Wind Energy and the Need to Understand Turbulence

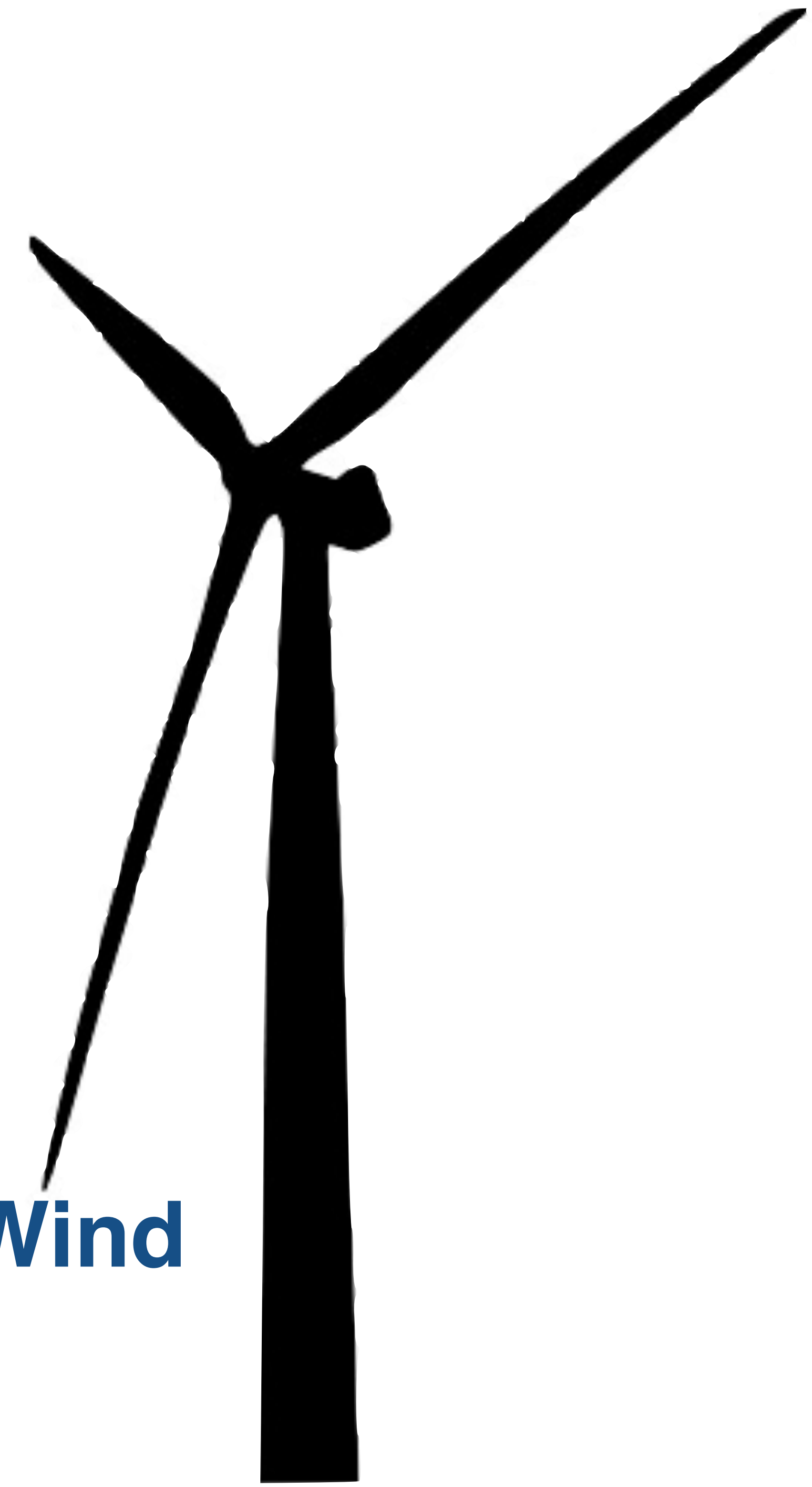
Michael Hölling

Experiments done by Thomas Messmer, Julian Jüchter, Jannis Maus, Lars Neuhaus, Frederik Berger, Ingrid Neunaber, …

ForWind - Center for Wind Energy Research
Institute of Physics
University of Oldenburg

Content

- **Motivation**
- **general comments on wind energy**
- **working conditions for wind turbines**
  - ➡ **need to understand turbulence**
- **ongoing experimental research at ForWind**



What is ForWind - Center for Wind Energy Research ?

Association of research groups and institutes of three universities covering a wide range of wind energy related research topics.

Carl von Ossietzky Universität Oldenburg

Leibniz Universität Hannover

Universität Bremen

What is ForWind - Center for Wind Energy Research ?

Research Alliance Wind Energy

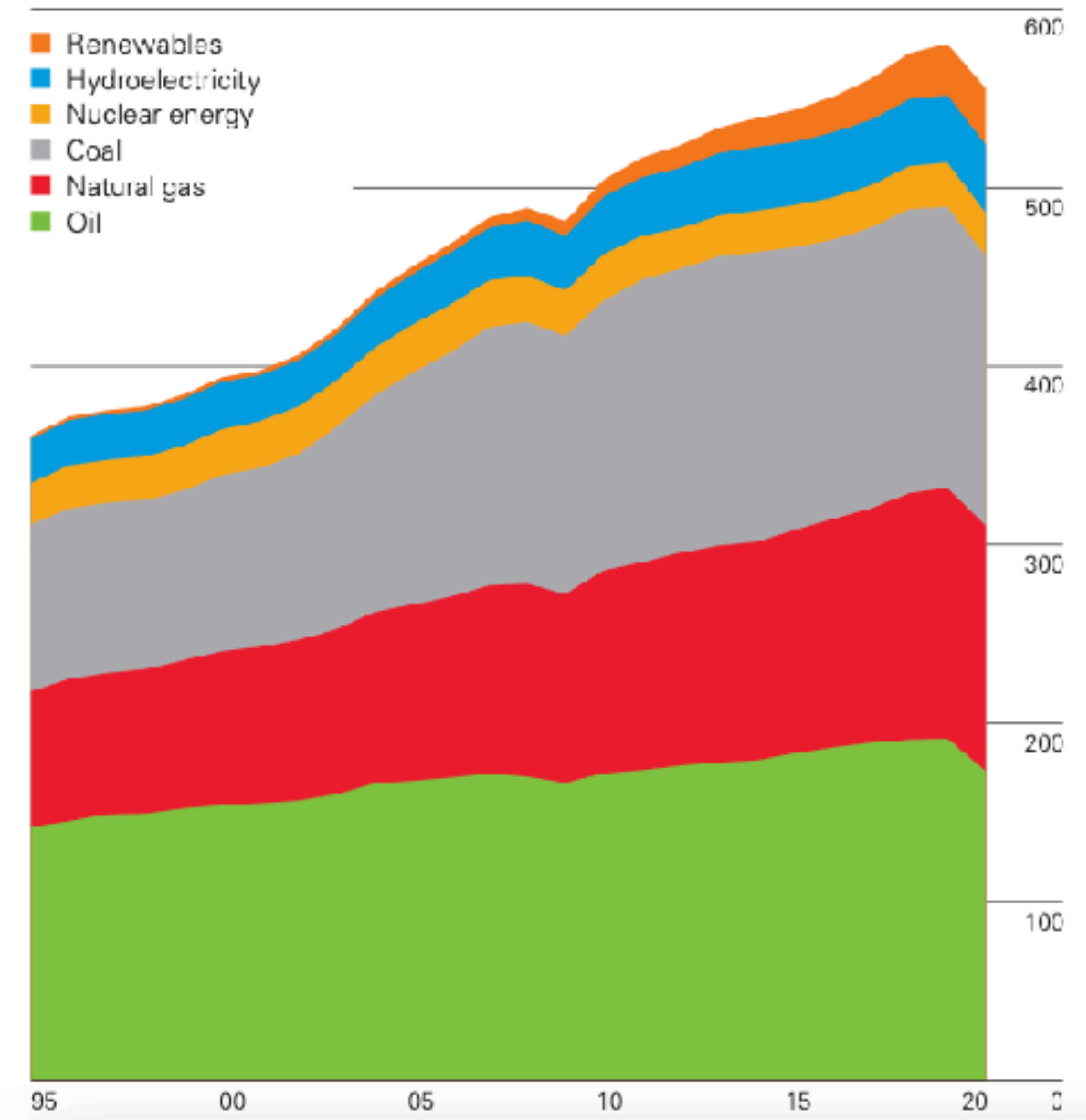
Deutsches Zentrum für Luft- und Raumfahrt
DLR

ForWind
Zentrum für Windenergieforschung
Bremen
Hannover
Oldenburg

Fraunhofer
IWES

Energy demand worldwide 2020

$1.55 \cdot 10^{14} kWh$ in 2020



Source: BP Statistical Review of World Energy, 2021, bp.com

Consumption of fossile fuels - oil

How much oil is consumed every day worldwide?

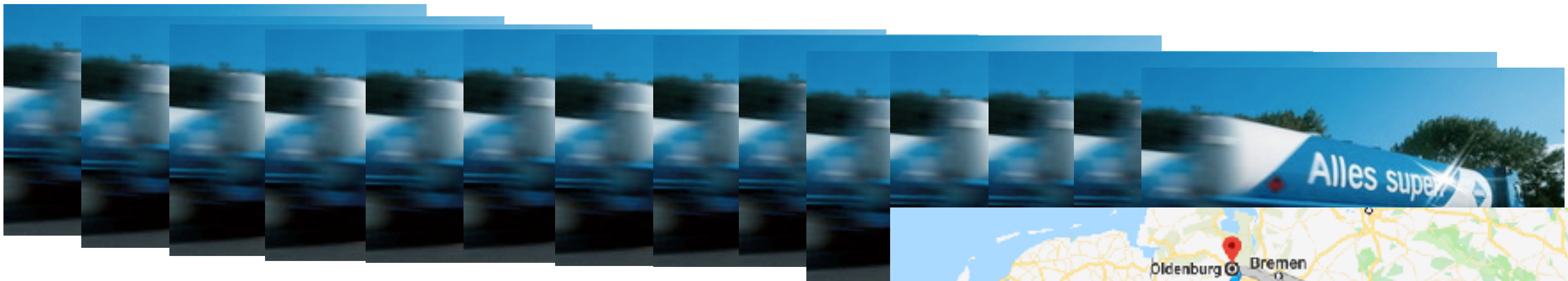
88 million barrels of oil — per day !!!

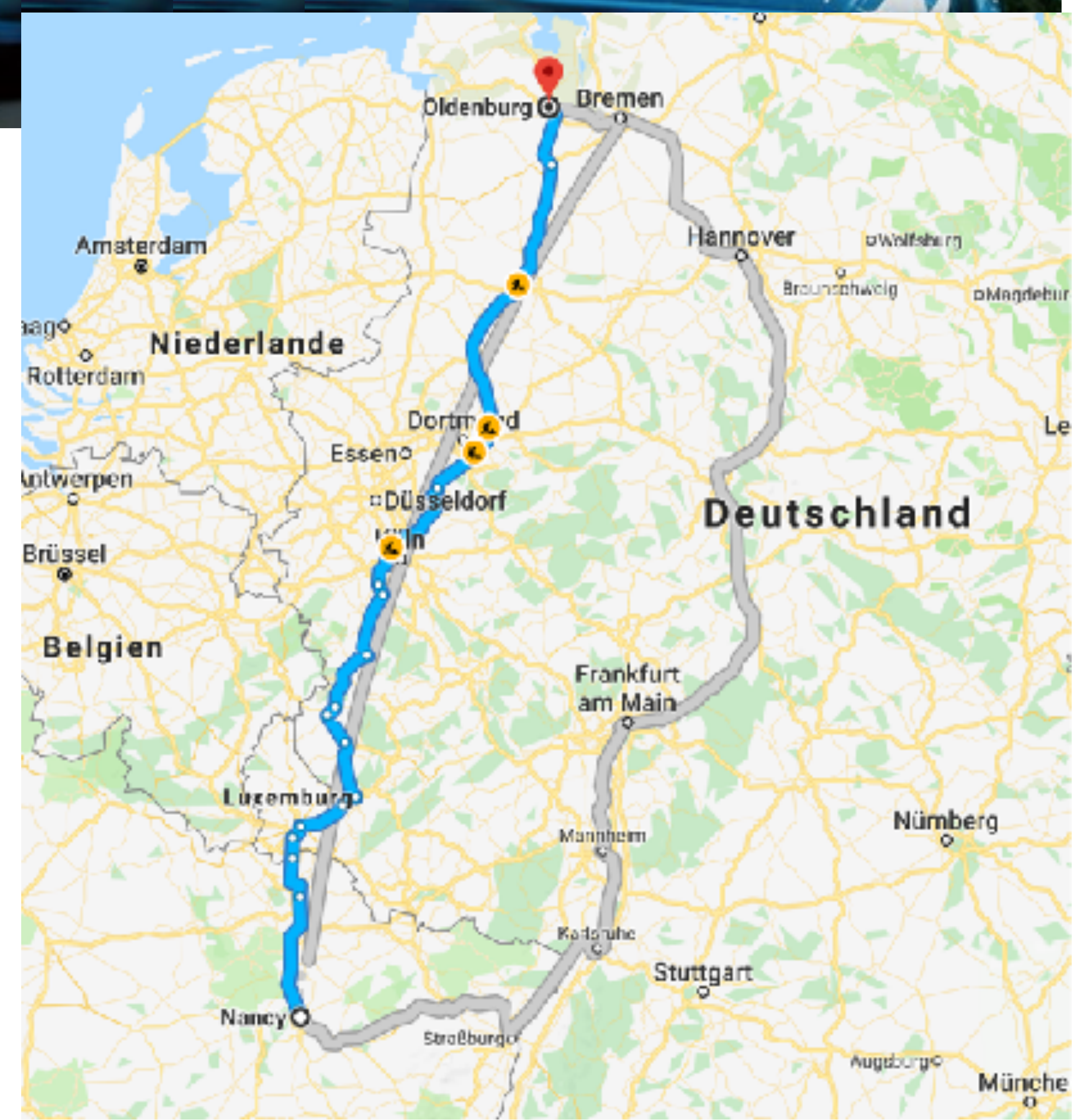
14 billion litres of oil — per day !!!

One oil truck can fit about 35.000 litres of oil

Consumption of fossile fuels - oil

14 billion litres of oil correspond to 402.000 filled trucks



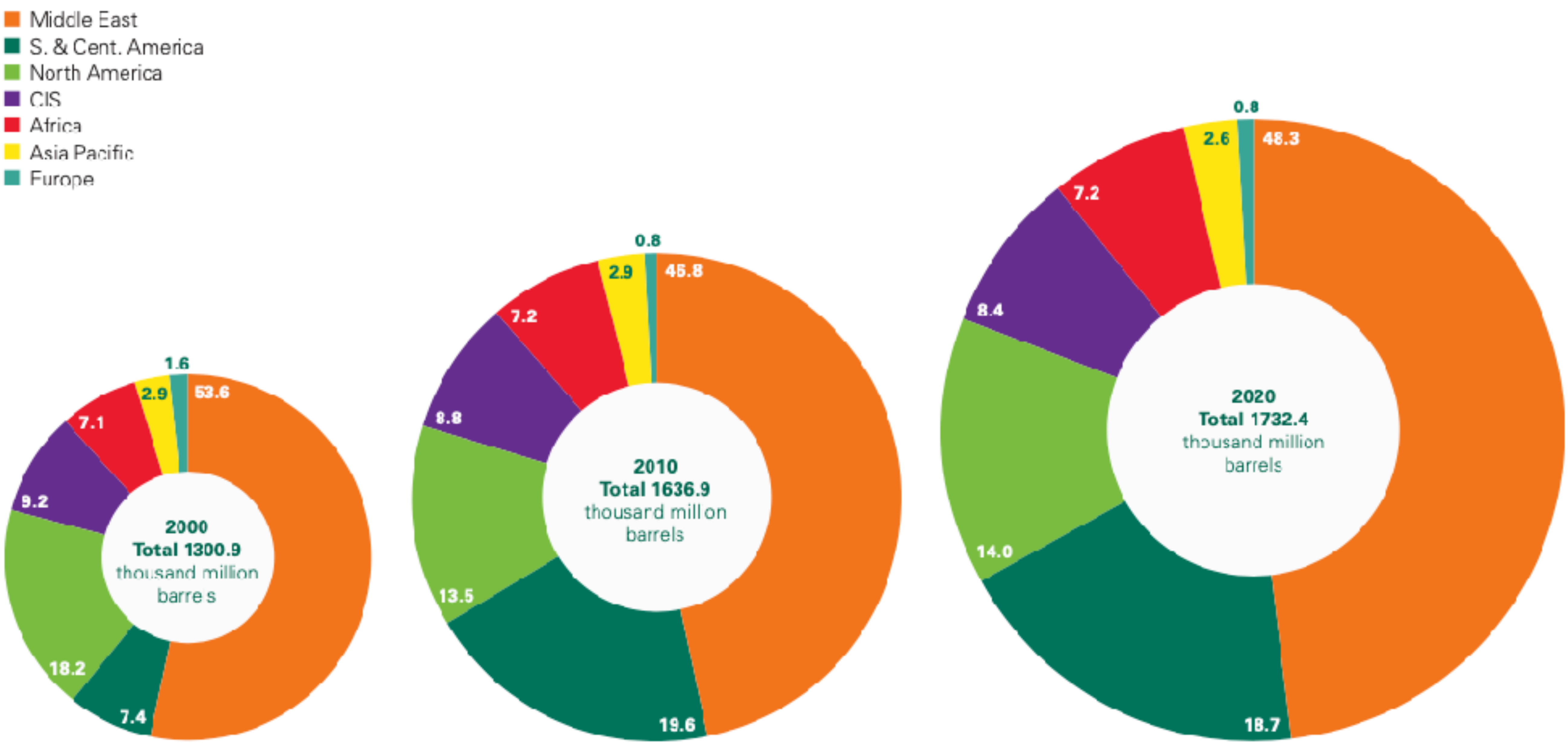


402.000 trucks aligned cover a distance of about 7236km

about 11 times the distance from Oldenburg to Nancy

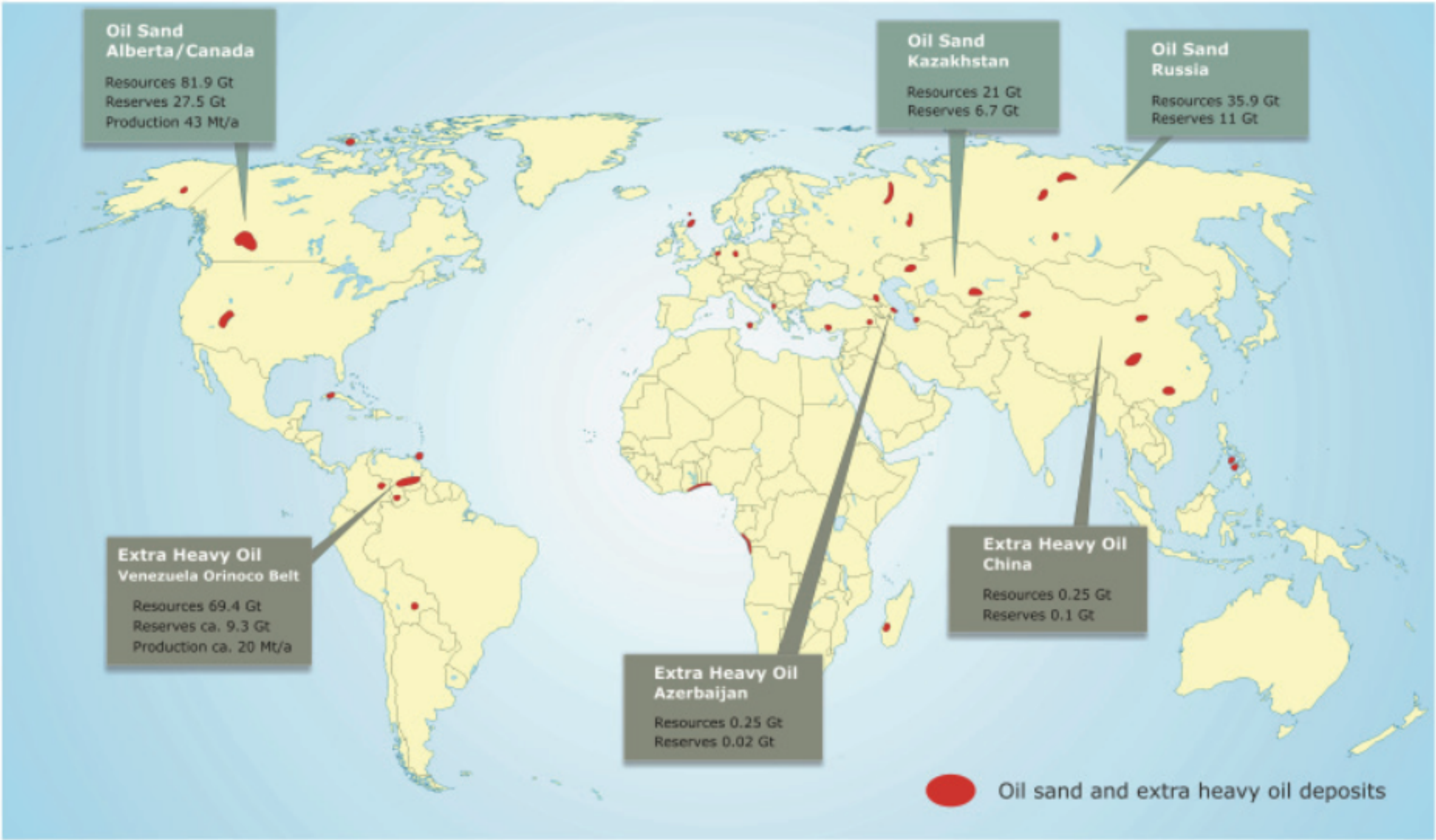
How much oil is left that we can continue at this rate?

