FLUCTUATIONS FROM PHOTOVOLTAIC AND WIND POWER SYSTEMS

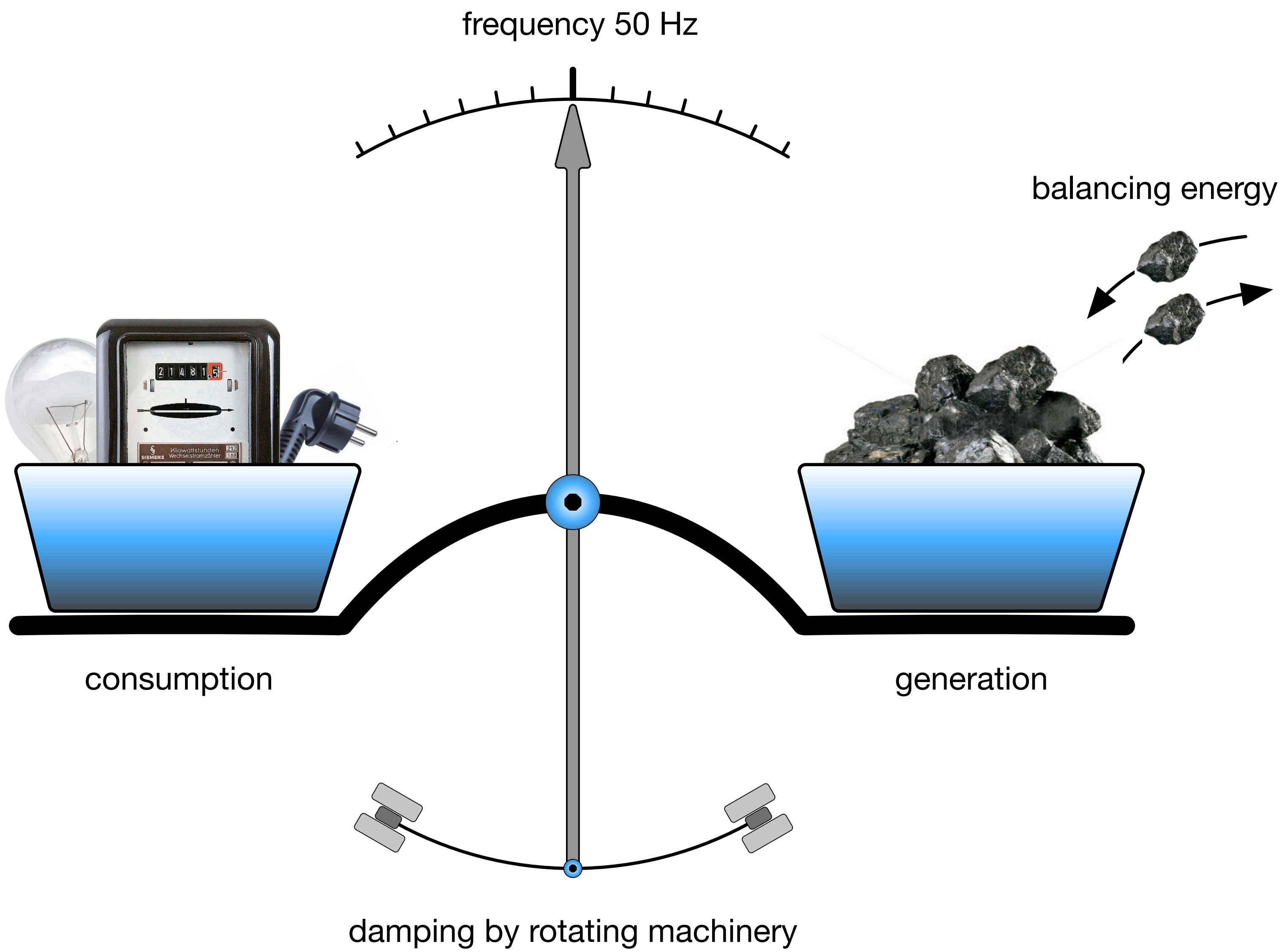
DETLEV HEINEMANN*, GERALD LOHMANN*
MOHAMMED REZA RAHIMI TABAR**, MEHRNAZ ANVARI**

Carl von Ossietzky Universität Oldenburg, Institut für Physik, ForWind
* AG Energiemeteorologie
** AG Turbulenz, Windenergie & Stochastik

OUTLINE

- Fluctuations in (future) power systems
- Characteristics of fluctuations in wind & solar power:
  - Increment statistics,
  - Higher moments,
  - Power spectra,
  - …
- Conclusion and Outlook

POWER SYSTEM OPERATION
CONTROL OF FREQUENCY, VOLTAGE & CURRENT



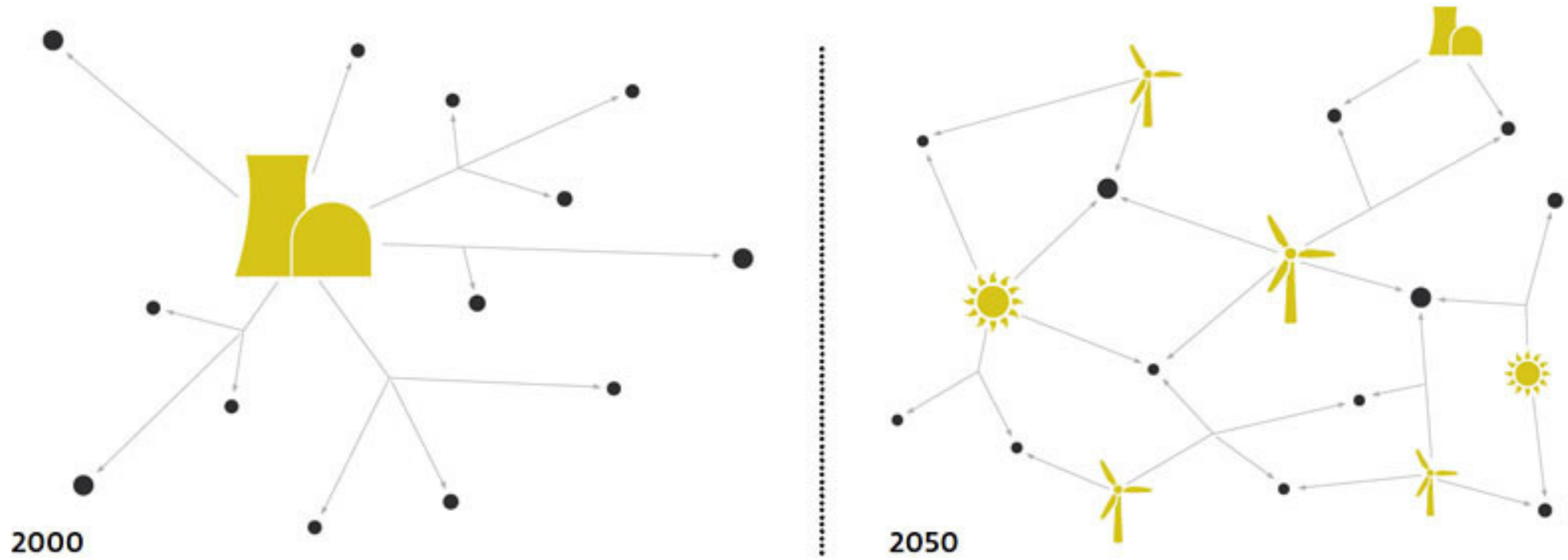
Grid operators have

- to ensure balance between generation and consumption and
- to keep U/I-limits

at any given time

ENERGY TRANSITION

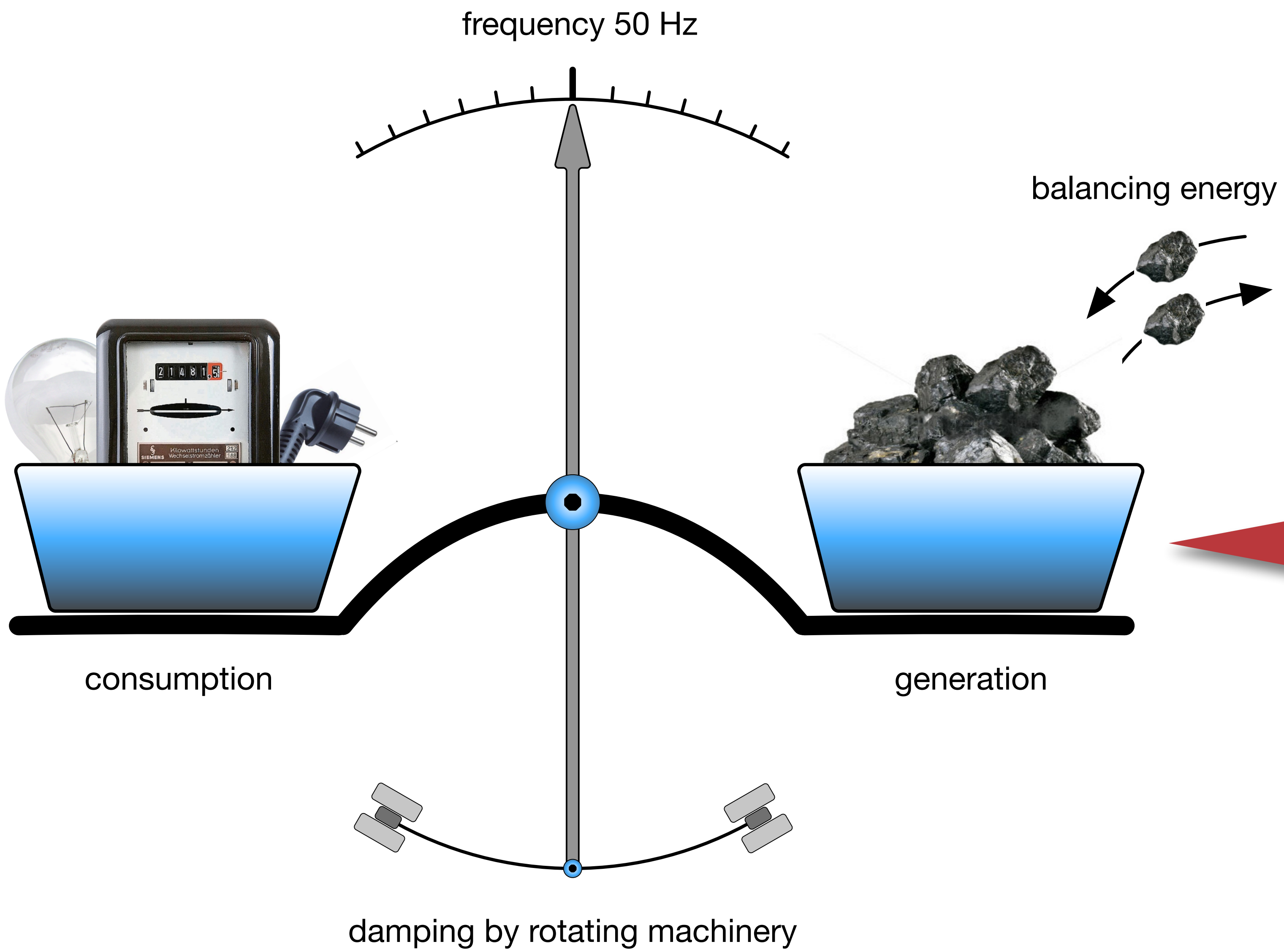
- Ongoing energy transition from non-renewable to renewable energies in Germany (and elsewhere)
- Shift of power production from mostly centralized to decentralized generation
- Change from demand-driven to supply-oriented energy system



