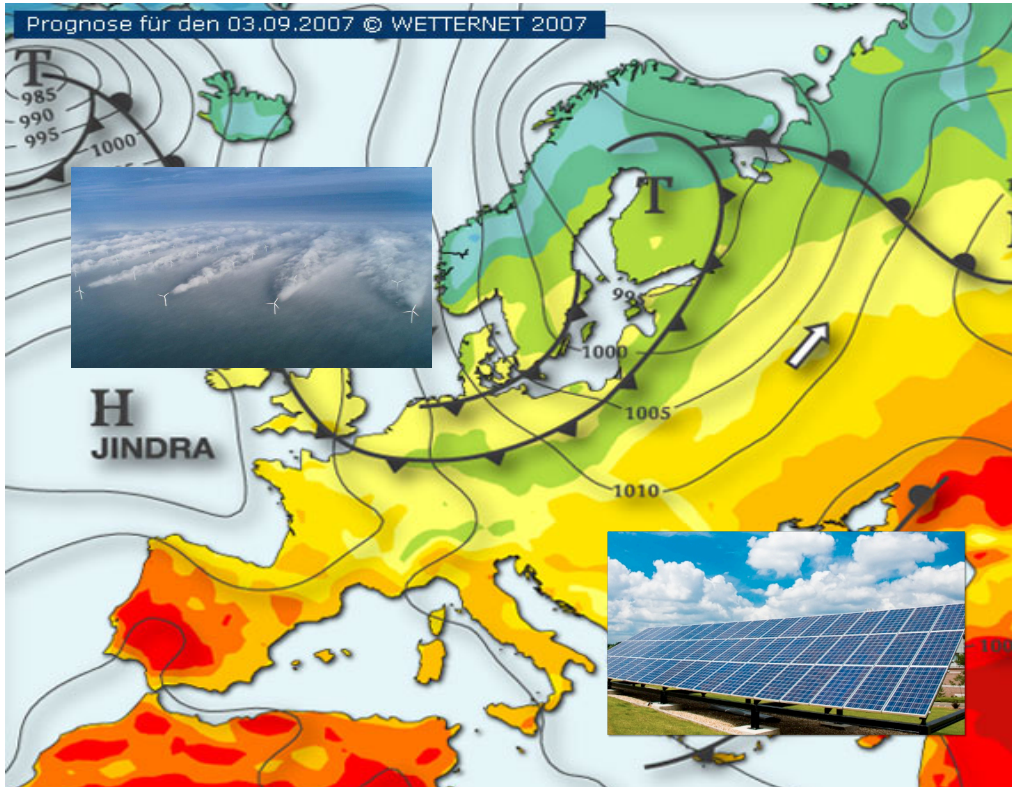
Exploring the functional organization of 100% Renewable macro Power Systems



renewables
… + more renewables
…….. + much more renewables

What is the end of the story?

How much …
… wind + solar power?
… balancing
+ storage
+ transmission?
… investments when and where?

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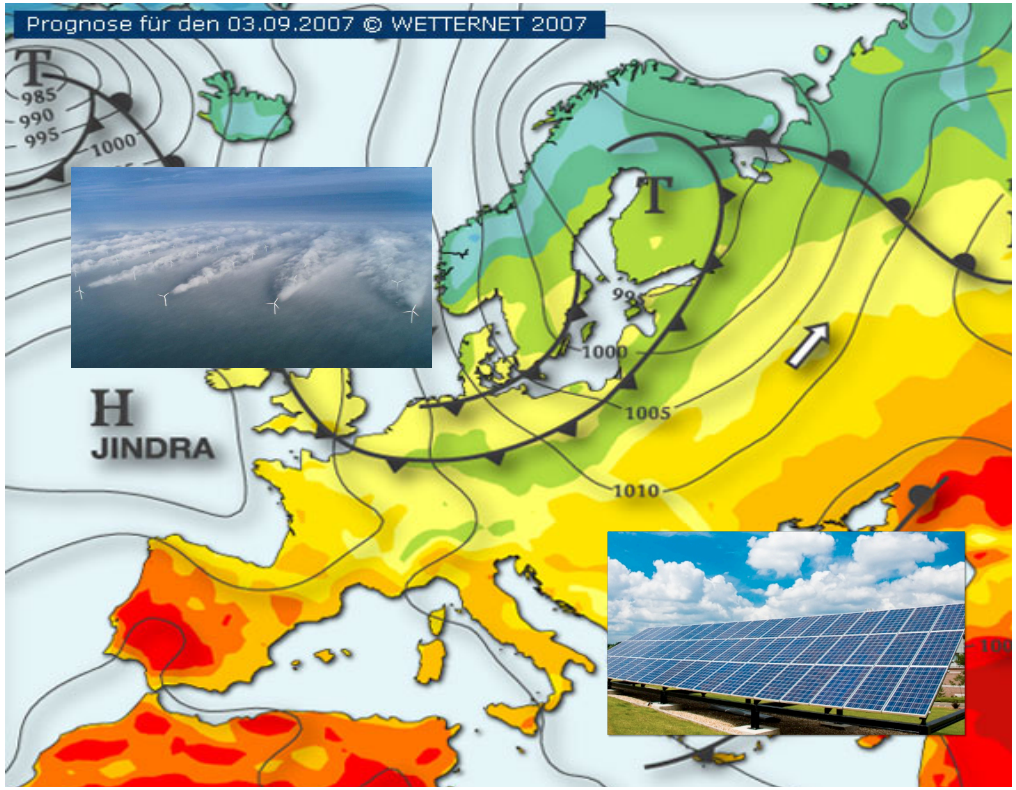
Exploring the functional organization of 100% Renewable macro Power Systems



Let the weather decide!

2000 – 2007: 1h, 45x45km²
1980 – 2010: 1h, 30x30km²

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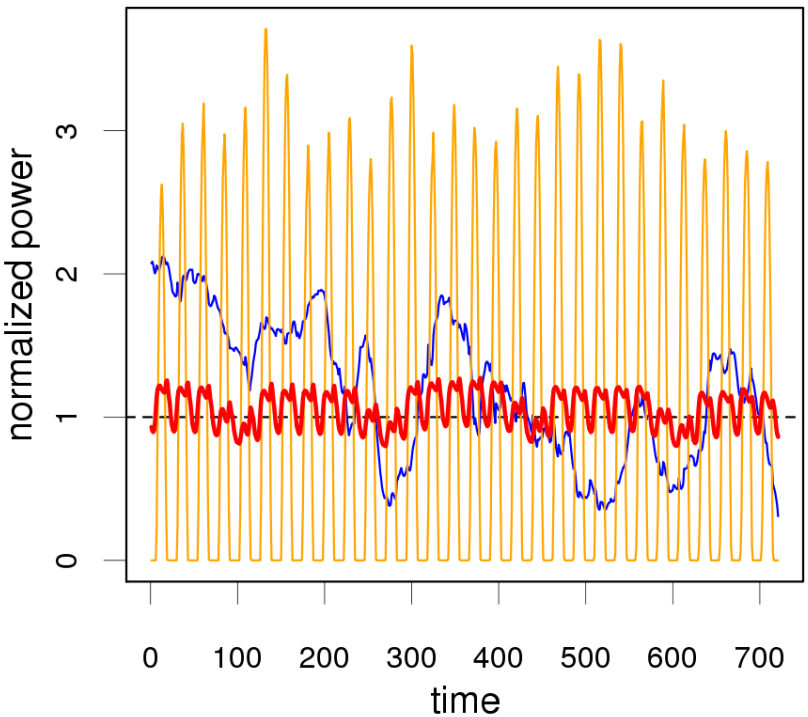
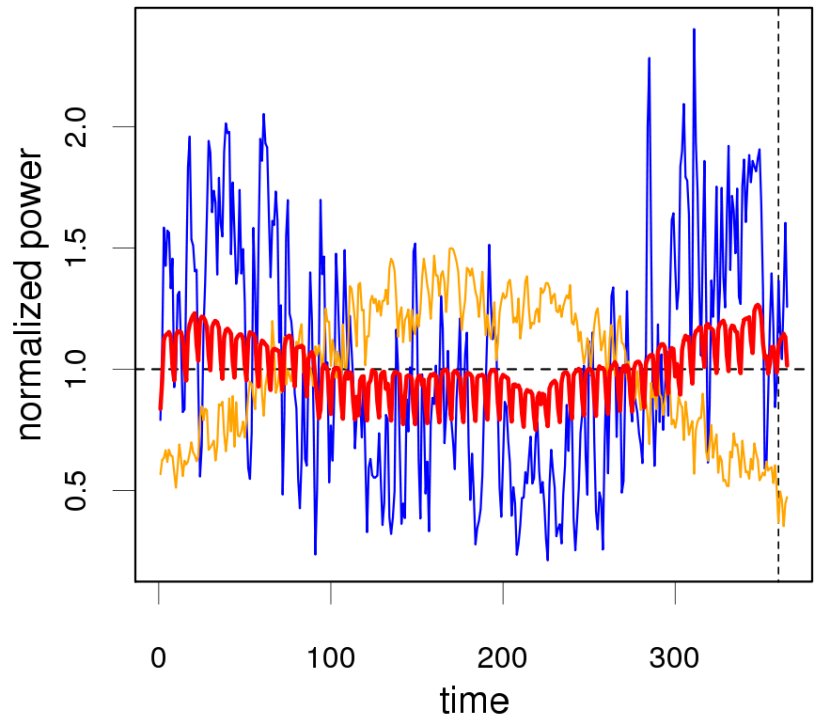
Wind + Solar PV + Load time series of aggregated Europe