Distribution of proved reserves



Source: BP Statistical Review of World Energy, 2021, bp.com

Resource oil



From "Reserves, Resources and Availability of Energy Resources 2014", BGR annual report
BGR : Bundesanstalt für Geowissenschaften und Rohstoffe

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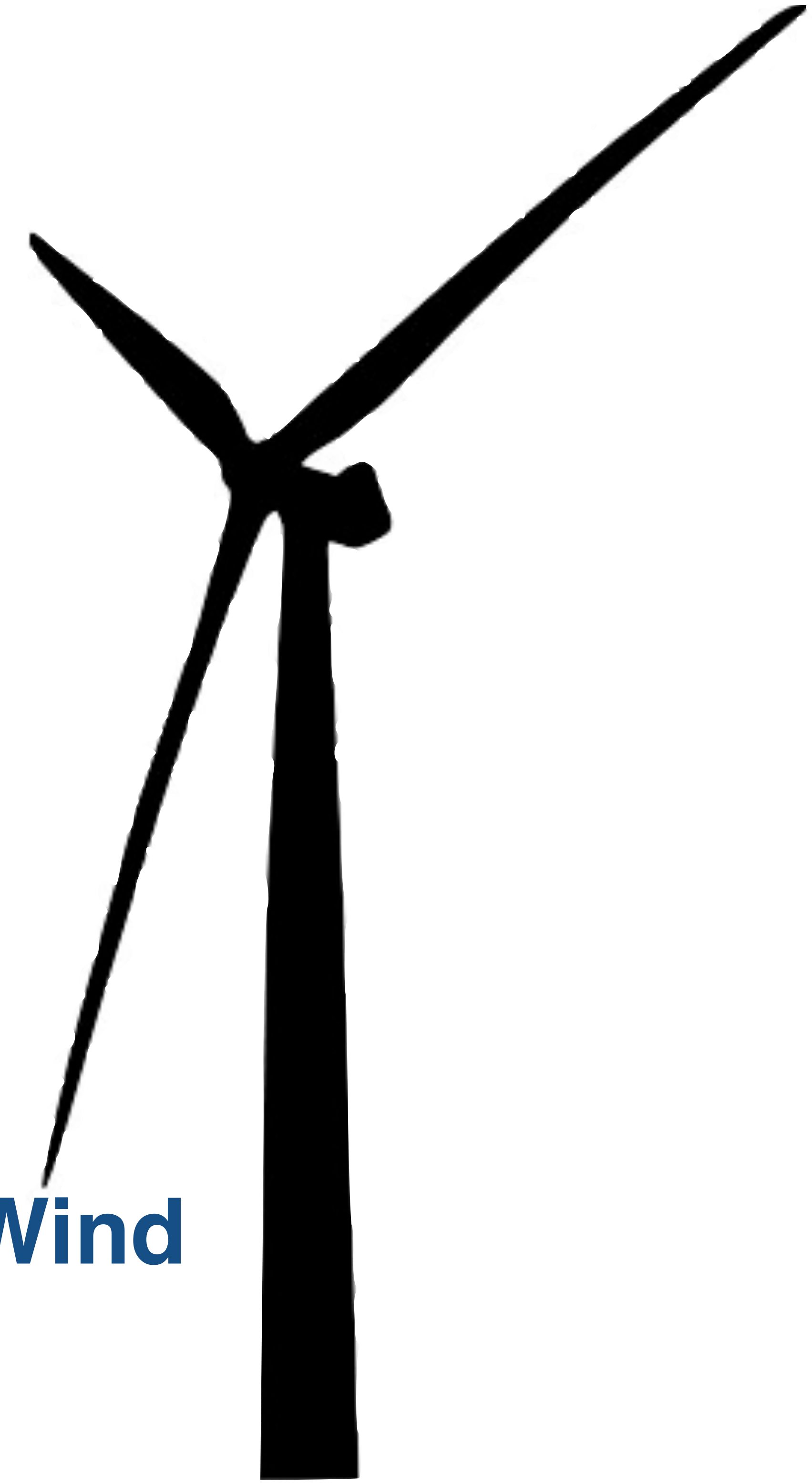


Kinetic energy

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

Power from wind

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

$$= \frac{1}{2} \dot{m} u^2 \quad \textbf{with} \quad \dot{m} = \rho \dot{V}$$

$$= \rho A \cdot u$$

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

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

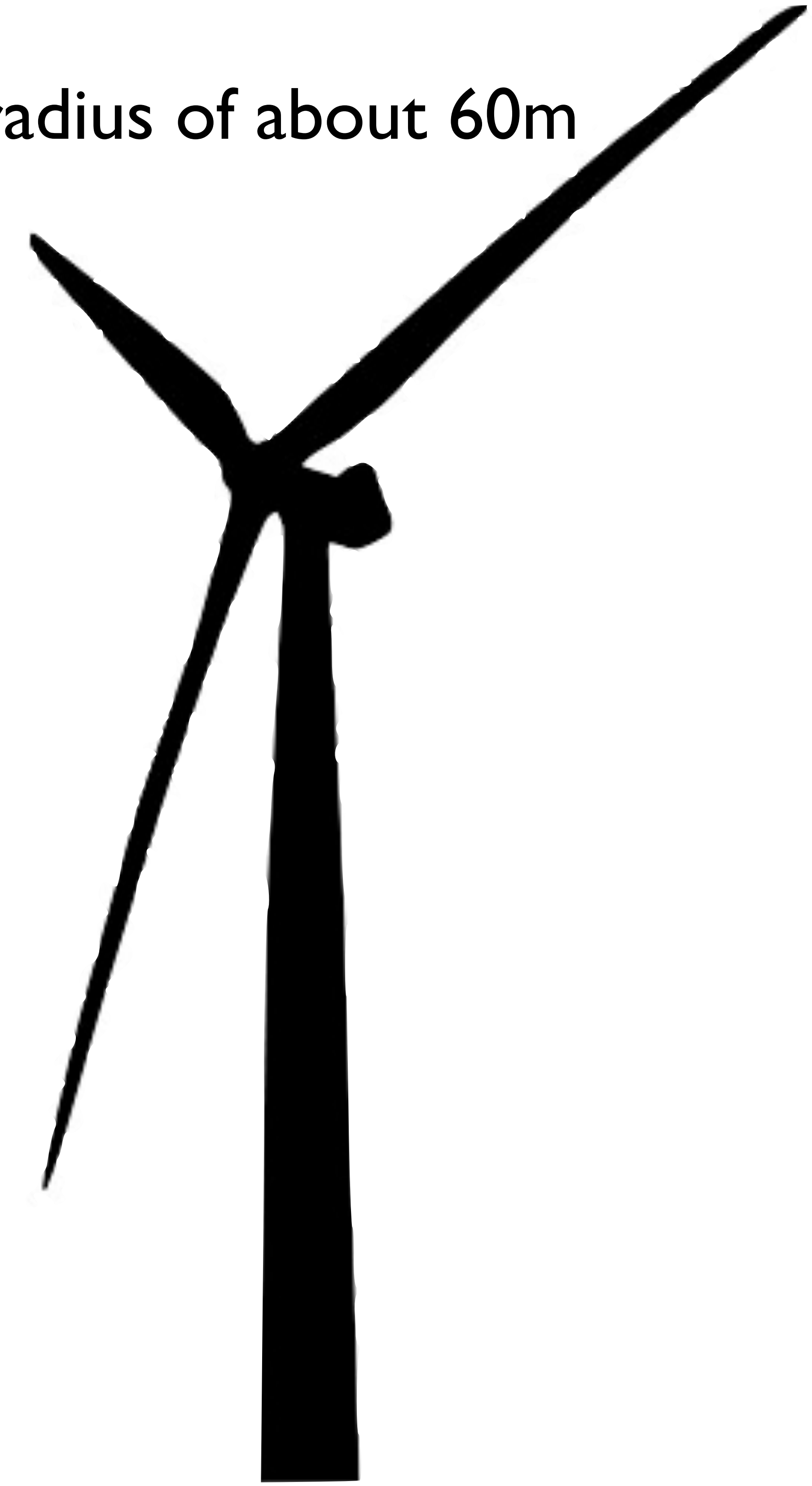
Wind energy converter (WEC)

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

$c_P \leq 0.59$ **Betz - limit**

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

radius of about 60m



area about 12000 m²

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

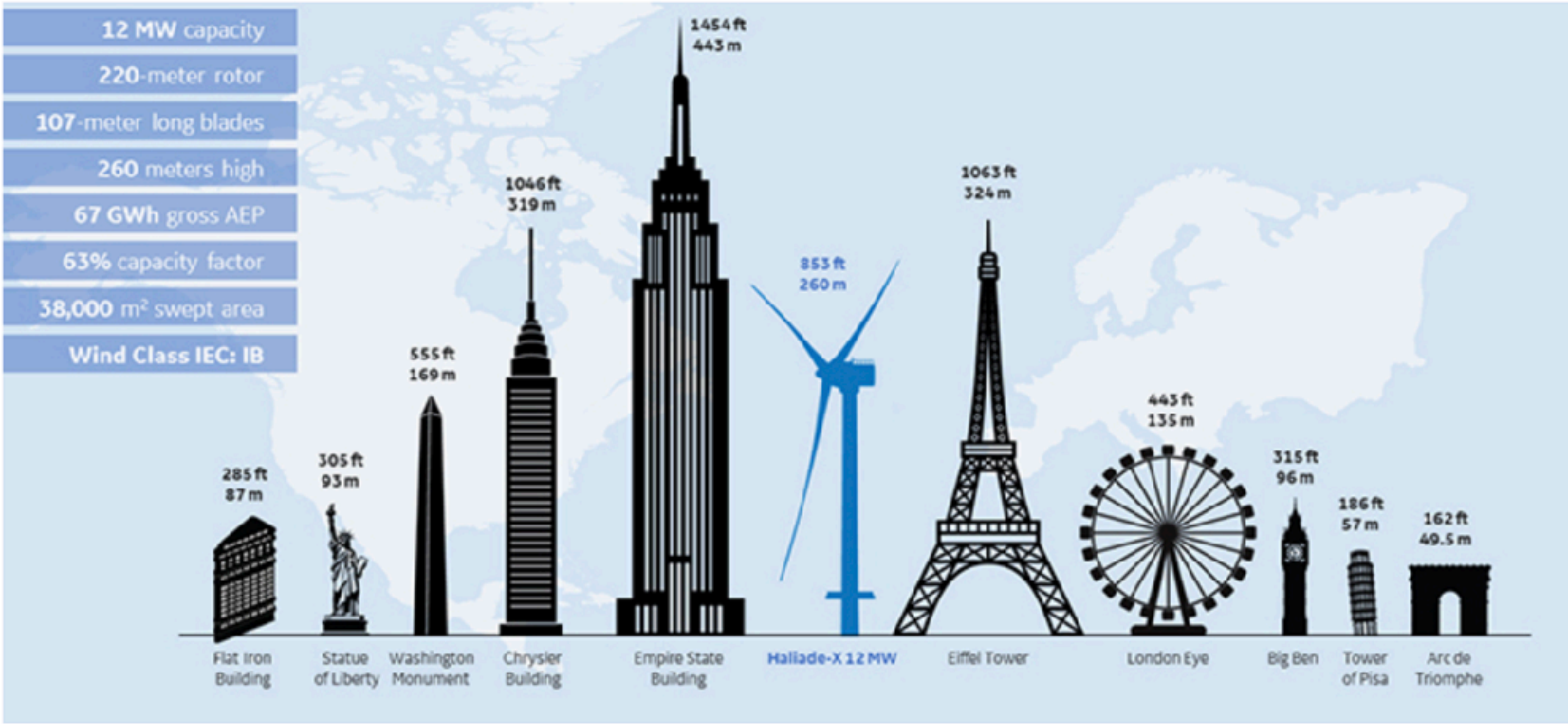
$$P_{WEC} = c_p \cdot P_{wind}$$

$$c_P \leq 0.59$$

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

World's largest wind turbine

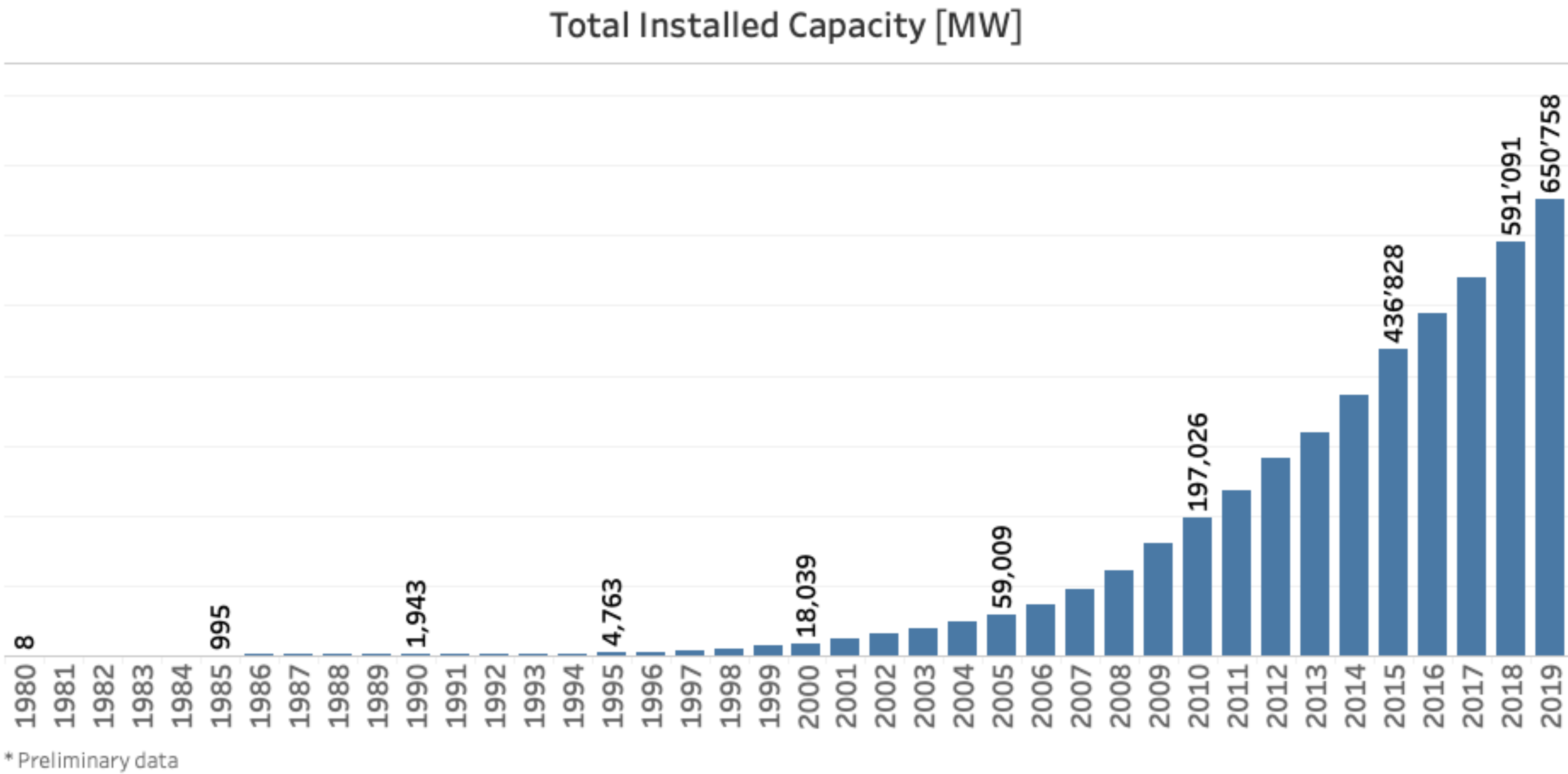
Haliade-X by GE



Source: https://www.eeworldonline.com/heres-what-it-takes-to-build-the-tower-for-the-worlds-most-powerful-offshore-wind-turbine/

Wind energy - a story of success

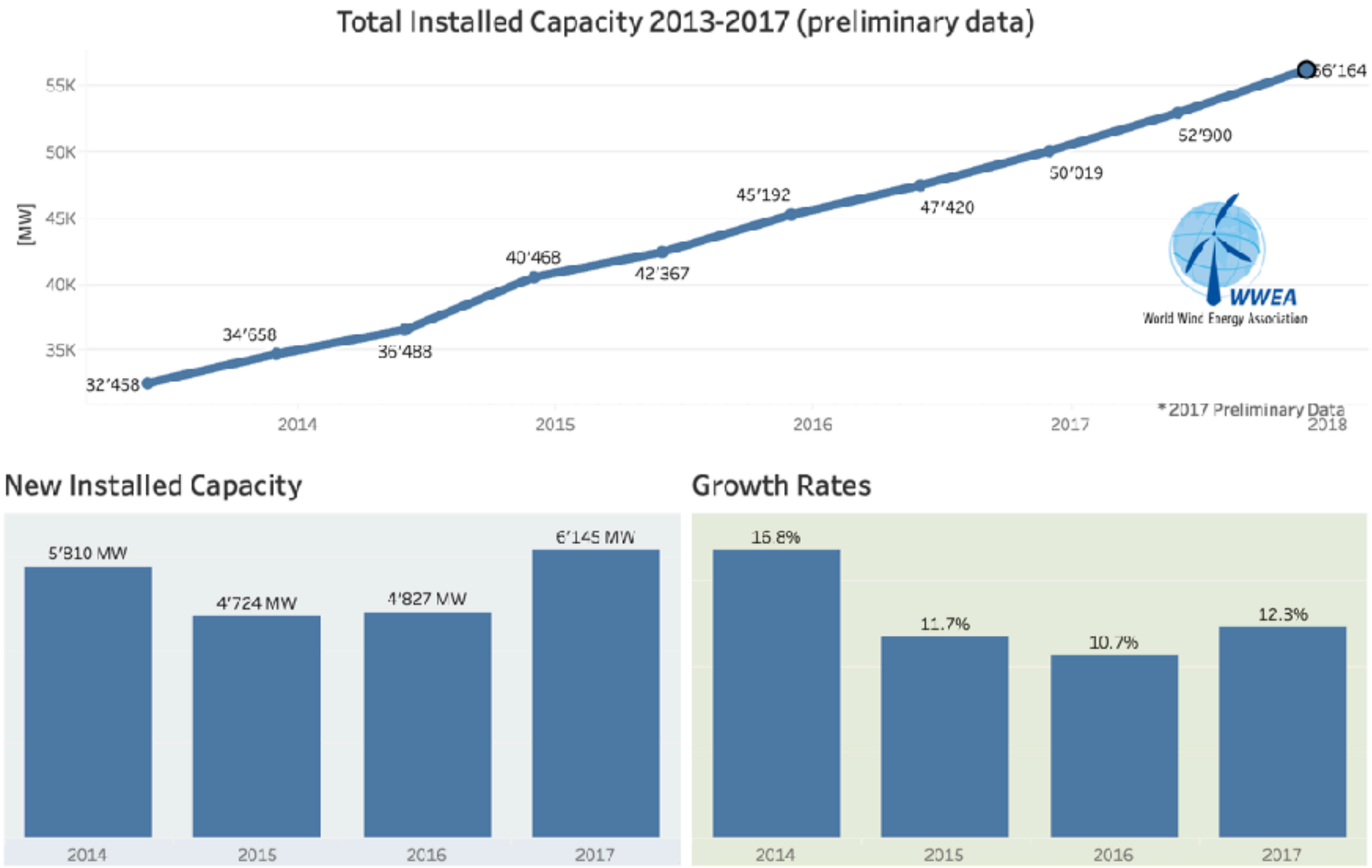
Worldwide



Source: Word Wind Energy association, wwindea.org

Wind energy - a story of success

Germany - about 62GW in 2020

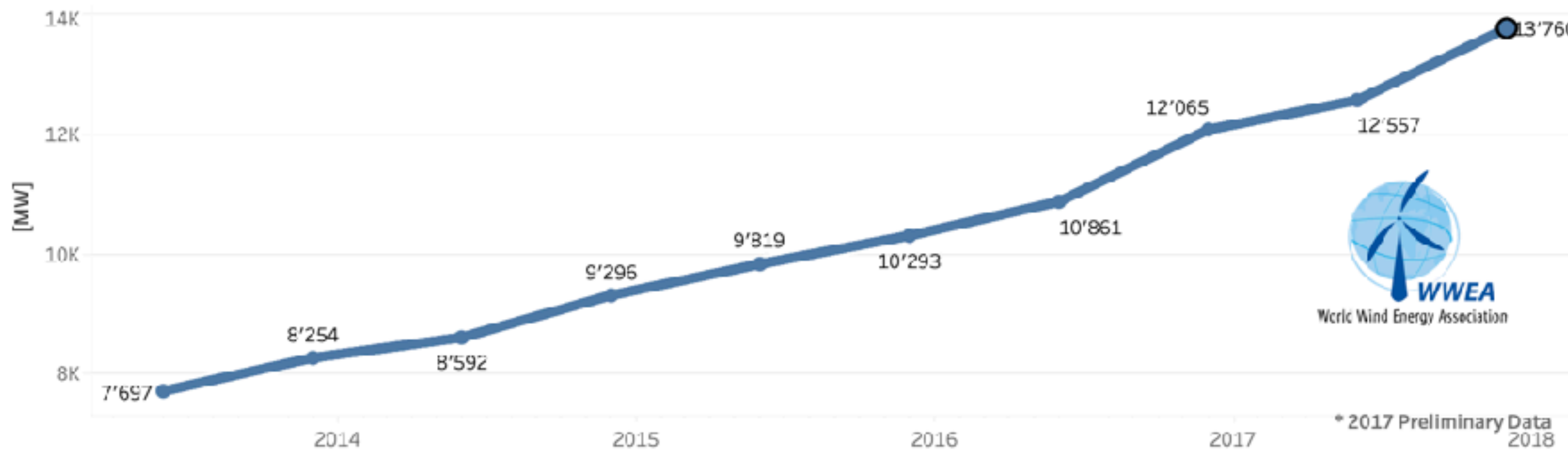


Source: Word Wind Energy association, wwindea.org

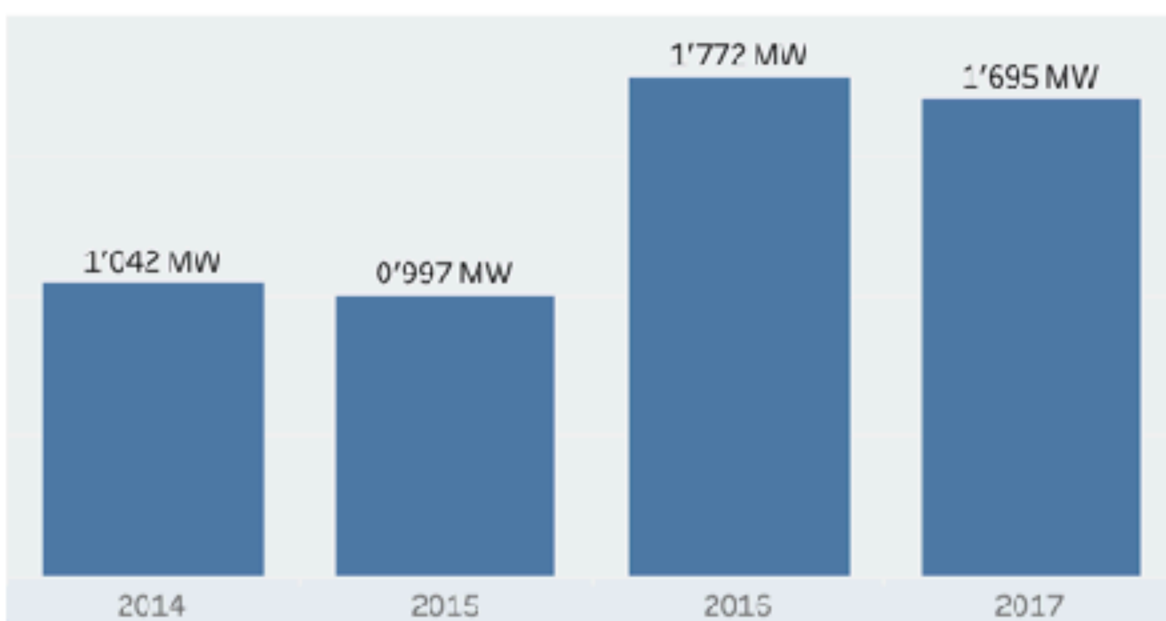
Wind energy - a story of success

France about 18 GW in 2020

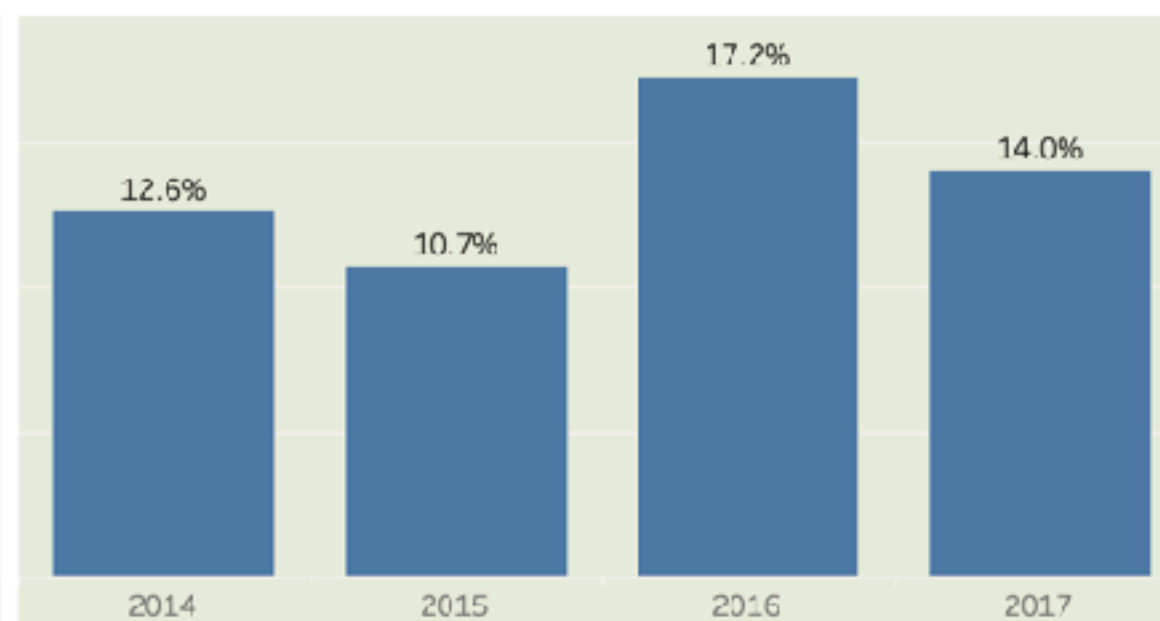
Total Installed Capacity 2013-2017 (preliminary data)