Source: Max Planck Institute for Dynamics and Self-Organisation

POWER SYSTEM OPERATION

CONTROL OF FREQUENCY, VOLTAGE & CURRENT



secured availability of conventional fuels

vs.

mostly non-deterministic availability of fluctuating renewable sources (i.e., wind & solar)

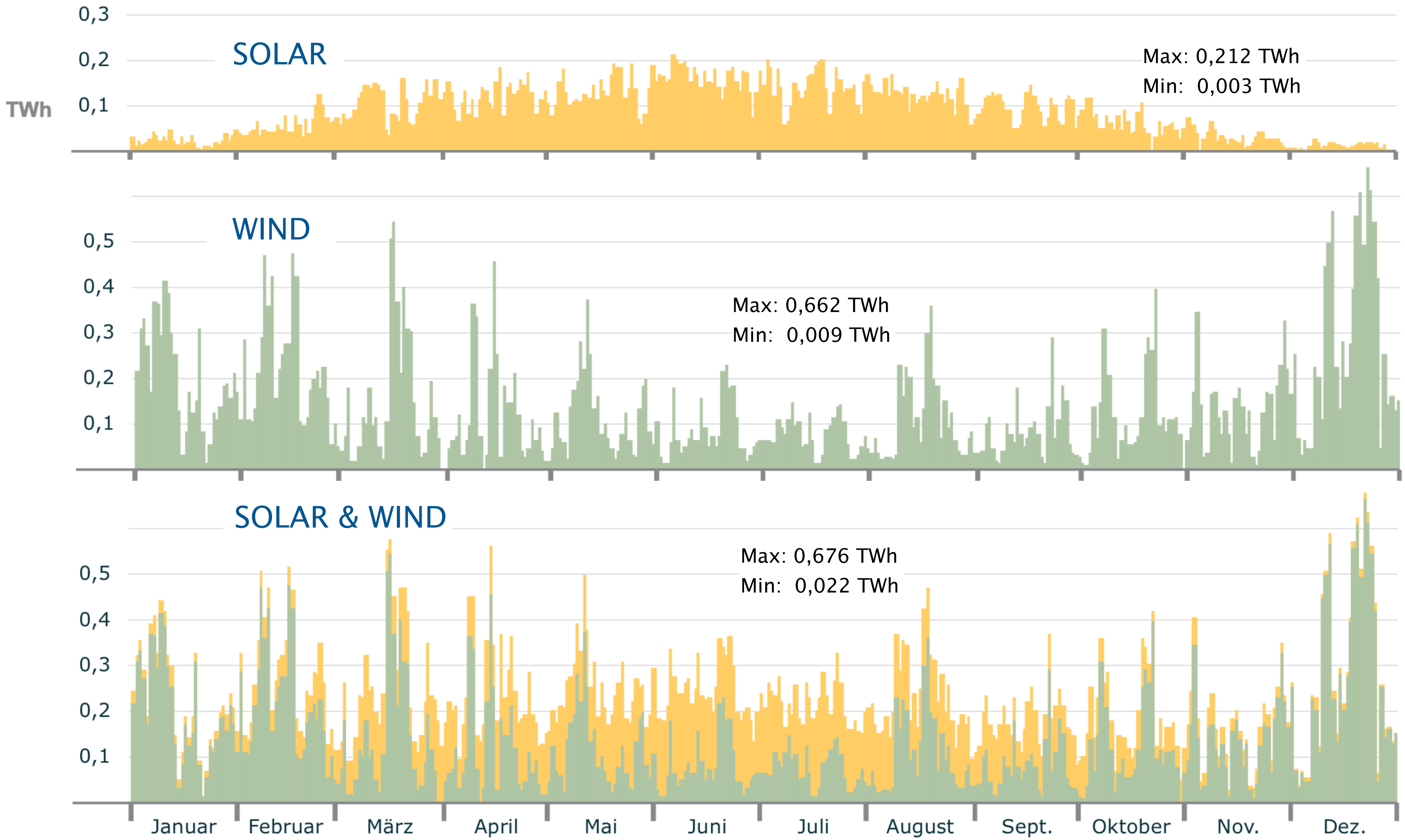
WEATHER DEPENDENCY

- Challenging integration of distributed generation
  especially due to non-controllable fluctuations (wind & PV)
- High importance of „commodity“ Information
  especially with meteorological content...

! An important – and new – constraint for future energy supply systems is its temporal and spatial varying production rate.

