First Insights into Wind Farm Data Analysis

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Group Seminar
AG Guhr

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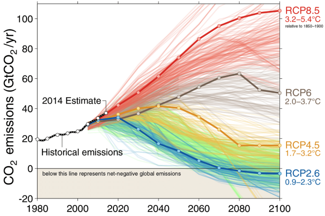
Motivation

Why should one be interested in wind farm data?

- **Climate Change:**
  to achieve $< 2^{\circ}$C–goal,
  coal demand has to decrease
  by 40% between 2012 and 2040



Source: IPCC report

Why should one be interested in wind farm data?

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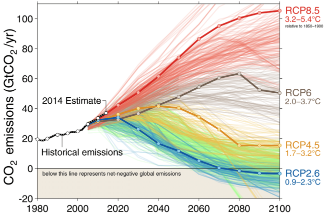
- **Today**:
  CO_2–emissions still **increasing**



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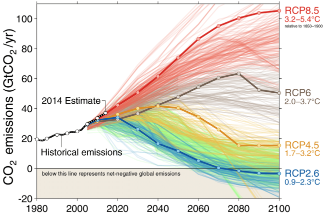
- **Emissions**:
  $20 \frac{g}{kWh}$ vs. $1000 \frac{g}{kWh}$ of CO_2 by wind energy resp. coal



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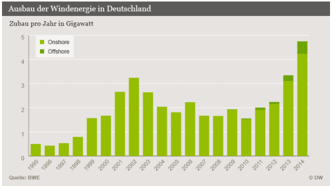

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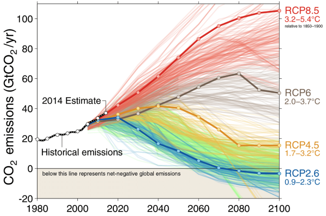
- **Emissions**:
  $20\frac{\mathrm{g}}{\mathrm{kWh}}$ vs. $1000\frac{\mathrm{g}}{\mathrm{kWh}}$ of $\mathrm{CO_2}$ by
  wind energy resp. coal

- Highest **expansion potential** and
  theoretical **effectiveness** up to 59%



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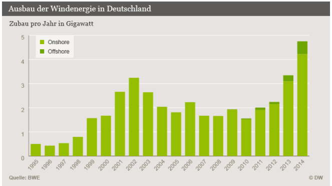
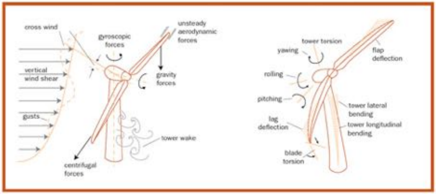


Why should we be interested in wind farm data?

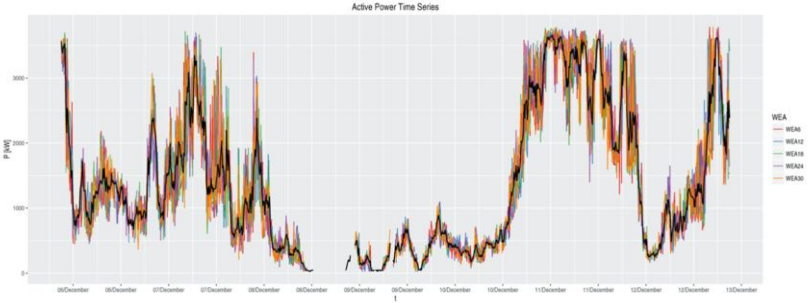
- *Single wind turbine*:
  highly complex system with a lot of analysable properties
- *Wind farm*:
  compound complex system with certain synchronicities



Source: Kießling, F. Modellierung des aeroelastischen Gesamtsystems einer Windturbine mit Hilfe symbolischer Programmierung. DFVLR-Report, DFVLR-FB 84-10, 1984.

Why should we be interested in wind farm data?

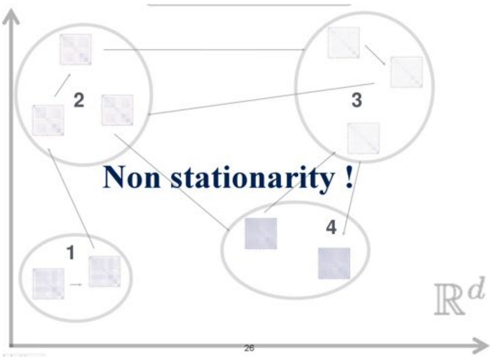
- *Single wind turbine*:
  highly complex system with a lot of analysable properties
- *Wind farm*:
  compound complex system with certain synchronicities
- Time series of several properties have stochastic, non-stationary and quasi-periodical character



→ **Present problems**: volatile power output and grid overload

What am I planning to do with wind farm data?

Find quasistationary states of wind farm with methods analogue to *Market States*!



