Turbulence Effecting Windturbines

modern wind turbines

power from wind

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

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

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

A cross section, ρ air density

modern wind turbines

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

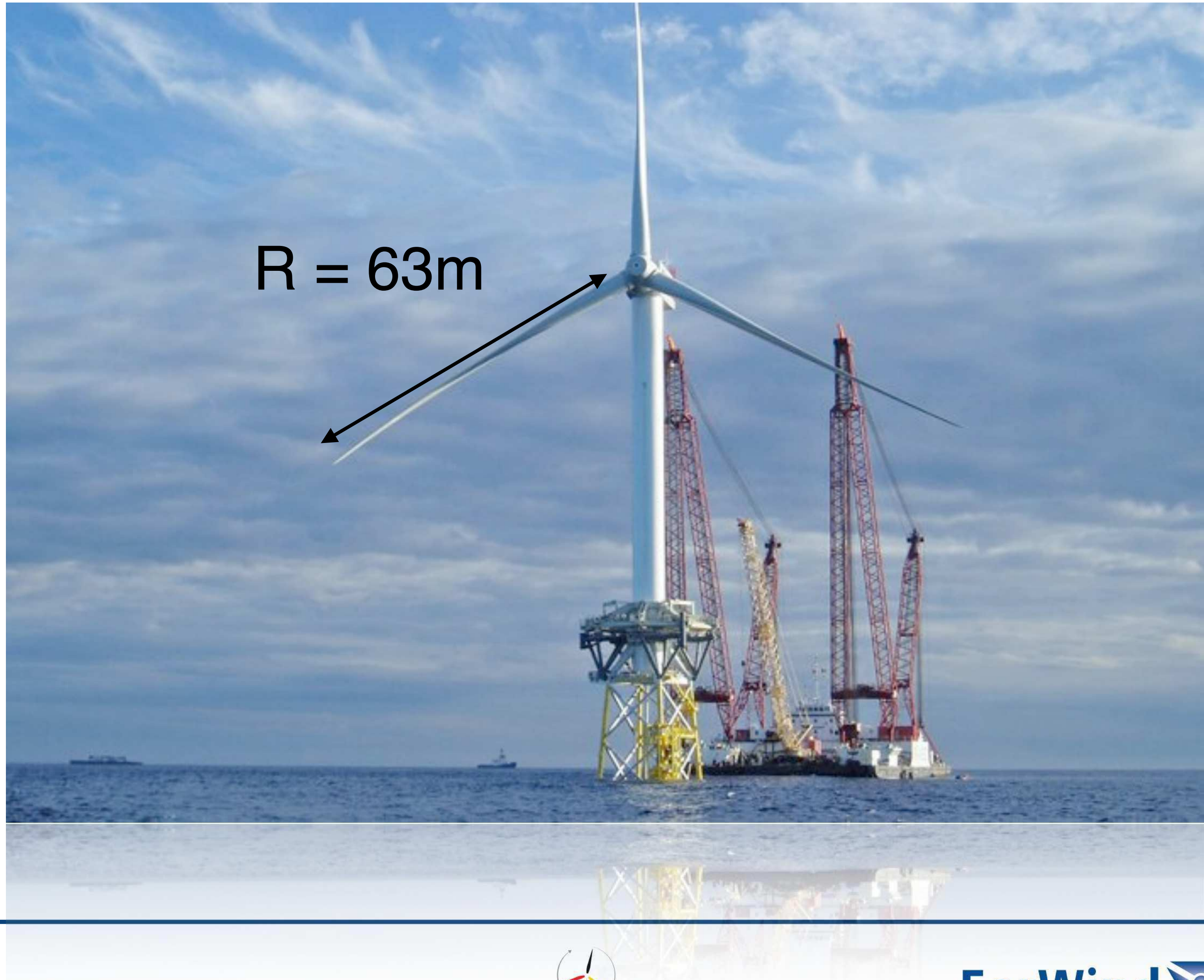
