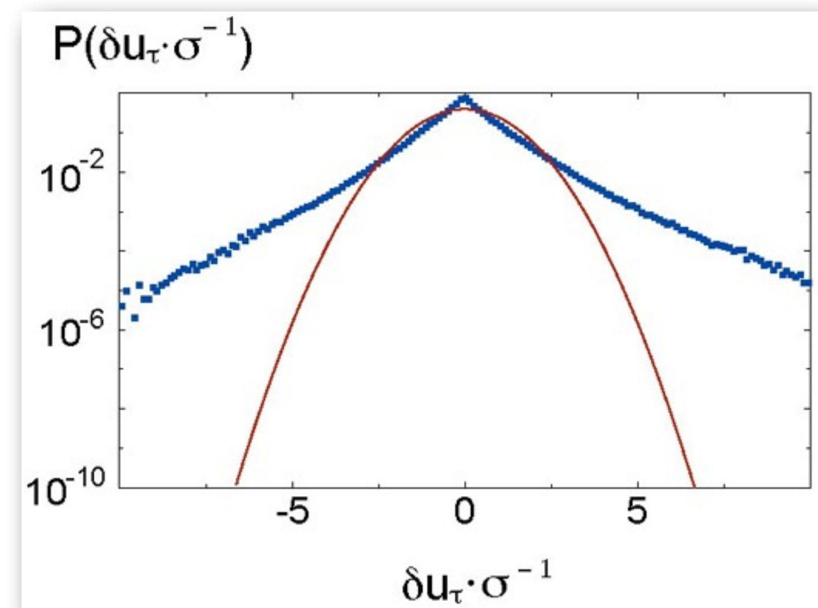
1/3000 years

IEC ◄——► statistical analysis









same mean and stand deviation

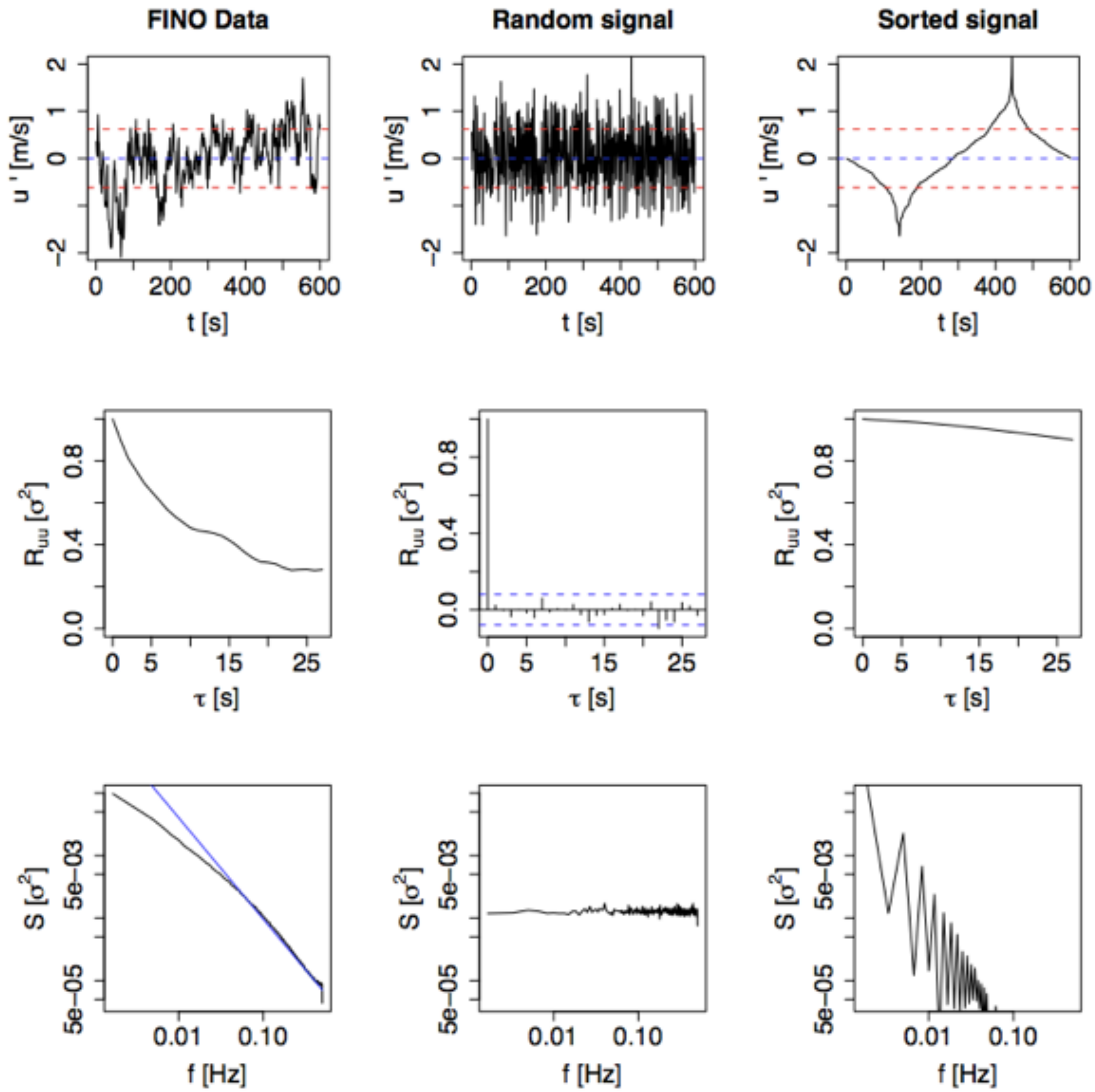


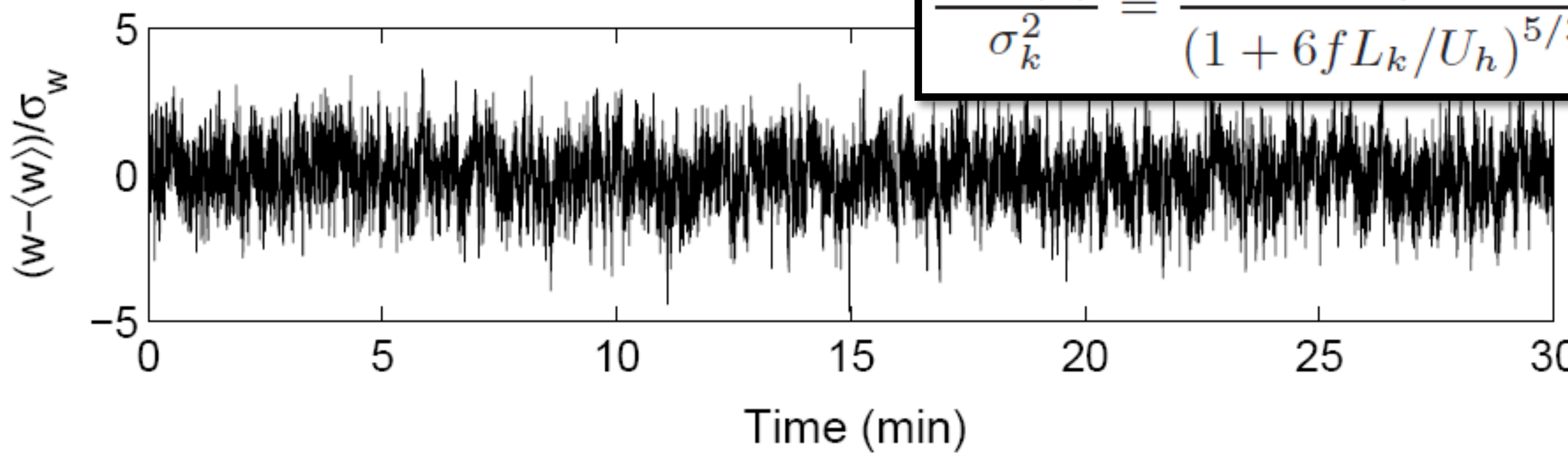
Table 1: Turbulence Characterization Scheme

Type of Statistics	Order	Feature	Random Data	Spectral Models	Wind Turbulence	Characterization
1-point	1	Mean speed	•	•	•	$\bar{u} = \langle u(t) \rangle_T$
	2	Turbulence Intensity	•	•	•	$I = \sigma_{u'} / \bar{u}$
	n	Extreme Fluctuations	-	-	•	$p(u')$
2-point	2	Distribution of σ_u over f	-	•	•	$S(f) = \mathcal{F}\{R_{uu}(\tau)\}$
	n	Intermittency of $p(\delta u(\tau))$	-	-	•	$\lambda(\tau)$
n-point	n	Arbitrary-order n-point correlations	-	-	•	To be investigated

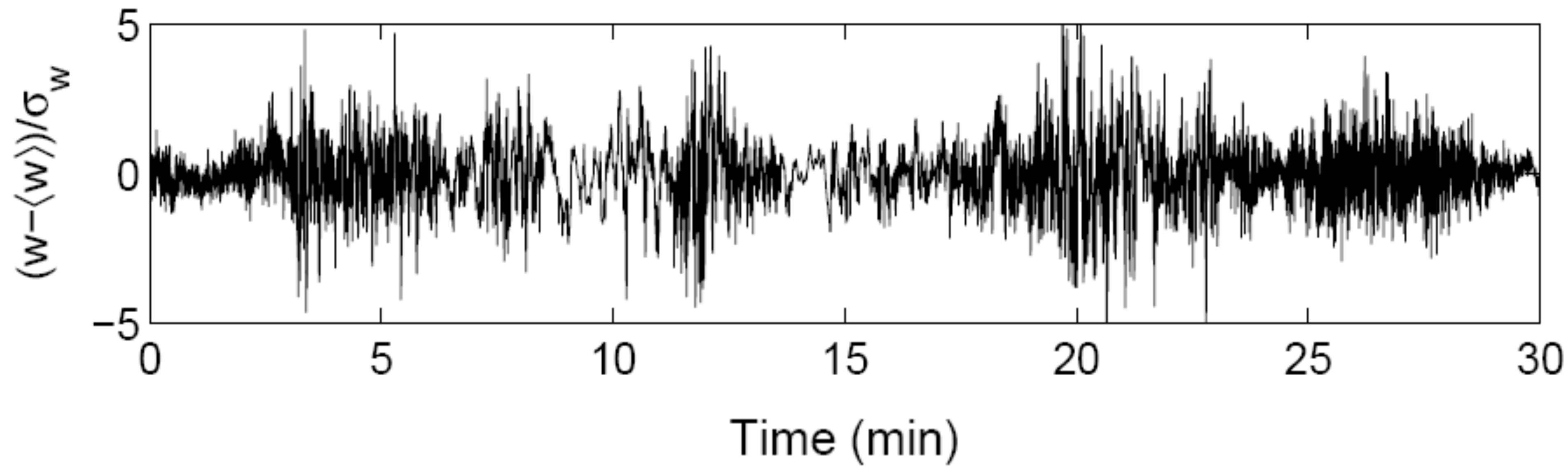
IEC Wind and measured

IEC Code

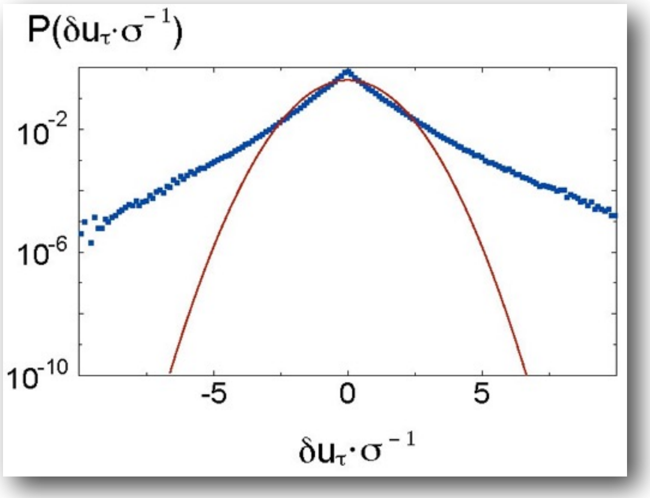
$$\frac{f S_k(f)}{\sigma_k^2} = \frac{4 f L_k / U_h}{(1 + 6 f L_k / U_h)^{5/3}}$$



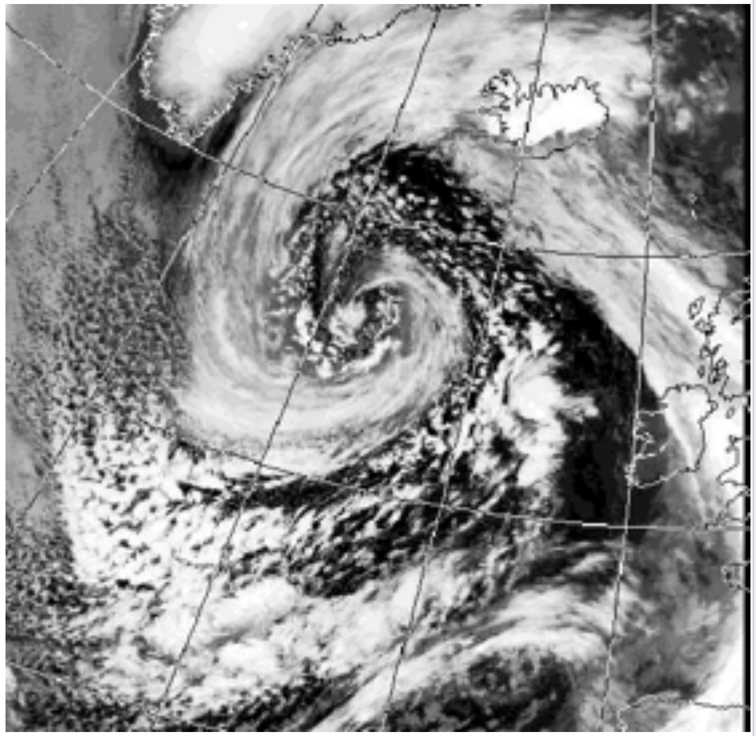
Observation



EUROMECH 528, ***S. Basu Uni Texas,***



- wind turbine in turbulent flows is a small scale object



does this intermittency matter?

