renewables

..... + more renewables

..... + much more renewables

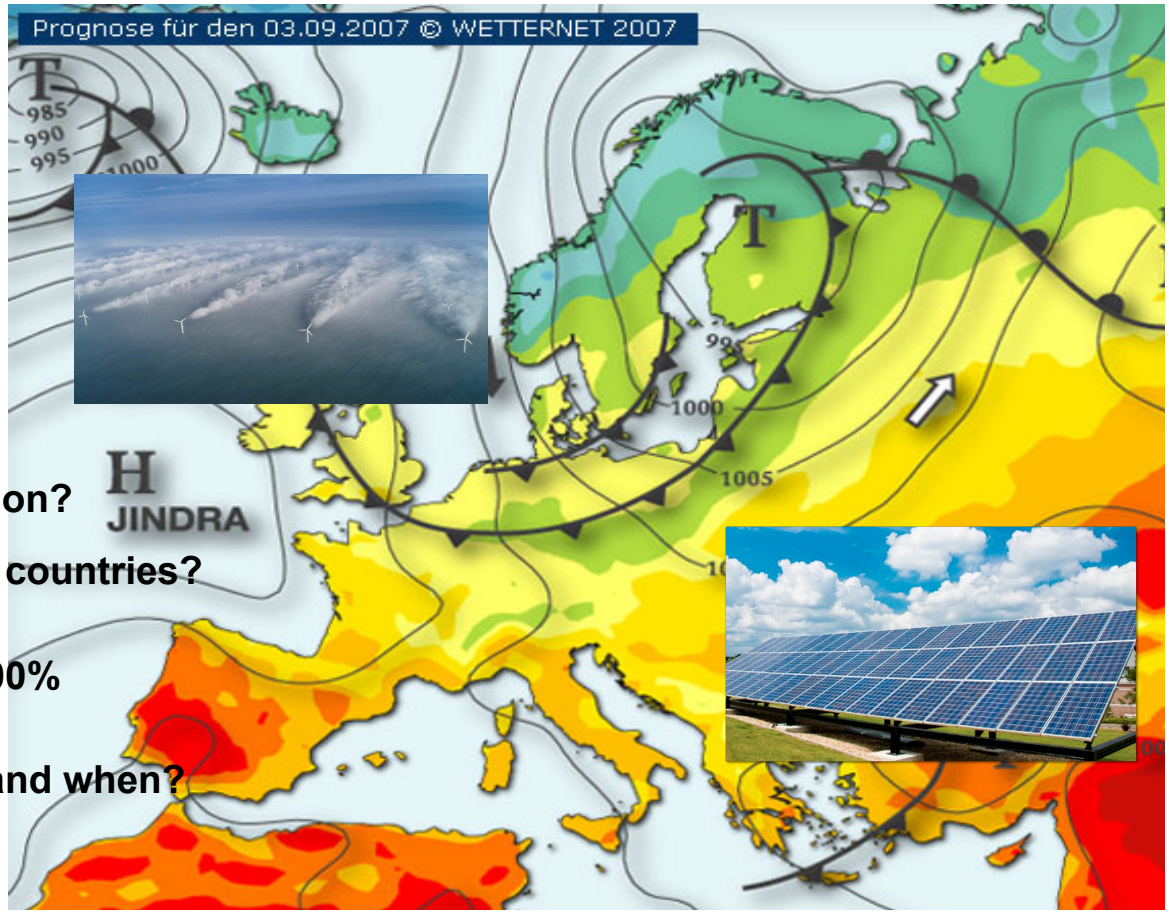
what is the end of the story?

Morten Grud Rasmussen
Gorm Bruun Andresen
Rolando Rodriguez
Dominik Heide [DLR]

Lueder v.Bremen [ForWind]
Clemens Hoffmann [Siemens]

100% Renewable pan-European Power System

Let the weather decide!



How much wind + solar power?

How much storage + transmission?

Cooperative Europe or autarkic countries?

Transition pathways from 0 – 100%

How much investments where and when?

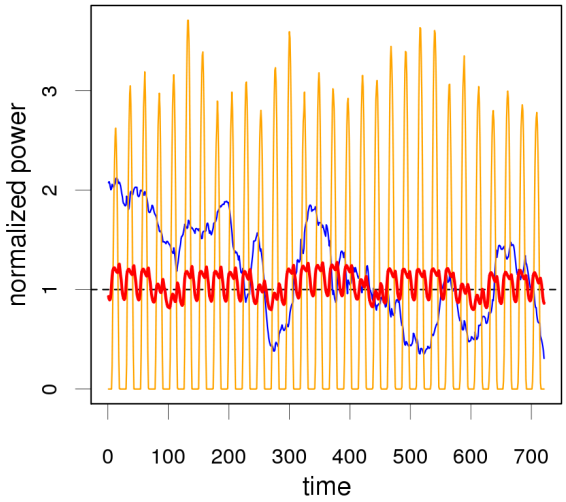
2000 – 2007: 1h, 45x45km²

AARHUS SCHOOL OF ENGINEERING

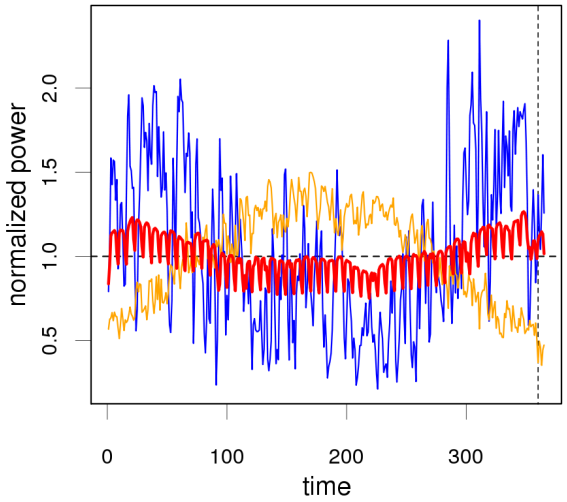
Weather contains 3 time scales: diurnal (1h-1d)
synoptic (2-10d)
seasonal (1y)

European copper plate

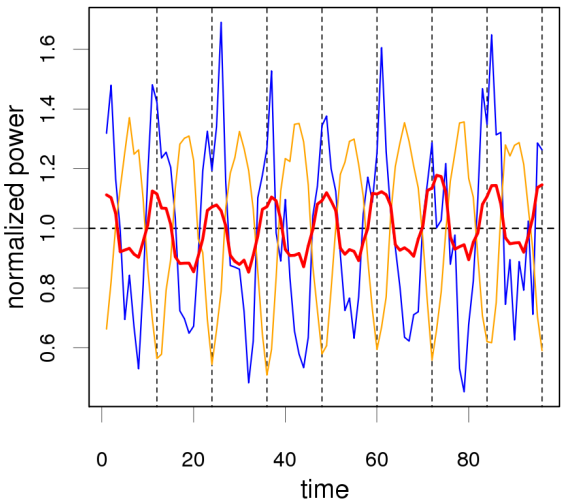
wind power generation
solar PV power generation
load



1hour resolution (of 1month)



1day resolution (of 1year)



1month resolution (of 8years)

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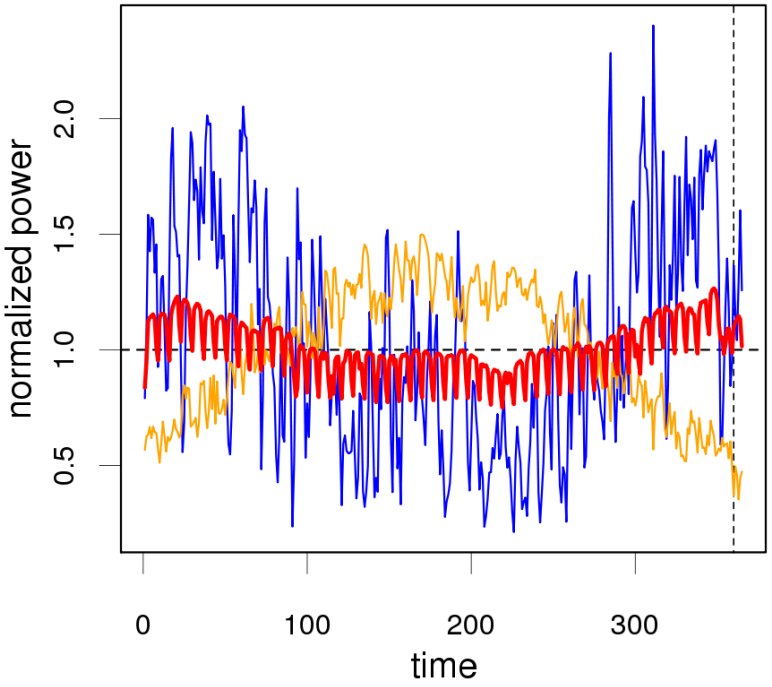
How much storage?



