wind energy

Joachim Peinke

Inst. Physik & ForWind,

Universität Oldenburg

Fraunhofer Institut IWES, Oldenburg

Fraunhofer IWES

Research Alliance Wind Energy

ForWind Center for Wind Energy Research Bremen Hannover Oldenburg

content

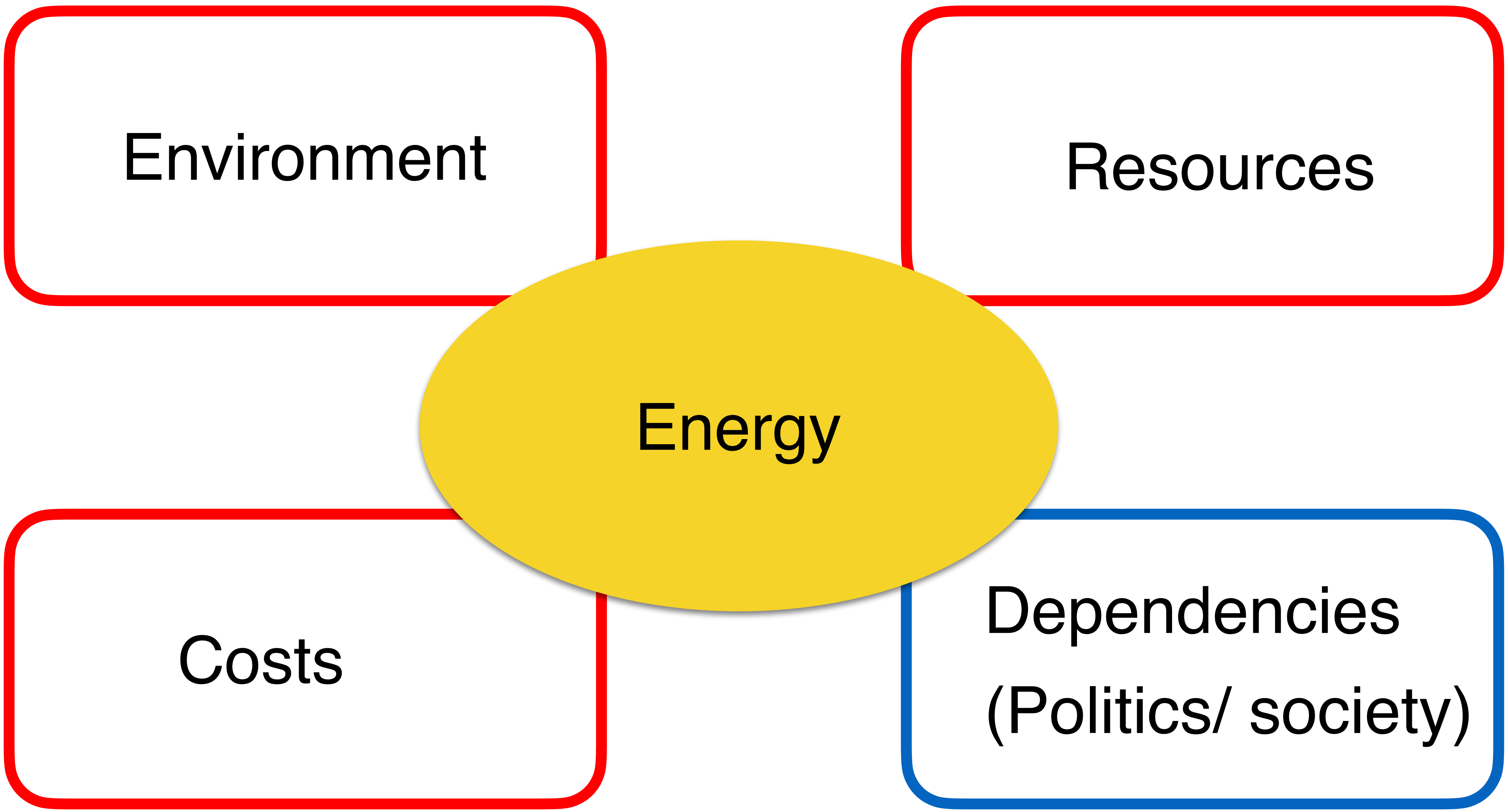
wind energy aim of the talk

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

Wind energy

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

Energy discussion



New? - Carter April 18, 1977

Address to the Nation on Energy

content

Part 1: wind energy

- basic concept of wind energy converters (WEC)

Part 2: wind energy and intermittency: challenges for physics

modern wind turbines - WEC (wind energy converter)

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

ForWind Zentrum für Windenergieforschung Bremen Hannover Oldenburg

modern wind turbines - WEC (wind energy converter)

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

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

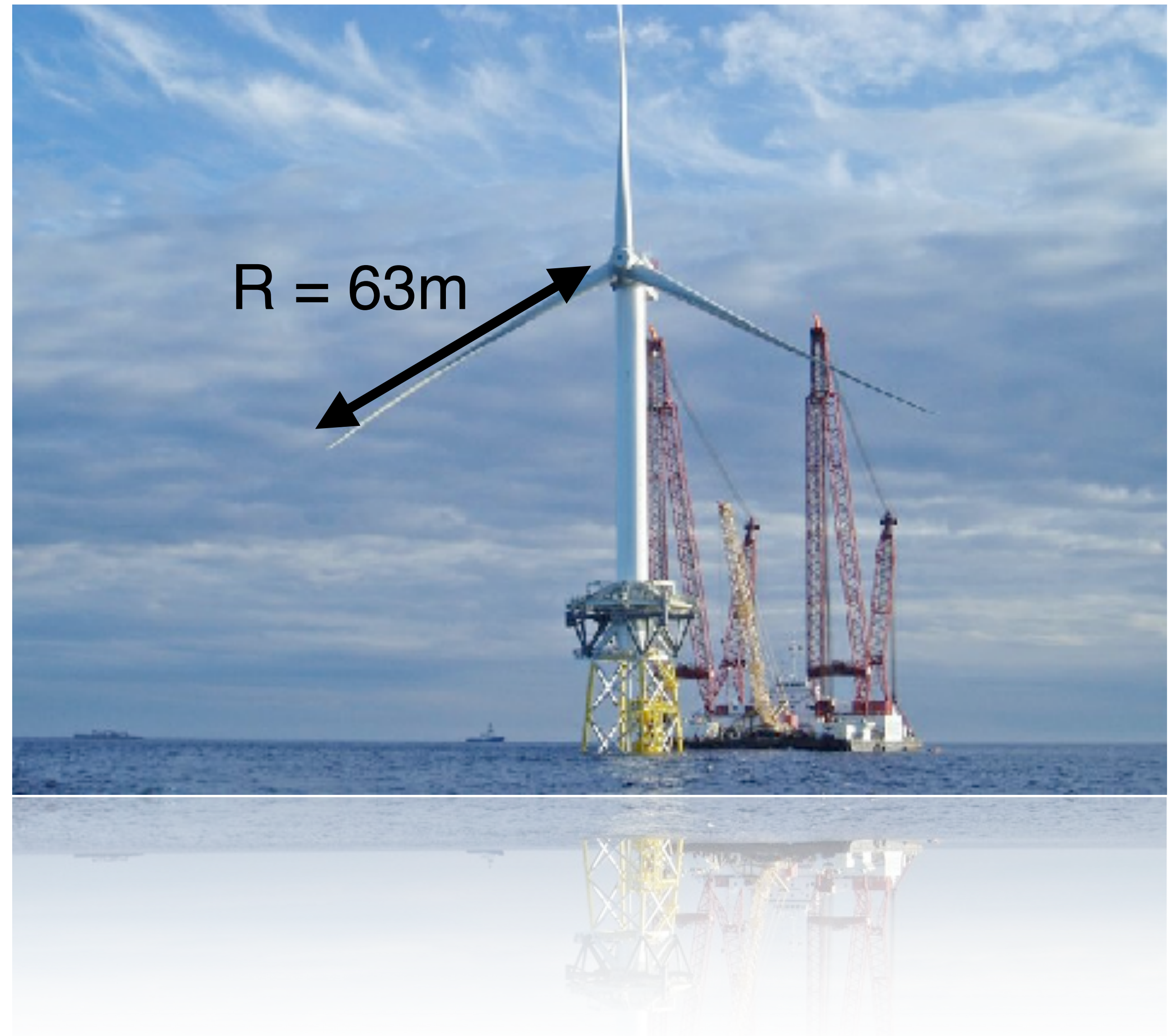
$c_P \leq 0.59$ Betz- Joukowsky limit

About 500 W/m²

modern wind turbines

area = 12469 m²

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



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

$$c_P \leq 0.59$$

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

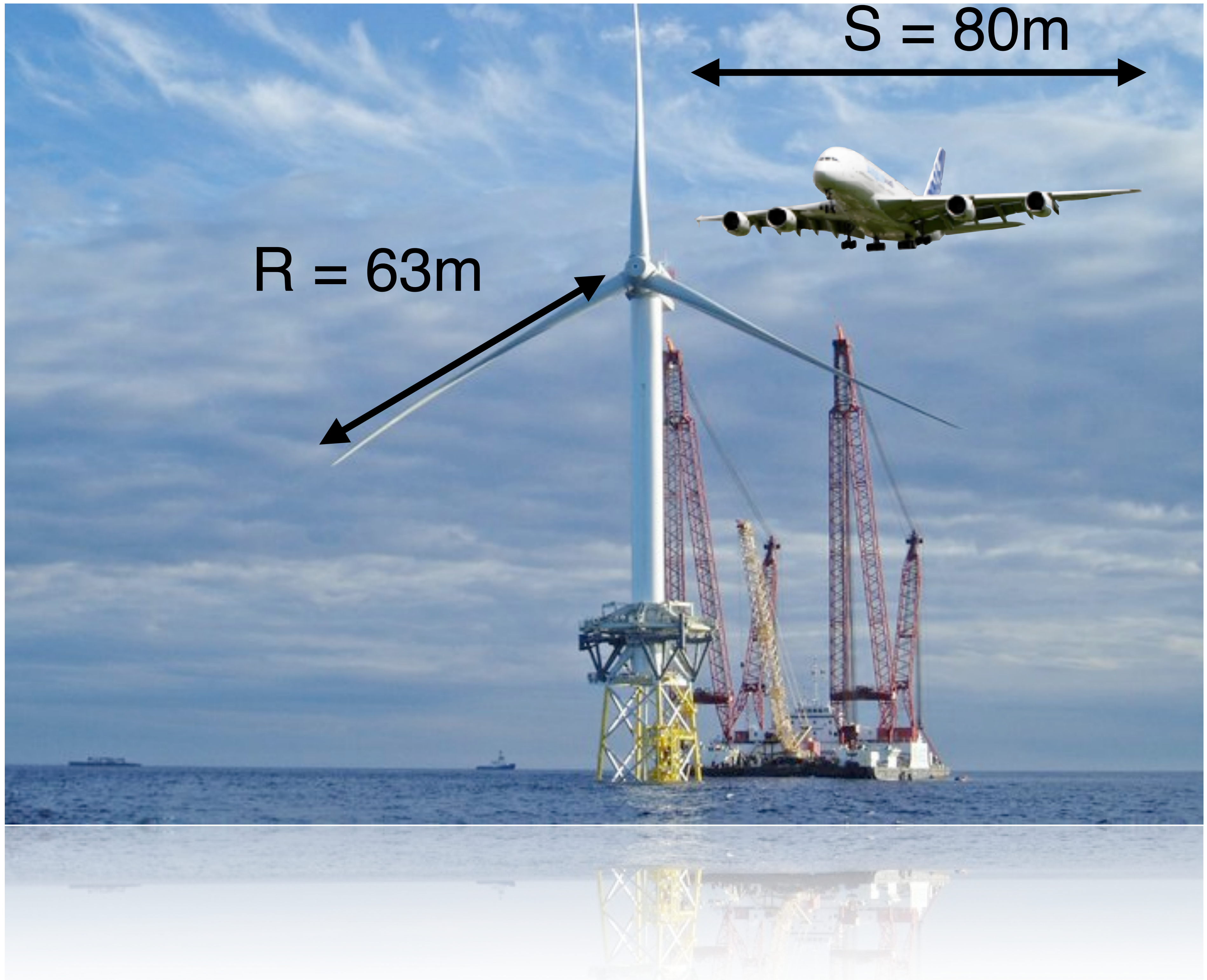
LM 61.5 P

Product specifications

Blade type	LM 61.5 P
Rotor diameter (max.)	126.3 m
Blade regulation	Pitch
Length	61.5 m
Max. chord	4,600 m
Profiled area	183.0 m^2
Weight	17,740 kg*
Number of bolts	128
Size of bolts	M36
Bolt circle diameter	3,200 mm

*Preliminary data

modern wind turbines



modern wind turbines

2019 - GE Haliade-X 12MW:

R= 110m

Haliade-X prototype GE.com

content

Part 1: wind energy

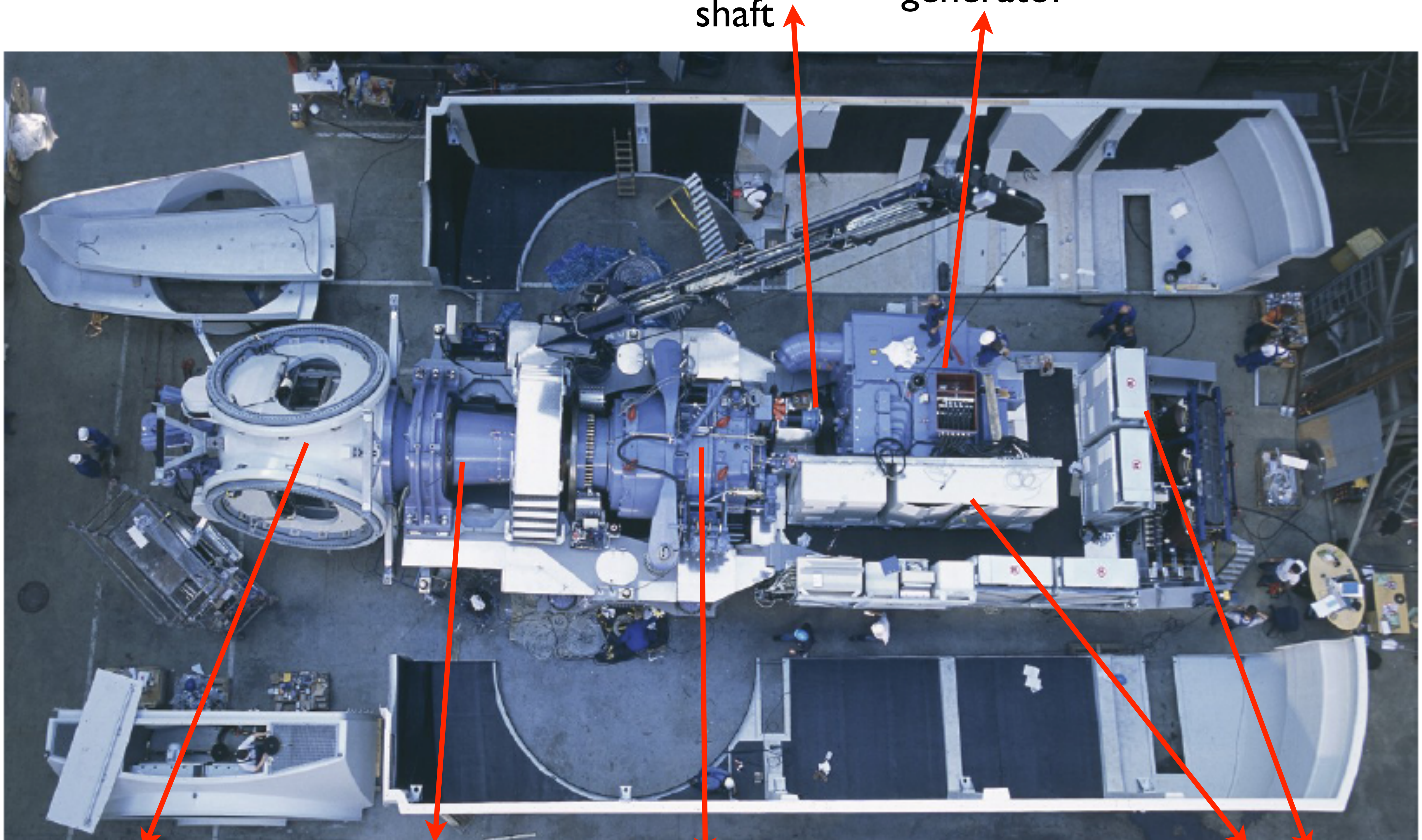
- basic concept of wind energy converters (WEC)
- system and costs