content

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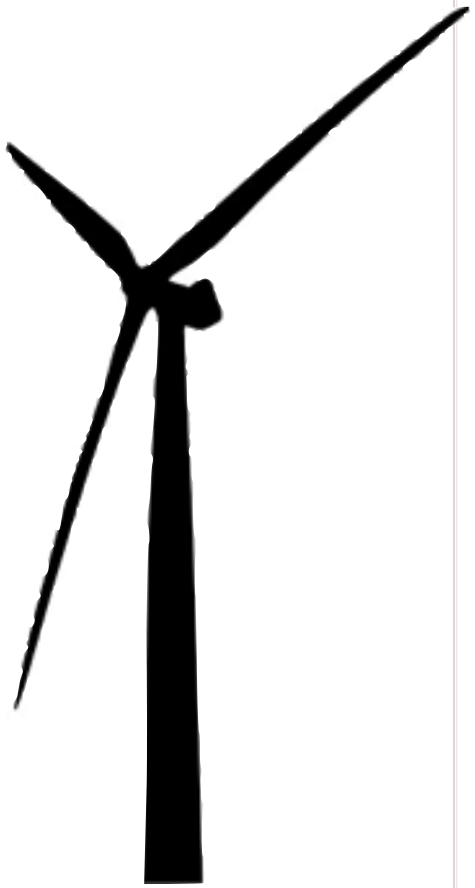
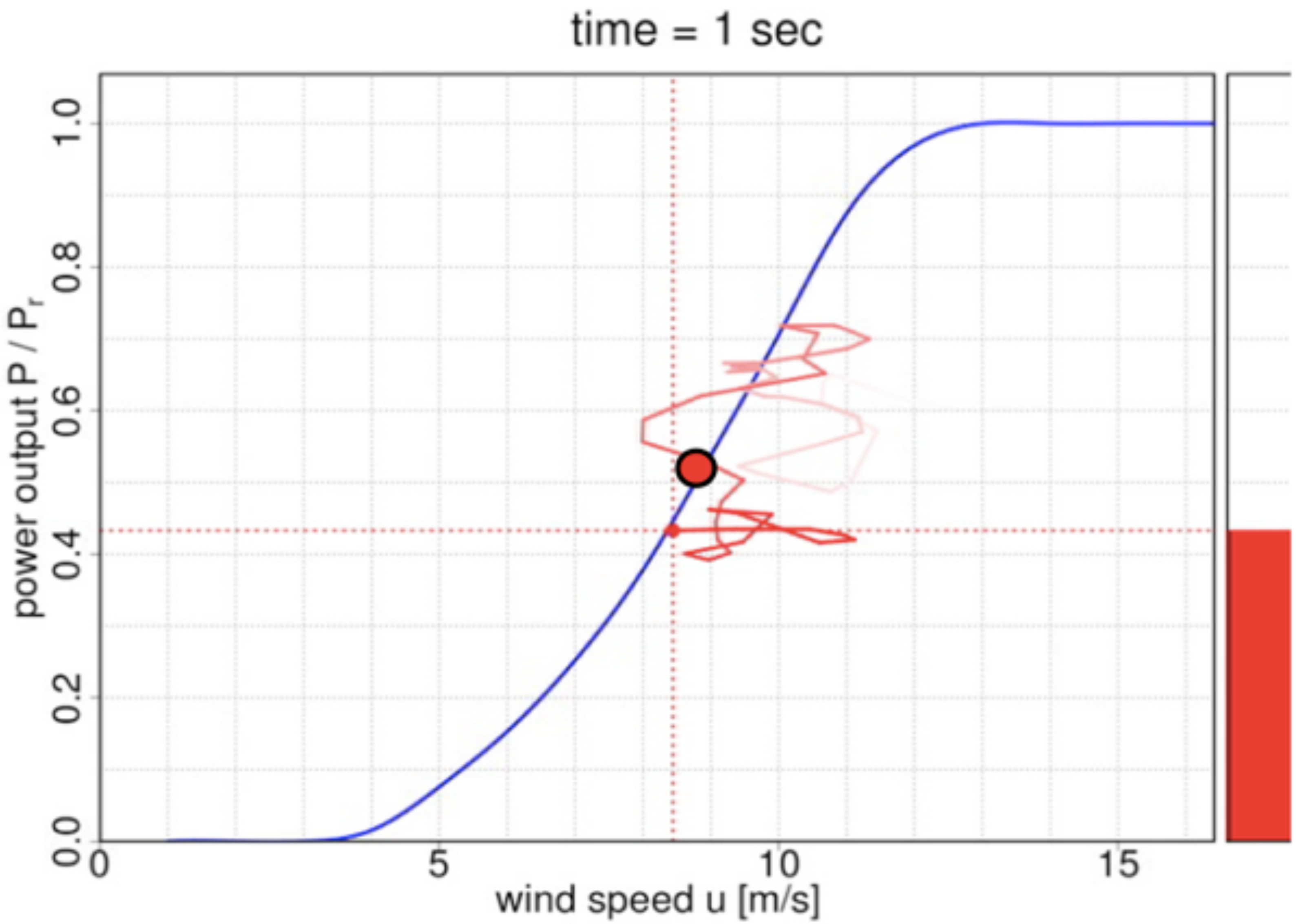


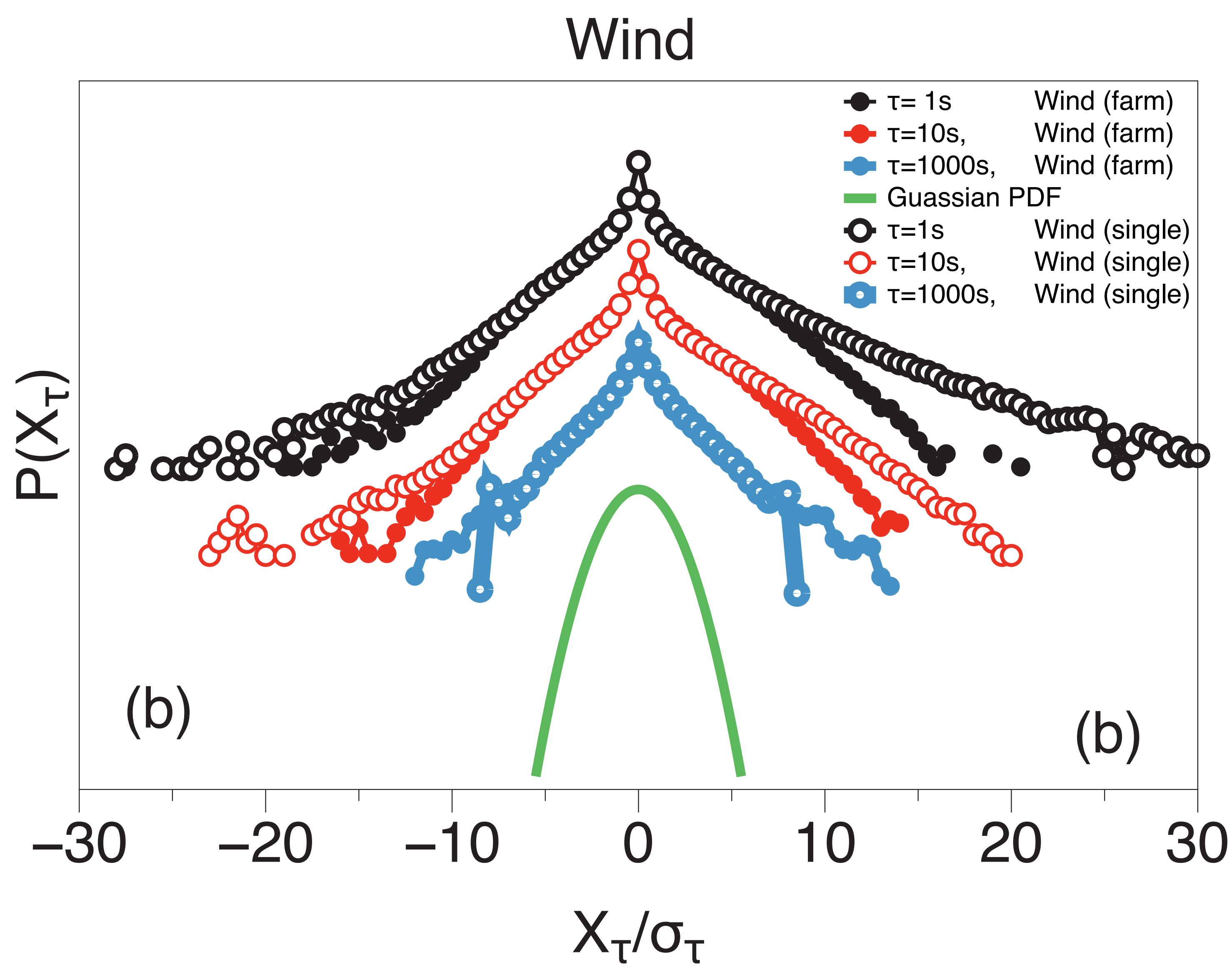
dynamics of power conversion

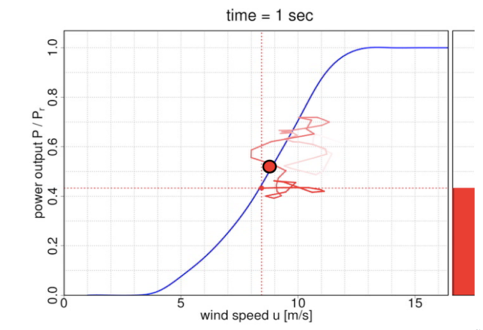
$$P_{WT} = \frac{1}{2} c_p(\lambda)\, \rho\, u_{wind}^3 \cdot A$$

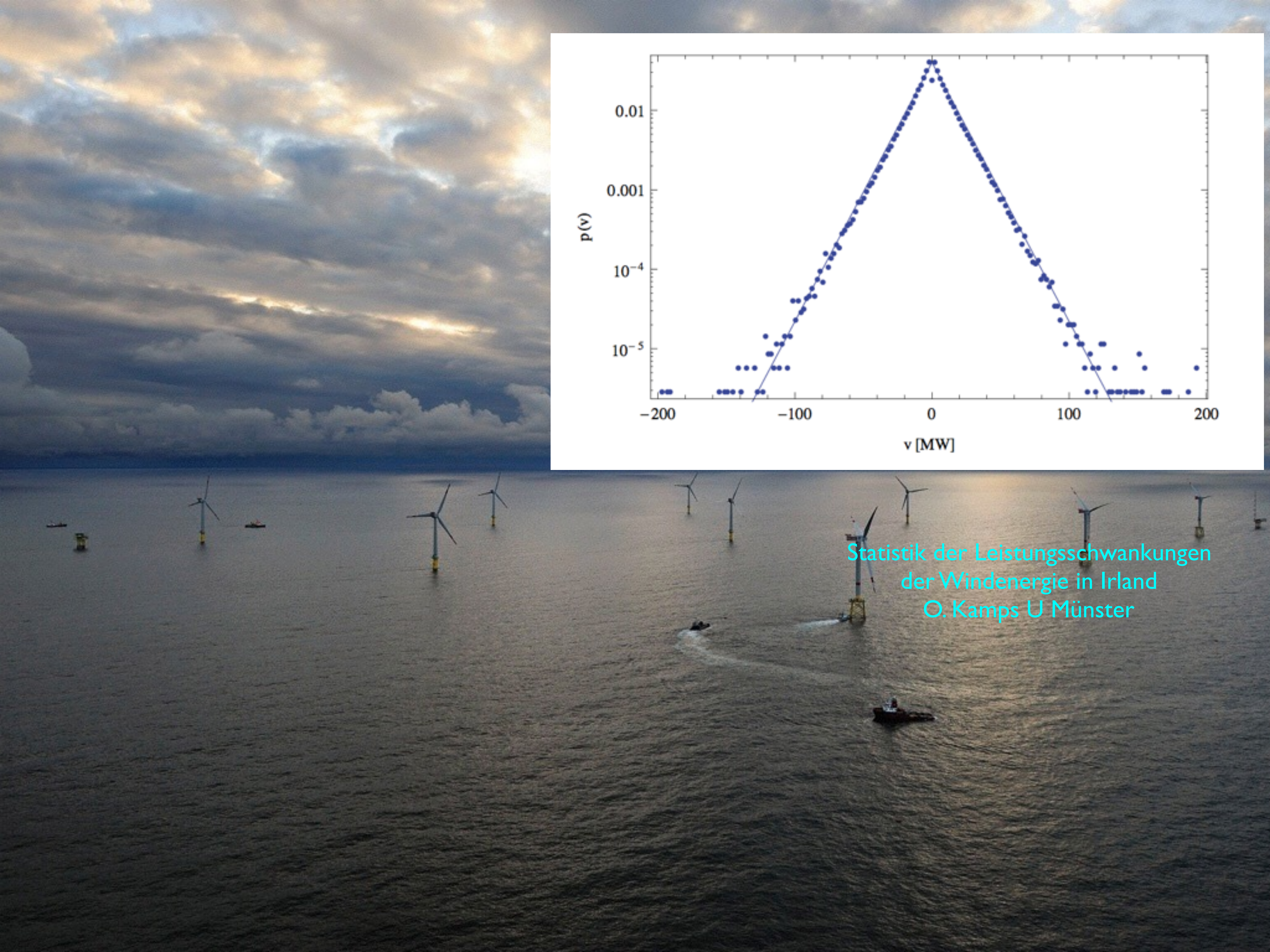


increment statistics of power fluctuations

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







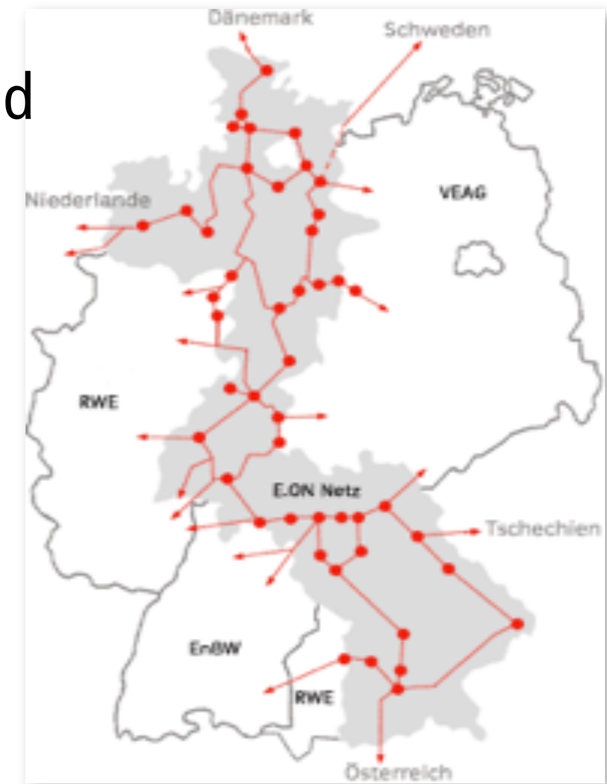
Statistik der Leistungsschwankungen
der Windenergie in Irland
O. Kamps U Münster

grid integration

- changed grid integration - not controllable power plant but local renewable source