$$a + b = 1$$

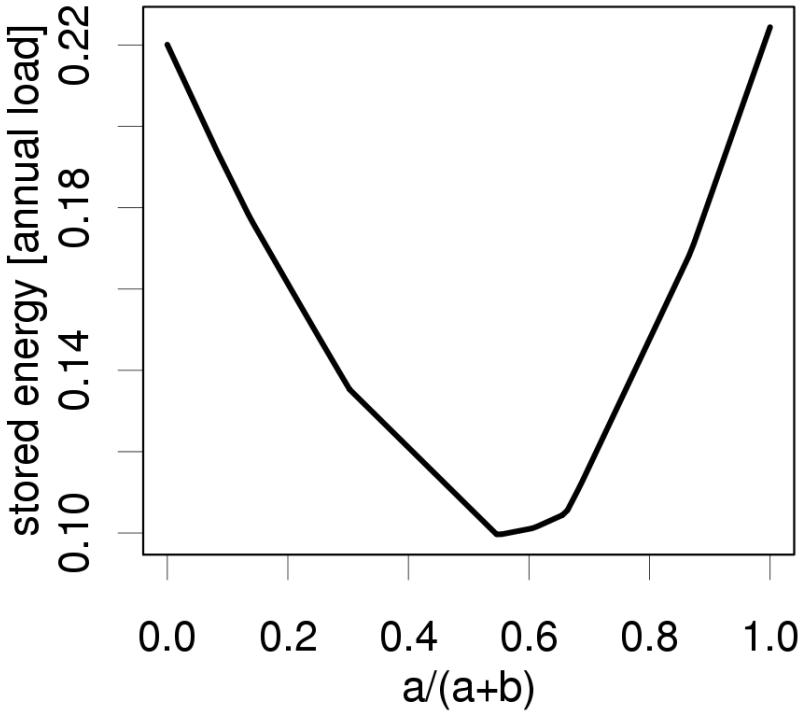
$$\Delta(t) = a\,W(t) + b\,S(t) - L(t)$$

$$H(t) - H(t-1) = \begin{cases} \eta_{\text{in}}\,\Delta(t) & (\Delta > 0) \\ \eta_{\text{out}}^{-1}\,\Delta(t) & (\Delta < 0) \end{cases}$$

$$E_S = \max_t H(t) - \min_t H(t)$$

AARHUS SCHOOL OF ENGINEERING

How much storage?



$$a + b = 1$$

$$\Delta(t) = a\,W(t) + b\,S(t) - L(t)$$

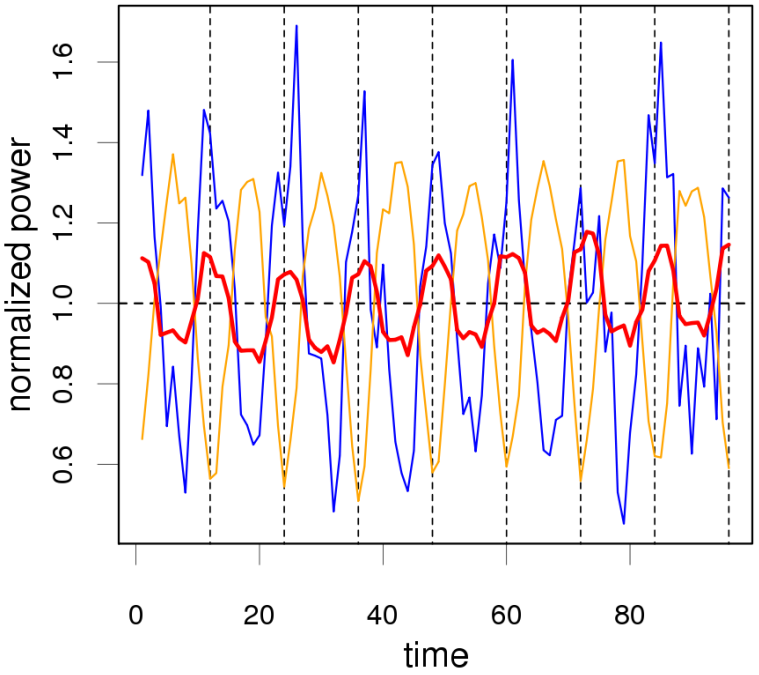
$$H(t) - H(t-1) = \begin{cases} \eta_{\text{in}}\,\Delta(t) & (\Delta > 0) \\ \eta_{\text{out}}^{-1}\,\Delta(t) & (\Delta < 0) \end{cases}$$

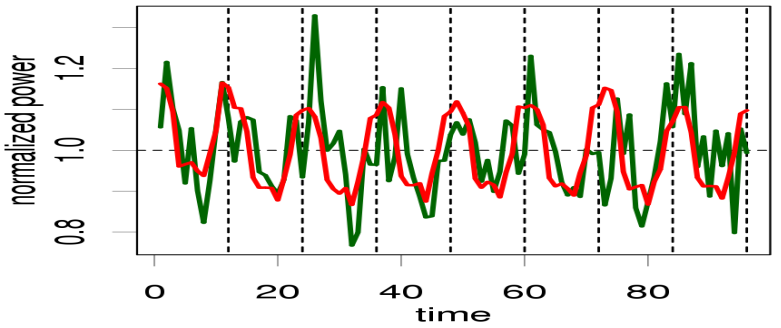
$$E_S = \max_t H(t) - \min_t H(t)$$

AARHUS SCHOOL OF ENGINEERING

Seasonal optimal mix

= 60% wind power + 40% solar power





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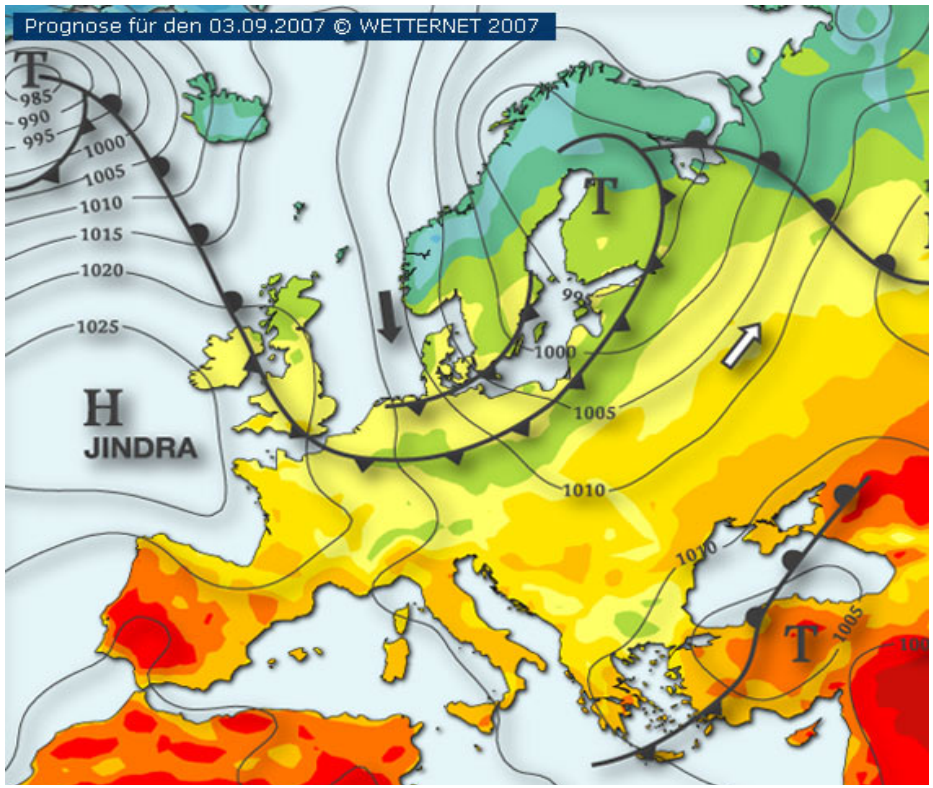
wind and solar power capacities



annual consumption (2009)
= 3360 TWh

60% wind power generation
= 750 GW installed capacity
= 150.000 x 5MW turbines
= 3750 x 200MW wind farms
≈ 100000 km²

40% solar PV power generation
= 750 GW installed capacity
≈ 5000 - 10000 km²

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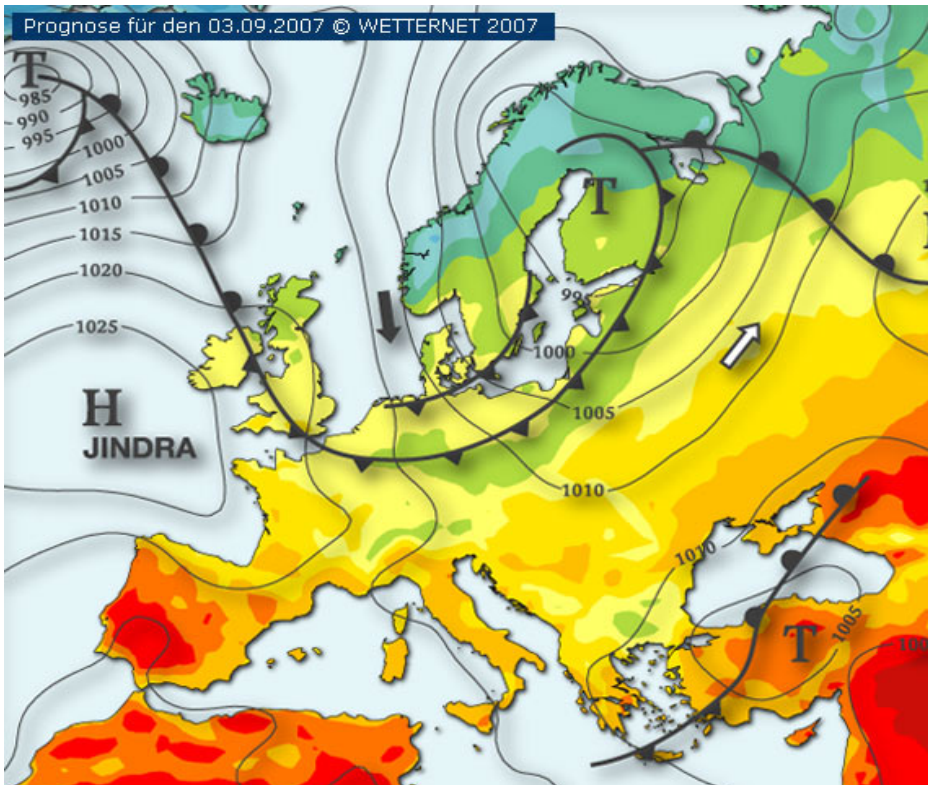
storage capacities