WEC

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

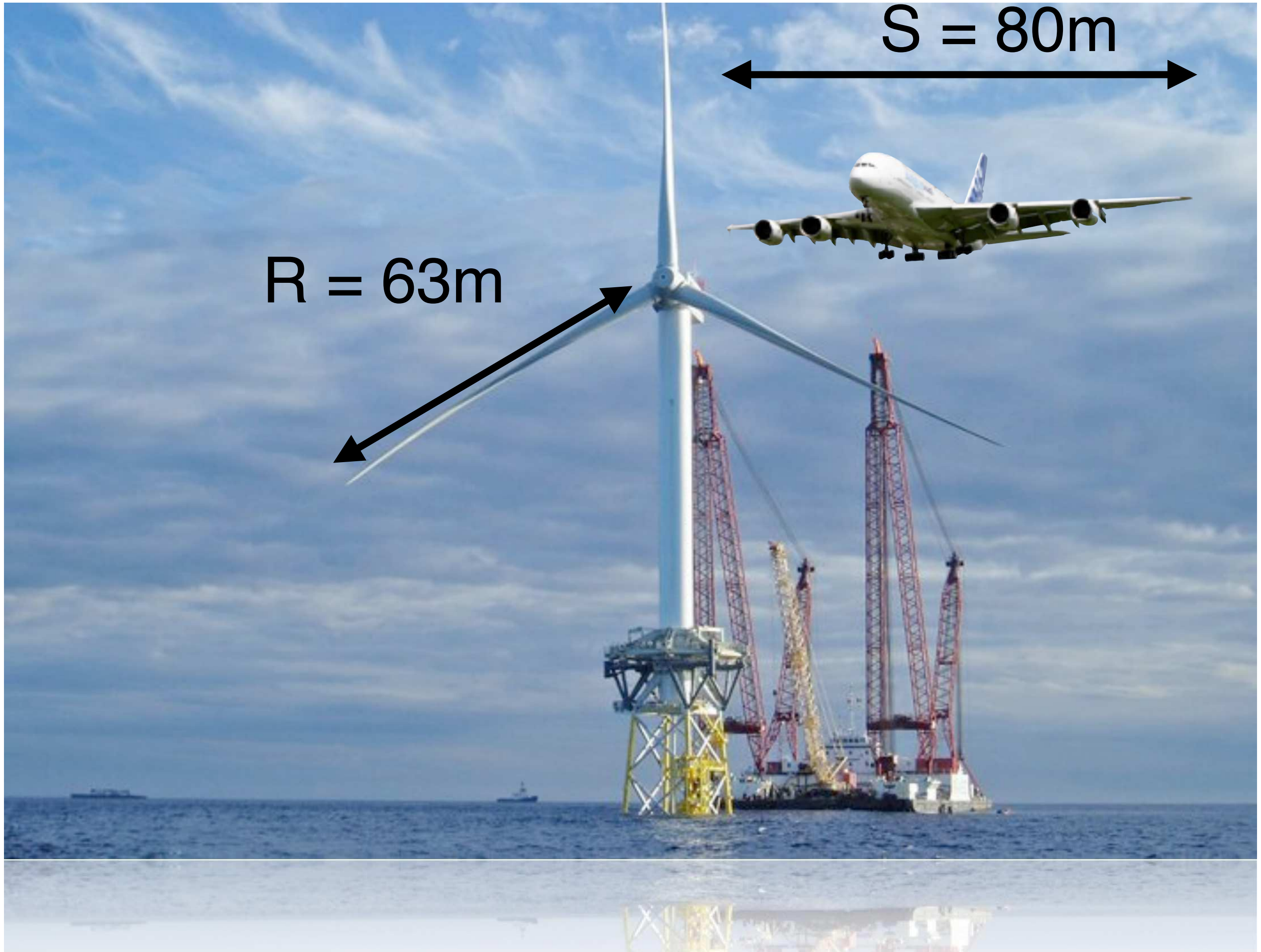
$c_P \leq 0.59$ Betz- Joukowsky limit

modern wind turbines

size : area = 12469 m^2 ⟶ 6MW - here 5MW turbine



modern wind turbines
size



modern wind turbines

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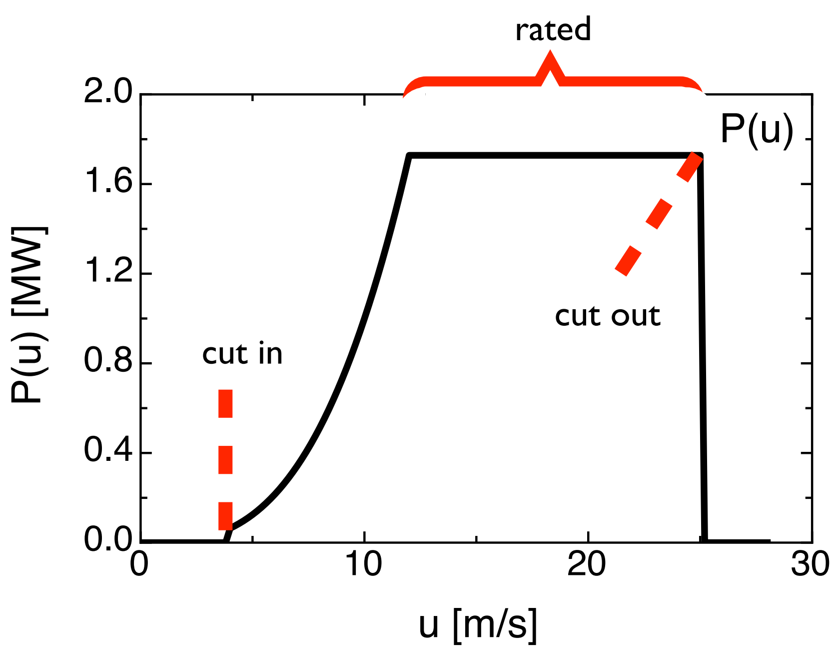
power characteristic