→ **Energy Meteorology**

GERMAN POWER SECTOR TODAY
DAILY PRODUCTION, SOLAR & WIND, 2014

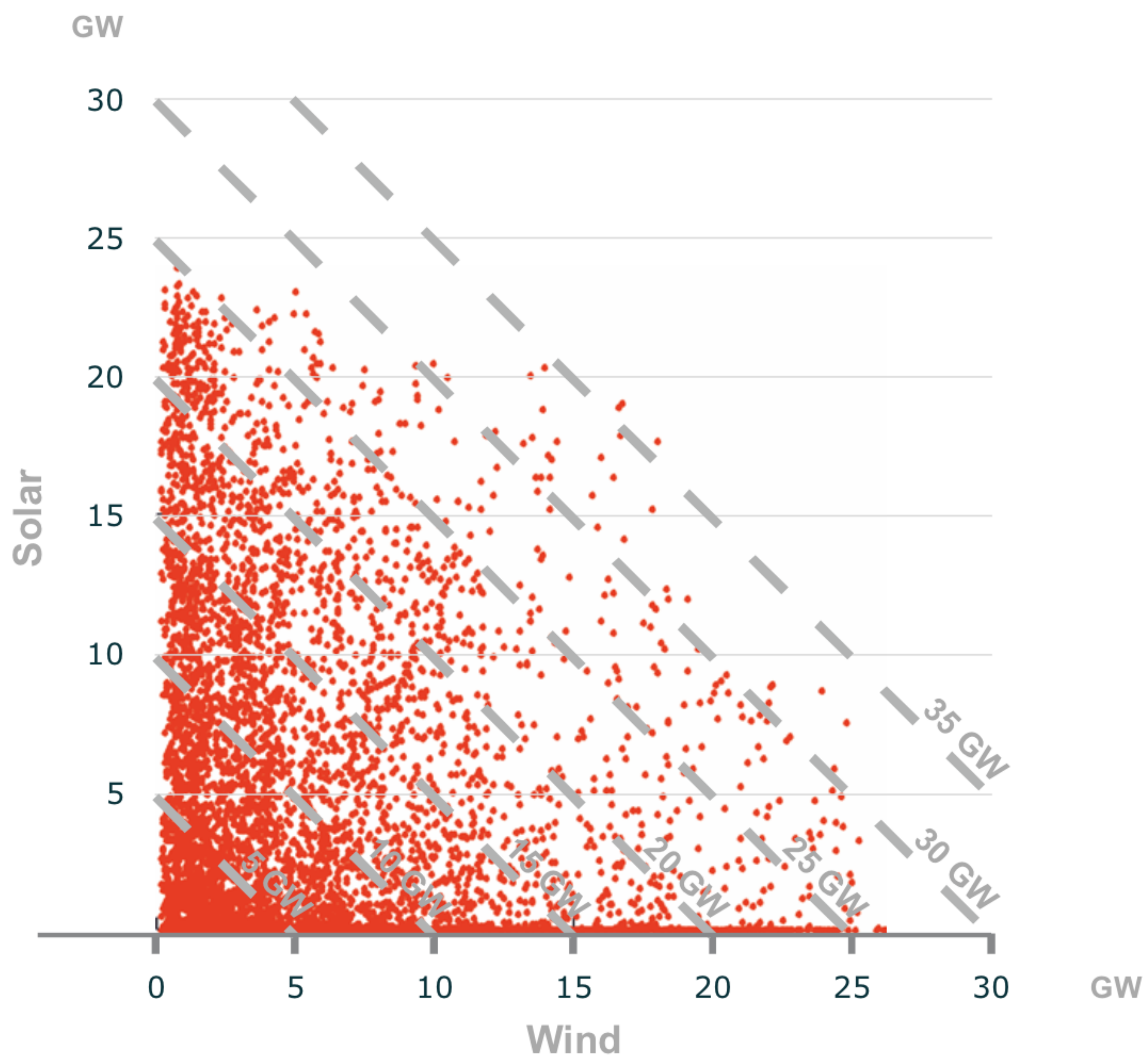


Sources: B. Burger, Fraunhofer ISE, Leipziger Strombörse EEX

GERMAN POWER SECTOR TODAY

POWER* – SOLAR vs. WIND, 2014

* 15-min averages



Simultaneous power production from solar and wind

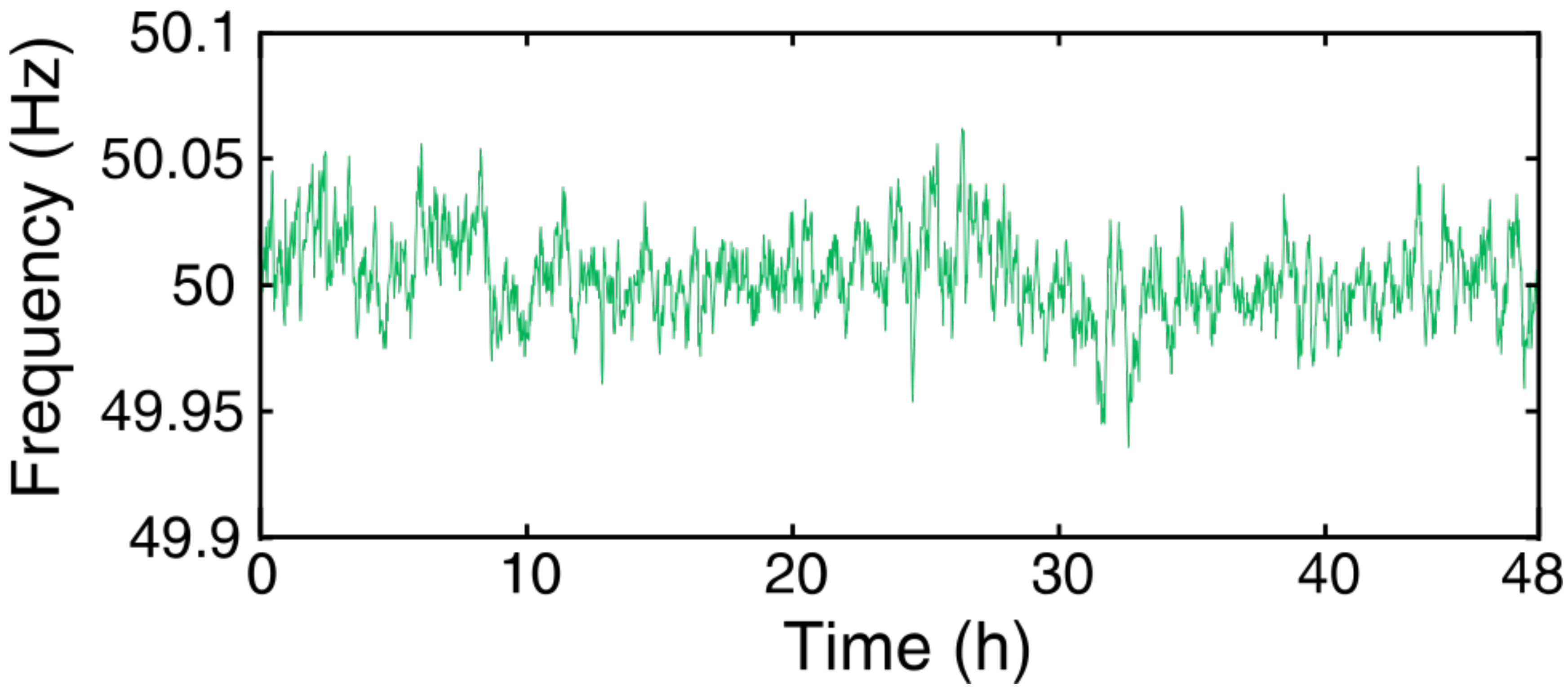
- Combined power production from solar and wind is approx. 38 GW max. (2014)
- Sum of solar and wind power generation is always smaller than installed single capacities
- Partial complementarity of wind and solar

Sources: B. Burger, Fraunhofer ISE, Leipziger Strombörse EEX

PROBLEMATIC FLUCTUATIONS

Fluctuations cause problems by …

- Endangering the guaranteed meeting of power demand
- Affecting power quality (voltage and frequency stability)
- Affecting the necessary dimensioning of distribution grids



Source: Wikimedia commons user 'Wdwd' (data for Central Europe)

FLUCTUATIONS IN POWER GRIDS

Aim:
Reliable grid* operation with high shares of renewables

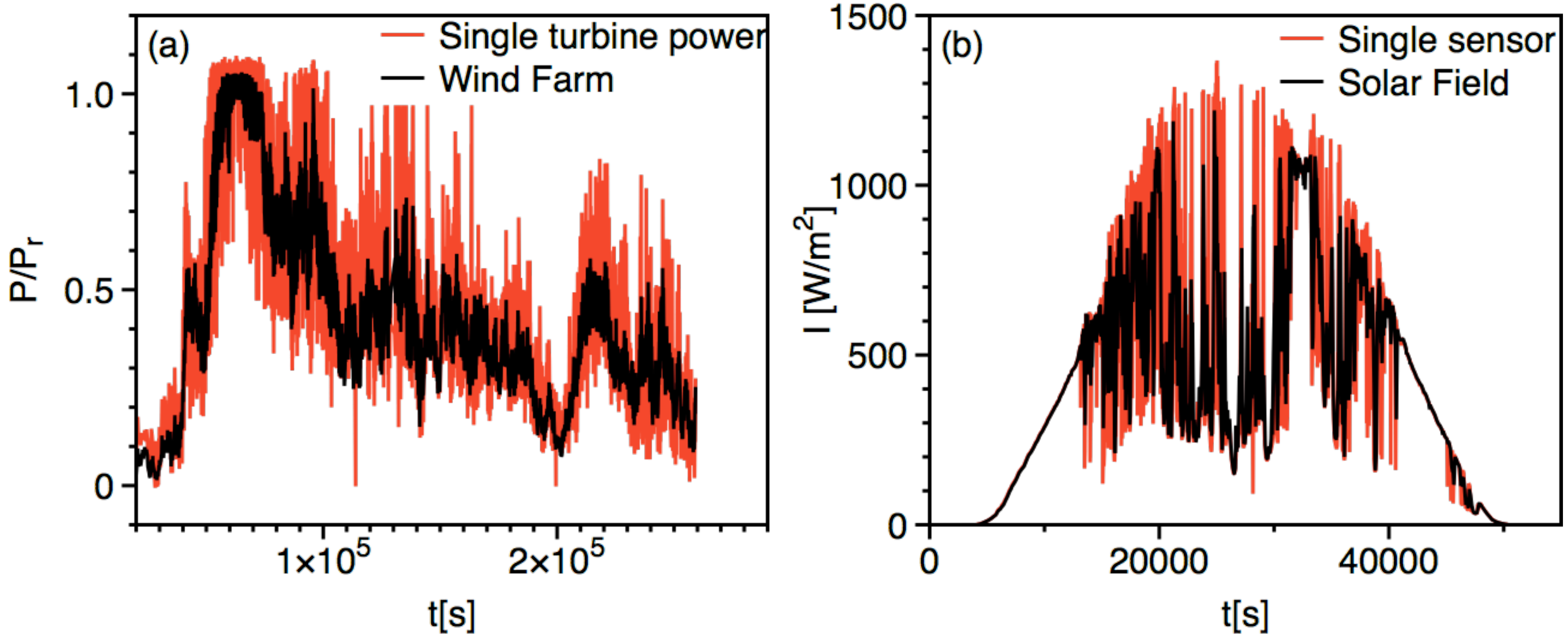
- Quality of their respective control strategies and products are strongly influenced by ‘flickering‘ in power input
- Generally, conditions of low flickering probabilities will allow more flexible network designs
- Conditions of high flickering call for larger aggregations of networks to balance the expected fluctuations

➡ **Classification of wind and solar power resources in terms of their stochastic properties**

* especially: distribution grid, incl. micro grids, virtual power plants

TYPICAL FLUCTUATIONS IN WIND & PV

- Variations on all time scales, from seconds to days
- Despite a smoothing effect, fluctuations in wind and solar power remain, even for spatial aggregations



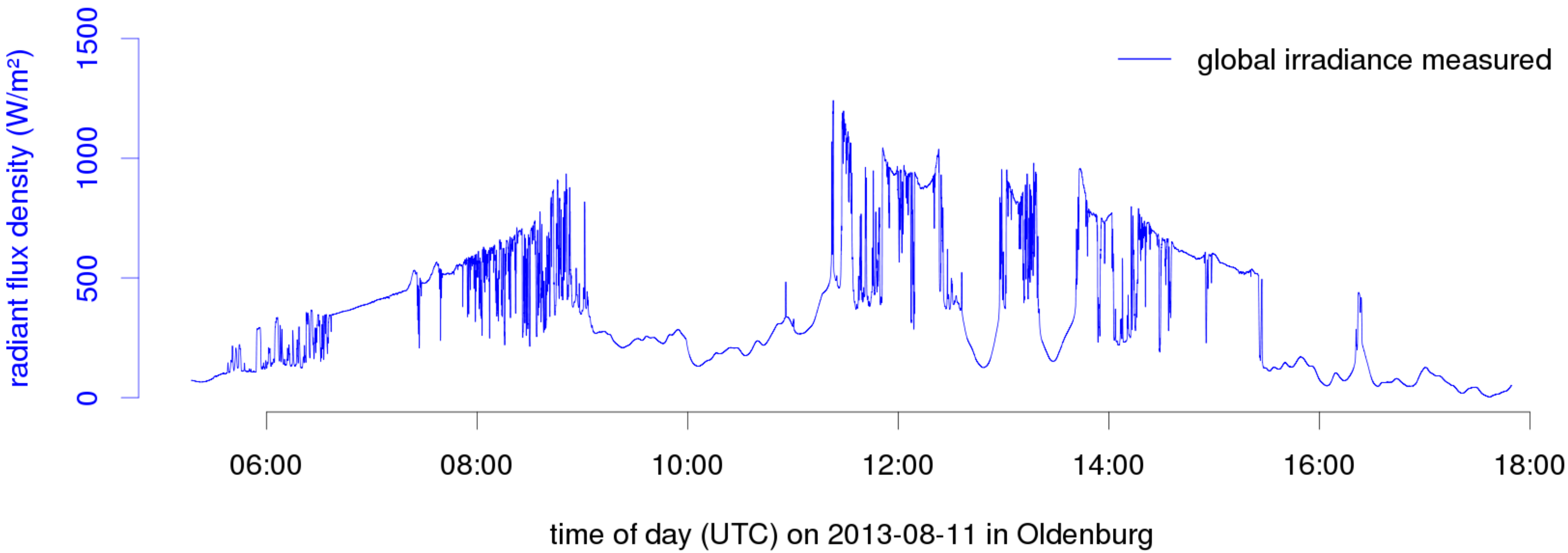
ORIGINS OF SMALL-SCALE FLUCTUATIONS

- Wind: Atmospheric turbulence
  - depending on large scale advection, local thermodynamics, surface characteristics
- Solar: Cloud dynamics and size distribution
  - rapid succession of sunlight exposure and cloud shadows