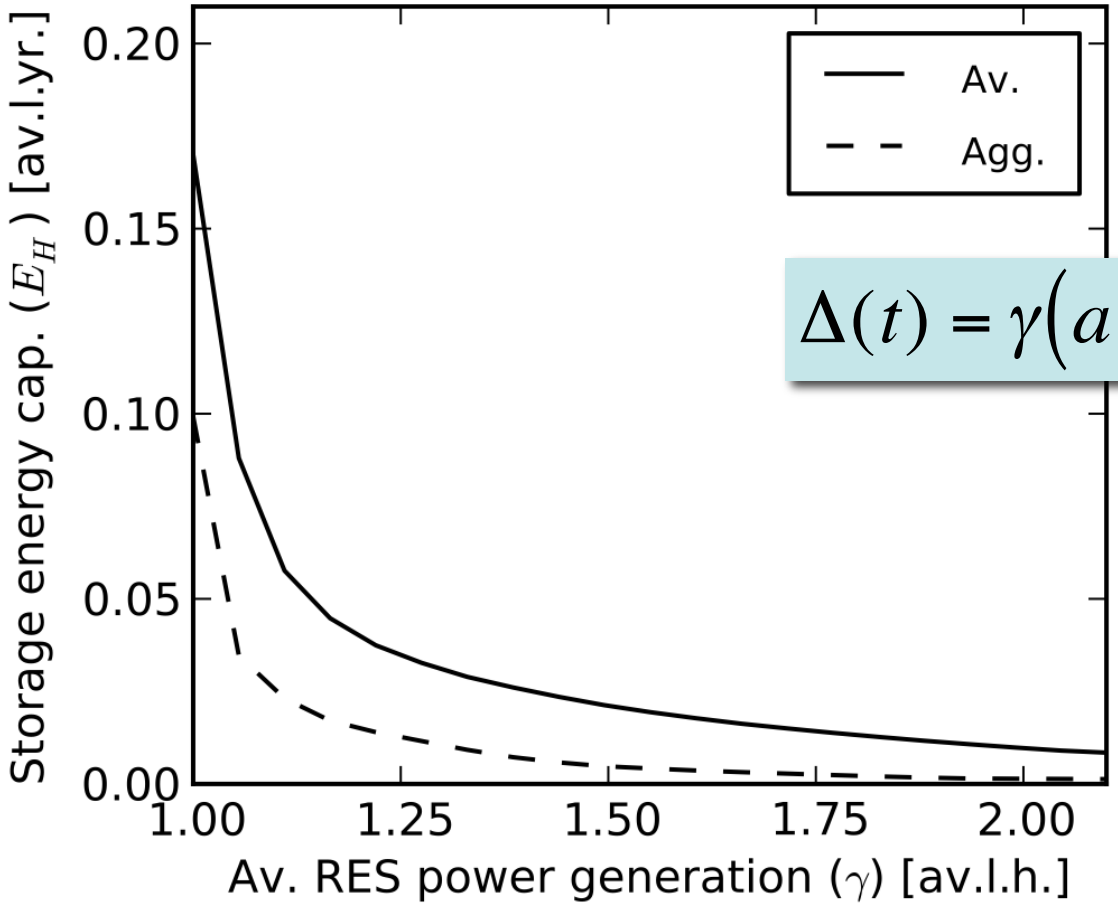
annual consumption = 3360 TWh
hourly load = 385 GW

Storage (roundtrip):
(energy) 340 TWh
(power) 300 GW

H2 storage (roundtrip):
(energy) 25 TWh
(power) 50 GW

AARHUS SCHOOL OF ENGINEERING

How to reduce storage needs? Storage + excess generation



$$\Delta(t) = \gamma\left(a\,W(t) + b\,S(t)\right) - L(t)$$

$\gamma = 1.5$

$\eta = 0.6$

(energy) 50 TWh
(power) 230 GW

H2 storage:
(energy) 25 TWh
(power) 50 GW

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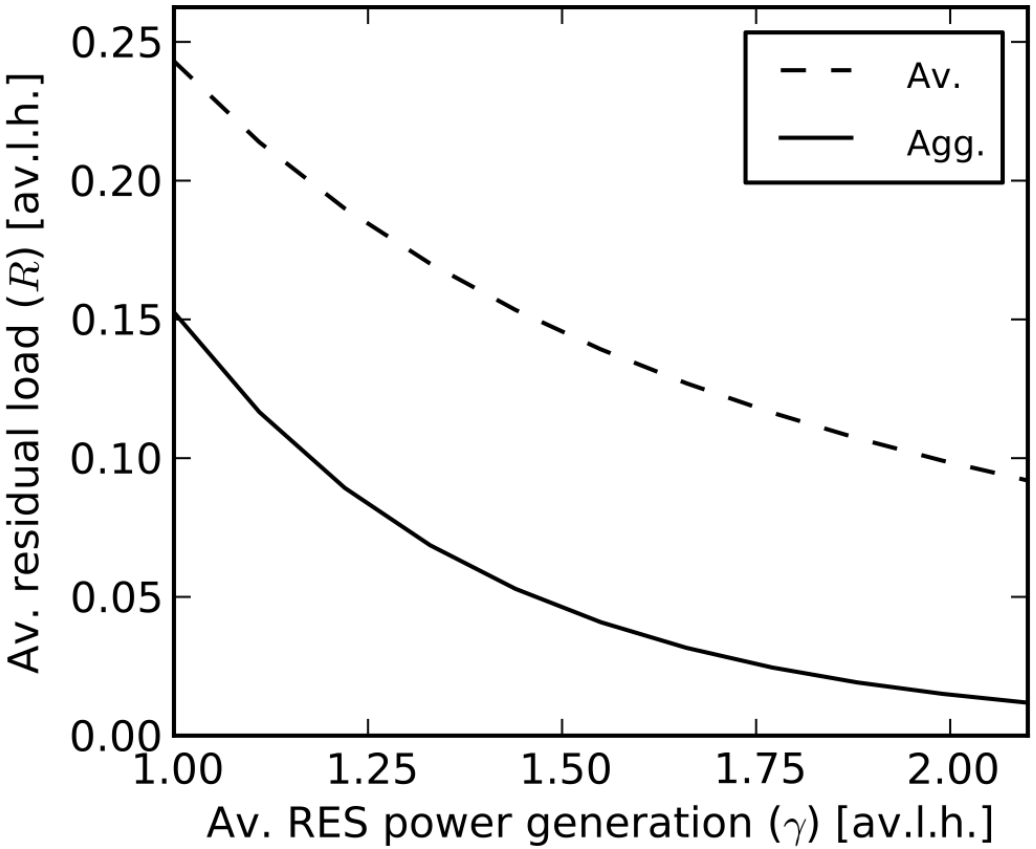
balancing capacities



hydro lakes (one-way)
(energy) 150 TWh
(power) 55 GW

$$B(t) = \begin{cases} -\Delta(t) & (\Delta < 0) \\ 0 & (\Delta > 0) \end{cases}$$