WEC

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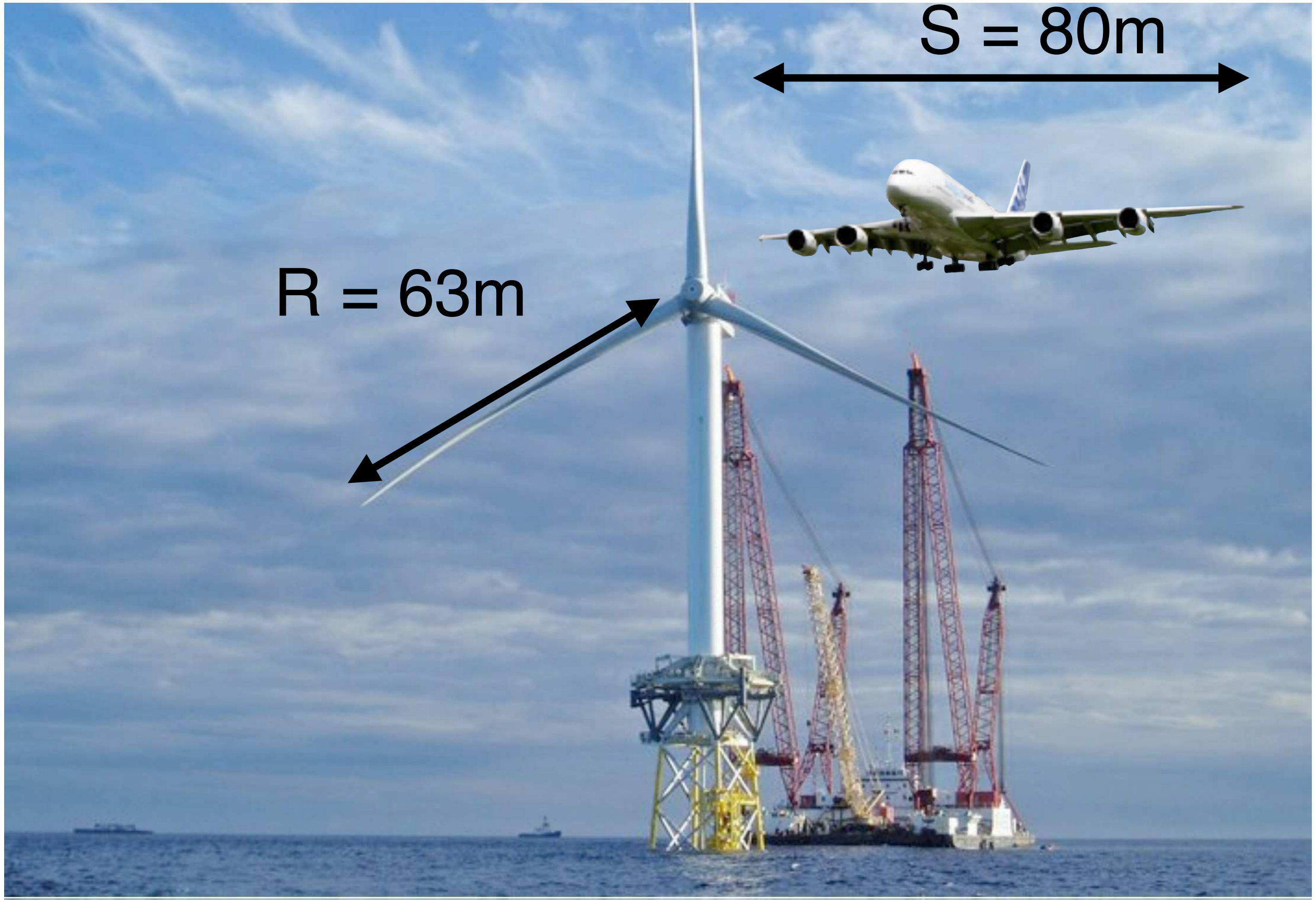
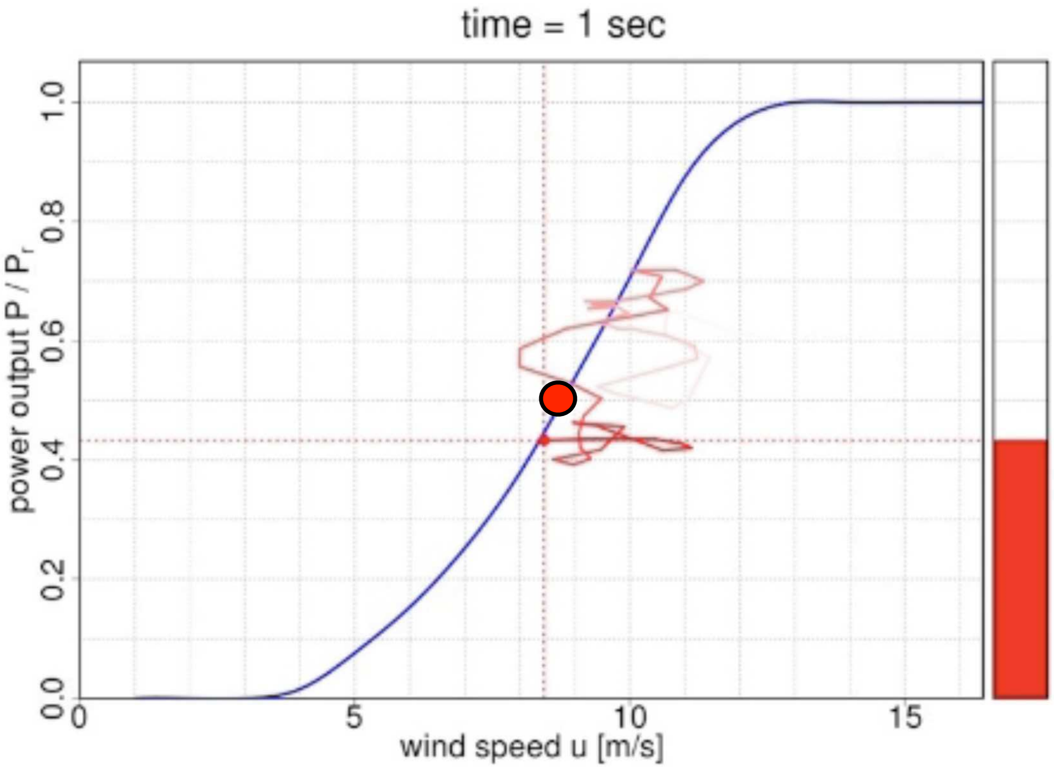
modern wind turbines
how dynamic is the conversion process?