1hour resolution (of 1month)



1day resolution (of 1year)

3 TIME SCALES:

diurnal (1h-1d)
synoptic (2-10d)
seasonal (1y)

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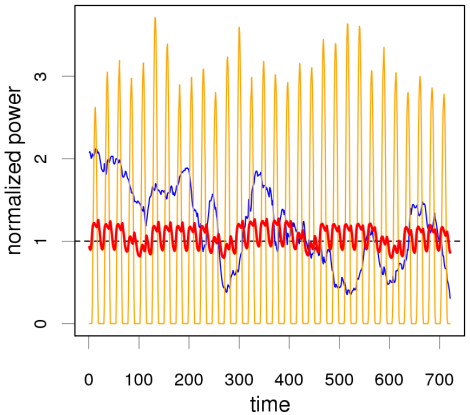
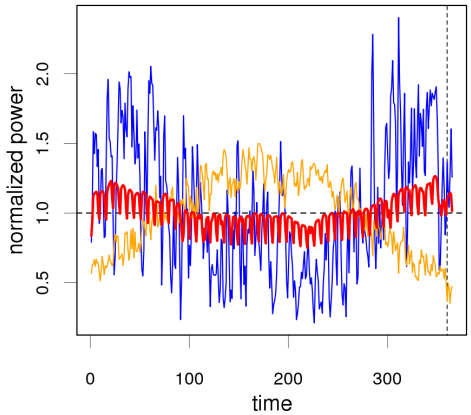
How much wind + solar power? How much storage?

(with penetration = 100%)

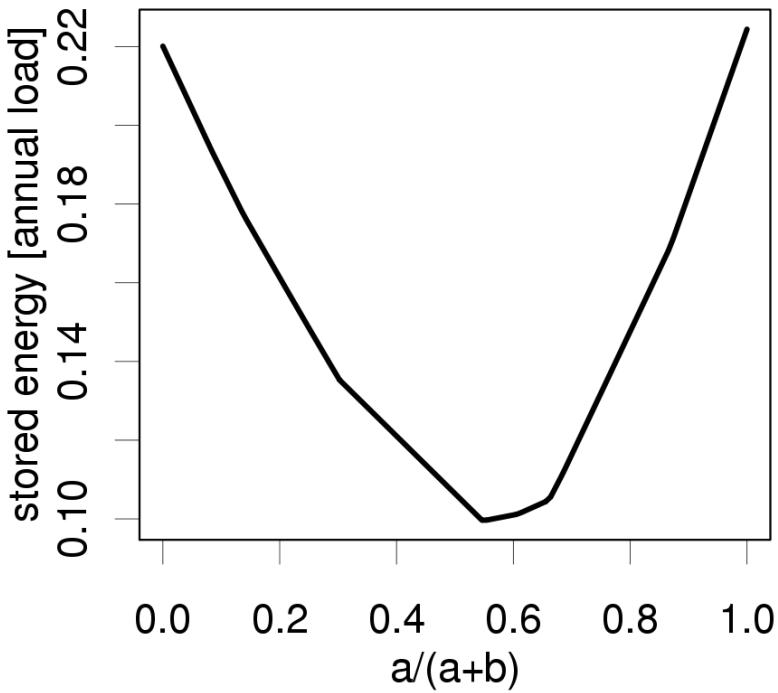




$$\Delta(t) = \alpha\, G_W(t) + (1-\alpha)\, G_S(t) - L(t)$$

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

Seasonal optimal mix
= 60% wind power
+ 40% solar power



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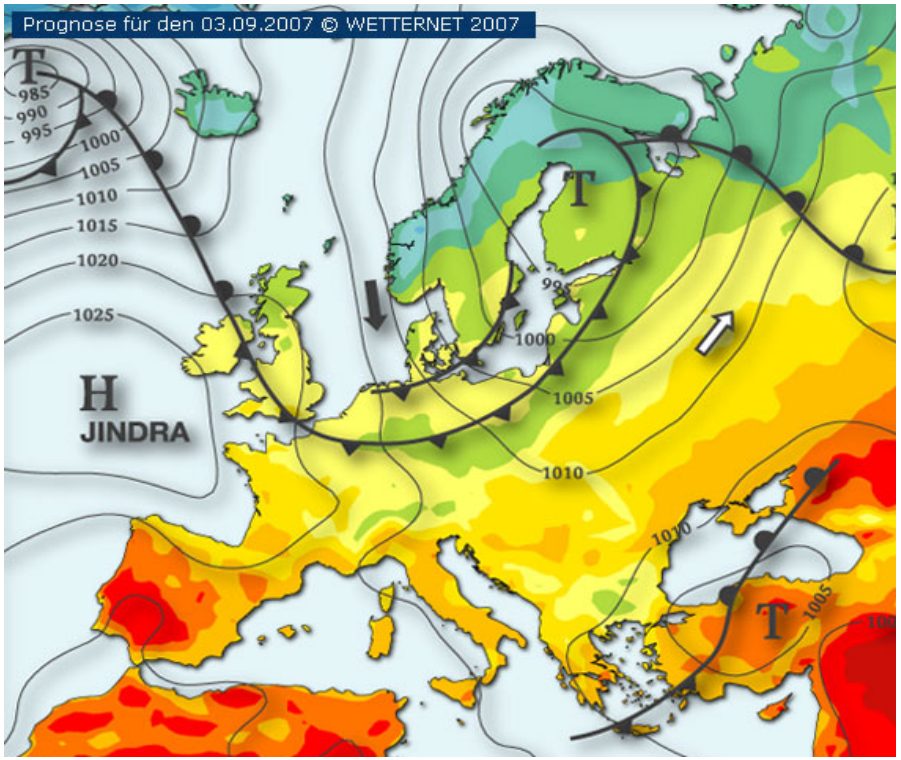
How much wind + solar power?



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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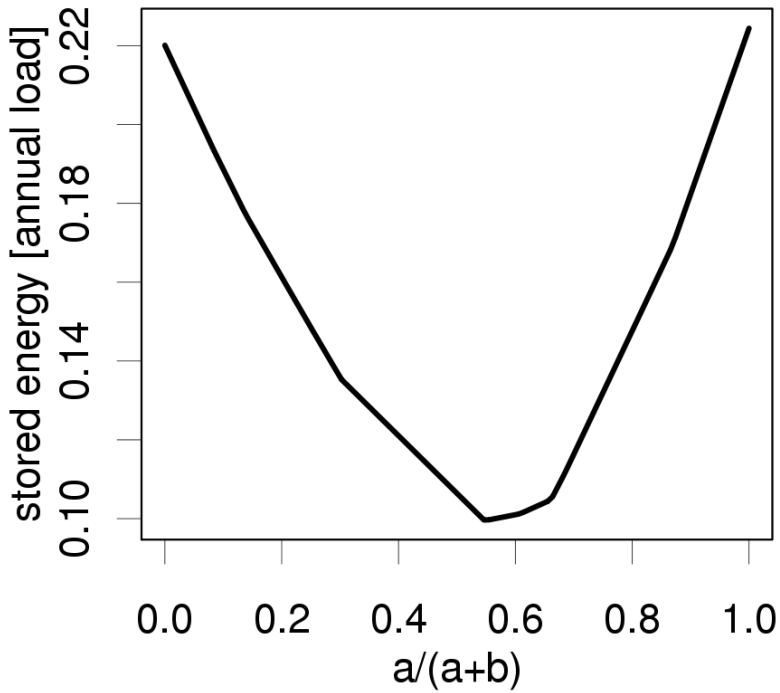
How much storage?