Y. Stepanov: Meta-Stable Stock Market Collective Dynamics with Applications, presentation 2016

General Facts & Literature Overview

General Physics of Wind Turbines

An easy estimation of Power Production

Power of wind results from kinetic energy of moved air:

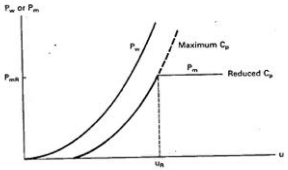
$$E_{\mathrm{kin}} = \frac{m}{2} u^2 \qquad \Leftrightarrow \qquad P_{\mathrm{W}} = \dot{E}_{\mathrm{kin}} = \frac{\dot{m}}{2} u^2 \quad \text{with} \quad u = \text{const.}$$

The *mass flow* $\dot{m} = A\rho u$ gives us

$$P_{\mathrm{W}} = \frac{A}{2} \rho u^3$$

Mechanical power can be estimated by including a performance constant C_{P}:

$$\boxed{P_{\mathrm{m}}(u) = C_{\mathrm{P}} P_{\mathrm{W}} = C_{\mathrm{P}} \frac{A}{2} \rho \, u^3}$$

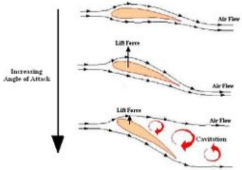


General Physics of Wind Turbines

Betz's law

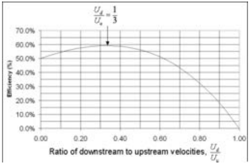
Rotor blades are driven by *lift force*
$\rightarrow$ **deceleration** of wind

- Very weak decelaration: weak lift force
- Very strong decelaration:
  $\dot{m} \rightarrow 0 \quad \Rightarrow \quad P_{\mathrm{m}} \rightarrow 0$



Conclusion: There is a best value for $\frac{u_{\mathrm{u}}}{u_{\mathrm{d}}}$ and a **limit** for aerodynamical efficiency!

$$C_{\mathrm{P}} \leq 0.59$$



Control of Wind Farms

SCADA and power control

SCADA

Supervisory **C**ontrol **a**nd **D**ata **A**cquisition

Collects real-time data to control the wind farm (mostly fully automatic)

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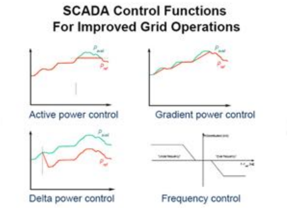
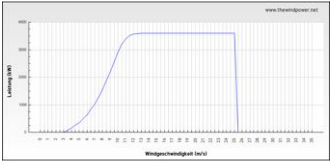
Active Power Control

Data is used to limit power within **operating range**:





Control of Wind Farms

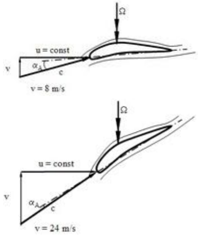
How it is realized

Pitch Control

$u < 3\,\frac{\mathrm{m}}{\mathrm{s}} \quad \text{or} \quad u > 25\,\frac{\mathrm{m}}{\mathrm{s}}: \qquad \phi \approx 90°$

$3\,\frac{\mathrm{m}}{\mathrm{s}} \leq u \leq 12\,\frac{\mathrm{m}}{\mathrm{s}}: \qquad \phi = 0°$

$12\,\frac{\mathrm{m}}{\mathrm{s}} < u \leq 25\,\frac{\mathrm{m}}{\mathrm{s}}: \qquad \phi \in [0°, 30°]$



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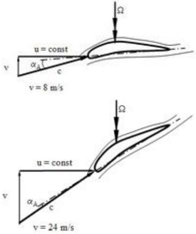

Autotracking and Trundeling

Autotracking: within operating range, nacelle rotates so that $\vec{u} \parallel \vec{A}$

Trundeling: beyond operating range, turbine is not shut down immediately but *trundles*

What are the main problems and approaches in wind energy research?

Brief Overview by Keywords

Popular Approaches

What already has been done

- **Aggregated windfarm models**:
  - Reducing complexity & computation times by determining multi machine representations (since ≈2000)
  - *Methods*:
    Clustering of wind velocities and further data mining methods

Popular Approaches

What already has been done

- **Aggregated windfarm models**:
  - Reducing complexity & computation times by determining multi machine representations (since ≈2000)
  - *Methods*:
    Clustering of wind velocities and further data mining methods

- **Power forecast**:
  - Several approaches to predict wind power from empirical or simulated data to e.g. minimize number of shutdowns (well advanced)
  - *Methods*:
    mostly sophisticated big data and machine learning methods

Popular Approaches

What already has been done

- **Reliability Assesment**:
  - Comprehensive analysis of wind energy reliability by including multiple wind farms
  - *Methods*:
    Correlations $\rightarrow$ wind velocity simulations

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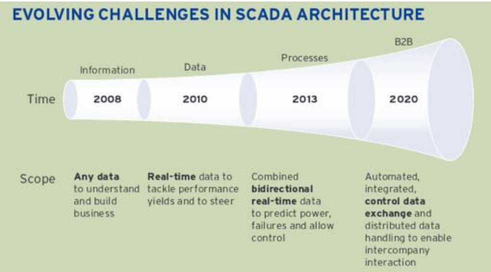
⋮

- **Structural Health Monitoring**
- **Wind Farm Integration into Power Grid**
- **Models for Power Fluctuations**
- **Operational Risk of Wind Farms**

What are the main problems and approaches in wind energy research?

..and how can I/we contribute?

Improve **grid integration** by balancing multiple intermittent power outputs of WTs, especially for **offshore** wind farms.



Expert Report: SCADA 2014 systems for wind

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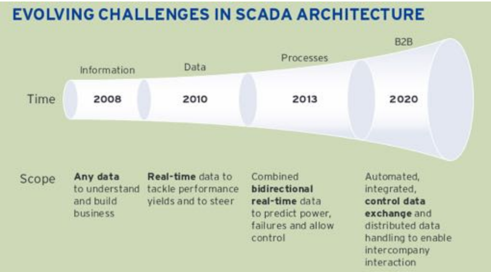

Expert Report: SCADA 2014 systems for wind

→ Learn more about (instationary) correlation structure between single WTs!