New Installed Capacity

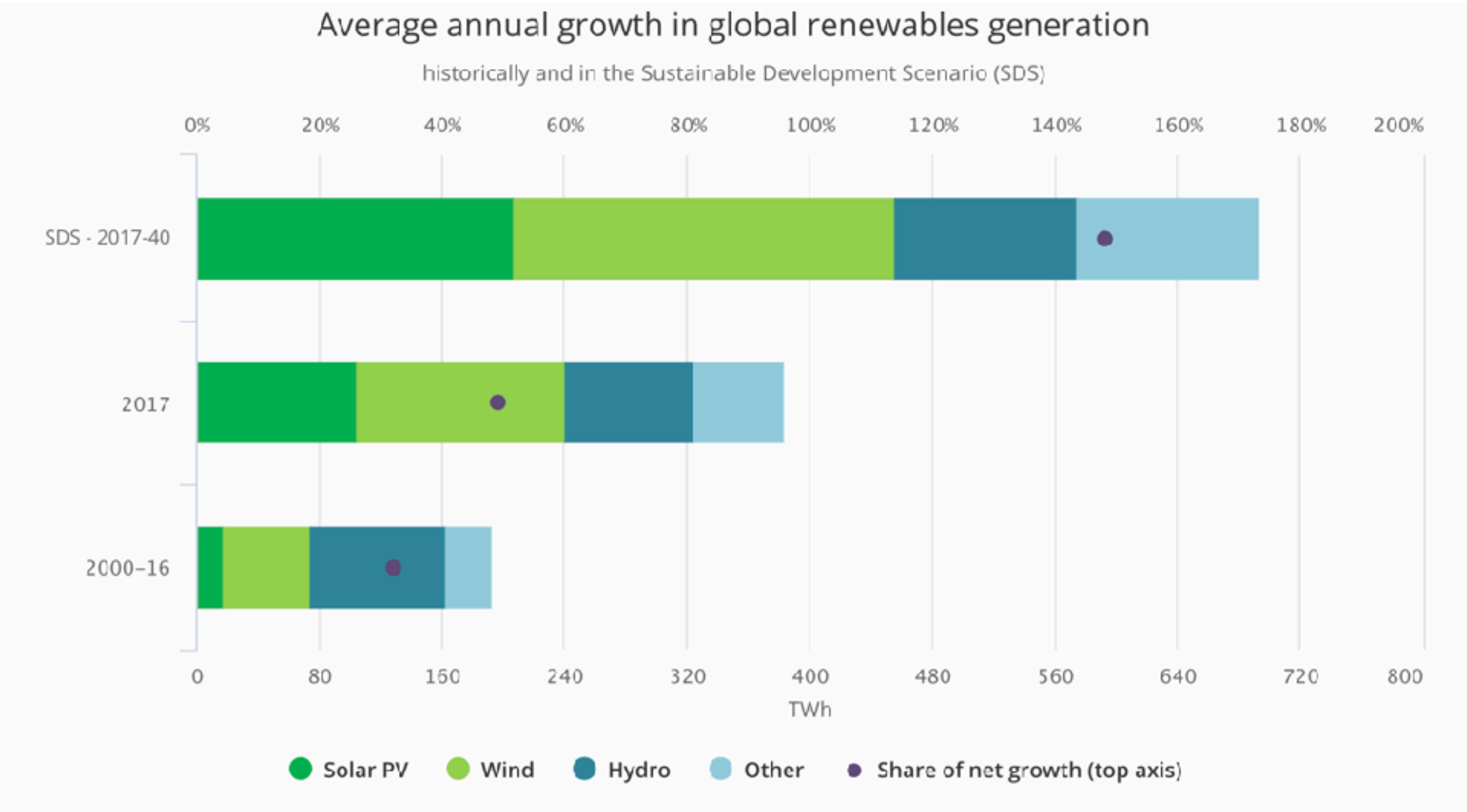


Growth Rates



Source: Word Wind Energy association, wwindea.org

Wind energy - a story of success



Source: International Energy Agency, iea.org

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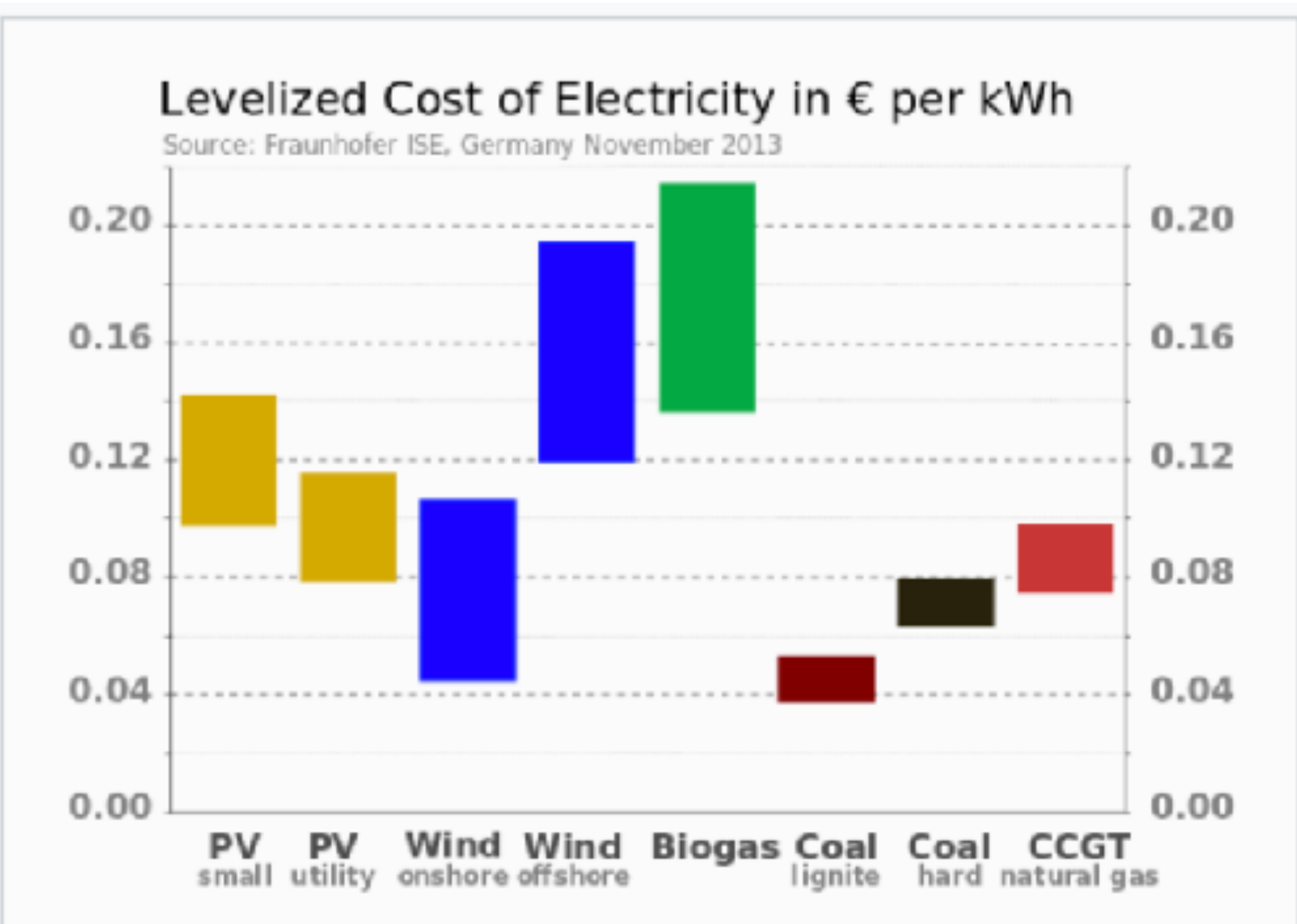
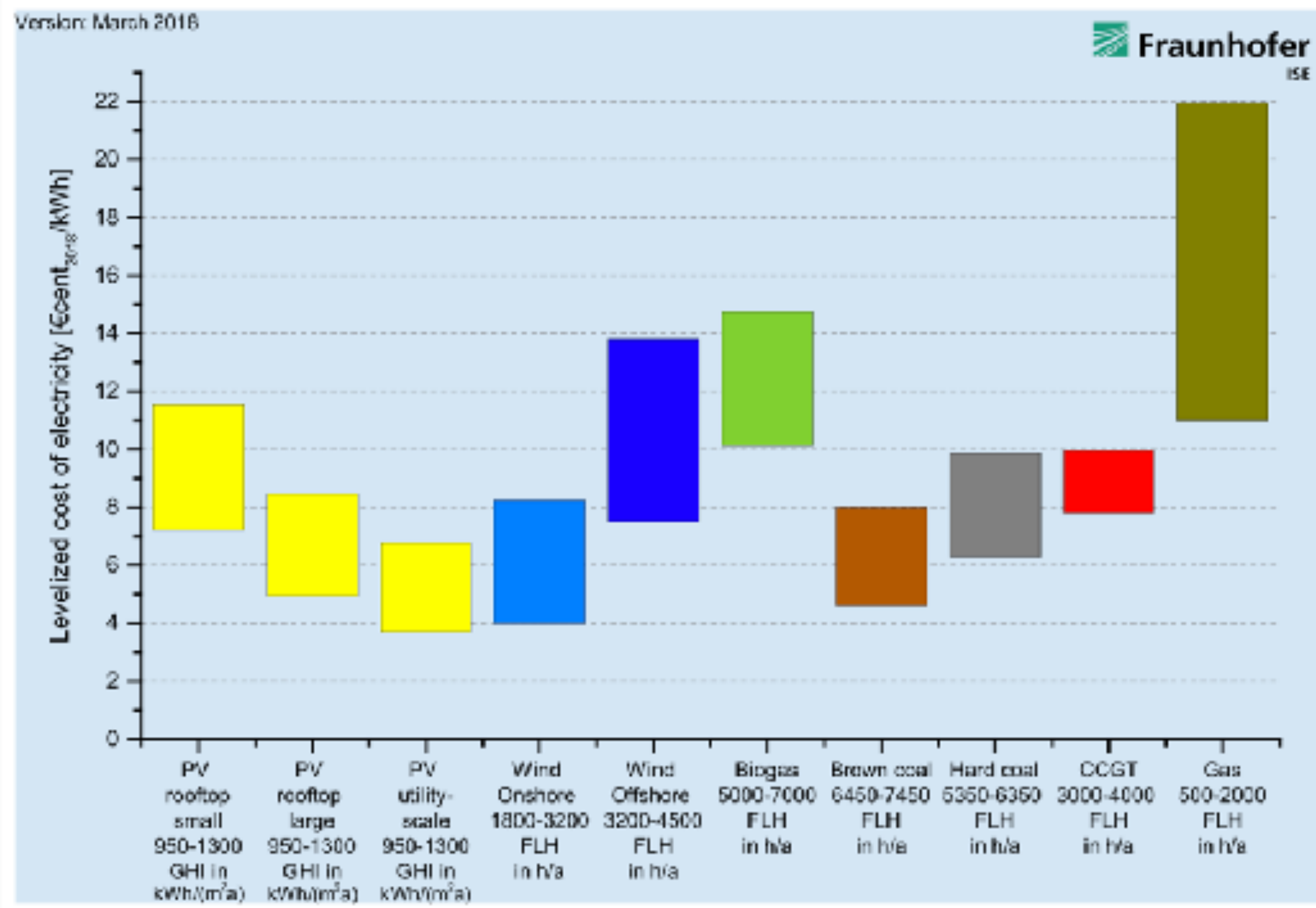
Wind energy - a story of success

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



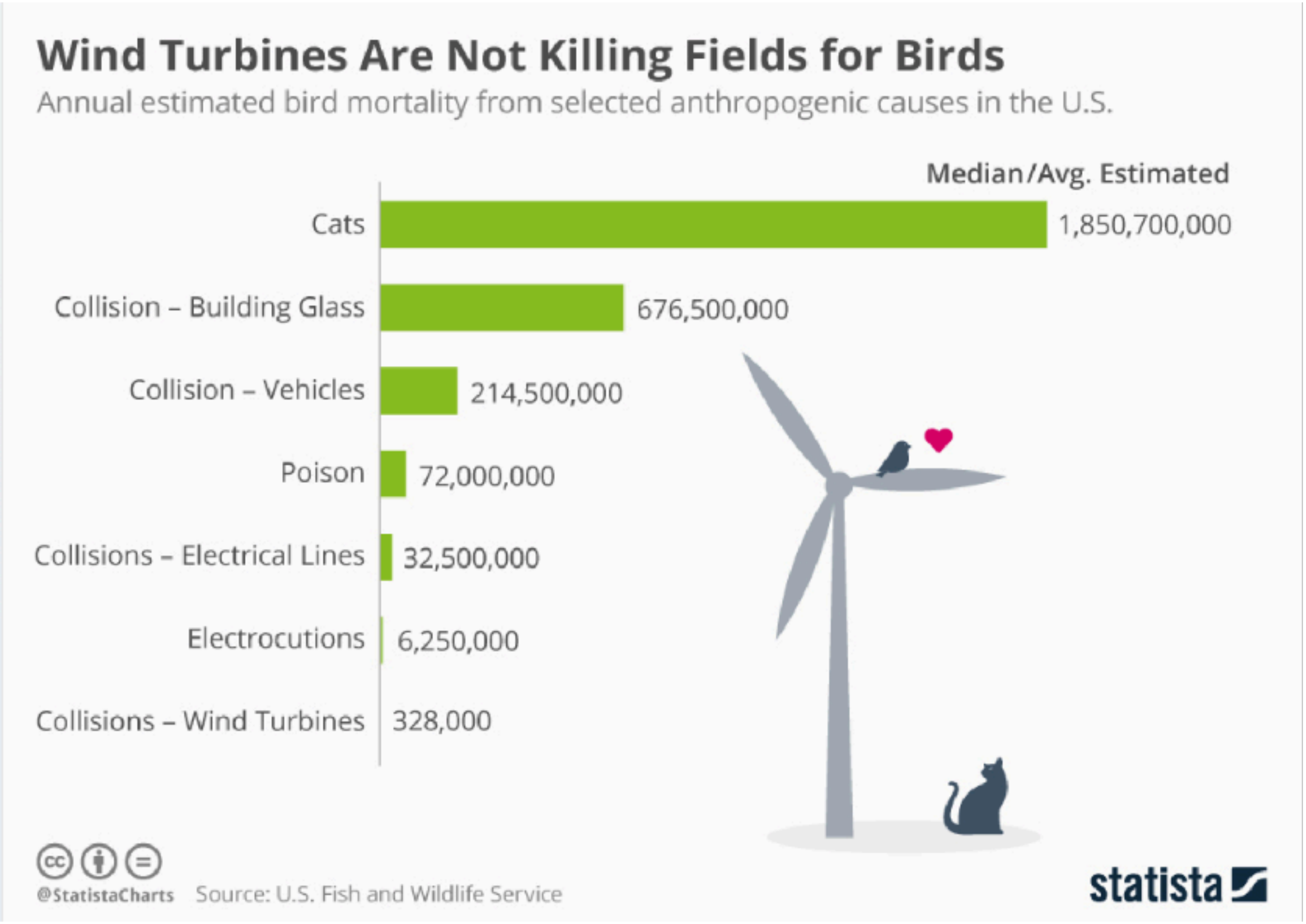
Source: Fraunhofer ISE, ise.fraunhofer.de



Source: Fraunhofer ISE, ise.fraunhofer.de

Wind energy - environmental impact

One urban legend about wind turbines: if you want to see a pile of dead birds, go visit a turbine.



What about rare earth e.g. Neodymium?

Table 11: Wind power technologies for large turbines and an indication of permanent magnet demand [Jensen, 2012]

Manufacturer	Technology	Generator type and capacity	Permanent magnet amount***
Siemens Wind Power	Low speed/direct drive	PMSG 6 MW	High
Vestas (MHI Vestas)	Mid speed/geared	PMSG 8 MW	Medium
Enercon*	Low speed/direct drive	EESG** 7.58 MW	None
Alstom	Low speed/direct drive	PMSG 6 MW	High
Senvion	High speed/geared	DFIG 6.2MW	None
Areva/Gamesa	Mid speed/geared	PMSG 5 MW	Medium

* Over time Enercon has upgraded the capacity of its generator
** EESG – electrically excited synchronous generator
*** Typical permanent magnet amount: High = 650 kg/MW; Medium = 160 kg/MW; Low = 80 kg/MW

Source: http://publications.europa.eu/resource/cellar/7f3762be-aafe-11e6-aab7-01aa75ed71a1.0001.02/DOC_2

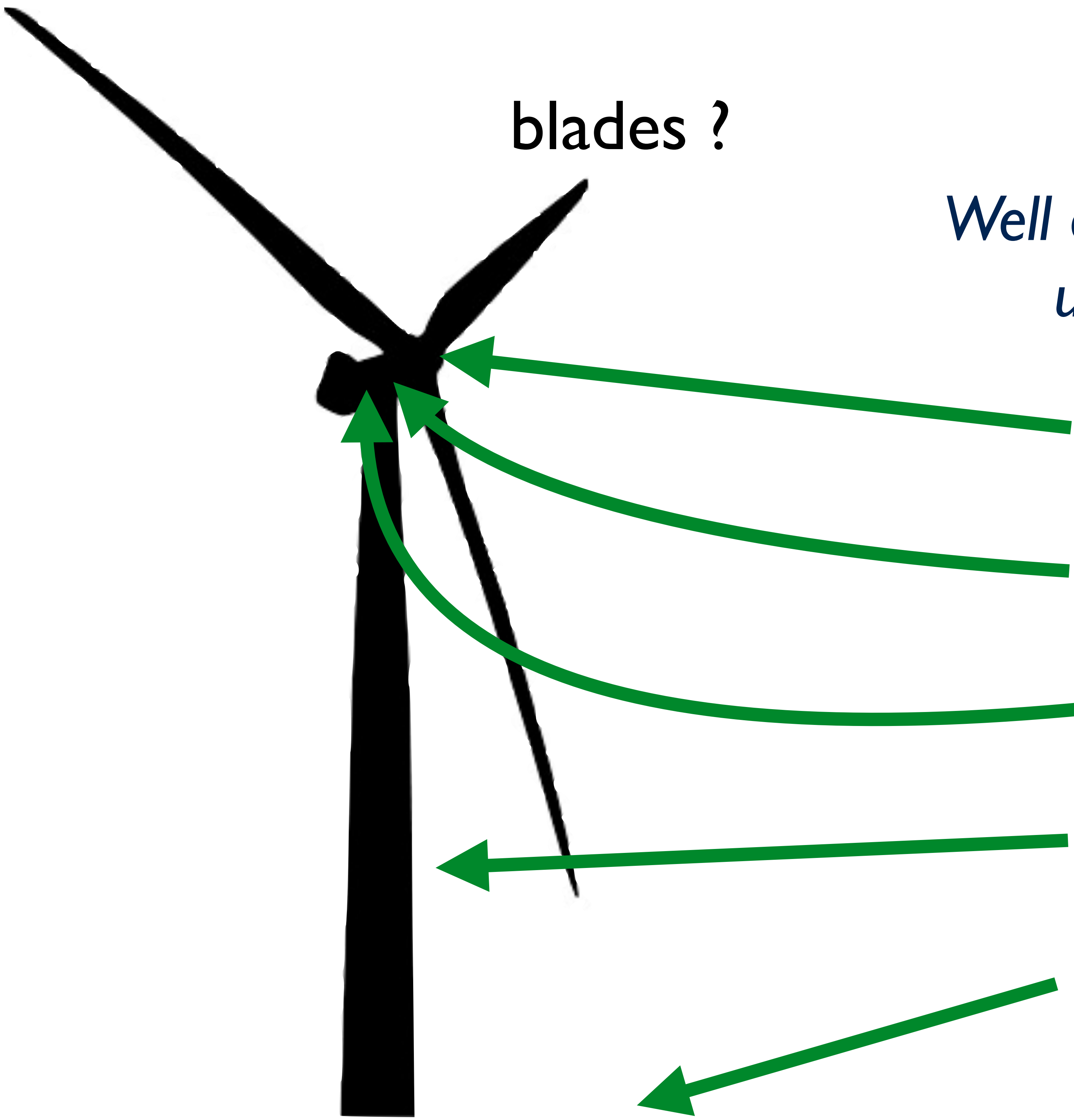
Alternative technologies e.g. the EU project EcoSwing

MISSION ACCOMPLISHED: The EU-funded EcoSwing project ended as scheduled on 30.04.2019. EcoSwing successfully aimed at demonstrating world's first superconducting low-cost and lightweight wind turbine drivetrain— on a large-scale commercial wind turbine.

Source: https://ecoswing.eu/project

Wind energy - environmental impact

What to do with the old wind turbines? Recycling ?



Well established recycling processes for up to 90% of the components

hub (iron)

electronics

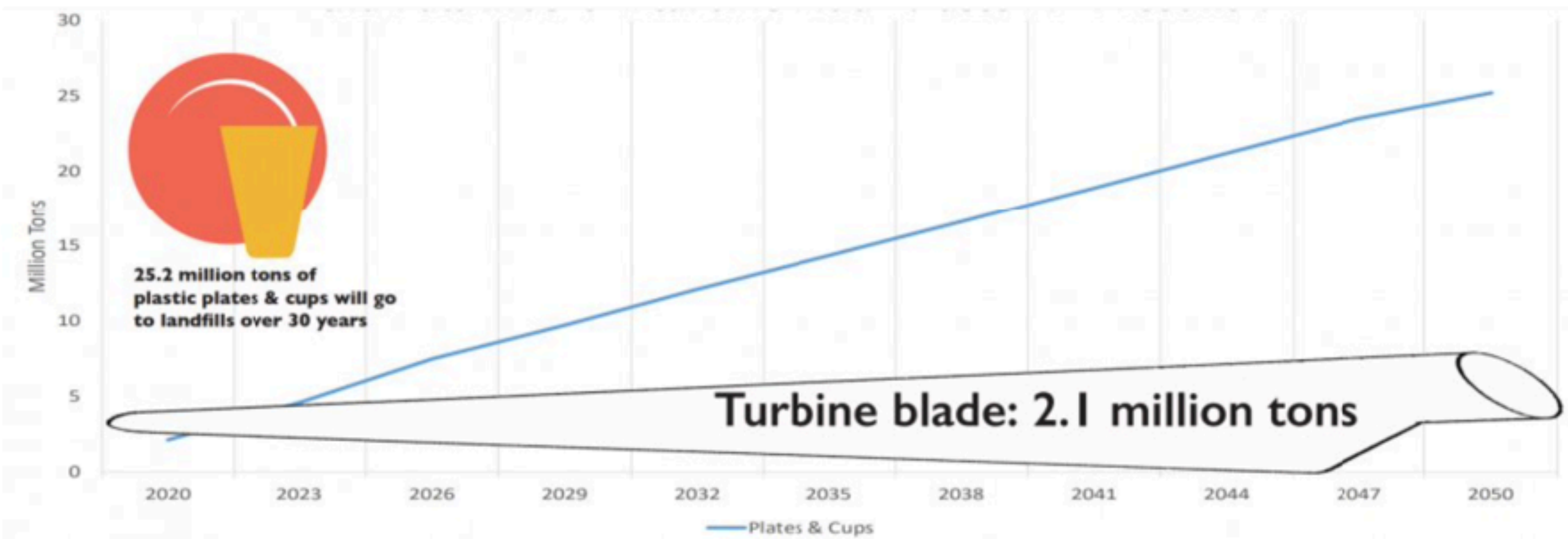
nacelle (mainly steel)

tower (steel, concrete)

foundation (concrete)

Wind energy - environmental impact

Problem: rotor blades with glass and carbon reinforced fibres



Source: https://cleangridalliance.org/blog/137/wind-turbine-recycling-and-disposal

Mechanical Recycling
shredding and mixing
to thermoplastic

Thermal Recycling
burning, leftovers can be reused
in concrete, paint and glue

Ongoing research: Project ZEBRA (Zero wastE Blade ReseArch)

What to do with the old wind turbines? Recycling ?

