Windenergie und Turbulenzprobleme

17th of October 2024, Bad Honnef

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Forschungsverbund Windenergie

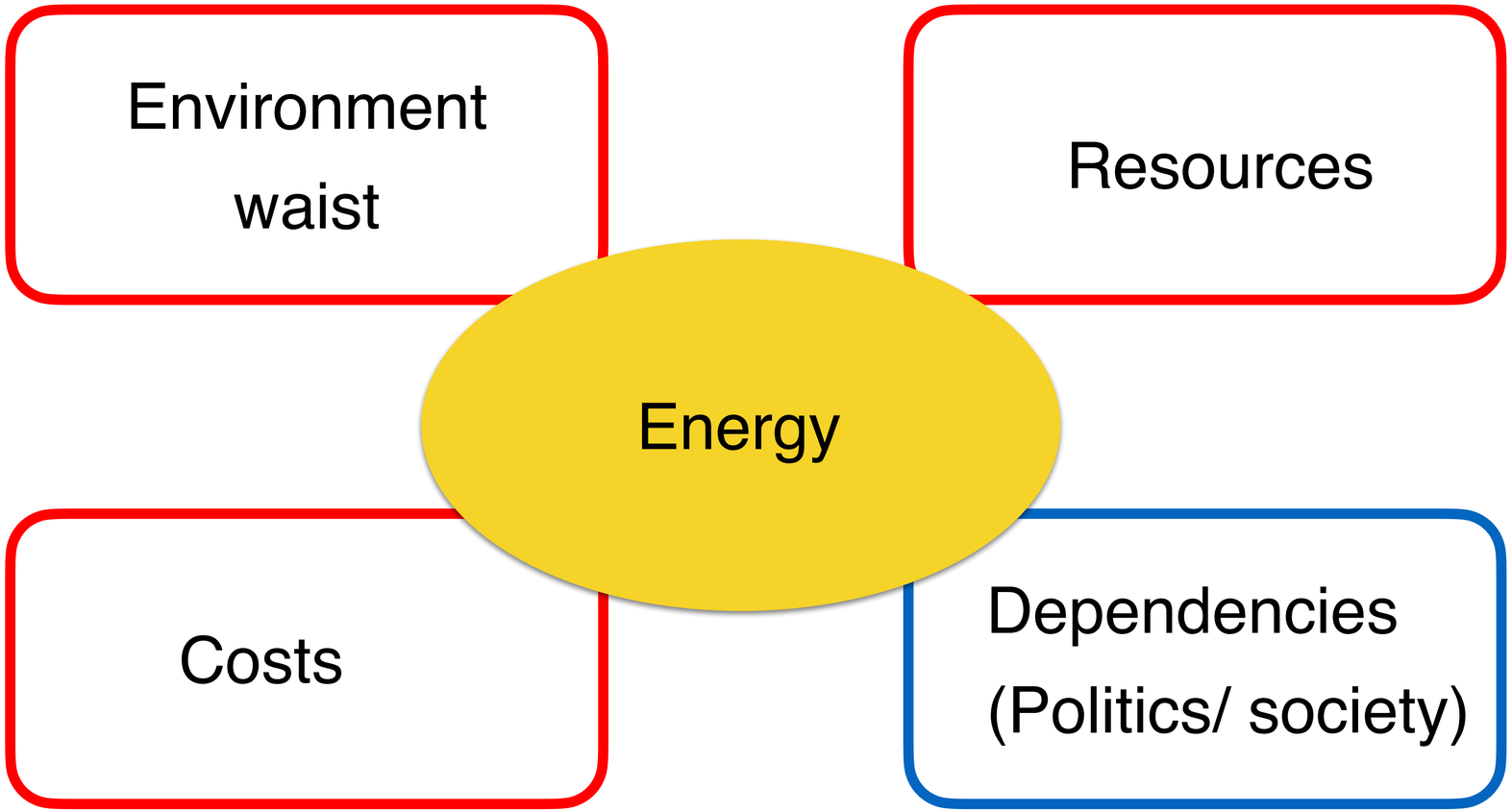
@ForWind_DE

DLR Deutsches Zentrum für Luft- und Raumfahrt

ForWind Zentrum für Windenergieforschung Bremen Hannover Oldenburg

Fraunhofer IWES

Energy discussion



New? - Carter April 18, 1977

Address to the Nation on Energy

Aim

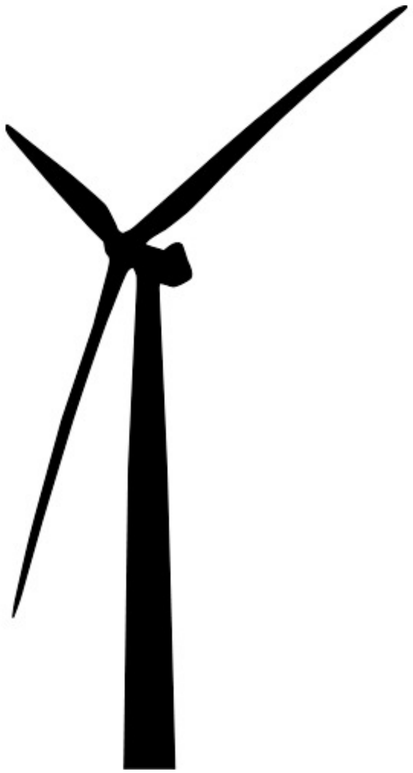
wind energy: aim of the talk

- some background informations on wind energy
- WE is not the solution of all energy but has some promising aspects
- the need of fundamental physics

Wind energy

- is too expensive
- is intermittent
- is no physics
- …

Content



Part 1: wind energy

- basic concept of wind energy converters (WEC)

- system and costs

Part 2: fluctuating wind energy - challenges for physics

How does a modern wind turbines work?

power from wind

$$P_{wind} = \dot{E}_{wind}$$

$$= \frac{1}{2}\dot{m}u^2 = \frac{1}{2}\rho A u^3$$

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

ρ density of air

A rotor area

u wind speed

How does a modern wind turbines work?

power from wind

$$P_{wind} = \dot{E}_{wind} = \frac{1}{2}\dot{m}u^2 = \frac{1}{2}\rho A u^3$$

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

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

$c_P \leq 0.59$ Betz- Joukowsky limit For 12m/s : about 500 W/m²

Needs to understand:

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

Precise wind prediction

https://map.neweuropeanwindatlas.eu

modern wind turbines

area = 12469 m²

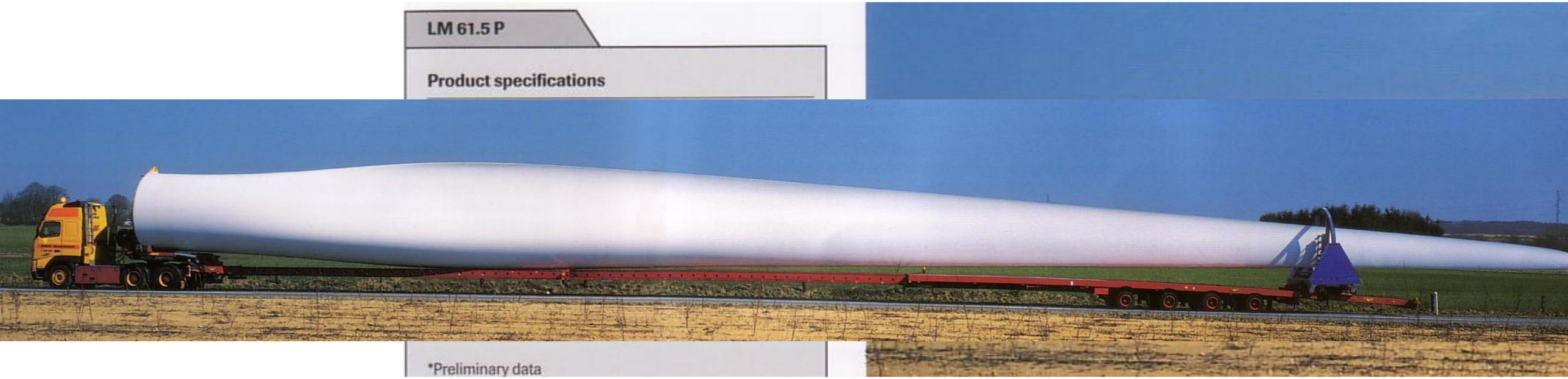
$$P_{wind} \leq 12MW$$

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

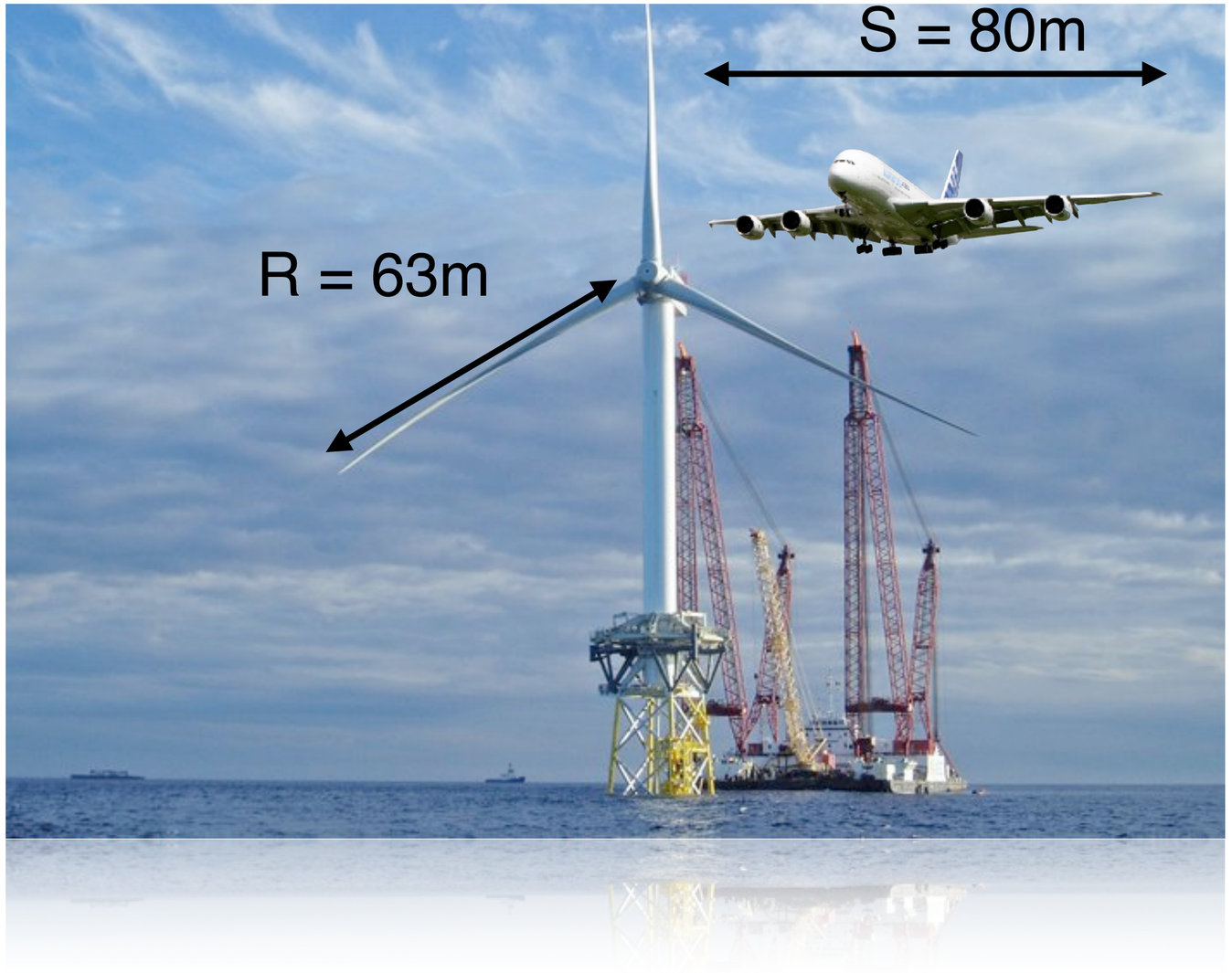
$$c_P \leq 0.59$$

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

60m rotorblade



modern wind turbines



modern wind turbines

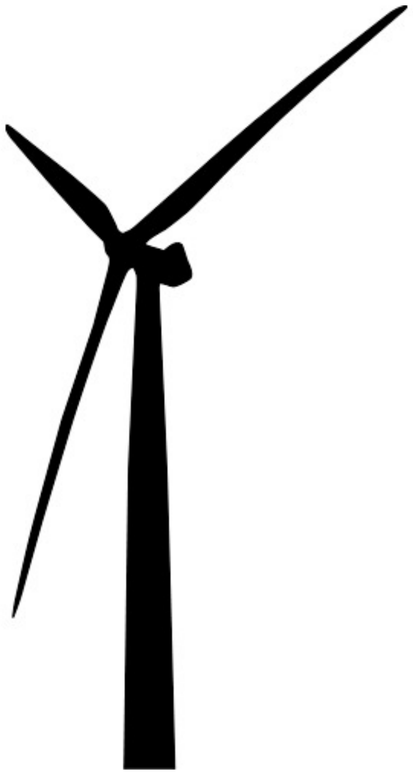
2019 - GE Haliade-X 12MW:
R= 110m

- biggest wind turbine 2021
- GE: Haliade- X 15MW
- 2024: Dongfang. 18MW

Haliade-X prototype GE.com

Offshore Wind park

Content



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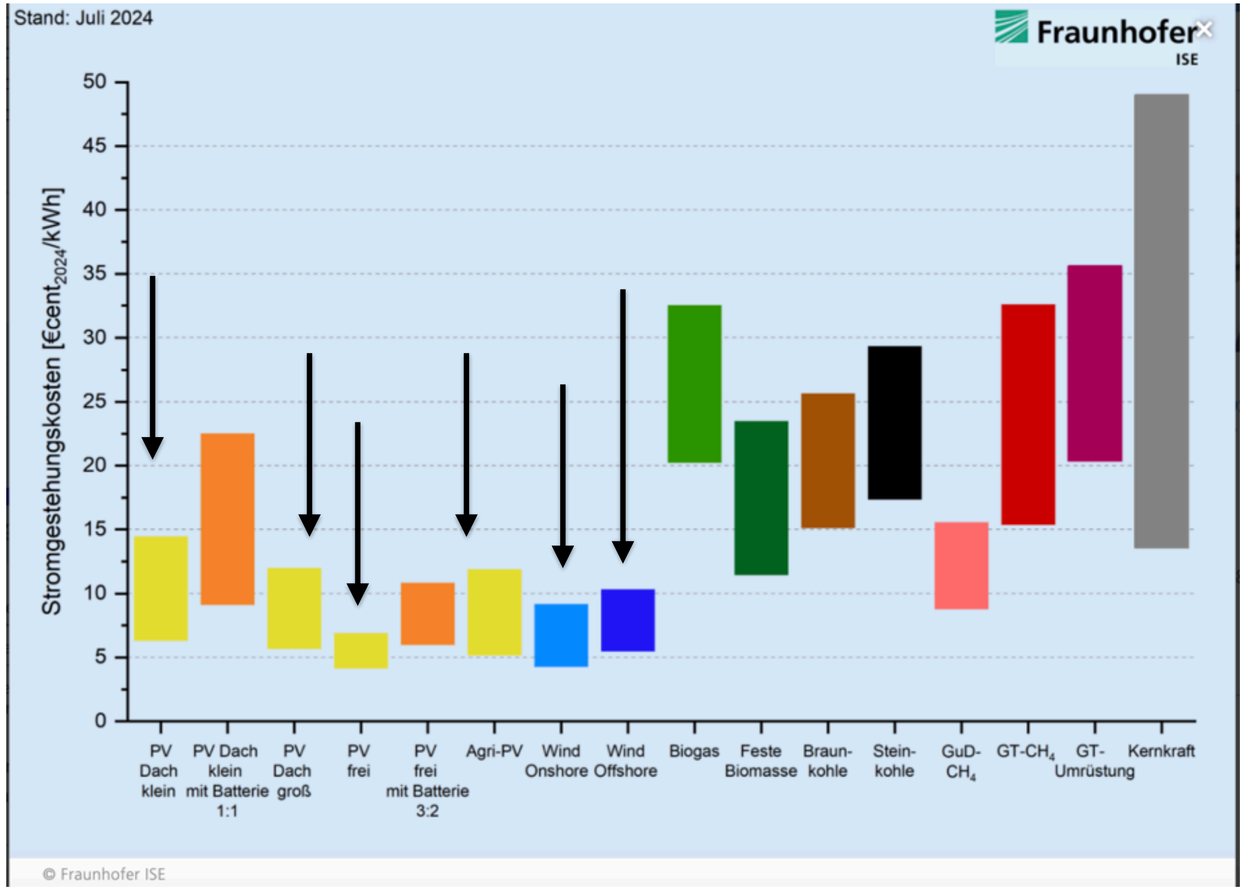
- basic concept of wind energy converters (WEC)
- **system and costs**