ForWind

Center for Wind Energy Research

- since 2003
- Oldenburg, Bremen and Hannover
- **Research**: many interdisciplinary topics, including turbulence, power forecast and stochastic modeling

- **Previous collaborations**: Yuriy and Philip Rinn about *Market States*
- Further collaboration with AG Peinke is intended

RIFFGAT

Offshore wind farm near Borkum

- 30 wind turbines with active power of 3.6MW $\widehat{=}$120.000 provided homes
- Operating range: $3 - 25\,\frac{\mathrm{m}}{\mathrm{s}}$ and $u \overset{!}{<} 70\,\frac{\mathrm{m}}{\mathrm{s}}$

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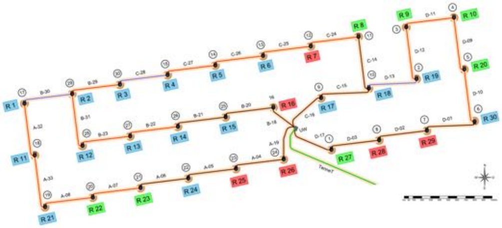
- Distances: 554m in rows and 600m between rows
- Diameter: 120m
- Height: 90m



Data Cleansing

My Dataset

WTs **Measured Quantities as Time Series**

$$30 \times \underbrace{\left.\begin{pmatrix} P \\ u \\ \alpha_{\mathrm{nac}} \\ \phi_{\mathrm{rot}} \\ \Omega_{\mathrm{T}} \\ \vdots \end{pmatrix}_{t_0} \right\rangle n \approx 20 \rightarrow \begin{pmatrix} P \\ u \\ \alpha_{\mathrm{nac}} \\ \phi_{\mathrm{rot}} \\ \Omega_{\mathrm{T}} \\ \vdots \end{pmatrix}_{t_1} \rightarrow \ldots}_{\mathrm{T} = 1 \text{ year}}$$

including values for mean, maximum, minimum and standard deviation always calculated over consecutive *10-minute intervals* (56.593 values per WT).

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Limiting to Operating Range

Operating Range:

$$
\begin{aligned}
3\,\tfrac{\mathrm{m}}{\mathrm{s}} \;&\leq\; u \;\leq\; 25\,\tfrac{\mathrm{m}}{\mathrm{s}} \\
20\mathrm{kW} \;&\leq\; P \;\leq\; 3800\mathrm{kW}
\end{aligned}
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Raw Data:

- 16% of $P_{\mathrm{raw}} < 0\mathrm{kW}$!
  But only 2% of $P_{\mathrm{raw}} < -20\mathrm{kW}$
- 10% of $u_{\mathrm{raw}} < 3\,\tfrac{\mathrm{m}}{\mathrm{s}}$!
  But only 0.1% of $u_{\mathrm{raw}} > 25\,\tfrac{\mathrm{m}}{\mathrm{s}}$

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Further discard redundant values and such with stddev = 0:

$\Rightarrow$ 32.42% **NAs**

Non-physical Relative Changes of Power Output

Insight into questionable values

Abs. Differenz/3600kW	Relat. Aenderung	P1	P2	Min1	Max1	Min2	Max2	Stddev1	Stddev2
0.9919554	117.7760137	30.3206000	3601.3600000	-718.0000000	2438.0000000	3509.0000000	3698.0000000	283.7120000	26.7370000
0.2458506	38.8493541	22.7819000	907.8440000	-95.0000000	1538.0000000	608.0000000	1396.0000000	194.7060000	149.3420000
0.1830456	24.0896190	27.3547000	686.3190000	-40.0000000	161.0000000	576.0000000	745.0000000	38.0380000	31.5924000
0.2426734	37.3410698	23.3958000	897.0200000	-60.0000000	330.0000000	796.0000000	1029.0000000	101.2240000	45.0744000
0.9326092	24.4695460	137.2070000	3494.6000000	-132.0000000	367.0000000	2103.0000000	3697.0000000	163.8960000	291.3220000
0.2235168	39.1688133	20.5434000	825.2040000	-58.0000000	178.0000000	746.0000000	938.0000000	57.0338000	42.0686000
0.2603715	32.5061400	28.8357000	966.1730000	-91.0000000	368.0000000	-97.0000000	2695.0000000	118.2420000	912.9050000

Possible Explanation & Rejection Criterion

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Possible Explanation & Rejection Criterion

Already discarded values could cause large changes → **partially verified**

Non-physical Relative Changes of Power Output

Insight into questionable values

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Possible Explanation & Rejection Criterion

Criterion: discard all values with $|\rho| > 10$ that show jump

$P_{\min}(t_2) - P_{\max}(t_1) > 360\text{kW} \mathrel{\widehat{=}} 0.1 P_{\text{WT}}$

$\Rightarrow$ 32.45% **NAs** but only 0.6% of $|\Delta P_{\text{WF}}| > 0.2 P_{\text{WF}}$

Remaining Data

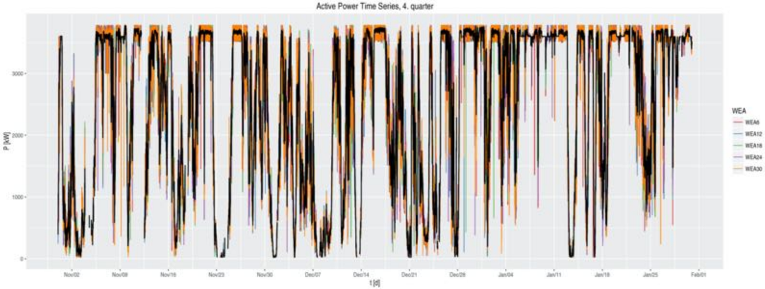
We arrive at $\Rightarrow$ 32.45% **missing values** $\widehat{=}$ 38.246 values per WT.

