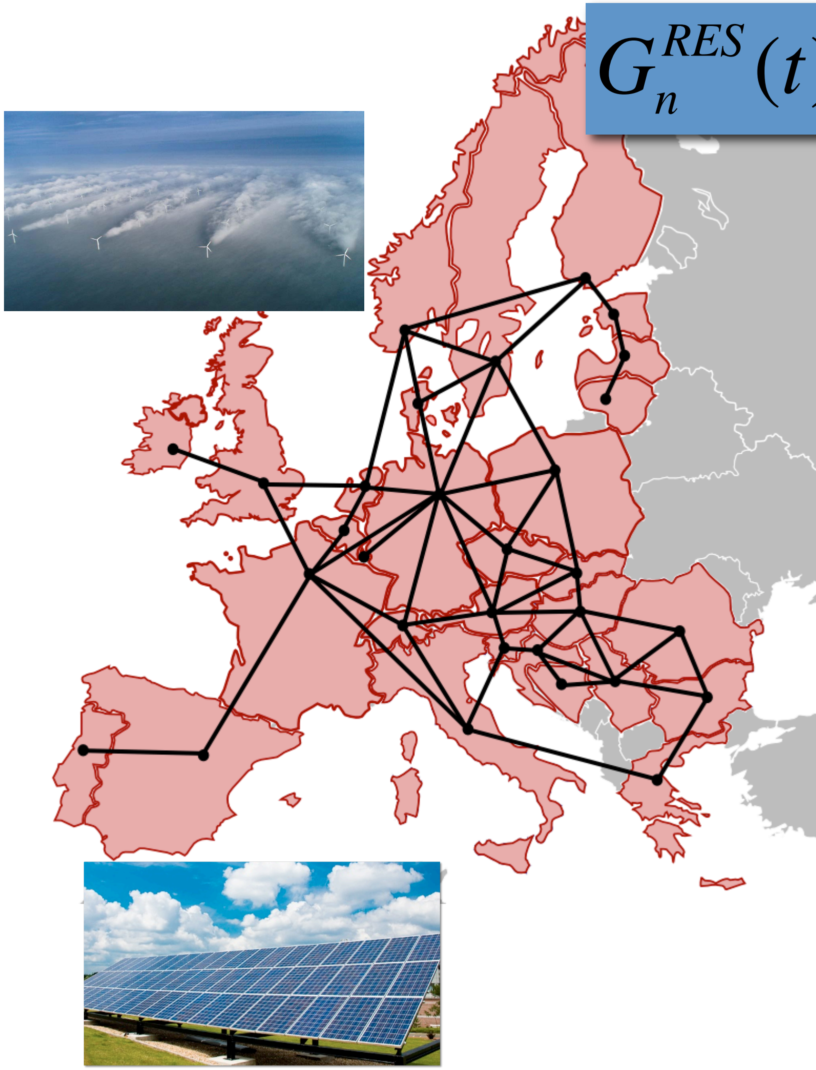
Complex Renewable Energy Networks



$$G_n^{RES}(t) + B_n(t) = L_n(t) + T_n(t) + C_n(t)$$

$$G_n^{RES}(t) = G_n^{W}(t) + G_n^{S}(t)$$

Renewable Energy Atlas

2000 – 2007: 1h, 45x45km²

1980 – 2010: 1h, 30x30km²

$$\left\langle G_n^{RES} \right\rangle_t = \left\langle L_n \right\rangle_t$$

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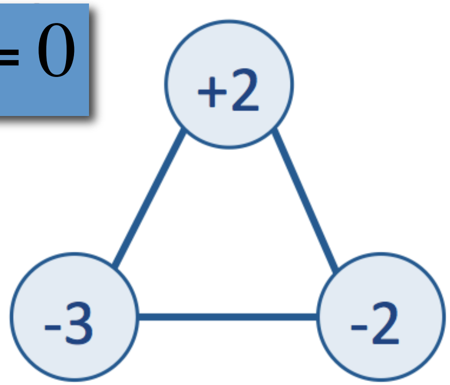
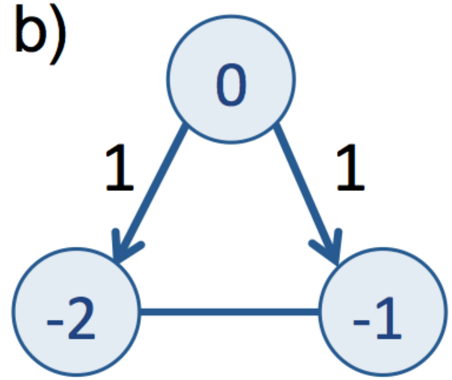
Coupling schemes between transmission and backup

$$\Delta_n(t) = G_n^{RES}(t) - L_n(t) - T_n(t)$$