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

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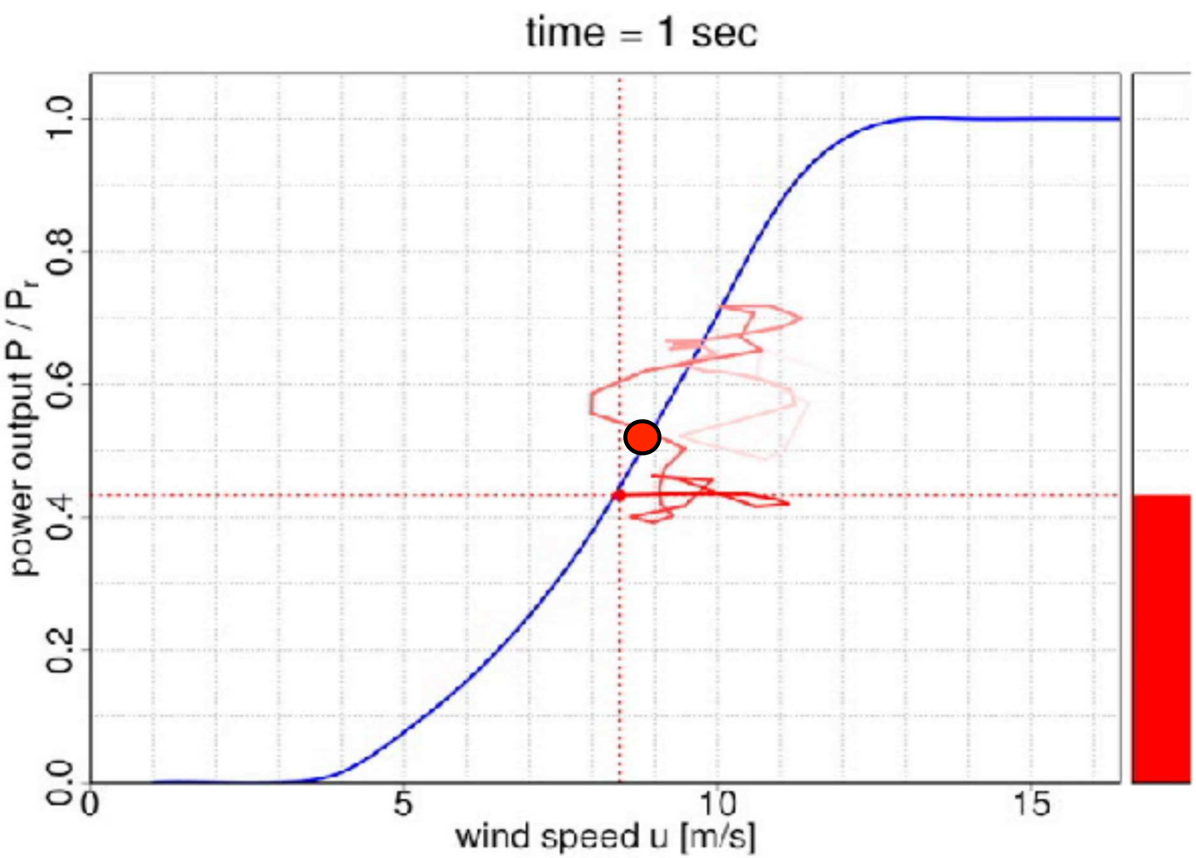

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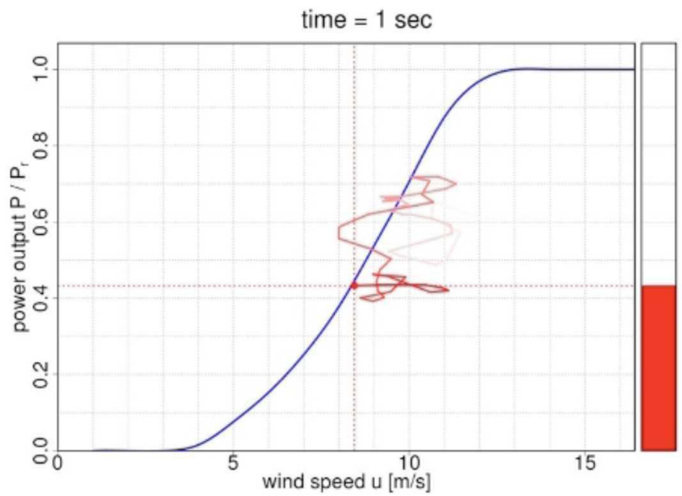
highly fluctuating power output,

what is the reason?

does turbulence of wind pay a role?



Turbulence one of 7 millenium problems

Clay Mathematics Institute
Dedicated to increasing and disseminating mathematical knowledge

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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

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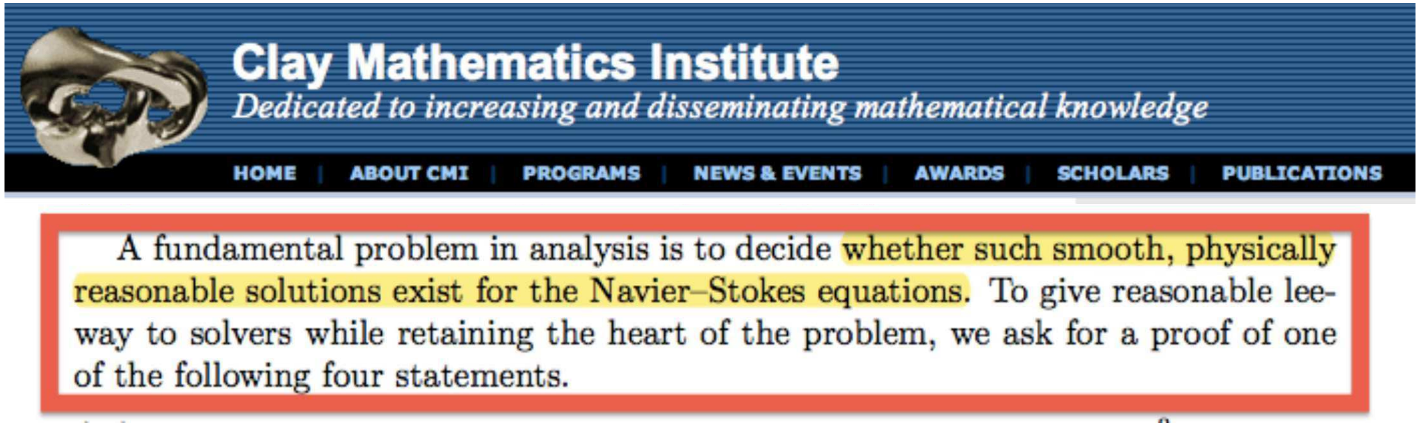
$$\frac{\partial}{\partial x} u(x) = lim_{r \to 0} \frac{u(x+r) - u(x)}{r}$$