Part 2: fluctuating wind energy - challenges for physics

Leveled osts of wind energy



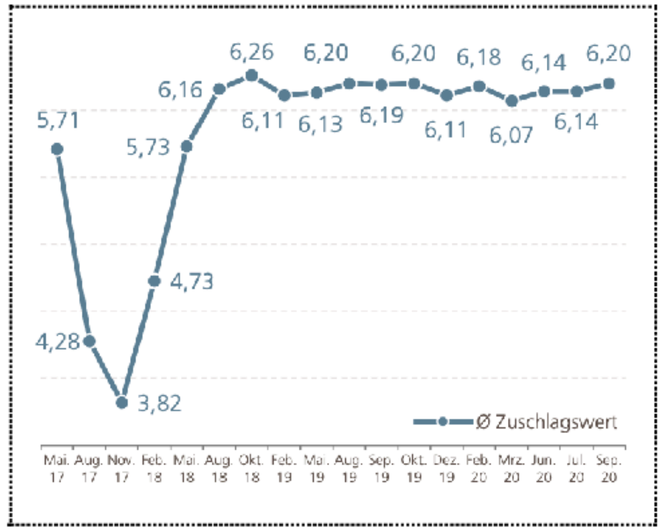
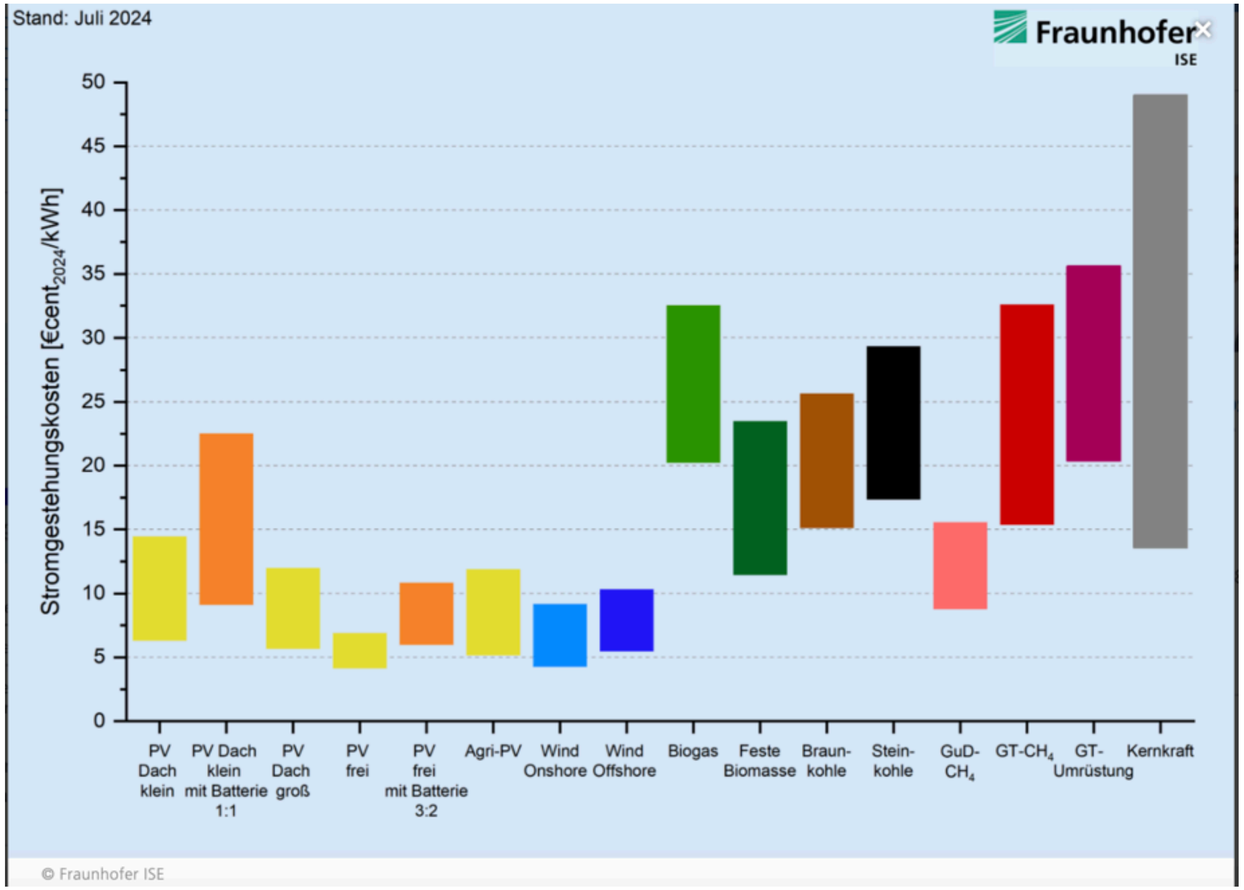


Abbildung 3: Mengengewichtige Zuschlagswerte [in ct/kWh] der Ausschreibungsrunden, aus denen bis dato tausend Anlagen in Betrieb gingen; Daten: BNetzA, Grafik: FA Wind

Costs of wind energy

wind energy one of the cheapest el. energies



-> costs 5 cent/kWh

Why is wind so cheap?

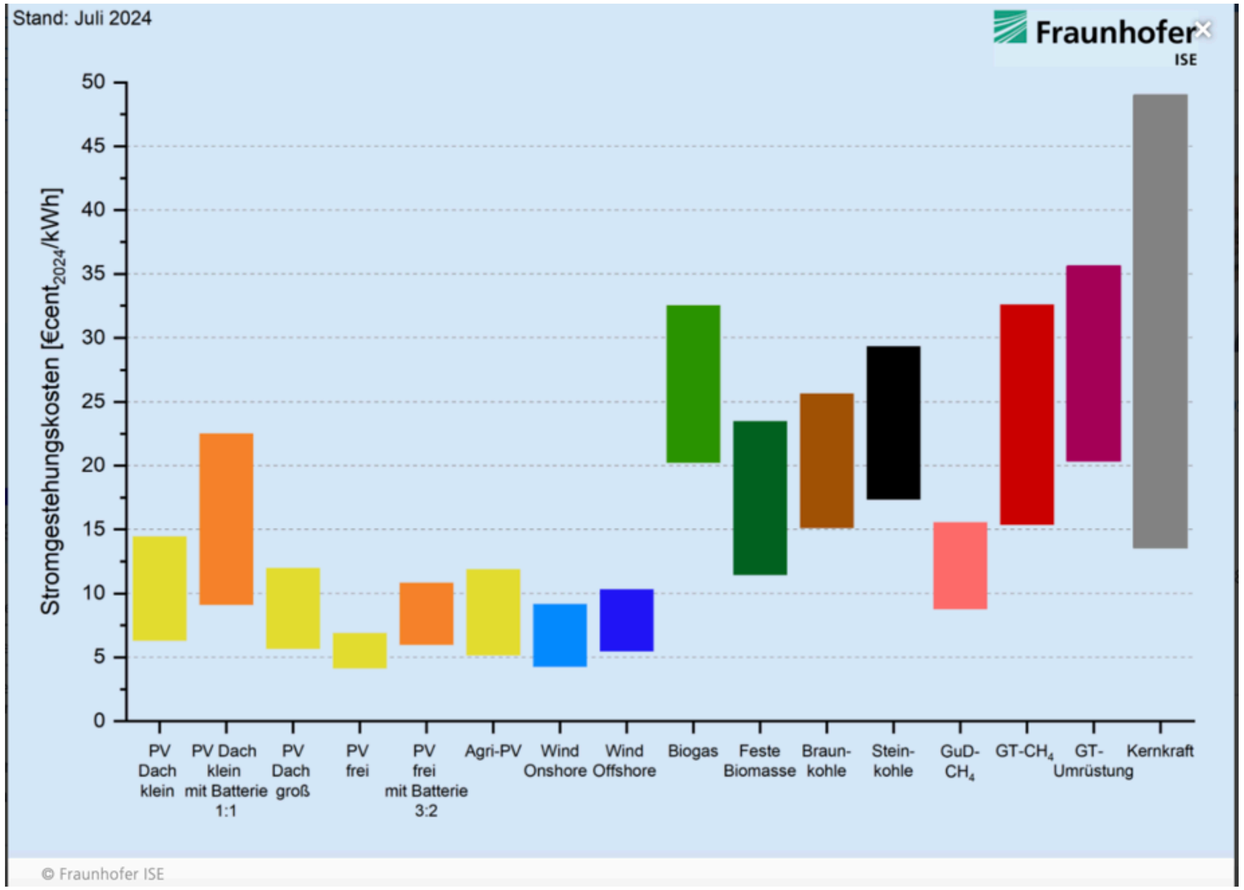
- resource 0cent/kWh

- 1-2 € / installed Watt - running time /Year - 2000 h => 2kWh ≈ 0.1 € or 10% of investment

Costs of wind energy

wind energy one of the cheapest el. energies

-> costs 5 cent/kWh



Compared to other resources:

Oil - 5cent/kWh

Gas 3 cent/kWh

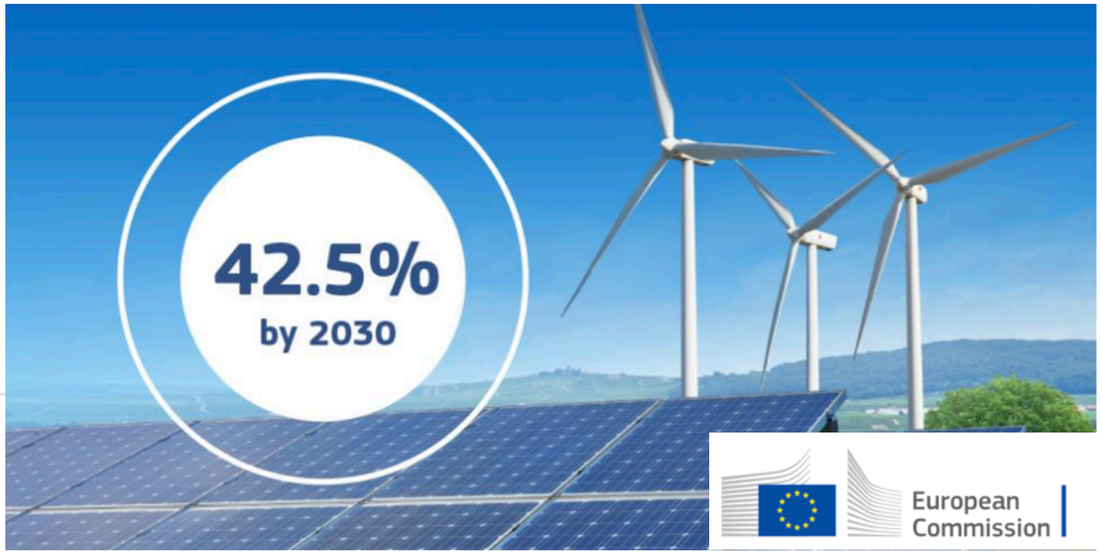
Coal 1-2 cent/kWh

Electric energy: 1kWh wind 3 kWh fossil

Wind is cheaper than fossil resource

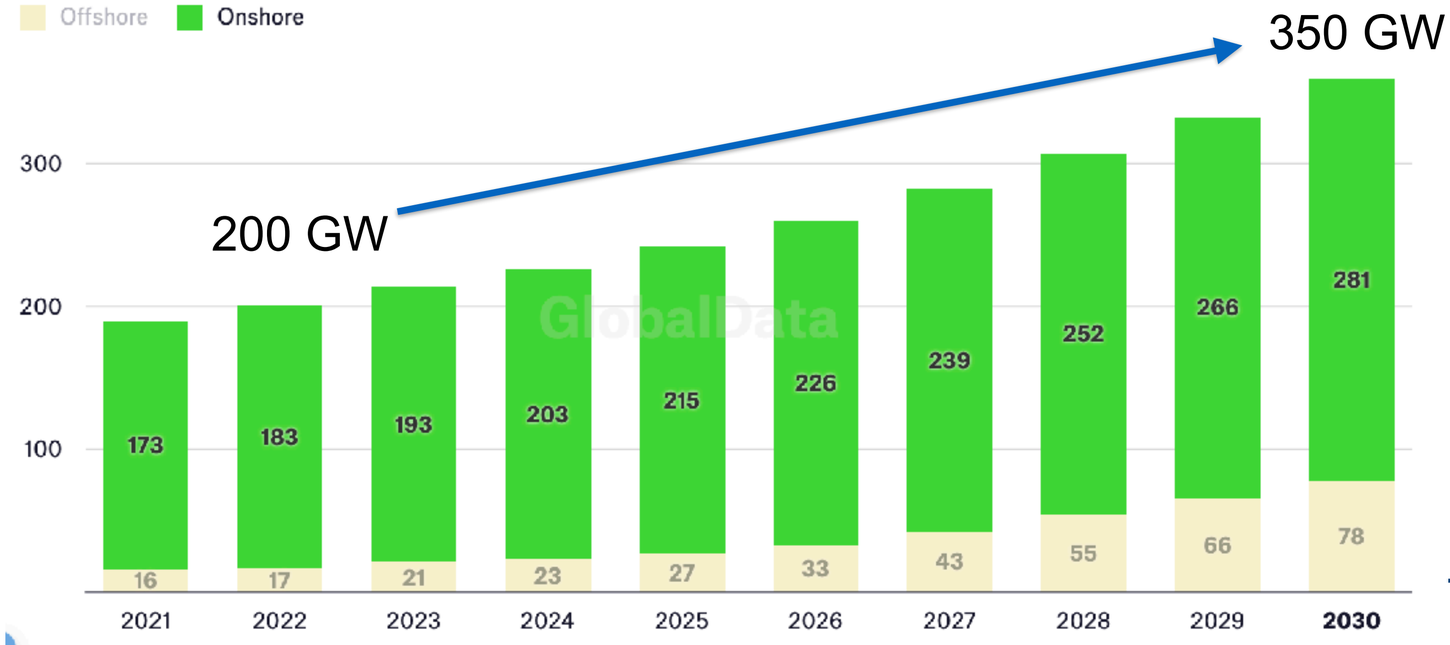
Wind energy

European renewable target for 2030



EU wind growth is set to pick up towards the end of the decade

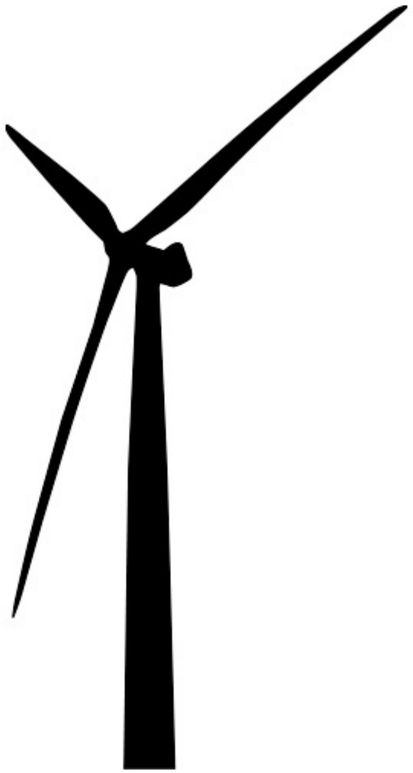
Forecast EU wind capacity based on current plans, 2021–30 (GW)



Source: GlobalData

ForWind
Center for Wind Energy Research
Bremen Hannover Oldenburg

Content



Part 1: wind energy

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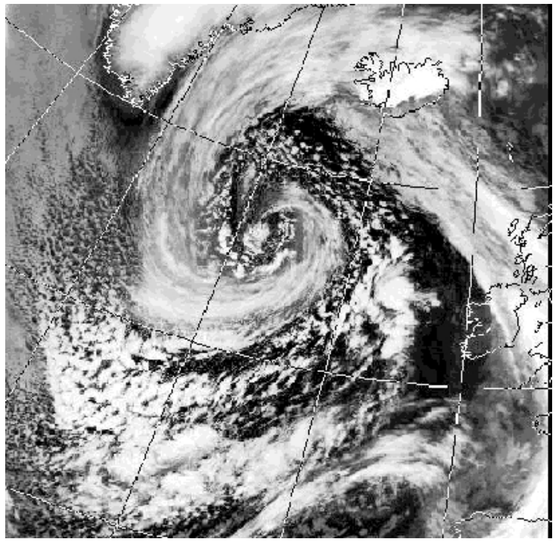
Part 2: fluctuating wind energy - challenges for physics

fluctuating wind energy

Is intermittency a problem?
- yes !
What to do ?
- showstopper ?
or a problem
which can be handled by understanding the physics ?

comment -
* Around 2000 impossible to have stable grid with more than 10% wind
Today up to 100% and overall a more state grid than 2000

fluctuating wind energy



Is intermittency a problem?