Or other innovative solutions

This image shows a section of turbine blade which shelters bikes in Denmark. Image: Siemens Gamesa via Twitter

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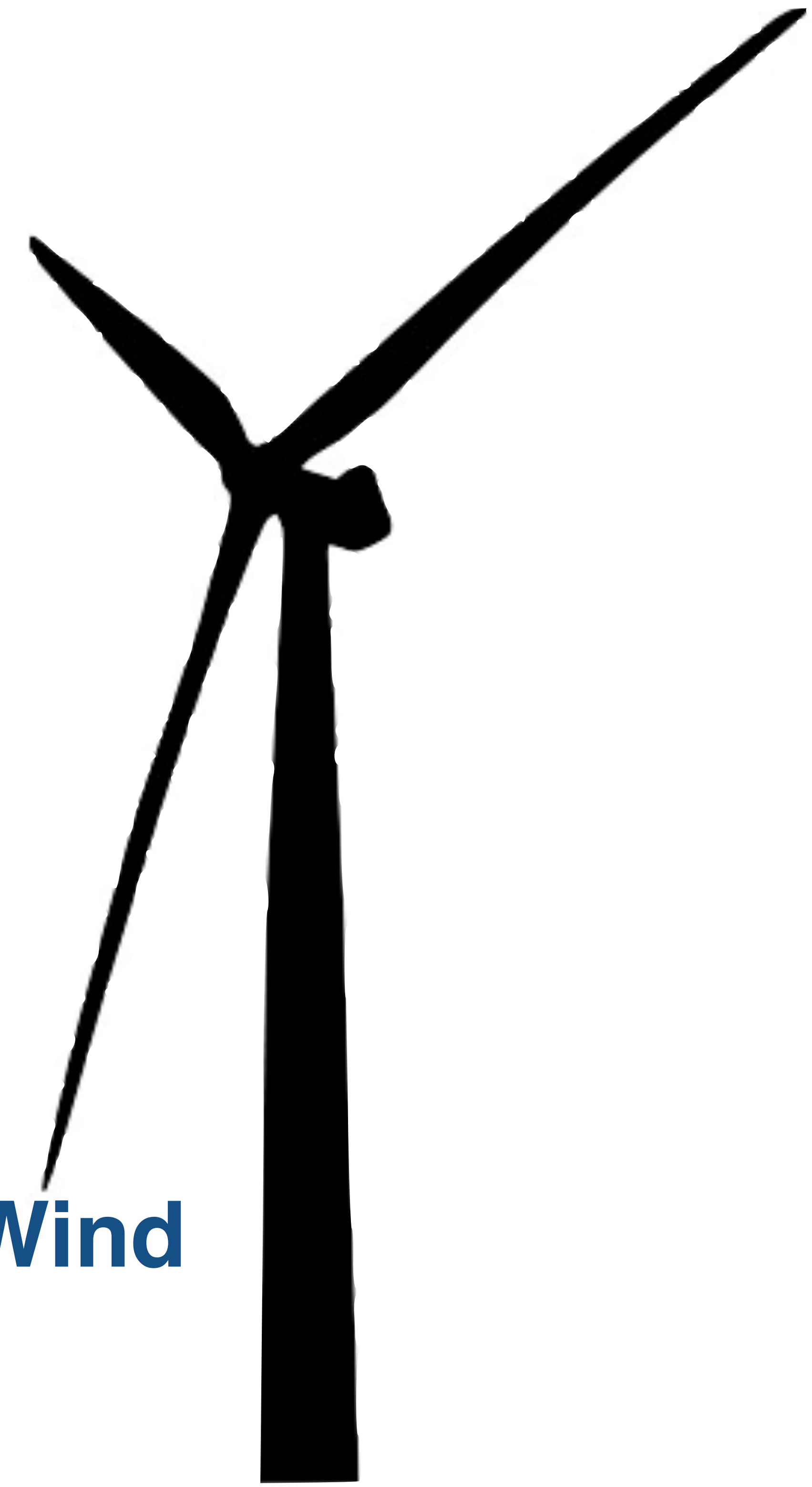


Atmospheric wind field is turbulent on different scales

on small scales

Source: youtube.com, American beauty (1999)

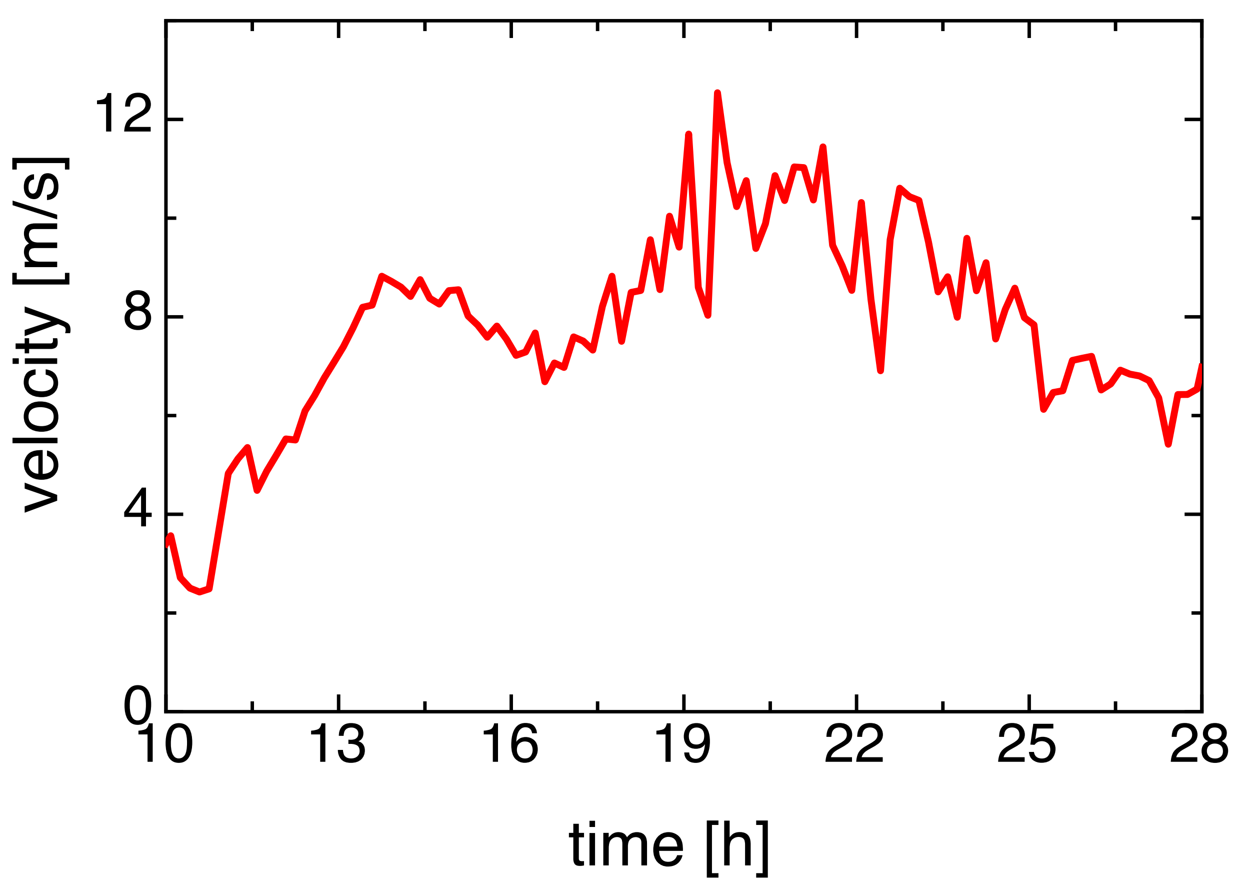
on large scales

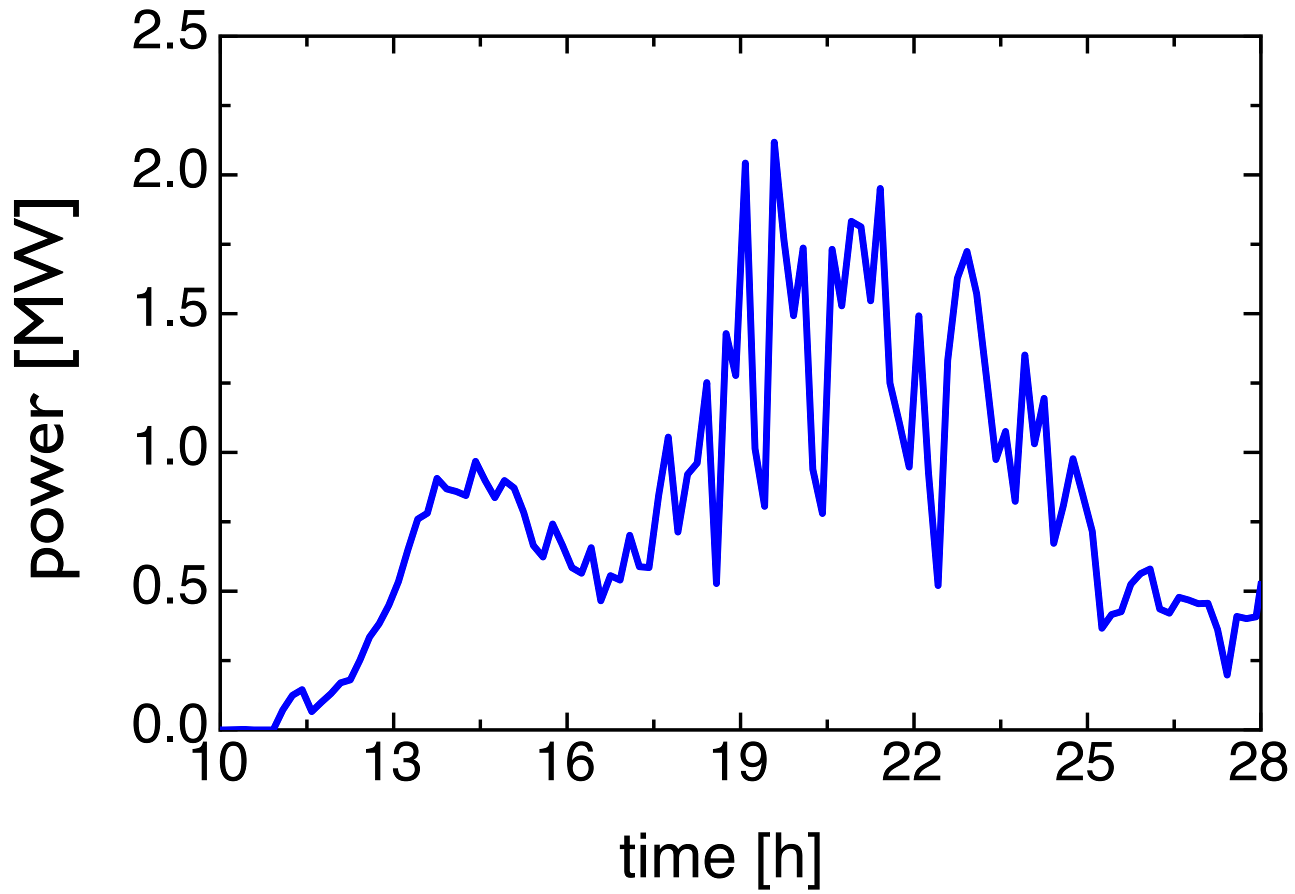
Source: youtube.com

These are the working conditions for wind turbines

Standard description

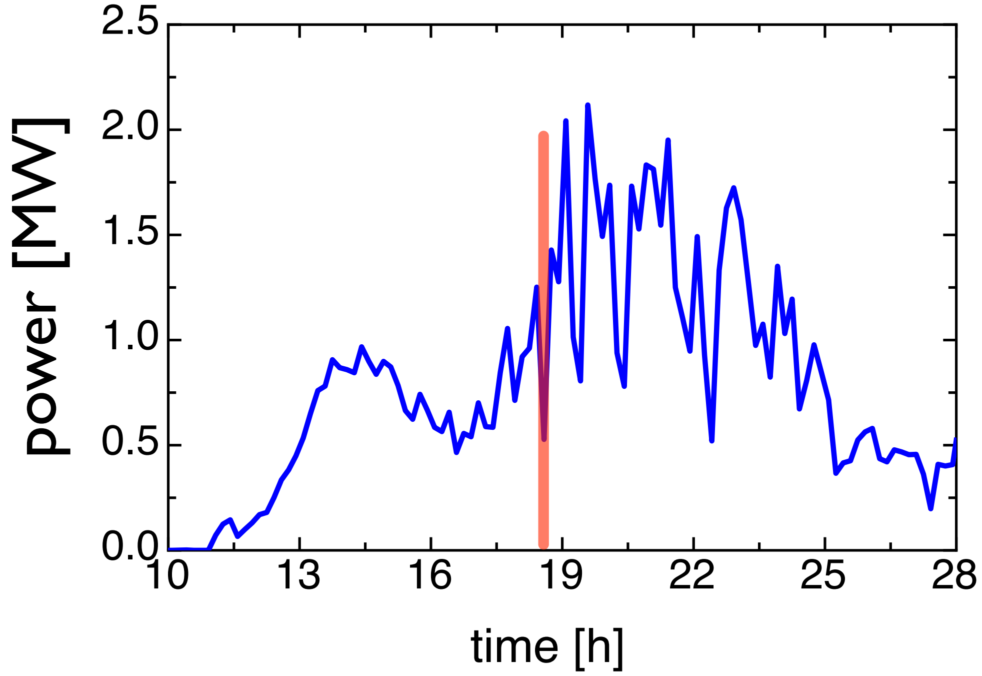
Problem: standard characterisation of wind fields and turbine response (power output) is based on 10-minute averaged data

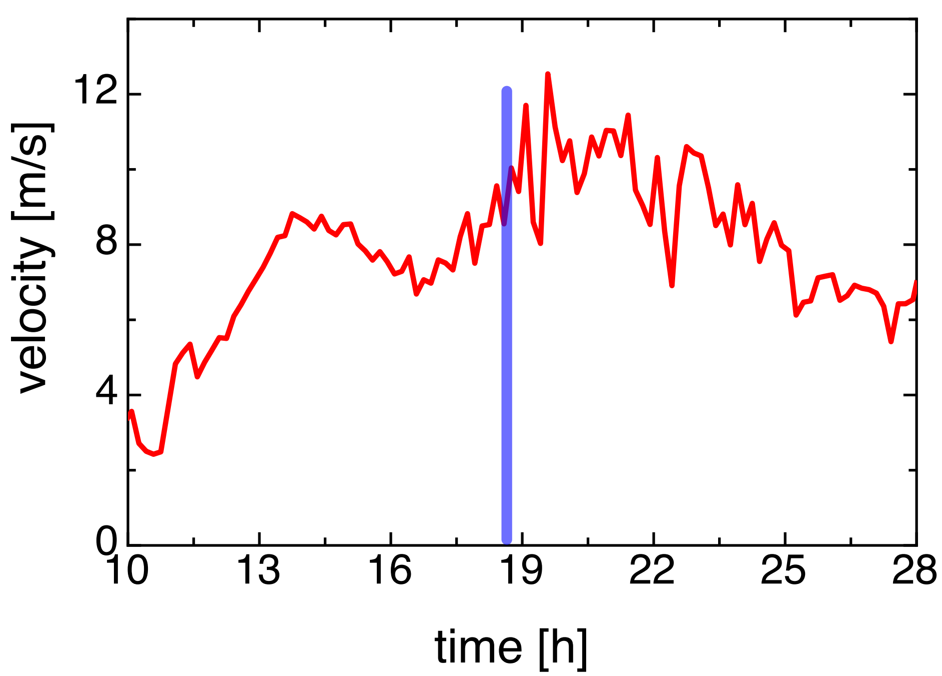


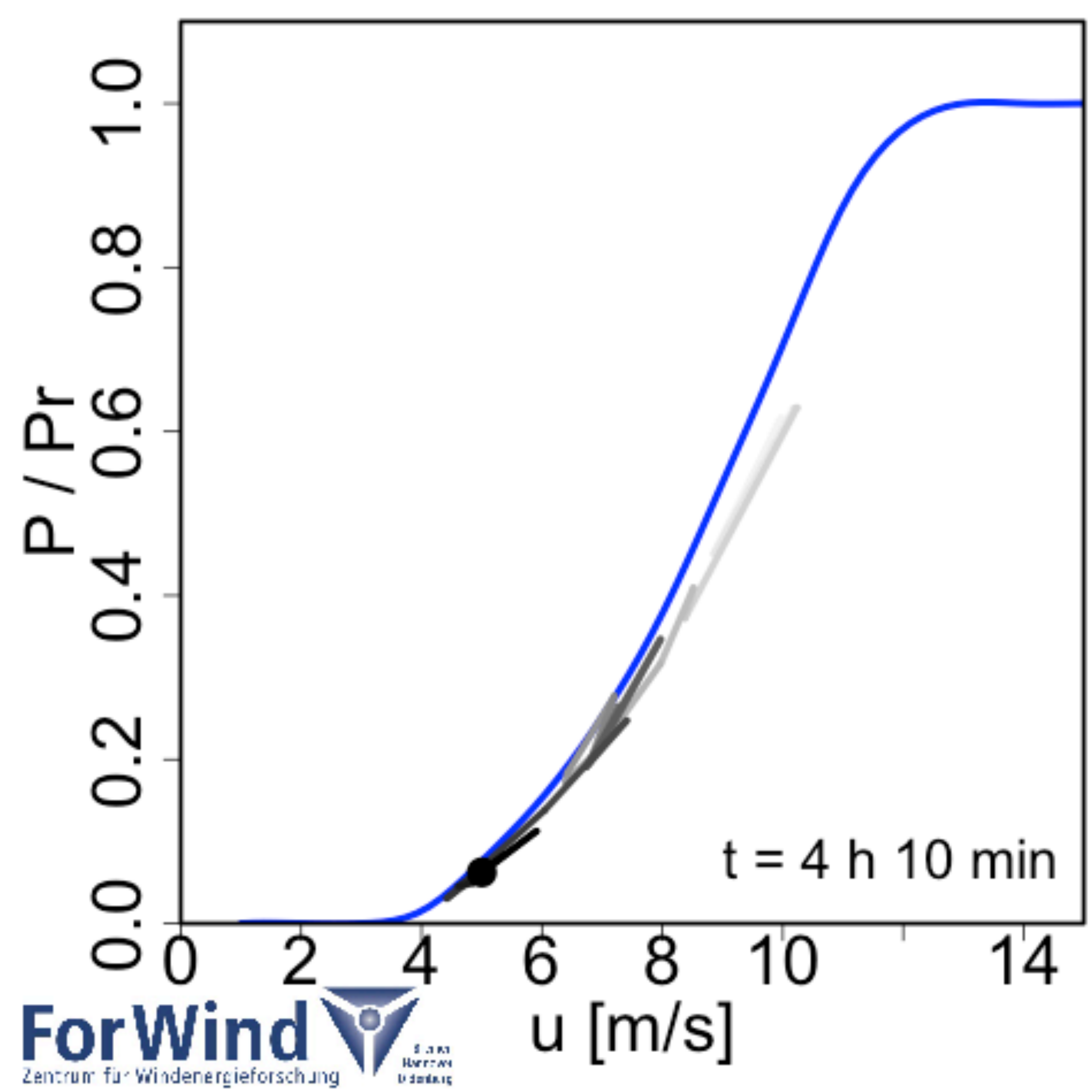


Standard description

Dynamics of 10-minute averaged data

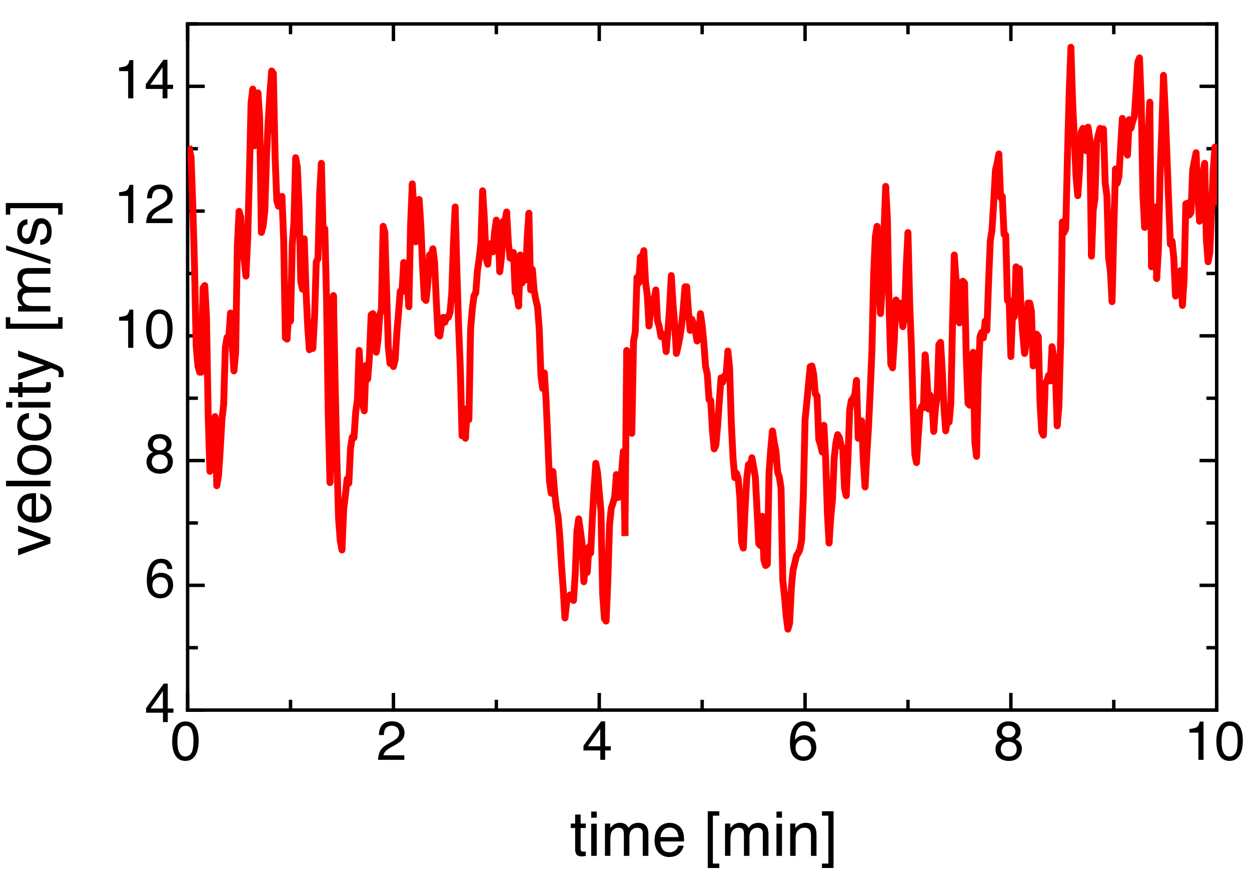


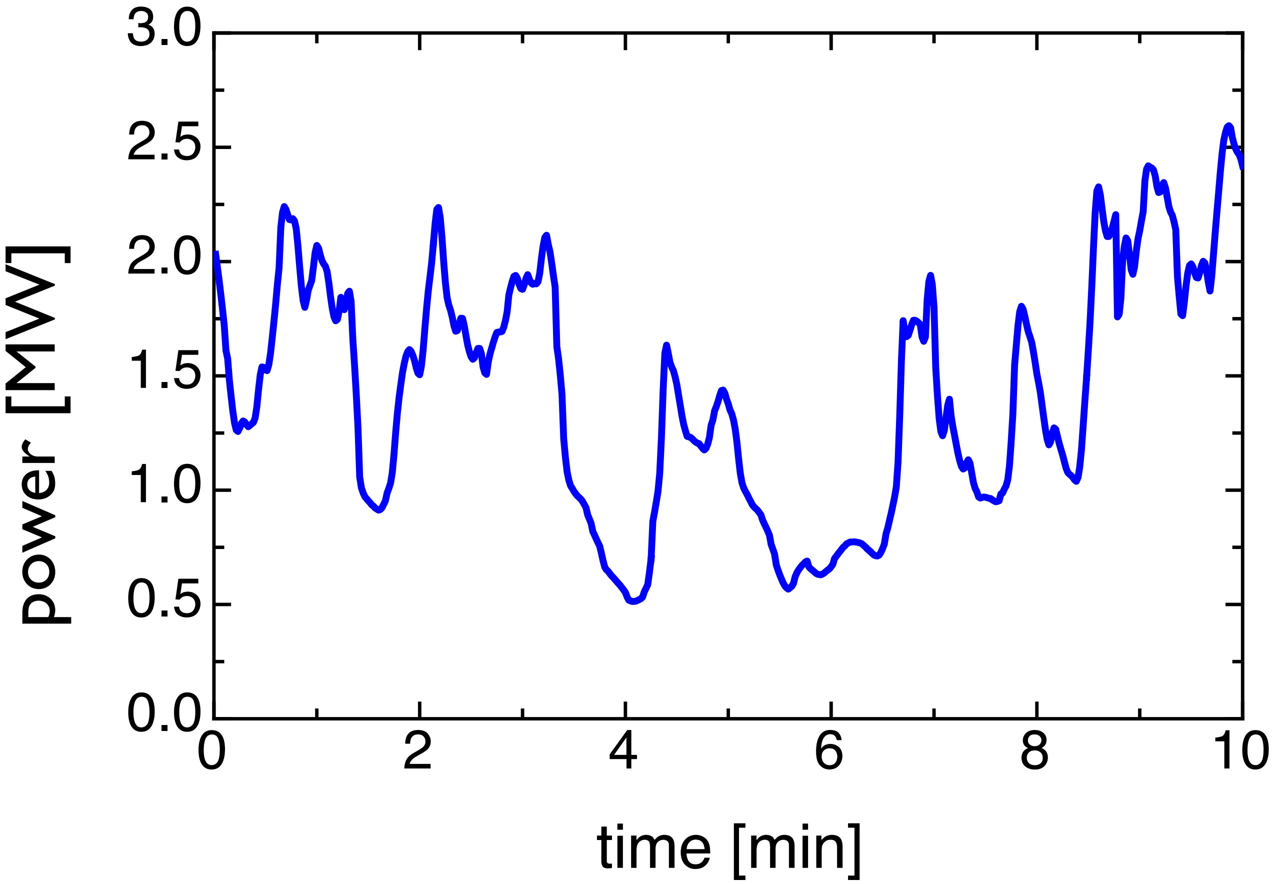




Fast dynamics

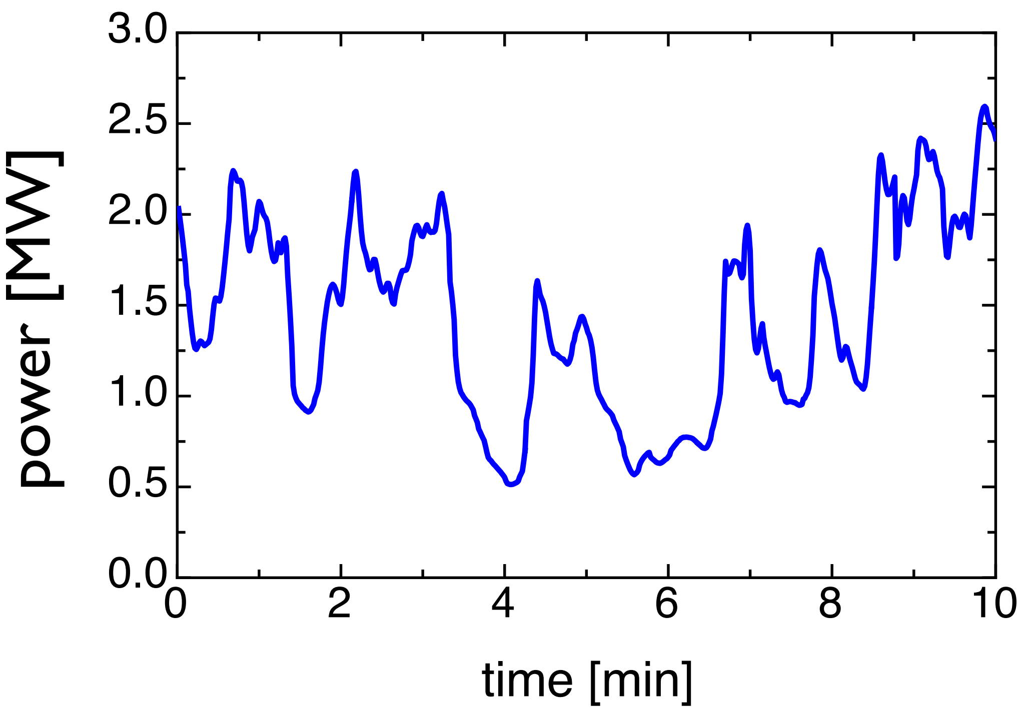
1Hz data within 10-minute windows reveals highly dynamical system on short time scales