$\gamma = 1.0$ **(energy) 500 TWh**
(power) 280 GW

$\gamma = 1.5$ **(energy) 170 TWh**
(power) 210 GW

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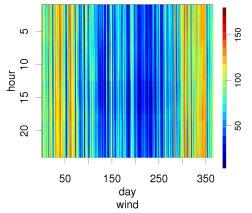
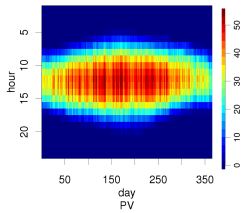
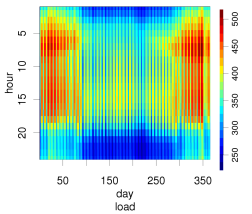
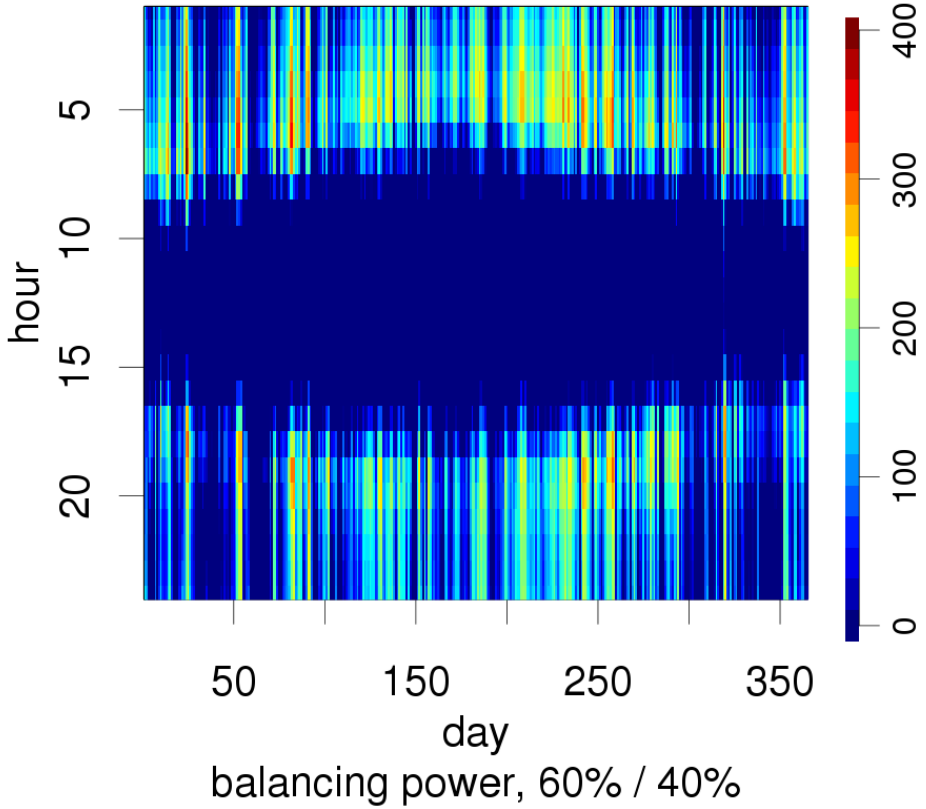
How to further reduce storage + balancing needs?









$$B(t) = \begin{cases} -\Delta(t) & (\Delta < 0) \\ 0 & (\Delta > 0) \end{cases}$$

!!! seasonal storage + balancing + intra-day storage !!!

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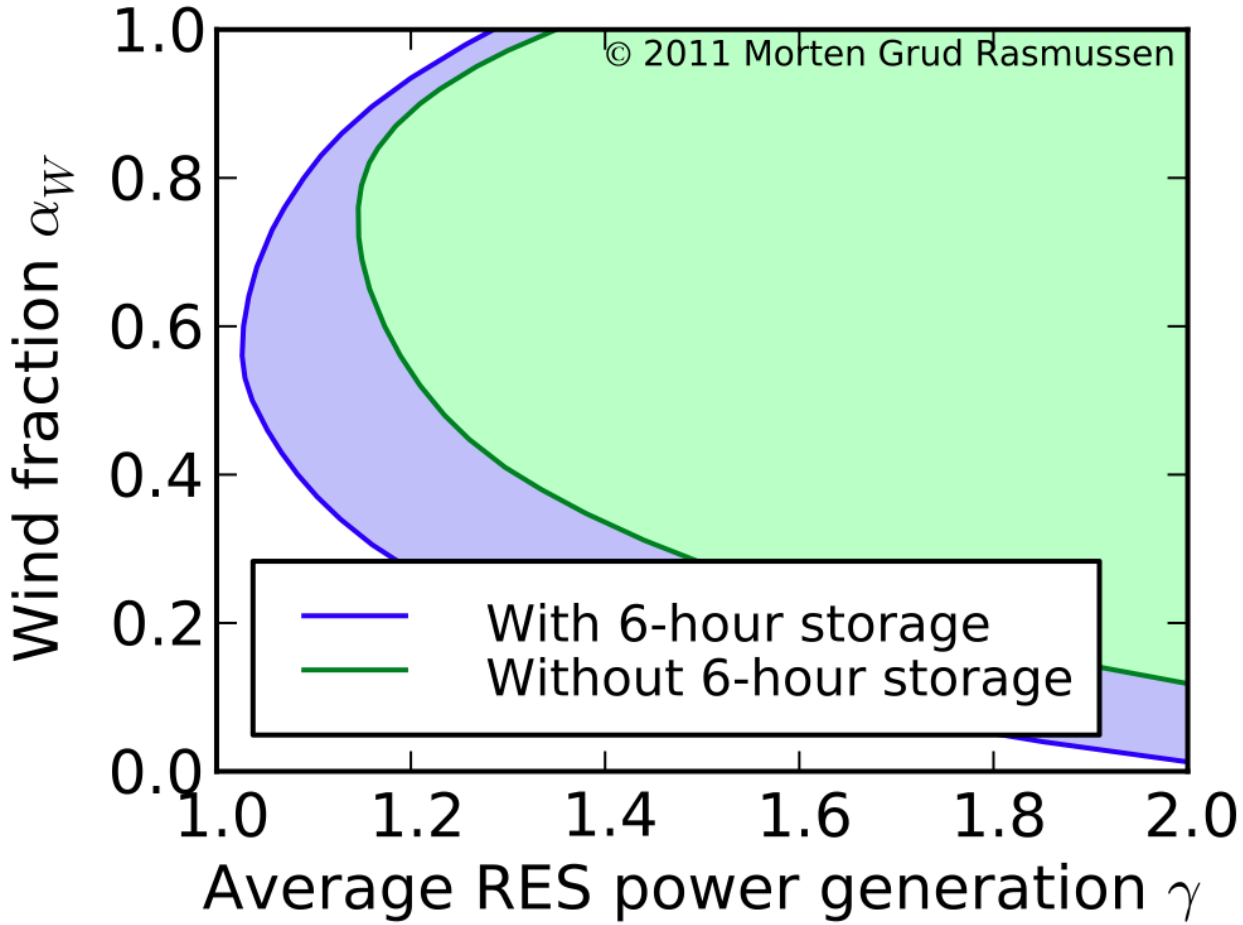
6h storage (2.2 TWh, η=1.0)
+ seasonal storage (25 TWh, η=0.6)
+ balancing (150 TWh)



$$\Delta(t) = -L(t) + \gamma\left(\alpha\, W(t) + (1-\alpha)\, S(t)\right)$$

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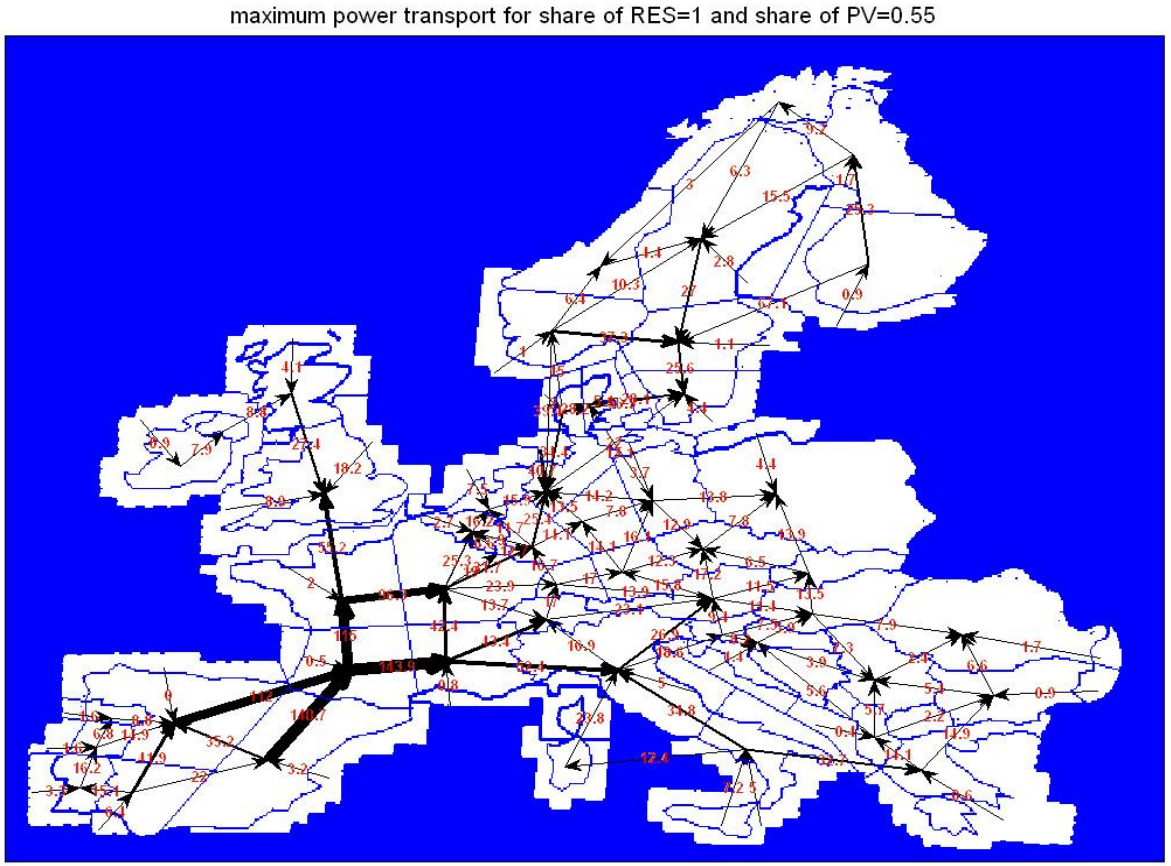
where storage + balancing?



power transmission!