conventional power plant

controllable units flowing the demand

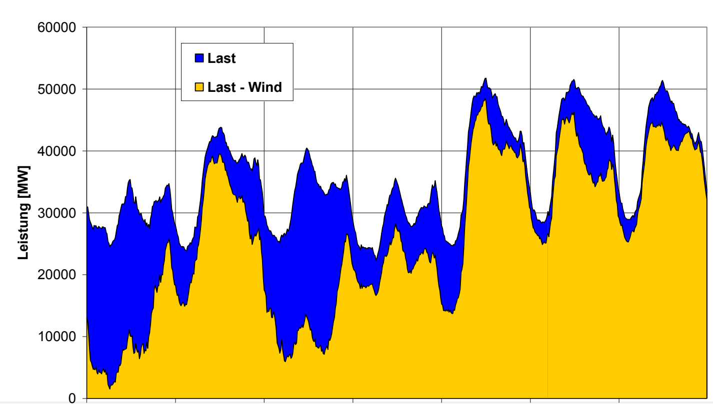


renewable energies -

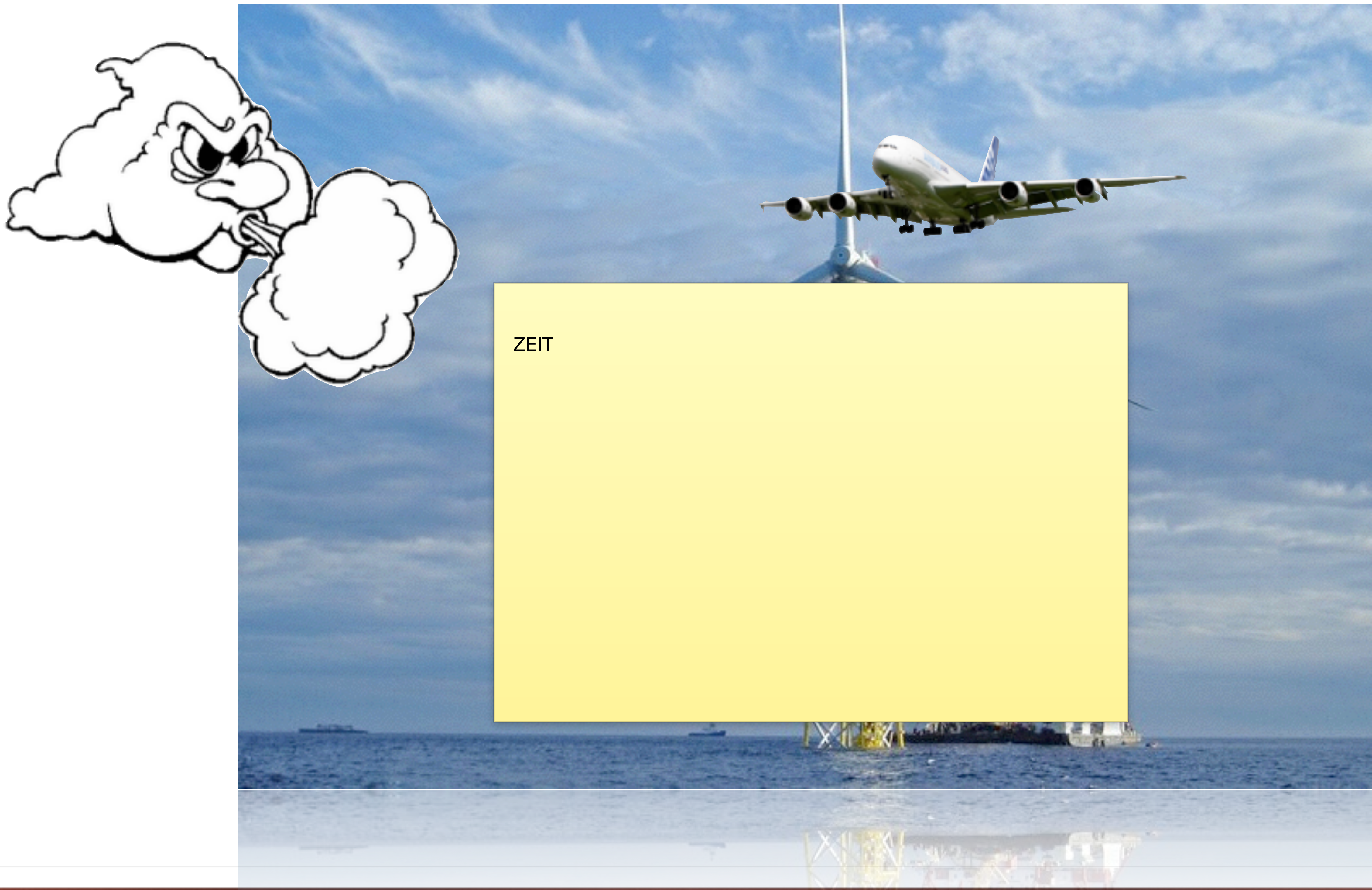
demand and supply fluctuating

new higher fluctuation load

to be controlled



wind turbine is a big turbulence engine



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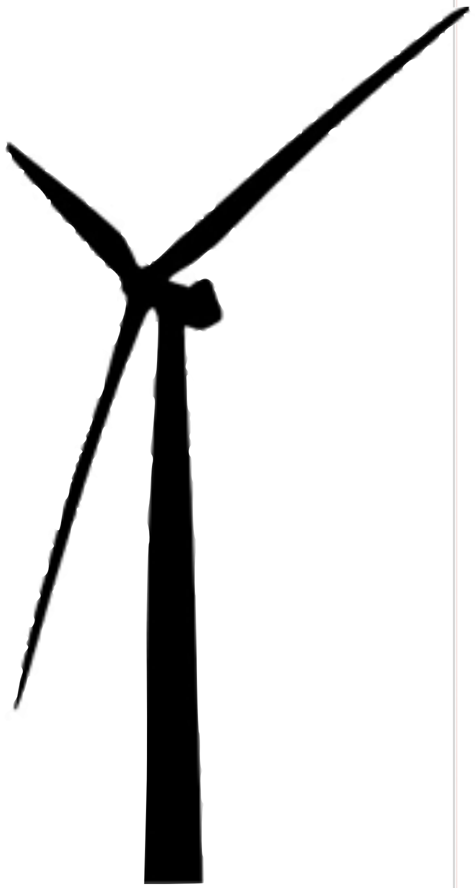

research challenges

- environmental conditions - wind and waves
  - high resolving sensors
  - multi-point characterization
- impact on WEC
  - lift force, thrust …. dynamics (dynamics of the conversion process)
  - stochastic characterization of a noisy (turbulent) driven system
  - turbulent wind tunnel
- grid integration
  - wind farm - interacting dynamical systems
  - collective behavior

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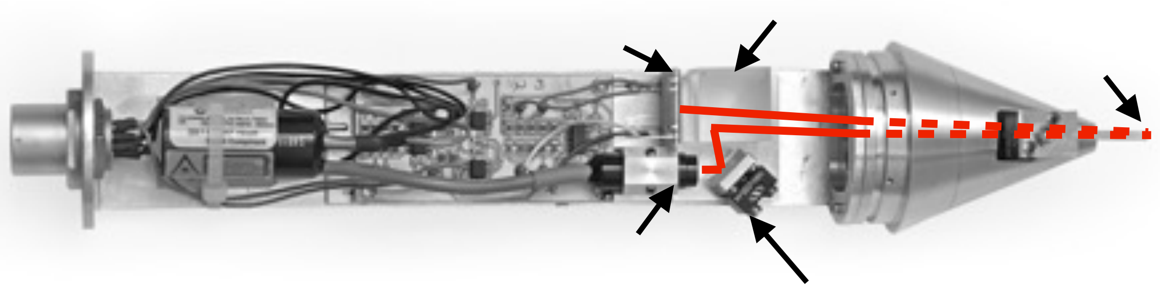
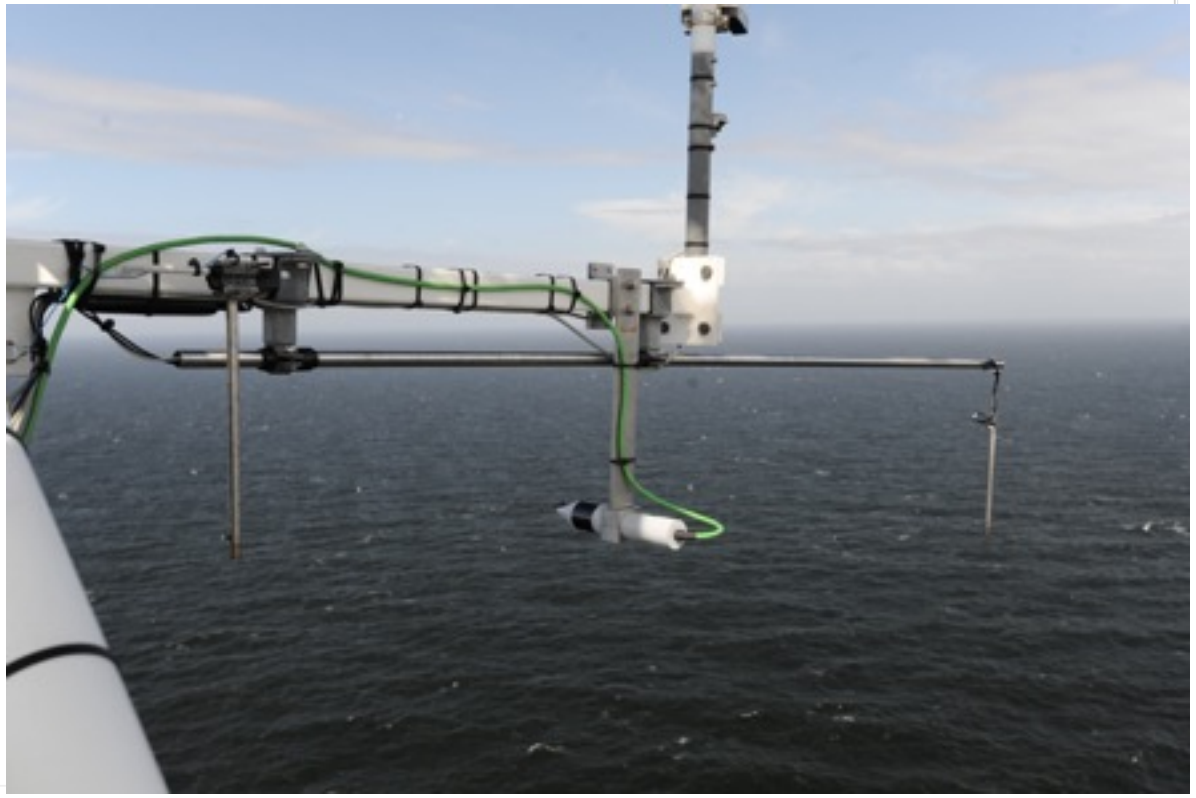
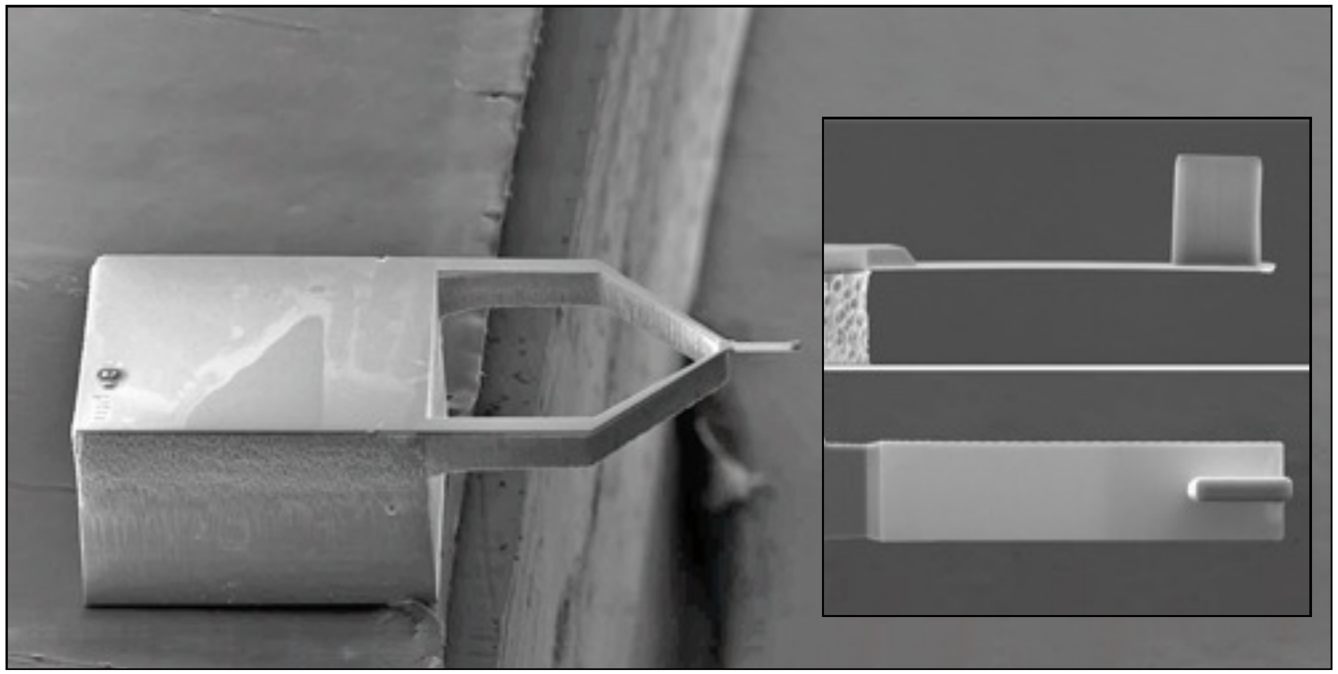