$$T_n(t) = 0$$



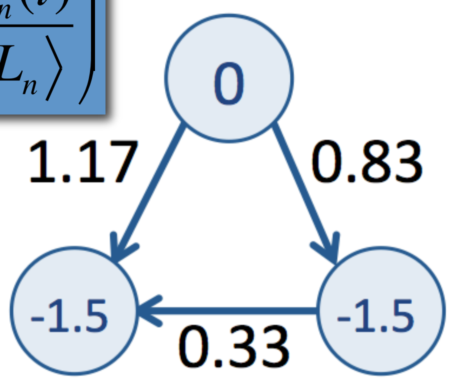
b)



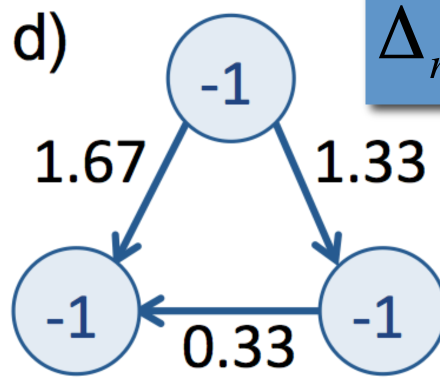
$$\min\left(\sum_n B_n(t)\right)$$

$$\min\left(\sum_l F_l^2(t)\right)$$

$$\min\left(\max_n \frac{B_n(t)}{\langle L_n \rangle}\right)$$



d)



$$\Delta_n(t) = \beta(t)\langle L_n \rangle$$

$$\beta(t) = \frac{\sum_n \Delta_n(t)}{\sum_n \langle L_n \rangle}$$

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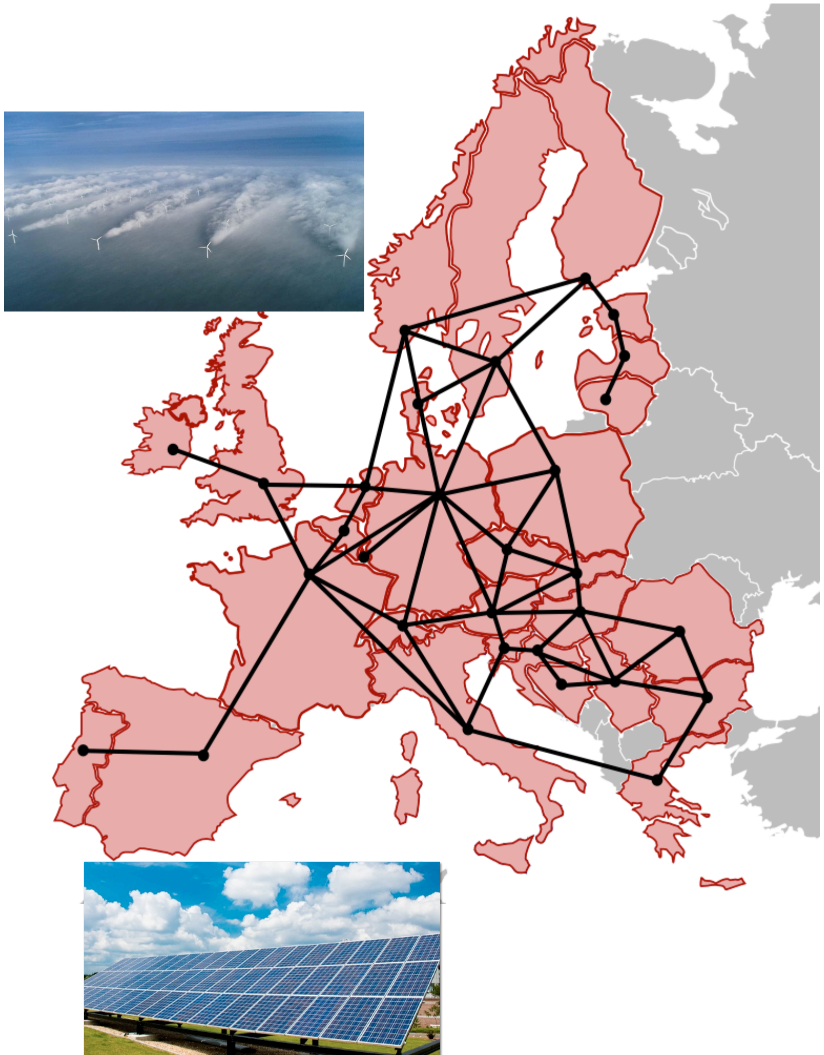
Design of a fully renewable European energy system
---- challenges for the physics of complex systems ----