Part 2: wind energy and intermittency: challenges for physics

Research Budget Sources

5MW WEC - electr. energy for about 10.000 to 20.000 persons

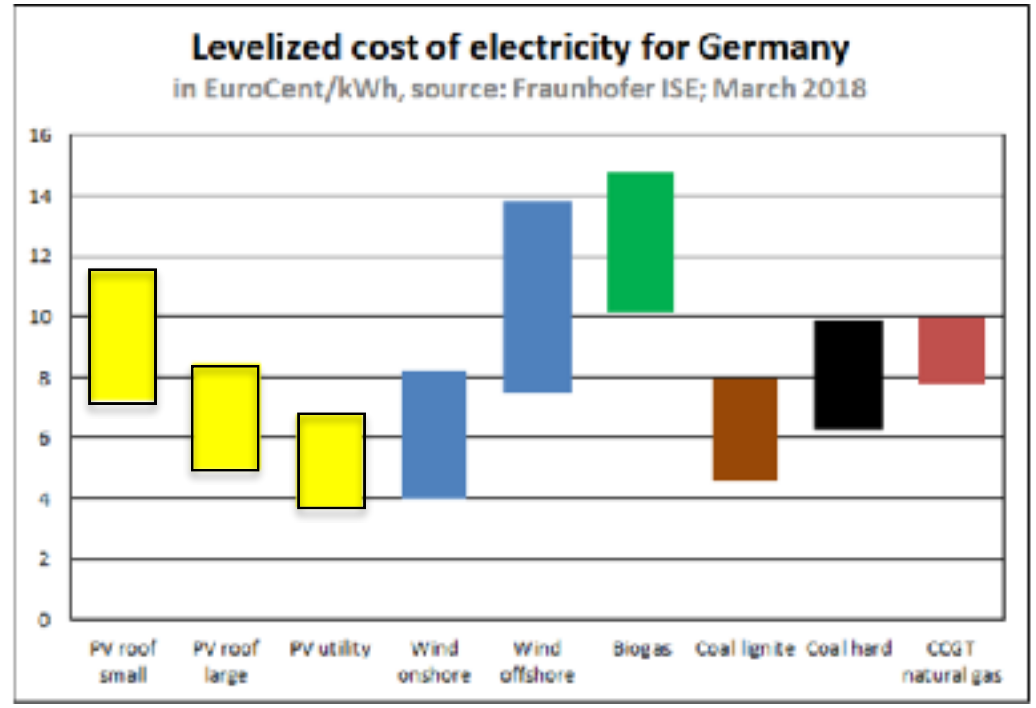
Turbine


high speed shaft
generator
nacelle
hub
main shaft
gearbox
electrical / control system

Costs of wind energy

wind energy one of the cheapest

el. energies



-> costs. 5cent/kWh

Compared to other resources:

Oil - 5cent/kWh

Gas 3 cent/kWh

Coal 1-2 cent/kWh

Electric energy:

1kWh wind $\widehat{=}$ 3 kWh fossil

Wind is cheaper than fossil resource

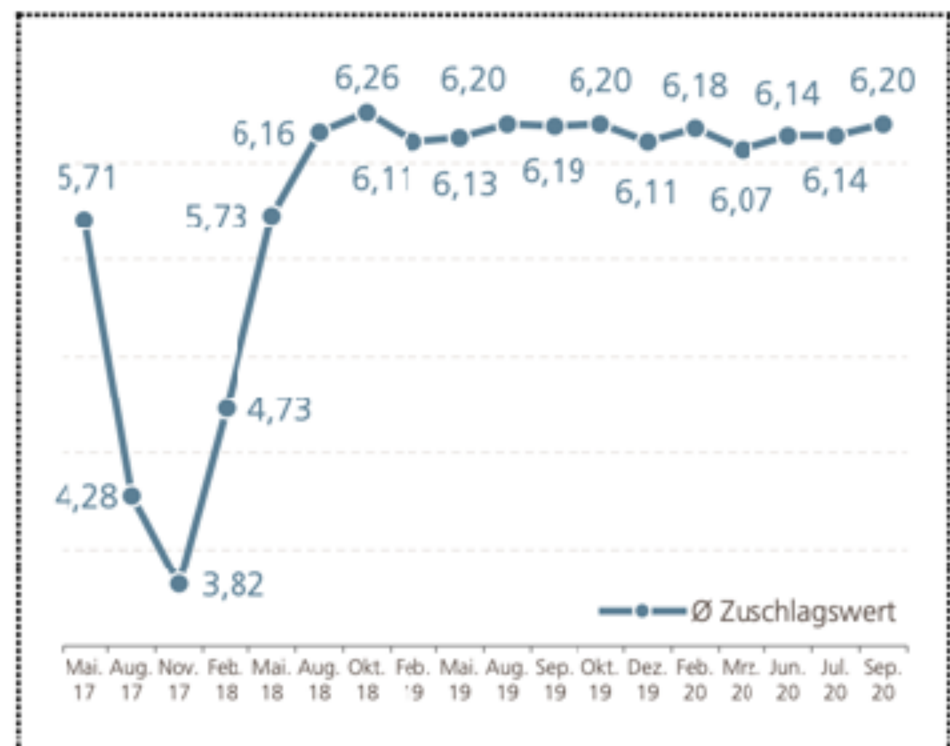


Abbildung 3: Mengengewichtige Zuschlagswerte [in ct/kWh] der Ausschreibungsrunden, aus denen bis dato tausend Anlagen in Betrieb gingen: Daten: BNetzA. Grafik: FA Wind

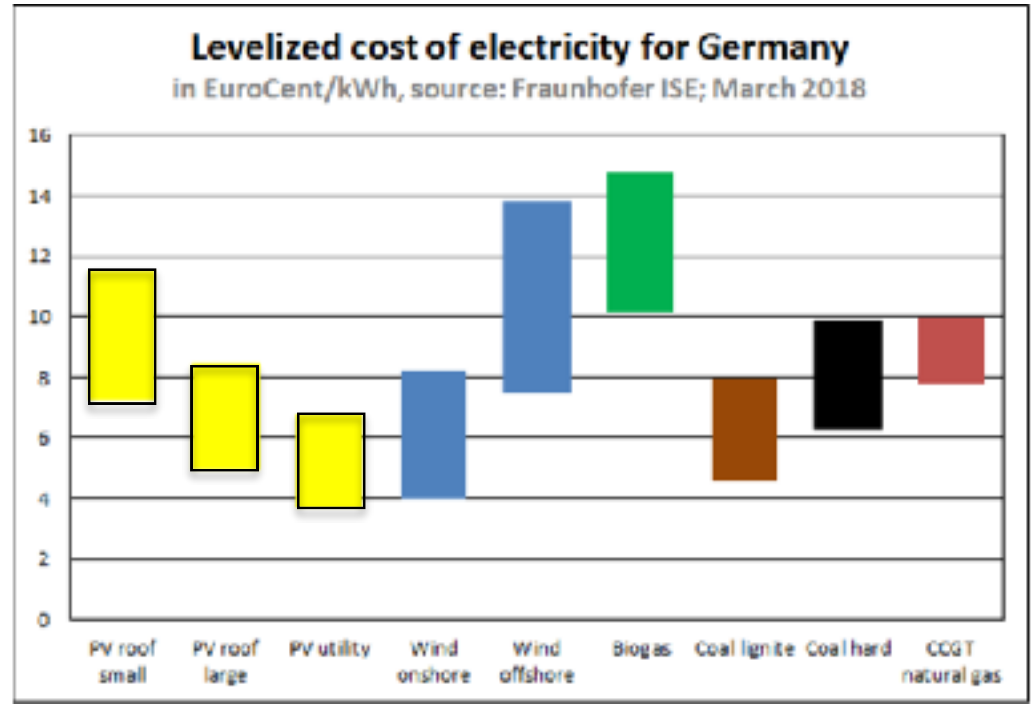
Costs of wind energy

wind energy one of the cheapest

el. energies

-> costs. 5cent/kWh

Why is wind so cheap?



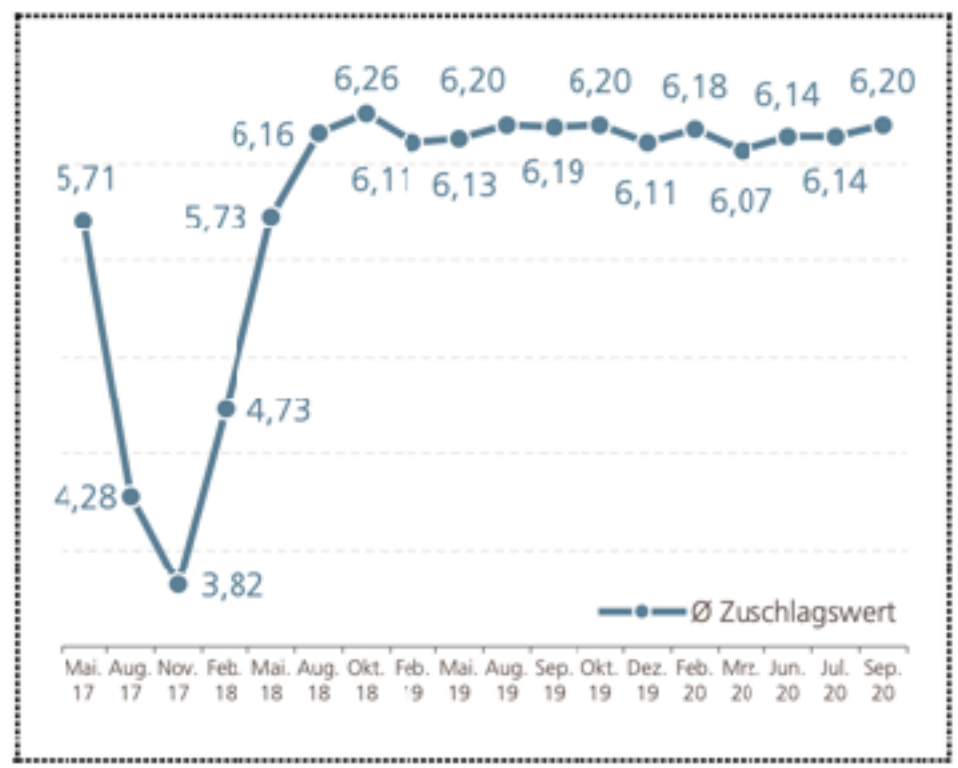
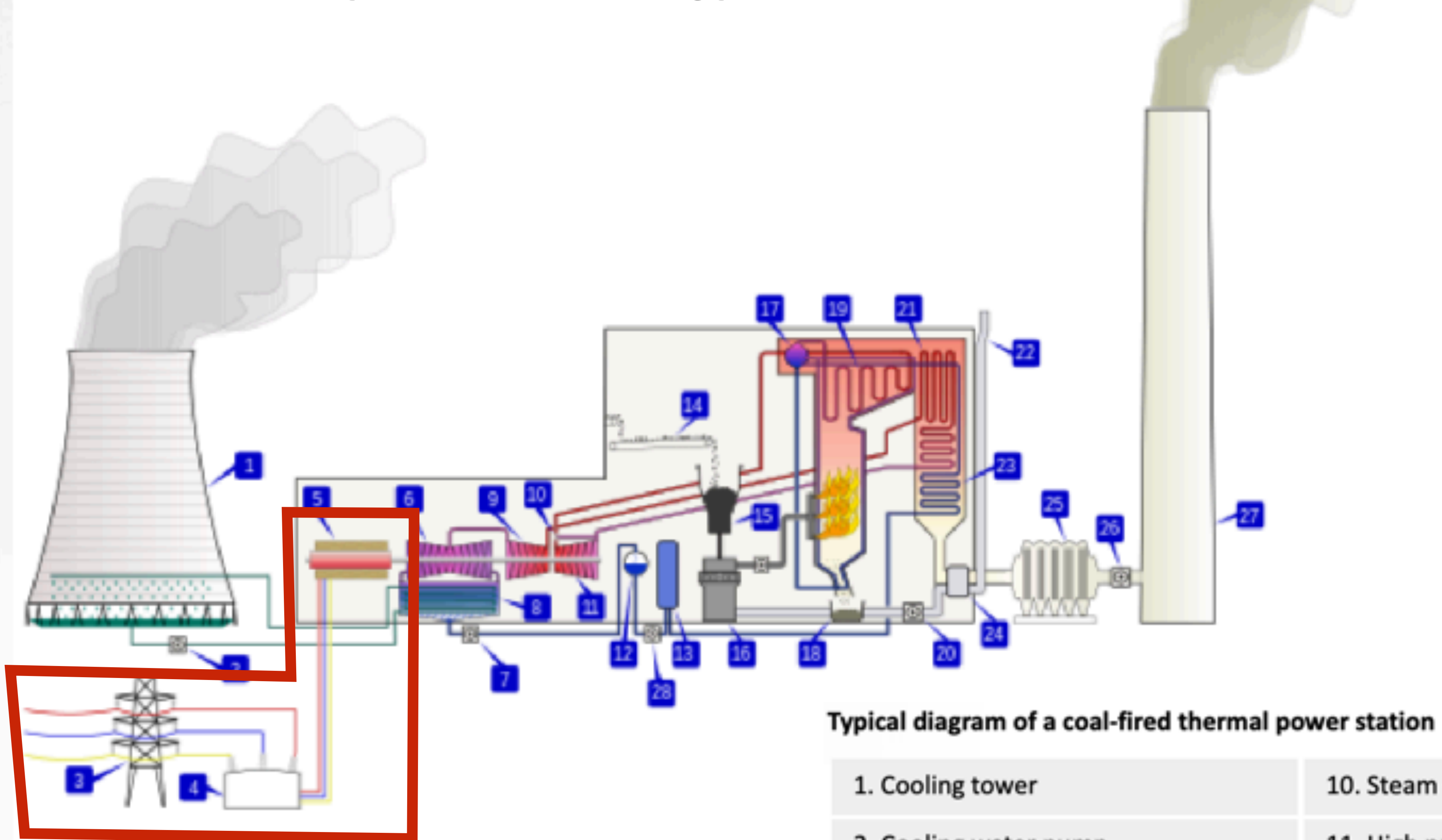


Abbildung 3: Mengengewichtige Zuschlagswerte [in ct/kWh] der Ausschreibungsrunden, aus denen bis dato tausend Anlagen in Betrieb gingen: Daten: BNetzA. Grafik: FA Wind

Why is wind energy so cheep?



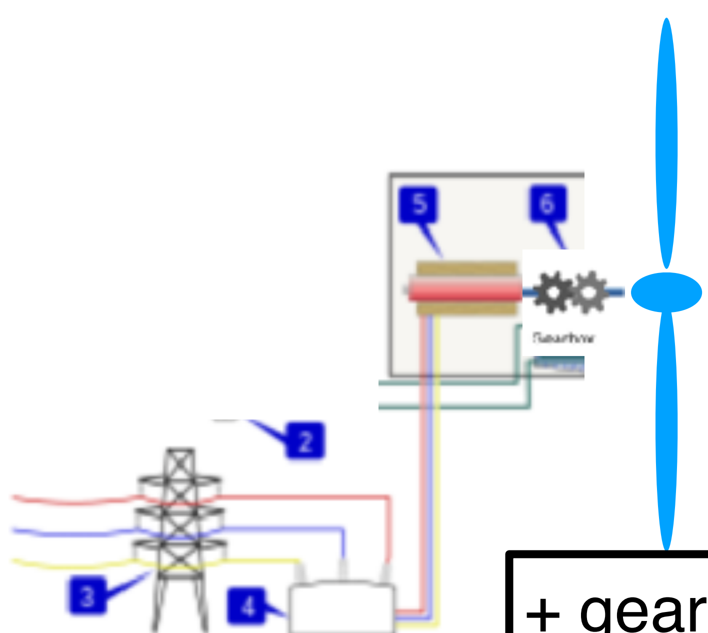
Typical diagram of a coal-fired thermal power station

Wind

- **resource 0cent/kWh**
- **1-2 € / installed Watt**

Typical diagram of a coal-fired thermal power station

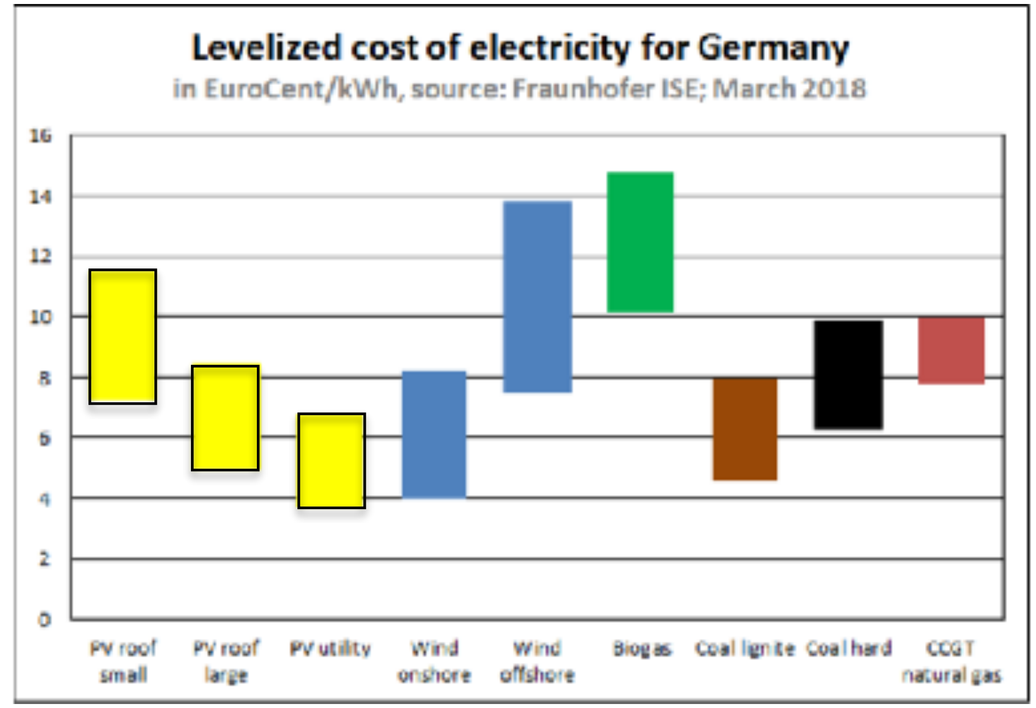
1. Cooling tower	10. Steam Control valve	19. Superheater
2. Cooling water pump	11. High pressure steam turbine	20. Forced draught (draft) fan
3. transmission line (3-phase)	12. Deaerator	21. Reheater
4. Step-up transformer (3-phase)	13. Feedwater heater	22. Combustion air intake
5. Electrical generator (3-phase)	14. Coal conveyor	23. Economiser
6. Low pressure steam turbine	15. Coal hopper	24. Air preheater
7. Condensate pump	16. Coal pulverizer	25. Precipitator
8. Surface condenser	17. Boiler steam drum	26. Induced draught (draft) fa
9. Intermediate pressure steam turbine	18. Bottom ash hopper	27. Flue gas stack