- yes !

What to do ?

- showstopper ?

or a problem

which can be handled by understanding the physics ?

Intermittency :

Large scale intermittency.

- long term variability - two days no wind (Dunkelflaute (dark doldrums) vs Hitzewelle (heat wave))

=> energy meteorology (D. Heinemann)

(-> energy & meteo systems GmbH, OL)

fluctuating wind energy

Is intermittency a problem?
- yes !

What to do ?
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Intermittency :

Large scale intermittency.
- long term variability - two days not wind

=> energy meteorology

Small scale intermittency
- fast changes of wind power

=> next topic - we need statistics

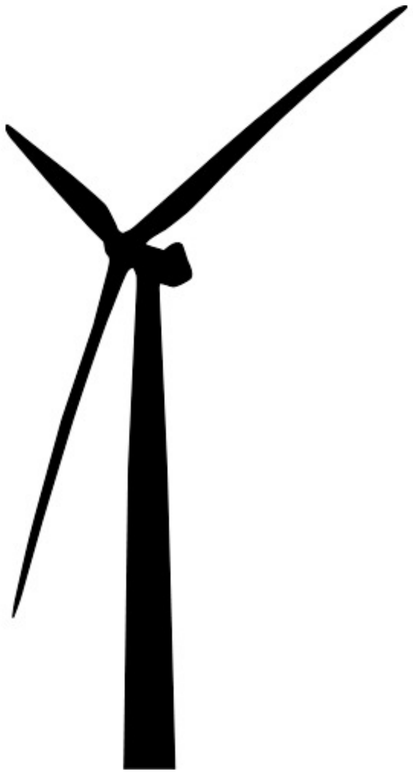
effects of non-normal wind

#Tornado #Crowell #Texas

CRAZY TORNADO BENDS WIND TURBINE BLADES!

https://www.youtube.com/watch?v=dRht4tkQJIM

Content



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- basic concept of wind energy converters (WEC)
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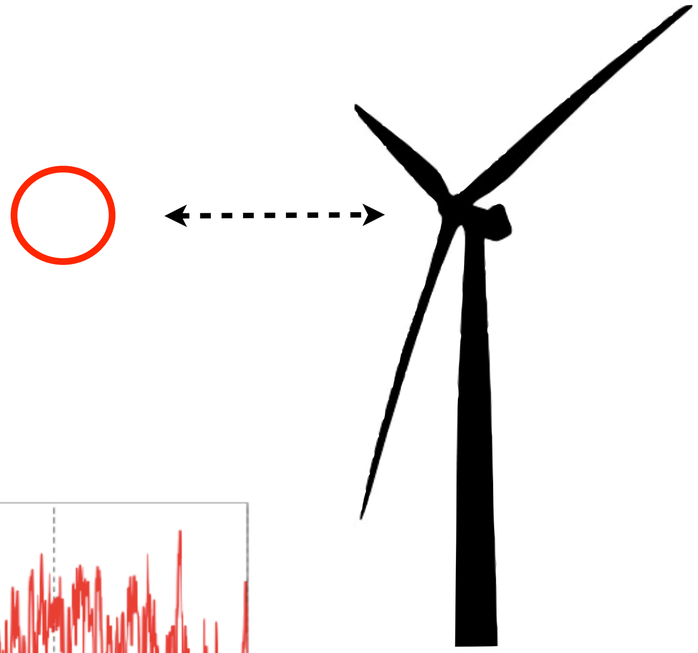
- energy resource: fluctuating wind

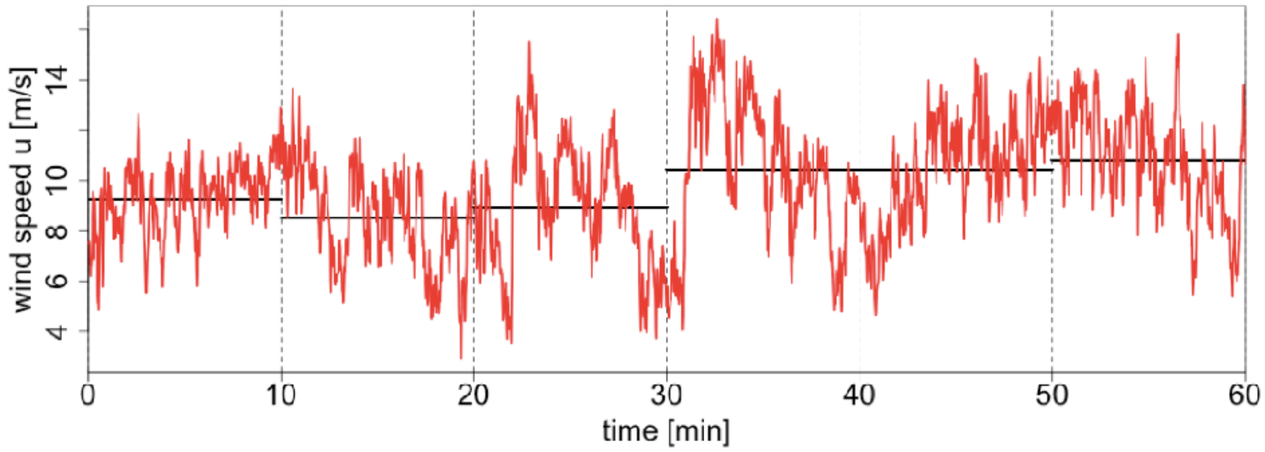
energy resource: wind gusts

INTERNATIONAL STANDARD **IEC 61400-1**

Third edition 2005-08



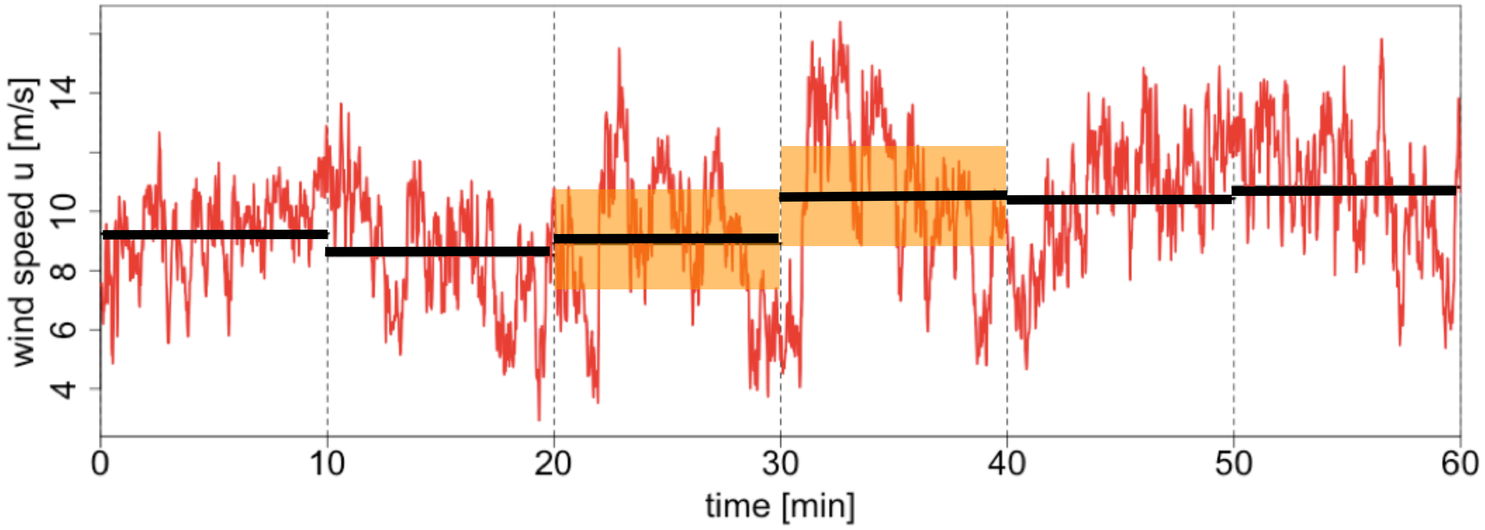
measured time series



wind measurements and data analysis

- characterisation after IEC norm

- 10 min mean value
- turbulence intensity



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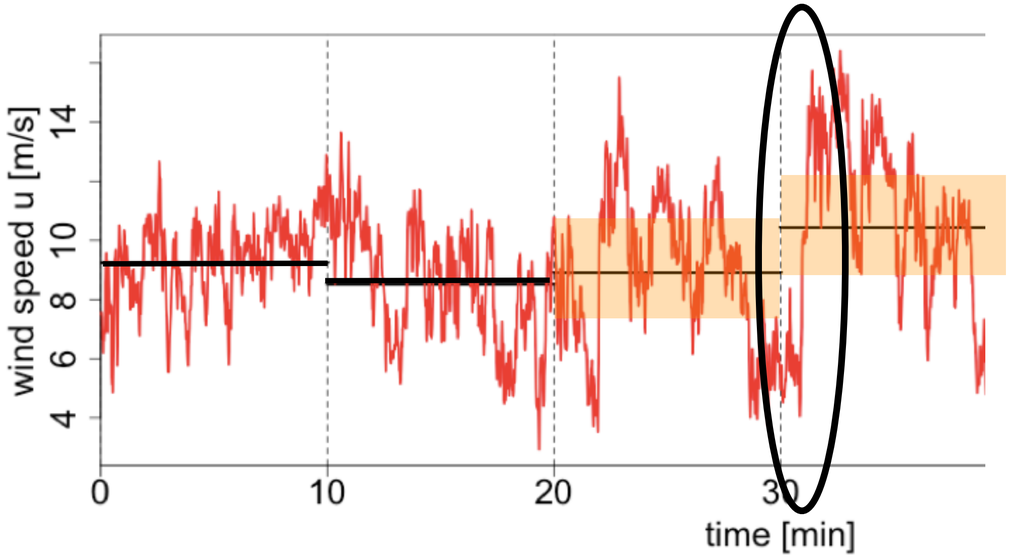
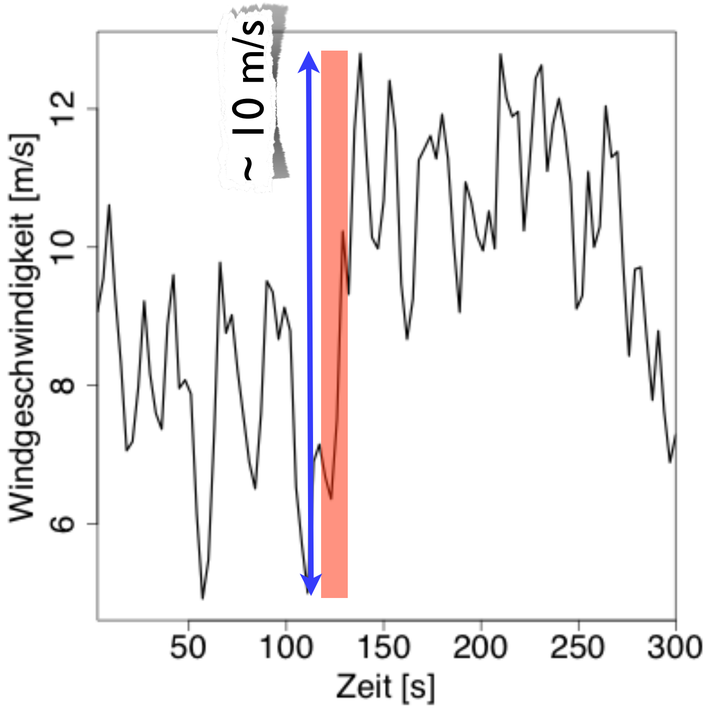
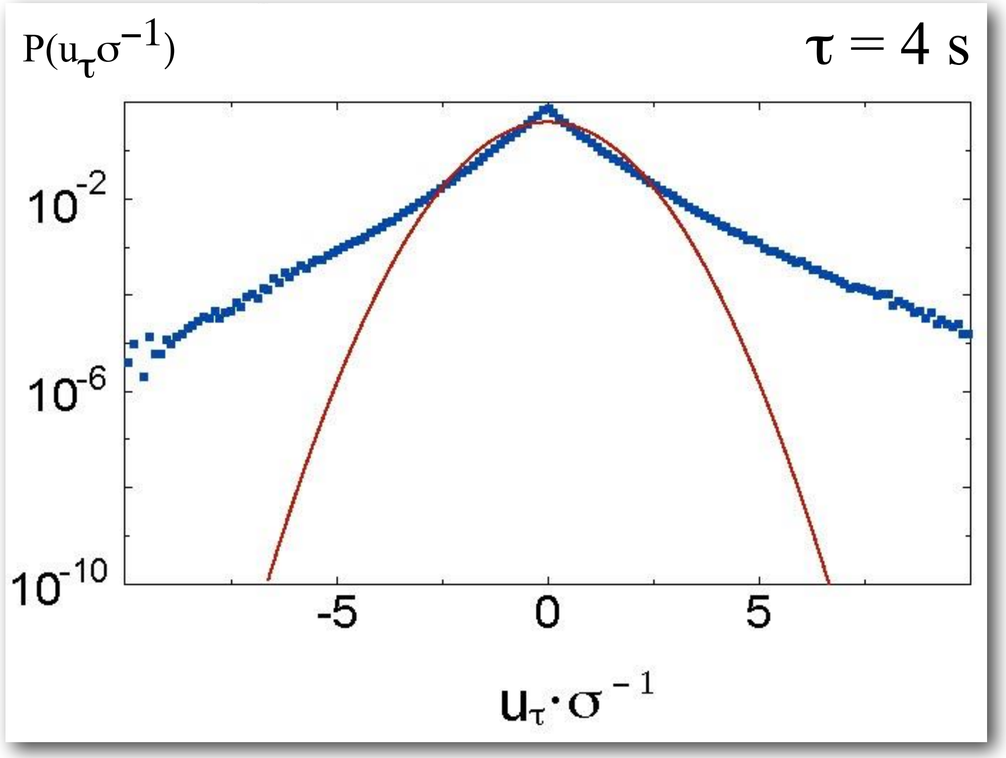