How much ...
... wind energy?
... solar PV energy?
... backup energy + power?
... transmission?
... storage?
... coupling of energy sectors?

and what about
... transition 2050 → 2014?

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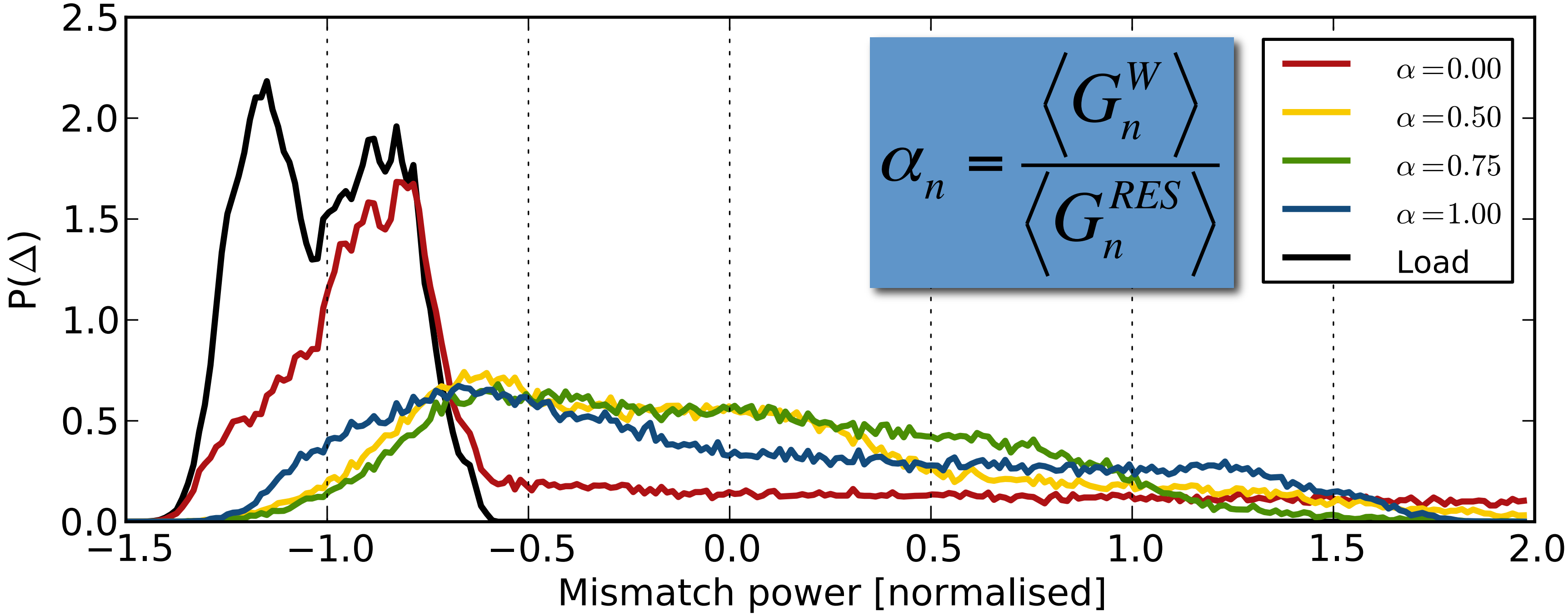
Mismatch distribution (Germany)