+ gearbox , Rotor

ForWind Zentrum für Windenergieforschung Bremen Hannover Oldenburg

Costs of wind energy



wind energy one of the cheapest

el. energies

-> costs

1kWh wind - replaces 3 kWh fossile

Cost 1-2 /€ per Watt

- for private 3000-5000 Euro

- 15 - 20.000 Euro for all energy

Per capita

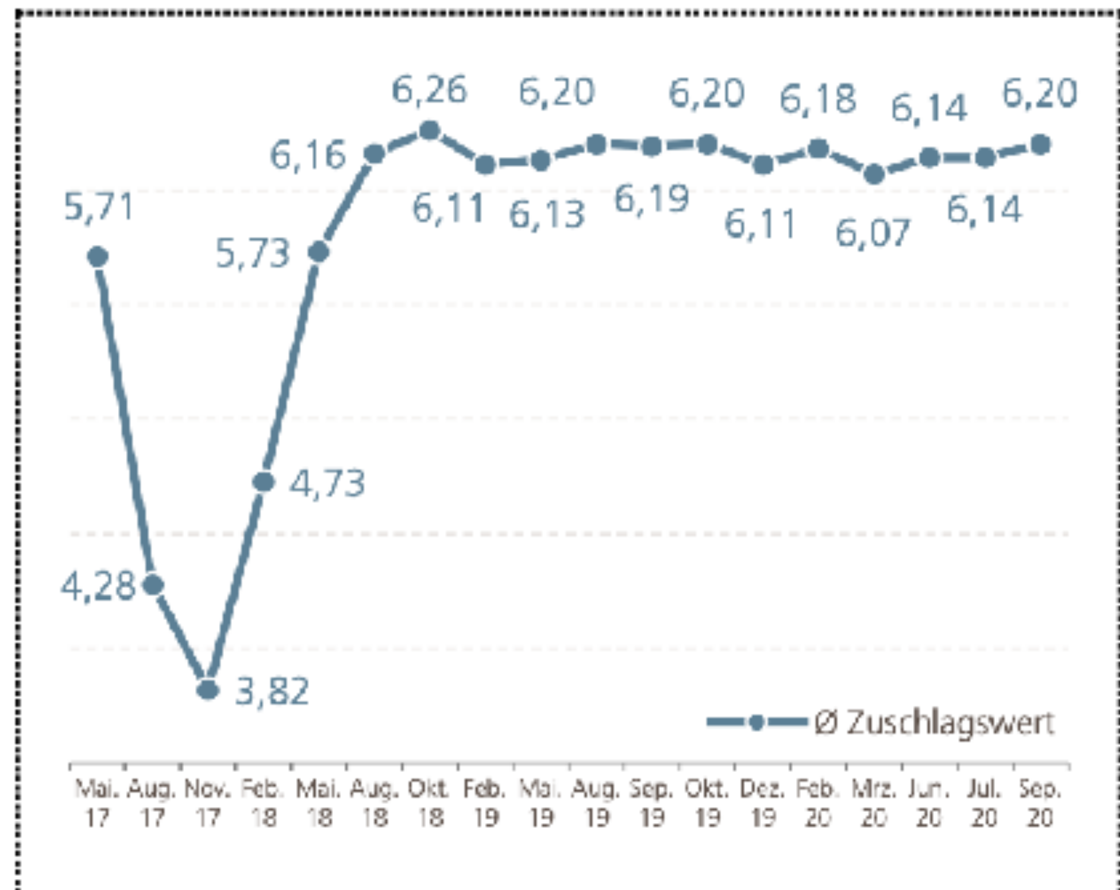


Abbildung 3: Mengengewichtige Zuschlagswerte [in ct/kWh] der Ausschreibungsrunden, aus denen bis dato tausend Anlagen in Betrieb gingen; Daten: BNetzA, Grafik: FA Wind

Costs of wind energy

wind energy one of the cheapest

el. energies

-> costs

Cost 1-2 /€ per installed Watt

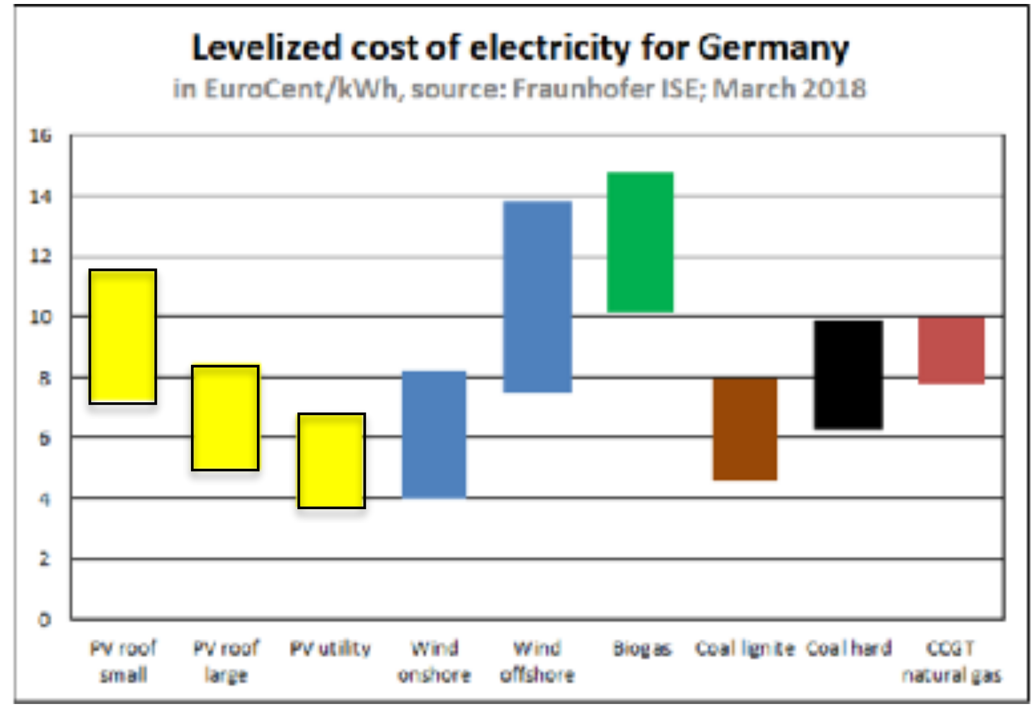
Mean power

- for private 1kW

- **3000-5000 Euro**

- all power per capita 5-6kW

- **15 - 20.000 Euro**



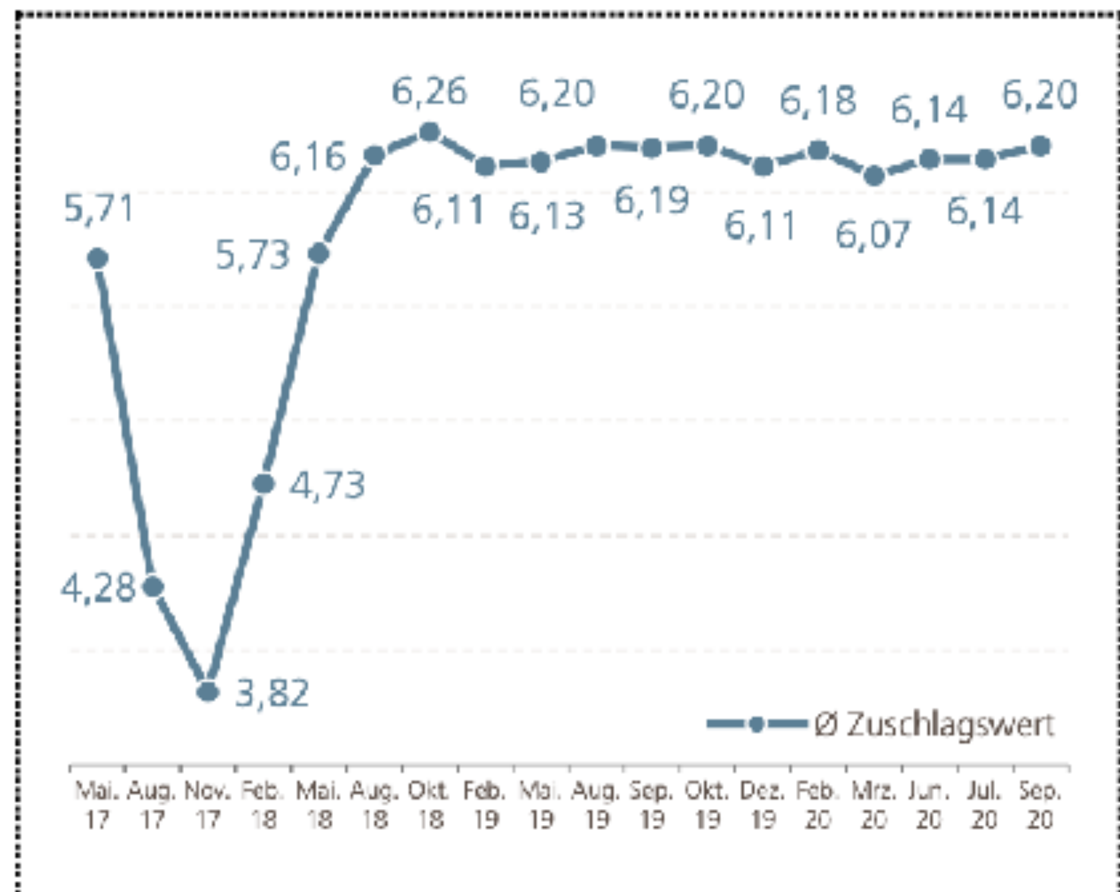
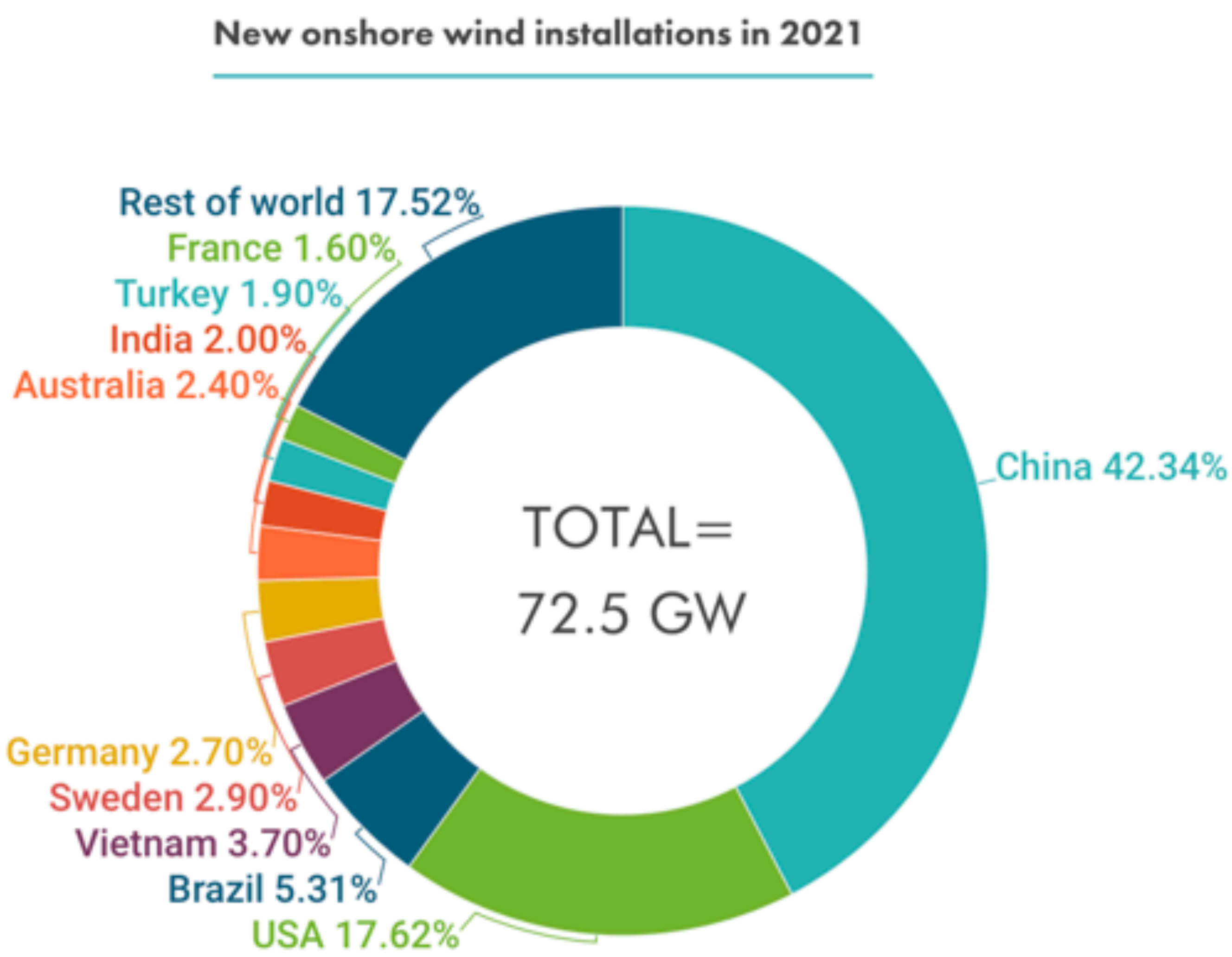


Abbildung 3: Mengengewichtige Zuschlagswerte [in ct/kWh] der Ausschreibungsrunden, aus denen bis dato tausend Anlagen in Betrieb gingen; Daten: BNetzA, Grafik: FA Wind

overall wind energy is a worldwide story of success

Annual new installation -> 100GW for 2022



Source GWEC annual report

See also iea Wind

ForWind Zentrum für Windenergieforschung Bremen Hannover Oldenburg

content

Part 1: wind energy

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

Part 2: wind energy and intermittency: challenges for physics

Intermittency a problem?
- yes !
What to do ?

- show stopper

or physical understanding to handle it

Intermittency :

Large scale intermittency.

- long term variability - two days not wind

=> energy meteorology

Two comments -

* Around 2000 impossible to have stable grid with more than 10% wind
Today up to 100% and more state grid than 2000
* running time : 25% - means at full power - running time much larger, like for a car - running with max speed.

Intermittency a problem?
- yes !
What to do ?
- **- show stopper**
- **or physical understanding to handle it**

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

Small scale intermittency
- fast changes of wind power

=> next topics

- we need statistics

- ….