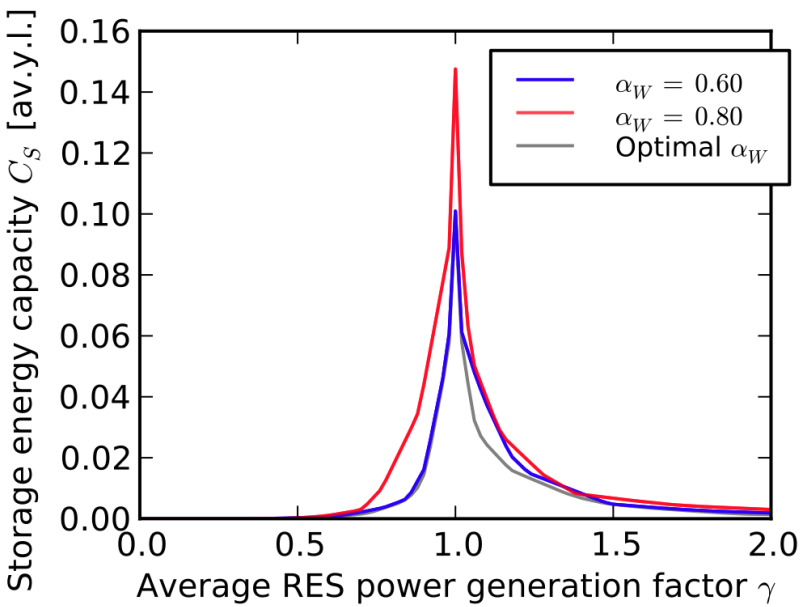
$$C_S = 10\% \langle L \rangle_{\text{annual}}$$
$$= 340 \text{ TWh}$$

NOT POSSIBLE:
Pumped Hydro,
Compressed Air

POSSIBLE:

H2 storage
25 TWh = 0.008 av.y.l.

6h storage
2.2 TWh = 0.0007 av.y.l.



Excess penetration:

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

$$\gamma > 1$$

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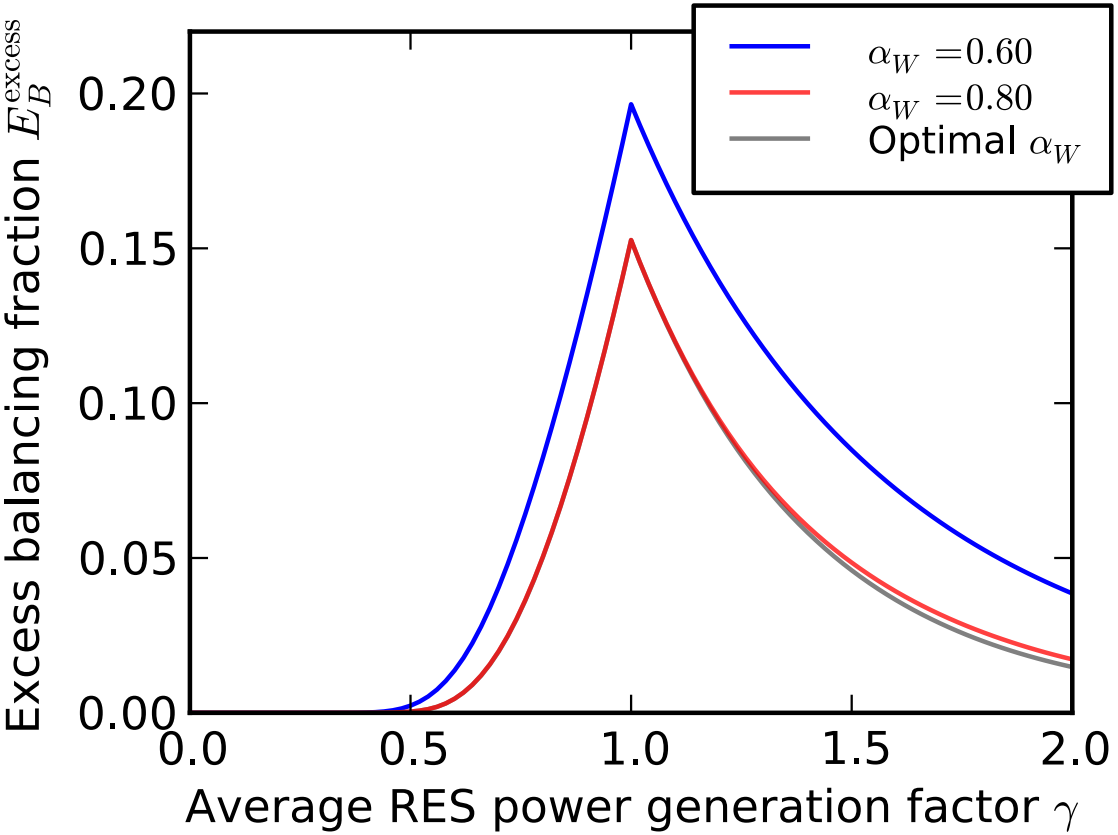
so far: only storage
now: what about only balancing?

$$\langle B(t)\rangle = \begin{cases} \langle \Delta_-(t)\rangle - (1-\gamma) = \langle \Delta_+(t)\rangle & (\gamma < 1) \\ \langle \Delta_-(t)\rangle & (\gamma > 1) \end{cases}$$



$\gamma = 1,\ \alpha = 0.8:$

$$\langle B(t)\rangle_{EU} = 15\% \langle L\rangle_{\text{annual}} = 510 \text{ TWh}$$