Source: Kris Arnold via Flickr
(http://flickr.com/people/wka/

PV: GLOBAL HORIZONTAL IRRADIANCE

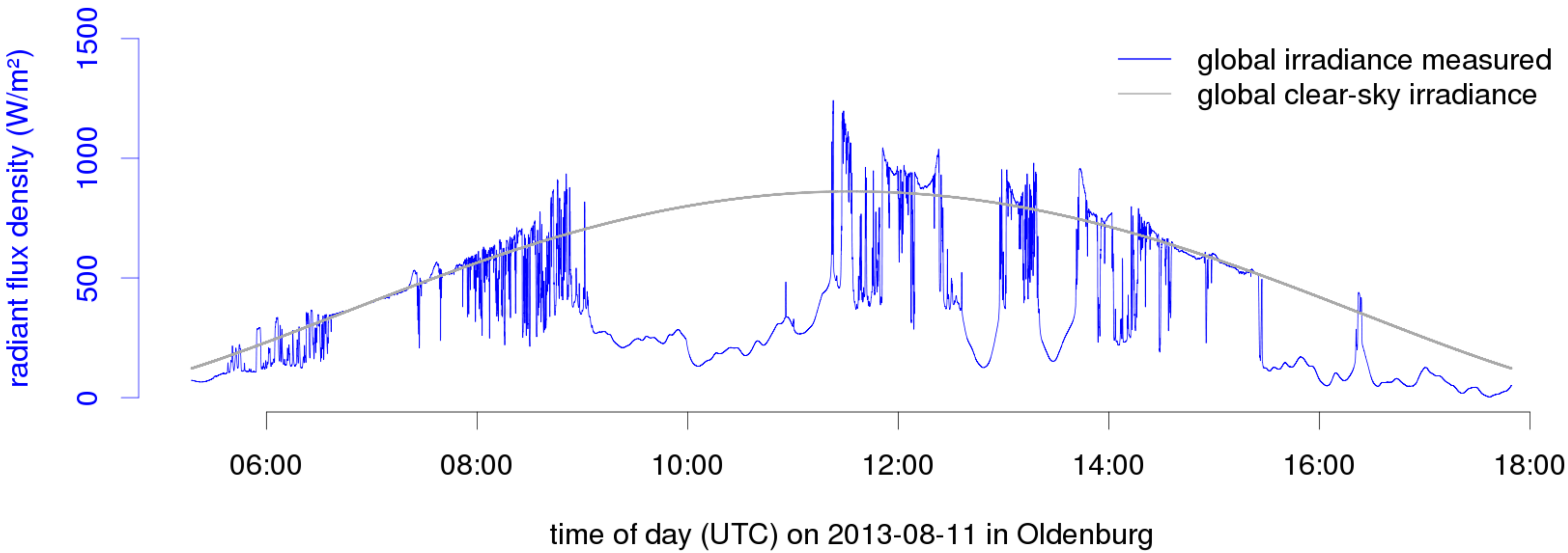
Deterministic diurnal and seasonal variations need to be considered



PV: GLOBAL HORIZONTAL IRRADIANCE

Detrending by normalization with clear-sky* irradiance

* irradiance under cloud-free conditions with fixed water vapor & aerosol content, i.e. deterministic

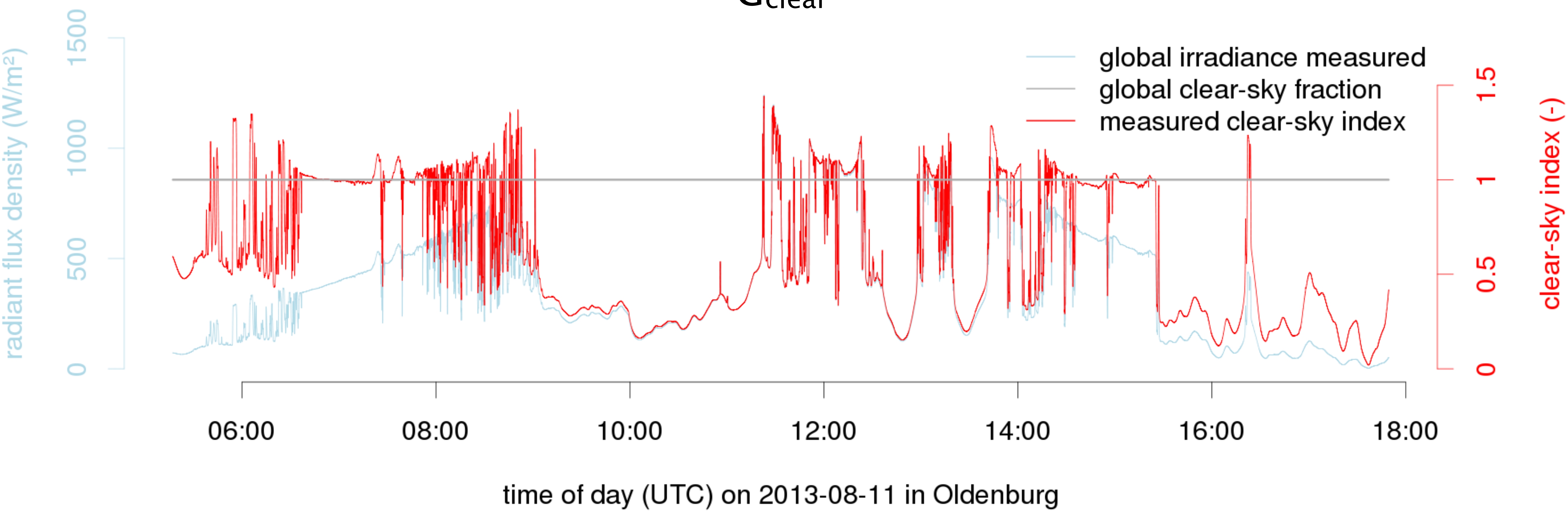


PV: CLEAR-SKY INDEX

Normalized clear-sky index k* as a measure of atmospheric influence independent on solar geometry:

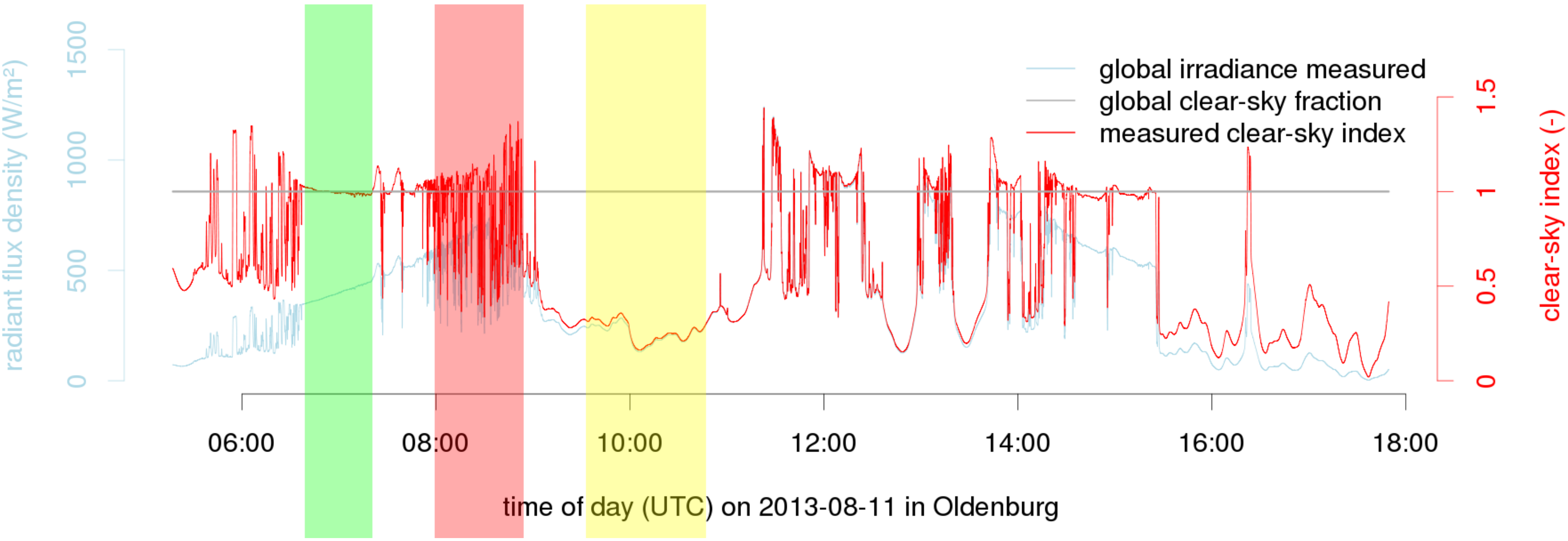
ratio of measured irradiance G and modelled clear-sky irradiance G_{clear}:

$$k^* = \frac{G}{G_{clear}}$$



PV: TYPICAL SKY TYPES

Clear sky: k* ≈ 1 (low variability)
Overcast: k* << 1 (low variability)
Broken clouds: high variability in k*