- Did we sort out *relevant* data?
- How *reliable* is the remaining data set?

$\rightarrow$ **How can we deal with all this missing data?**

First Glance of Qualitative Behaviour

Time Series


Active Power Time Series, 4. quarter
P [kW]
3000
2000
1000
0
Nov/02
Nov/09
Nov/16
Nov/23
Nov/30
Dec/07
Dec/14
Dec/21
Dec/28
Jan/04
Jan/11
Jan/18
Jan/25
Feb/01
t [d]
WEA
WEA6
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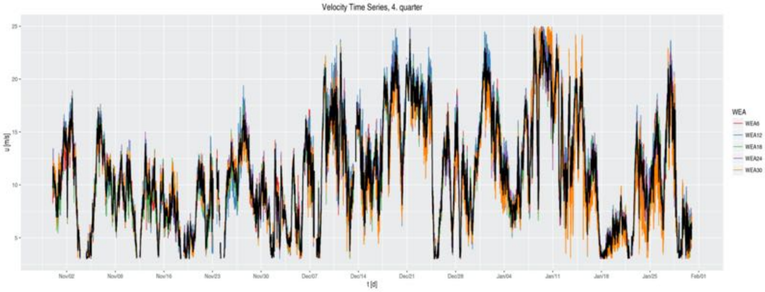
WEA18
WEA24
WEA30


Velocity Time Series, 4. quarter
u [m/s]
25
20
15
10
5
Nov/02
Nov/09
Nov/16
Nov/23
Nov/30
Dec/07
Dec/14
Dec/21
Dec/28
Jan/04
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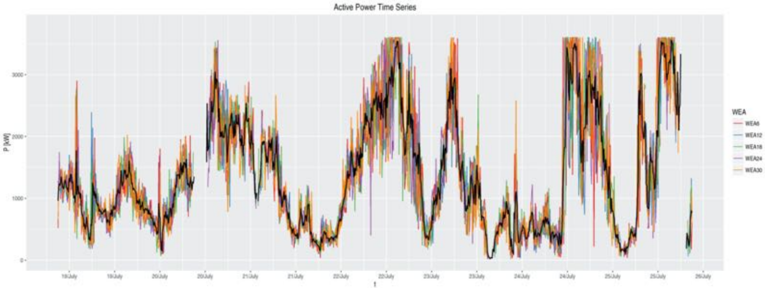
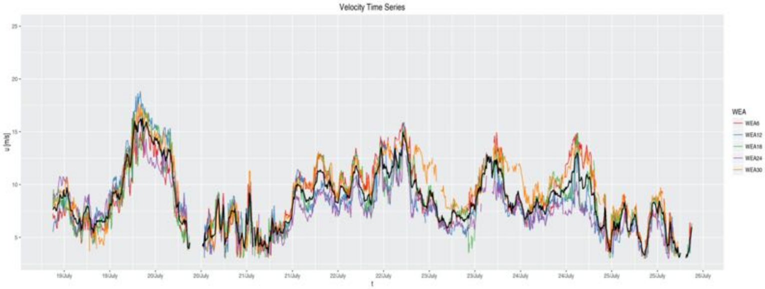
WEA30

Time Series


Active Power Time Series
P [kW]
3000
2000
1000
0
t
WEA
WEA6
WEA12
WEA18
WEA24
WEA30


Velocity Time Series
u [m/s]
25
20
15
10
5
t
WEA
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WEA24
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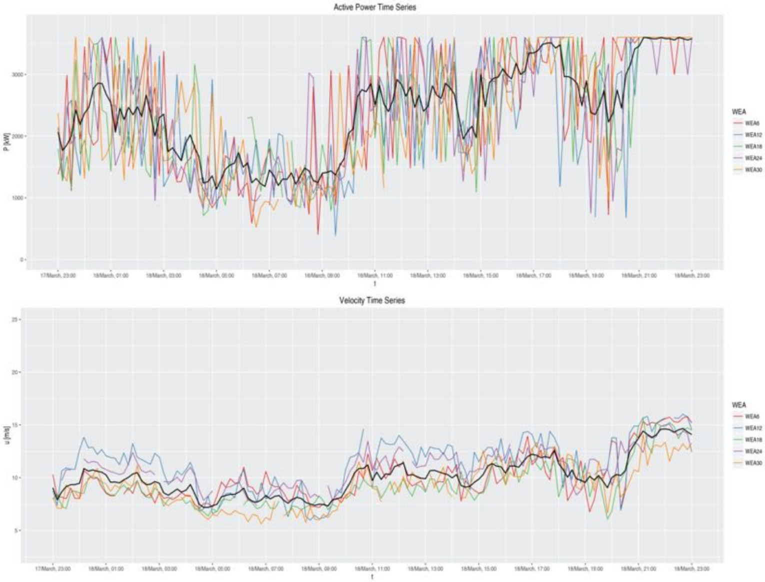
Time Series