Turbulence one of 7 millenium problems



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velocity increment

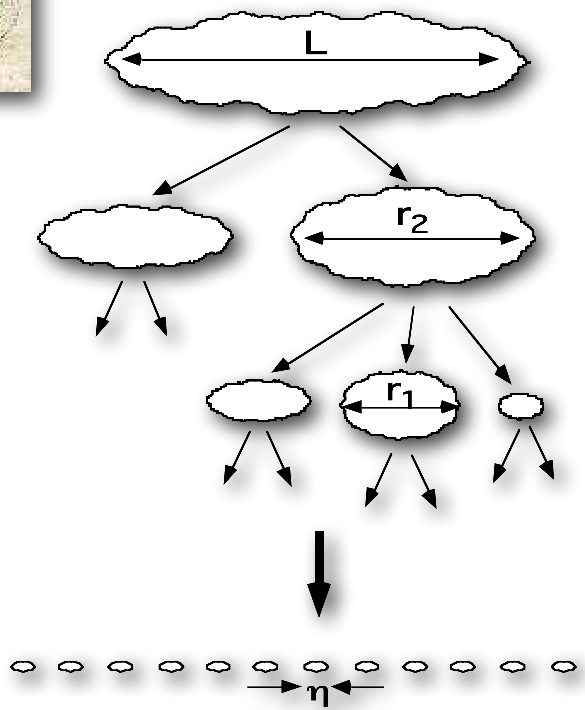
$$= lim_{r\to 0} \frac{u_r}{r}$$

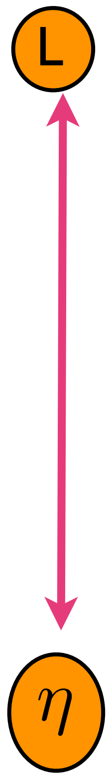
have to understand

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

homogeneous isotropic turbulence -- hit

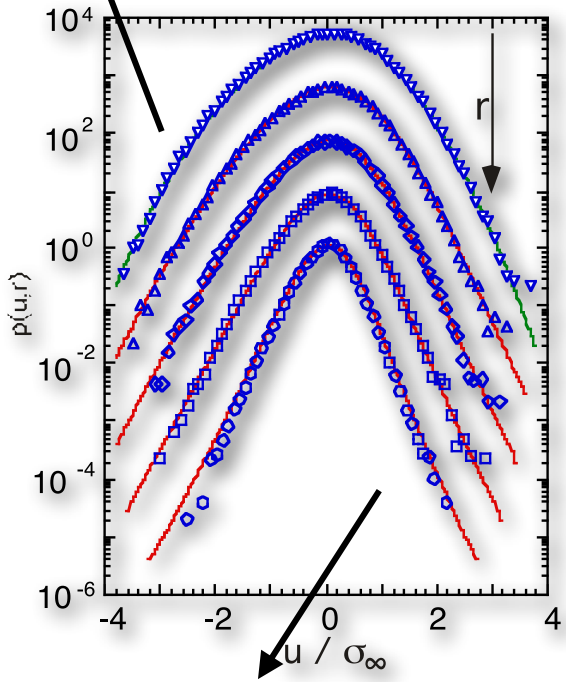
- r - depend of velocity increments: $u_r = u(x+r) - u(x)$
- cascade and statistics of increments