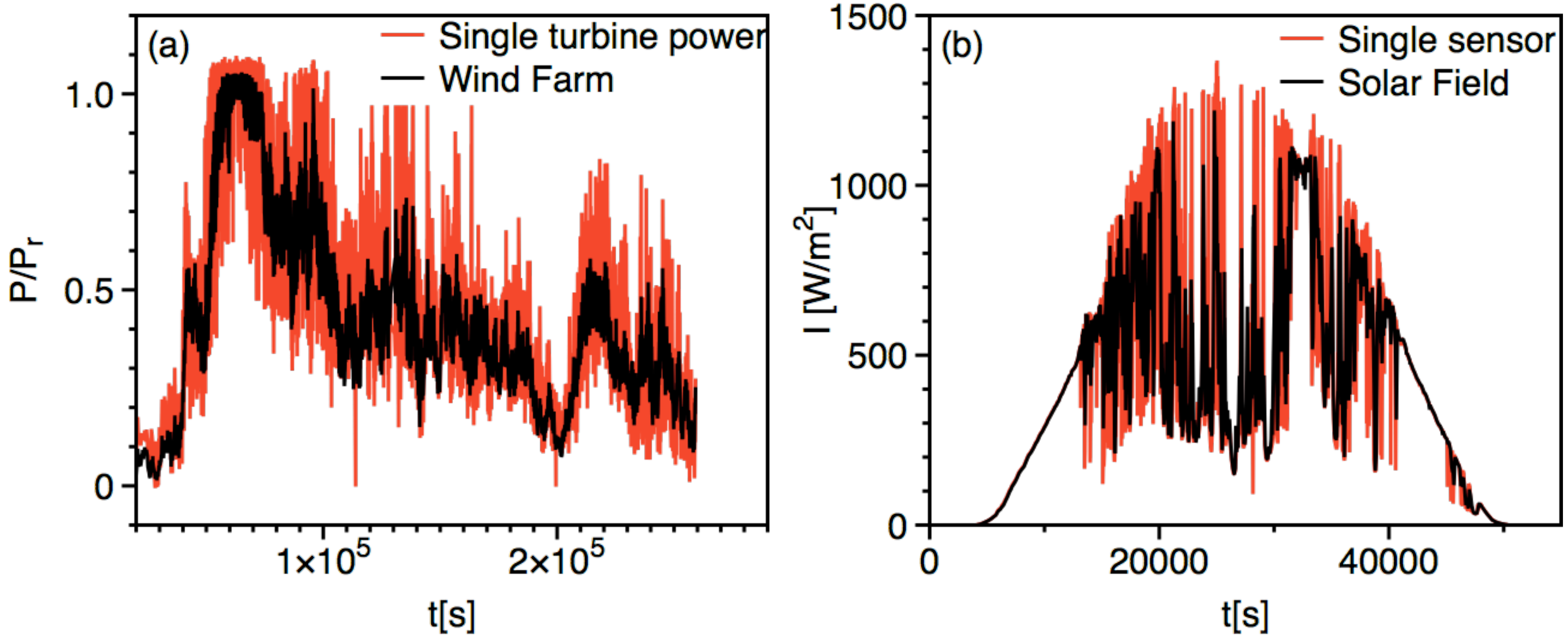


STUDYING THE FOLLOWING ASPECTS…

- Understand the nature of such fluctuations in order to successfully manage decentralized power production
- Investigate the non-Gaussian characteristics of solar and wind power time series
- Study the occurrence and risk of flickering events with respect to different wind speeds and solar elevation angles for single point measurements and spatially averaged data

DATA USED IN SUBSEQUENT EXAMPLES:

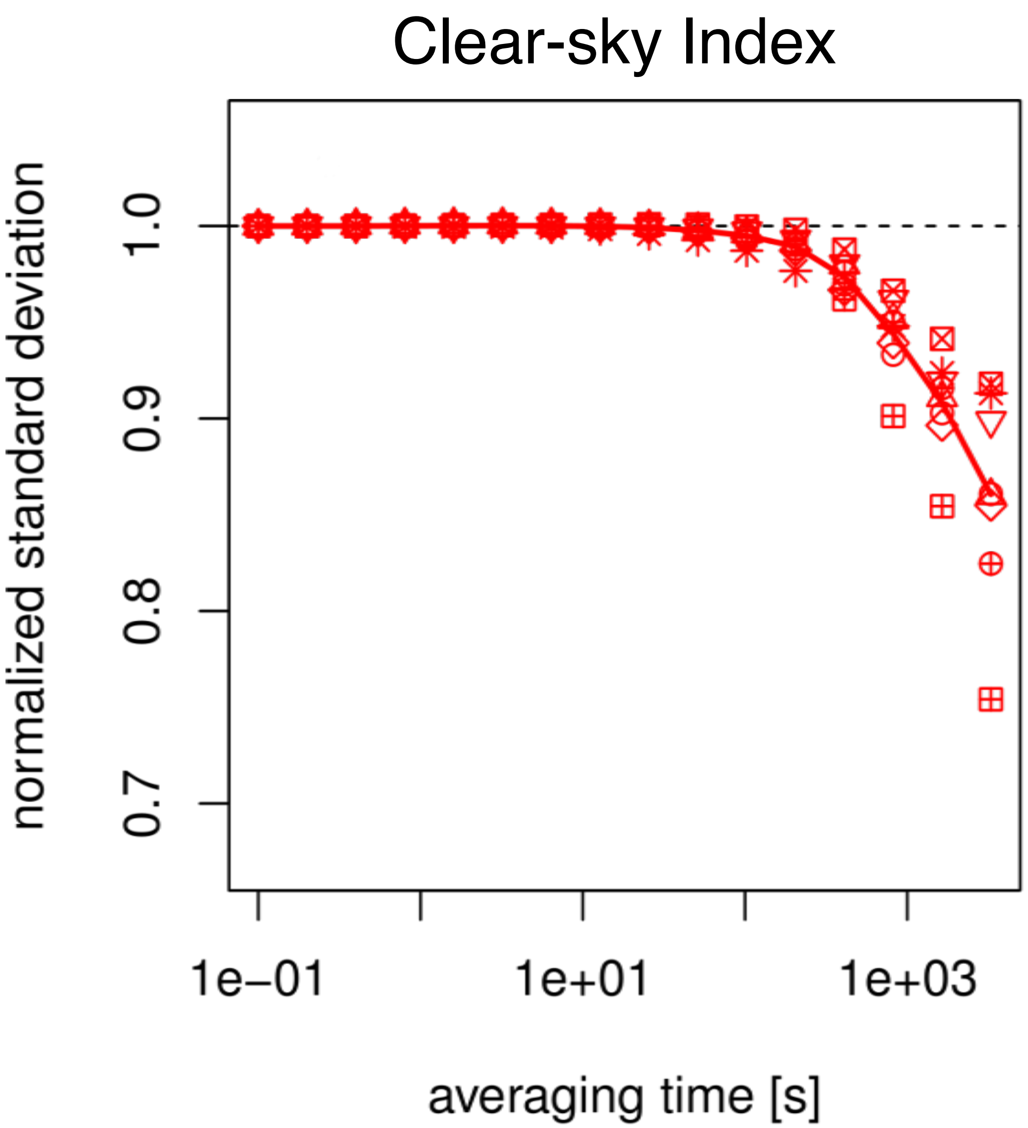
- Normalized power from 12 German wind turbines
  - area covered: approx. 4 x 4 km^2, 1 Hz
- Global irradiance from 17 sensors in Hawaii
  - area covered: approx. 1 x 1 km^2, 1 Hz