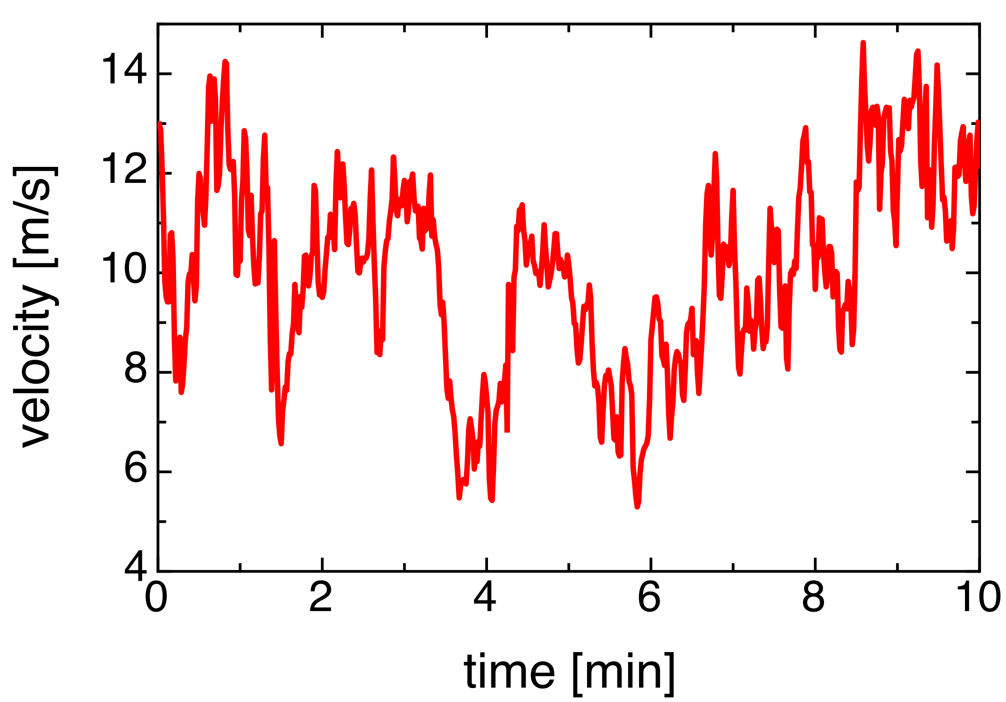


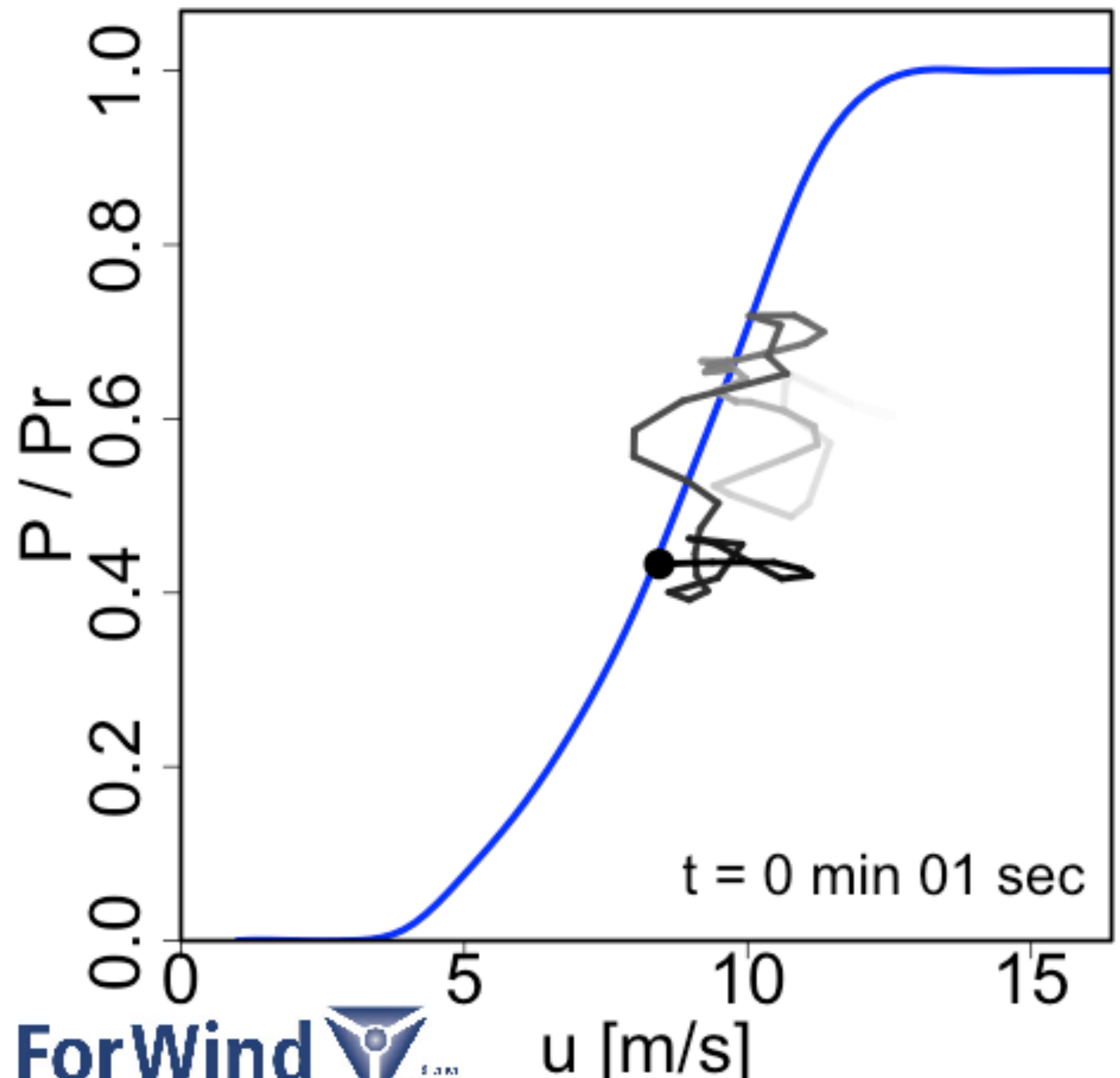


Fast dynamics

Dynamics within 10 minute window at 1Hz

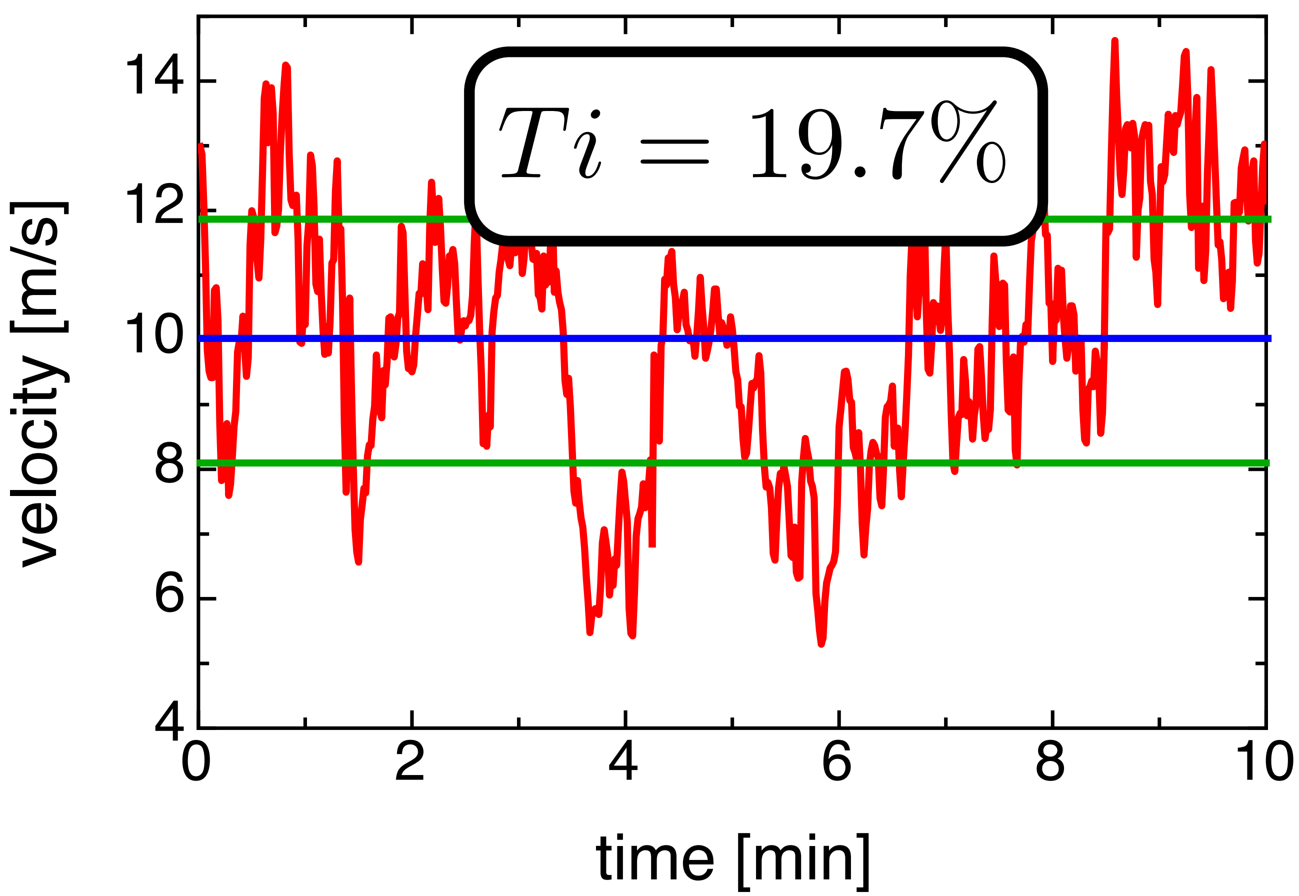


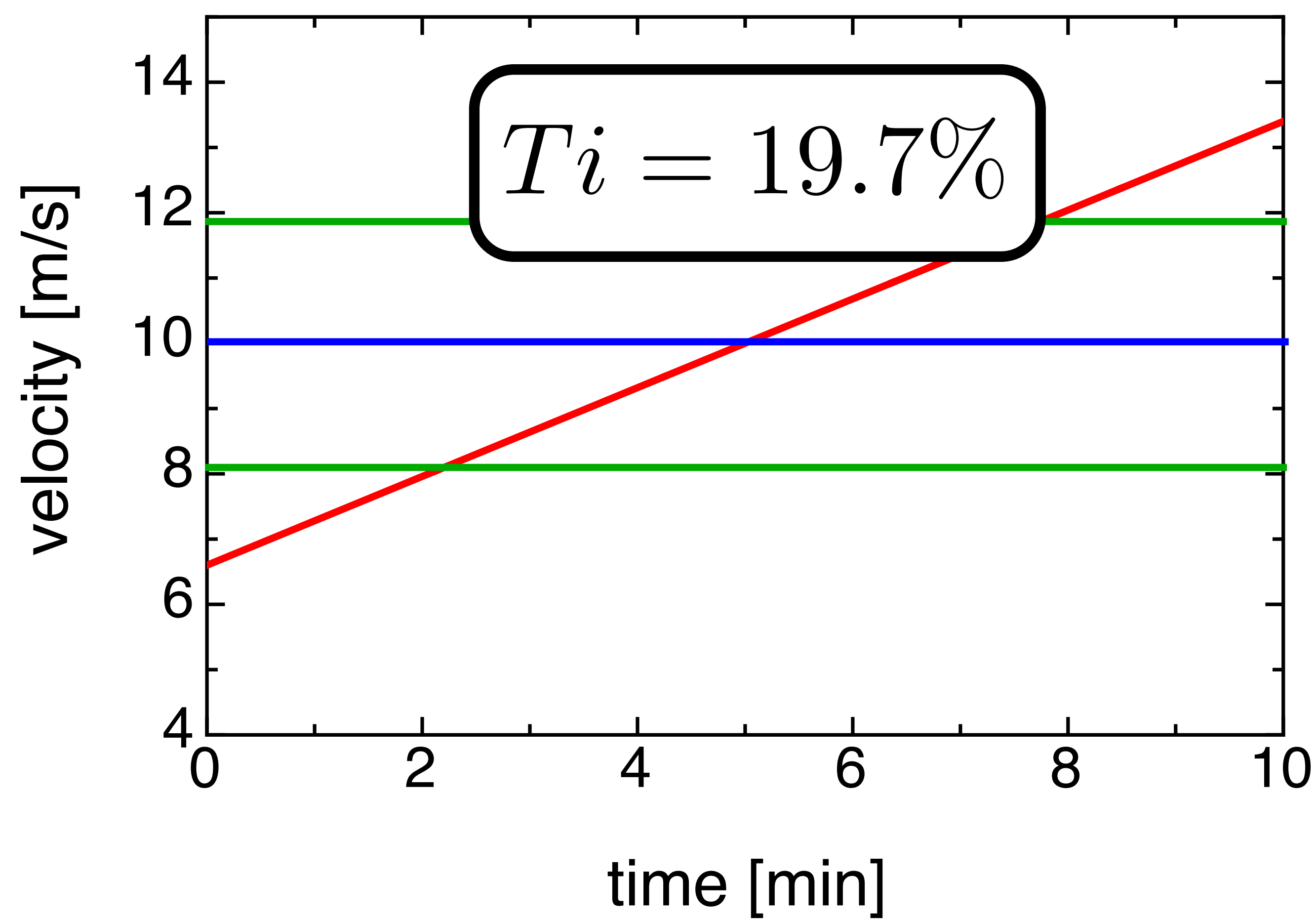




Dynamics within 10-minute windows are accounted for by turbulence intensity

$$Ti = \frac{\sigma_u}{\langle u \rangle}$$





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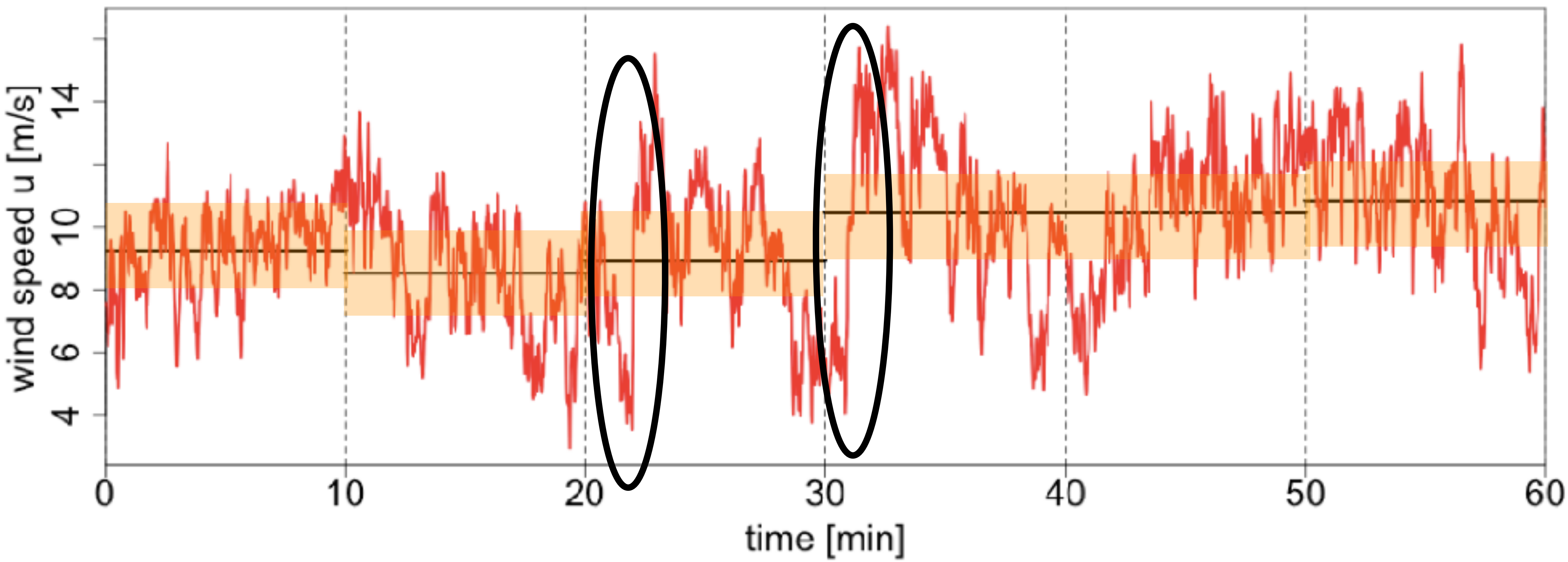
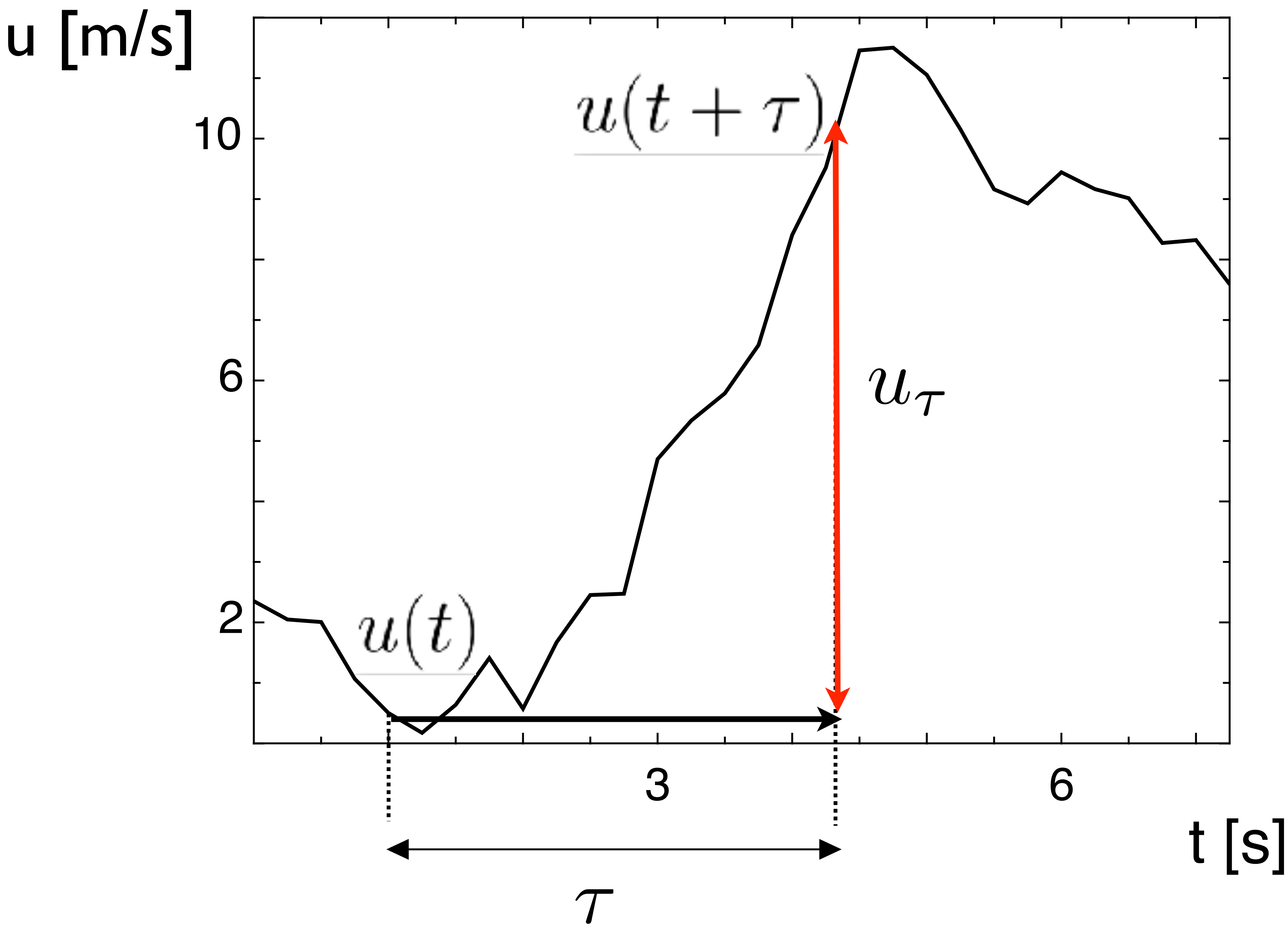
Standard description

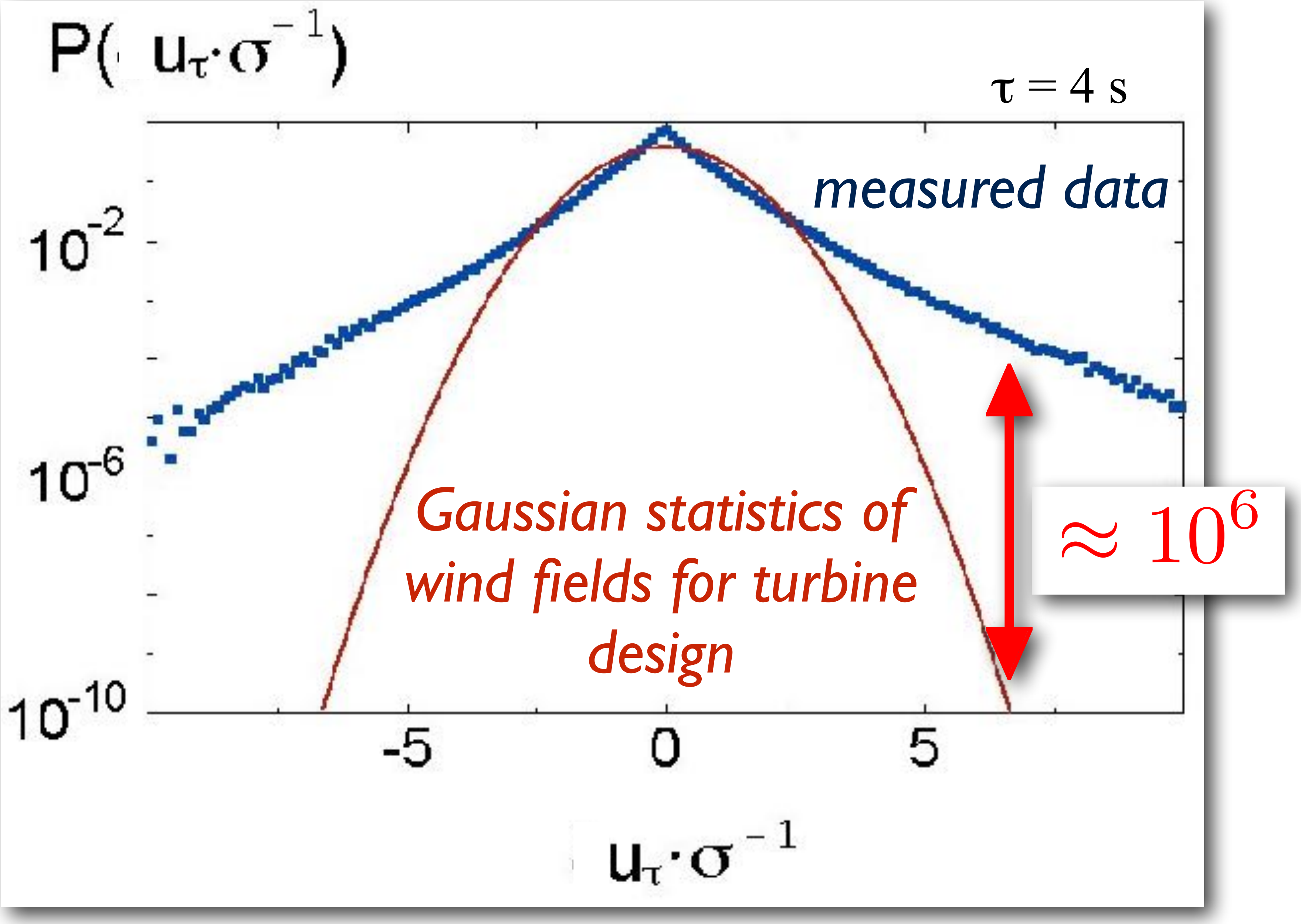
Temporal events e.g. gusts are not captured by turbulence intensity