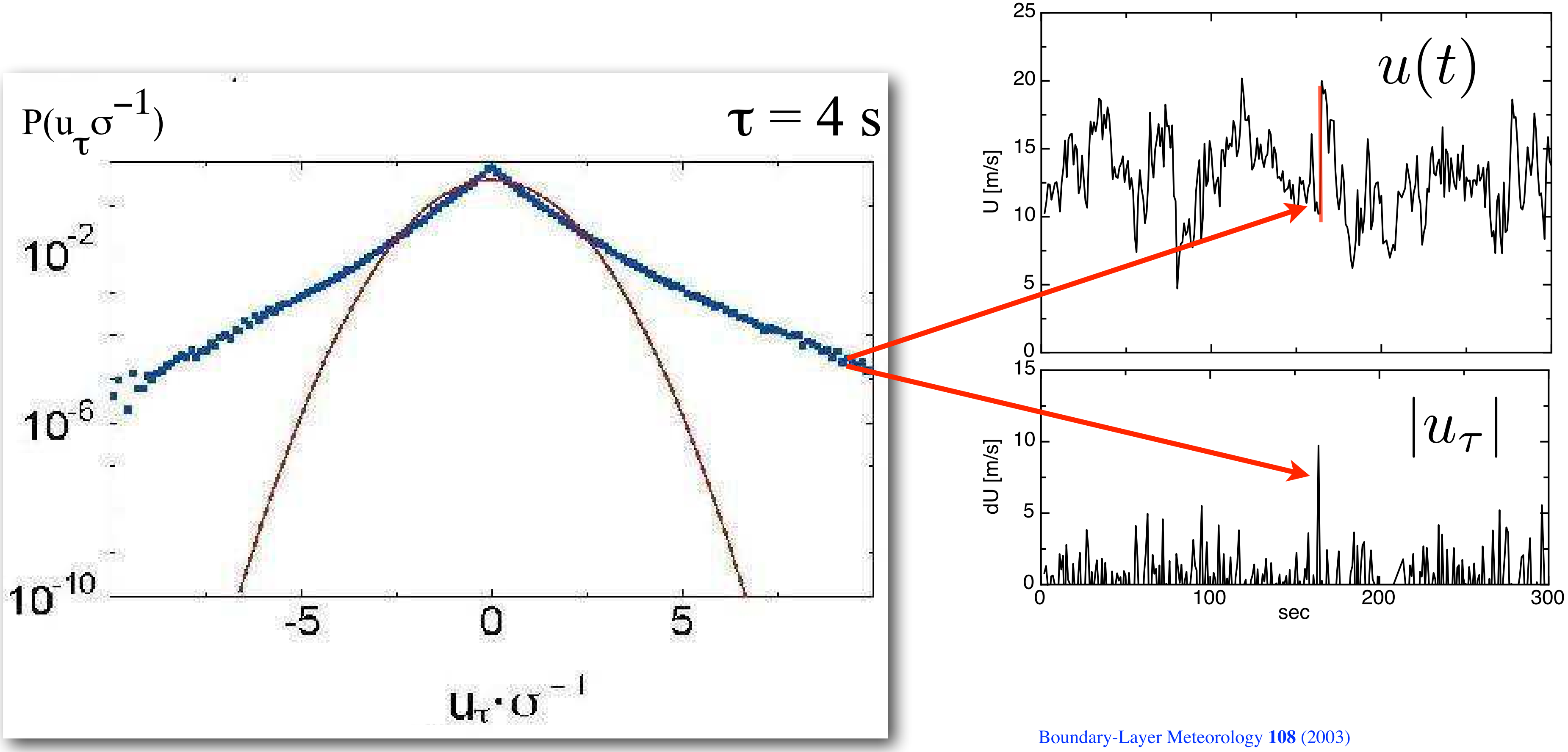
Gaussian

A.N. Kolomogorov



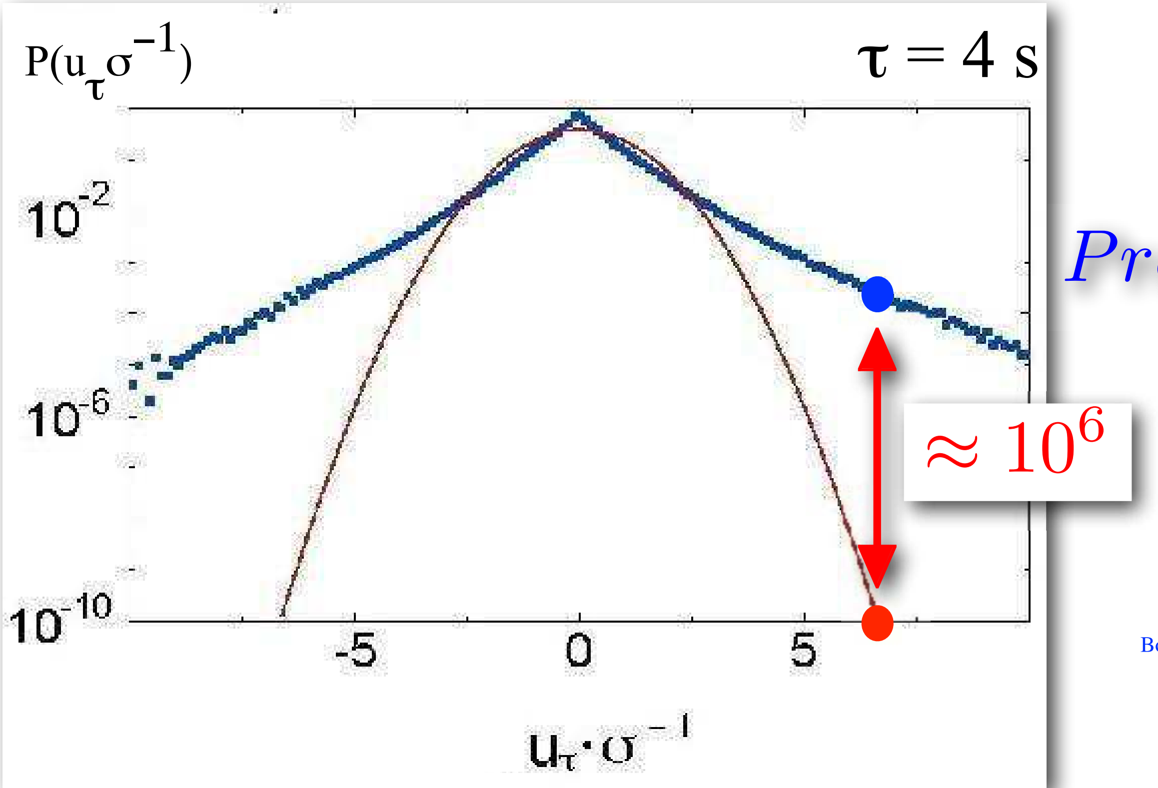
intermitent

statistics of turbulent wind: $u_\tau = u(t+\tau) - u(t)$



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

statistics of gusts



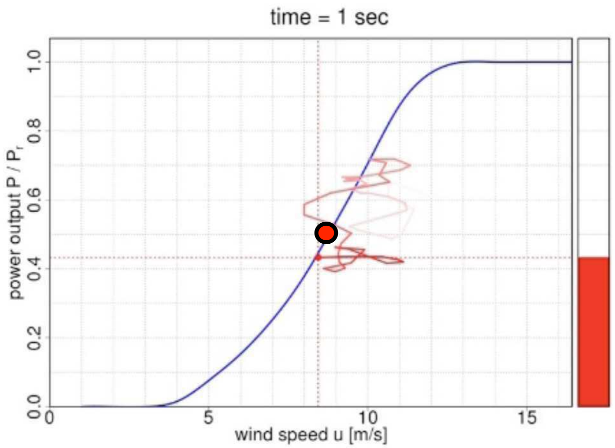
$Prob(u_\tau > 6\sigma) \approx 10^{-4}$ → 1/day

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

$Prob(u_\tau > 6\sigma) \approx 10^{-10}$ → 1/3000 years

what is the power statistics?