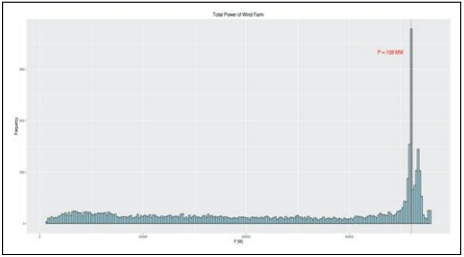

Active Power Time Series
P [kW]
WEA
WEA6
WEA12
WEA18
WEA24
WEA30
t
Velocity Time Series
u [m/s]
WEA
WEA6
WEA12
WEA18
WEA24
WEA30
t

Distributions

Power and Velocity

Power

- sharply massed around actual rated output
- lower output approx. equally distributed



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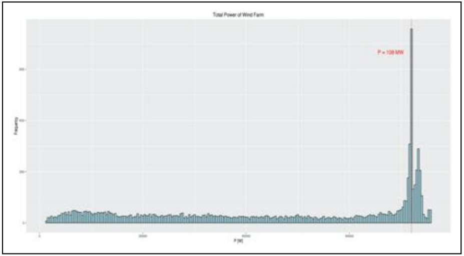
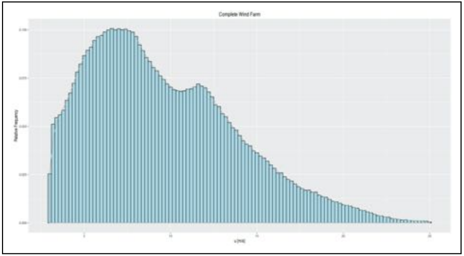


Velocity

- not Weibull-distributed, bimodal!
- second maximum because WTs mostly run at nominal power at around $\approx 12 \frac{m}{s}$



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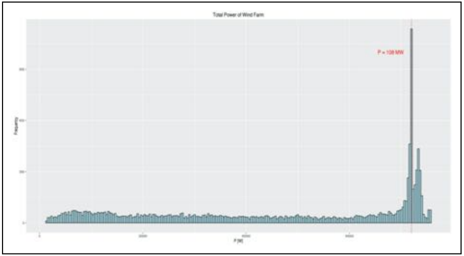

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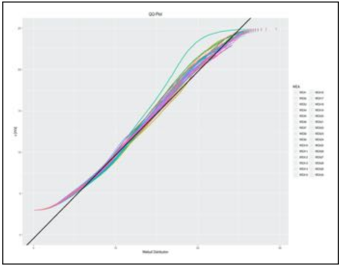
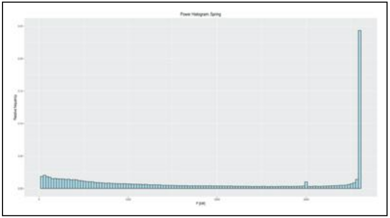
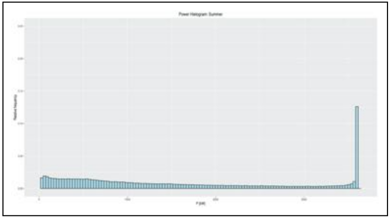


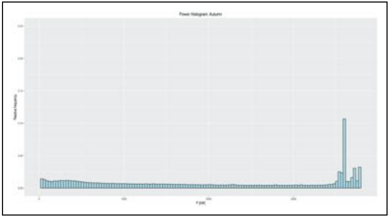
Distributions

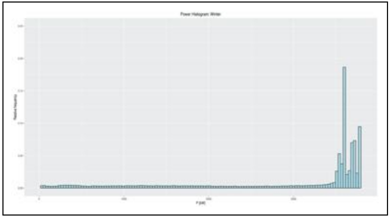
Power and Velocity – Seasons of the Year

Power









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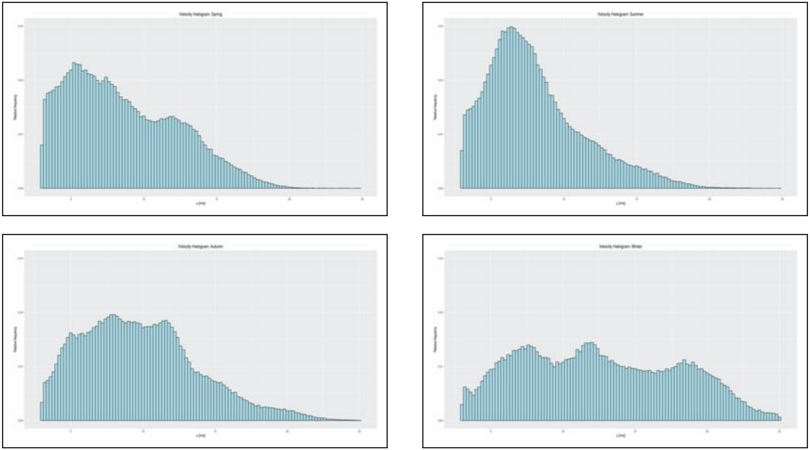
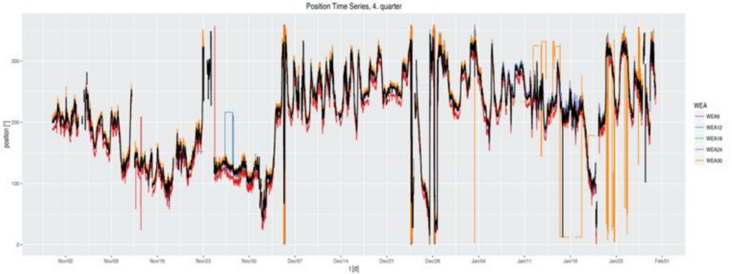
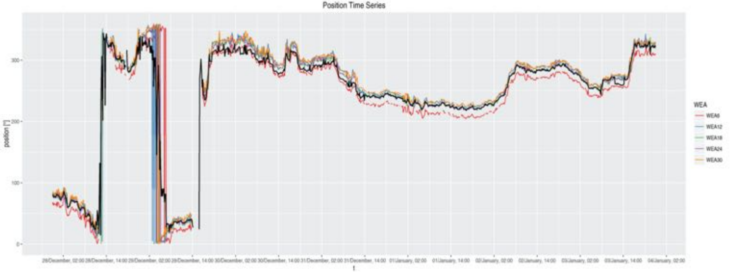