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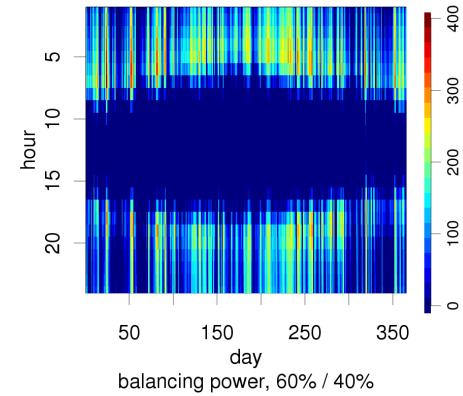
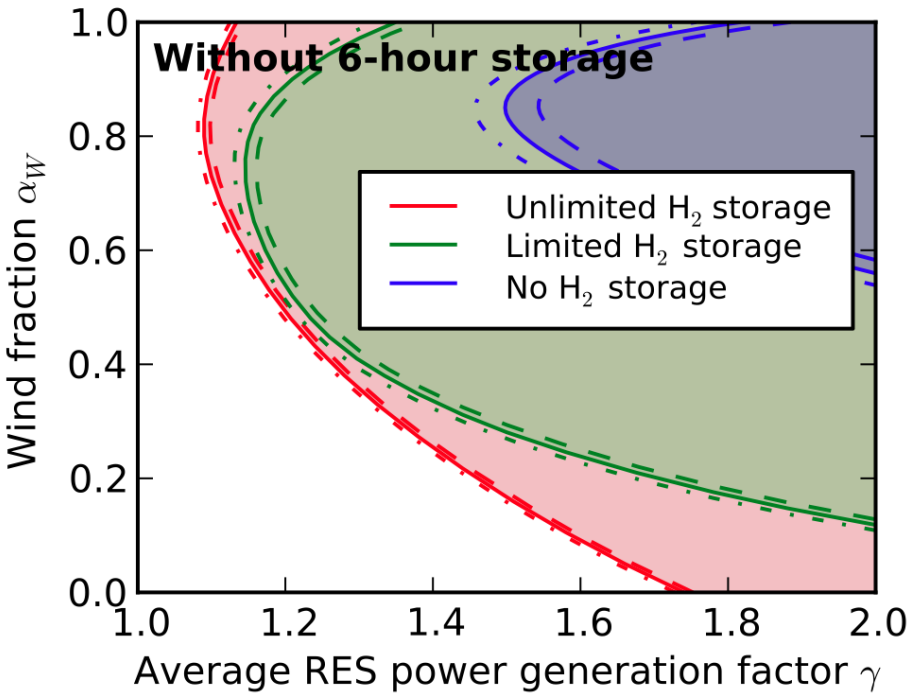
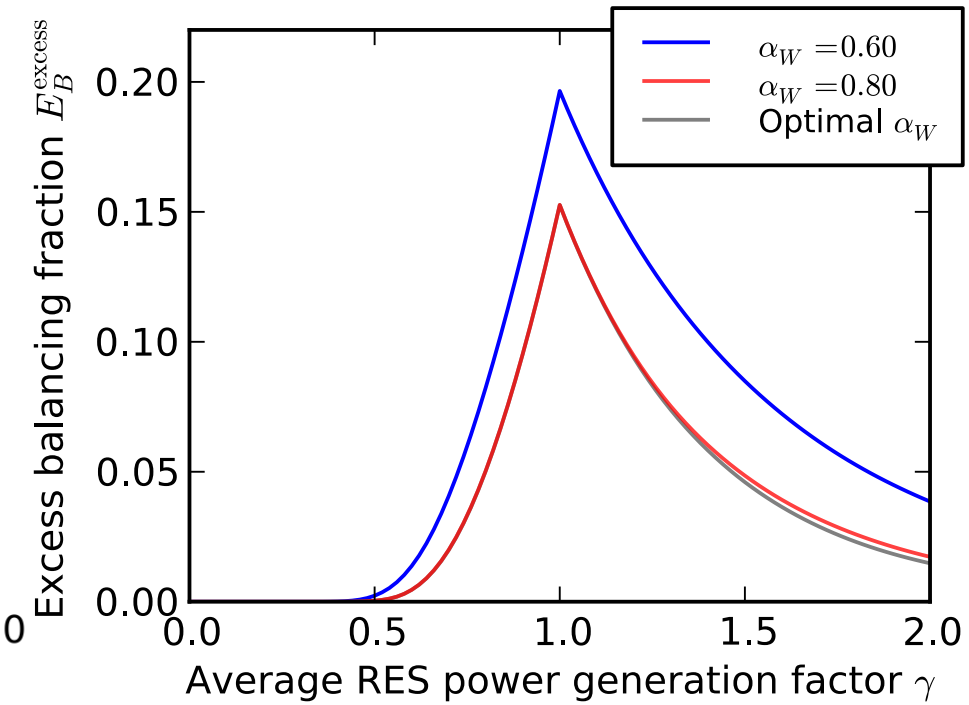
What about synergies: "storage + balancing"?