- stochastic process for advanced understanding

energy resource: wind
wind measurements and data analysis

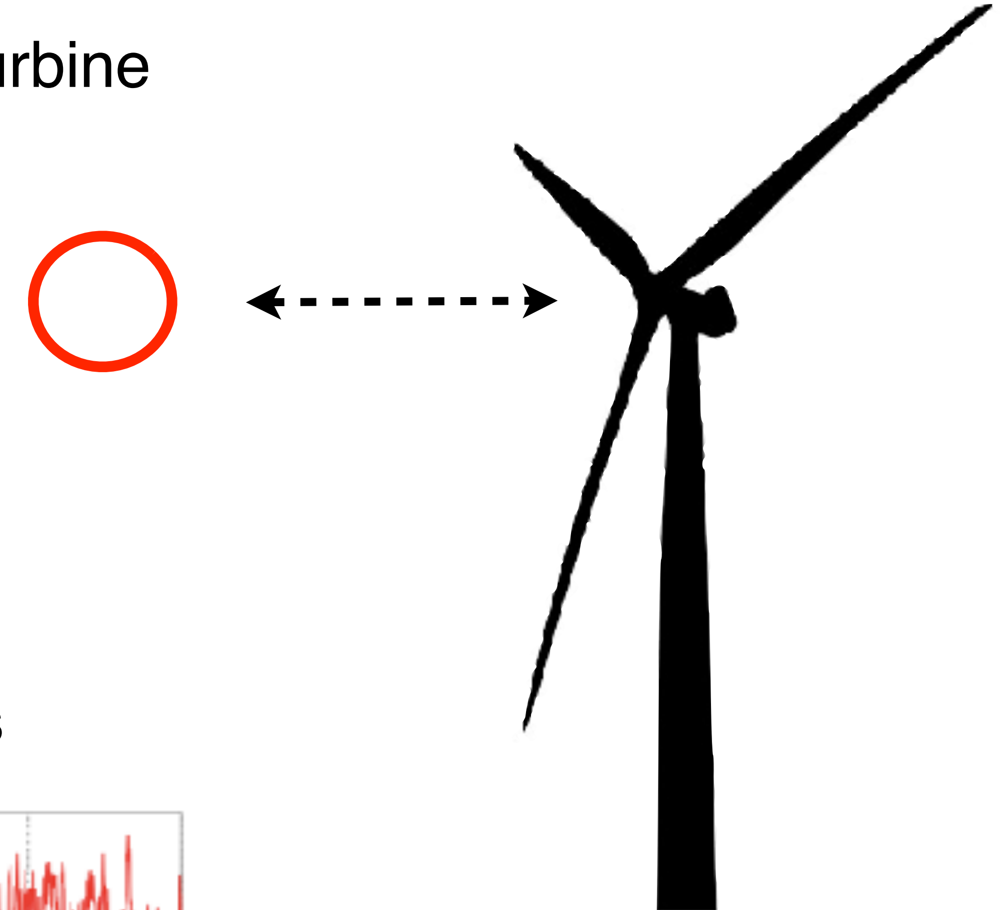
INTERNATIONAL STANDARD

IEC 61400-1

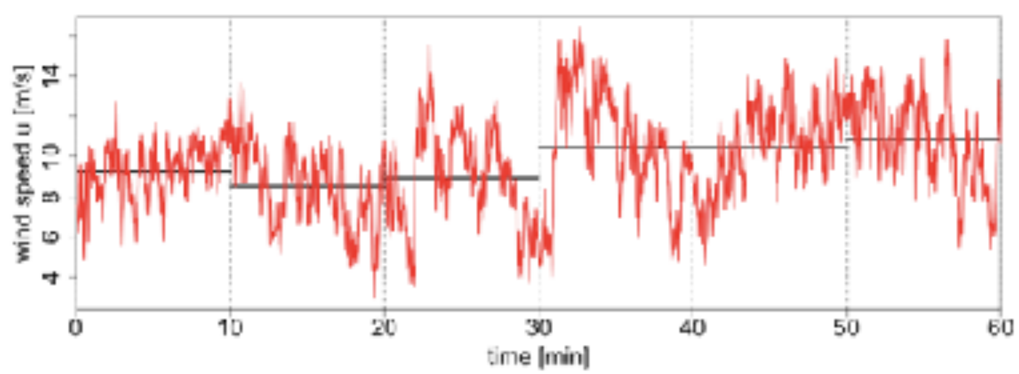
Third edition 2005-08

wind conditions after IEC

- measurement at hub height in front of a turbine

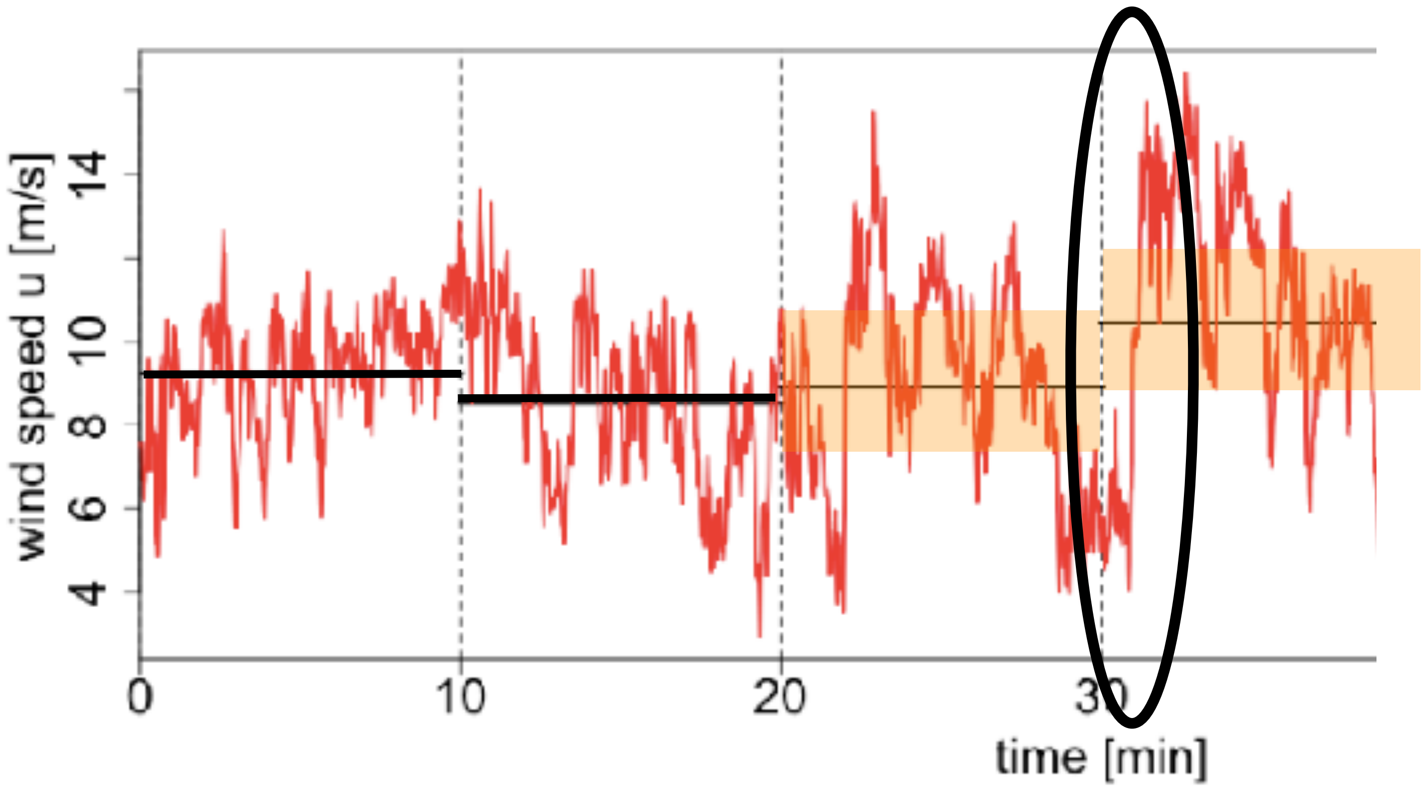


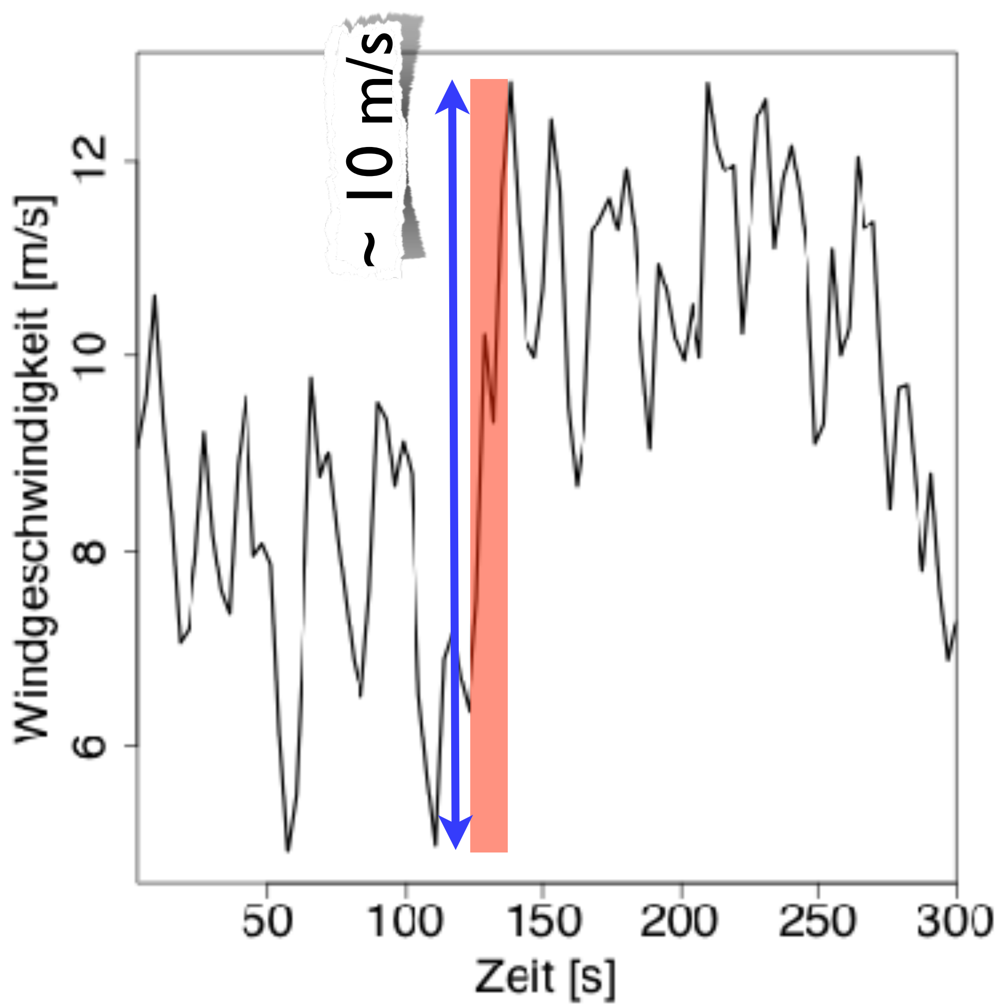
measured time series



wind measurements and data analysis

- characterisation after IEC norm

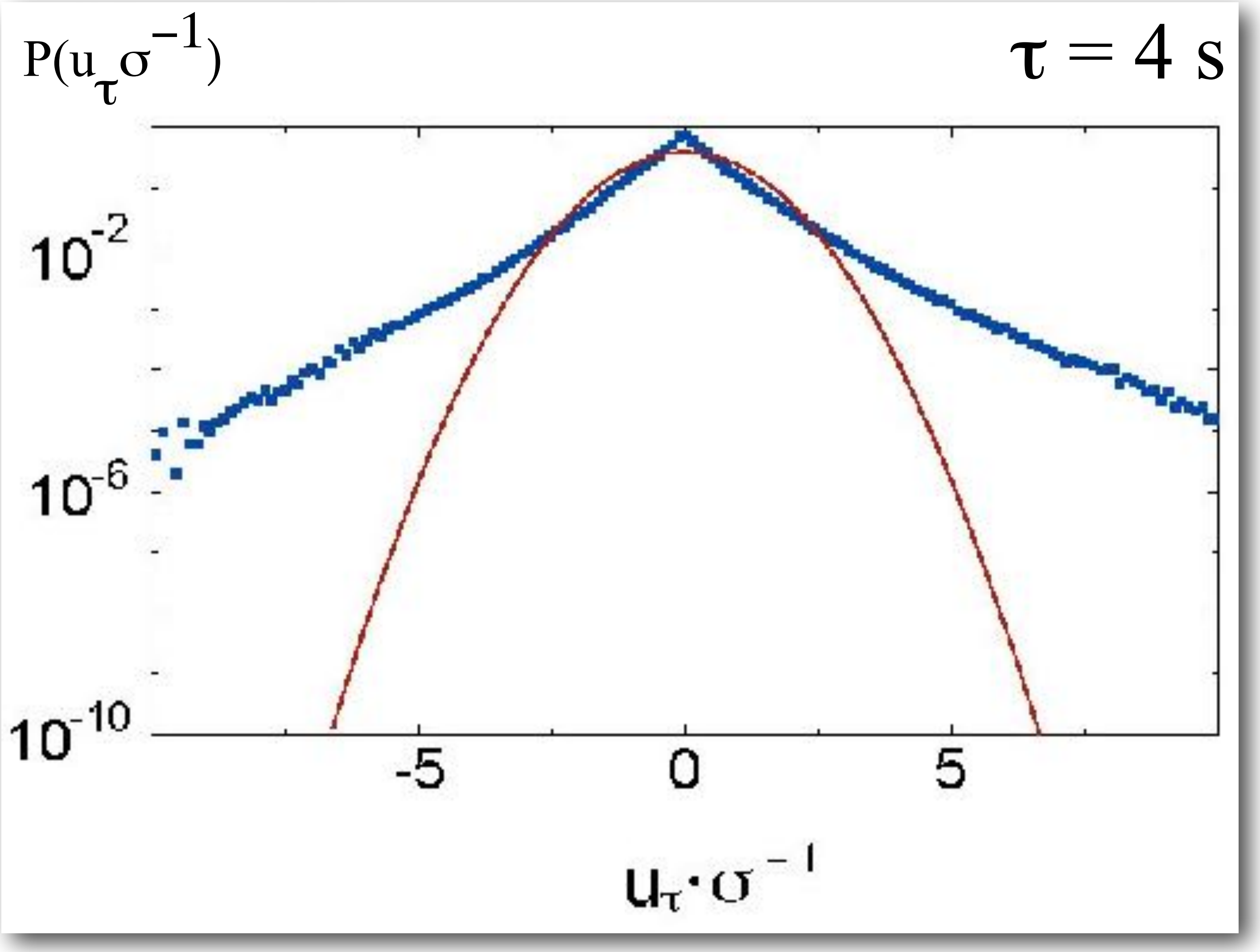


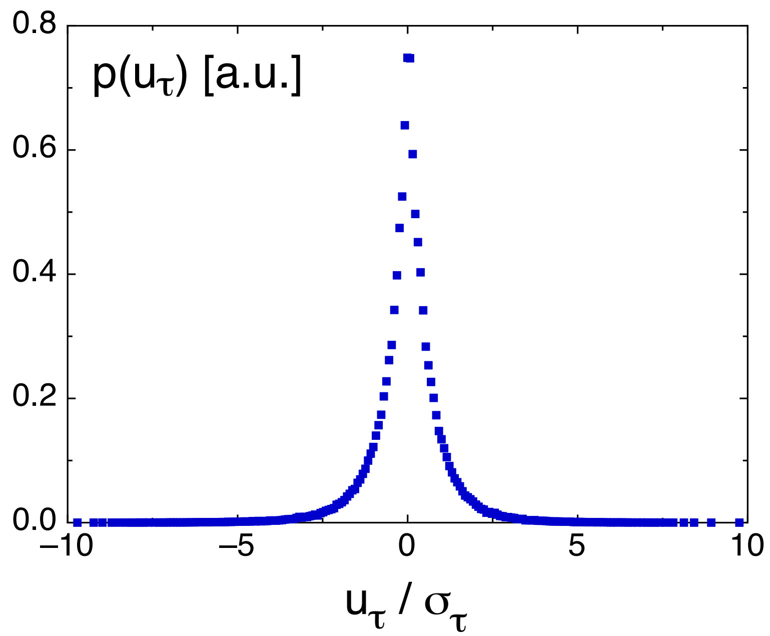


statistics of gusts

- wind fluctuations can be measured by velocity increments

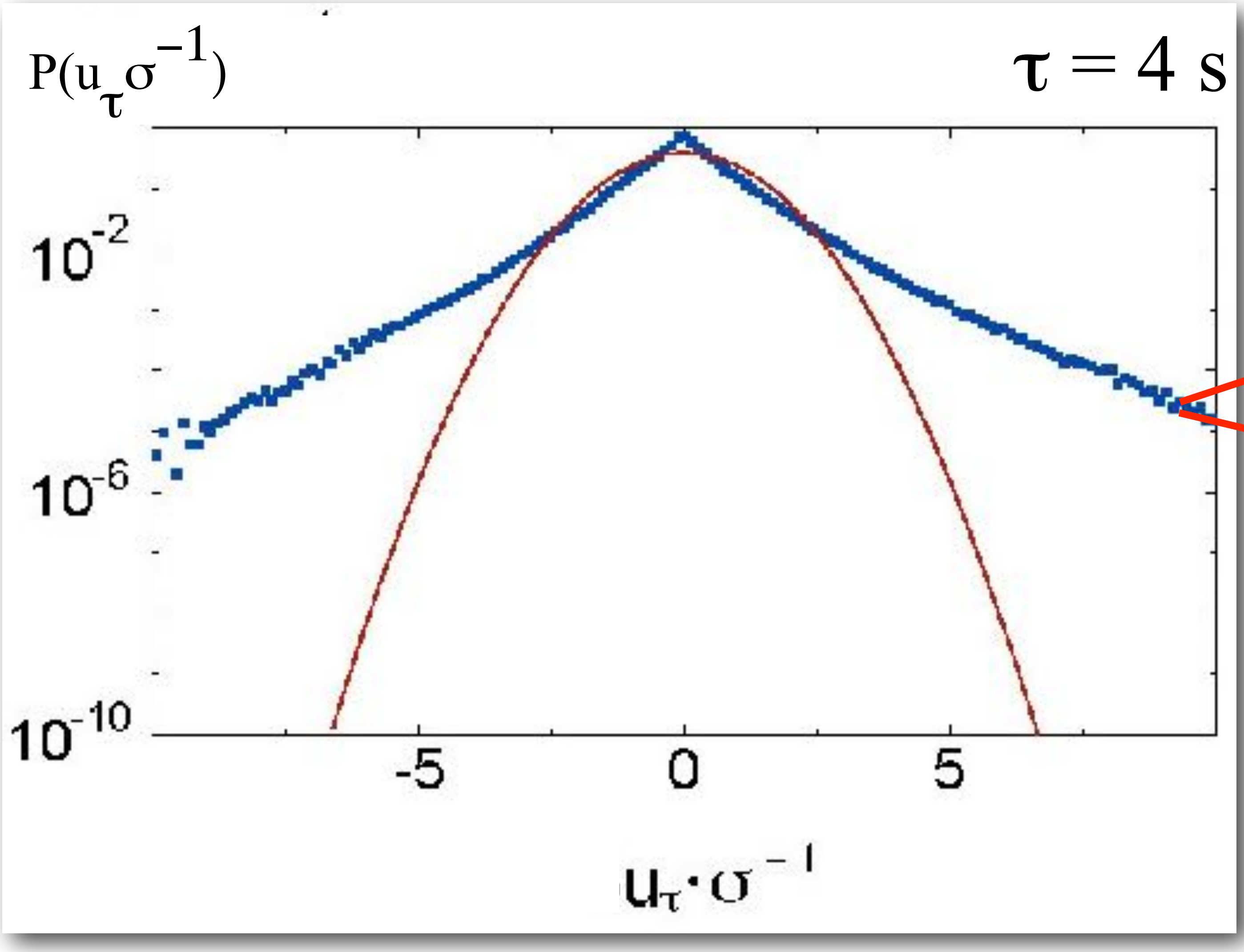
$$u_\tau = u(t+\tau) - u(t)$$