Time Series

Nacelle direction





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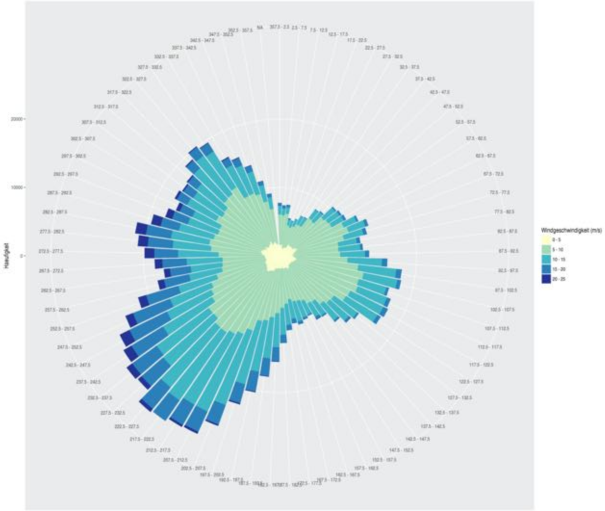
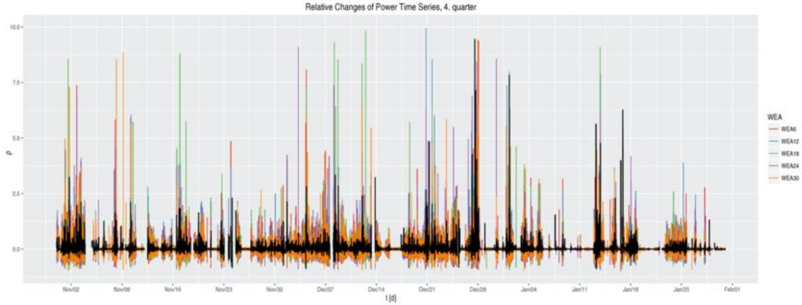


Time Series

Relative Changes of Power



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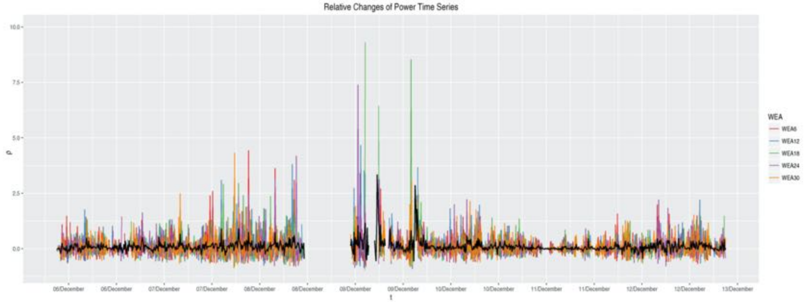

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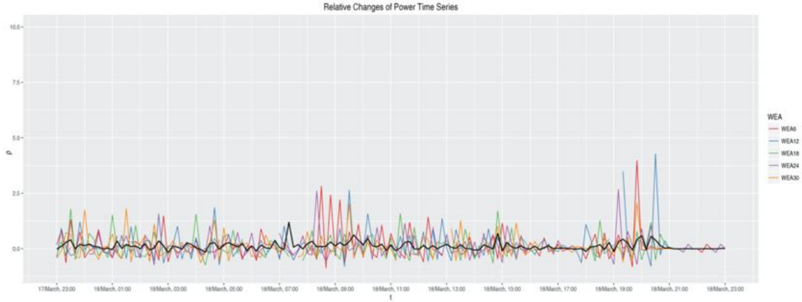
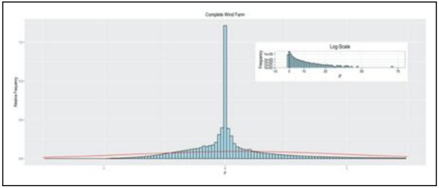
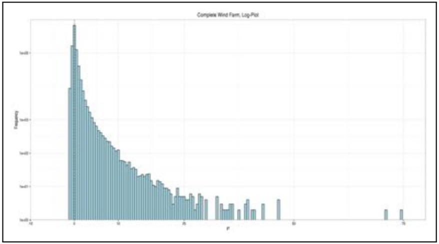


Distributions

Relative Changes of Power

- Non–Gaussian but not heavy tailed!
- Roughly symmetric around zero
- $\approx$ 13% of $\rho \in [-0.0125, 0.0125]$
- QQ–Plot: really strong deviations for large values