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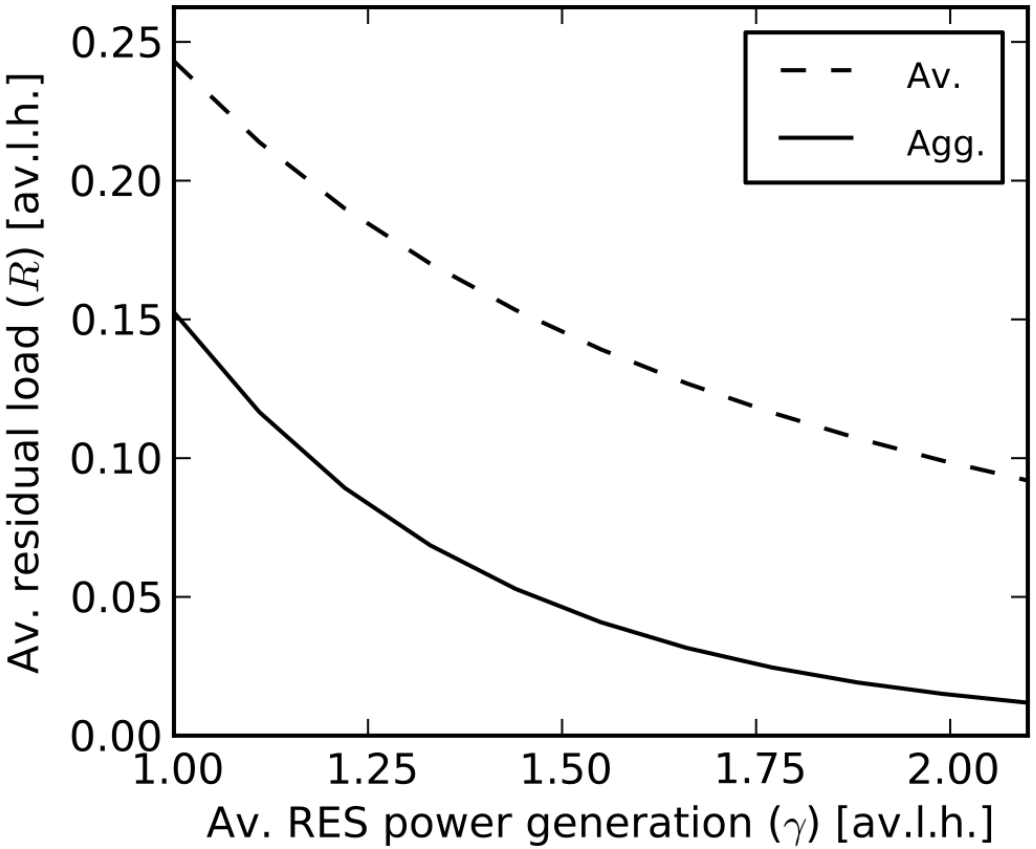
balancing capacities



$$B(t) = \begin{cases} -\Delta(t) & (\Delta < 0) \\ 0 & (\Delta > 0) \end{cases}$$

$\gamma = 1.0$ **(energy) 500 TWh**
(power) 280 GW

$\gamma = 1.5$ **(energy) 170 TWh**
(power) 210 GW

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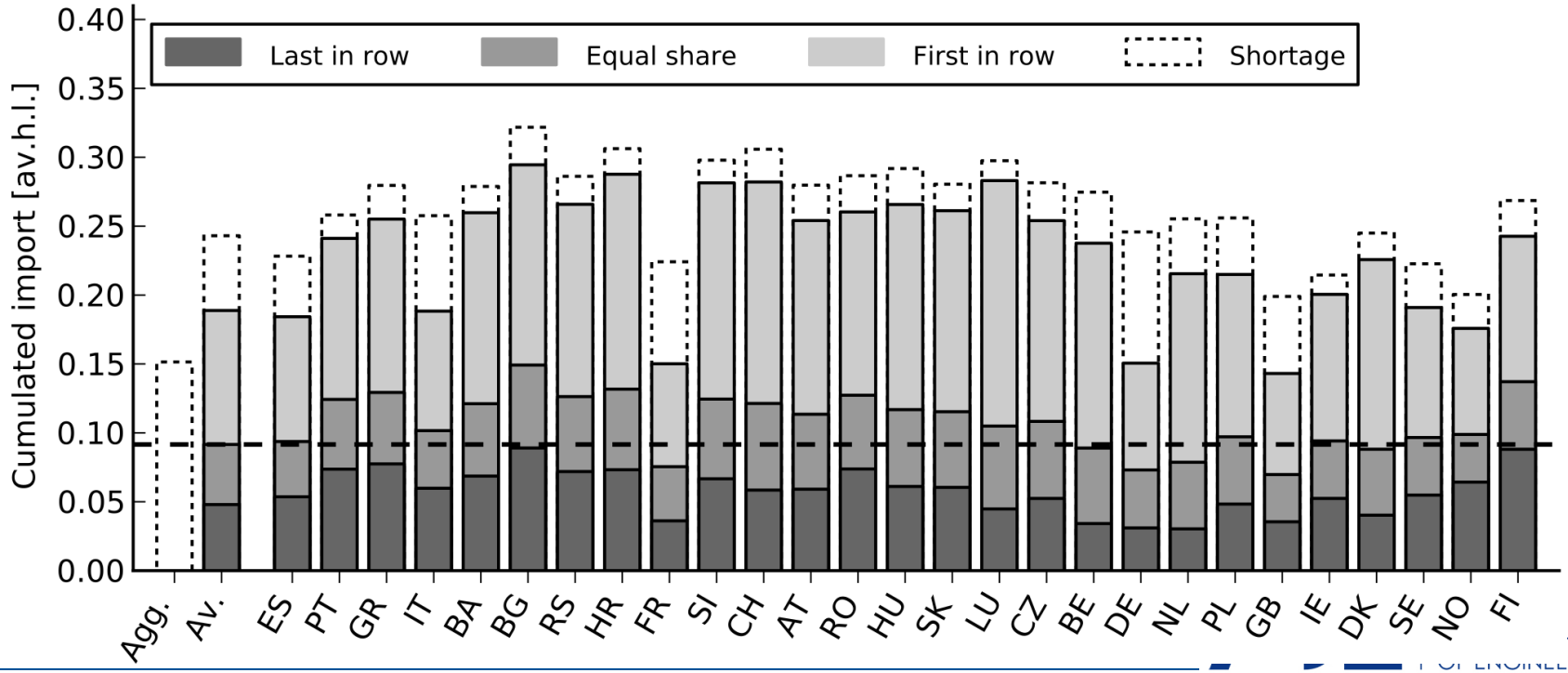
autarkic countries **vs.** **cooperative Europe**

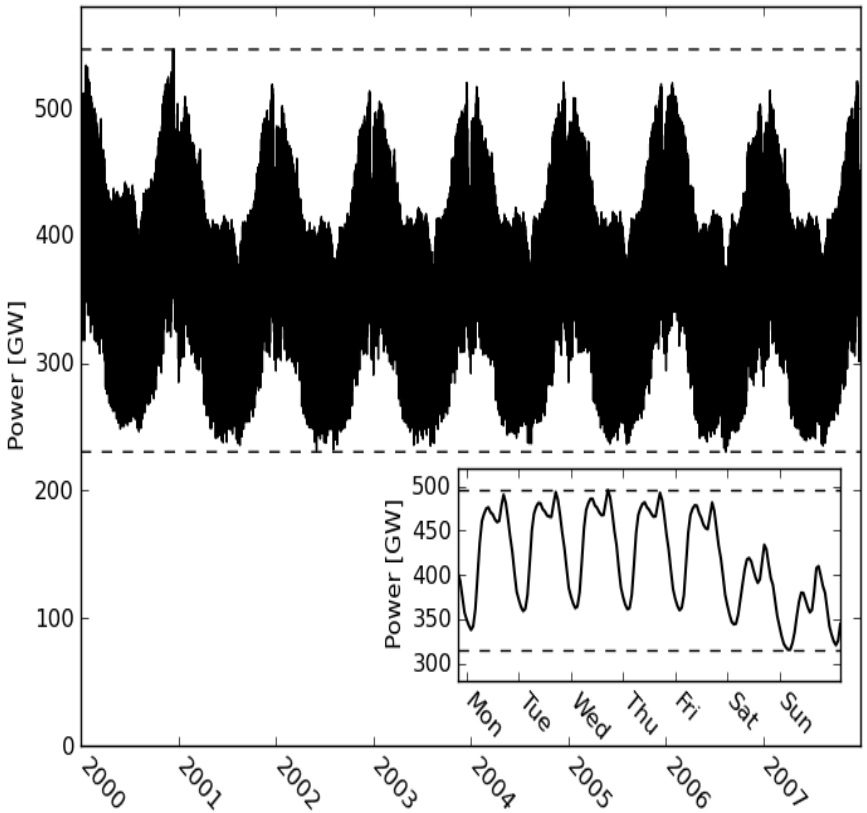
$$\sum_X \langle B(t) \rangle_X = 0.24 \qquad \gamma = 1.0 \qquad \langle B(t) \rangle_{EU} = 0.15$$

Each country can expect to import / export only about 40% of what they would like to, due to competition in a 100% renewable Europe.