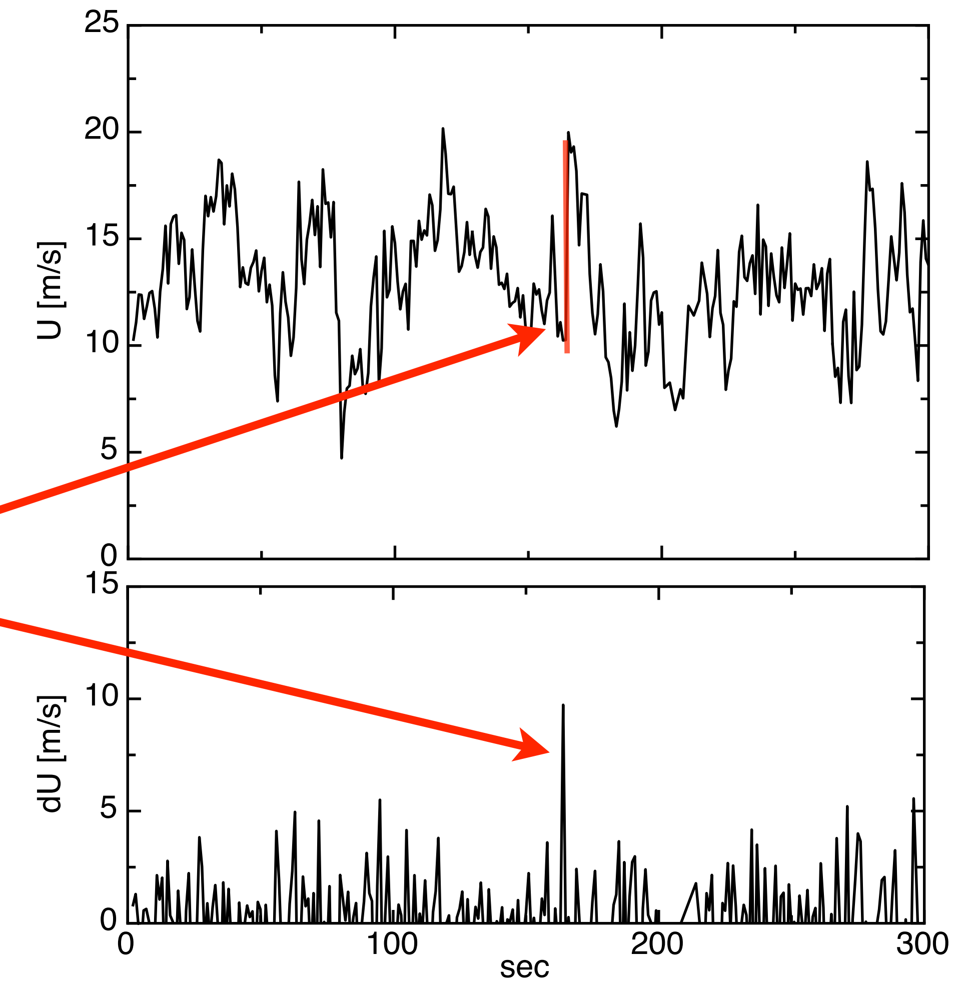




Boundary-Layer Meteorology **108** (2003)

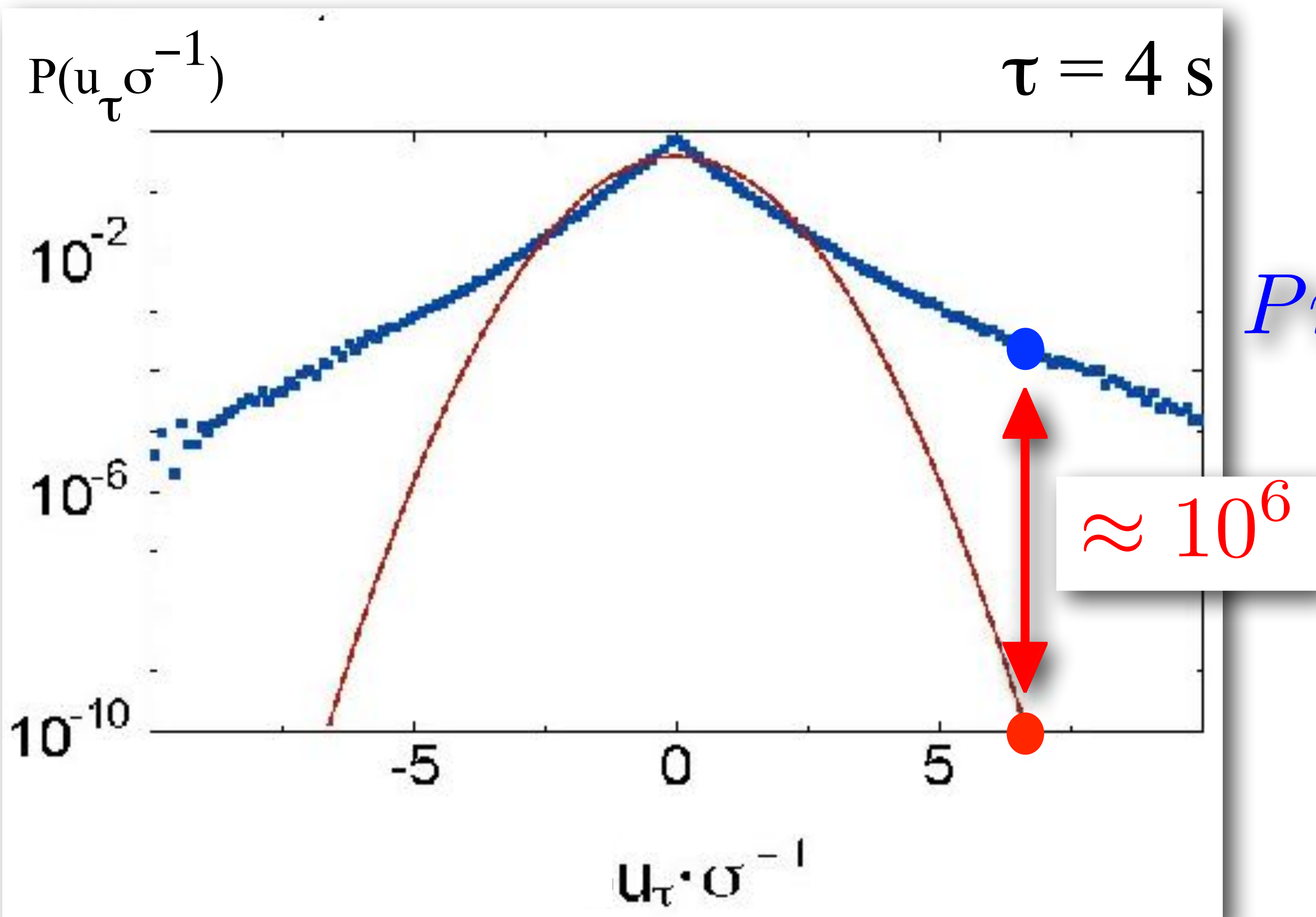
statistics of gusts





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

statistics of gusts



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

1/day

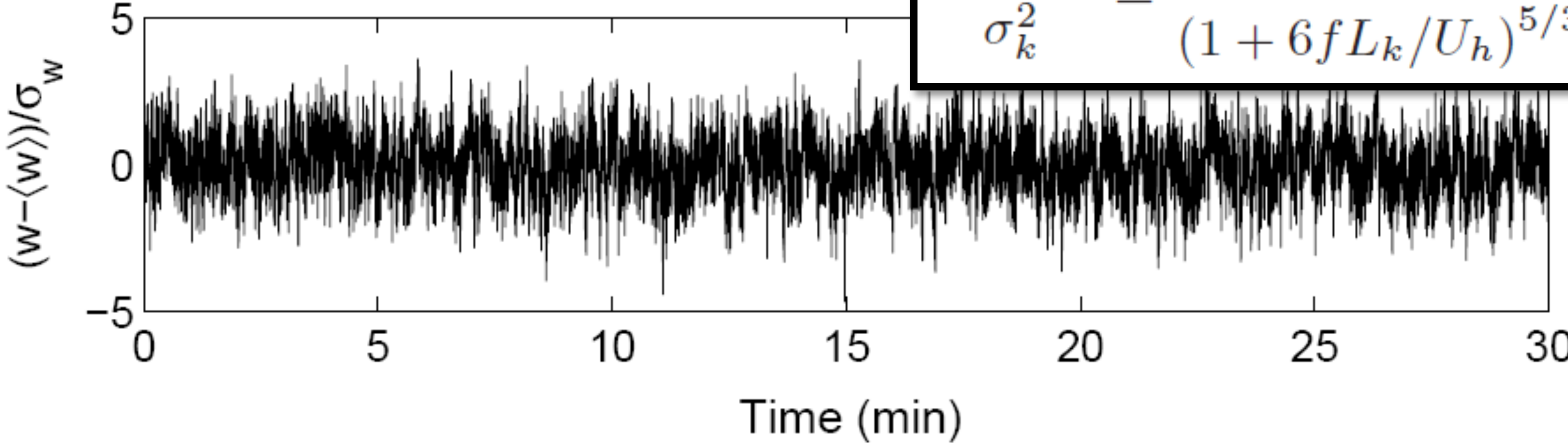
$Prob(u_\tau > 6\sigma) \approx 10^{-10}$

1/3000 years

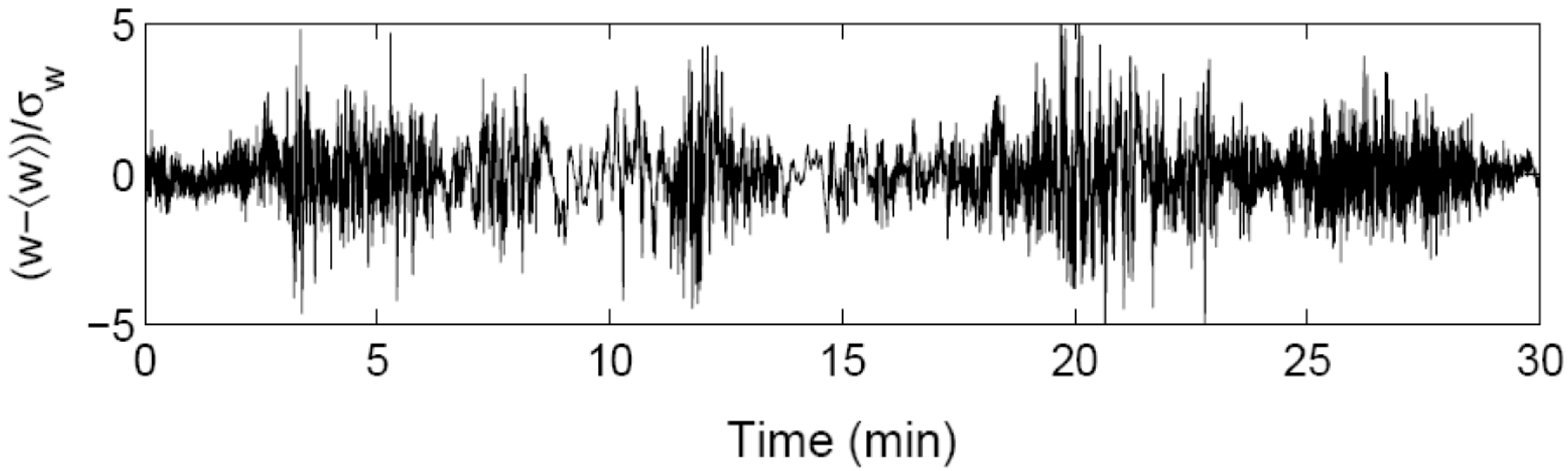
IEC Wind and measured

IEC Code

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

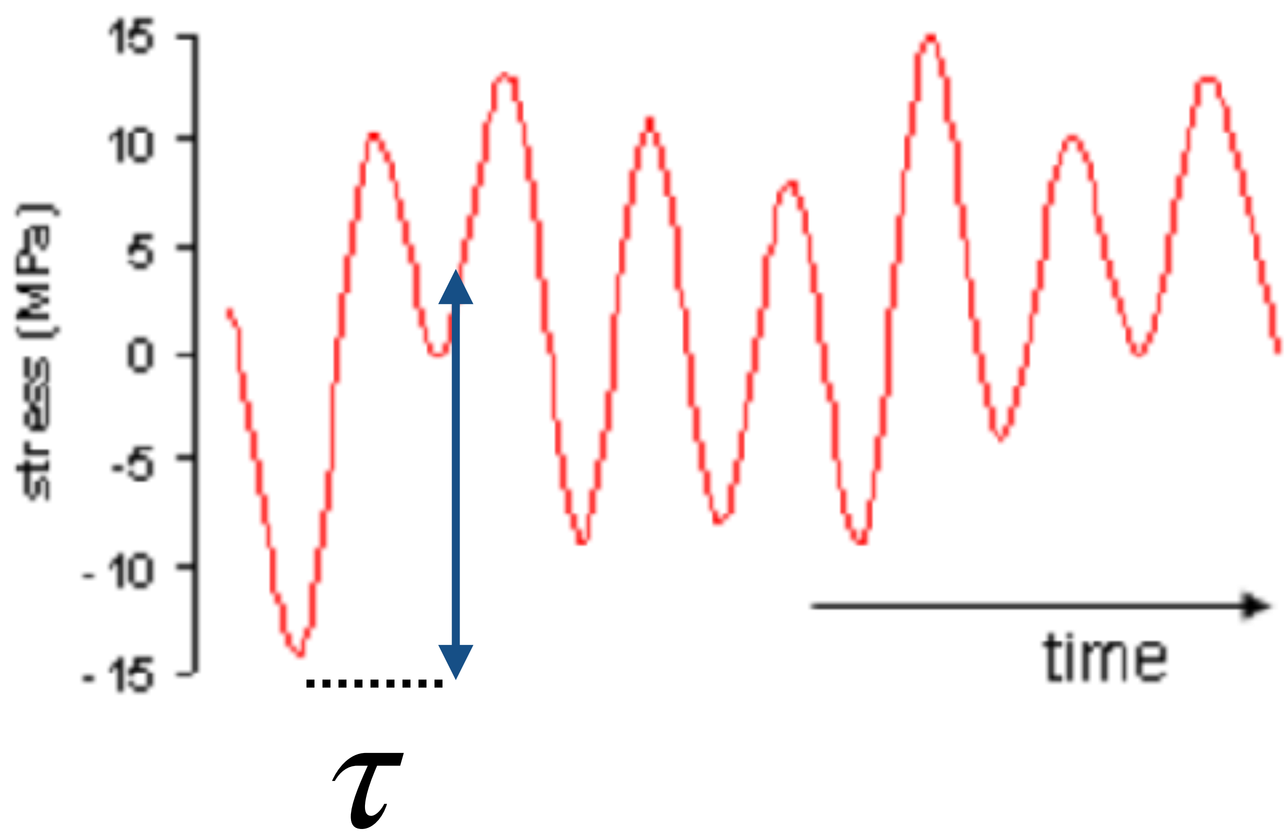


Observation



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

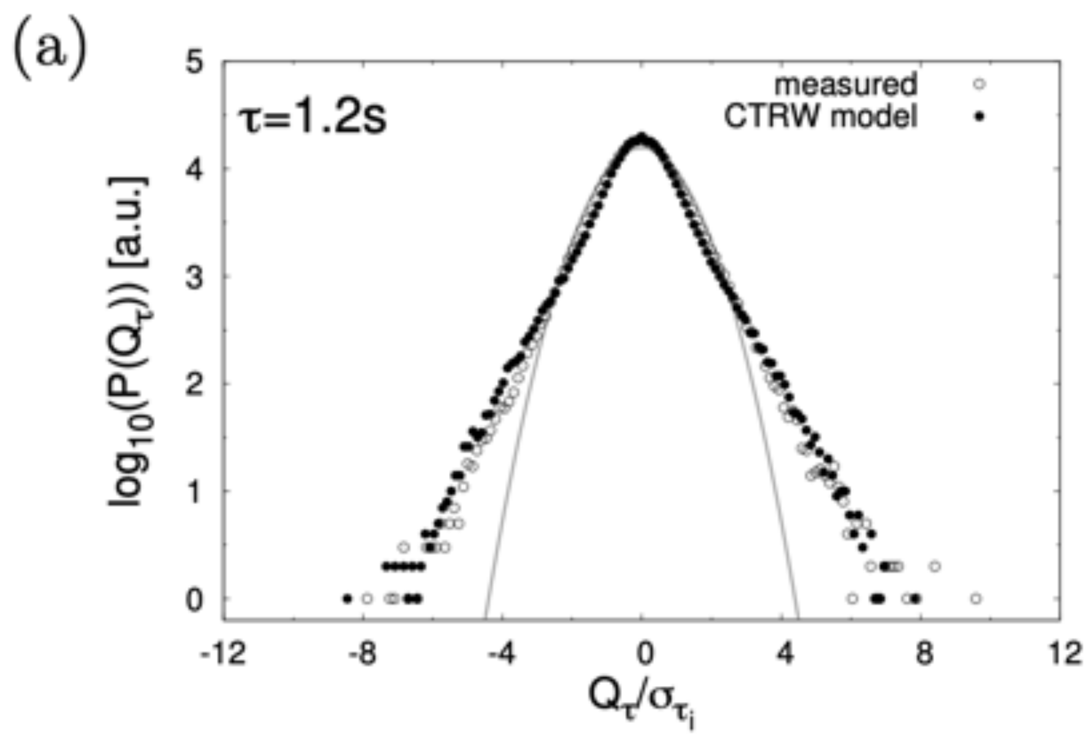
Load and damage estimation
- intermittency