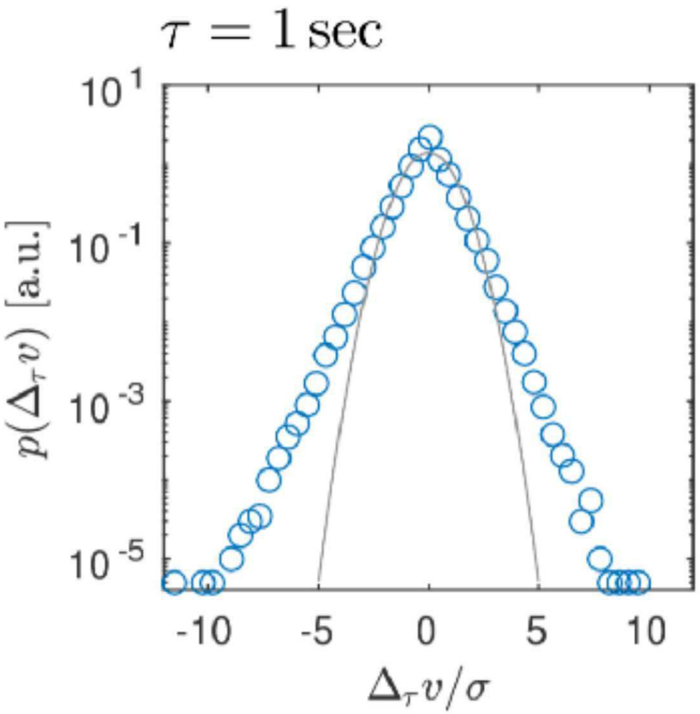
$$P_{WT} = \frac{1}{2} c_p(\lambda)\, \rho\, u_{wind}^3 \cdot A$$

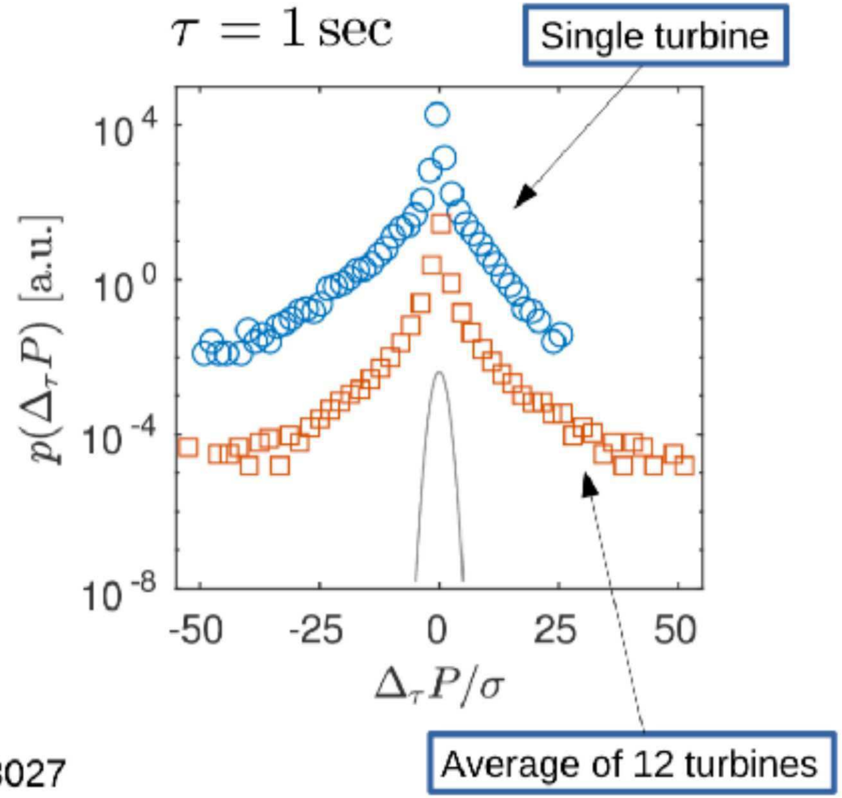


power output of wind energy

turbulent power dynamics

$$p(P_\tau)$$

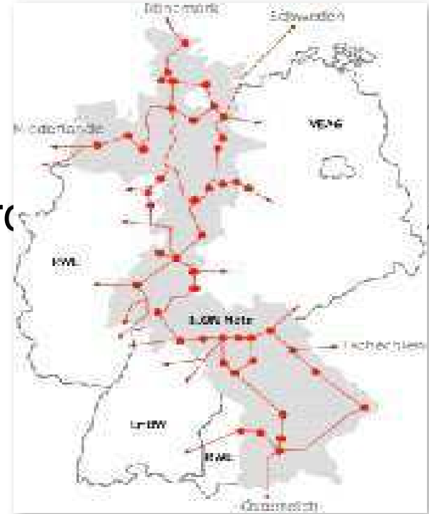




M. Anvari *et al.*, *New J. Phys.* **18** (2016) 063027

handling high frequency

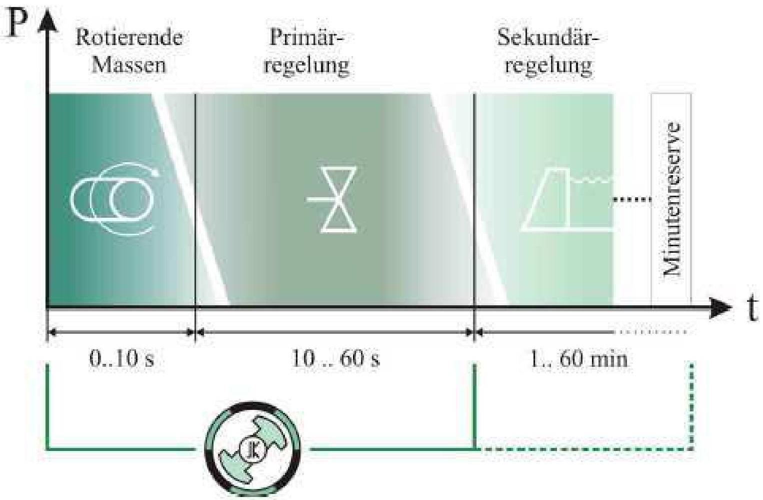
ch - n ntr t local renewa



short time grid frequency

stabilisation by rotating mass of synchronous generators — grid frequency changes in the range of mHz