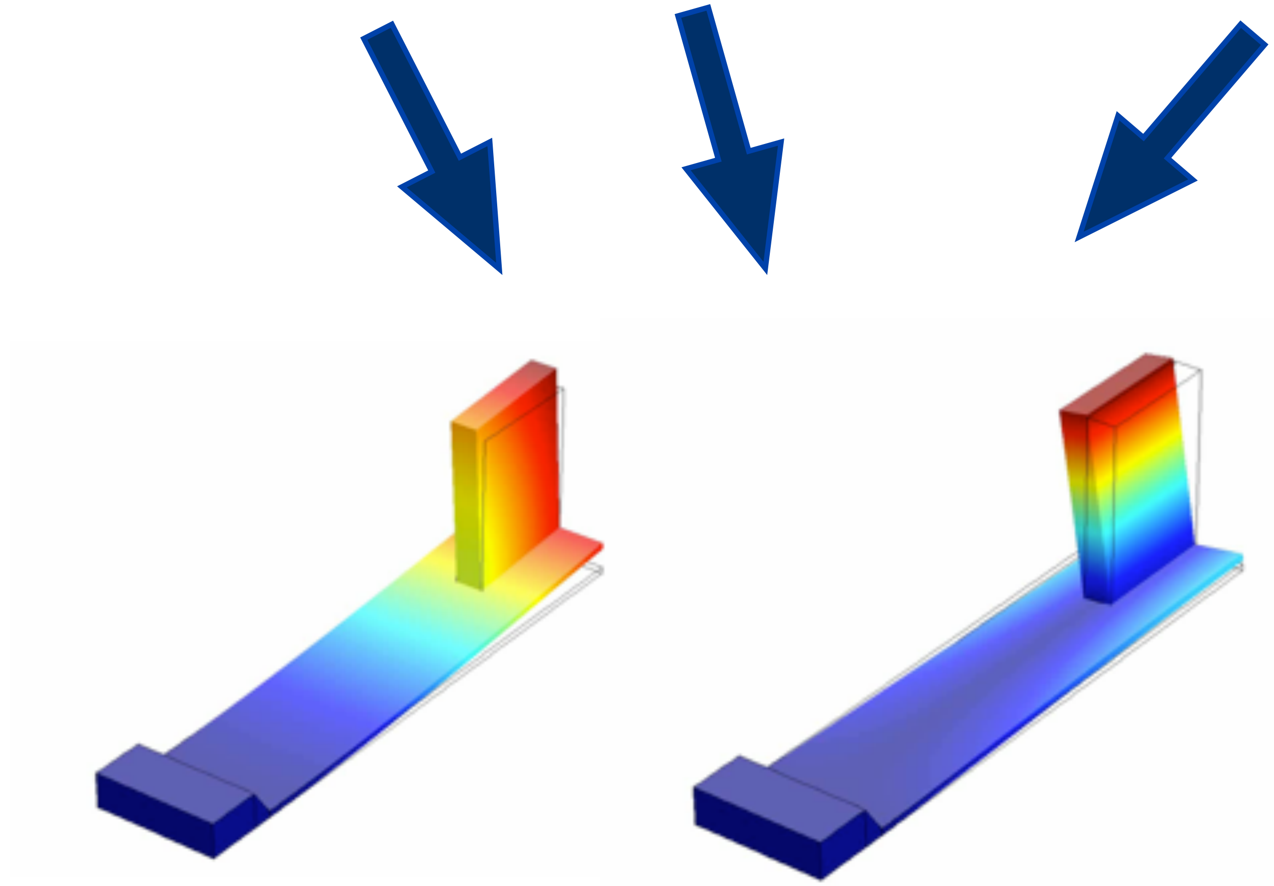


DEFLECTION MODES OF THE CANTILEVER

- Motivation



wind flow



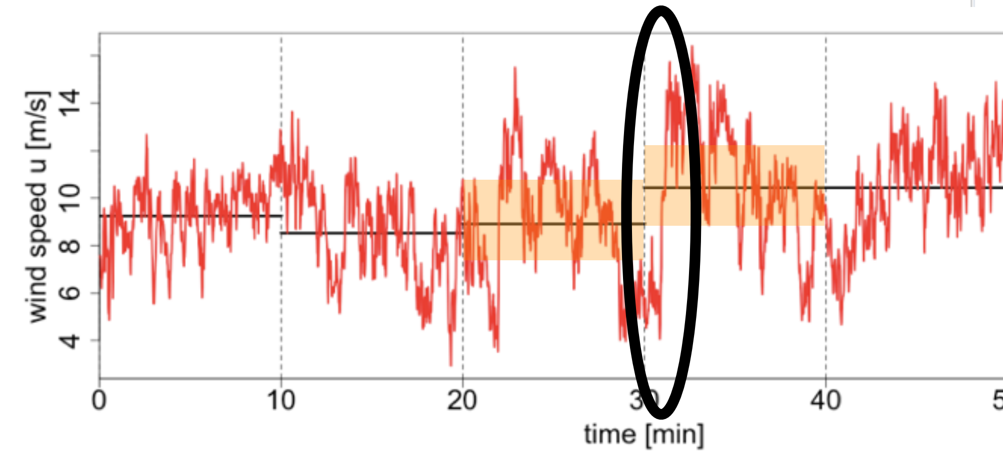
bending and twisting

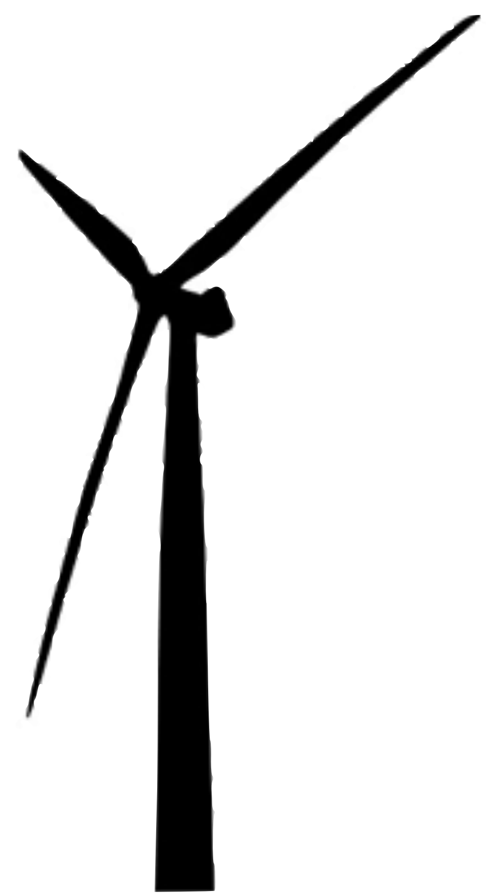
LiDAR - Light Detection and Ranging

research challenges

- environmental conditions - wind and waves
  - high resolving sensors
  - multi-point characterization
- impact on WEC
  - lift force, thrust .... dynamics (dynamics of the conversion process)
  - stochastic characterization of a noisy (turbulent) driven system
  - turbulent wind tunnel
- grid integration
  - wind farm - interacting dynamical systems
  - collective behavior

- Wind is the energy resource - we should know is well
  - more than increments - two point quantity





increments - 2 point statistics

$$u_r = u(x+r) - u(x)$$

using velocity increments - 2 point quantity

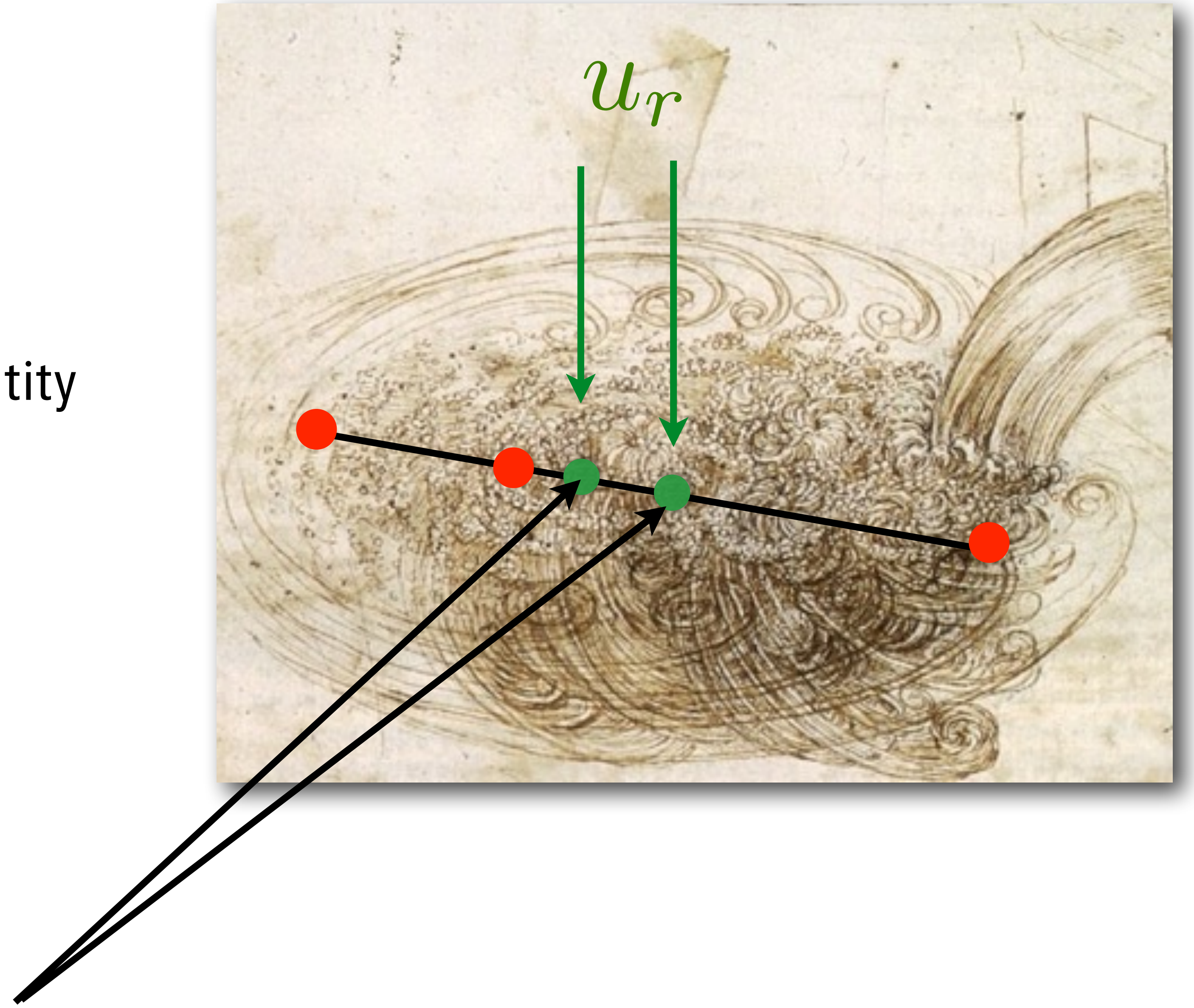


Table 1: Turbulence Characterization Scheme

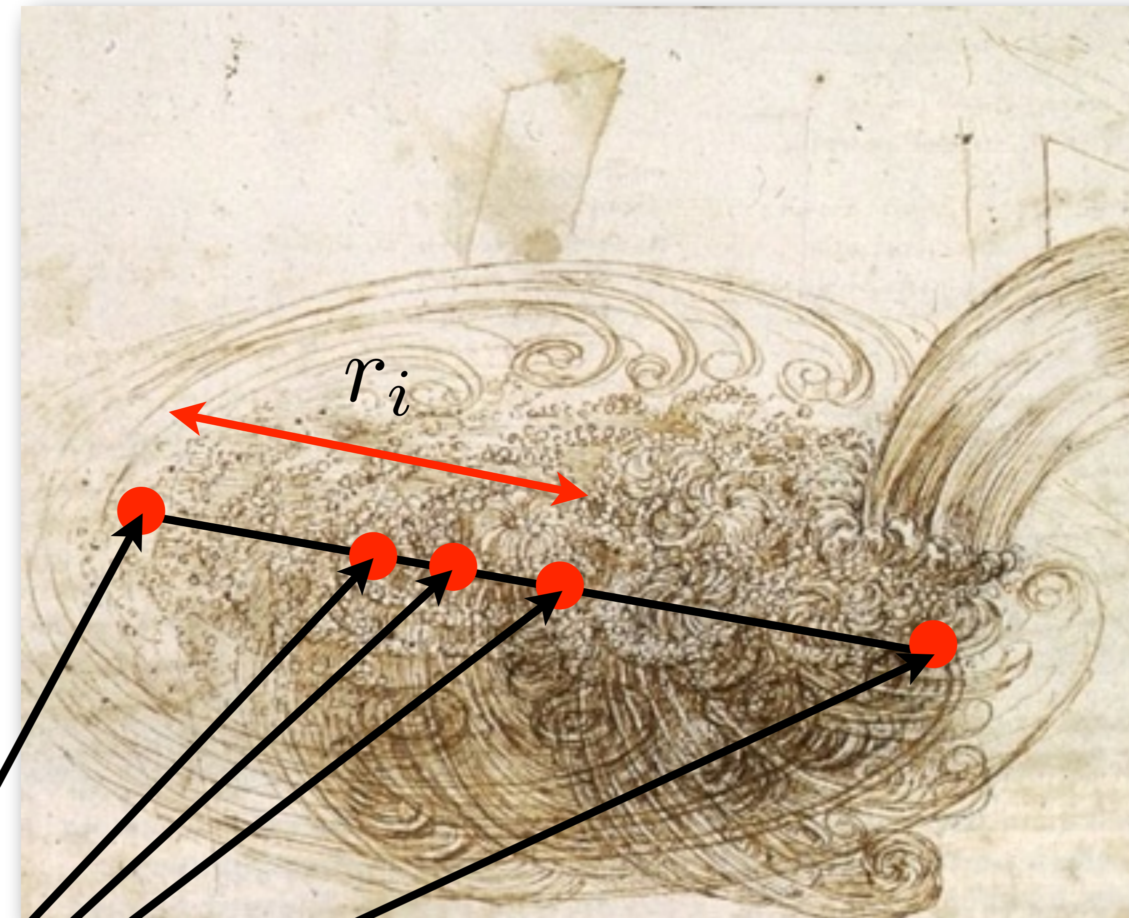
Type of Statistics	Order	Feature	Random Data	Spectral Models	Wind Turbulence	Characterization
1-point	1	Mean speed	•	•	•	$\bar{u} = \langle u(t) \rangle_T$
	2	Turbulence Intensity	•	•	•	$I = \sigma_{u'} / \bar{u}$
	n	Extreme Fluctuations	-	-	•	$p(u')$
2-point	2	Distribution of σ_u over f	-	•	•	$S(f) = \mathcal{F}\{R_{uu}(\tau)\}$
	n	Intermittency of $p(\delta u(\tau))$	-	-	•	$\lambda(\tau)$
n-point	n	Arbitrary-order n-point correlations	-	-	•	To be investigated

turbulence: n - point statistics

$$p(u(x_1), ..., u(x_{n+1}))$$

using velocity increments:

$$u_{r_i} = u(x + r_i) - u(x_i)$$

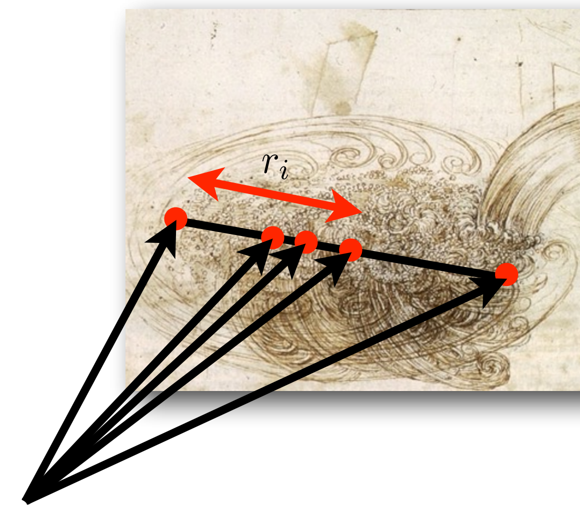


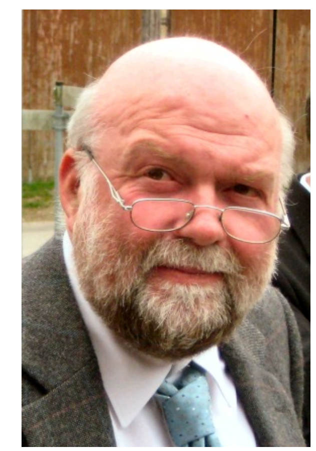
$$\boxed{p(u(x_1), \ldots, u(x_{n+1})) = p(u_{r_1}, \ldots, u_{r_n}, u(x_1))}$$

n+1 -point statistics can be expressed be joint n-increment statistics

n-point statistics

$$p(u(x_1),\ldots,u(x_{n+1}))$$
$$= p(u_{r_1}|u_{r_2},u(x_1))\ \ldots\ p(u_{r_{n-1}}|u_{r_n},u(x_1))\cdot p(u(x_1))$$

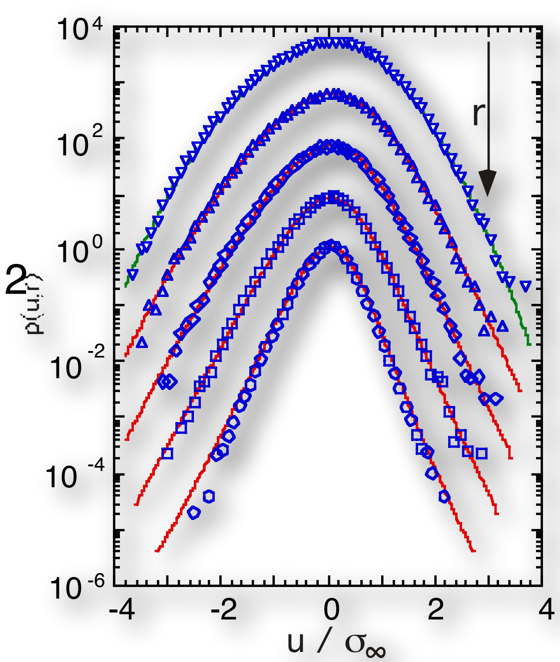




R. Friedrich 1956 - 2012

$$L \longrightarrow r \longrightarrow \eta$$

....



new view of cascade process :