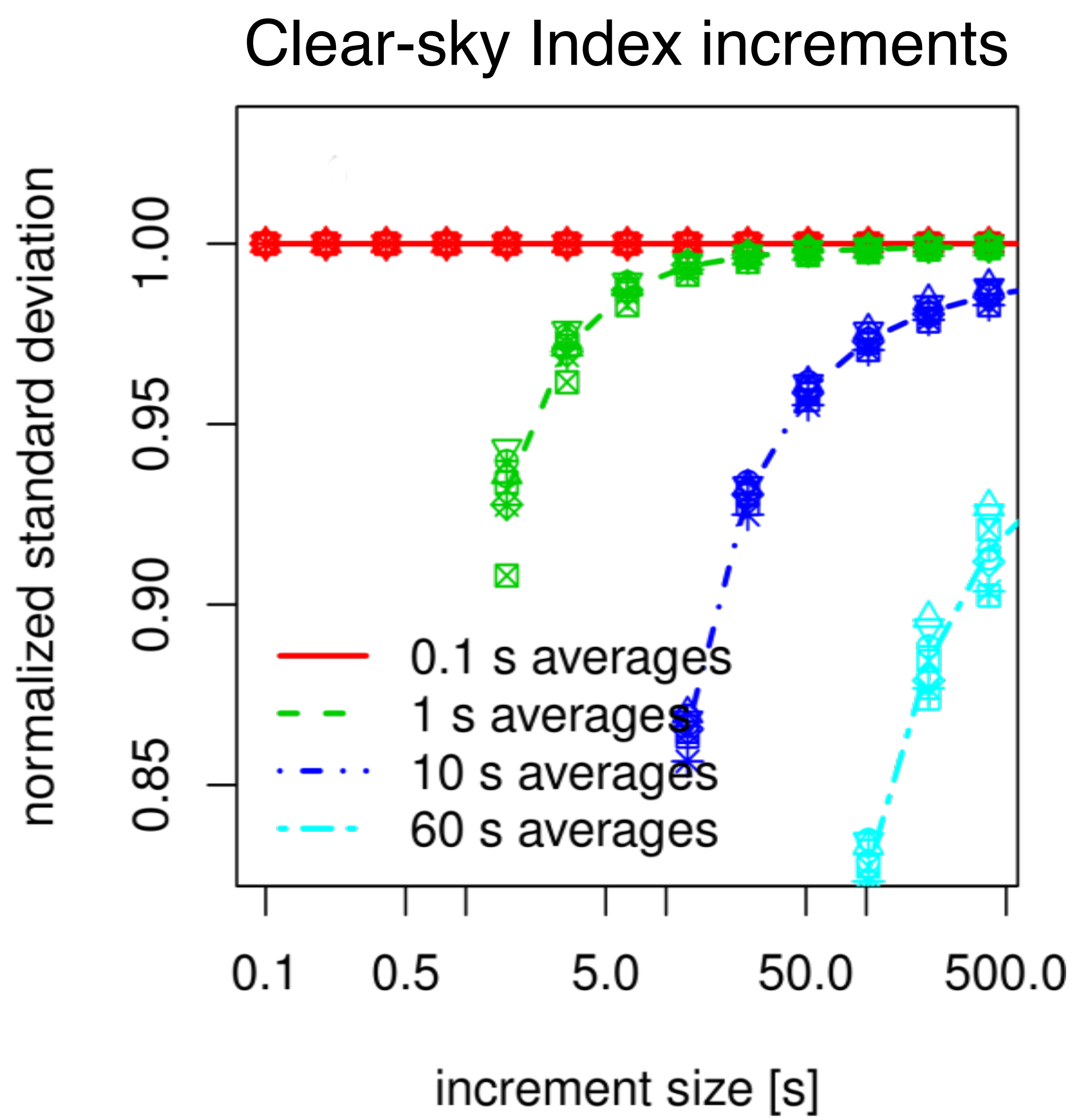


PV: TEMPORAL RESOLUTION OF MEASUREMENTS

For detailed resource analysis, ~ 1 min averages are ok

For analysis of local fluctuations, at least 1 Hz is needed (otherwise a loss of information occurs)





ANALYZING SHORT-TERM INTERMITTENCY

Increment analysis

- Contour plots
  - values X(t) as a function of preceding values X(t−τ) with time increment τ
  - high short-term correlation between subsequent states --> more diagonal configuration

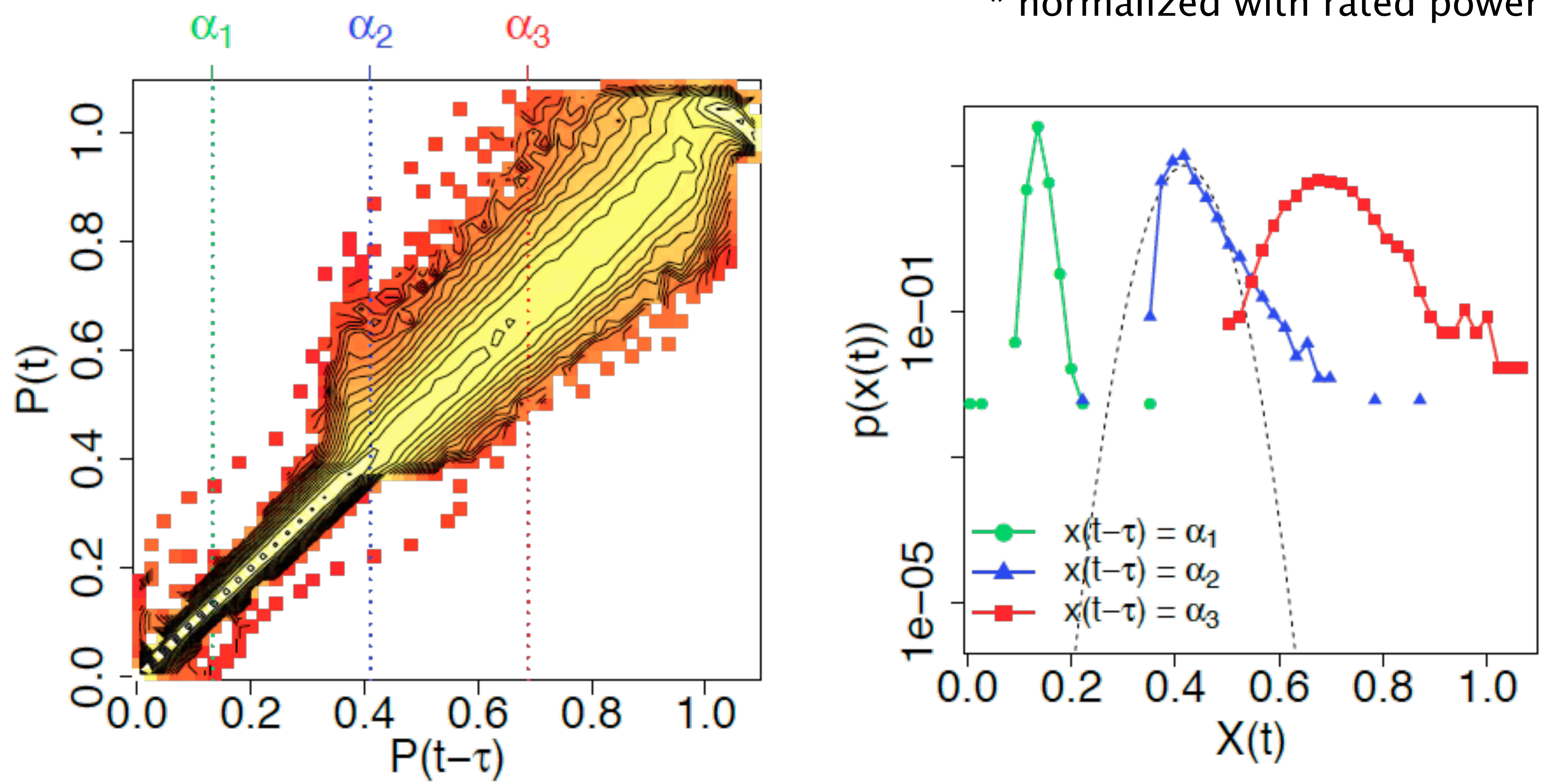
- Conditional probability density functions (cpdf)
  - of certain levels in the contour plots
  - visualizing the probabilities of values X(t) based on their preceding values X(t−τ)

SHORT-TERM INTERMITTENCY

WIND, 5 SEC INCREMENTS

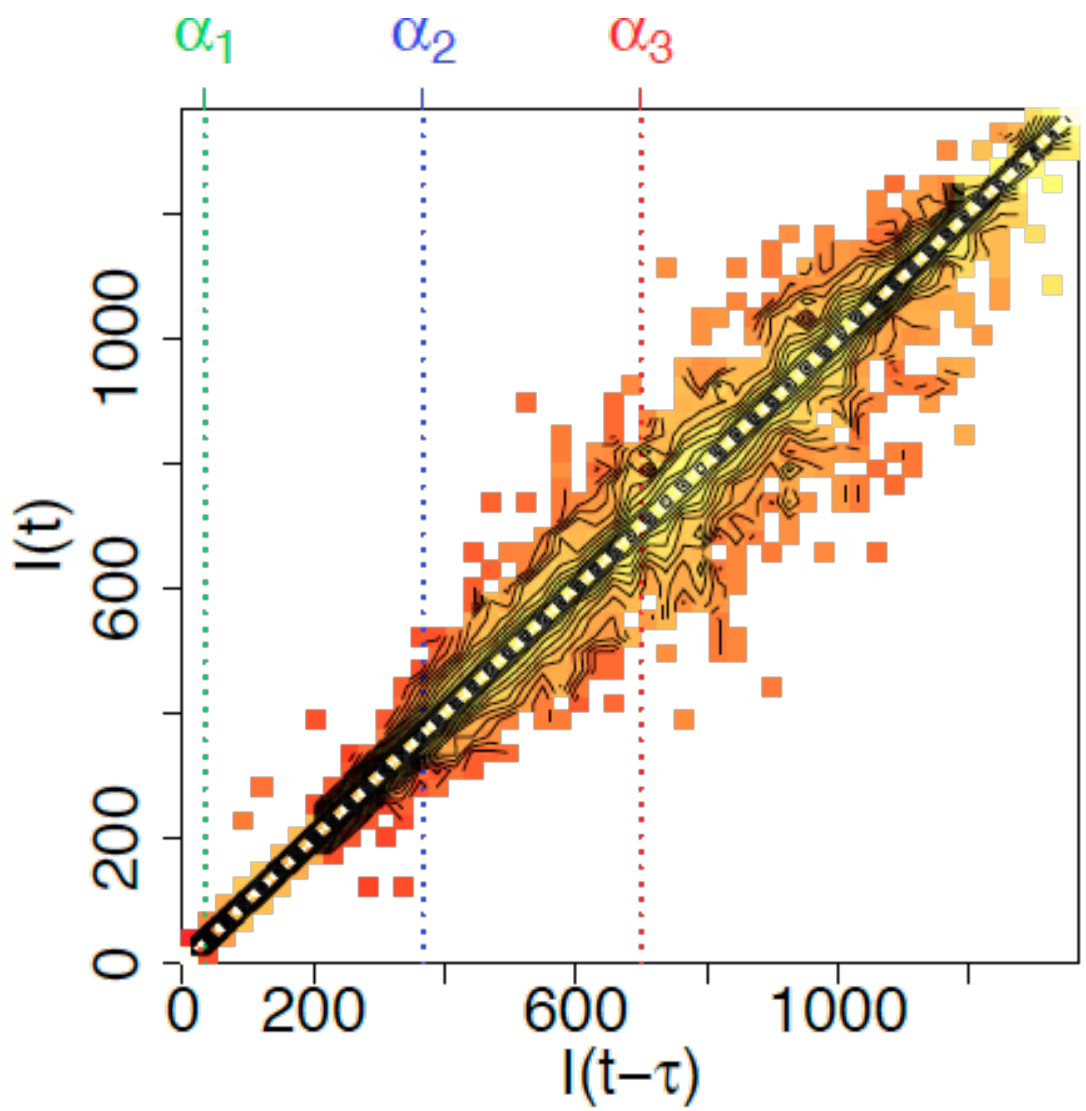
Contour plot and conditional pdfs for three different power* levels