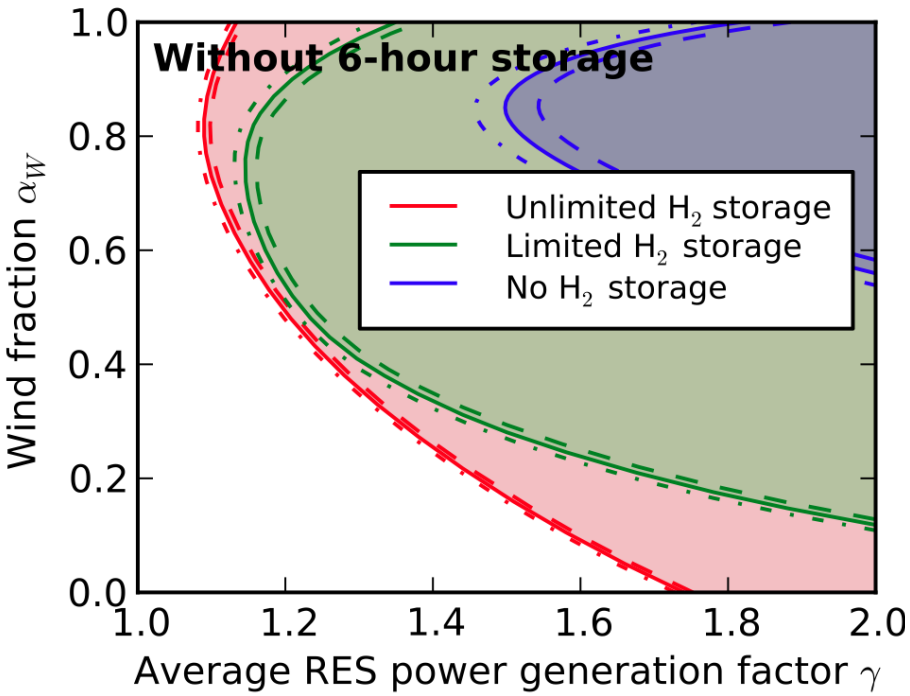


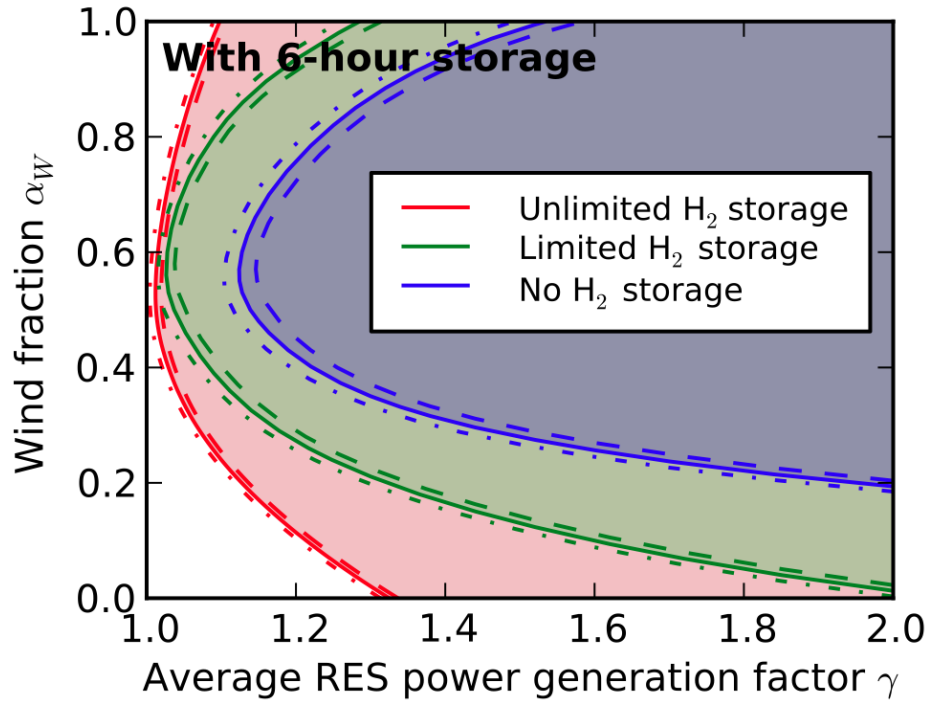


$\gamma = 1,\ \alpha = 0.8:$

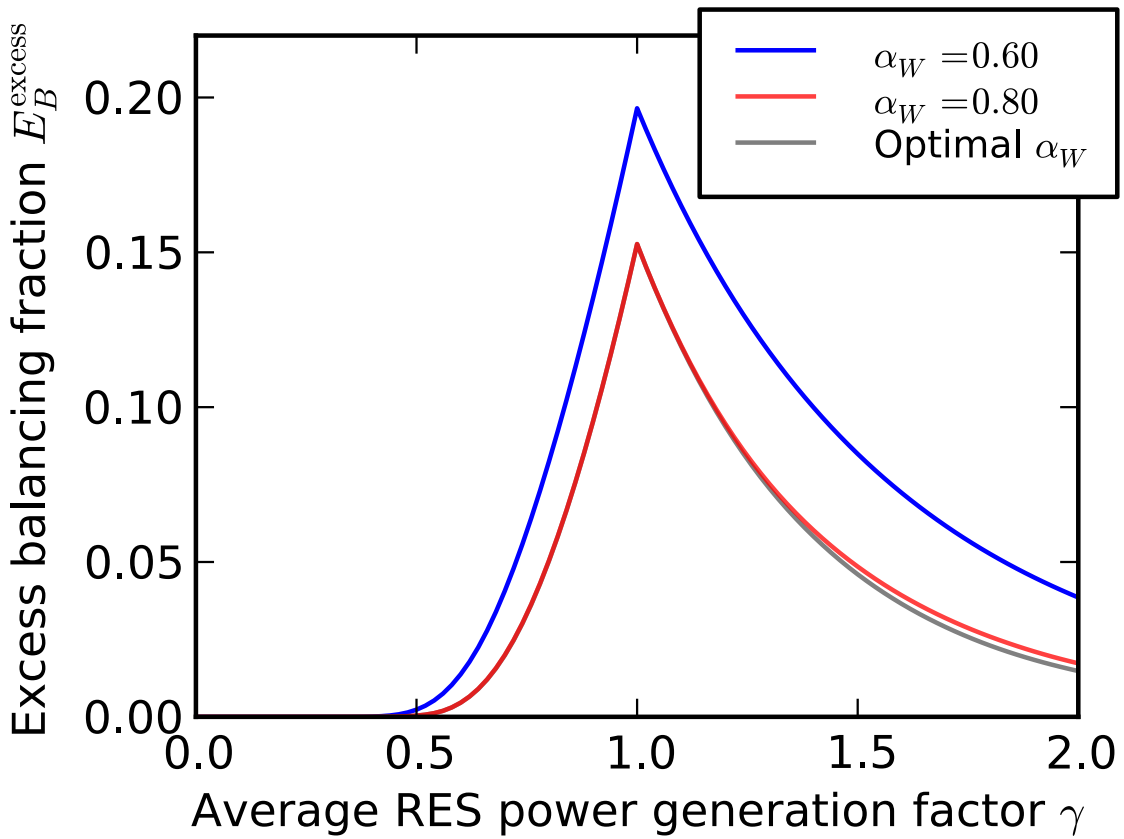
$$\langle B(t) \rangle_{EU} = 15\% \langle L \rangle_{\text{annual}} = 510 \text{ TWh}$$

6h storage (2.2 TWh, η=1.0)
+ seasonal H2 storage (25 TWh, η=0.6)
+ "hydro" balancing (150 TWh)





Cooperative Europe vs. Selfish Countries



$\gamma = 1,\ \alpha = 0.8:$

$$\langle B(t) \rangle_{EU} = 15\% \langle L \rangle_{\text{annual}} = 510 \text{ TWh}$$

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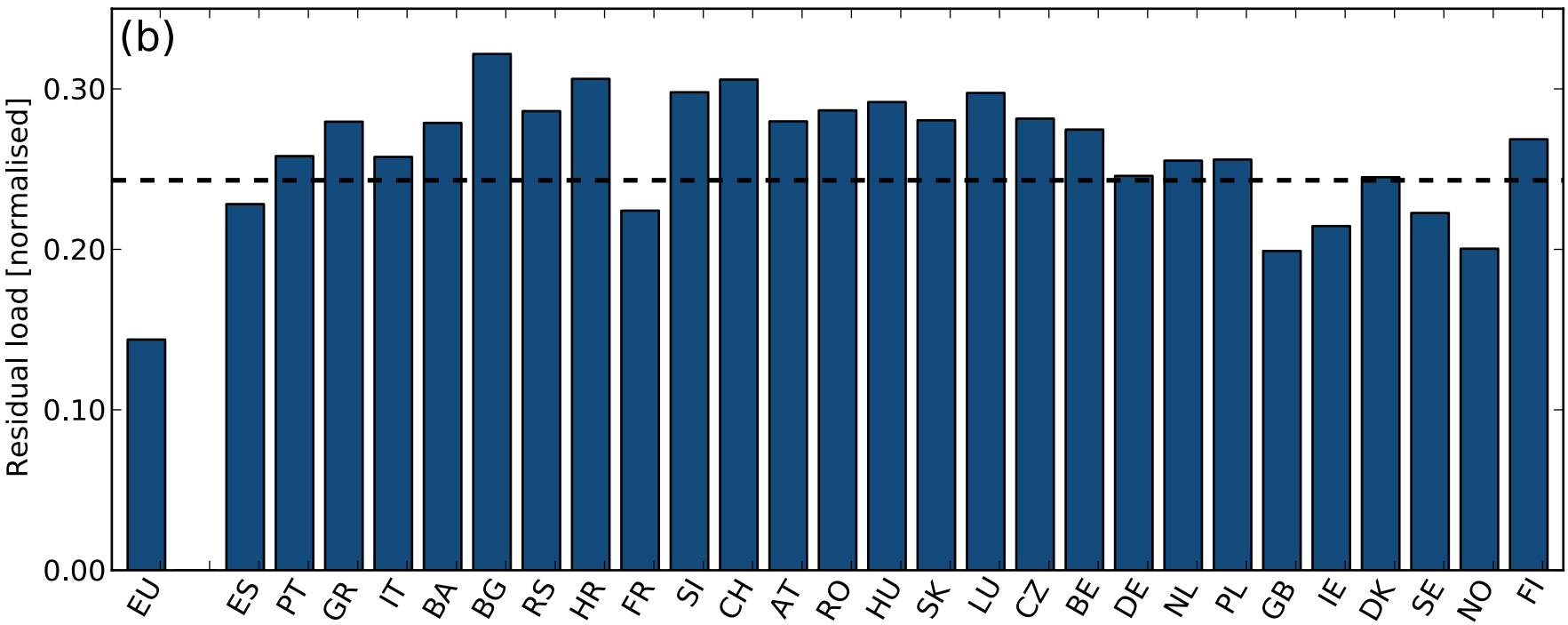
Cooperative Europe vs. Selfish Countries