Velocity increment: $u_\tau := u(t+\tau) - u(t)$



Atmospheric turbulence - increments

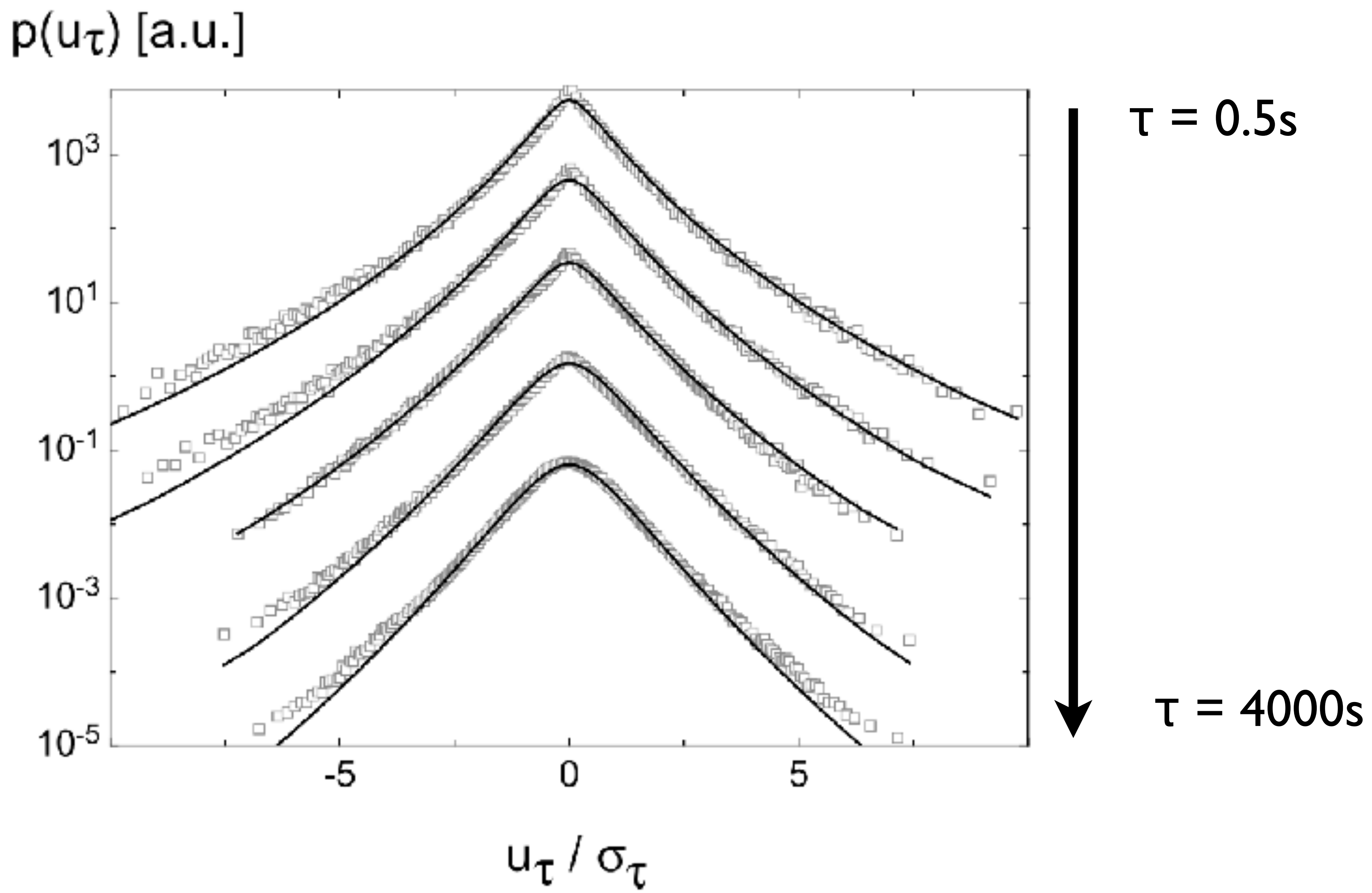


Boundary-Layer Meteorology **108** (2003)

$$Prob(u_\tau > 6\sigma) \approx 10^{-10}$$ → 1/100 years

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

Intermittent velocity increments on small and large scales

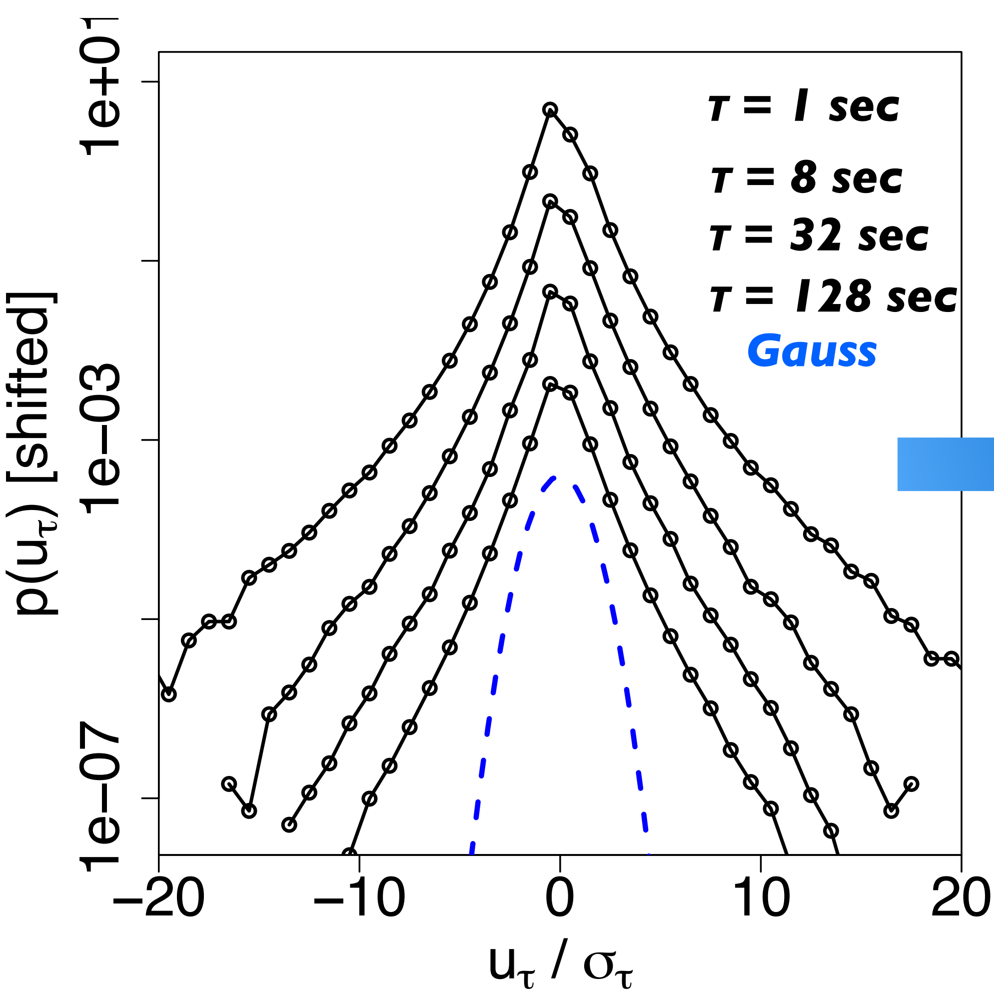


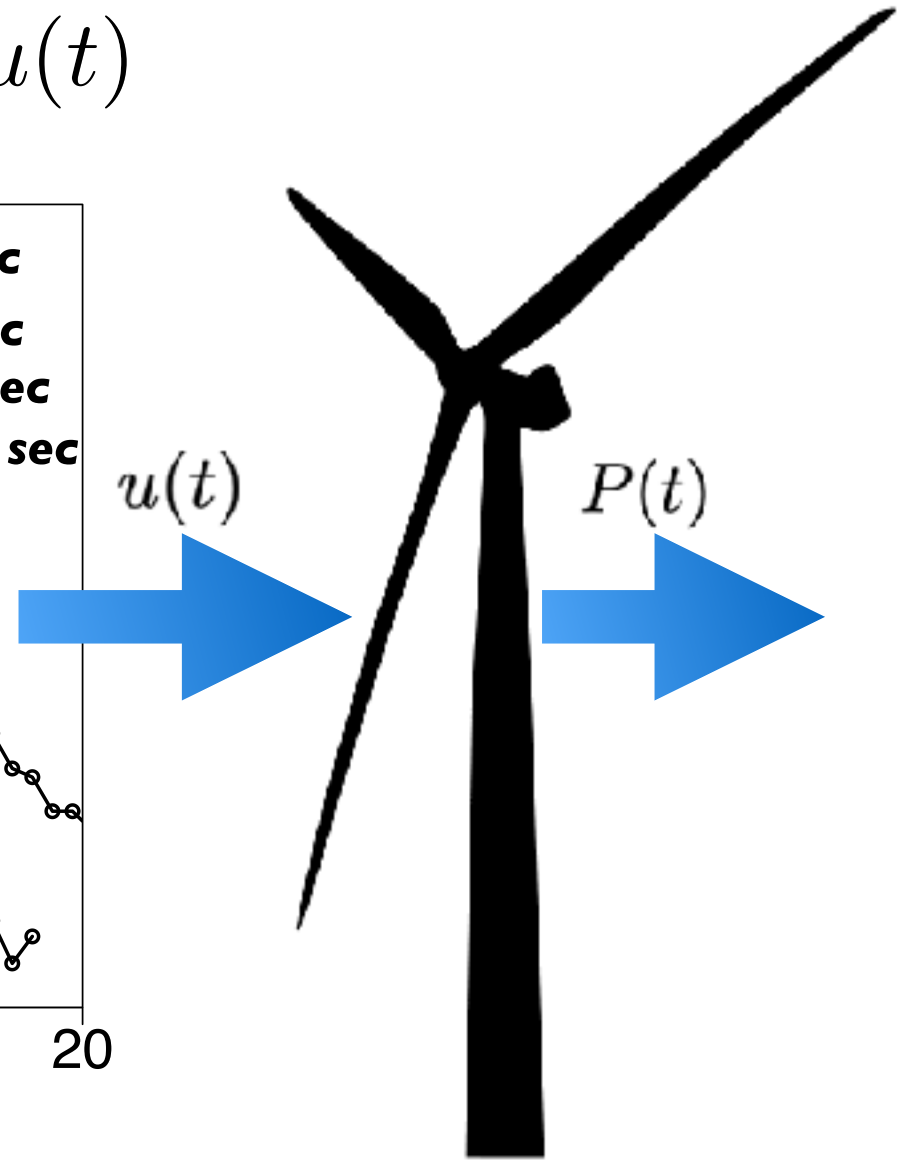
Böttcher et al., Small and Large Scale Fluctuations in Atmospheric Wind Speeds, 2004

Is intermittency a problem?

Intermittent velocity increments

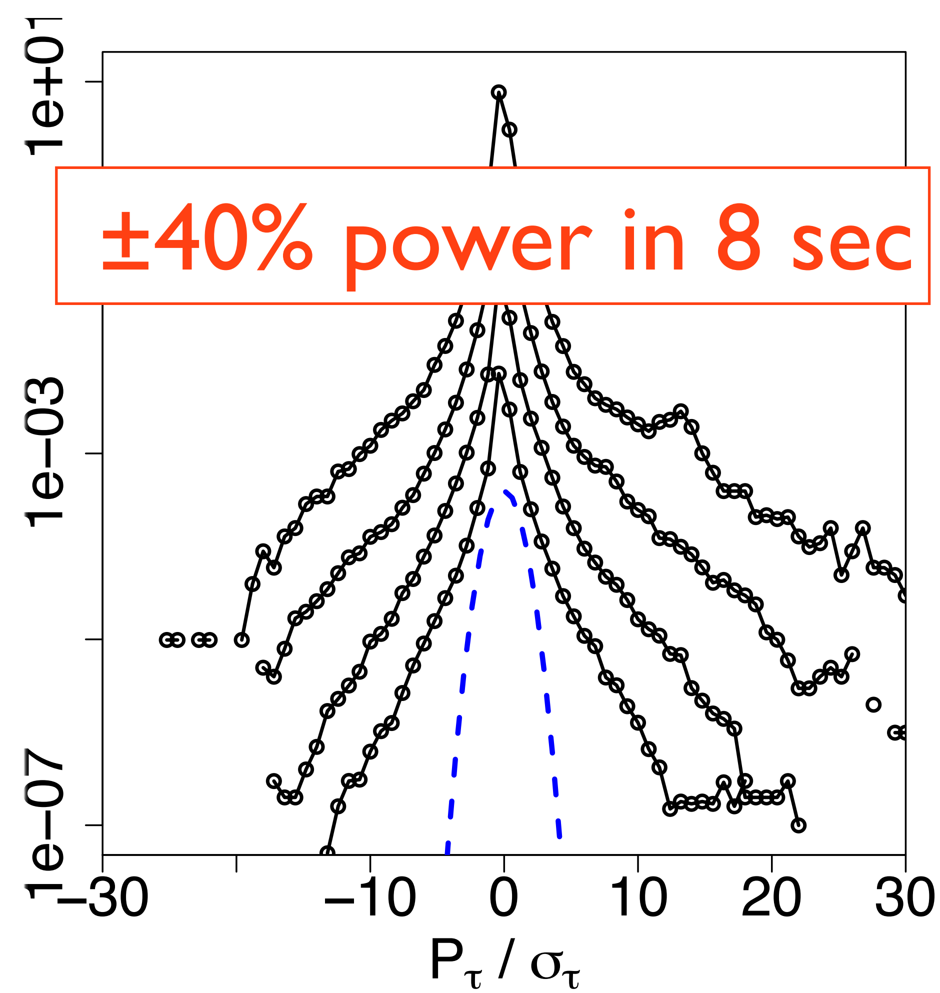
$$u_\tau = u(t+\tau) - u(t)$$





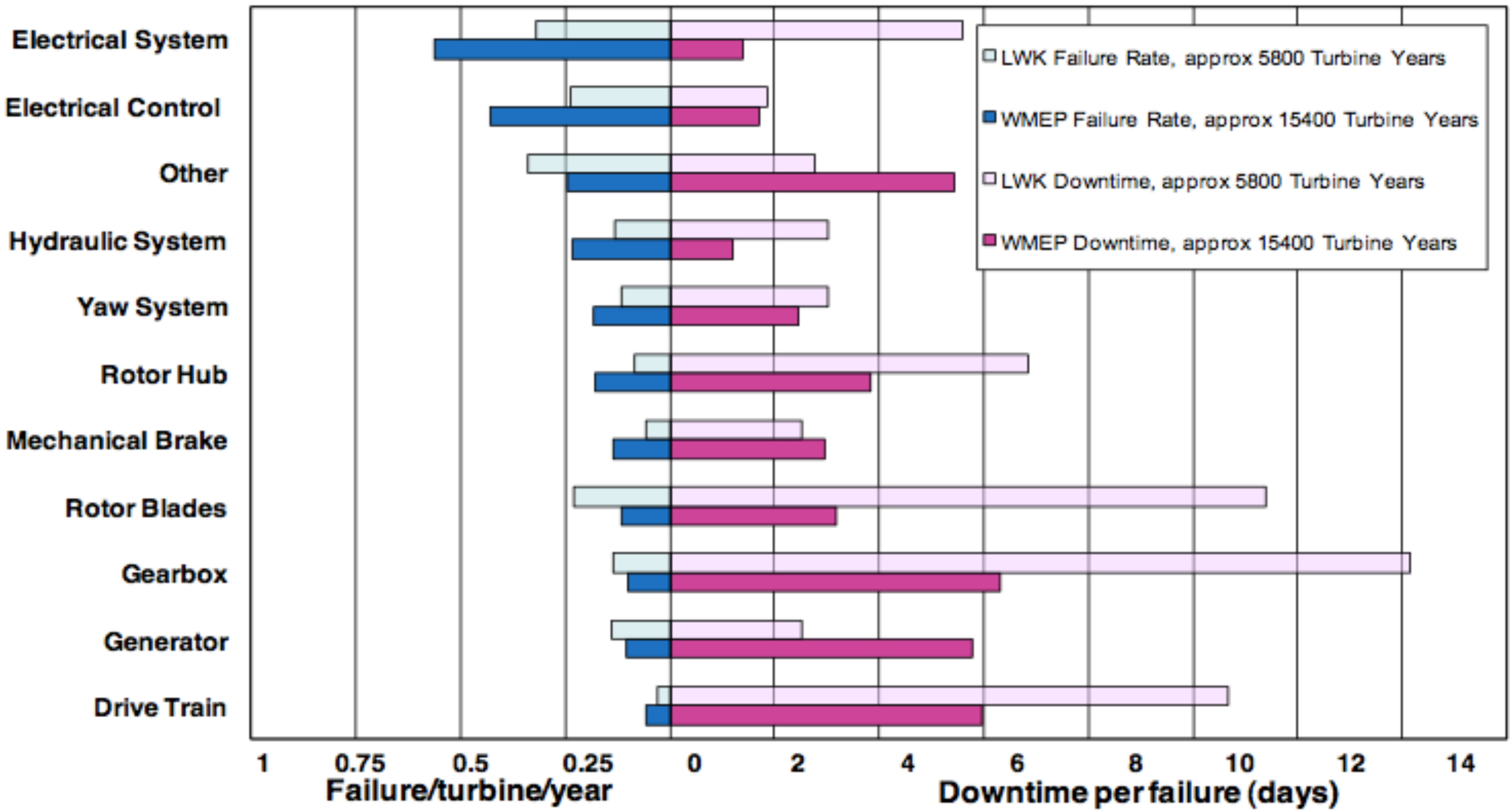
Intermittent increments of power output

$$P_\tau = P(t+\tau) - P(t)$$



Motivation for research

Underestimation of turbulence can lead to higher failure rates



P. Tavner et.al EWAE 2011

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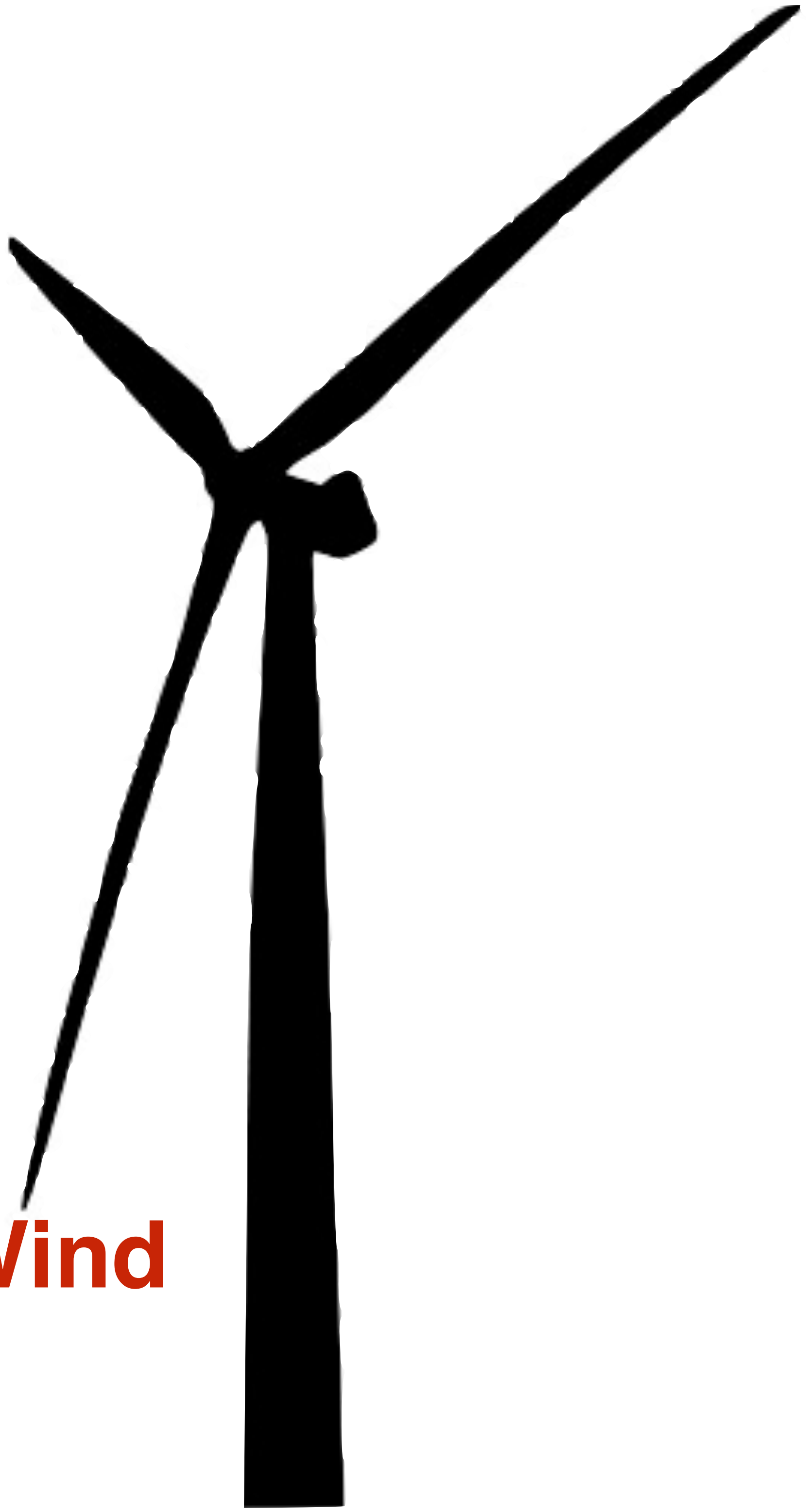
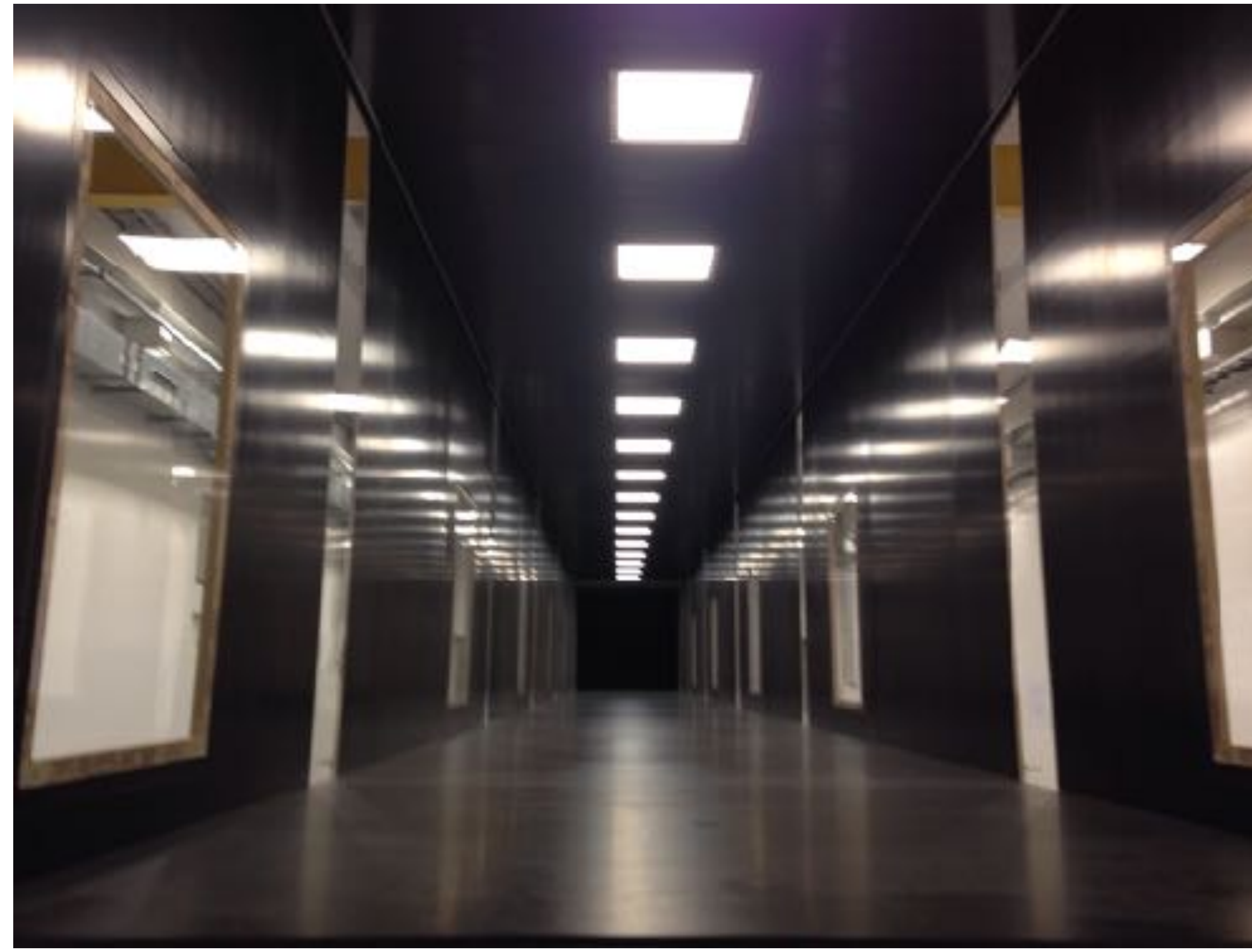