Load signal

Increment analysis:

Turbulent intermittency

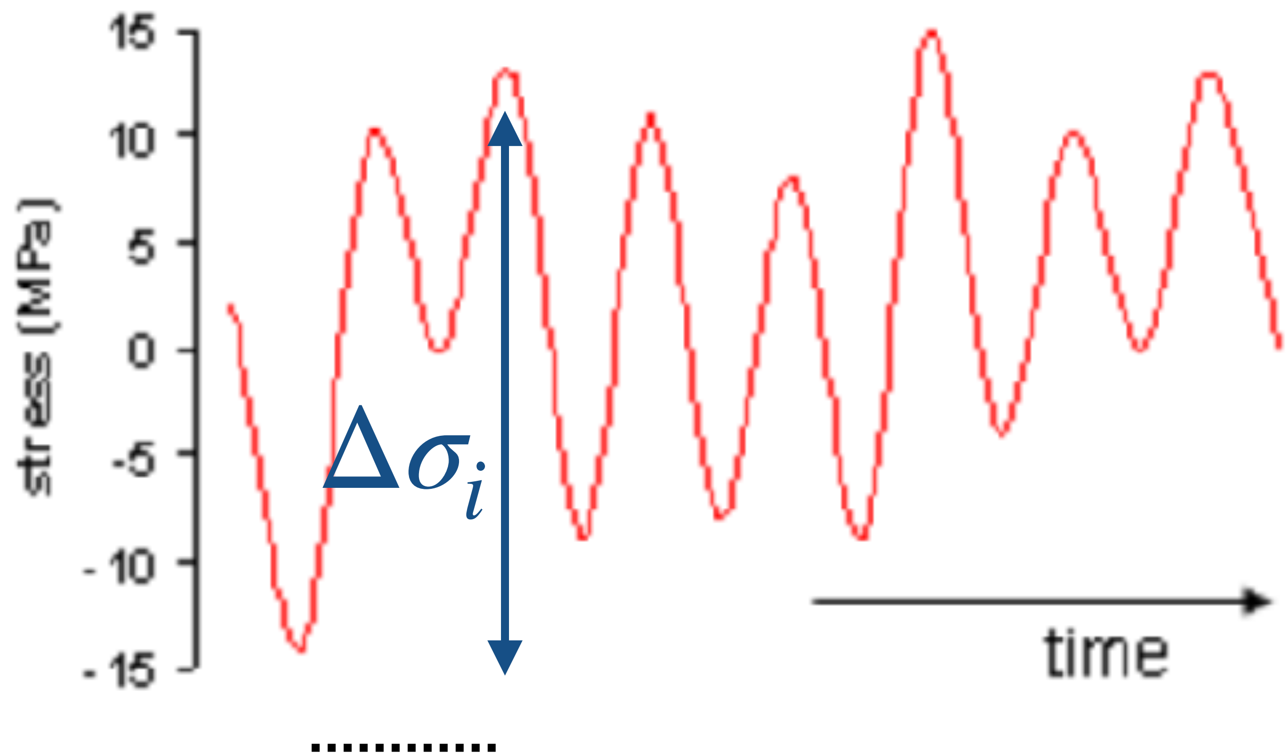


T. Mücke, et al. Wind Energy 14, 301 (2011)

ForWind Zentrum für Windenergieforschung Bremen Hannover Oldenburg

Load and damage estimation
- rainflow counting

Load signal



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

Damage equivalent

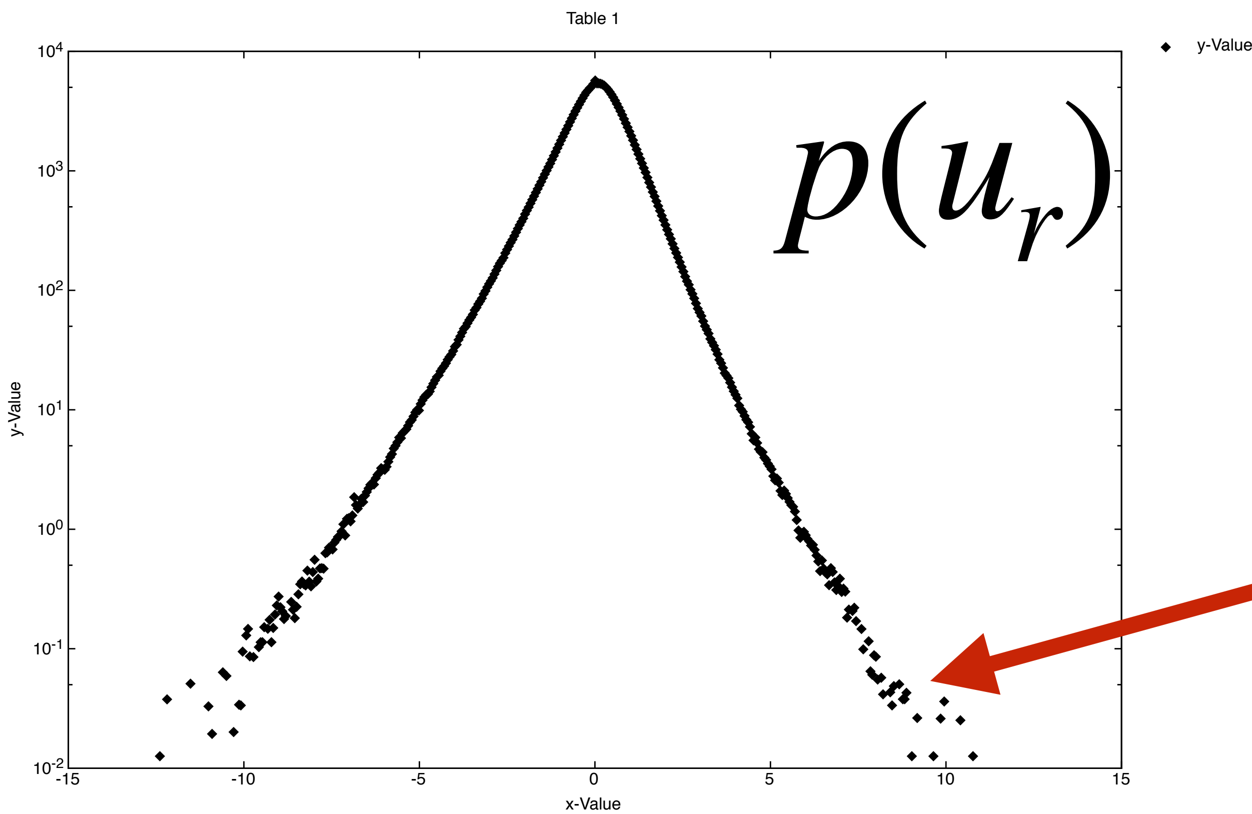
$$\Delta\sigma_{ref} = \left[\frac{\sum_i n_i \cdot (\Delta\sigma_i)^m}{N_{ref}}\right]^{\frac{1}{m}}$$

Wöhler coefficient m

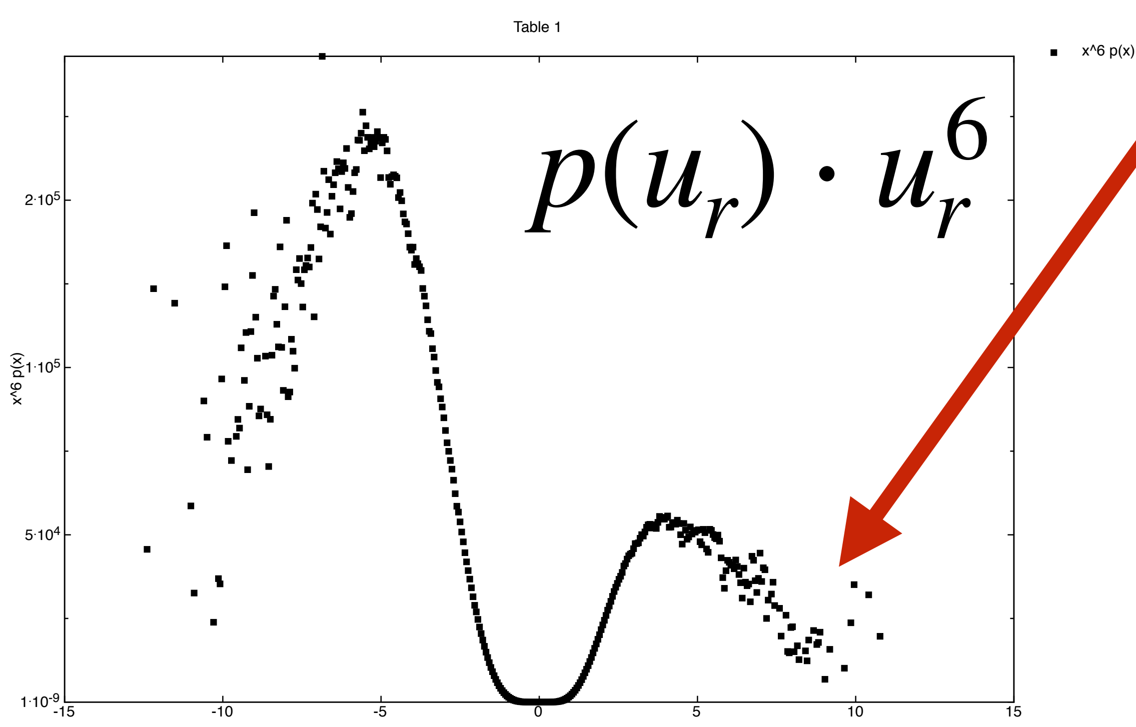
metal m=3

Composite **m=10**

ForWind Zentrum für Windenergieforschung Bremen Hannover Oldenburg



We need to have an understanding of these extreme events



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

Small scale intermittency
- fast changes of wind power
=> next topics

- we need statistics

- ….

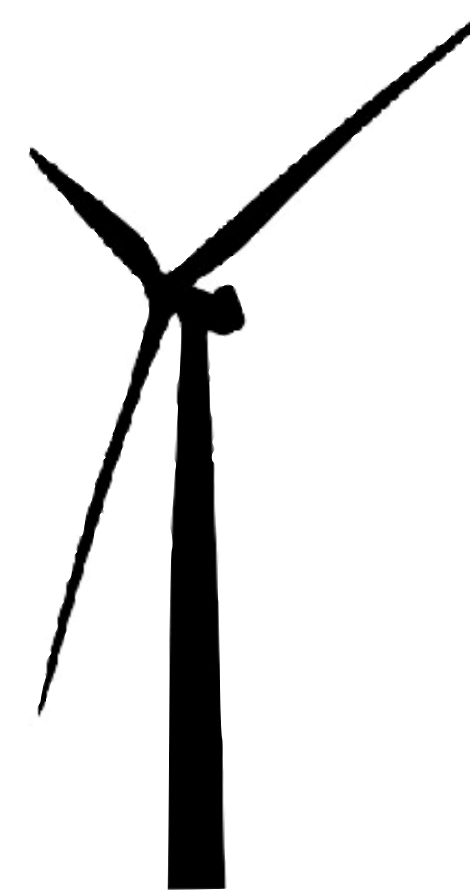
- stochastic process for advanced understanding

contribution of physics to wind energy:

Inflow is energy resource

claim - need to understand turbulence

what is the turbulence problem?



Turbulence one of 7 milenium problems

Clay Mathematics Institute

Dedicated to increasing and disseminating mathematical knowledge

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

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 milenium 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.