$$\Delta_n(t) = G_n^{RES}(t) - L_n(t) - T_n(t)$$

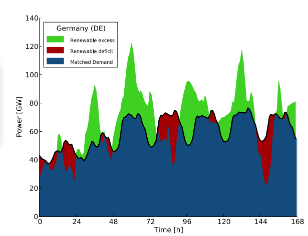
$$T_n(t) = 0$$

$$\langle G_n^{RES} \rangle = \langle L_n \rangle$$



$$\alpha_n = \frac{\langle G_n^{W} \rangle}{\langle G_n^{RES} \rangle}$$

$$B_n(t) = -\min(\Delta(t), 0)$$



$$C_n(t) = \max(\Delta(t), 0)$$

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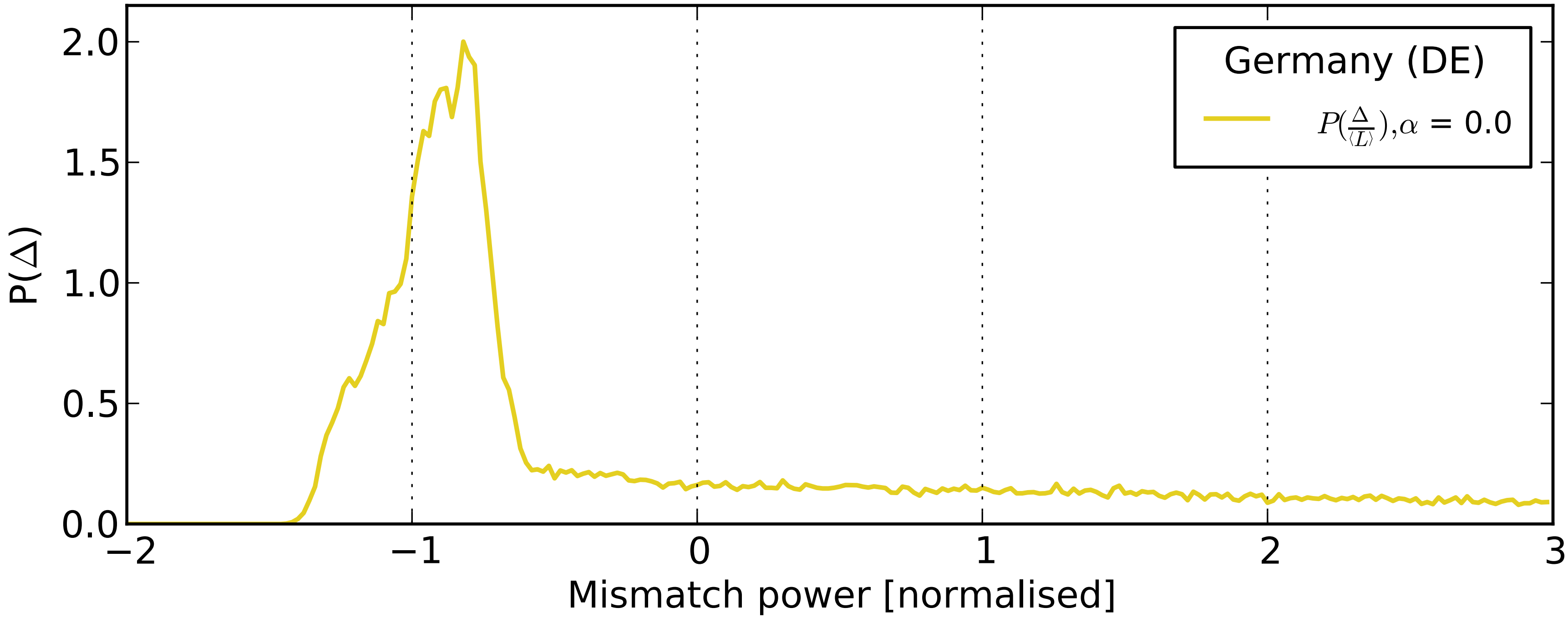