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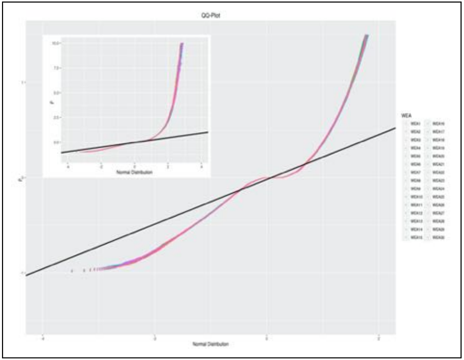
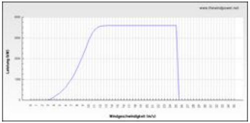
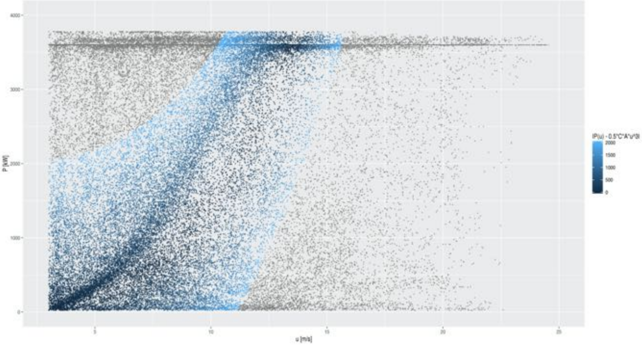


Power Curve

$$P_{\mathrm{m}}(u) = \frac{C_{\mathrm{P}} A \rho}{2} \, u^3$$

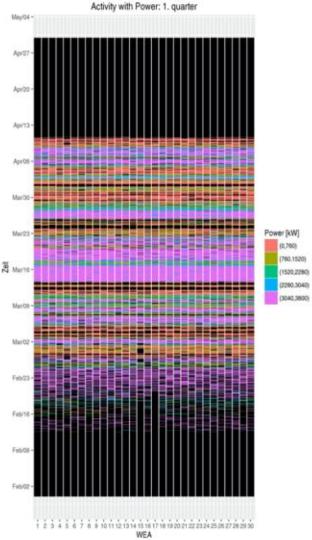


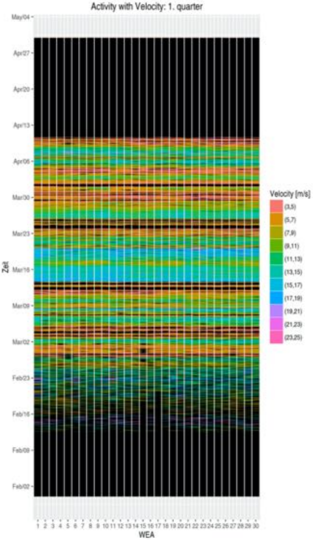
Averaged over all Wind Turbines



Activity

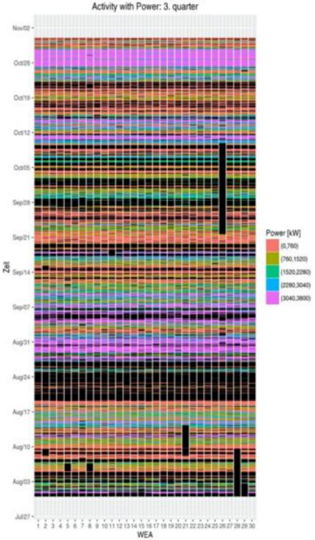
1. Quarter

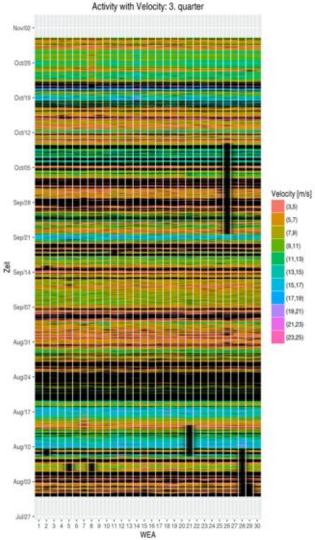




Activity

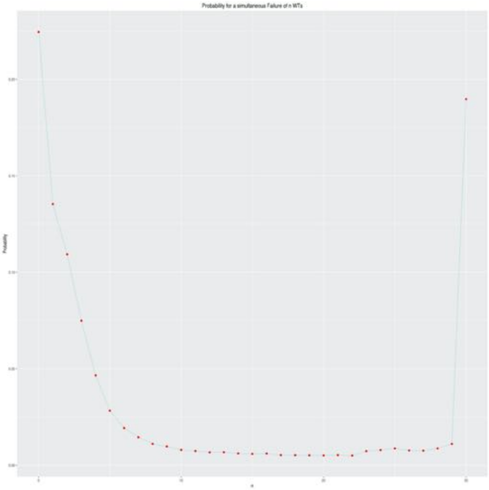
3. Quarter





Activity

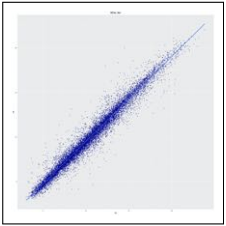
How high is the probability for n WTs being out of operating range or failing from another reason?