Facility WindLab
—
Wind tunnel with active grid

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



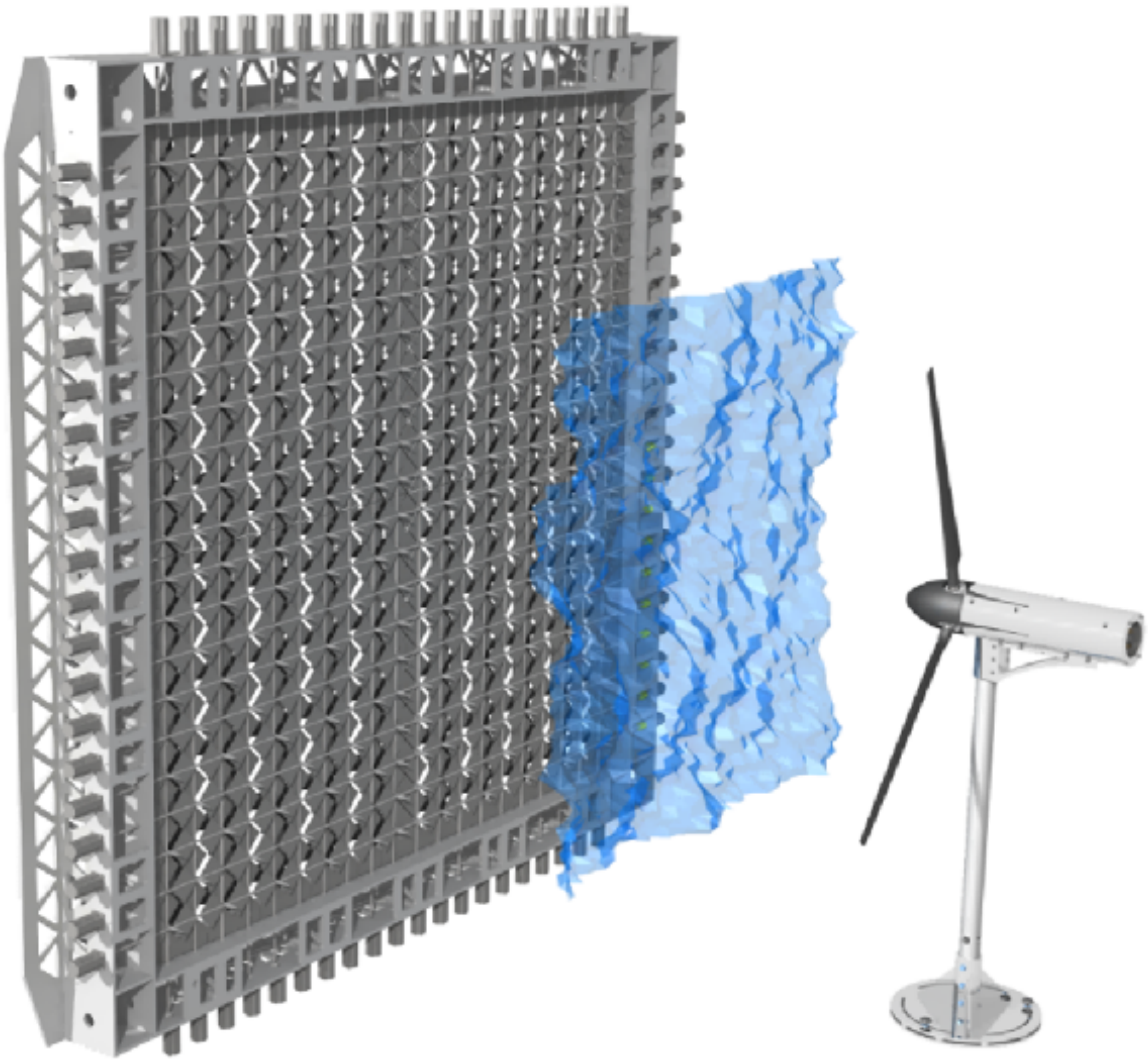
Model Wind Turbine Oldenburg - MoWiTO

MoWiTO 1.8

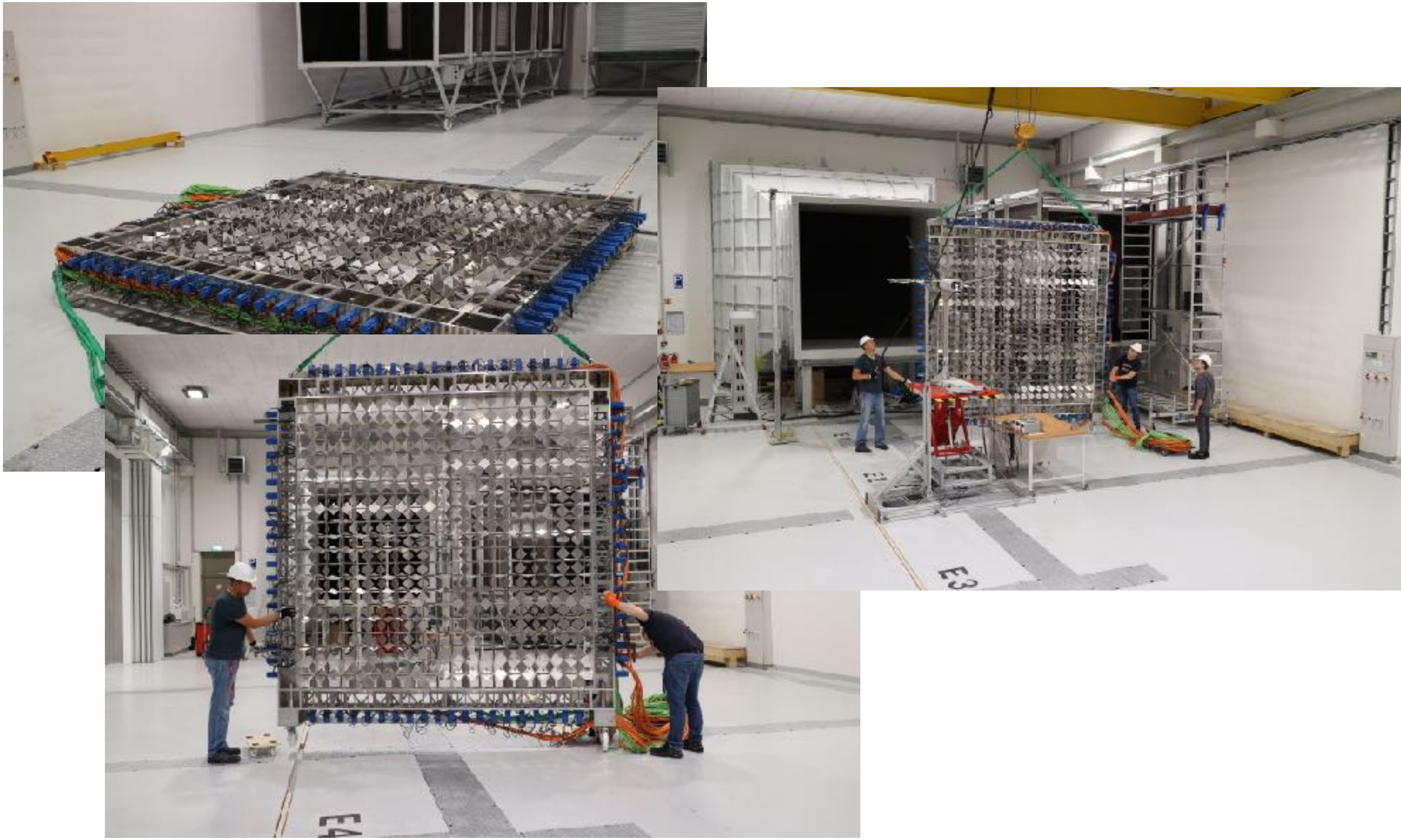
11 of MoWiTO 0.6

Idea - turbulent flow instead of laminar flow

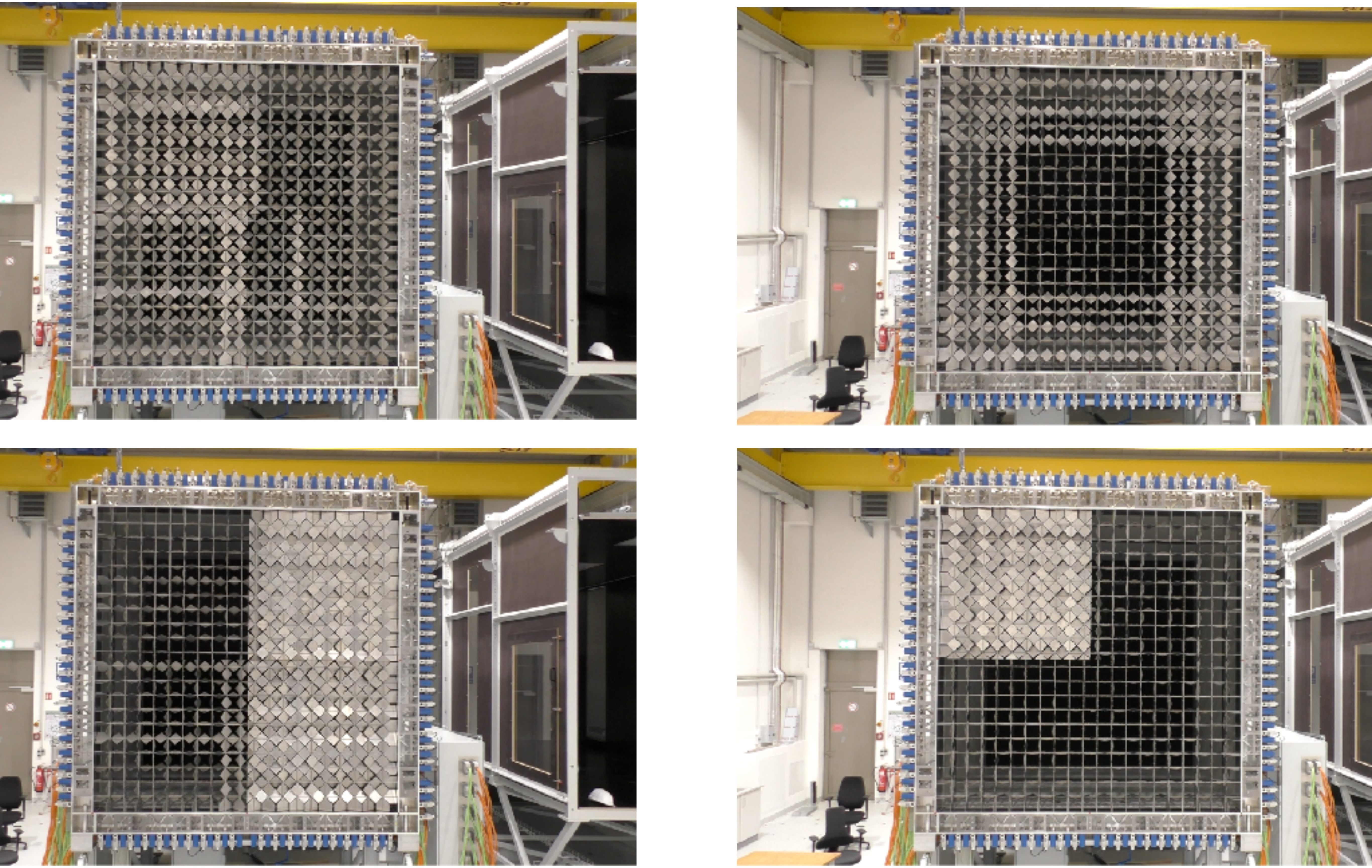
Generation of reproducible turbulent inflow conditions with defined characteristics, e.g intermittency and gusts



Active grid



Active grid



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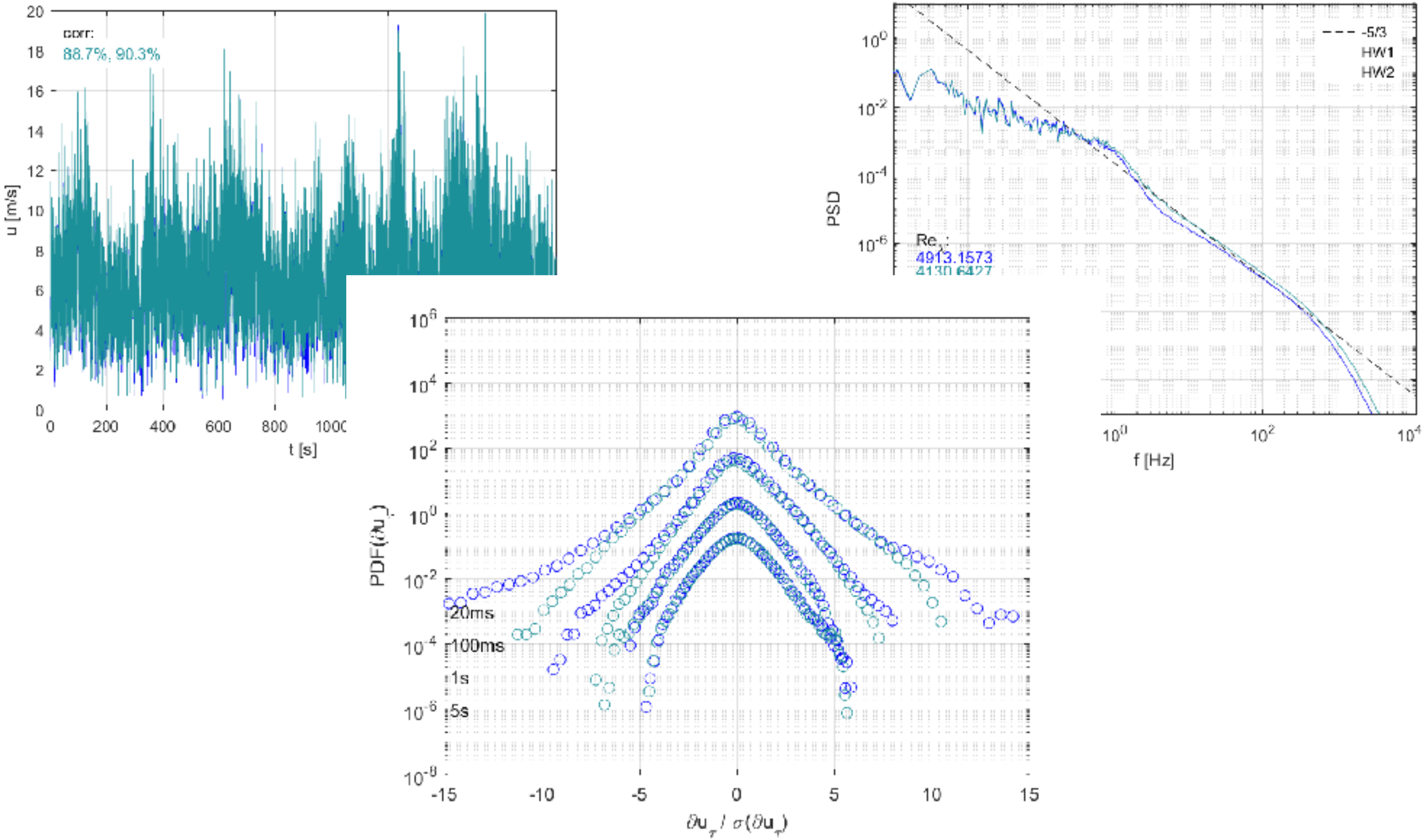
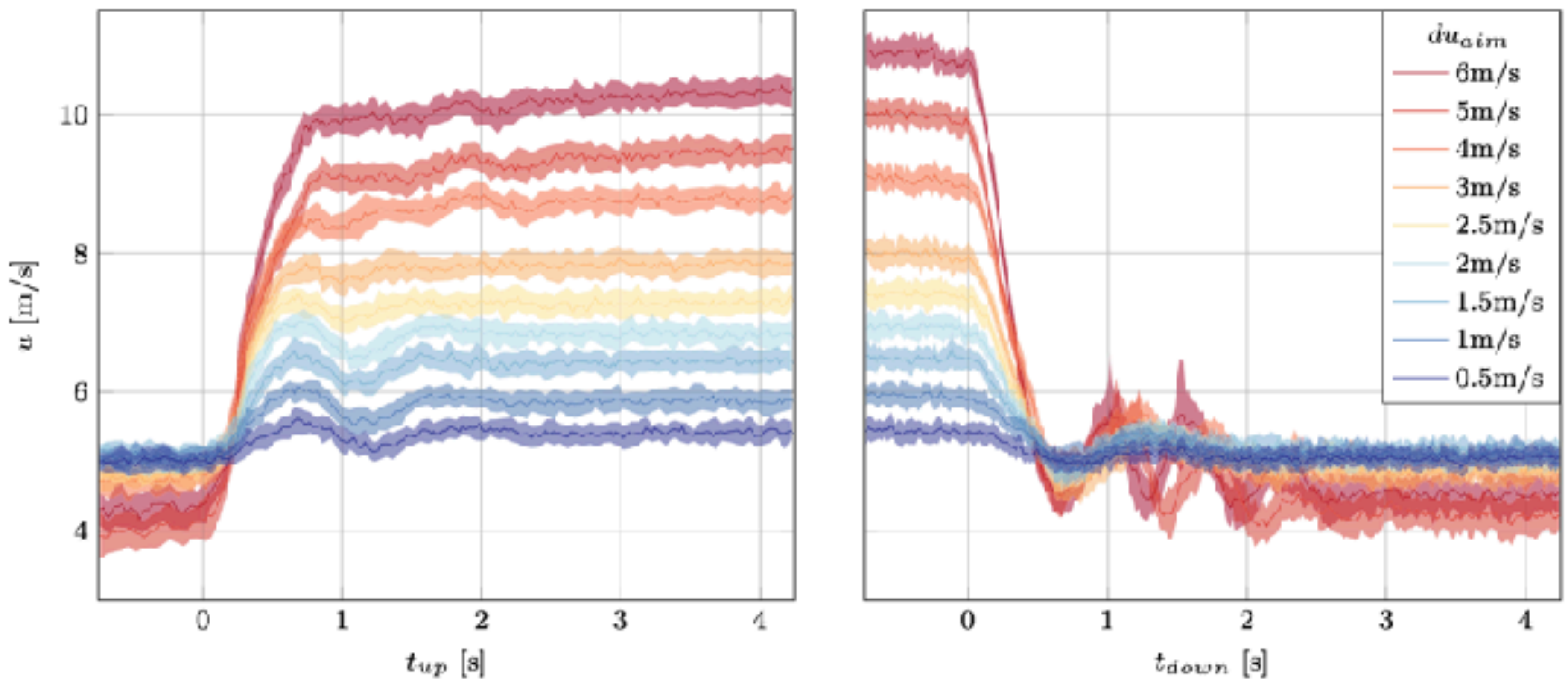
Generation of realistic inflow conditions

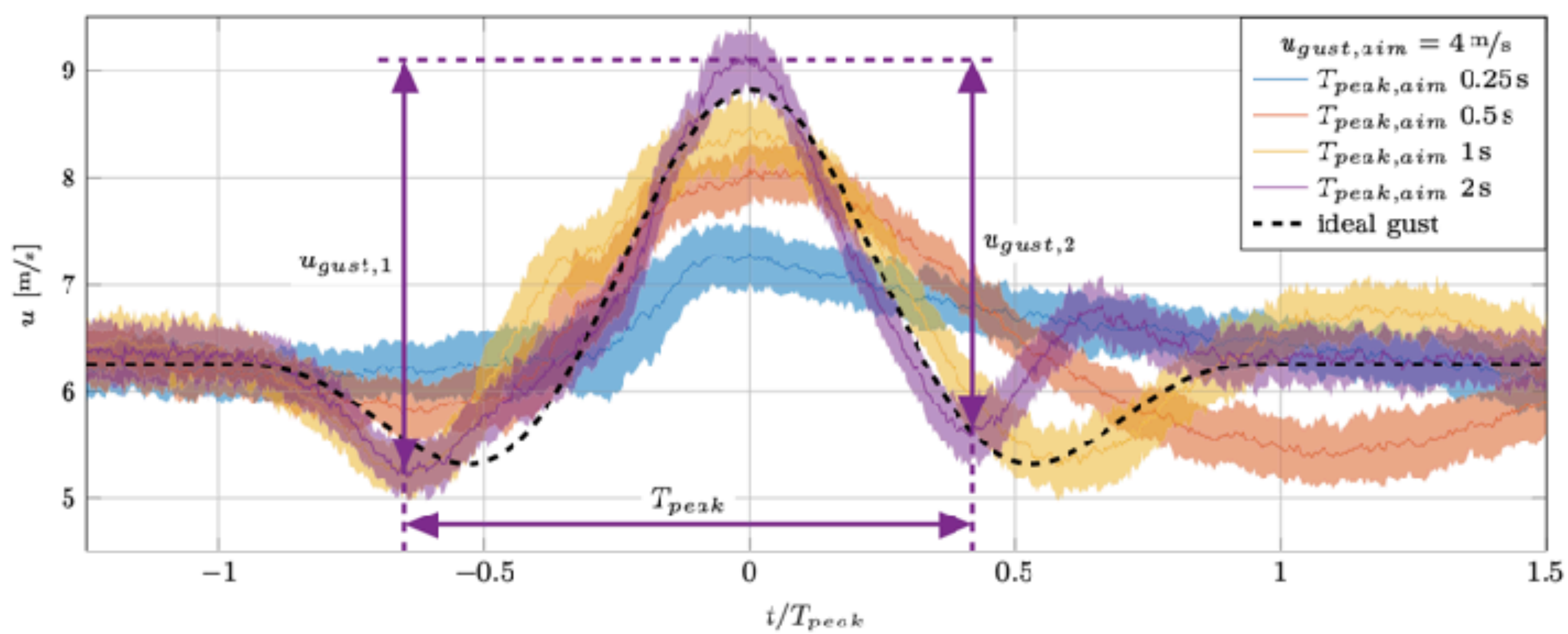


Generation of special inflow conditions

velocity step



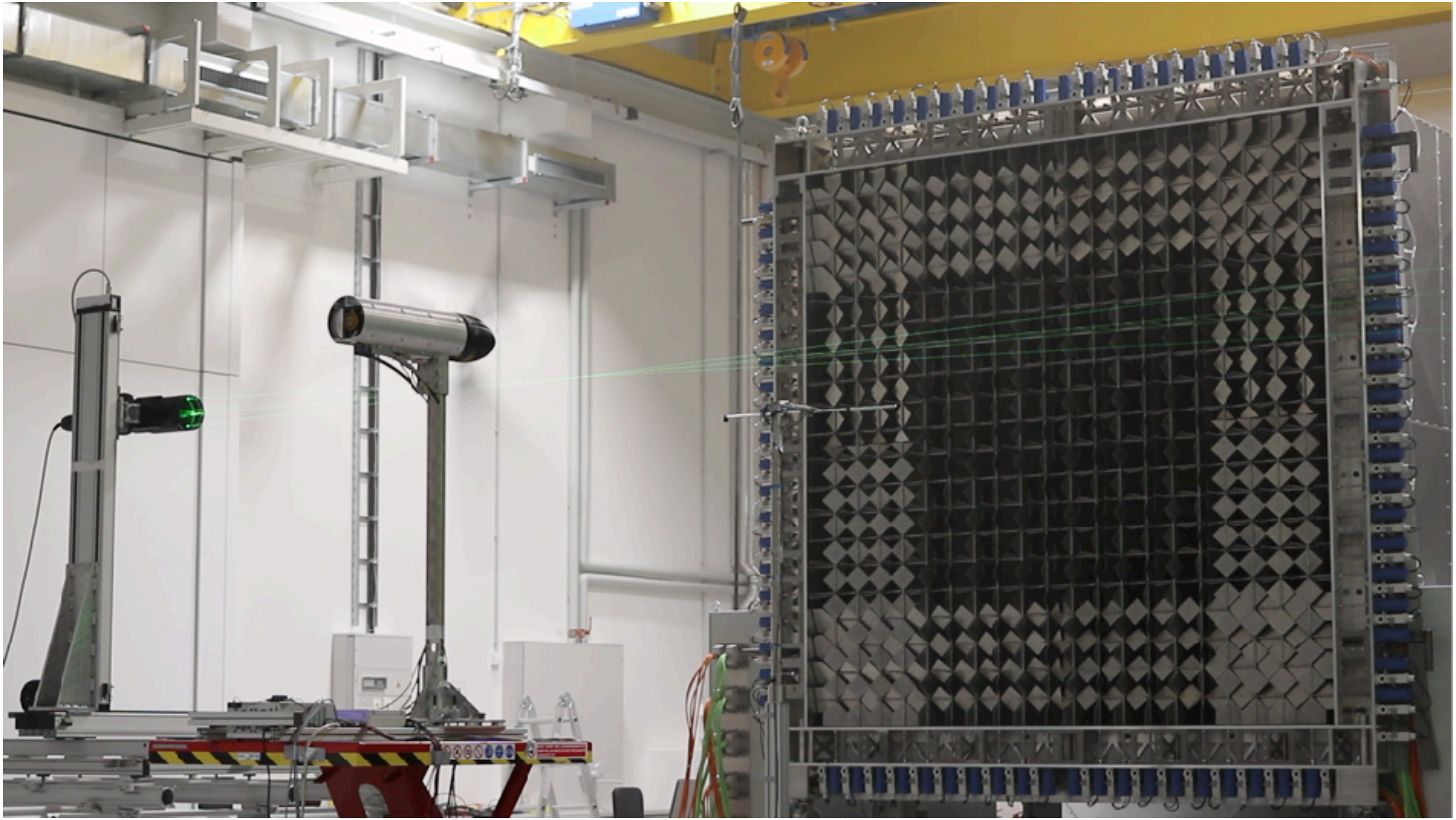
"norm" gust



Source: Neuhaus et al. Experiments in Fluids,(2021) https://doi.org/10.1007/s00348-021-03224-5