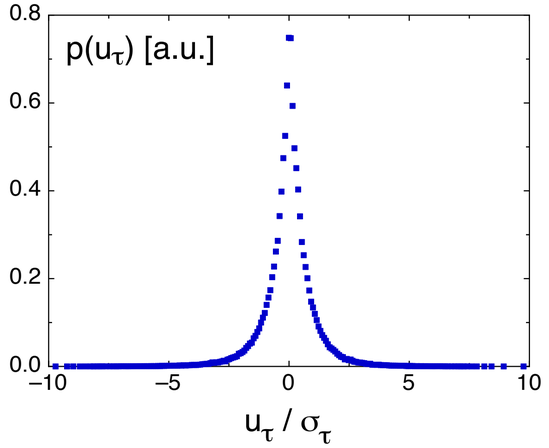


statistics of gusts

- wind fluctuations can be measured by velocity increments

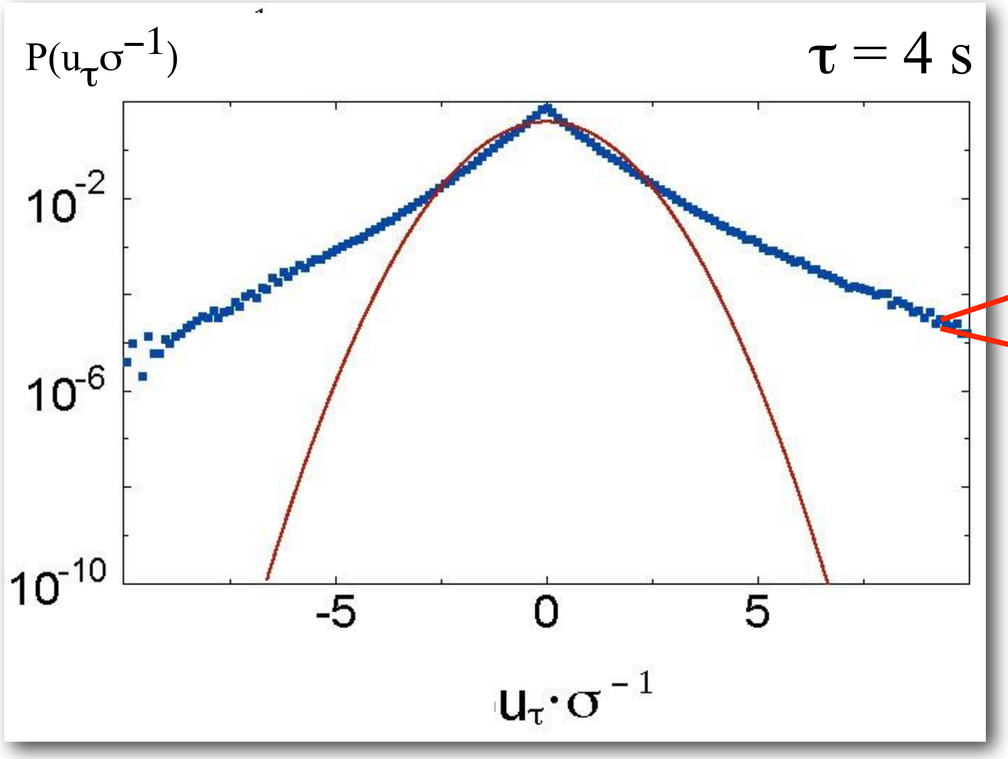
$$u_\tau = u(t+\tau) - u(t)$$

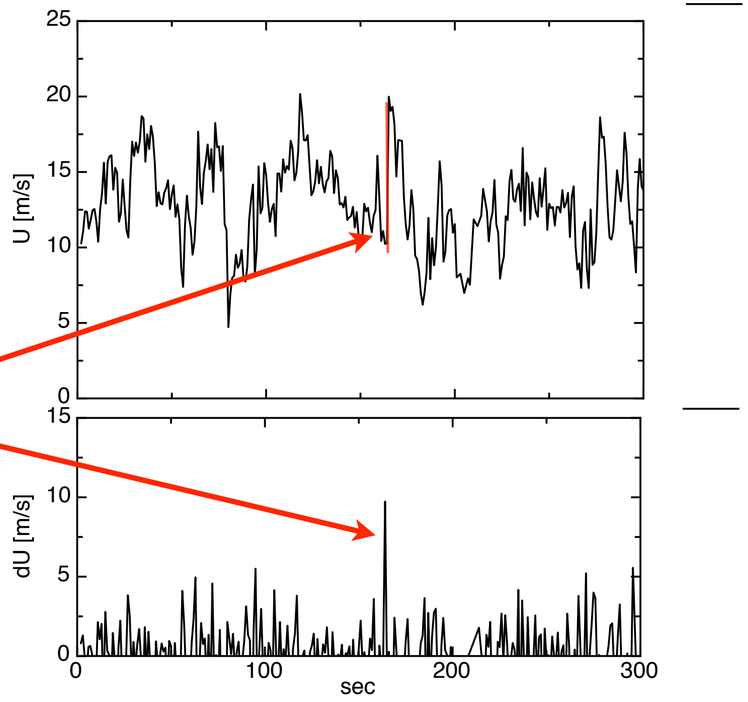




Boundary-Layer Meteorology **108** (2003)

statistics of gusts

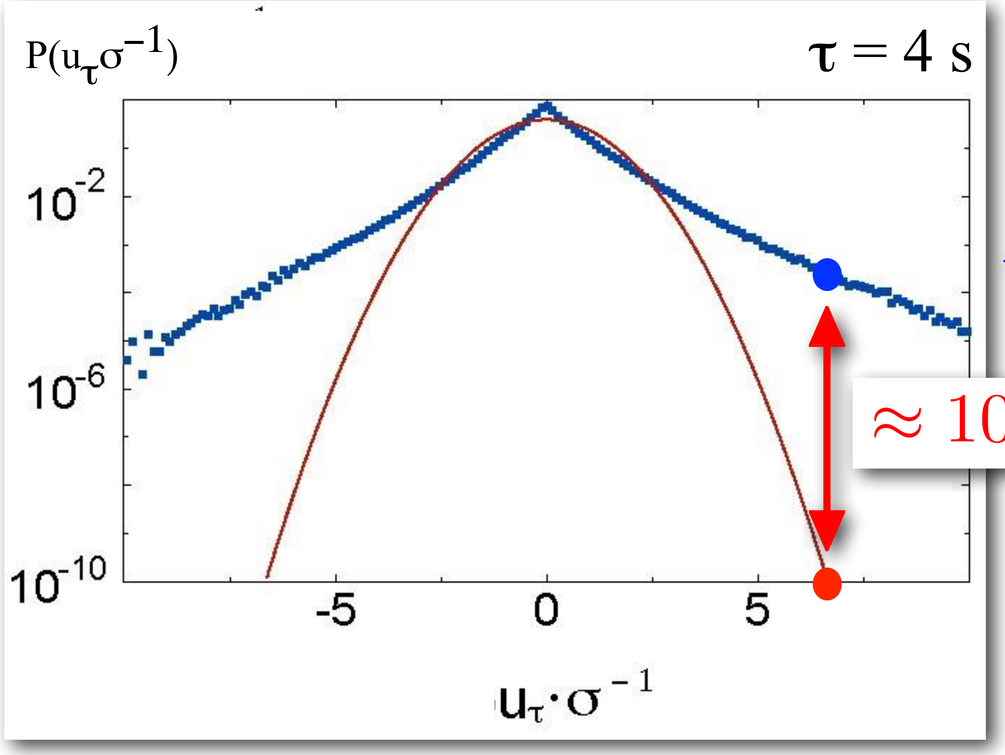




Boundary-Layer Meteorology **108** (2003)

statistics of gusts

non-Gaussian called intermittency



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

1/day

=> Importance of statistics p(x)

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

1/3000 years

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

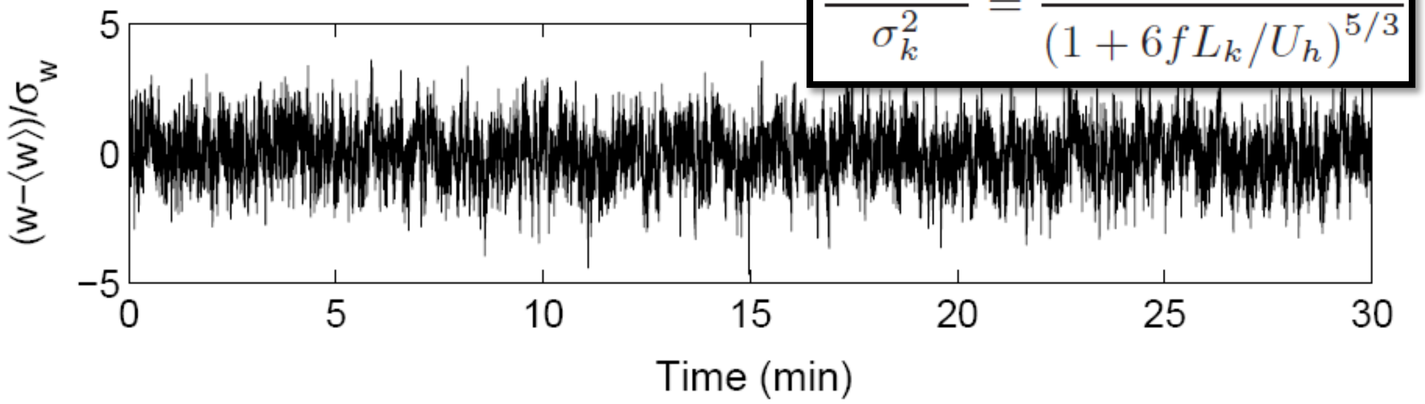
CARL VON OSSIETZKY universität OLDENBURG

ForWind Zentrum für Windenergieforschung Bremen Hannover Oldenburg

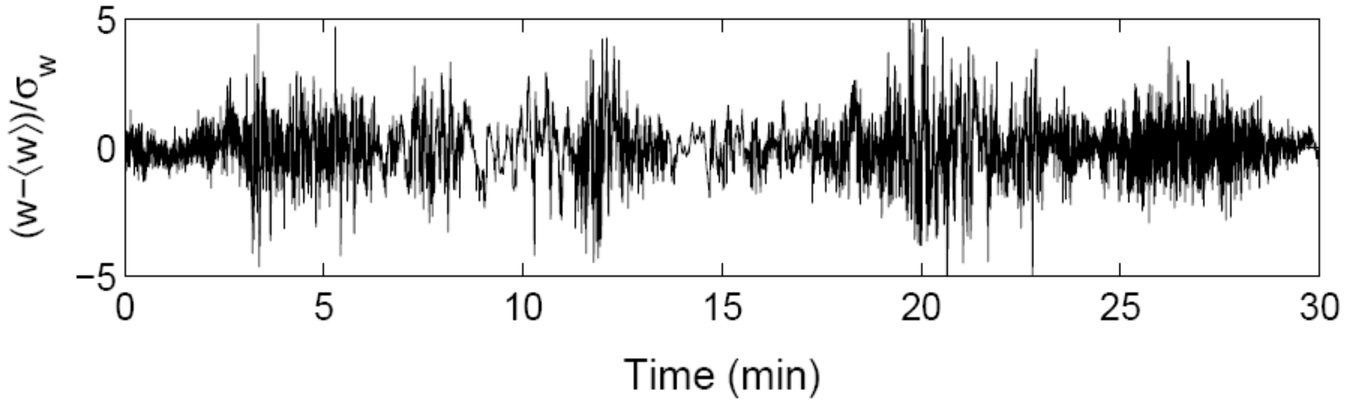
IEC Wind and measured

IEC Code

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



Observation



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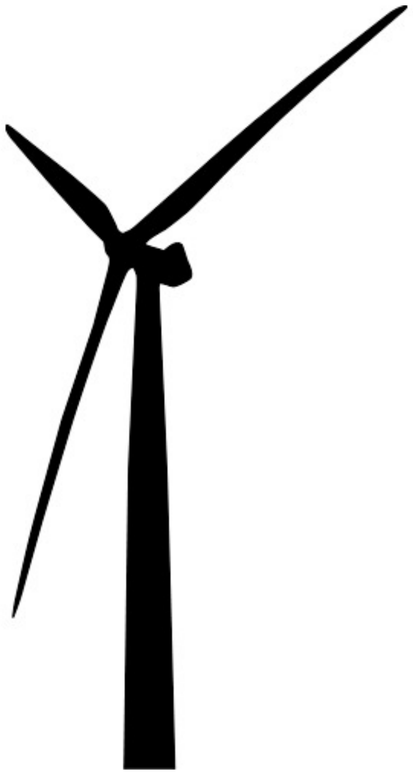

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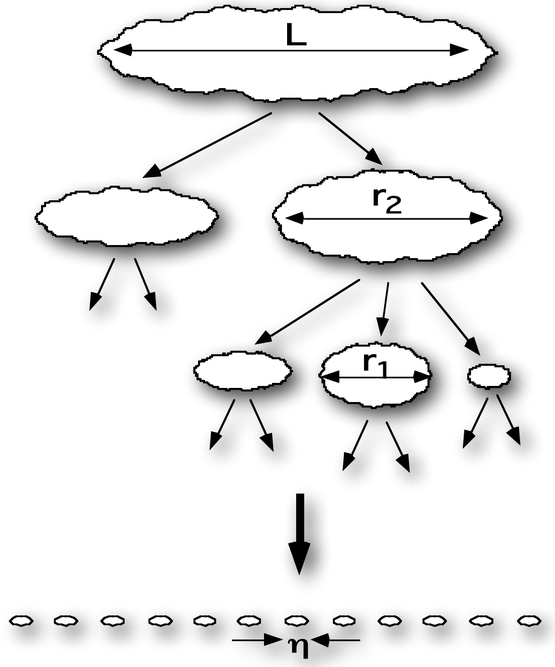
Part 2: fluctuating wind energy - challenges for physics