velocity increment

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

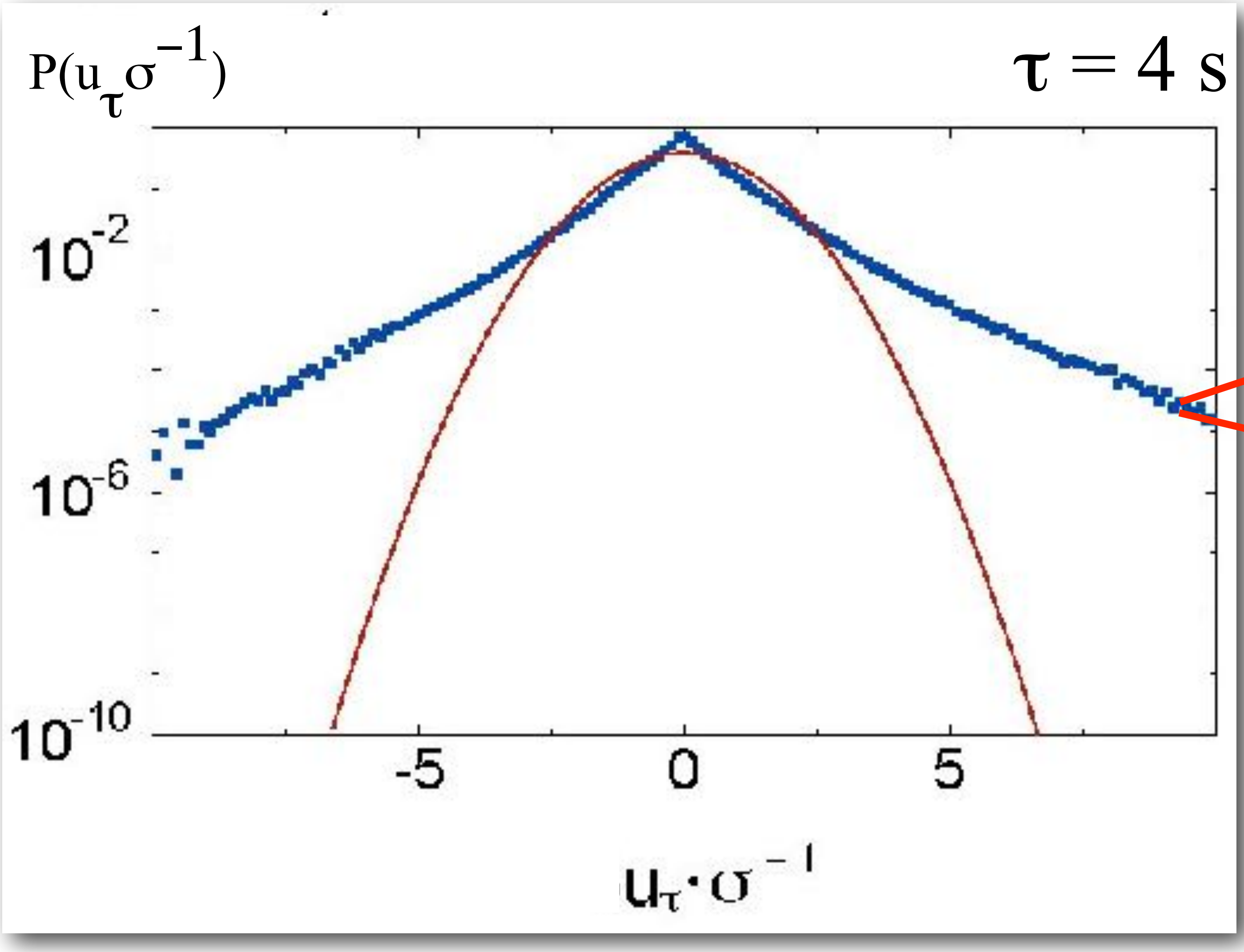
$$= lim_{r \to 0} \frac{u_r}{r}$$

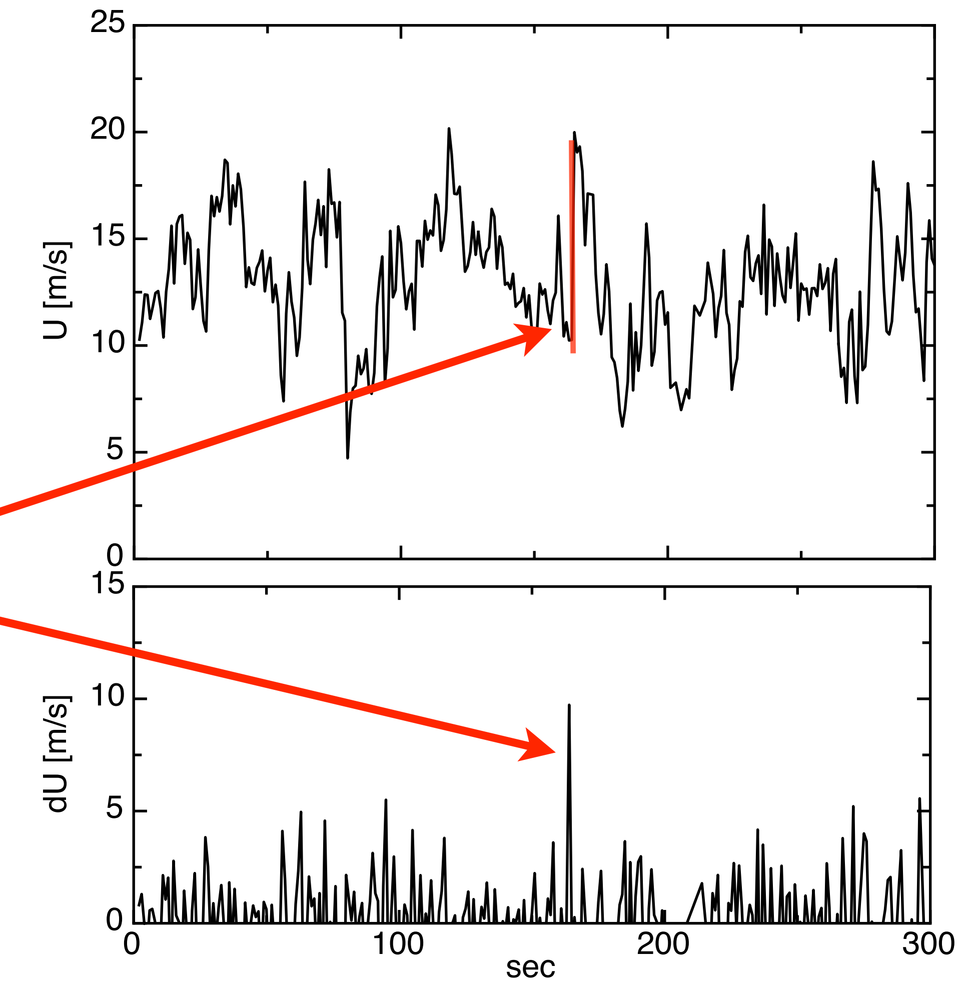
have to understand

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

statistics of gusts

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





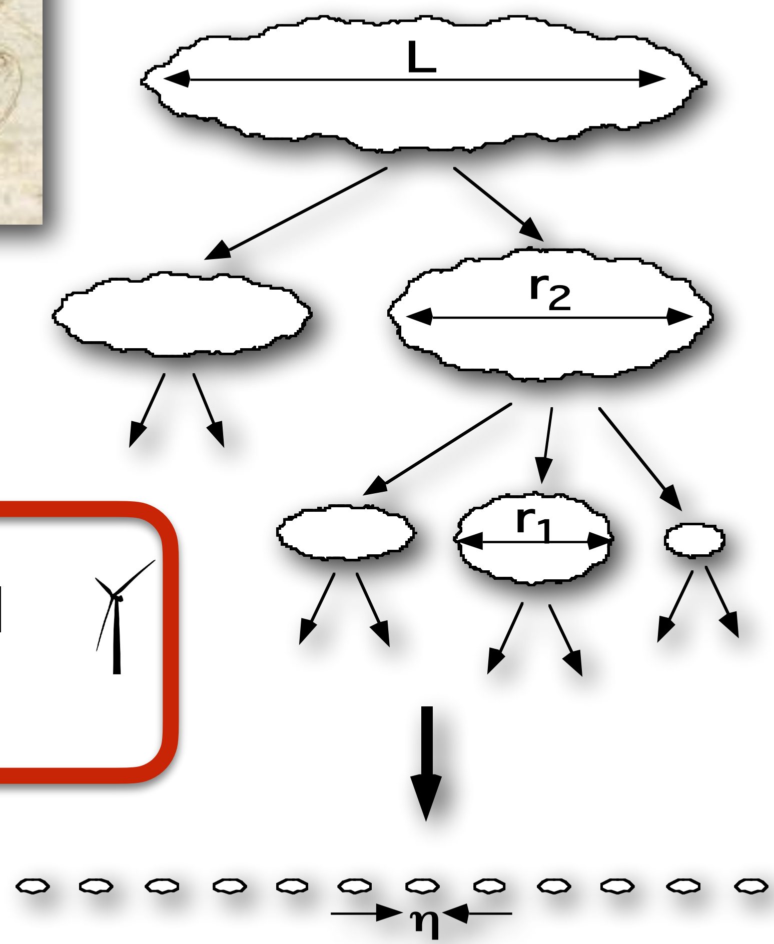
Boundary-Layer Meteorology **108** (2003)

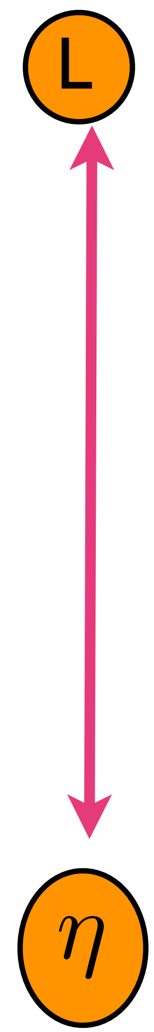
homogeneous isotropic turbulence -- hit

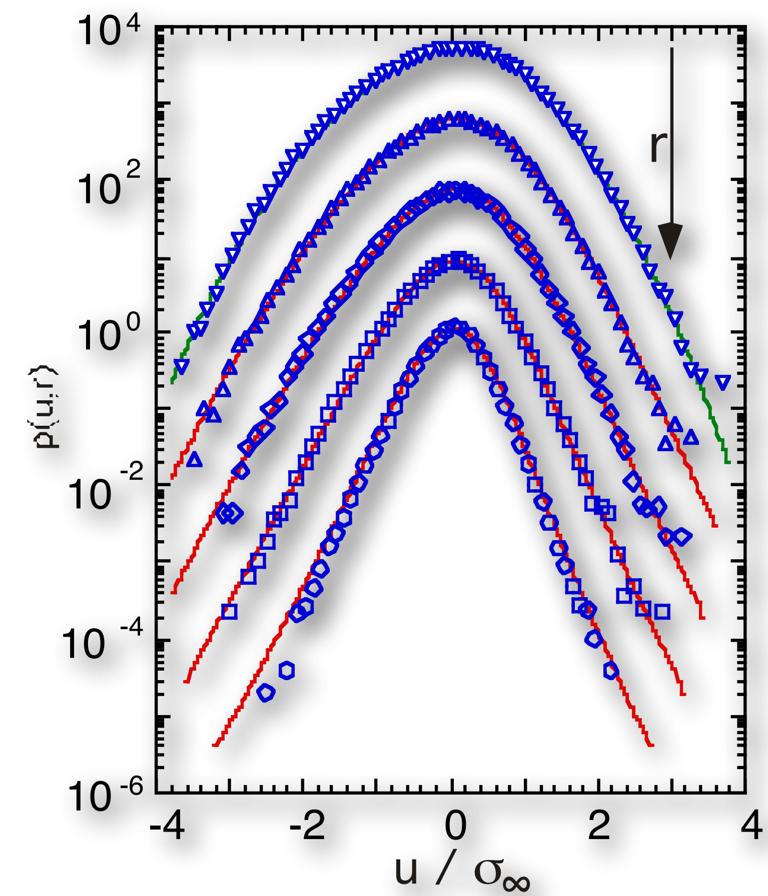
- r - depend of velocity increments: $u_r = u(x+r) - u(x)$
- cascade and statistics of increments

Leonardo da Vinci

A.N. Kolomogorov

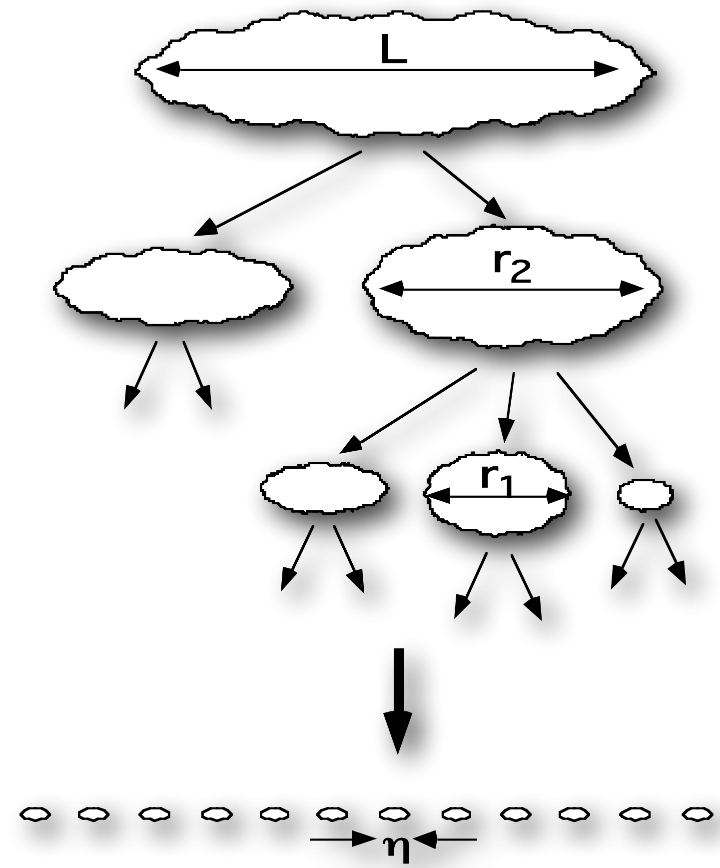


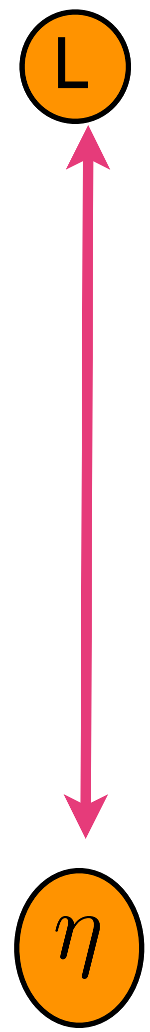




WEC sees small scale turbulence

turbulence - statistical physics
cascade as stochastic process in scale

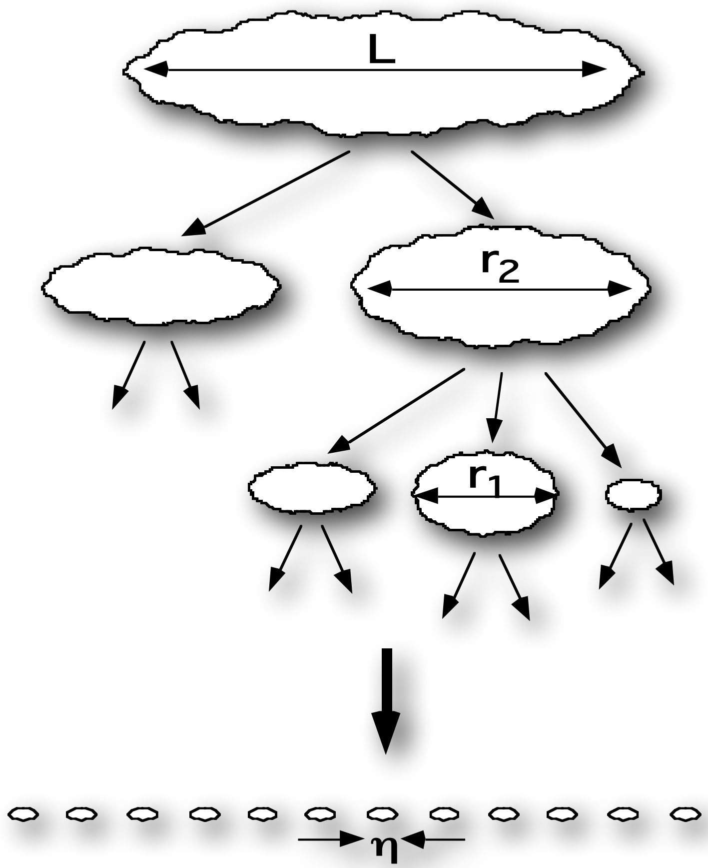


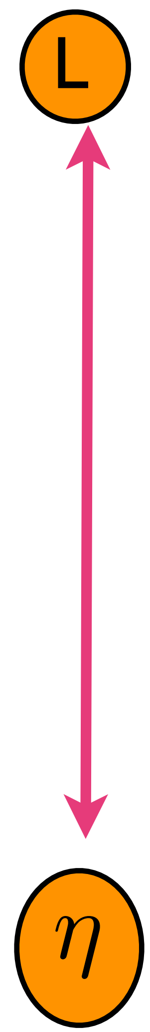


R. Friedrich

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

turbulence - statistical physics
cascade as stochastic process in scale





Knowledge of Fokker-Planck equ

Negative entropy events =

wind gusts or intermittency =

Instantones

Fluctuation theorems

(noise and structures)

Precise forecasting of extreme events -

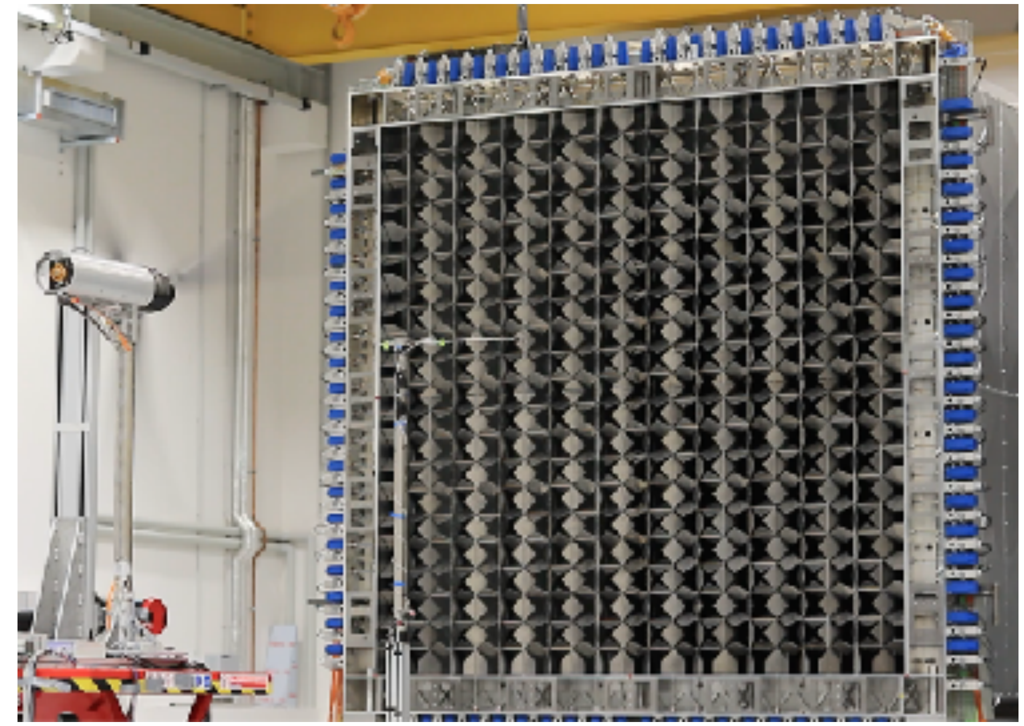
$$-r_j \frac{\partial}{\partial r_j} p(u_{r_j}|u_{r_k}, u(x_1)) = \{-\frac{\partial}{\partial u_{r_j}} D^{(1)}(u_{r_j}, r_j, u(x_1)) + \frac{\partial^2}{\partial \xi_j^2} D^{(2)}(u_{r_j}, r_j, u(x_1))\}\, p(u_{r_j}|u_{r_k}, u(x_1))$$

Annual Review of Condensed Matter Physics (2019)