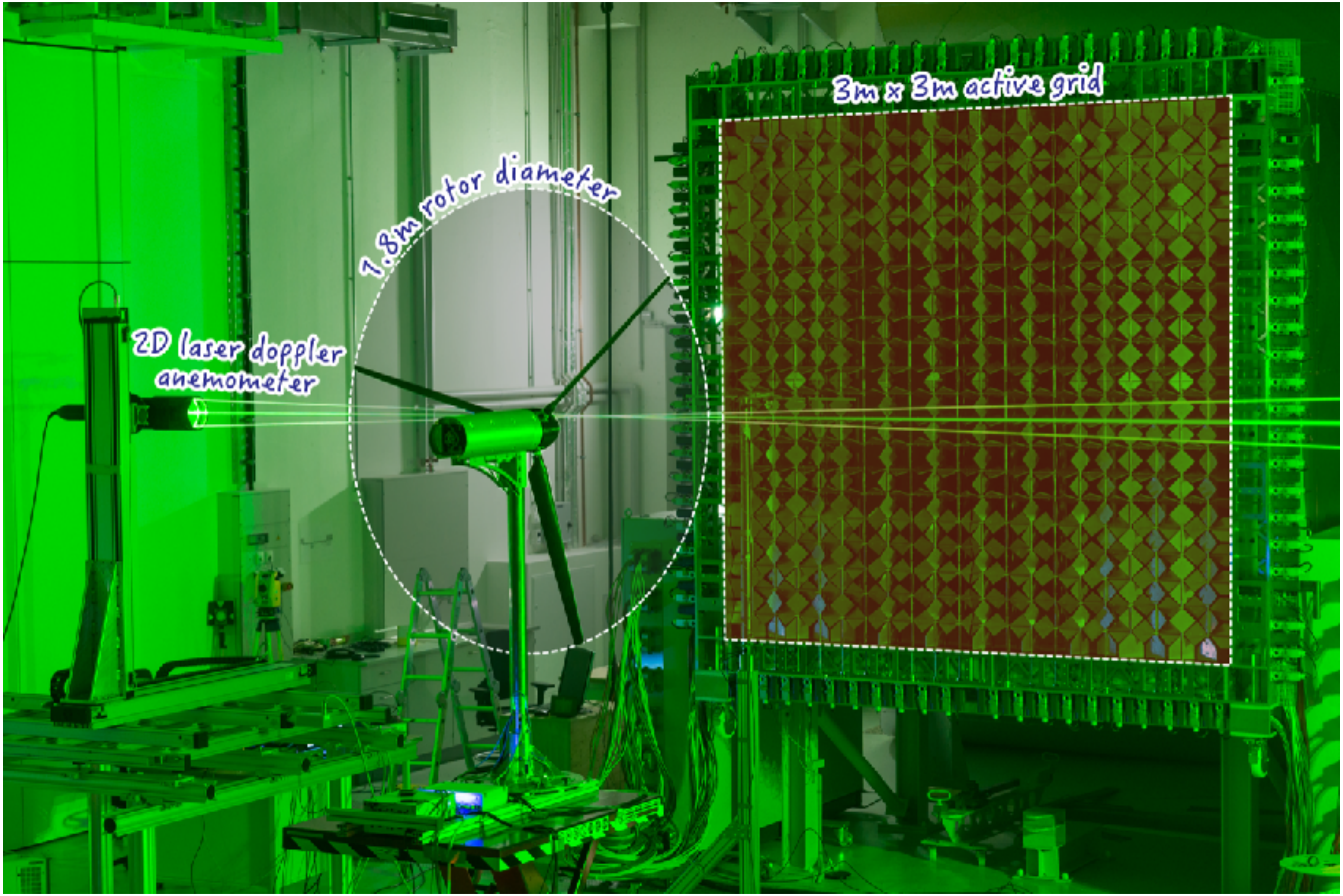
MoWiTO 1.8

Dynamic response of MoWiTO to different inflow conditions and control strategies



MoWiTO 1.8

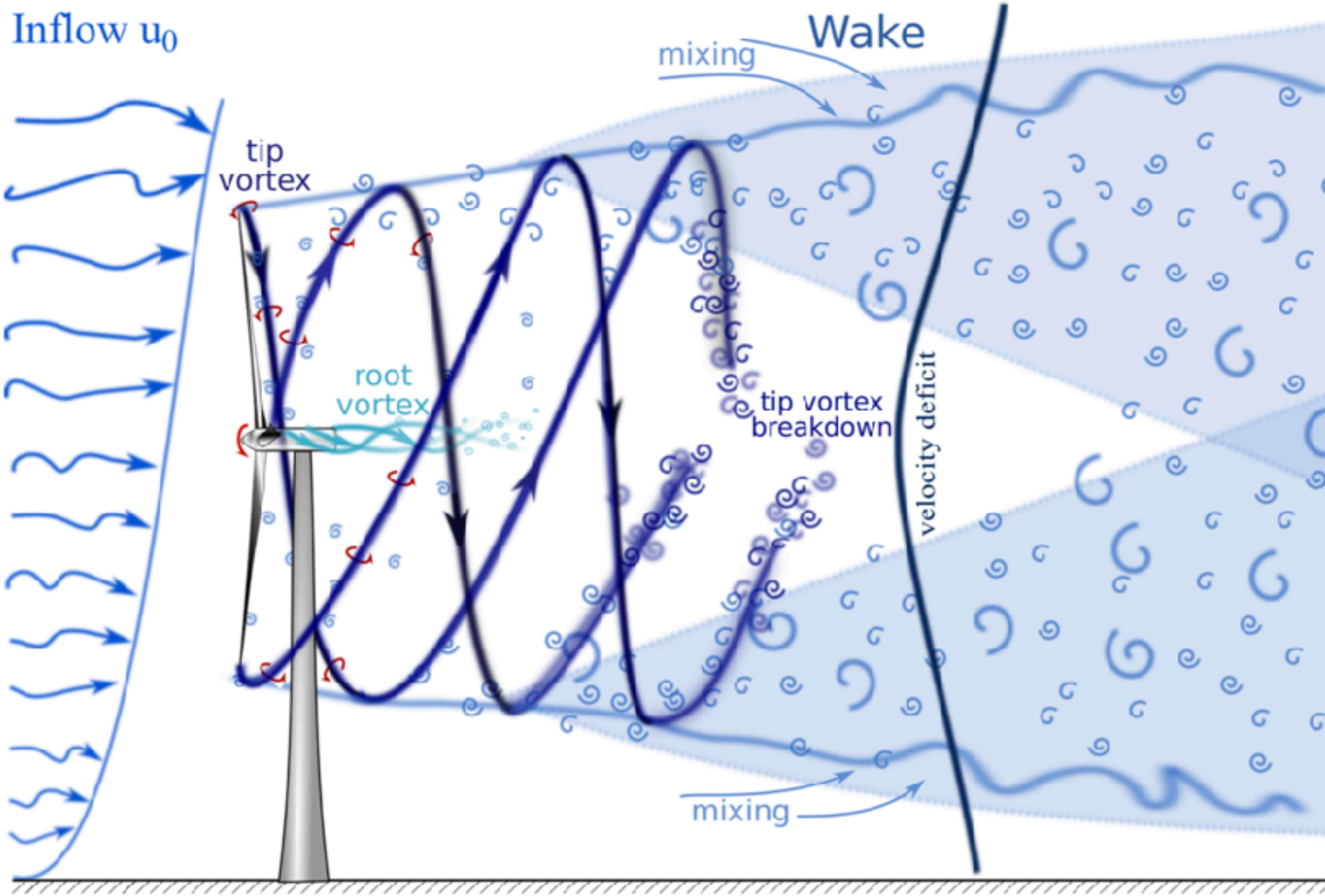
Velocity measurements in plane of rotation



Wind farms and wakes

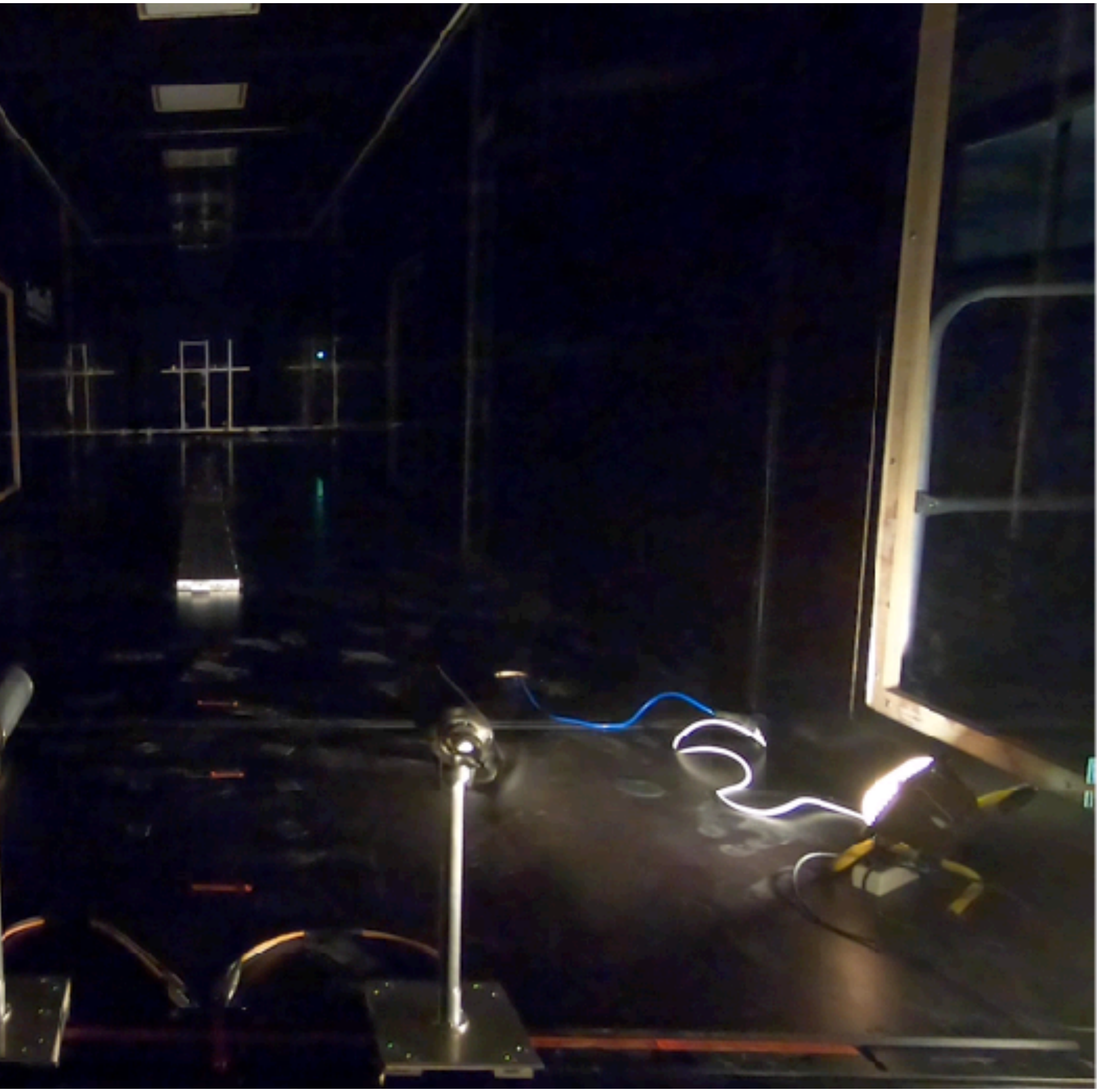
Christian Steines, Vattenfall

MoWiTO 0.6 - wake measurements



Ingrid Neunaber, Dissertation, Oldenburg 2018

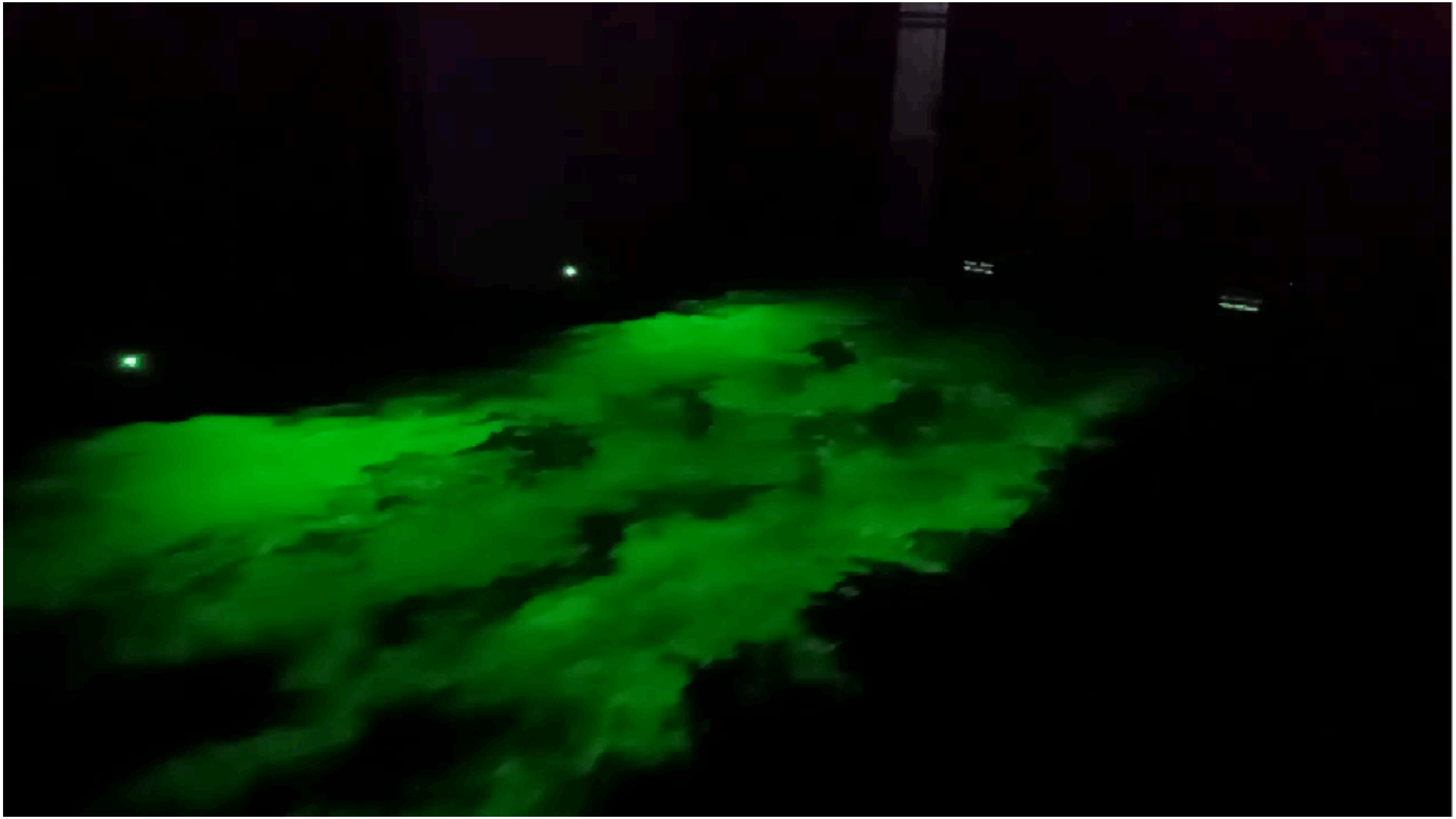
MoWiTO 0.6 - wake visualisation



MoWiTO 0.6 - wake visualisation

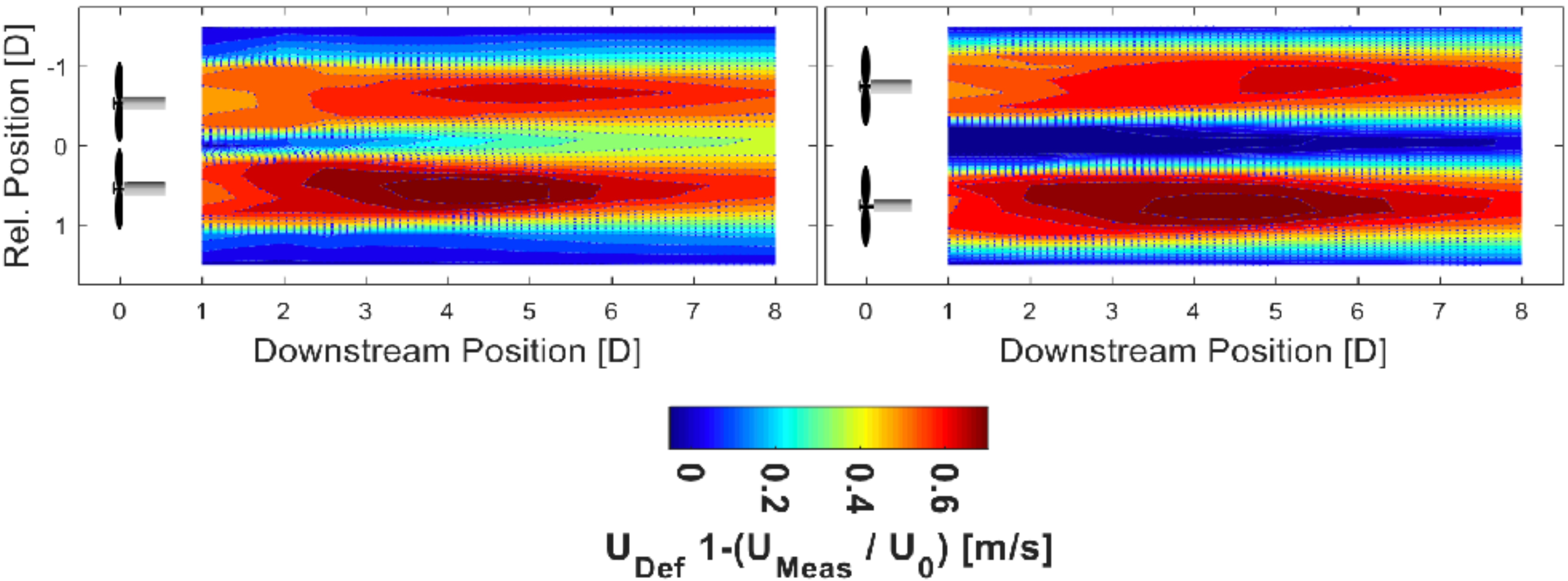
MoWiTO 0.6 - wake measurements

Wake development of two neighbouring turbines



MoWiTO 0.6 - wake measurements

Wake deficit of two neighbouring turbines

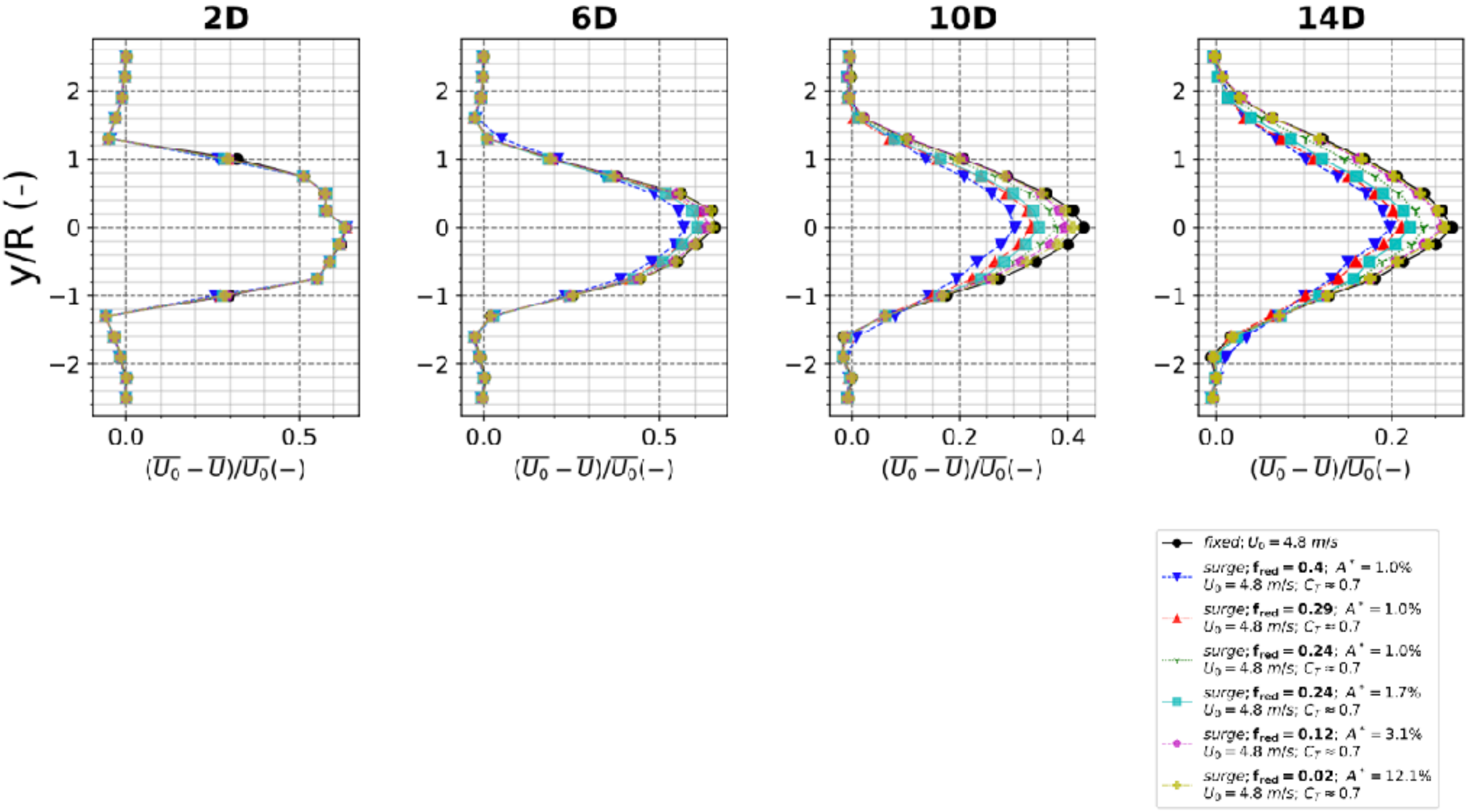


MoWiTO 0.6 - wake measurements

Wake recovery of floating turbines

MoWiTO 0.6 - wake measurements

Wake recovery of floating turbines for surge motion



ForWind Zentrum für Windenergieforschung Bremen Hannover Oldenburg


3m x 3m active grid
1.8m rotor diameter
2D laser doppler anemometer
Thank you for you attention