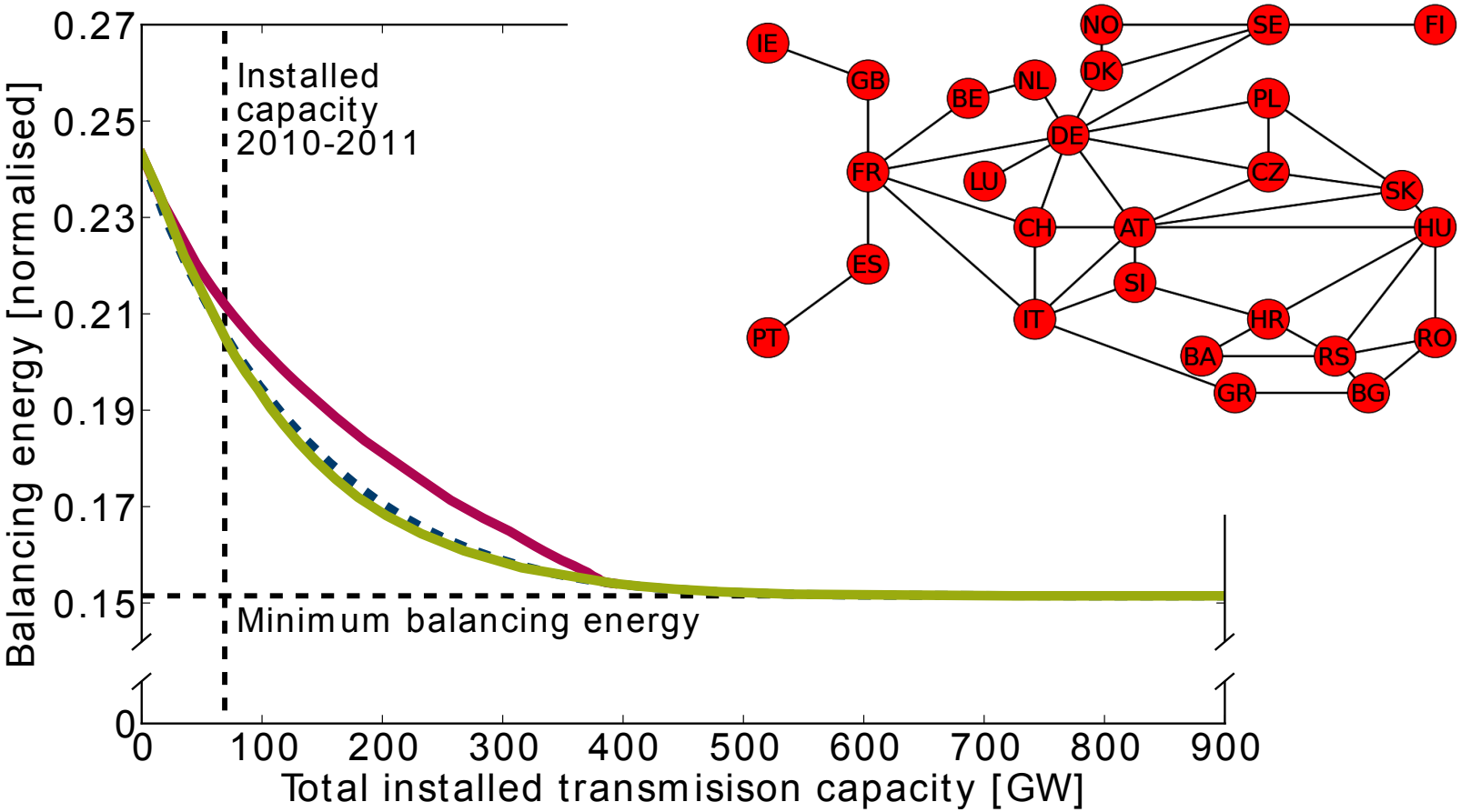
$\gamma = 1$

minimum balancing energy at optimal wind / solar mix



$\langle B(t) \rangle_{EU} = 0.15$ **vs.** $\sum_X \langle B(t) \rangle_X = 0.24$

Balancing vs. Transmission



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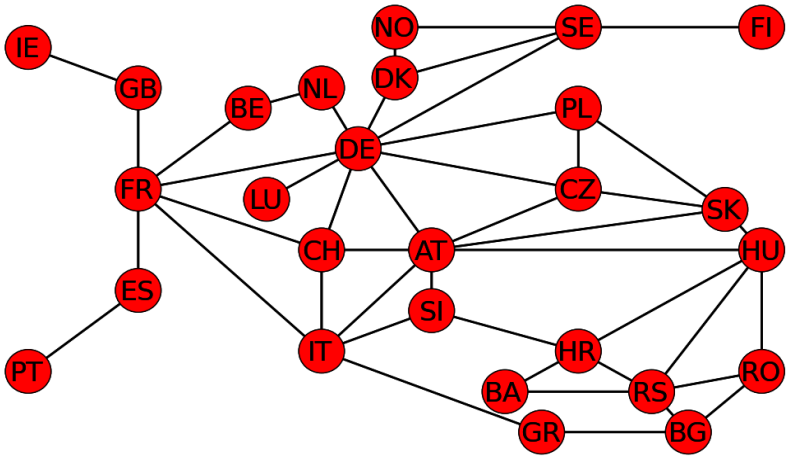
Balancing vs. Transmission