- **energy resource: fluctuating wind**
- **turbulence and intermittency**

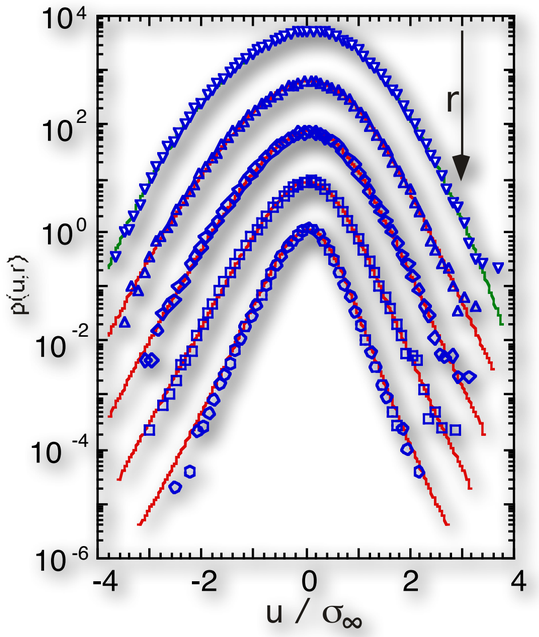
homogeneous isotropic turbulence -- hit

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

Leonardo da Vinci



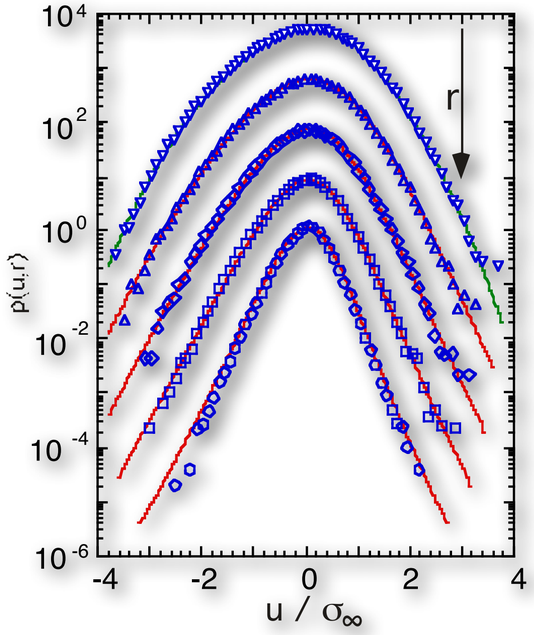
A.N. Kolomogorov



homogeneous isotropic turbulence -- hit

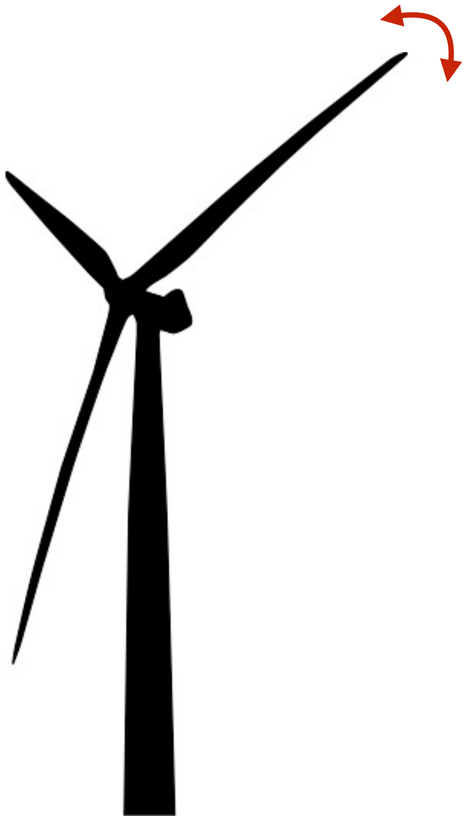
$$u_r = u(x+r) - u(x)$$

A.N. Kolomogorov



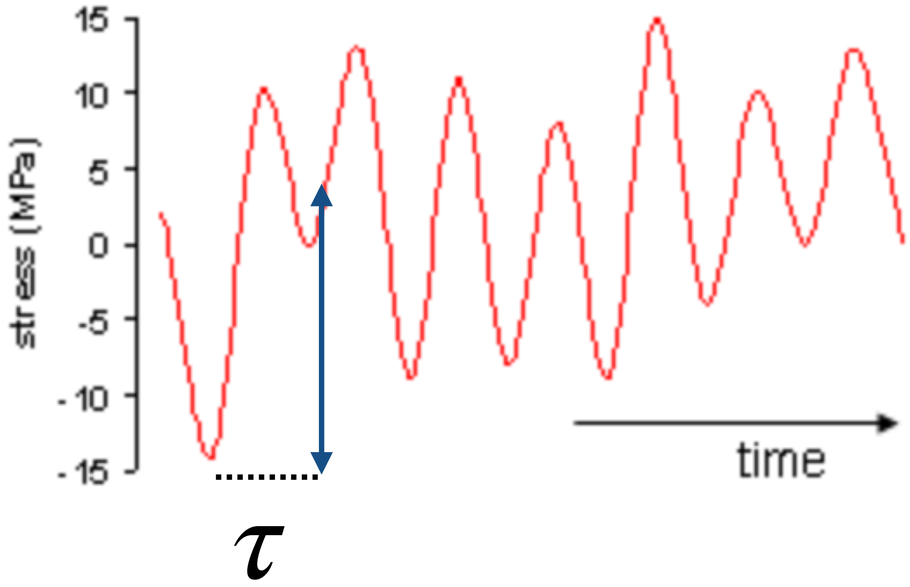
Wind turbine is a small scale structure

Load and damage estimation
- intermittency



Load and damage estimation
- intermittency

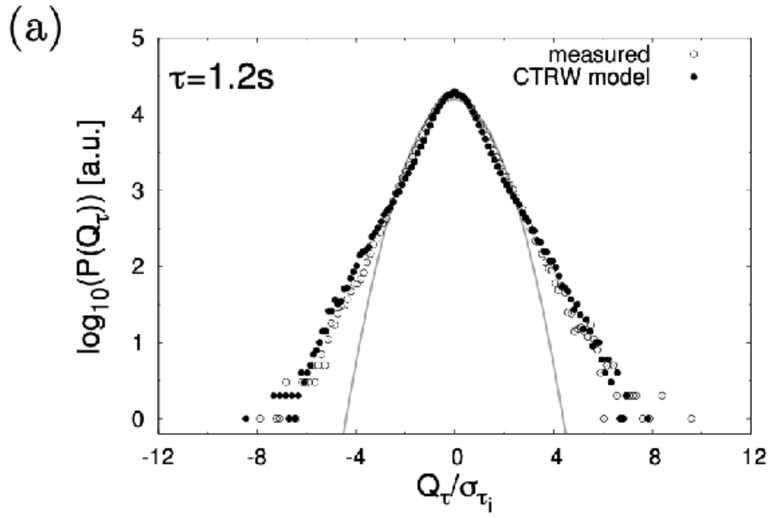
Load cycles



Load signal

Increment analysis:

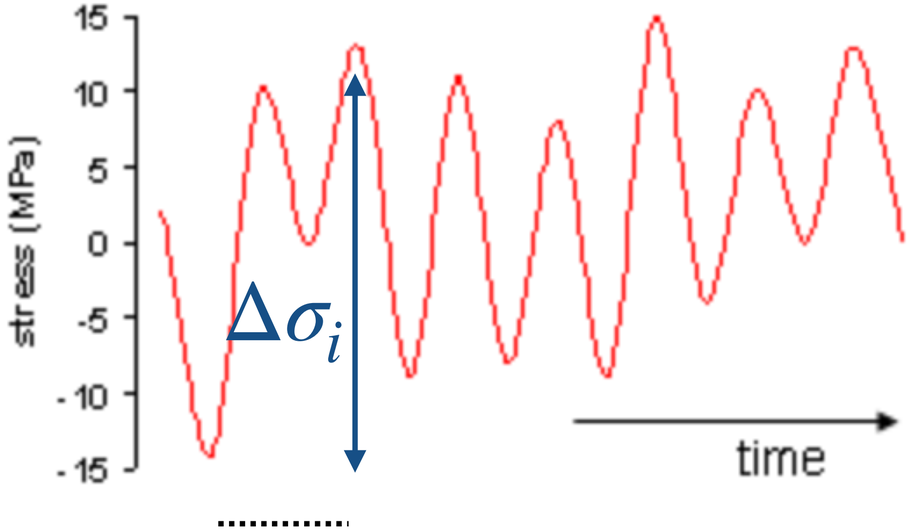
Turbulent intermittency



T. Mücke, et al. Wind Energy 14, 301 (2011)

Load and damage estimation
- rainflow counting

Load signal



Counting (n_i) the **load cycles** $\Delta\sigma_i$

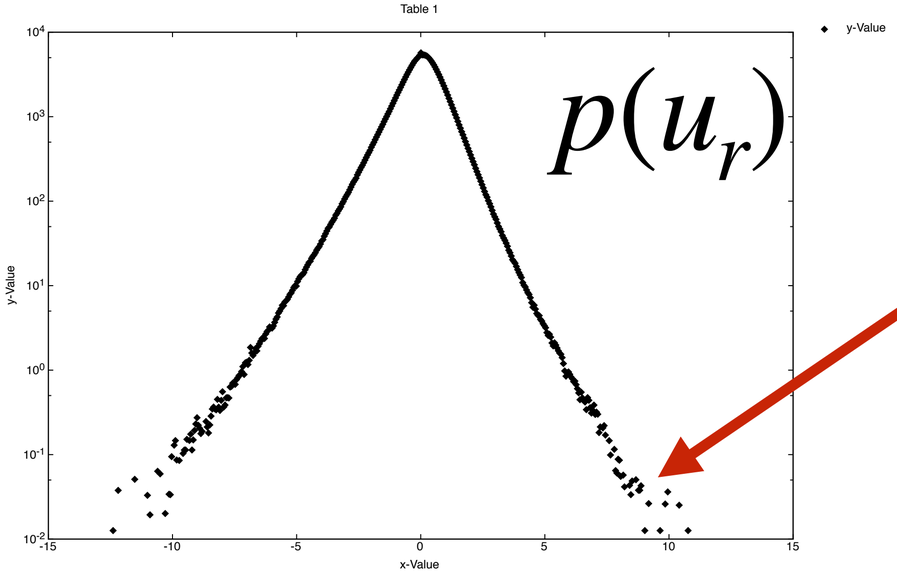
Damage equivalent

$$\Delta\sigma_{ref} = \left[\frac{\sum_i n_i \cdot (\Delta\sigma_i)^m}{N_{ref}}\right]^{\frac{1}{m}}$$

Wöhler coefficient m

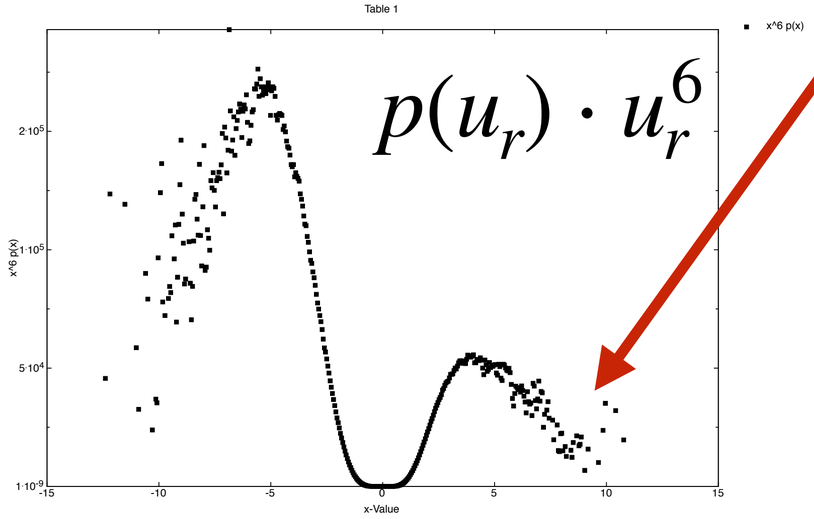
metal m=3

Composite **m=10**



We need to have an understanding of these extreme events

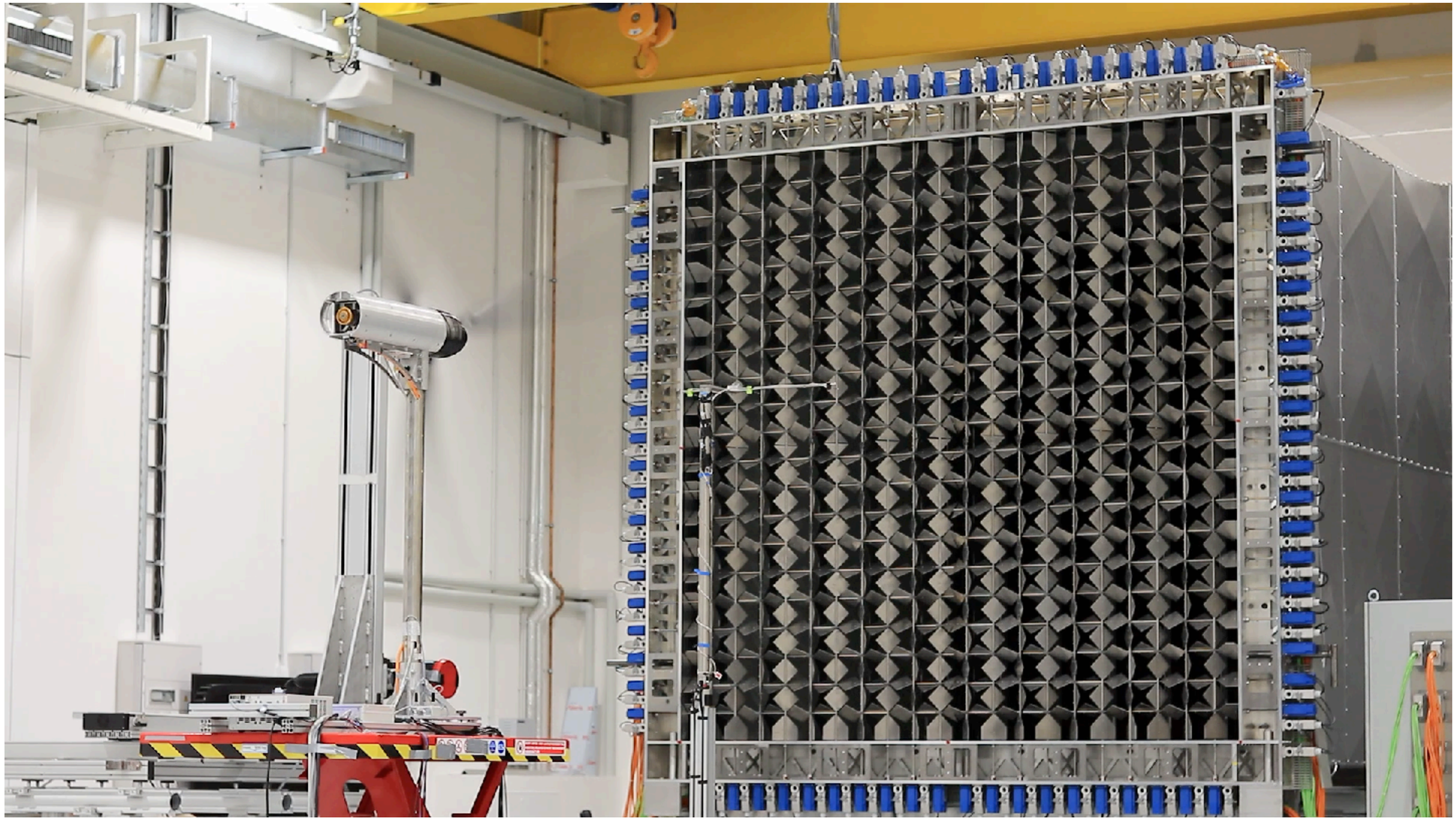
- How frequent
- How big



$$\Delta\sigma_{ref} = \left[\frac{\sum_i n_i \cdot (\Delta\sigma_i)^m}{N_{ref}} \right]^{\frac{1}{m}}$$

Wind energy cost - up to about 25% O&M

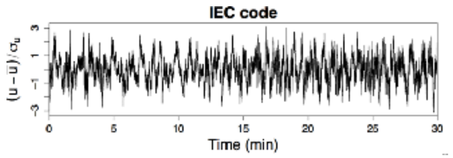
Exp - Active grid in wind tunnel of Oldenburg