www.netzfrequenzmessung.de



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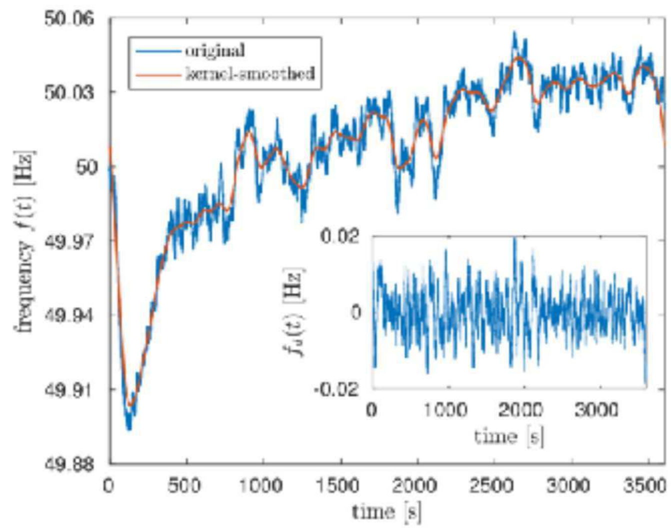
- intermittency in grid - measurements

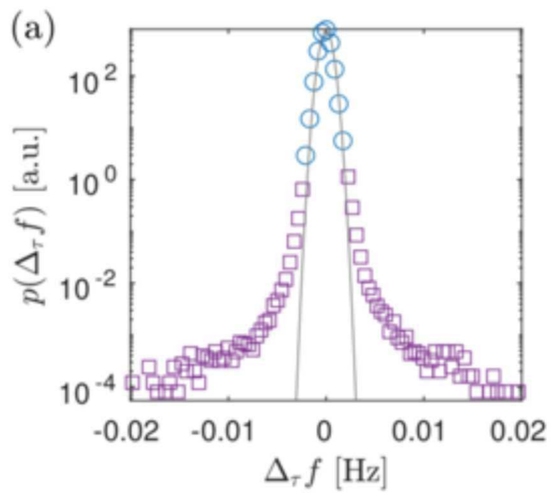
analysis of the grid frequency

measurement at the plug connector

- frequency increments

$$\tau < 1sec$$



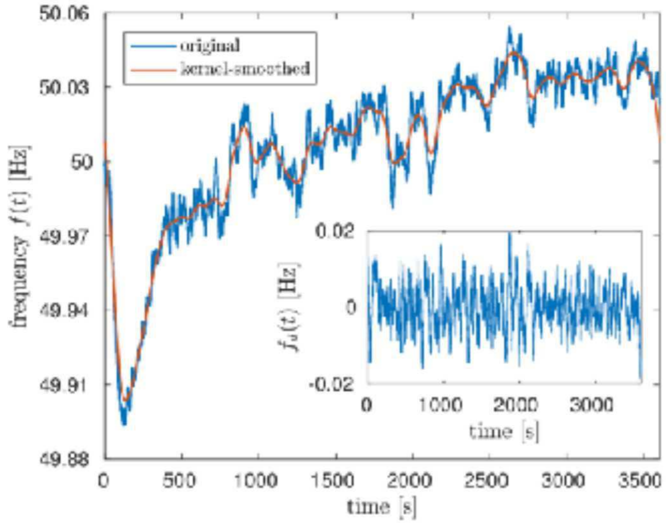


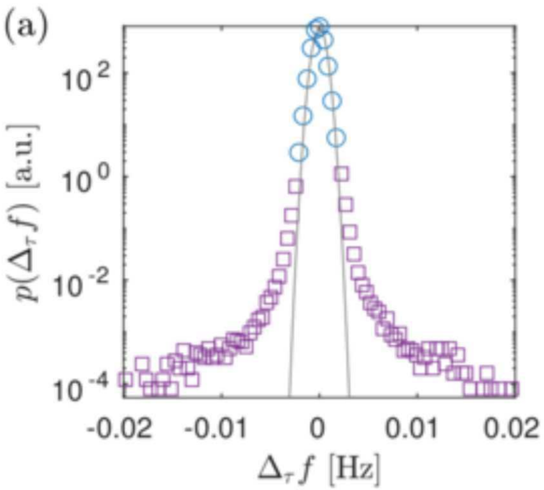
H. Hähne, et al. Europhysics Letters 121, 30001 (2018)

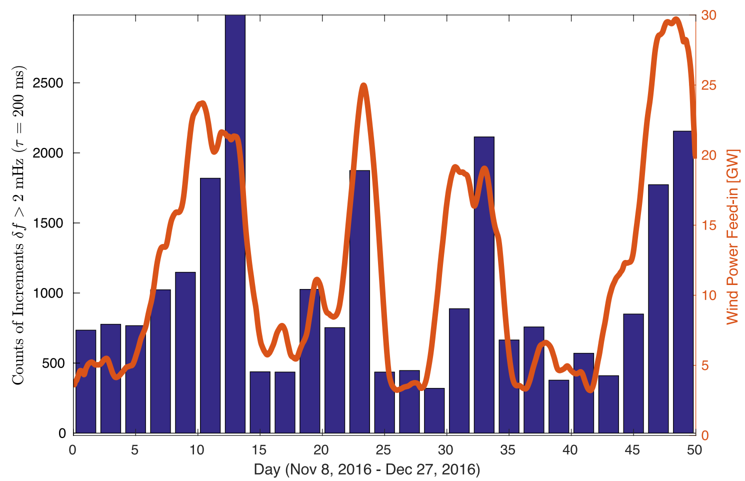
- intermittency in grid

analysis of the gird frequency

— clear fingerprint of renewable energies







H. Hähne, et al. Europhysics Letters 121, 30001 (2018)

wind energy is driven by turbulence

Inflow is energy resource

claim - need to understand turbulence
and other details of the wind

Oldenburg

- free field measurements. Lidar
- CFD - turb inflow LES
- wind tunnel, active gid