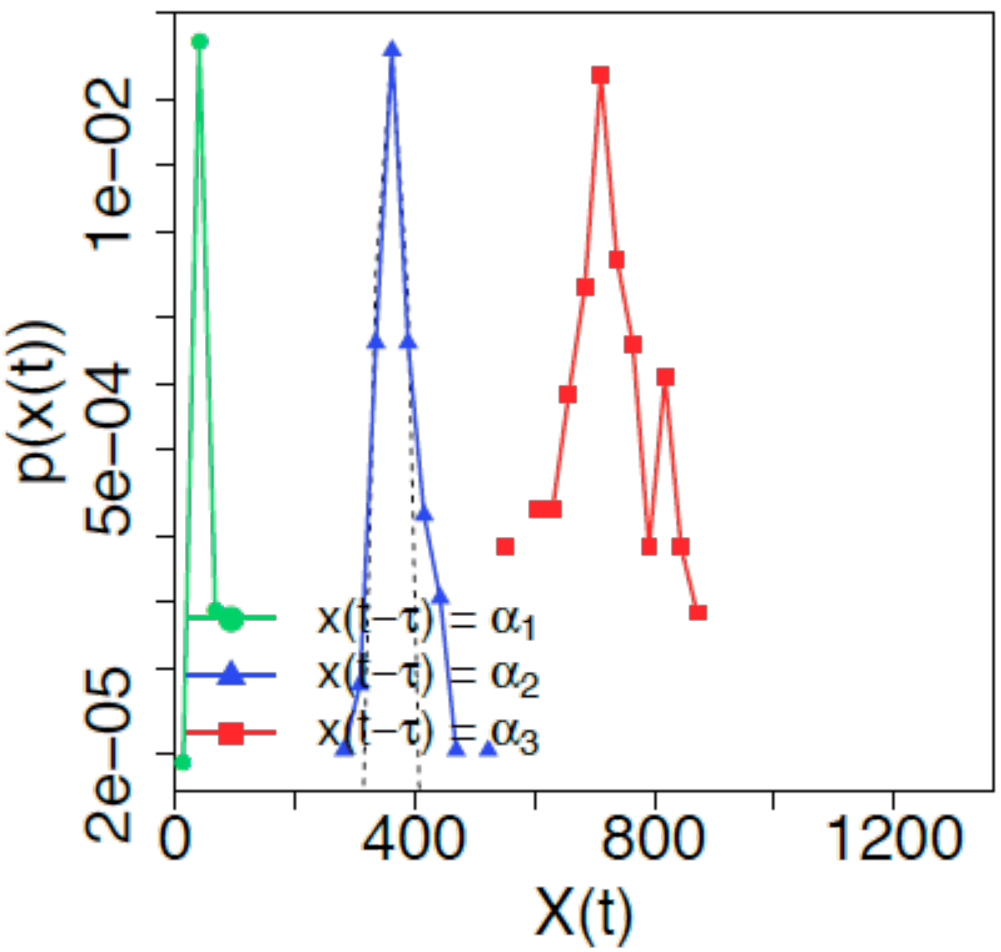
* normalized with rated power



SHORT-TERM INTERMITTENCY
SOLAR, 1 SEC INCREMENTS

Contour plot and conditional pdfs for three different irradiance levels



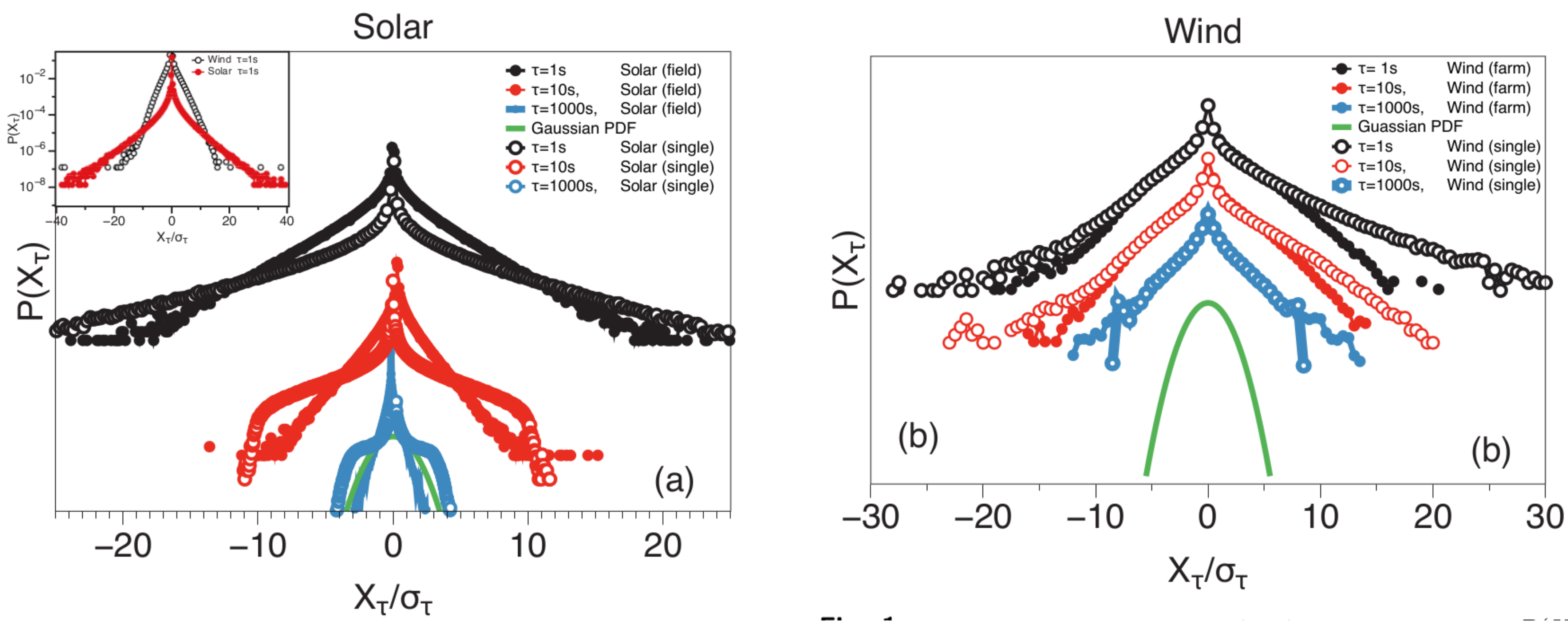


WIND/SOLAR COMPARISON

- **Wind**
  - strong correlation for $P(t) < 0.4$
  - weaker correlation for $P(t) > 0.4$
  - positive skewness: fast increase more likely than decrease
  - tails in cpdfs: large magnitude fluctuations → flickering

- **Solar**
  - strong correlation for $I(t) < 200\ Wm^{-2}$ and $I(t) > 1200\ Wm^{-2}$
  - weaker correlation for $200\ Wm^{-2} < I(t) < 1200\ Wm^{-2}$
  - positive skewness less pronounced than for wind power
  - tails less obvious (different τ!), but strongly non-Gaussian

INCREMENT STATISTICS
PROBABILITY DISTRIBUTION FUNCTIONS (PDF)