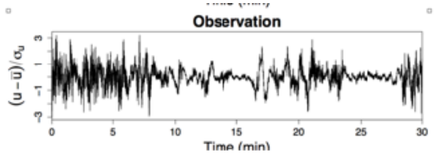


L. Neuhaus, et al. P.R.L. 125, 154503 (2020) atmospheric turbulence Re 10^7

Modellanlage AG von M. Kühn

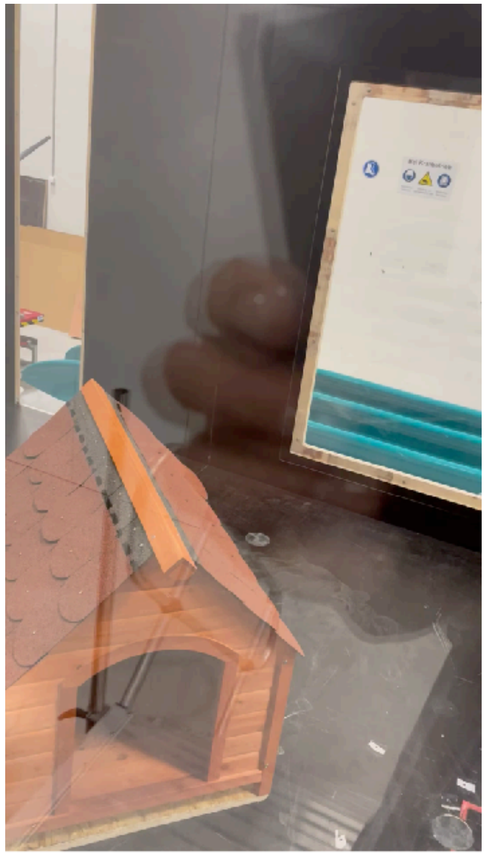
Same wind speed





Laminar u

u with turbulent Gaussian fluctuations u´

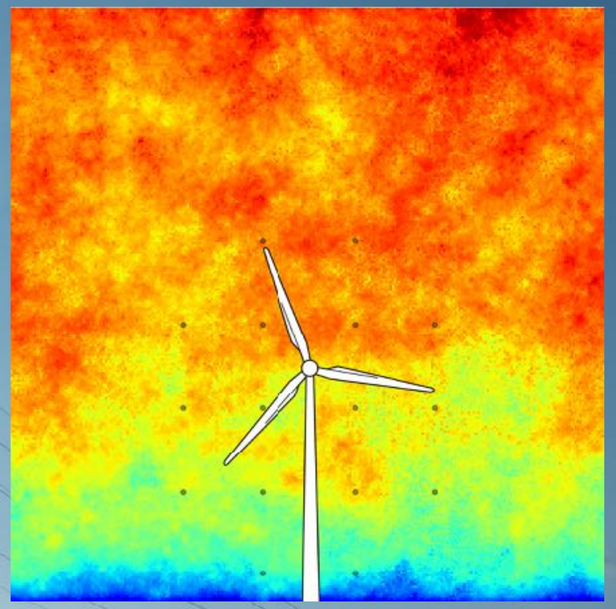


u with turbulent Intermittent fluctuations u´ Same turbulent intensity

Effect of wind on roofing shingles

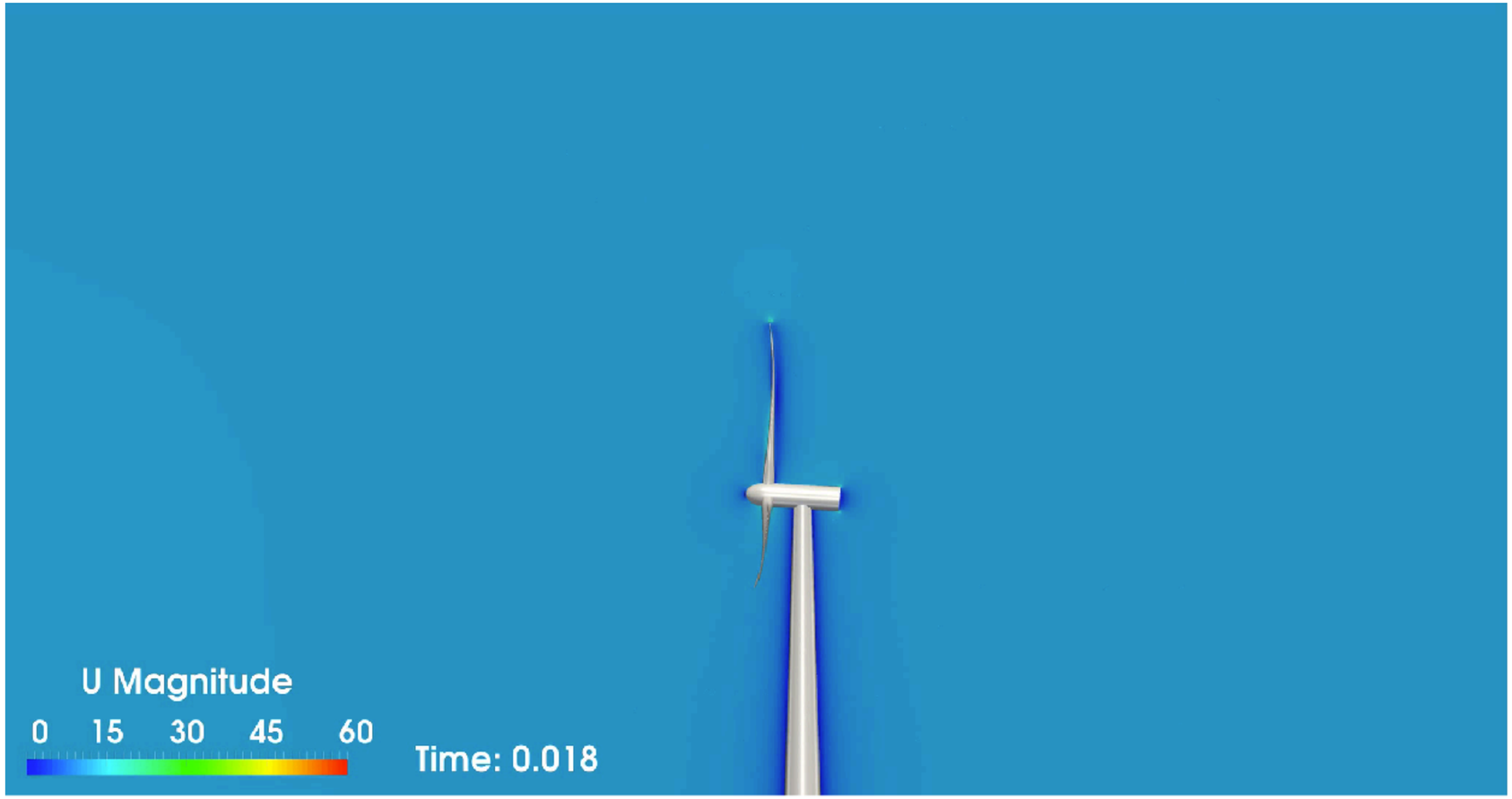
Freifeldmessungen. - Forschungspark WiValdi - DLR, ForWind und Fraunhofer

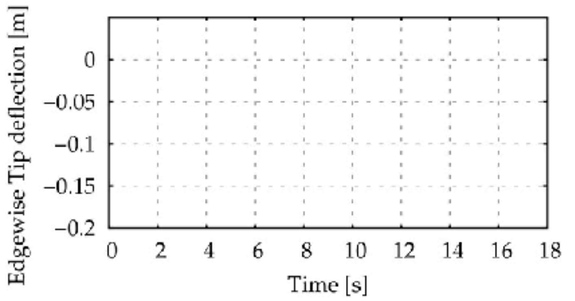
Loads are more complex than one time series

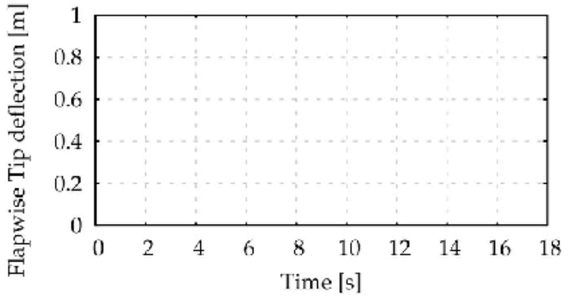


Further topics of wind physics

Numeric approach - CFD / LES







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Zentrum für Windenergieforschung
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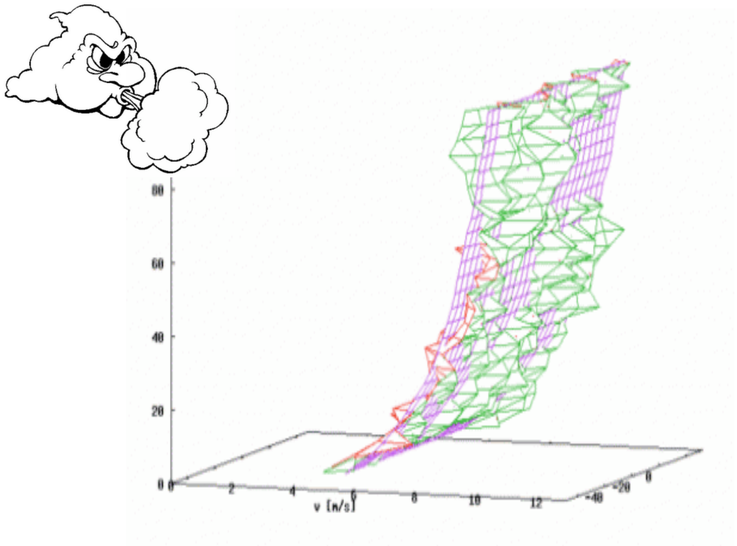
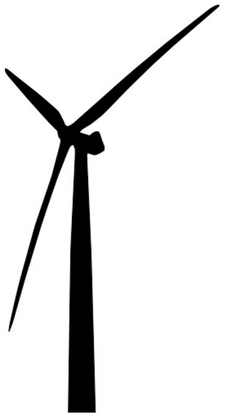
Hannover
Oldenburg

LiDAR - Light Detection and Ranging

Motivation for turbulence research - energy

Wind energy operating under turbulent conditions





JOSEFINE PROLL

TURBULENCE IN FUSION PLASMAS

A visualization of high energy particles, in the form of plasma, flowing through a tokamak-type reactor. (Photo: Shutterstock)

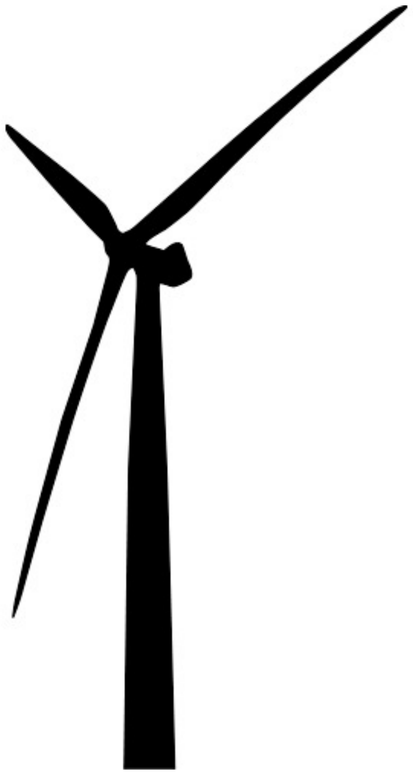
Fusion - tokamak type factor

Turbulence is a major obstacle for building fusion reactors.

Claim - need of a profound understanding of turbulence

ForWind
Center for Wind Energy Research
Bremen
Hannover
Oldenburg

Content



Part 1: wind energy

- basic concept of wind energy converters (WEC)
- system and costs

Part 2: fluctuating wind energy - challenges for physics

- **energy resource: fluctuating wind**
- **turbulence and intermittency**
- **Fundamental understanding of turbulence**