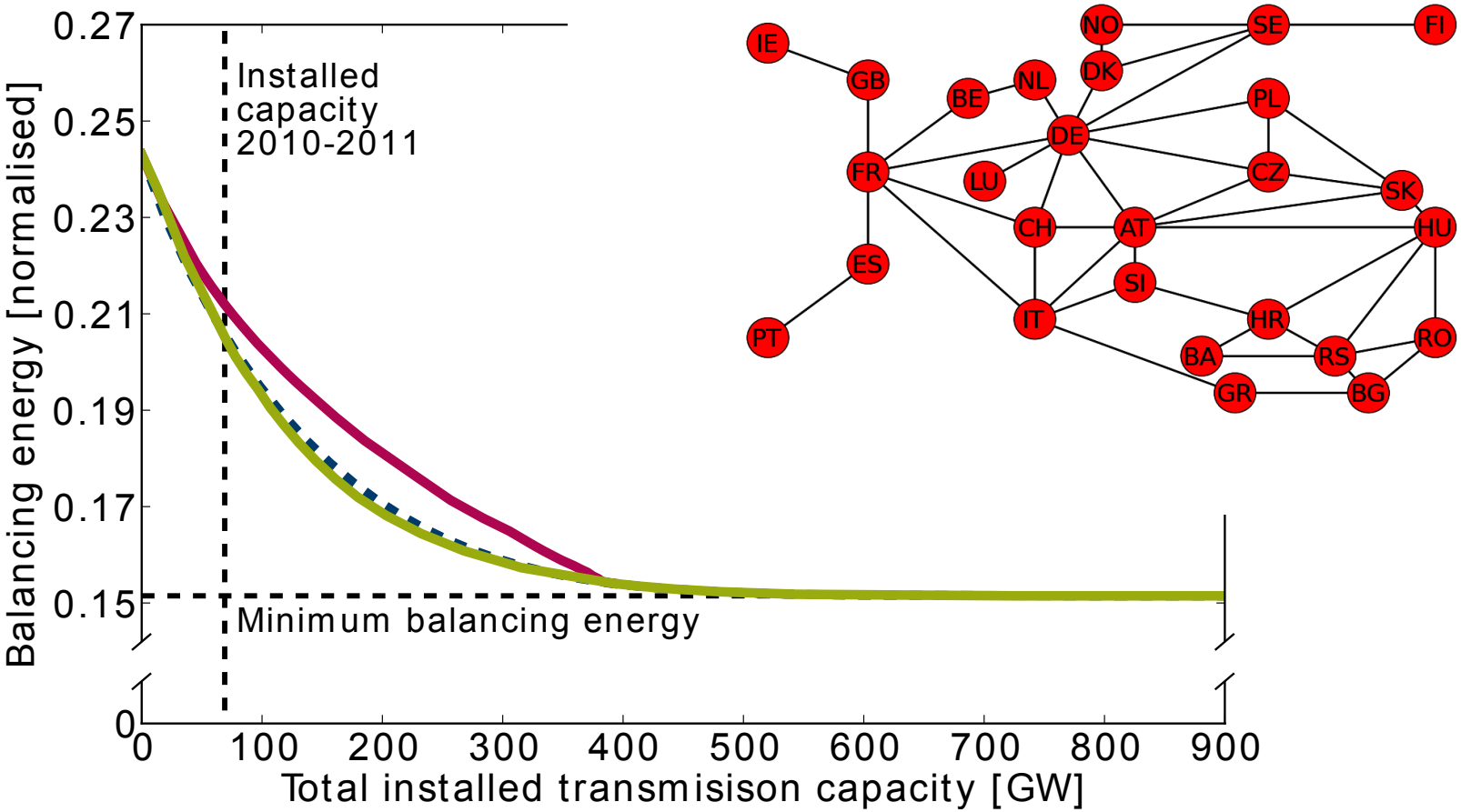
$$\min \sum_n B_n$$

$$\min \sum_l F_l^2$$



MOVIE

Balancing vs. Transmission



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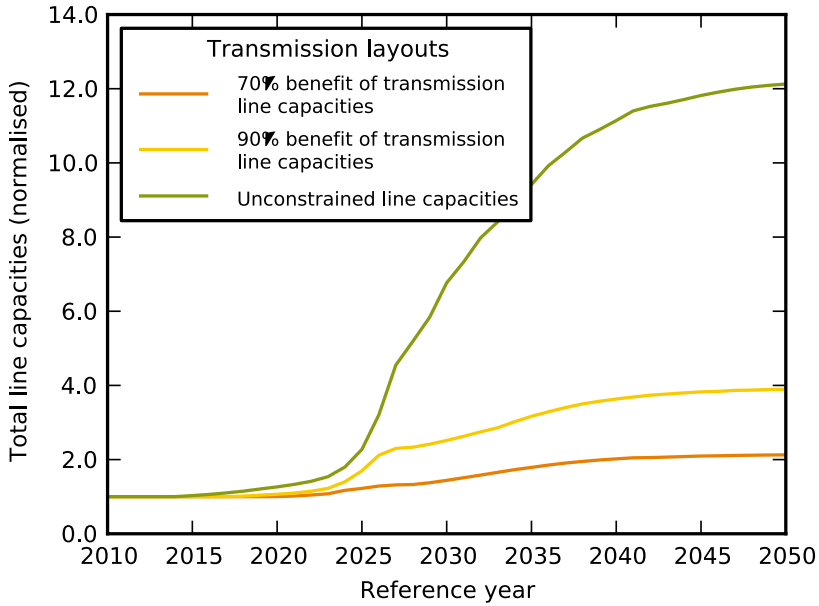
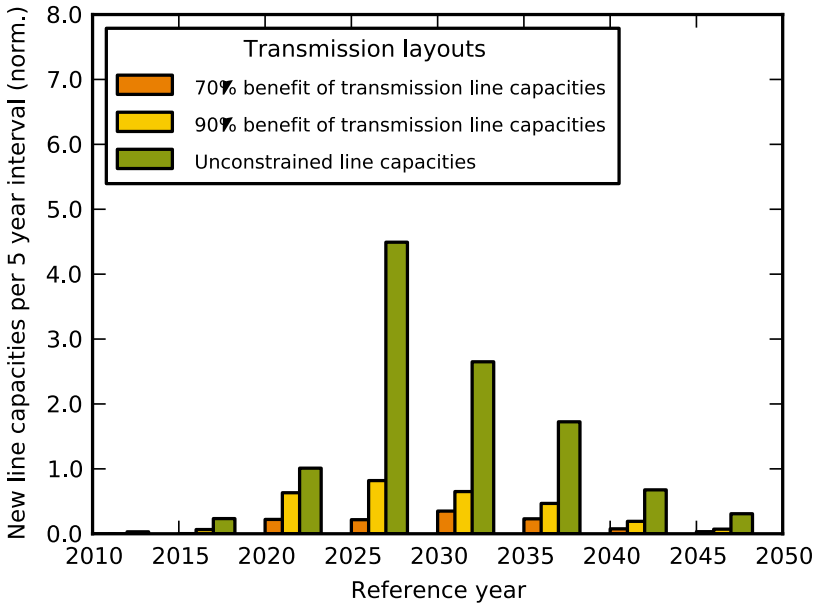
Transmission 2013 → 2050





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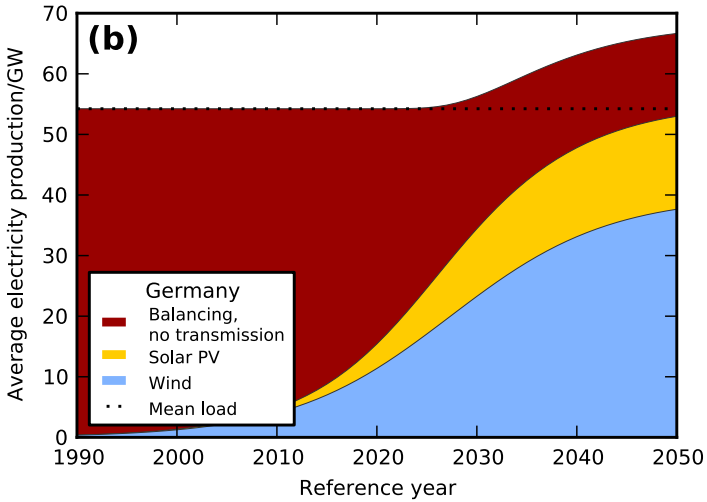
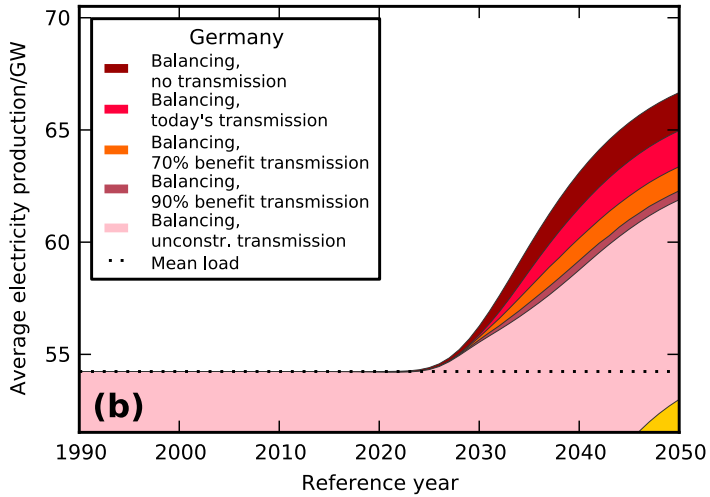
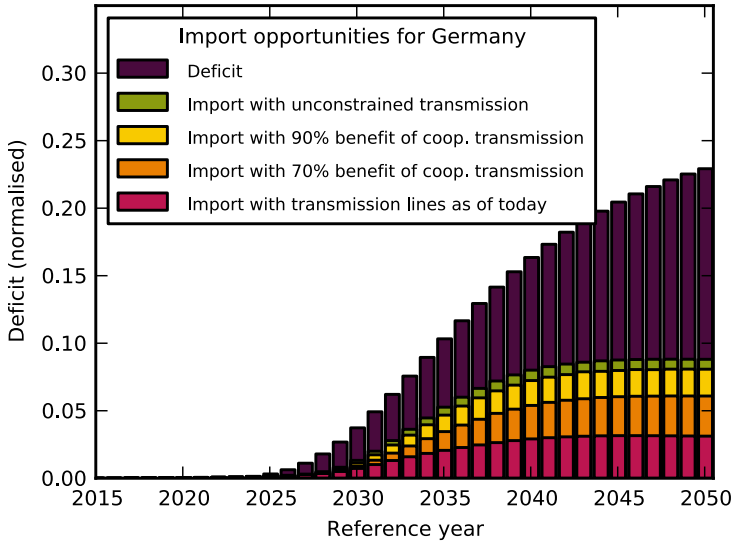
Transmission + Excess Balancing