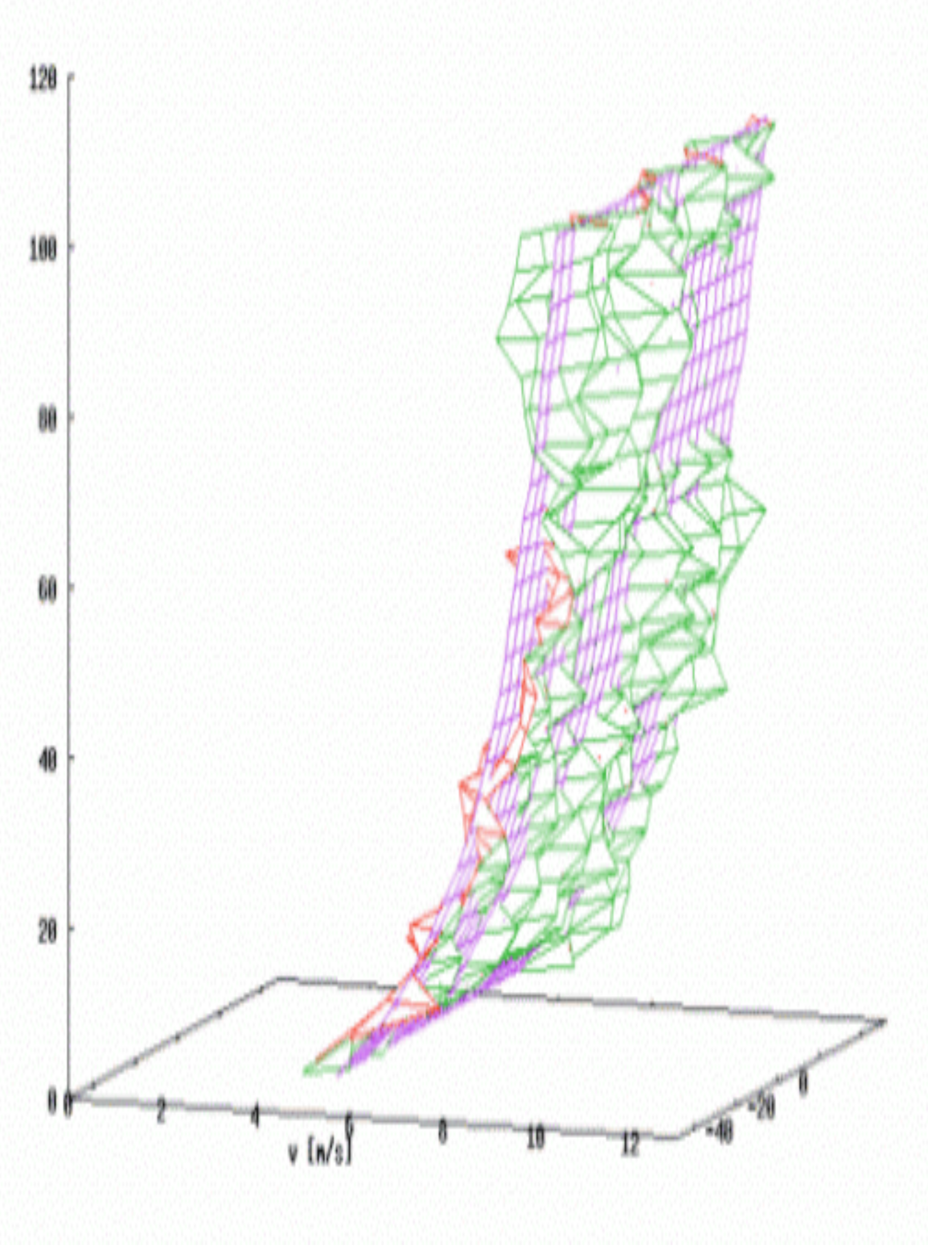
it is local in the cascade - three point closure !

and is given by a Fokker-Planck equation

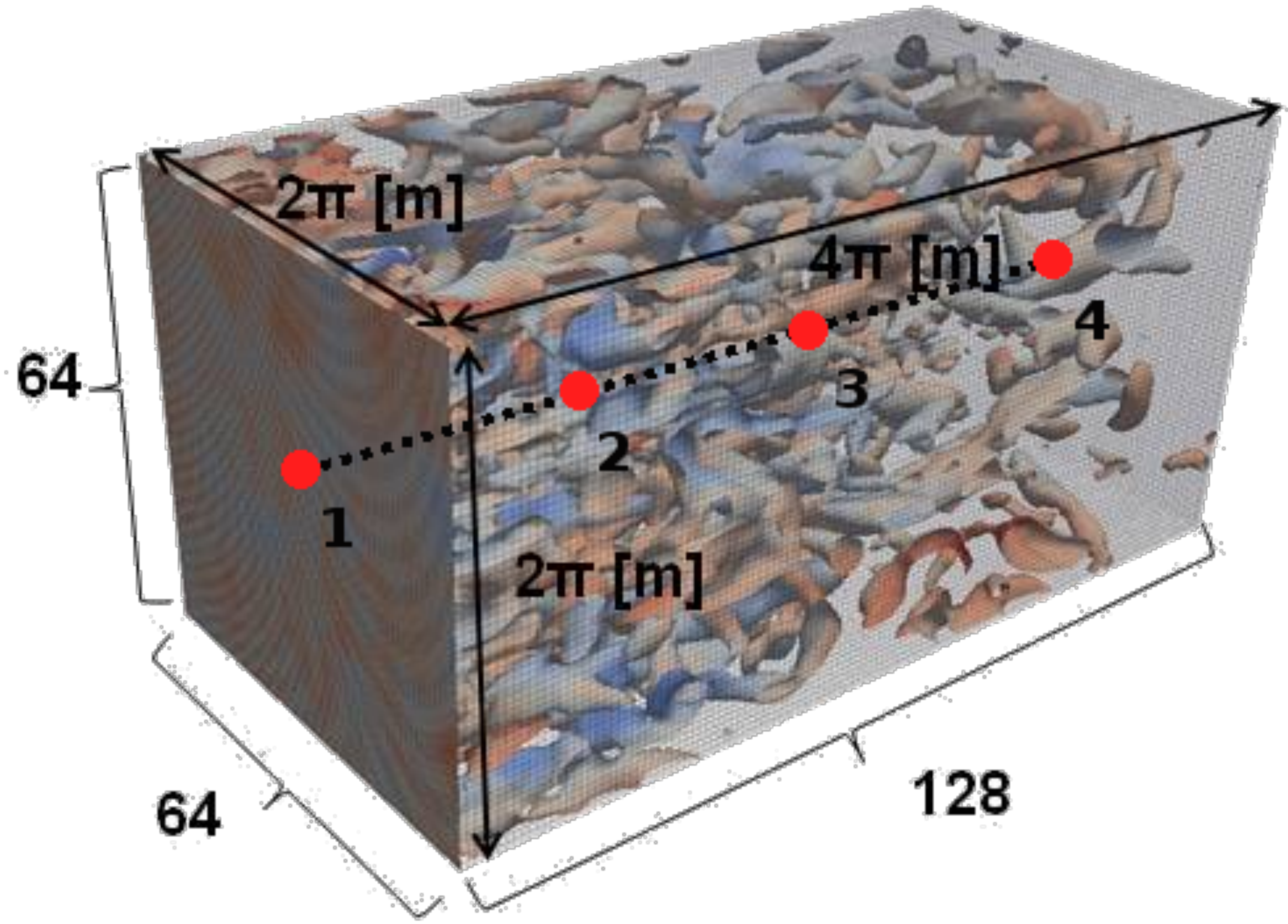
$$\boxed{-r_j\frac{\partial}{\partial r_j}p(u_{r_j}|u_{r_k},u(x_1)) = \{-\frac{\partial}{\partial u_{r_j}}D^{(1)}(u_{r_j},r_j,u(x_1)) + \frac{\partial^2}{\partial \xi_j^2}D^{(2)}(u_{r_j},r_j,u(x_1))\}\ p(u_{r_j}|u_{r_k},u(x_1))}$$

Stresing et.al. New Journal of Physics **12** (2010)

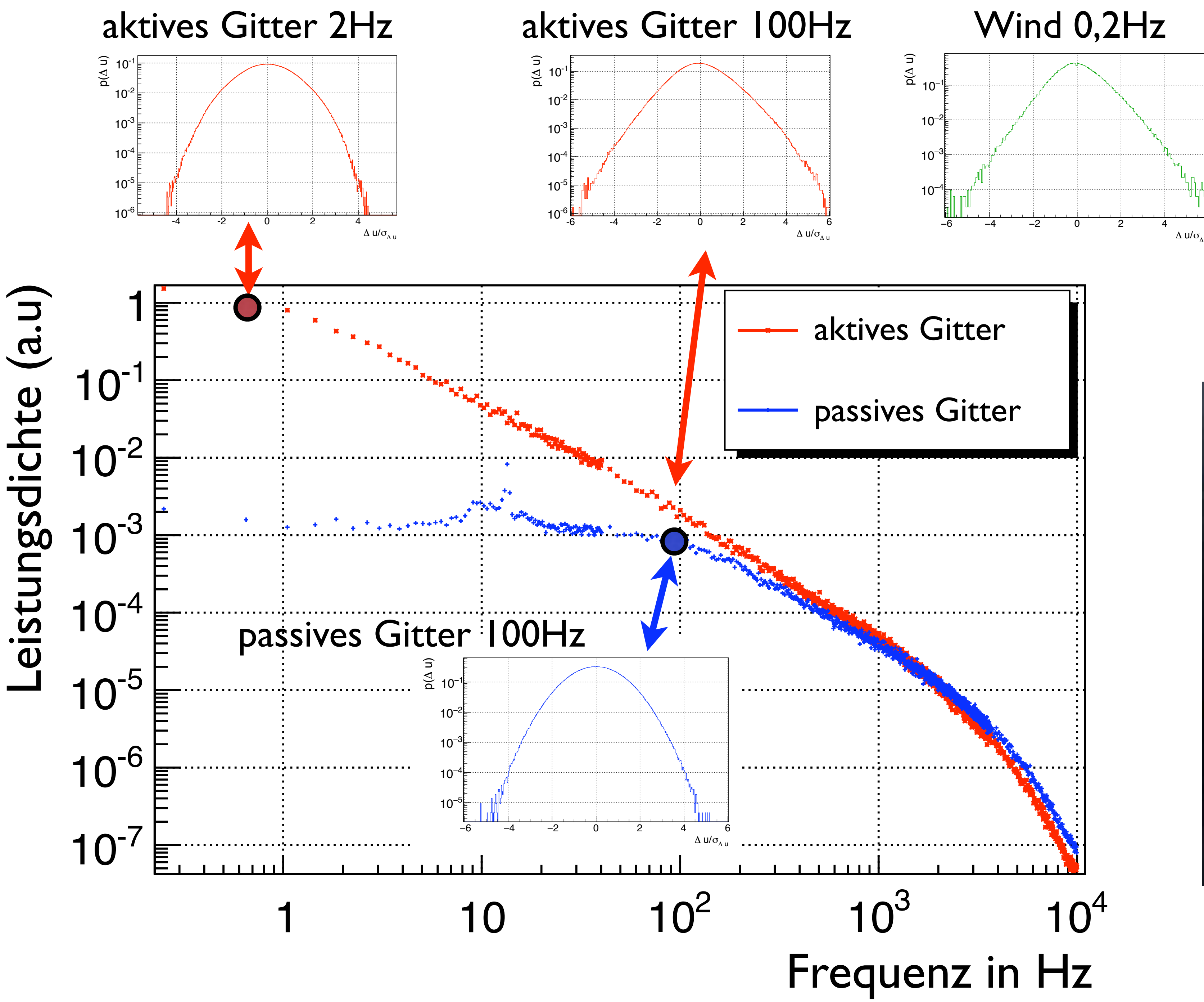
- next step - wind fields modeling

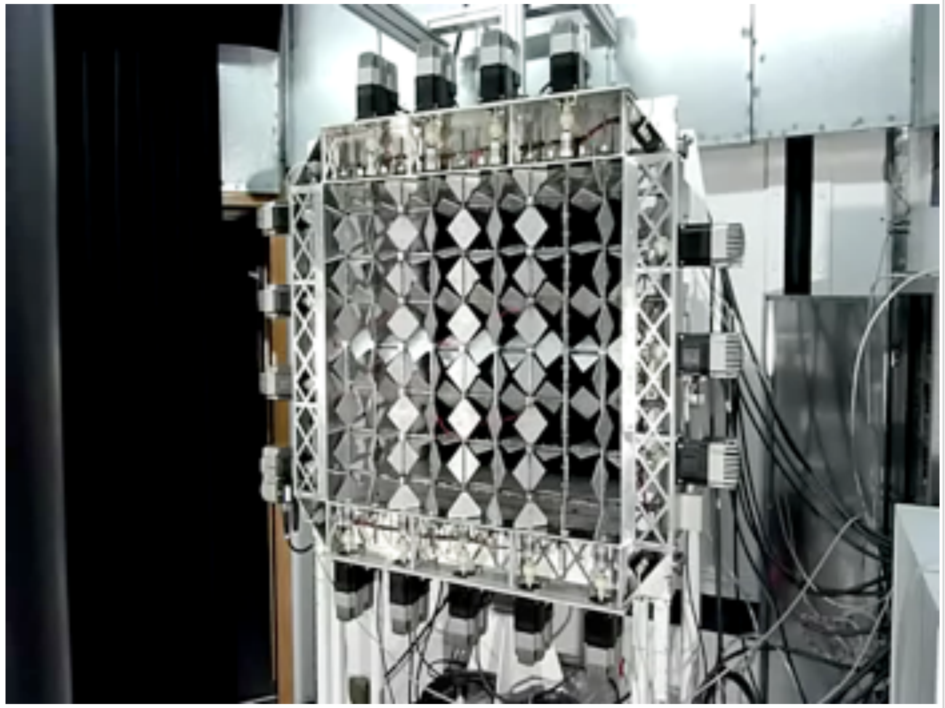


- next step - wind fields modeling - CTRW model of Kleinhans / Friedrich
- first results with CFD - numeric simulations