Turbulence one of 7 milenium problems

Clay Mathematics Institute

Dedicated to increasing and disseminating mathematical knowledge

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

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

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

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

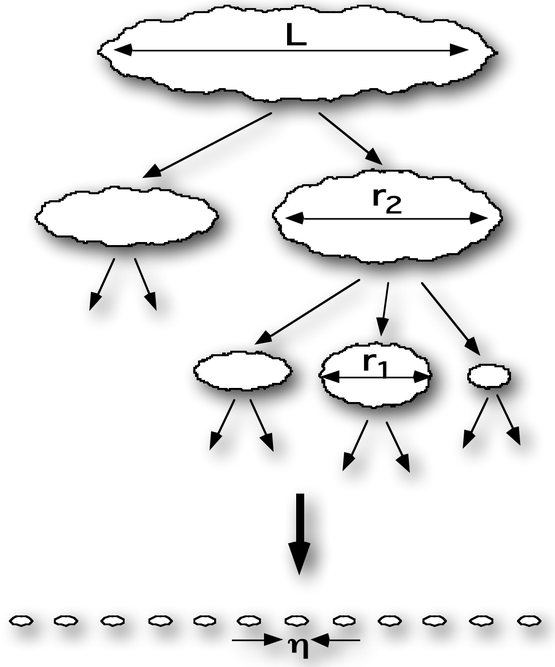
have to understand

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

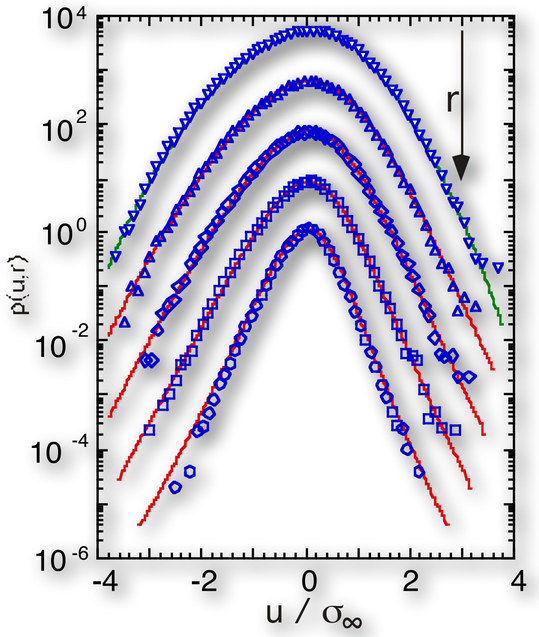
homogeneous isotropic turbulence -- hit

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

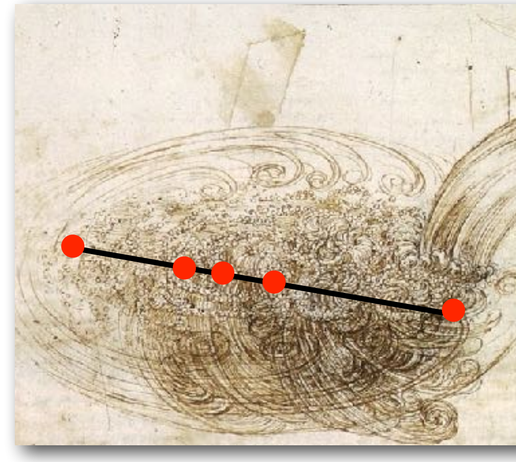
Leonardo da Vinci

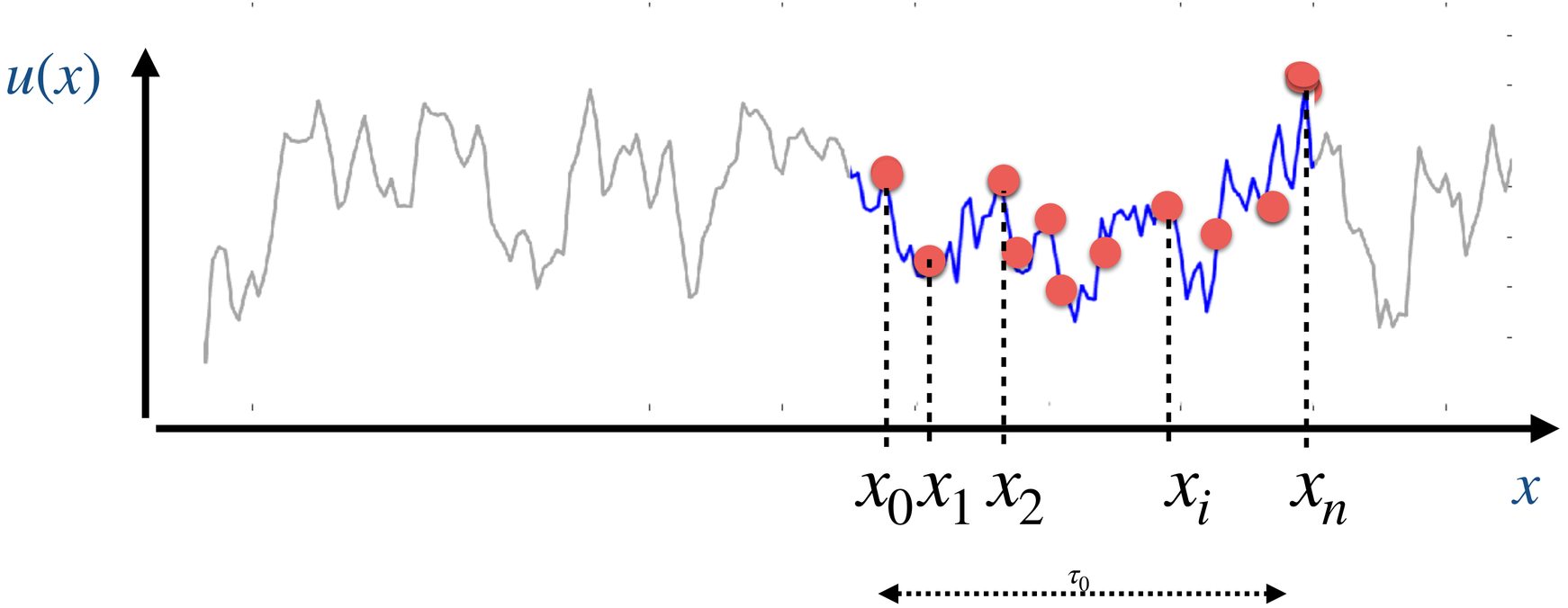


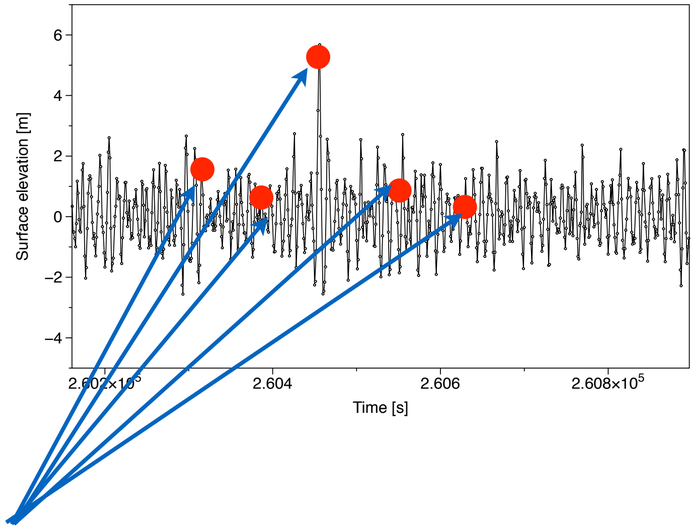
A.N. Kolomogorov



Data set of velocities $u(x)$ or heights $h(x)$ or other complex systems







Aim to get the joint multi-time statistics $p(u(x_0), u(x_1), \ldots, u(x_n))$

J.P., et al., Annu. Rev. Condens. Matter Phys., 10 (2019) 107

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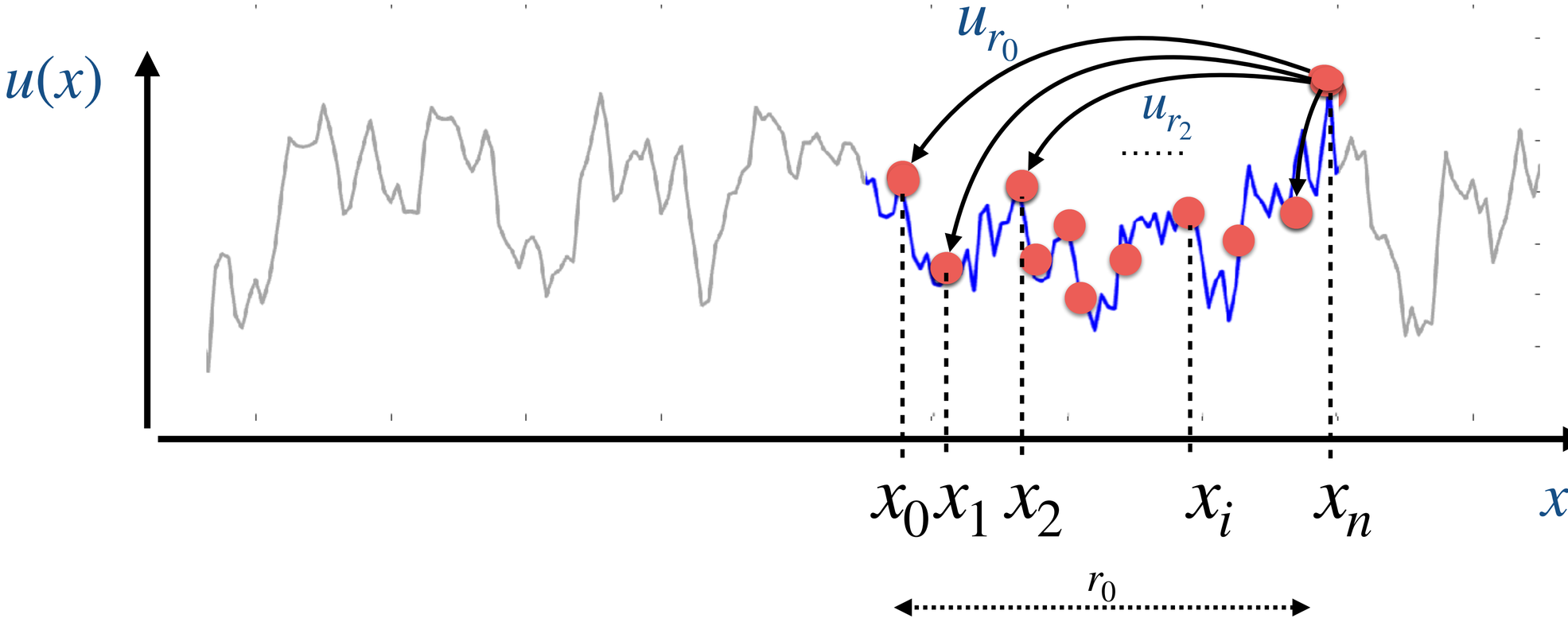
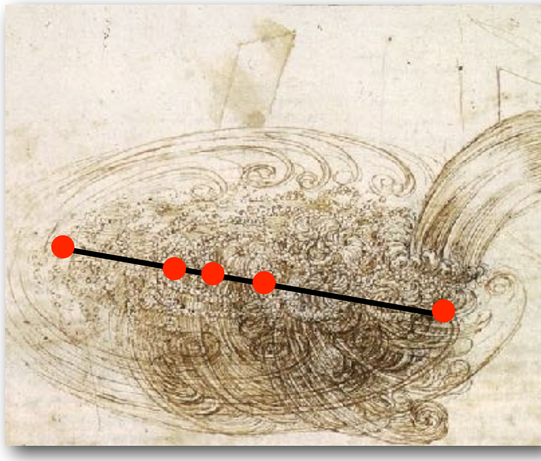
Data set $u(x)$ / $h(x)$





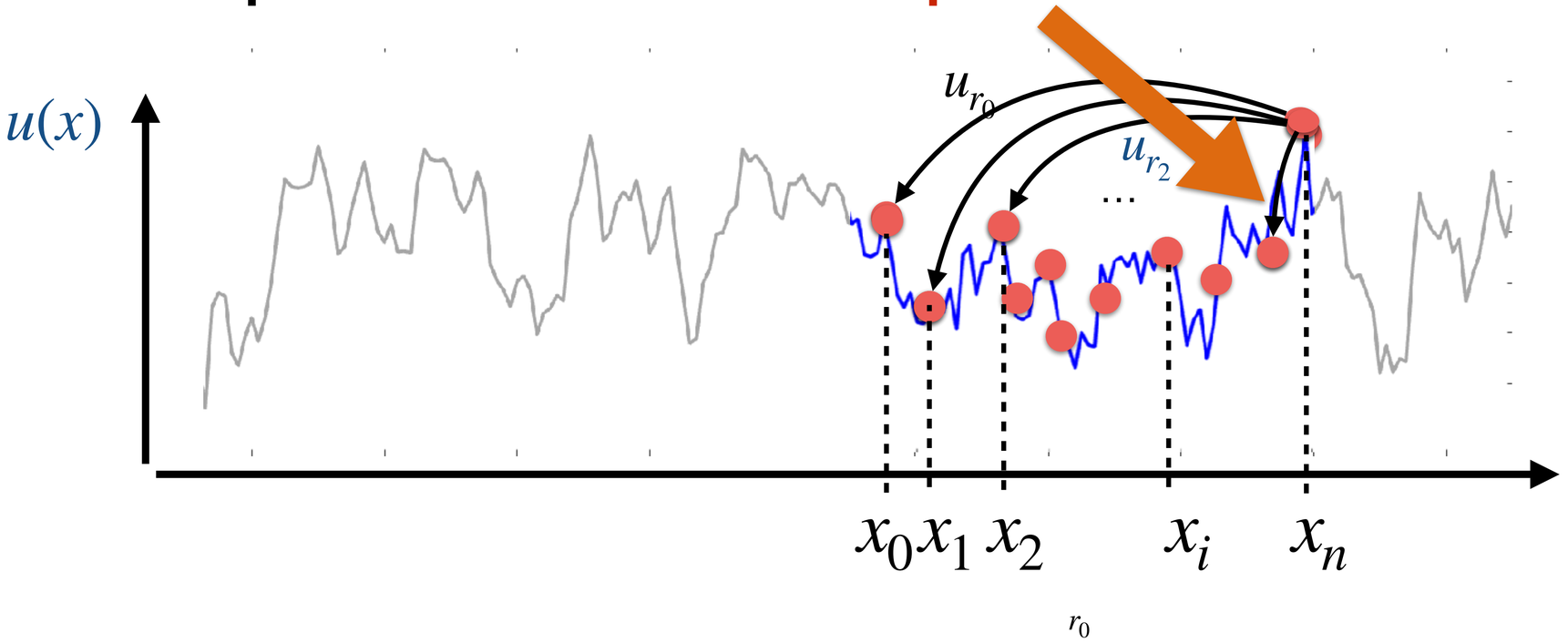
Aim to get the joint multi-time statistics $p(u(x_0), u(x_1), \ldots, u(x_n))$

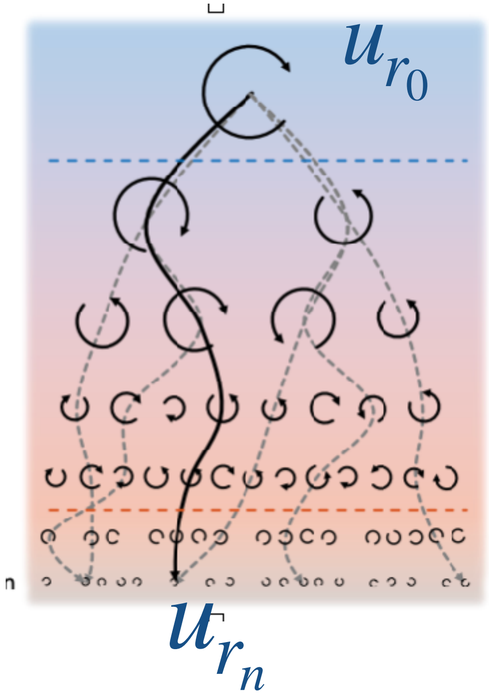
can be expressed by statistics of **increments** $u_r = u(x + r) - u(x)$

$$p(u(x_0), u(x_1), \ldots, u(x_n)) = p(u_{r_0}, u_{r_1}, \ldots, u_{r_{n-1}}, u(x_n))$$

J.P., et al., Annu. Rev. Condens. Matter Phys., 10 (2019) 107

Joint- n-point statistics and three point closure => Markow process in scale



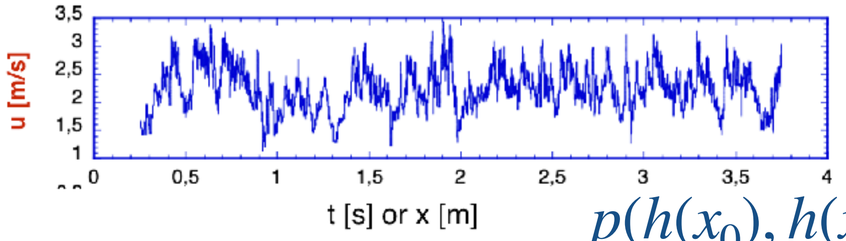


increments $u_r = u(x+r) - u(x)$

Cascade path $u(\cdot)$ goes from u_{r_0} to u_{r_n} and $r_0 > r_1 > \ldots r > \ldots r_n$

Recipe for stochastic analysis

$$p(u(x_0), u(x_1), \ldots, u(x_n))$$



$$p(h(x_0), h(x_1), \ldots, h(x_n))$$

data

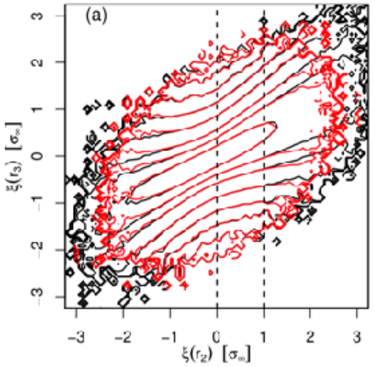
Joint - n-point statistics reduces to

conditional pdfs

L ⟶ r ⟶ η

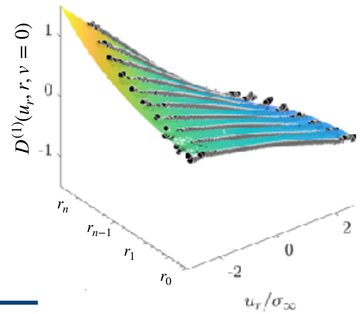
$$p(u_{r_i} | u_{r_{i+1}}, u(x_n))$$

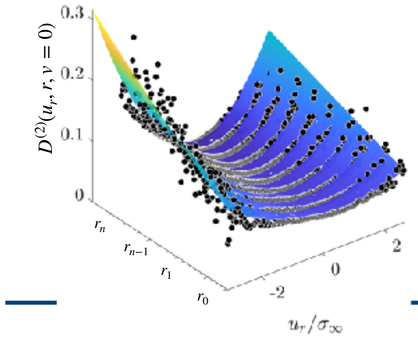
$$p(h_{r_i} | h_{r_{i+1}}, h(x_n))$$



Drift - $D^{(1)}$

Diffusion - $D^{(2)}$





Fokker-Planck equation describes the conditional pdf

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

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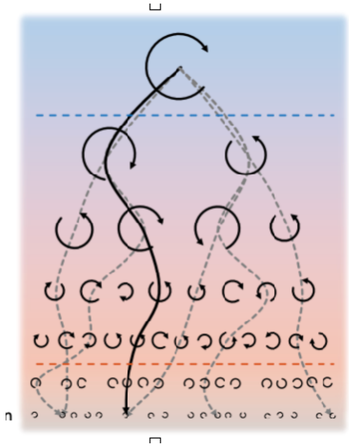
entropy of cascade trajectories

2nd law : entropy balance

there are two contributions of the entropy (cf. **Seifert 2005**) to the subsystem

$$S_{tot}(u_r) = S_m(u_r) + \Delta S$$



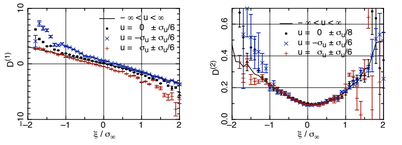
(1) interaction with the medium results in **power done on the subsystem**

$$\dot{x}F = \dot{x}\partial_x\varphi$$

for the cascade path u_r

$$S_m(u_r) = -\int_L^\lambda \partial_r u_r \; \partial_u\varphi(u_r, r)dr$$

$$\varphi(u_r) = \ln D^{(2)}(u_r, r) - \int_{-\infty}^{u_r} \frac{D^{(1)}(u', r)}{D^{(2)}(u', r)} du'$$