Further topics- wind physics

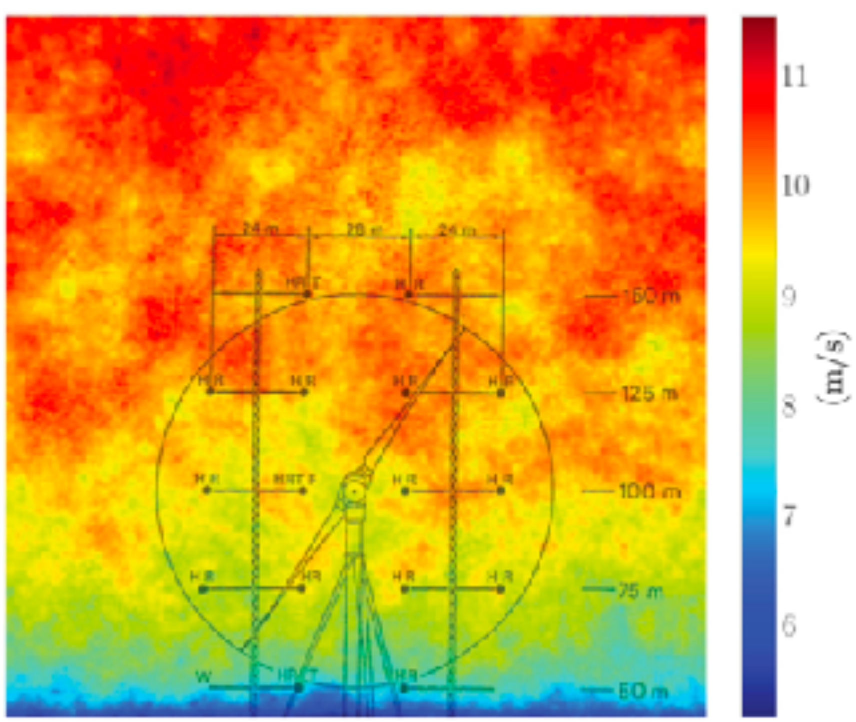
Free field

Controlled lab conditions

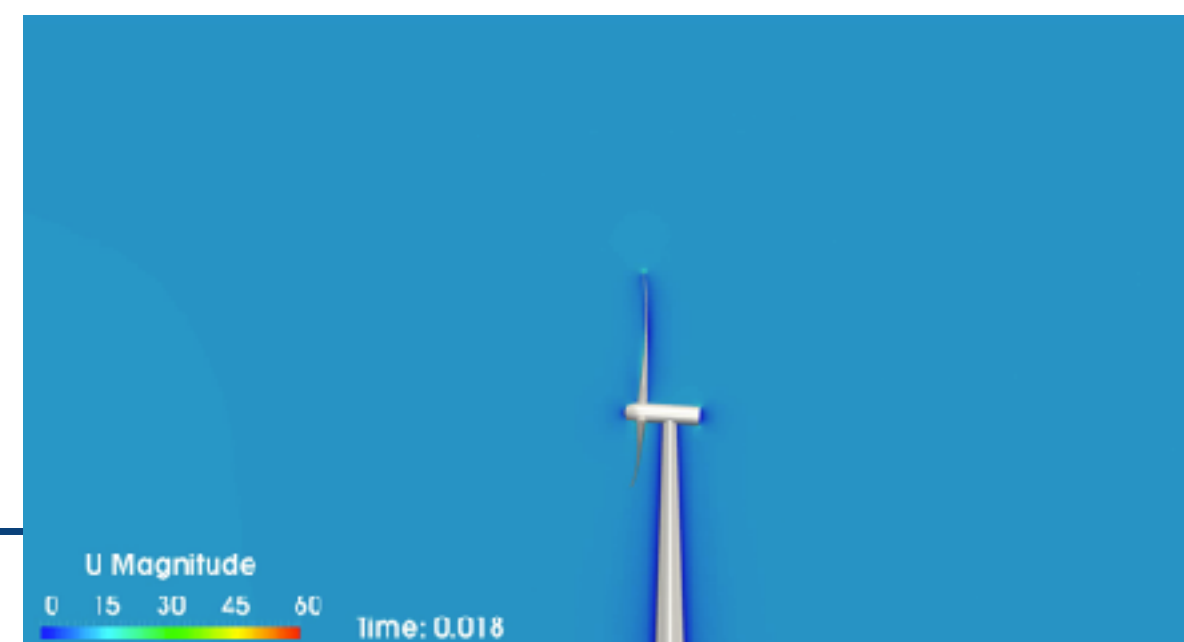


Active grid to design turbulence

Superstatistical wind fields = correct multipoint stat



Numeric approach - CFD / LES



Just discussed one small aspect

Multiscale problem

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

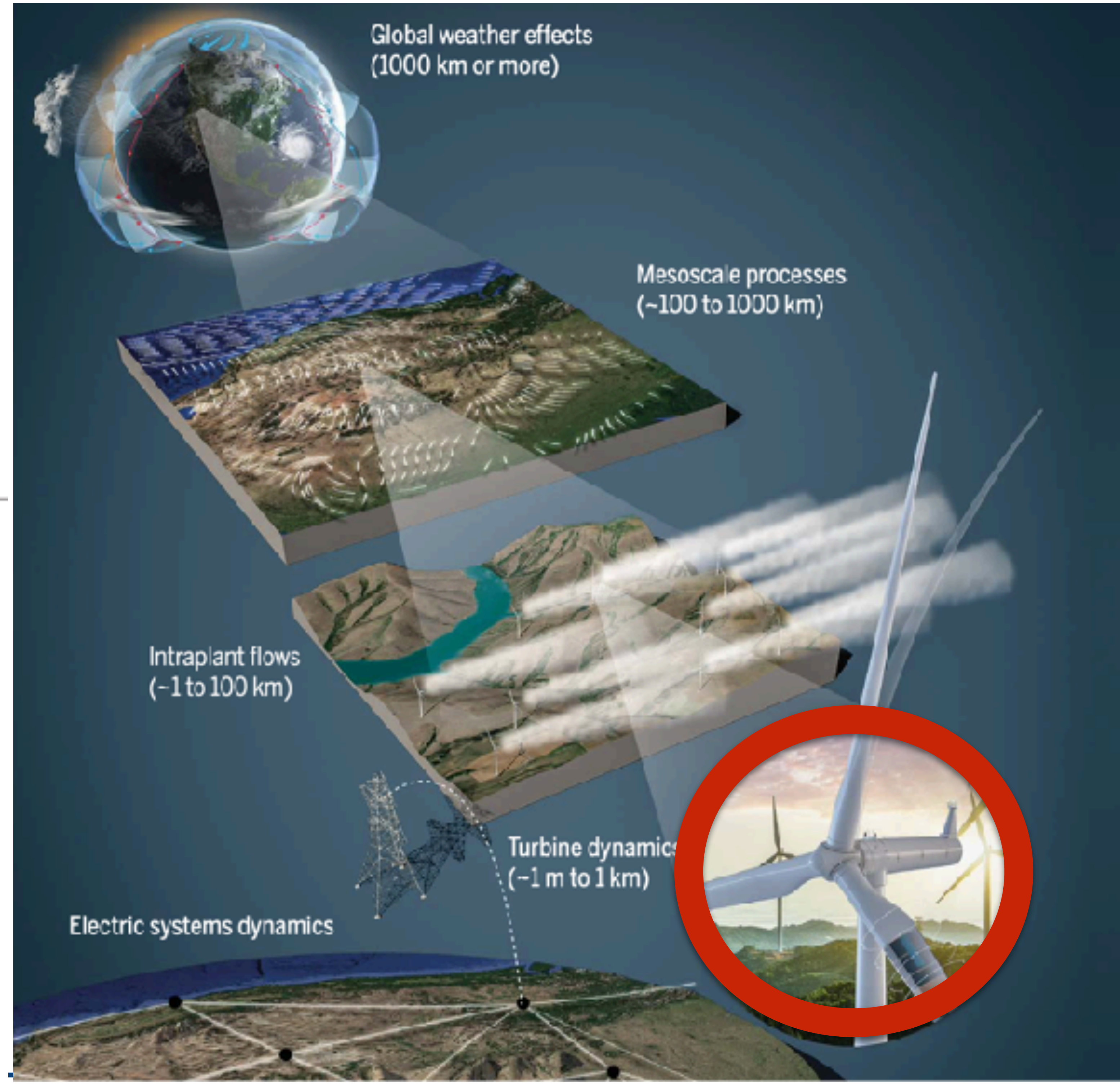
REVIEW SUMMARY

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. Additional research and exploration of design options are needed to drive innovation to meet future demand and functionality. The growing scale and deployment expansion will, however, push the technology into areas of both scientific and engineering uncertainty. This Review explores grand challenges in wind energy re-



CARL VON OSSIETZKY universität OLDENBURG

Research Alliance Wind Energy

ForWind Center for Wind Energy Research Bremen Hannover Oldenburg

Conclusion

Wind energy

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

- 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

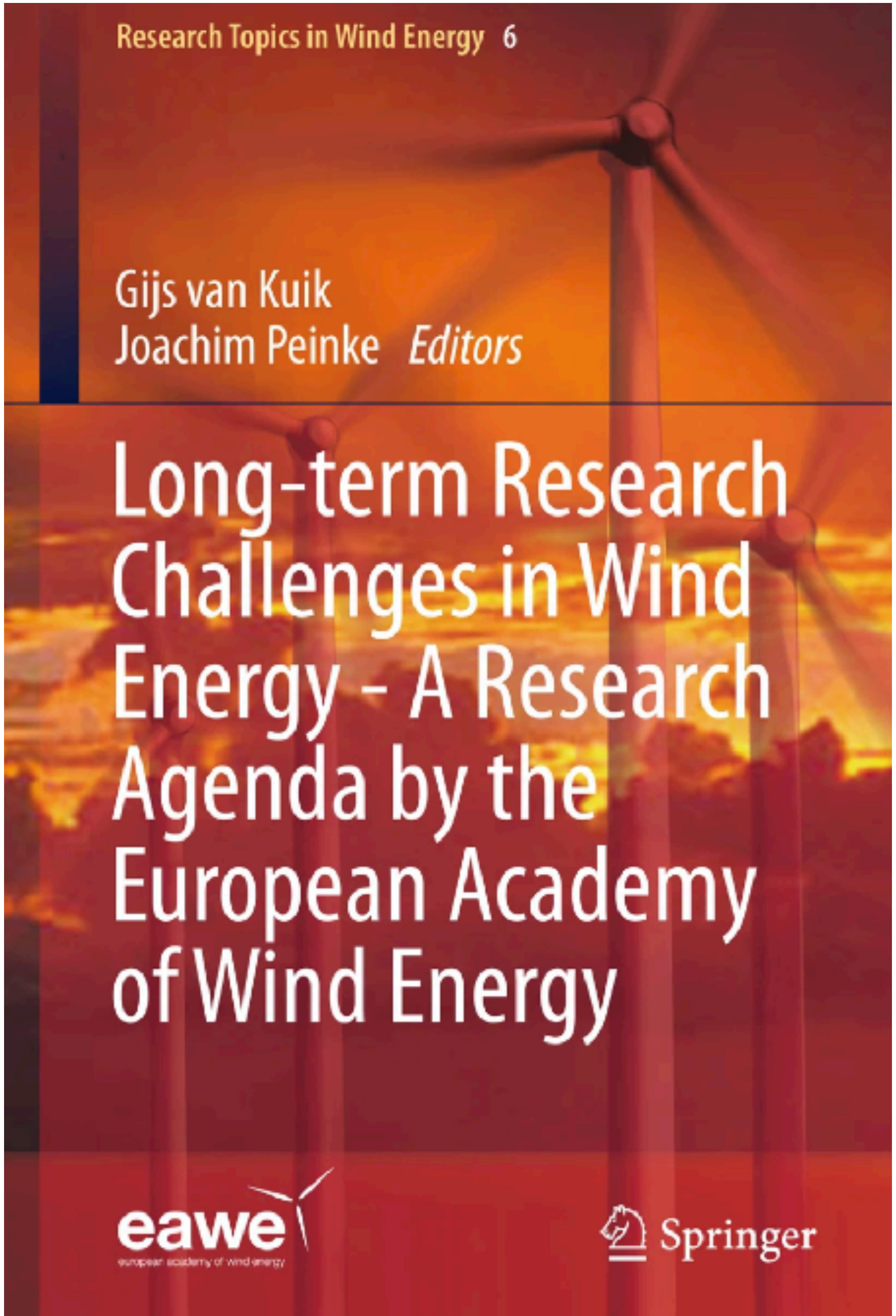
wind energy aim of the talk

- some background informations on wind energy
- WE is not the solution of all energy but has some promising aspects
- aim intelligent use combined with other systems!

Future of energy: be open minded!

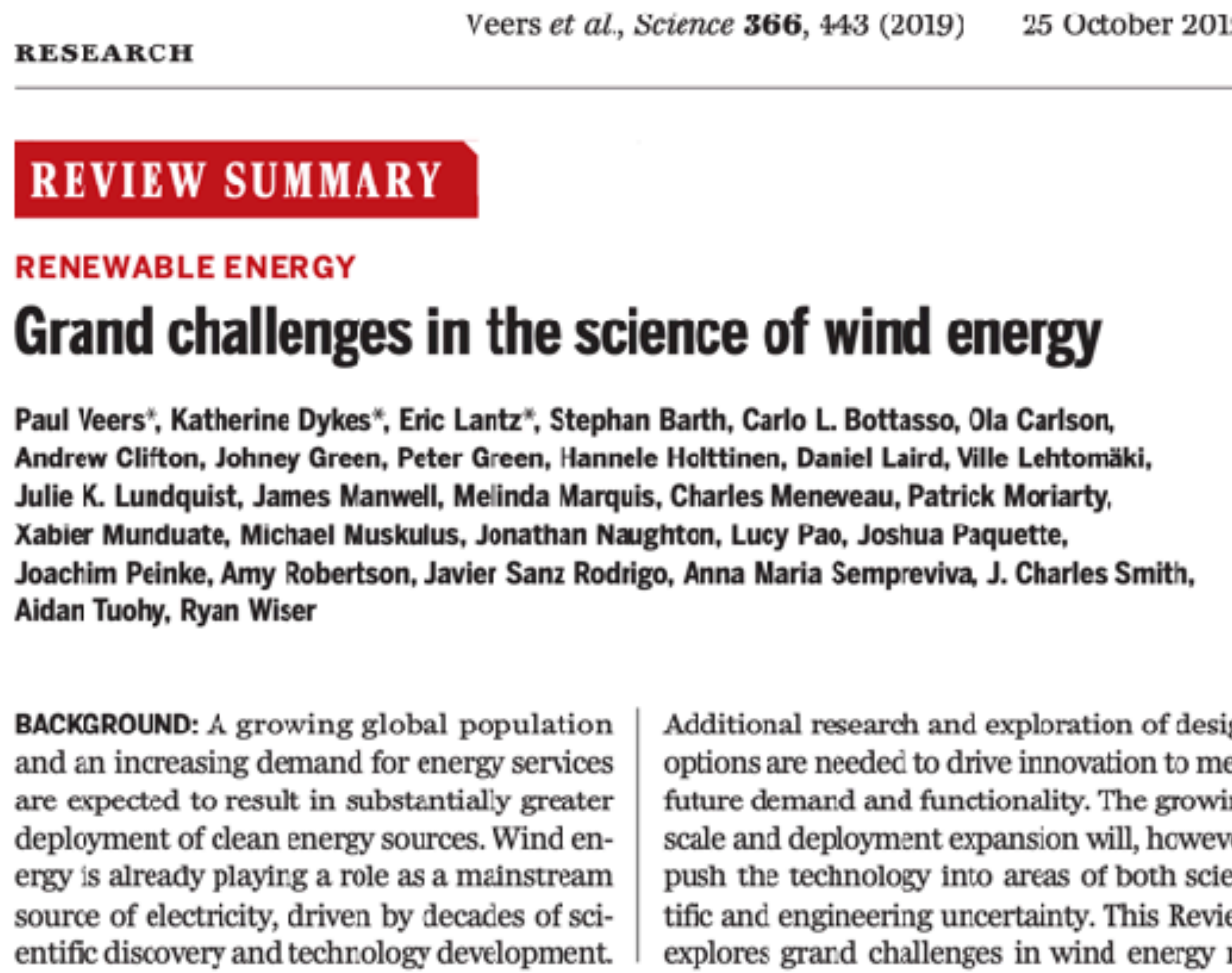
- make up your own opinion,

look at „facts“ but put this again and aging into questions



Further reading

Initiated by eawe and iea-Wind



Veers *et al.*, *Science* **366**, 443 (2019)   25 October 201

RESEARCH

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.

Additional research and exploration of desi options are needed to drive innovation to me future demand and functionality. The growi scale and deployment expansion will, howev push the technology into areas of both scie tific and engineering uncertainty. This Revie explores grand challenges in wind energy

Carl von Ossietzky Universität Oldenburg

Research Alliance Wind Energy

ForWind Center for Wind Energy Research Bremen Hannover Oldenburg

End
And many thanks to my group