reproduction of wind fields with active grid





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- impact on WEC
  - lift force, thrust …. dynamics (dynamics of the conversion process)
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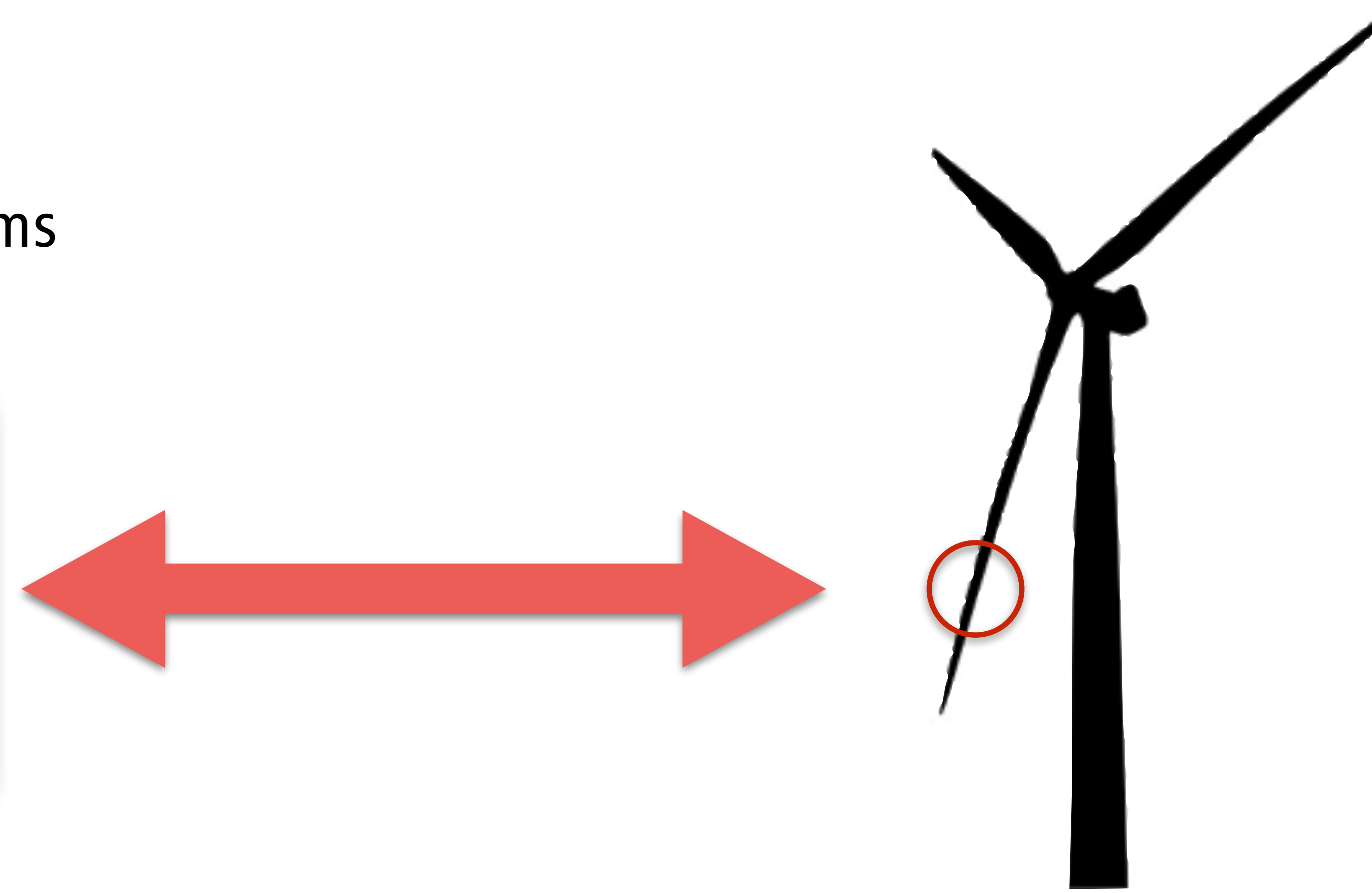
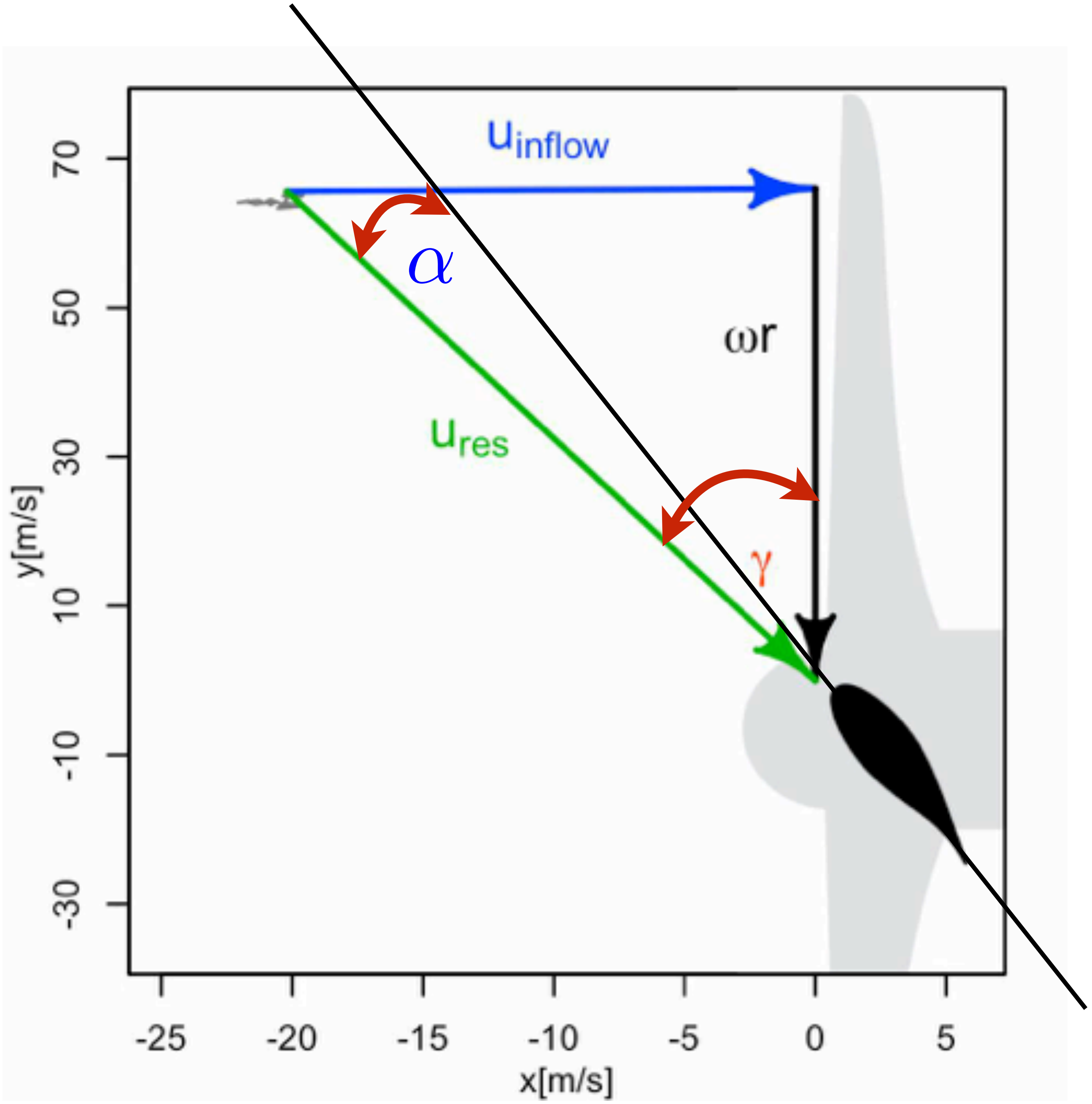
  - turbulent wind tunnel
- grid integration
  - wind farm - interacting dynamical systems
  - grid stability under turbulent noise
  - collective behavior



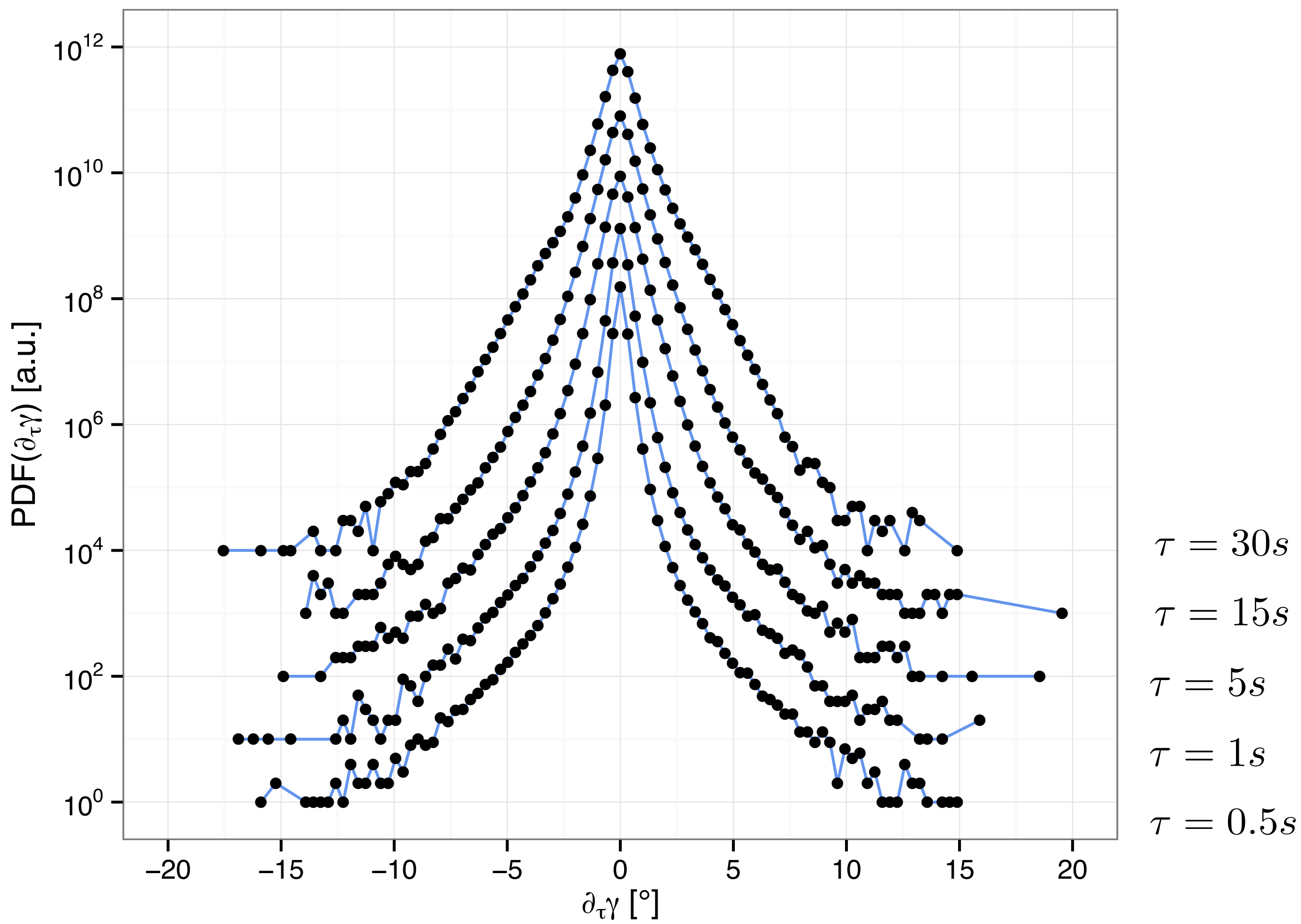
angle of attack

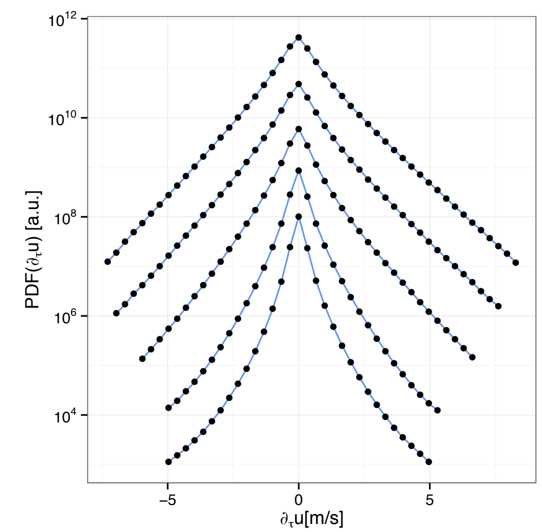


γ inflow angle for rotor plane

α angle of attack: γ - pitch angle

increment statistics of angle of attack (1 Year - Gerrit Kampers Fino 1)



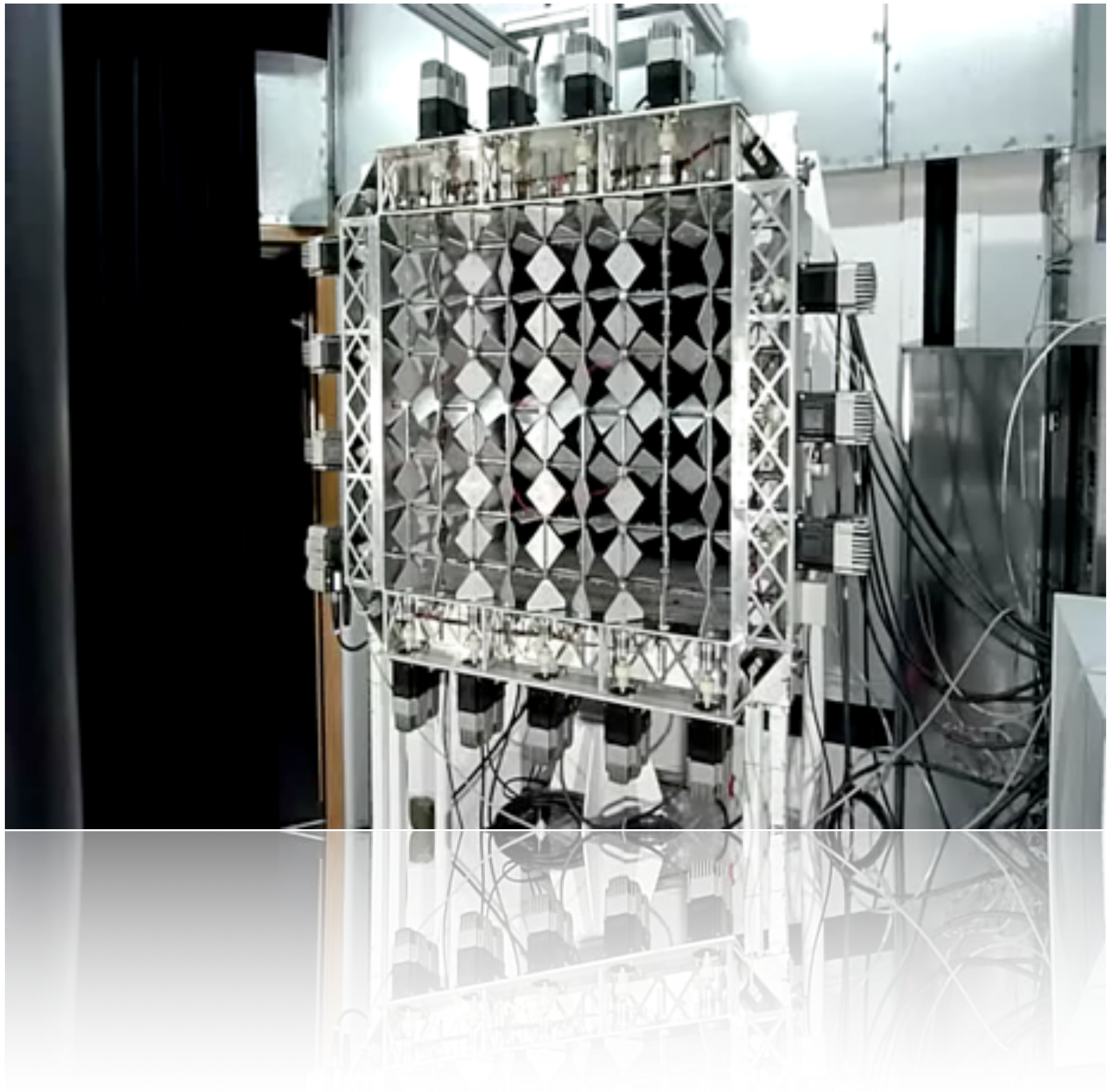


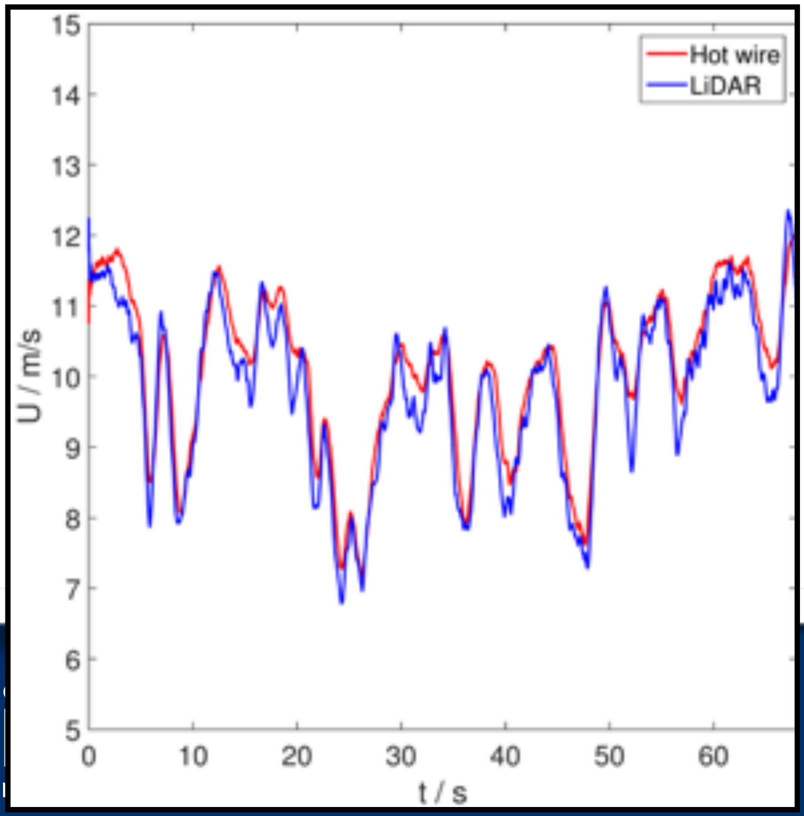
corresponding wind speed increments

Stoevesandt EWEC PO.223 (2009)