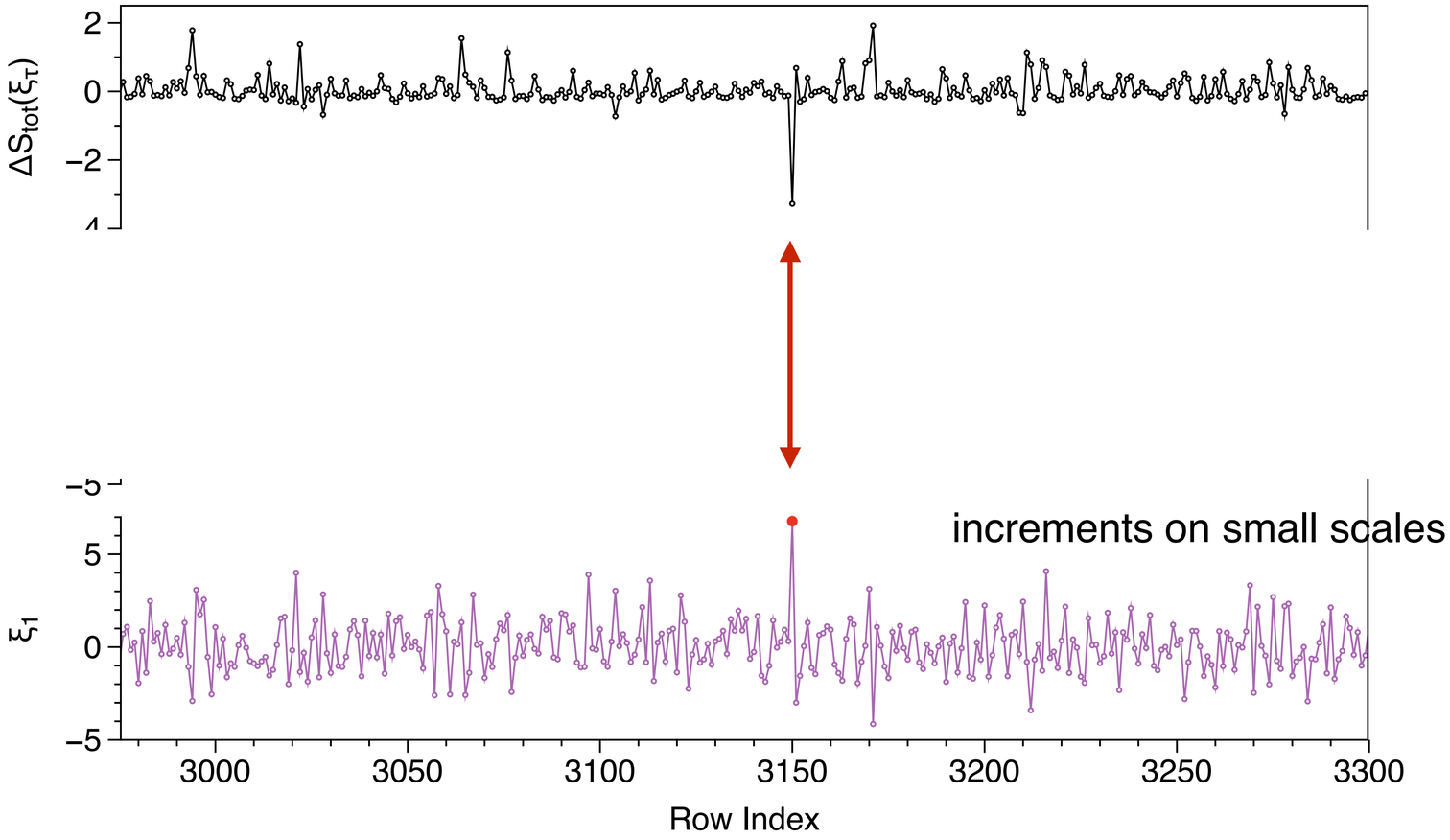


shift of drift function, no *u*-dependence of diffusion function

$$\Delta S = -ln\frac{p_\lambda(u_\lambda)}{p_L(u_L)}$$

- Nickelsen Engel PRL 110 (2013)

rogue wave: event of negative entropy production



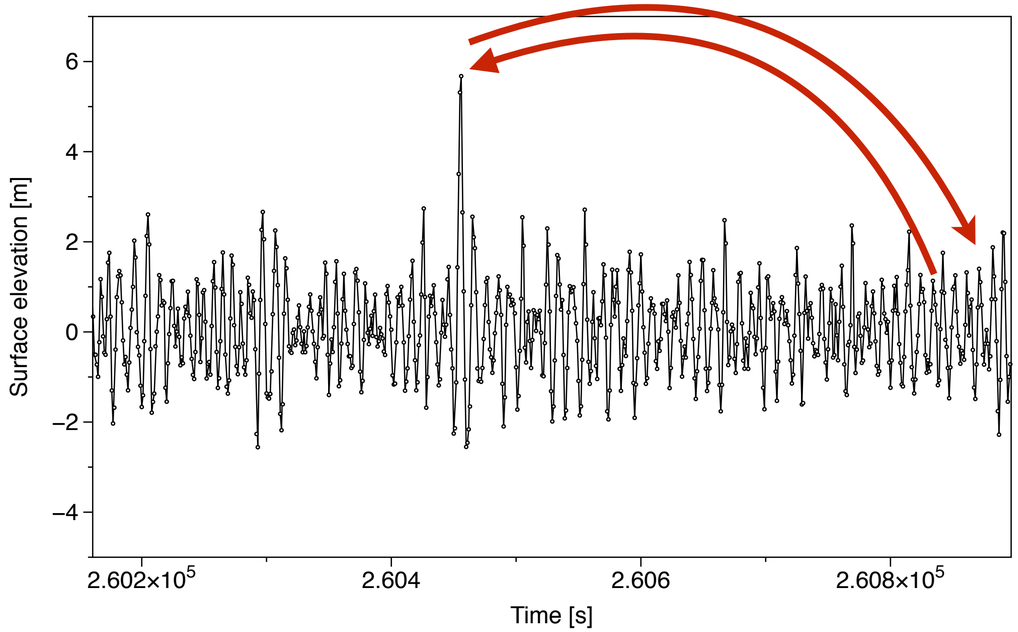
A. Hadjihosseini, P. G. Lind, N. Mori, N. P. Hoffmann, and J. Peinke :

Rogue waves and entropy consumption, europhysics letters 120, 30008 (2018)

Stochastic data seem to be realistic - with extreme events

Events with negative entropy are the extreme events

Fluctuation theorem balances negative & positive entropy events



Stochastic data seem to be realistic - with extreme events

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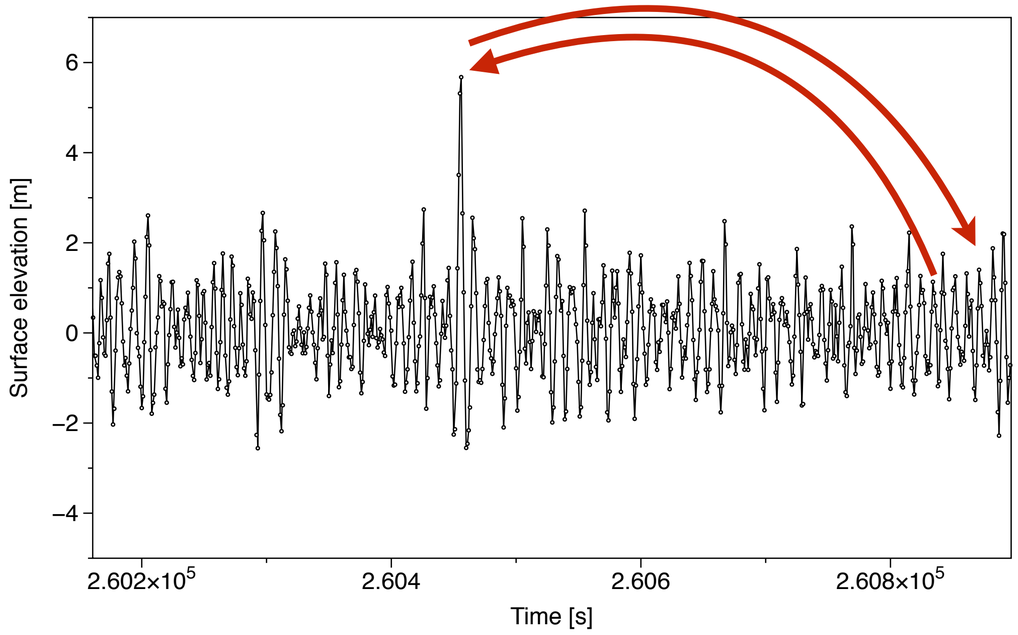
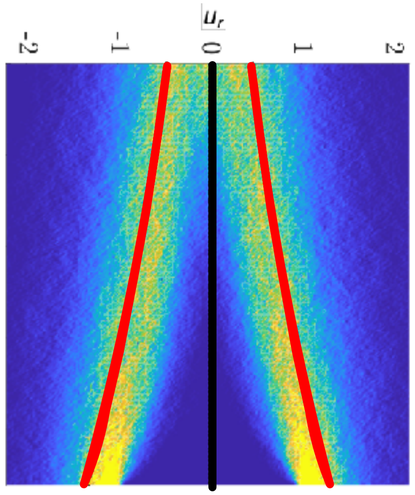


For neg. entropy - extreme events instants or entropons can be determined

$\Delta S = -6$



A.Fuchs , et al PRL 129 (2022)

For waves and ideal turbulence this works -

- promising first results for wind (in stationary turbulence)

Aim - how frequent and how big are the wind extremes

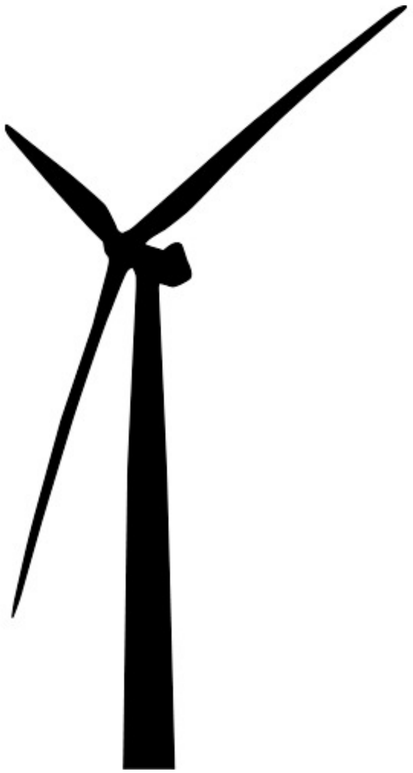
Conclusion

Wind energy

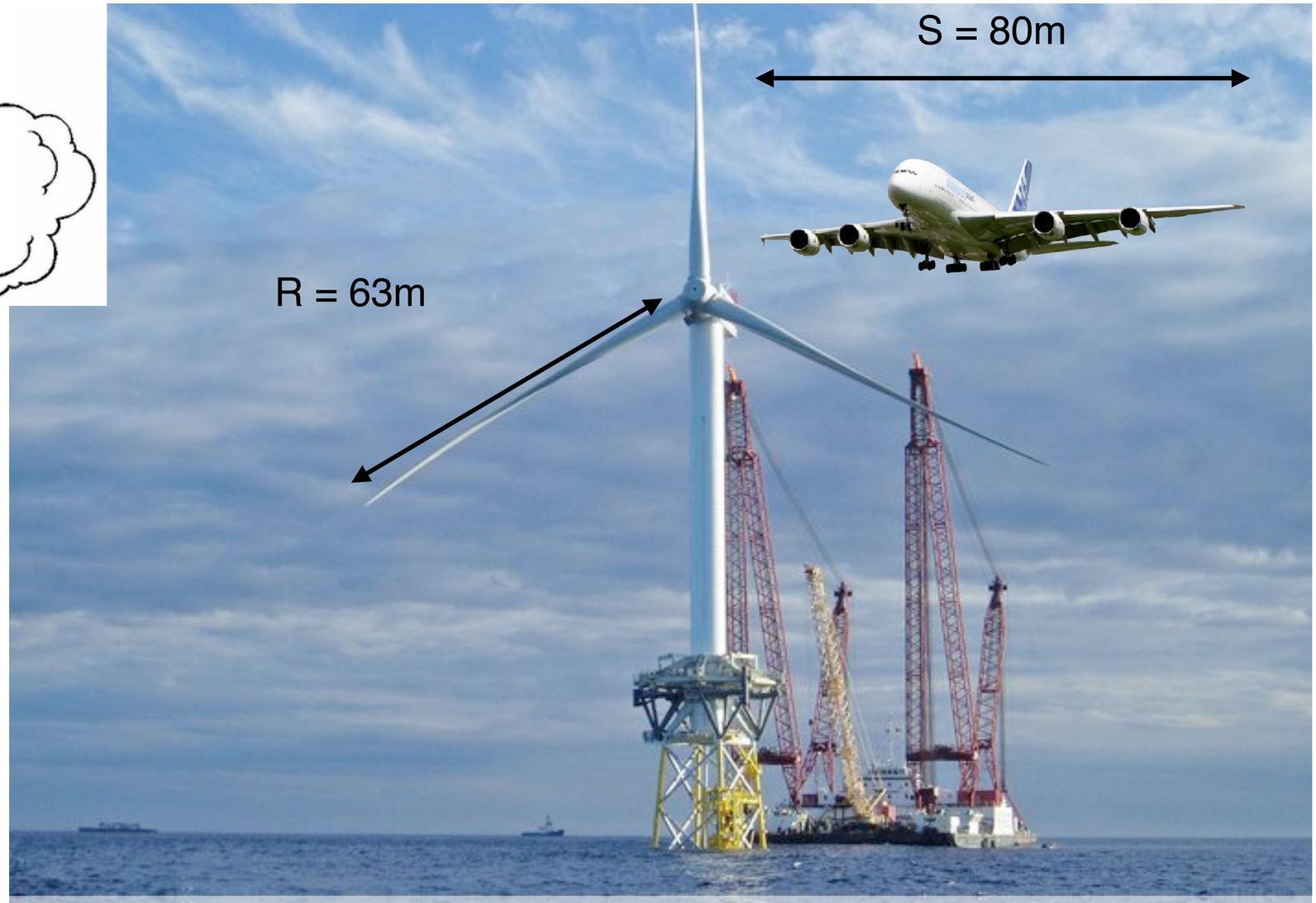
- is no physics.
  - — connected to one of the big scientific challenges: turbulence

- is too expensive
  - — no, is with solar the cheapest and environmental friendly

- is intermittent
  - — yes, but we need a smart approach to make profit of WE and solar



Conclusion



Research

Initiated by eawe and iea-Wind

RESEARCH

Veers *et al.*, *Science* **366**, 443 (2019) 25 October 2019

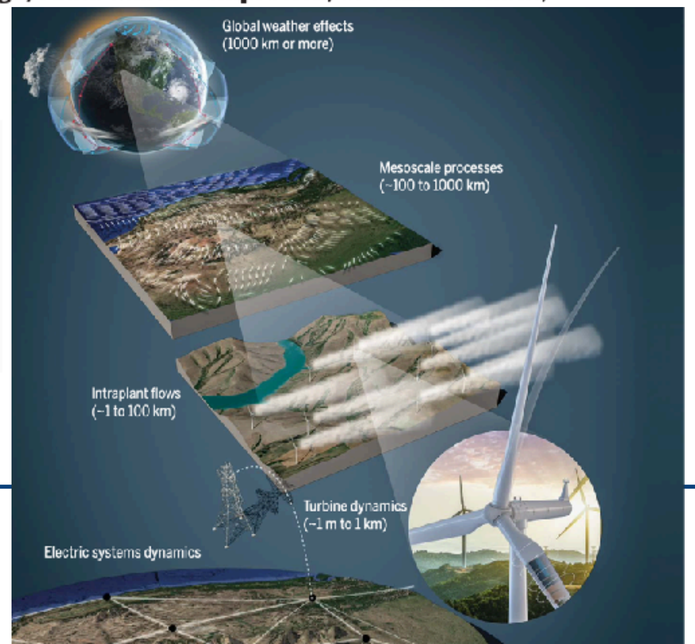
REVIEW SUMMARY

RENEWABLE ENERGY

Grand challenges in the science of wind energy

Paul Veers*, Katherine Dykes*, Eric Lantz*, Stephan Barth, Carlo L. Bottasso, Ola Carlson, Andrew Clifton, Johney Green, Peter Green, Hannele Holttinen, Daniel Laird, Ville Lehtomäki, Julie K. Lundquist, James Manwell, Melinda Marquis, Charles Meneveau, Patrick Moriarty, Xabier Munduate, Michael Muskulus, Jonathan Naughton, Lucy Pao, Joshua Paquette, Joachim Peinke, Amy Robertson, Javier Sanz Rodrigo, Anna Maria Sempreviva, J. Charles Smith, Aidan Tuohy, Ryan Wiser

BACKGROUND: A growing global population and an increasing demand for energy services are expected to result in substantially greater deployment of clean energy sources. Wind energy is already playing a role as a mainstream source of electricity, driven by decades of scientific discovery and technology development.



And thanks to my group

- to the Forschungsverbund

Forschungsverbund Windenergie

DLR Deutsches Zentrum für Luft- und Raumfahrt

ForWind Zentrum für Windenergieforschung Bremen Hannover Oldenburg

Fraunhofer IWES

And funding agencies

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DFG Deutsche Forschungsgemeinschaft

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Research Alliance Wind Energy

ForWind Center for Wind Energy Research Bremen Hannover Oldenburg