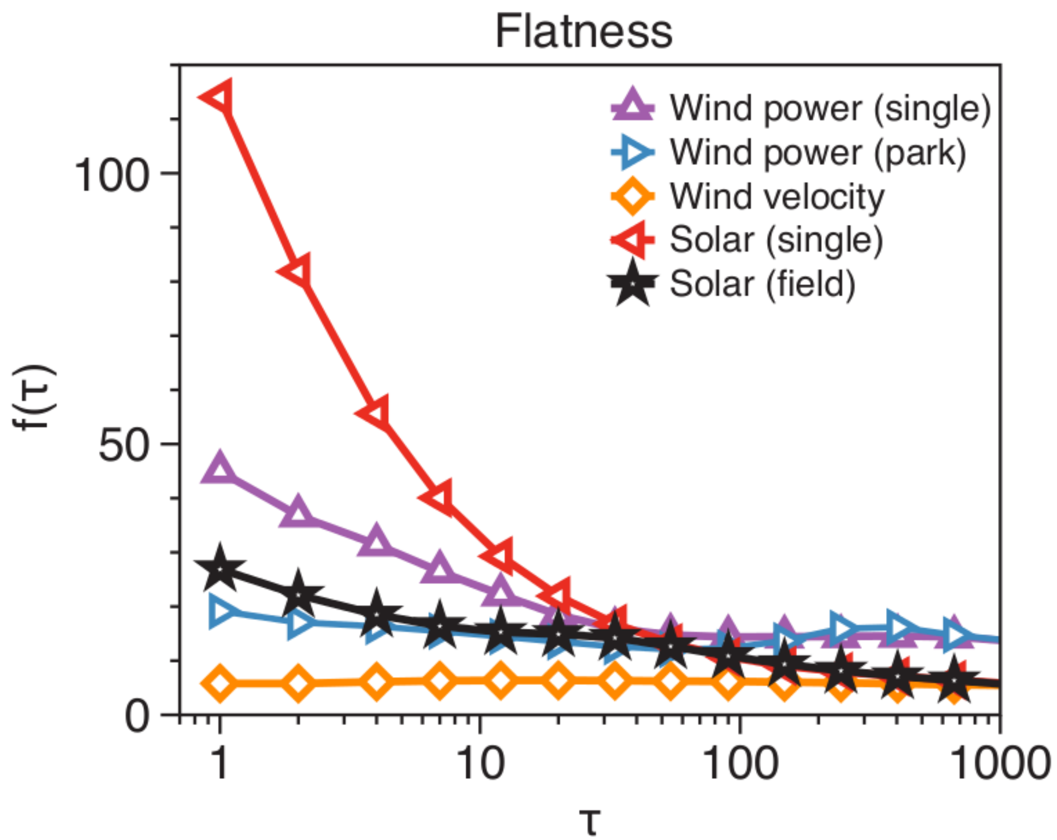


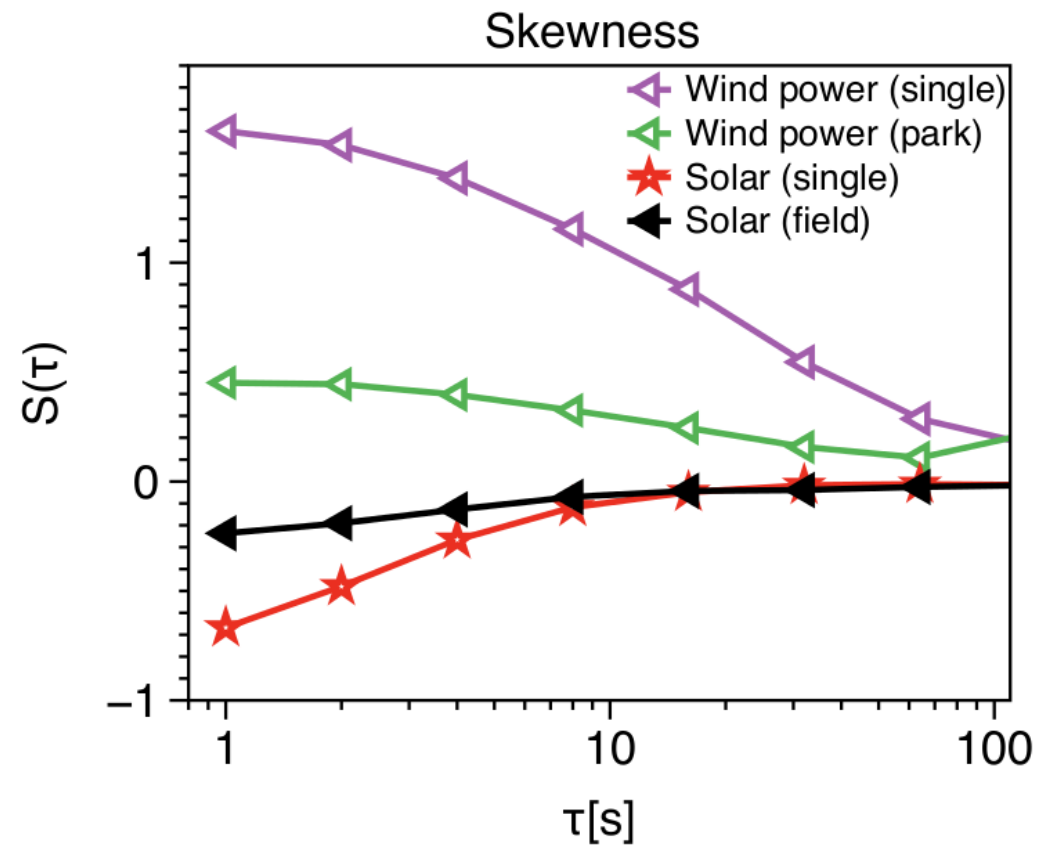
On local scale: strongly non-Gaussian increment statistics

(pdfs are vertically shifted)

CARL VON OSSIETZKY universität OLDENBURG

SHAPE OF INCREMENT PDFS





f=3 —> Gaussian distribution

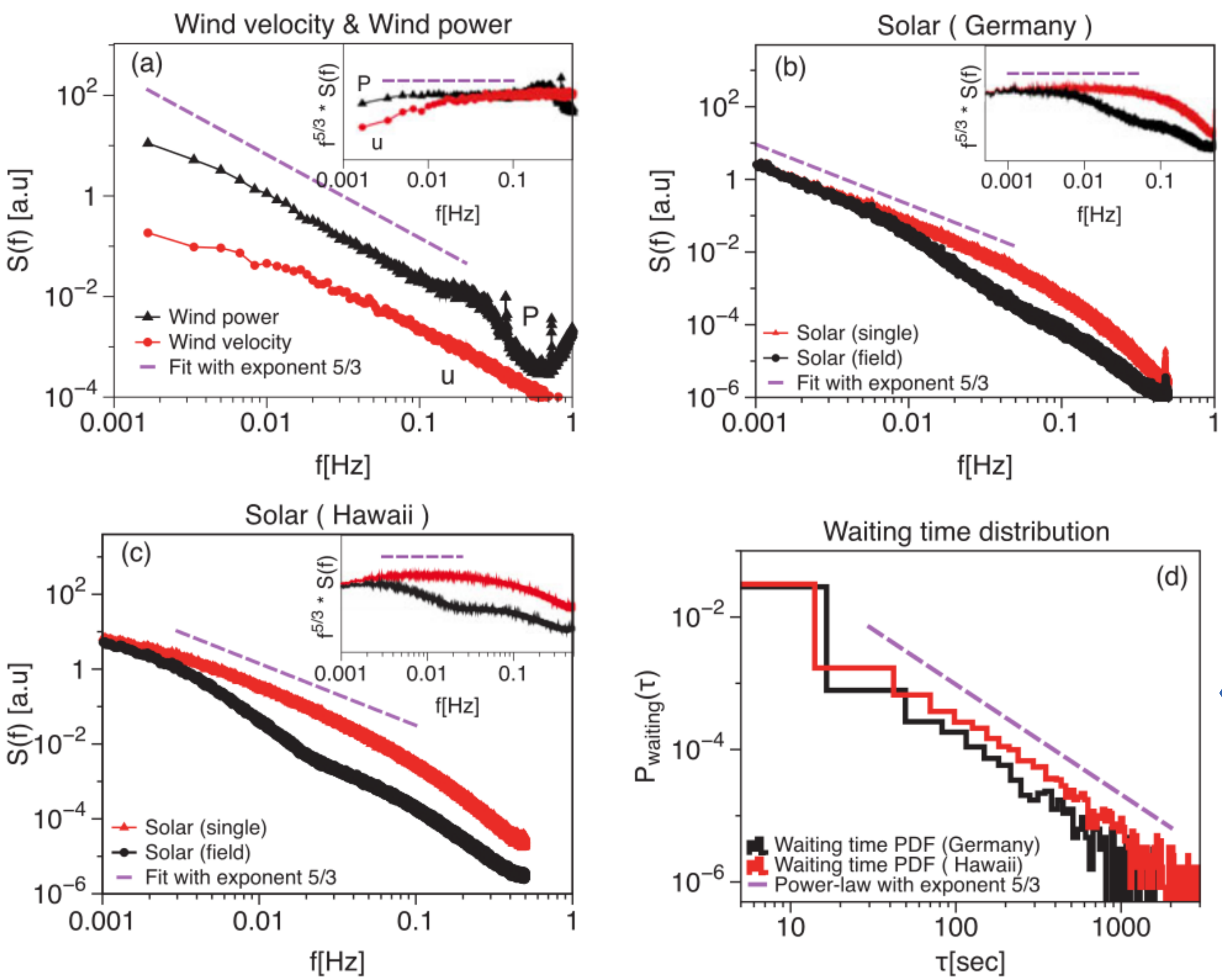
S=0 —> symmetric distribution

Large flatness:
more intermittent

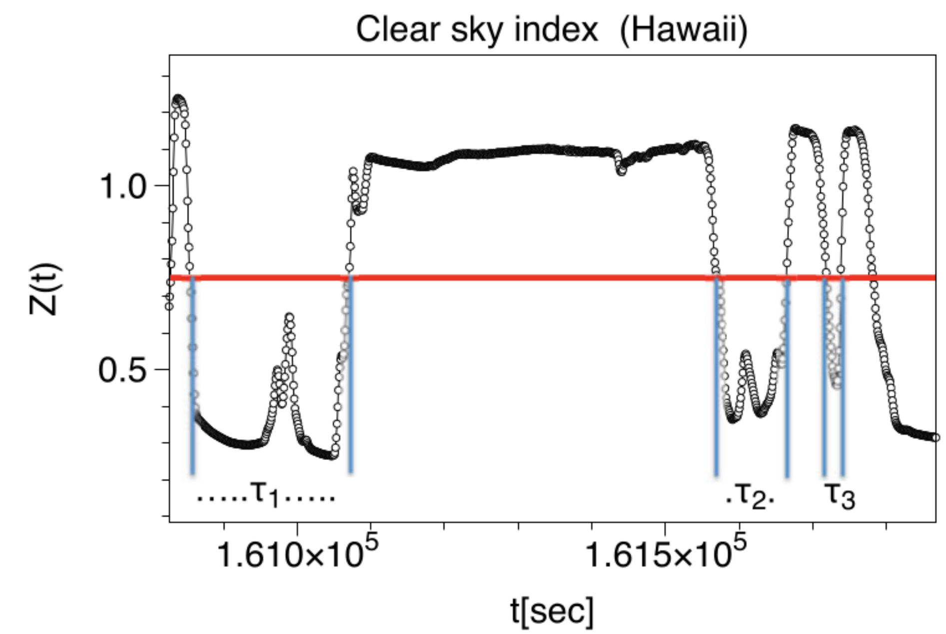
note: $f_{windpower} > f_{windspeed}$

Large skewness:
large difference between up- and down-fluctuations

WIND & SOLAR: POWER SPECTRUM ANALYSIS



On local scale: turbulent-like behavior of renewables



- Dashed line: Kolmogorov exponent 5/3
- Inserts: compensated energy spectra f5/3S(f) vs. f

Stochastic dynamics of clear-sky index: Waiting times for the cloudy-sky state

CONCLUSION

- High variability in local wind and solar power
  - weak short-term correlation for most values
  - non-Gaussian, fat-tailed cpdfs with positive skewness
- Risk of flickering increases with available energy
  - spatial smoothing reduces conditioned variability for wind
  - less pronounced smoothing effect for solar irradiance
- To improve comparisons of the fluctuation characteristics, measurements from the same location are needed

OUTLOOK

- Develop methods to suppress flickering events based on power electronics and control strategies
- Account for PV characteristics that affect flickering in system power output rather than solar irradiance
- Study impact of flickering on the operation of distribution grids, micro grids and virtual power plants
  - Low flickering probabilities allow flexible network designs
  - Conditions of high flickering call for larger aggregations of networks to balance the expected fluctuations