Active Grid and Dynamic Stall

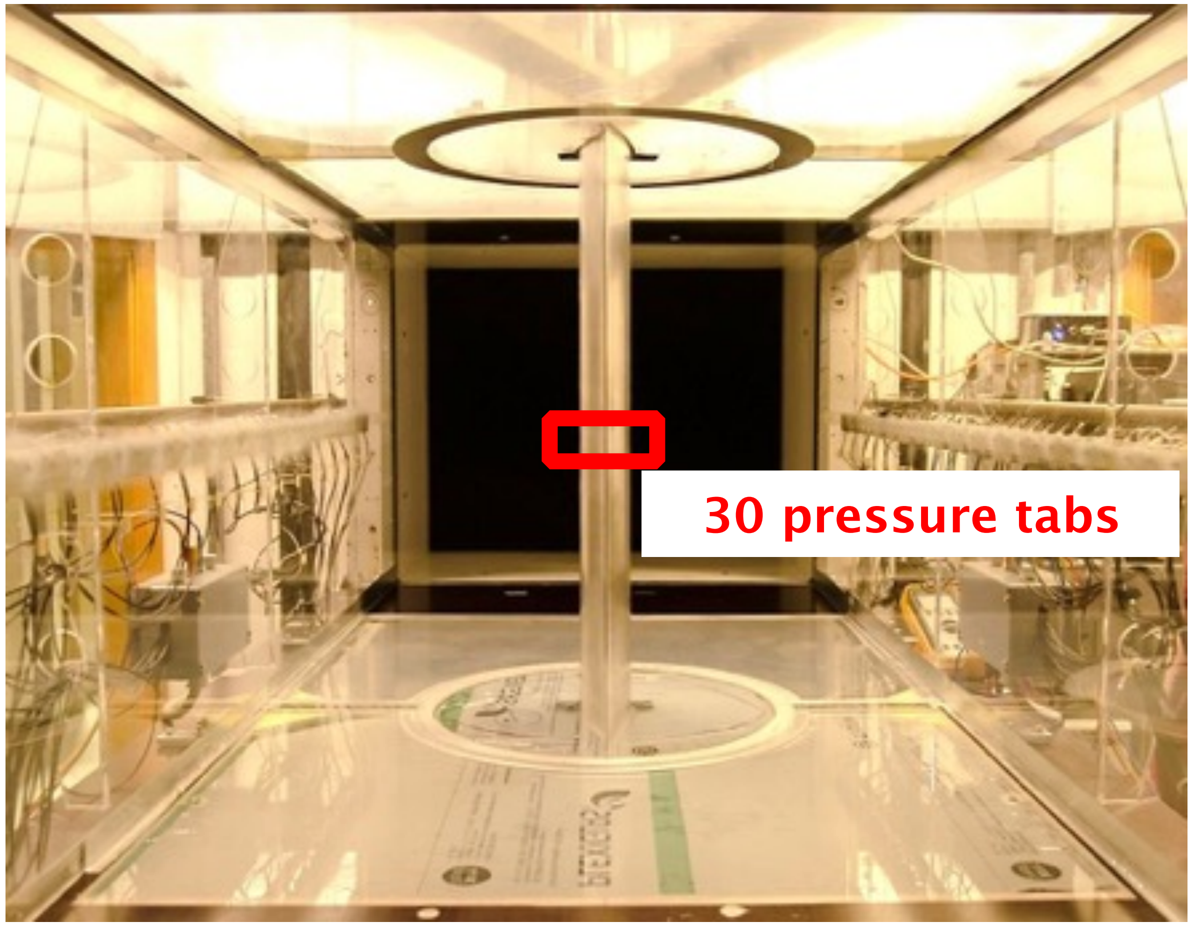
- 16 axes with square plates
- Independent movements with stepping motors
- Controlled by "excitation protocols"
- Reproducible wind fields with adjustable intermittency statistic
- Generation of atmospheric turbulence possible

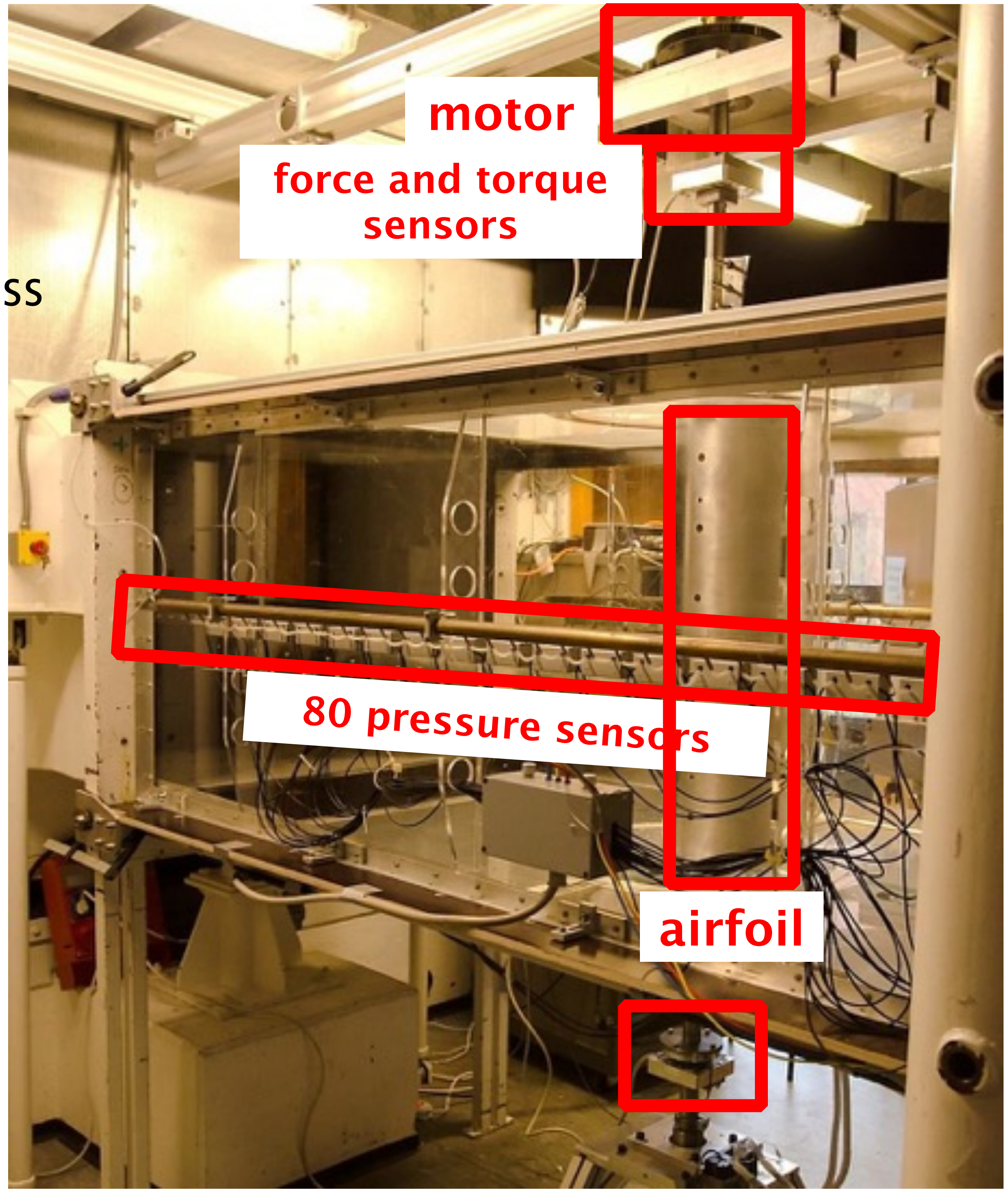




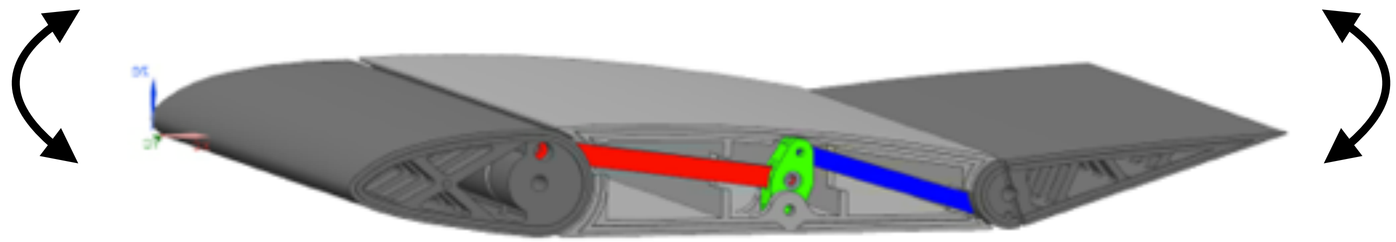
Wind tunnel and measuring techniques

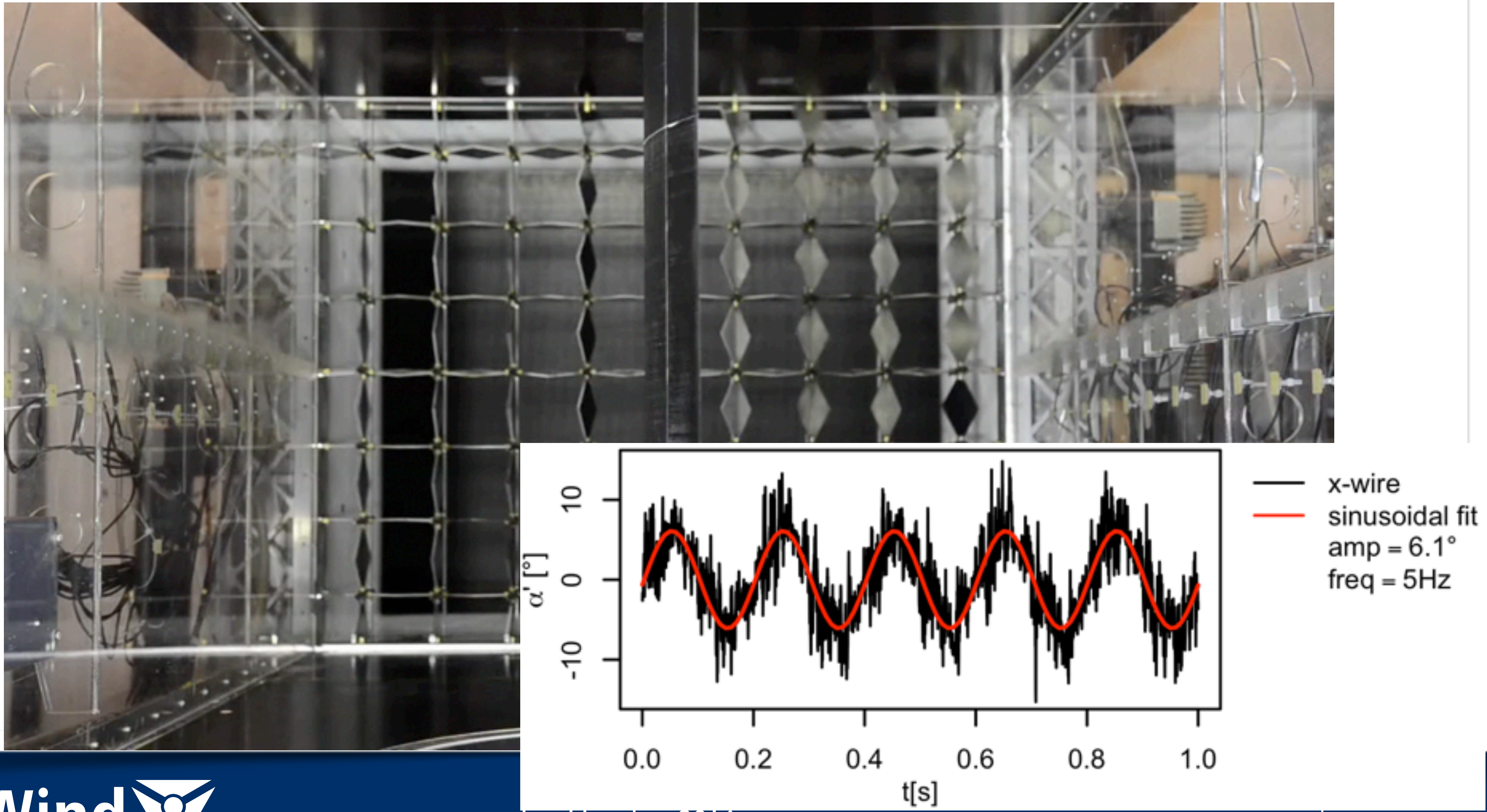
- Outlet 100 x 80 cm
- Up to 50 m/s, TI ≈ 0.3 %
- Closed test section (260 cm) with optical access
- Airfoil chord 30cm