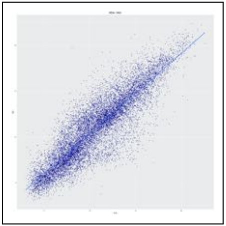
Scatter Plots

Velocity and Power

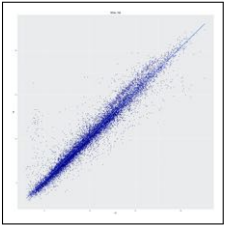
3&4

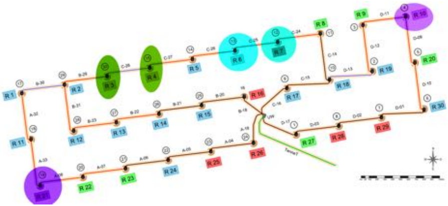


10&21



7&6





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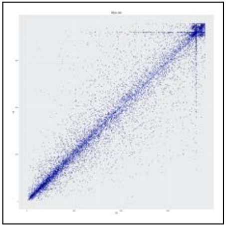

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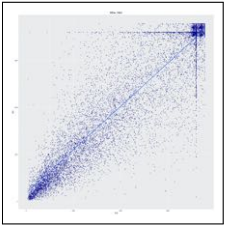

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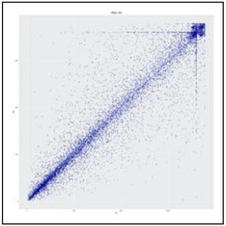

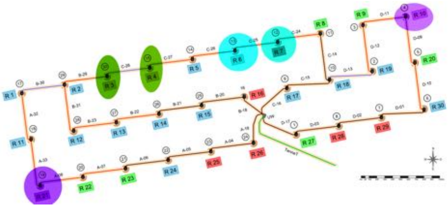

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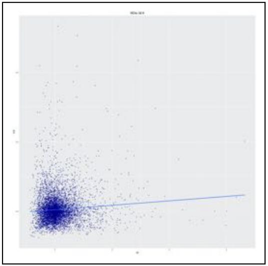

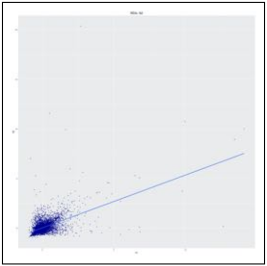

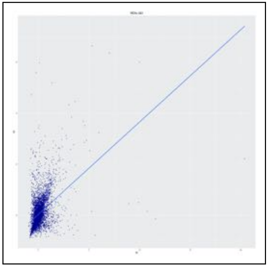

Ideas and Prospect

Next Steps

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   (without introducing any statistical bias!)

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4. Start with cluster–computation etc.

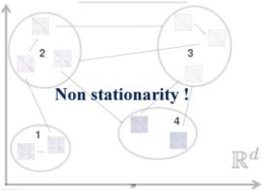
Idea of my Master Thesis

Summary

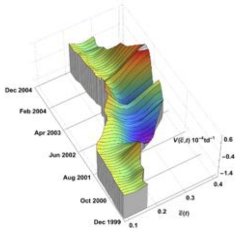
- **First Approach**:
  - Calculate $\underline{\underline{C}}$ for *locally normalized* values of $\rho(t) = \frac{P(t+\Delta t)-P(t)}{P(t)}$
  - Build clusters of instationary $\underline{\underline{C}}(t)$ by *bisecting k–means* ("Wind Farm States")
  - Extend analysis by stochastic description of dynamics via *potential functions*

$$V(\bar{c}, t) = -\int^{\bar{c}} f(x,t)dx$$

with empirically estimated drift function $f(x,t)$



Y. Stepanov: Meta-Stable Stock Market Collective Dynamics with Applications, presentation 2016



Y. Stepanov et al: Stability and Hierarchy of Quasi-Stationary States: Financial Markets as an Example, 2015

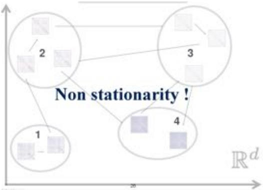
Idea of my Master Thesis

Summary

- **Advanced Approach**:
  - Use all measured data in

$$30 \quad \times \quad \begin{pmatrix} P \\ u \\ \alpha_{\mathrm{nac}} \\ \phi_{\mathrm{rot}} \\ \Omega_{\mathrm{T}} \\ \vdots \end{pmatrix}_t$$

  - Derive only state of **one** WT first with the same methods
  - Compare structure and stability of all single–WT–states



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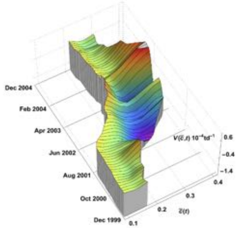

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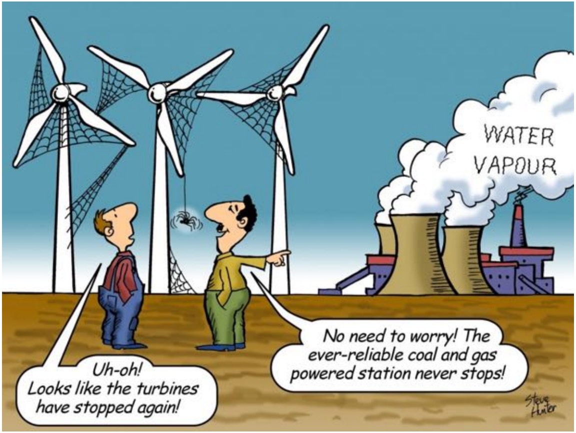
Thank you for your attention!



References: Feel free to ask me!