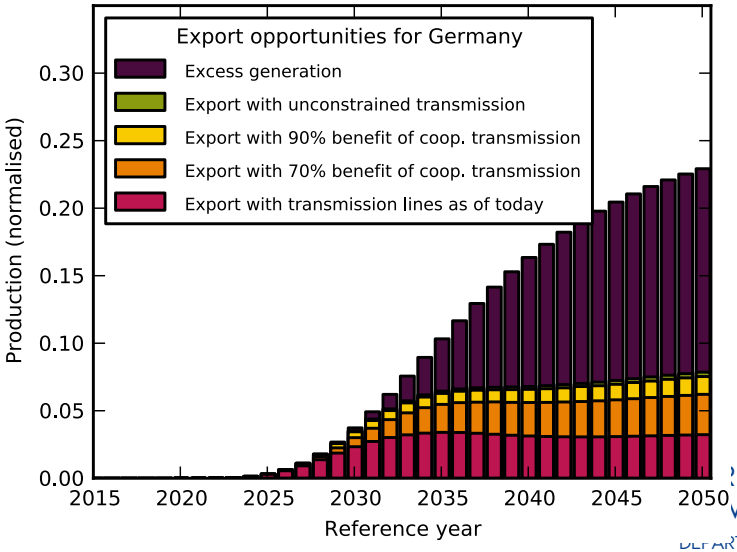




GERMANY

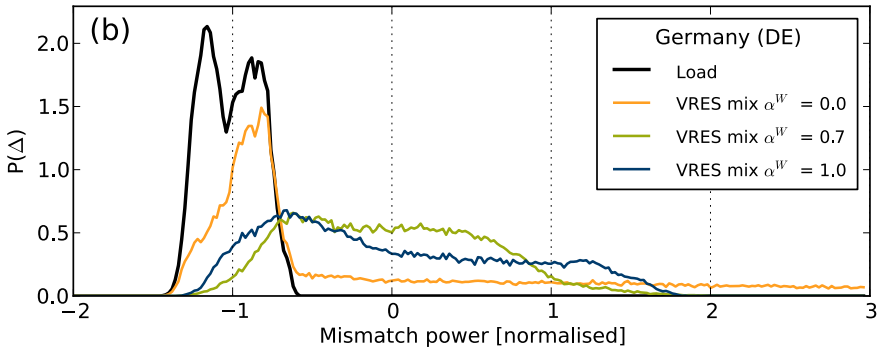
Imports + Exports





RHUS
VERSITY
DEPARTMENT OF ENGINEERING

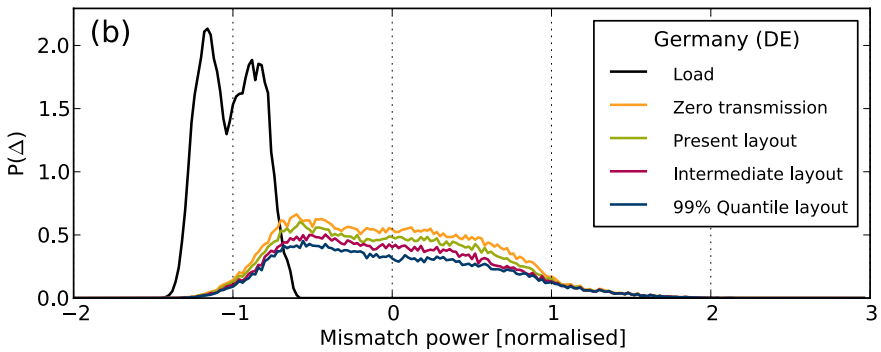
Transmission + Balancing Power



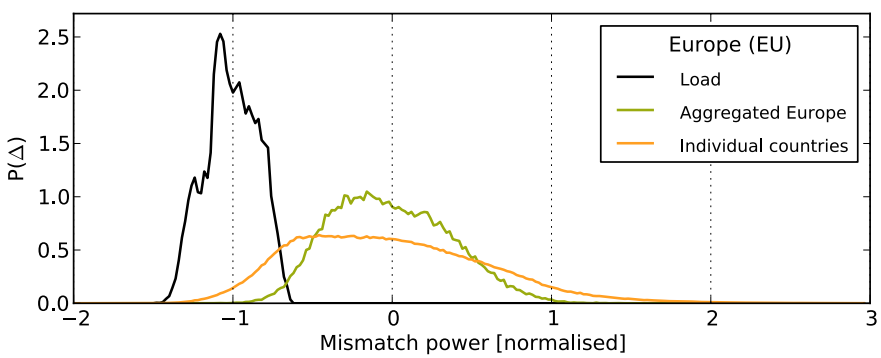
Mismatch without Transmission

$$\Delta(t) = \alpha\, G_W(t) + (1-\alpha)\, G_S(t) - L(t)$$

$$\gamma = 1$$



Mismatch with Transmission



Transmission ≠ Transmission

Cooperative Markets !

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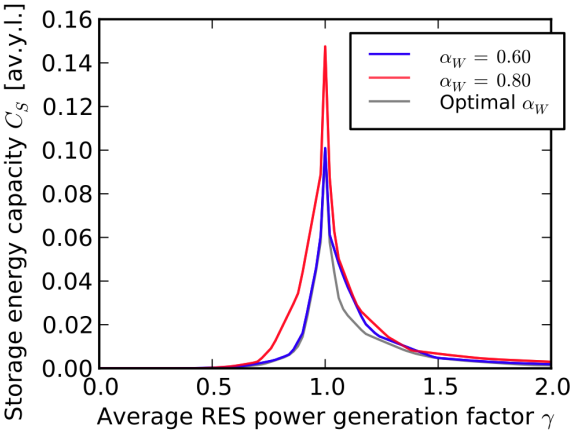
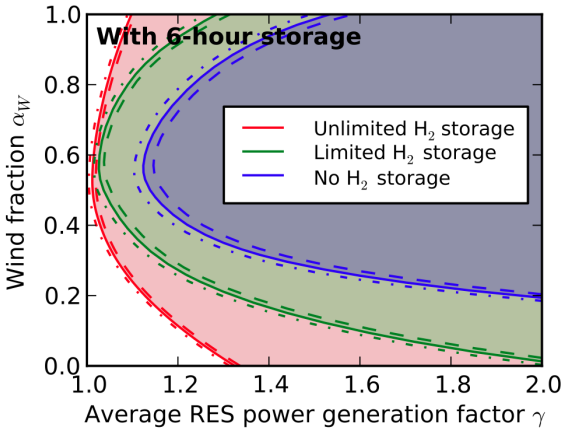
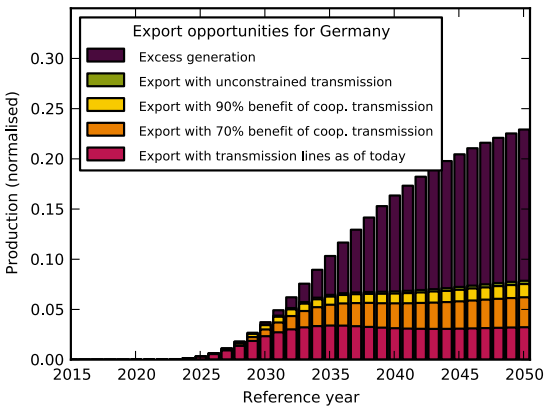




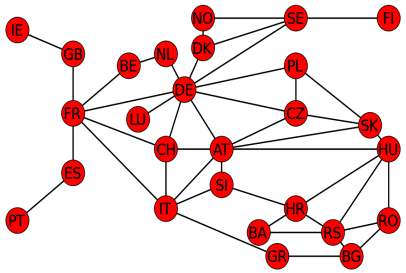


Fundamental Research on Renewable Energy Systems

at the interface between engineering + mathematics + physics

BIG SIMULATIONS: CONSENSYS-2050

transmission + storage + balancing,
smart energy systems,
coupled infrastructures,
economics + markets,
OPTIMAL TRANSITION 2013 → 2050



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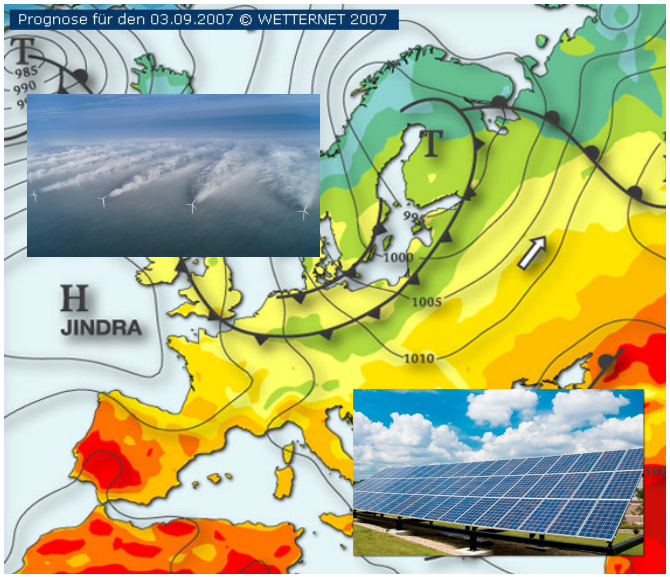
Thank you!

Martin Greiner
Aarhus University
greiner@imf.au.dk

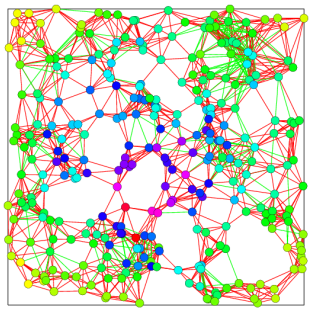
System Engineering .....
..... Physics of Complex Systems .....
..... Applied Mathematics

Fundamental Research on Renewable Energy Systems



(1) 100% Renewable Energy Systems

(2) Complex Networks



(3) Wind-farm Modeling
+ Optimization

G Andresen	(Industrial PostDoc)
R Rodriguez	(PHD)
S Becker	(PhD)
T Jensen	(Master)
A Søndergaard	(Master)
T Zeyer	(Master)

U Poulsen	(Assistant Professor)
J Herp	(Master)
T Bonde	(Master)

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