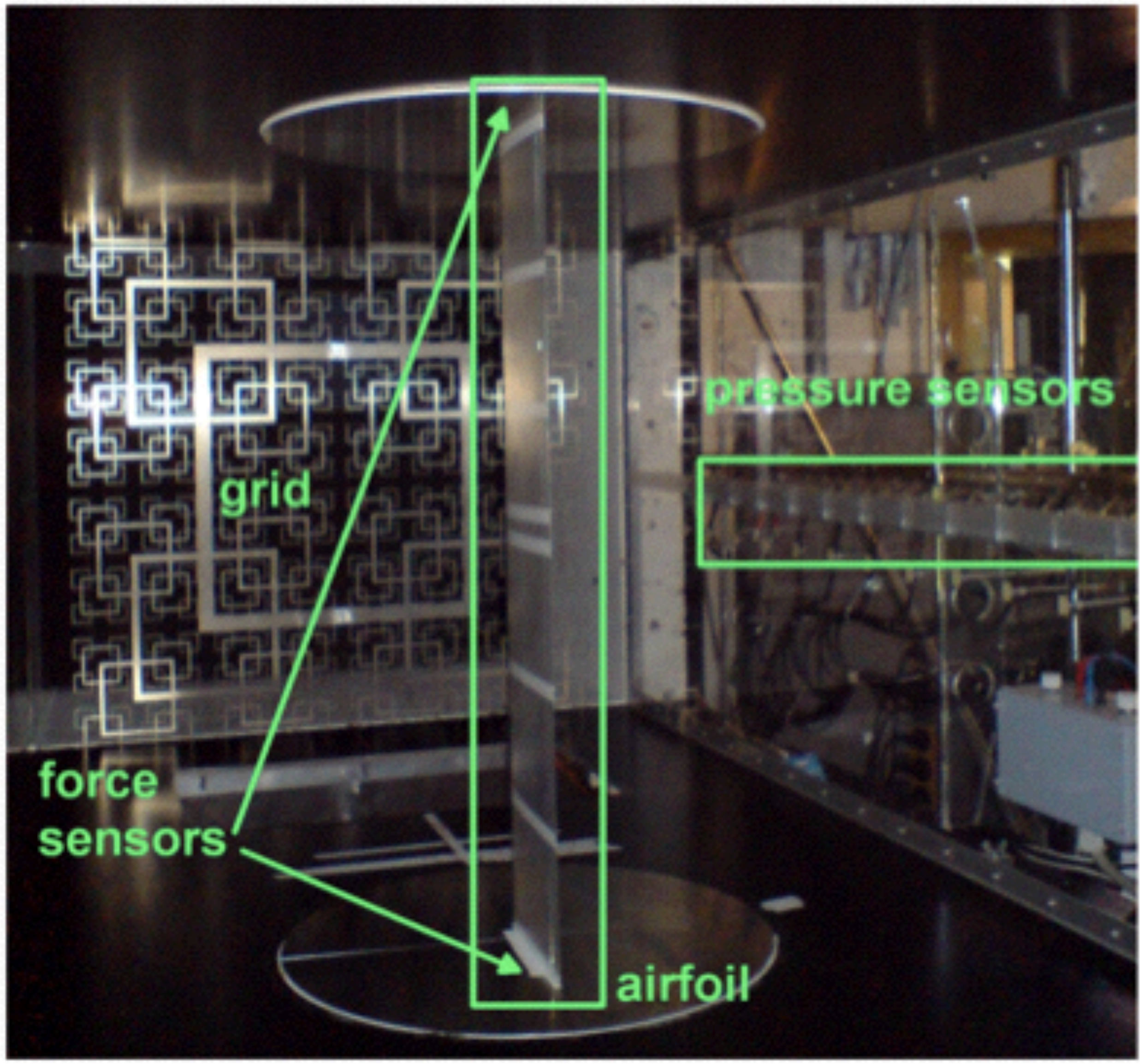


experimental setup

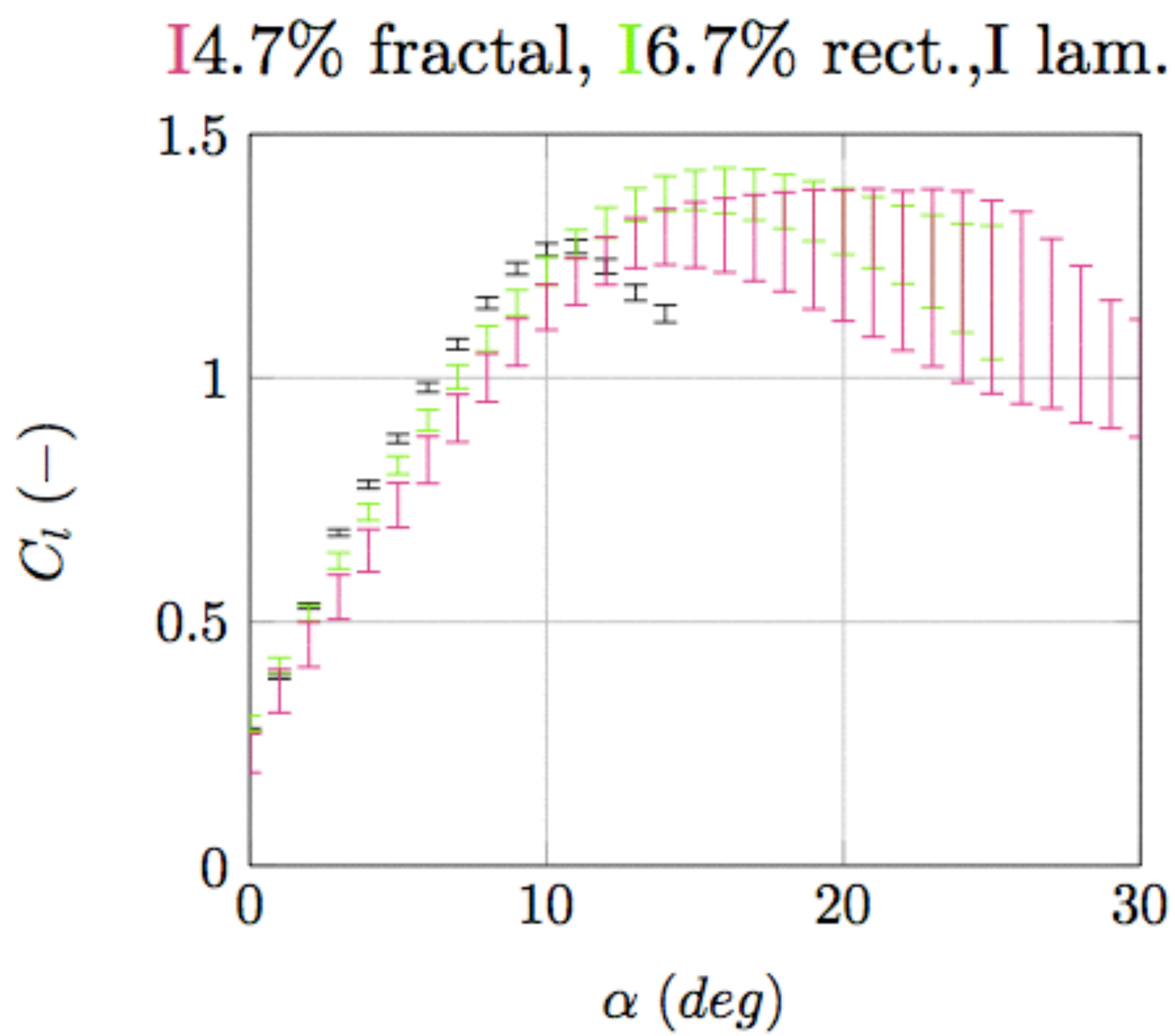




dynamic stall for different inflow



Homeyer EFMC 20 TU 17:00



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  - power output dynamics
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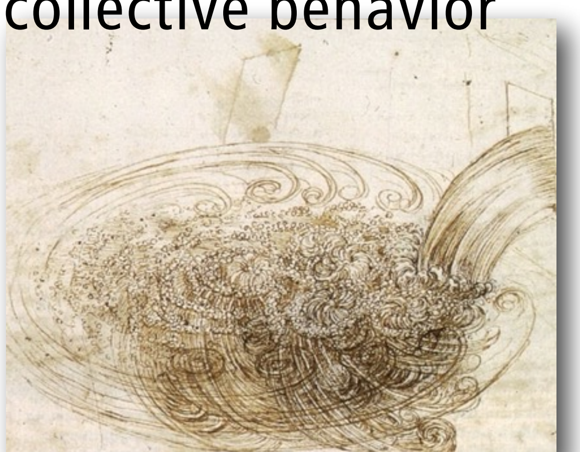
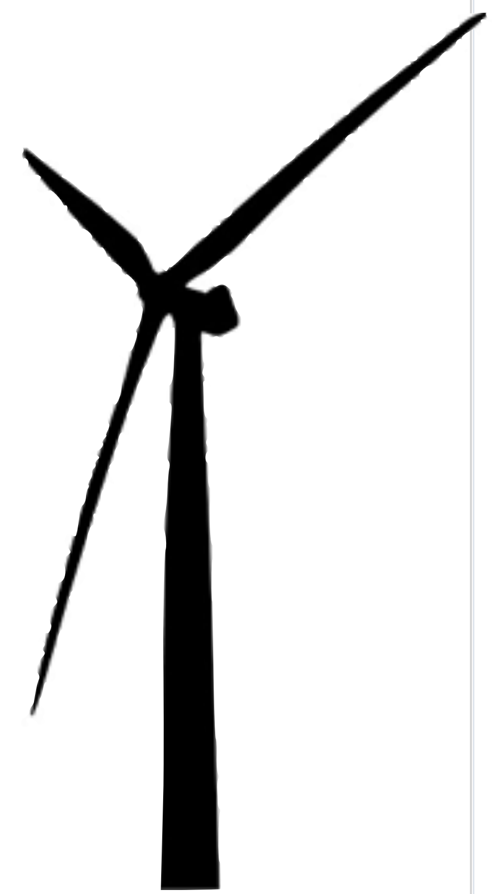




Research Alliance Wind Energy

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

DLR

ForWind Zentrum für Windenergieforschung

Fraunhofer IWES

Norddeutscher Wissenschaftspreis 2014

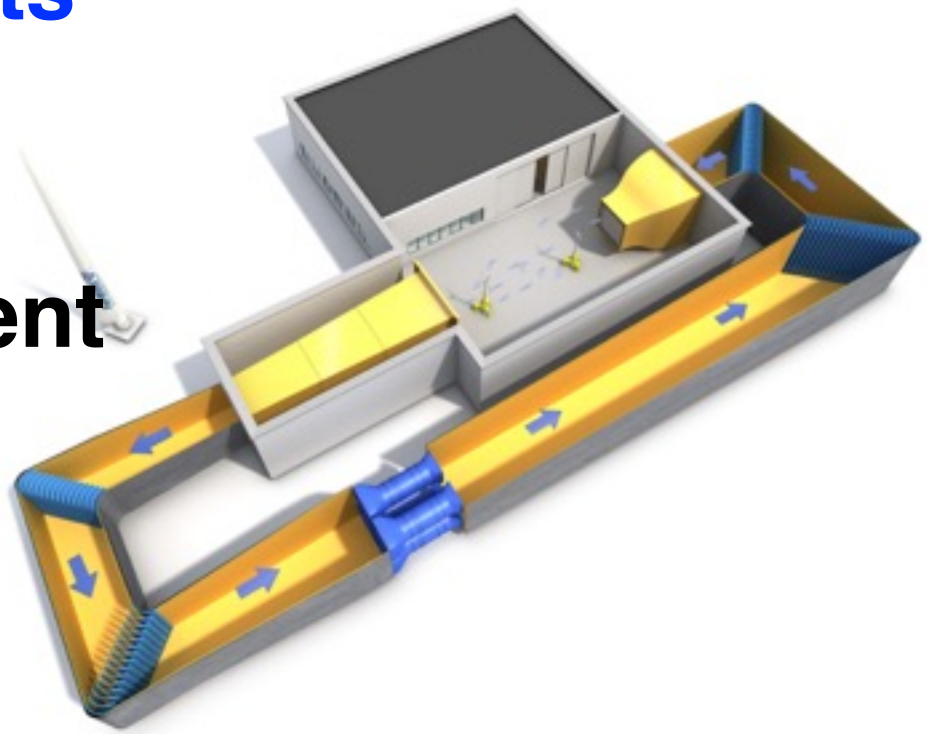
aim to combine

free field measurements

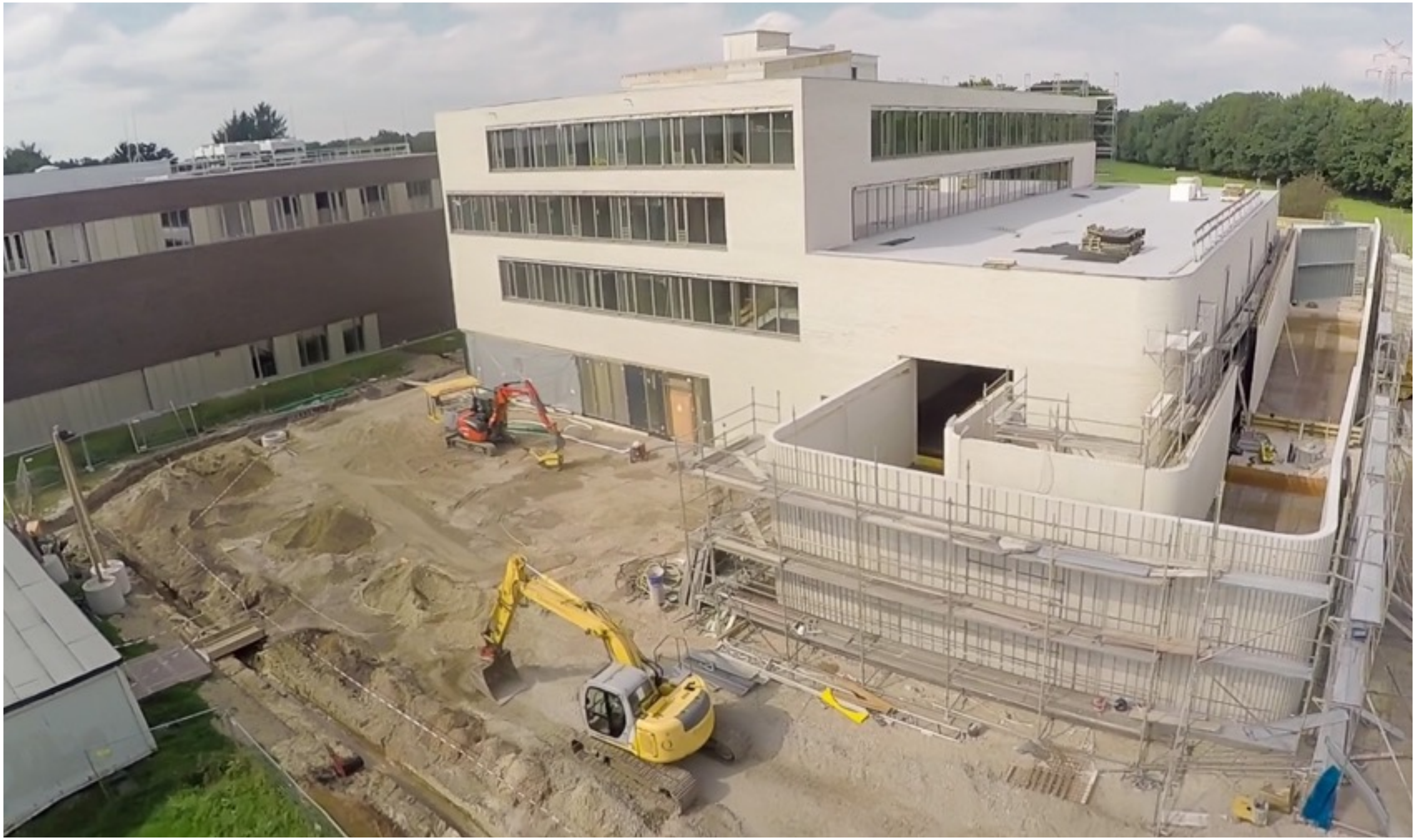
wind tunnel

CFD- simulations

- main focus on turbulent
- wind fields



Forschungsbau "Windlab"




STRAIGHT

turbulence is challenging for wind energy

European Commission

Bundesministerium für Wirtschaft und Energie

Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit

Niedersächsisches Ministerium für Wissenschaft und Kultur

VolkswagenStiftung

DFG

DBU