"No storage": Reverse engineering the present day conventional power system

European electricity demand 2000-2007:



load curve contains three time scales:

- **Intra-day (1-24 hours)**
- **Intra-week (1-7 days)**
- **Seasonal (7-365 days)**

Minimum peak capacities:

- **Intra-day: 165 GW**
- **Intra-week: 133 GW**
- **Seasonal: 273 GW**

AARHUS SCHOOL OF ENGINEERING

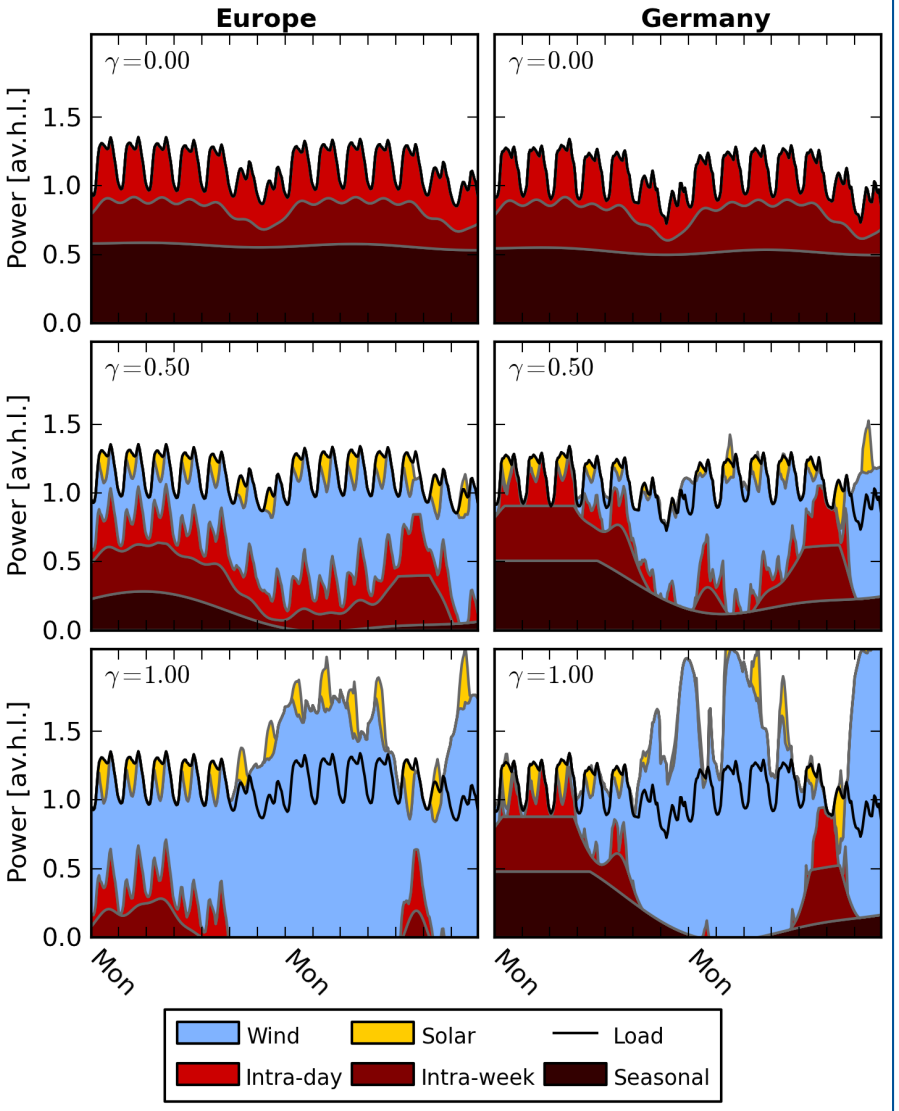
Power dispatch

Requirements:

- 99% Security of supply.
- Minimal excess power generation.
- Forced shut-down of conventional capacity.

Simple Rules of operation:

- Seasonal power generation follows 7-day moving average.
- Intra-week power generation follows 24-hour moving average.
- Intra-day power generation follows 1-hour moving average.



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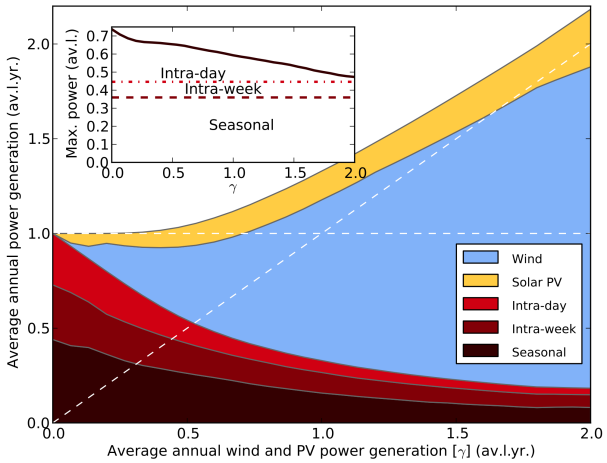
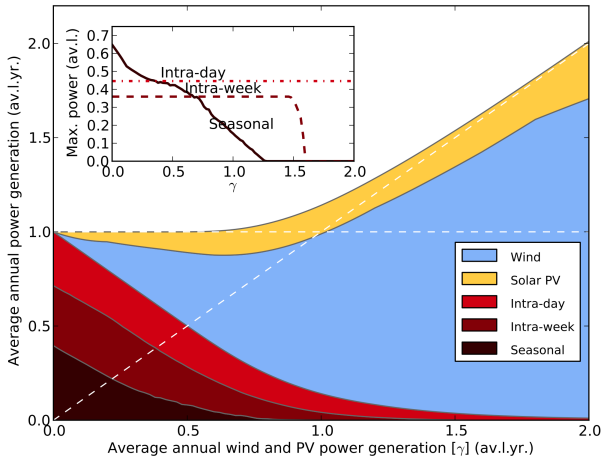
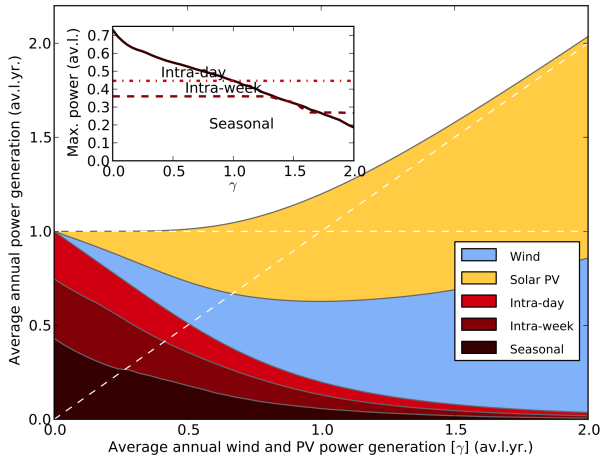
Transition: 0% → 100% renewables

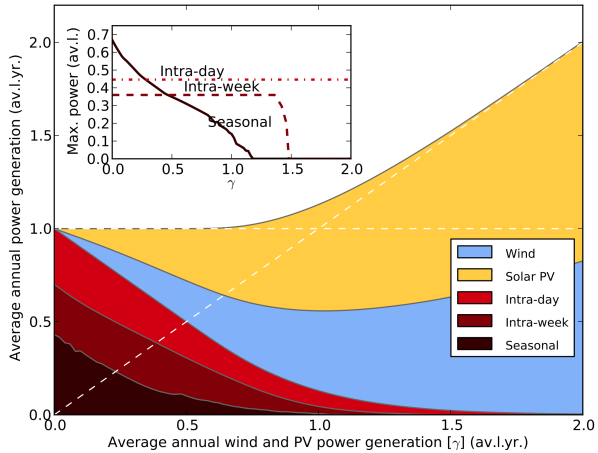
no … cross-border transmission … yes

yes…short-term storage…no





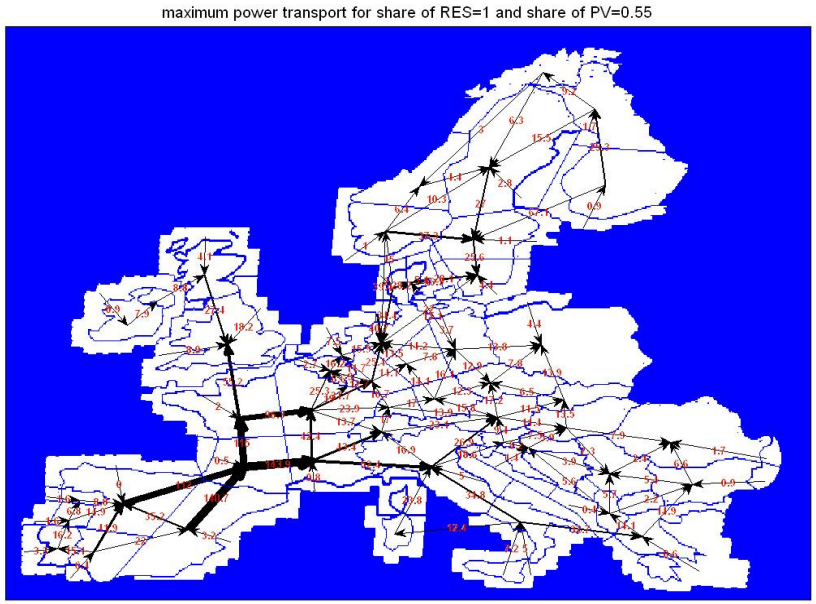




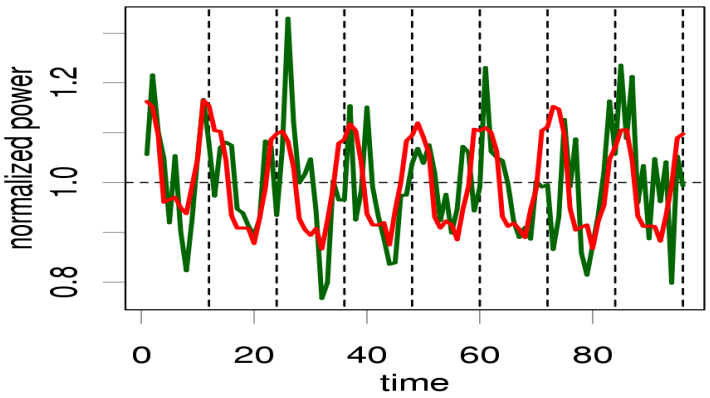
AARHUS SCHOOL OF ENGINEERING

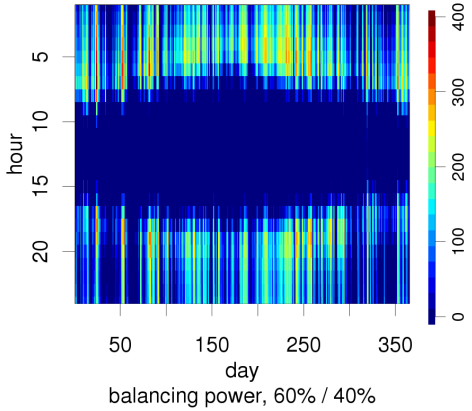
optimization:
pan-European energy system

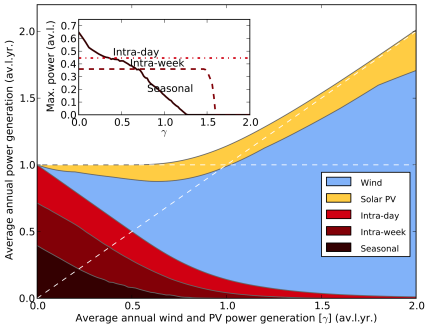
+ renewable generation
+ balancing/storage
+ transmission
+ heating / transportation
+ economics
+ social network engineering



AARHUS SCHOOL OF ENGINEERING







„A goal is a dream with a deadline!“

greiner @ imf.au.dk

Morten Grud Rasmussen
Gorm Bruun Andresen
Rolando Rodriguez
Dominik Heide **[DLR]**
Lueder v.Bremen **[ForWind]**
Clemens Hoffmann **[Siemens]**

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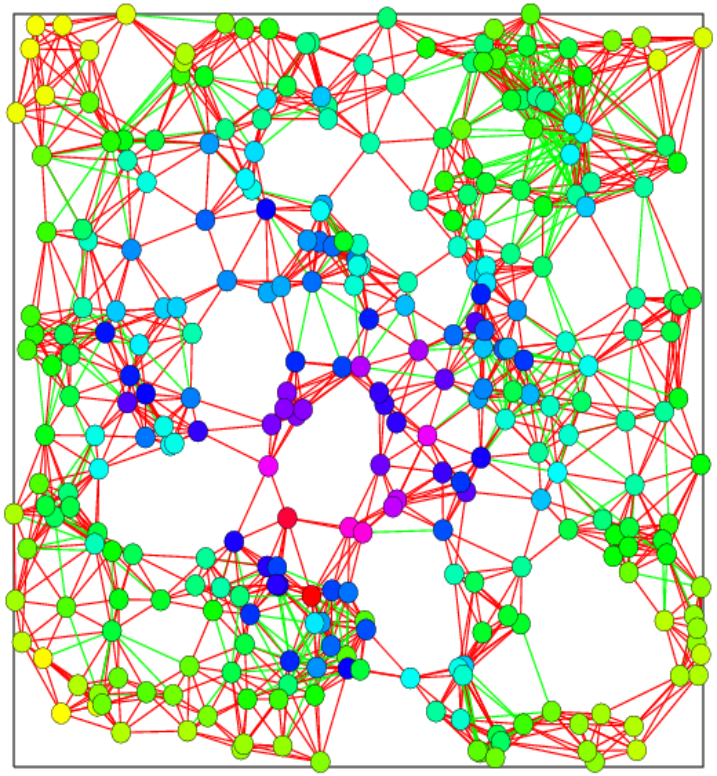
Physics of Complex Networks



Communication networks (Internet)

Biological networks (gene interactions)

Social networks (WWW, communities)

Electricity networks, …

Structure, Dynamics, Function,

Robustness, Reliability,

Self-organization.

Rolando Rodriguez
Sarah Becker
Tue Jensen
Anders Soendergaard

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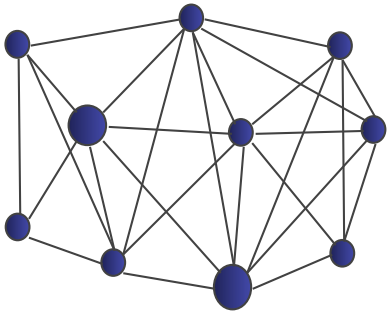
challenging problem:
dynamical power flows and self-organizing networks



$$P_{ij} = w_{ij}(\theta_i - \theta_j)$$

Statistical Physics:

$$\dot{\theta}_i = \omega_i + \sum_j A_{ij} \sin(\theta_i - \theta_j)$$

$$x_i^{t+1} = (1-\varepsilon) f(x_i^t) + \frac{\varepsilon}{k_i} \sum_j A_{ij} g(x_j^t)$$

Mirko Schaefer: Synchronization in coupled chaotic networks

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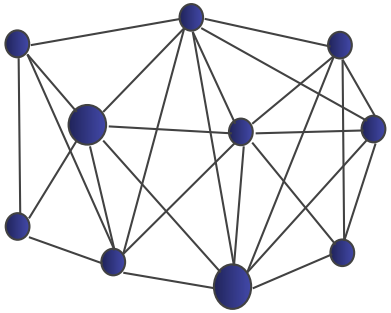
challenging problem: social network engineering

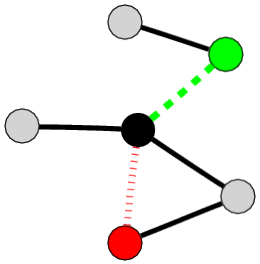
Jan Scholz: network creation game



cooperation vs. selfishness

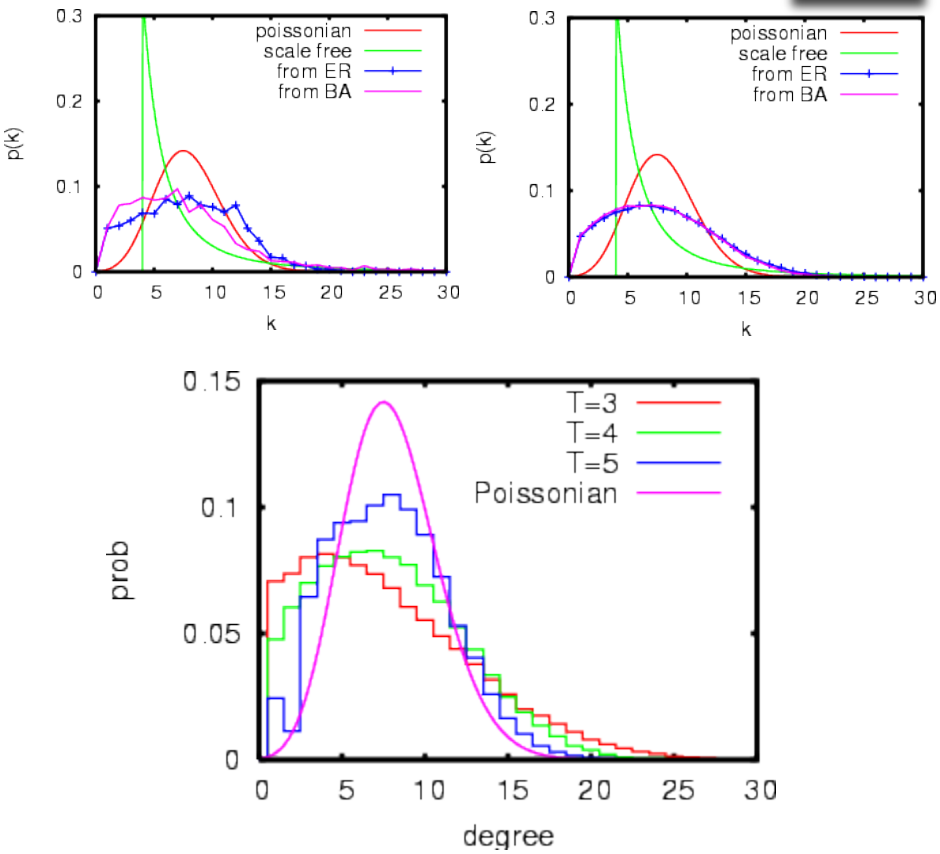
$$\text{payoff} = \begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix}$$

new-node encounter



degree distribution

$T = 4$



T = self-organizing control parameter

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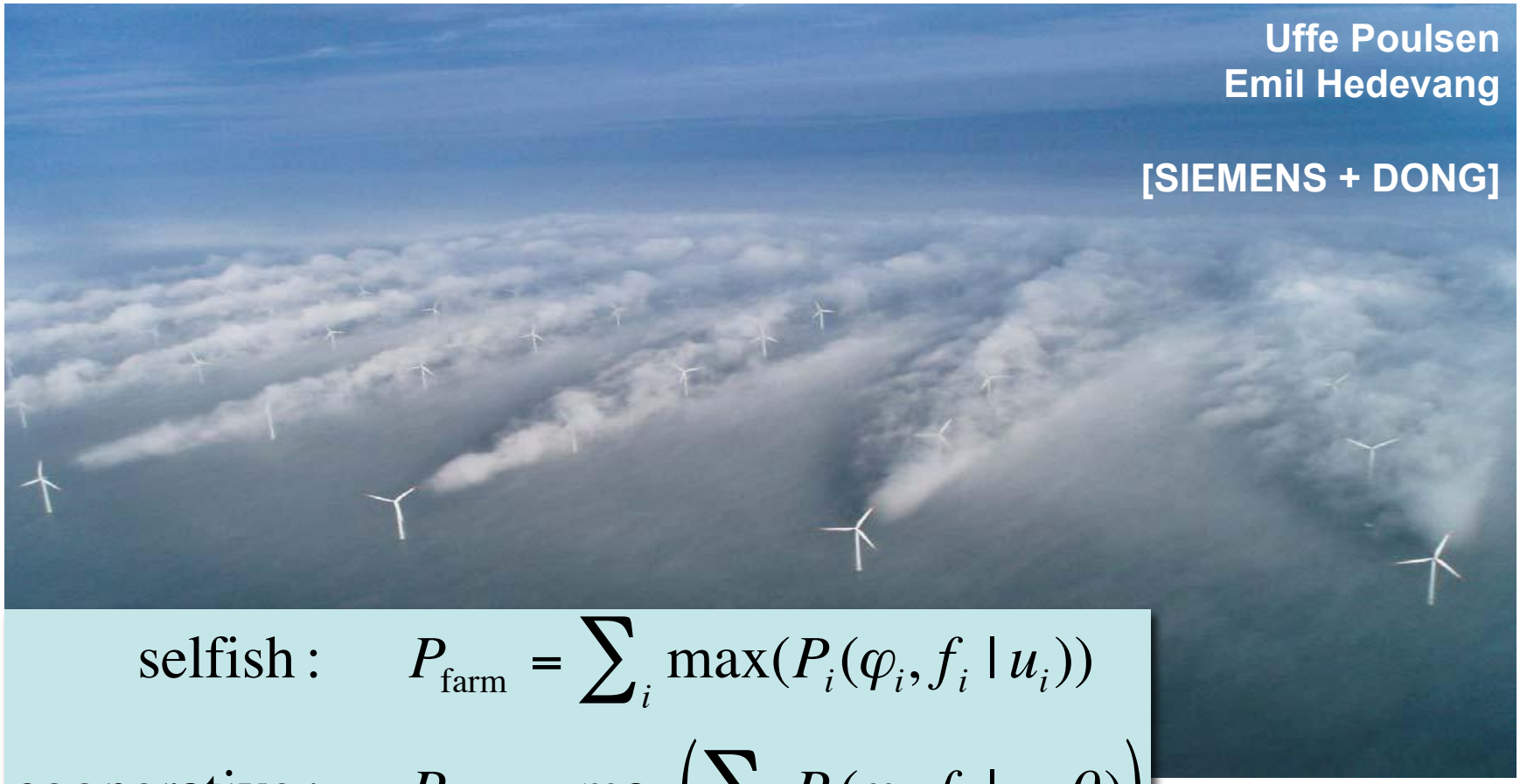
Wind-farm modeling + optimization + control



Uffe Poulsen
Emil Hedevang

[SIEMENS + DONG]

$$\text{selfish}: \quad P_{\text{farm}} = \sum_i \max(P_i(\varphi_i, f_i \mid u_i))$$

$$\text{cooperative}: \quad P_{\text{farm}} = \max\left(\sum_i P_i(\varphi_i, f_i \mid u_i, \theta)\right)$$

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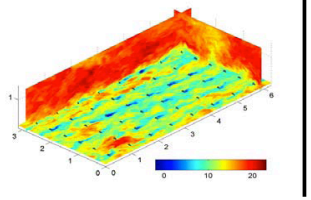
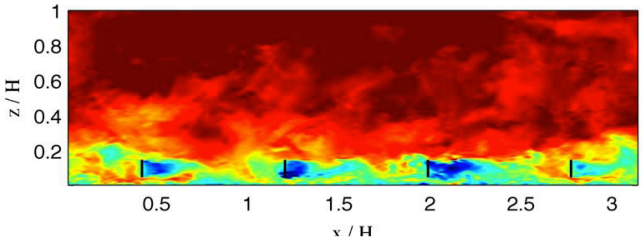
Charles Meneveau (John Hopkins University)

Simulations results:

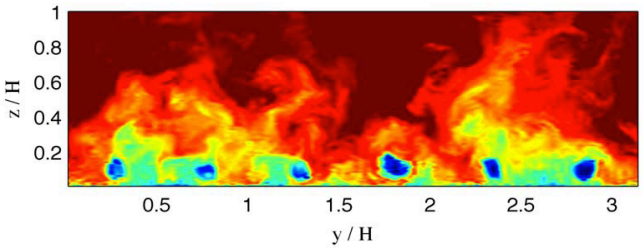


Instantaneous stream-wise velocity contours:

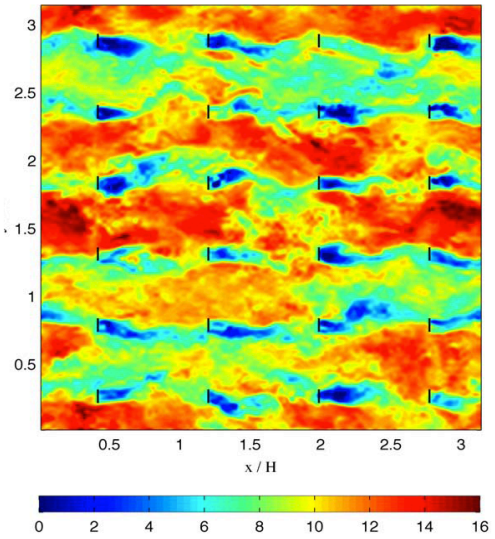
side-view



front-view



top-view



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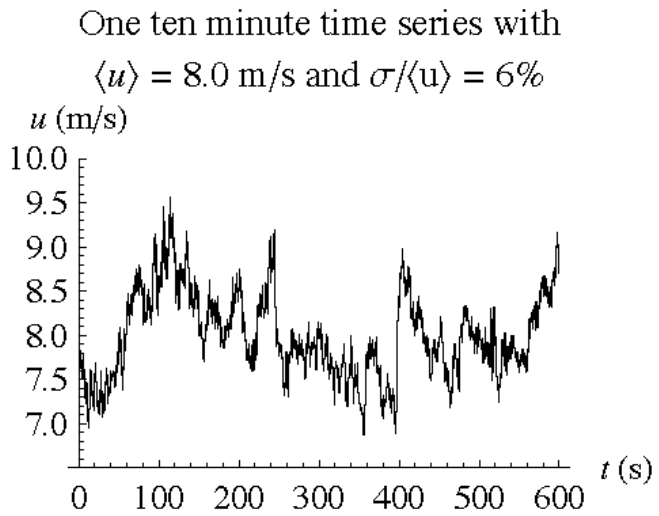
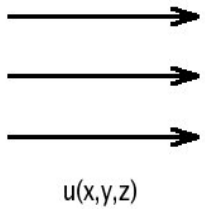
Turbulence modeling of wind fields





(1) ambient turbulence,
(2) wake turbulence.

External wind conditions affect structural loading, durability and operation of wind turbines.

engineering + mathematics + physics:

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