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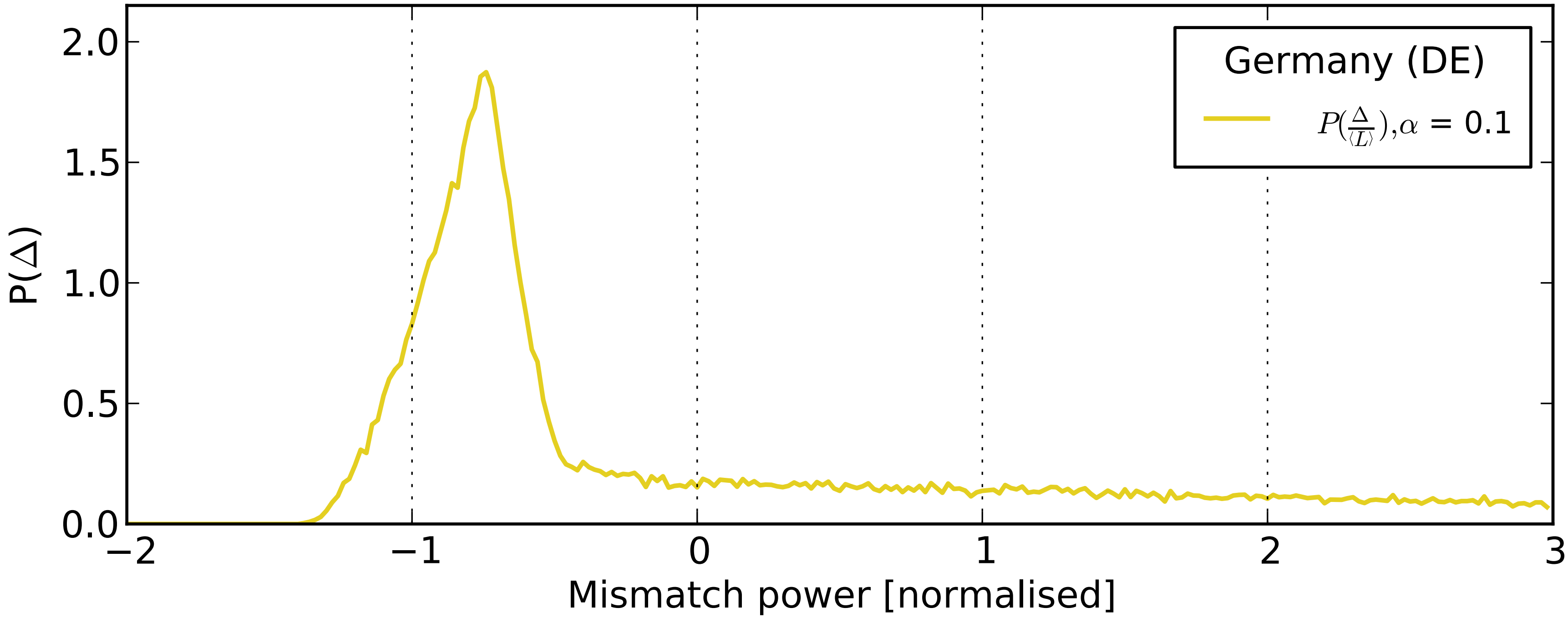

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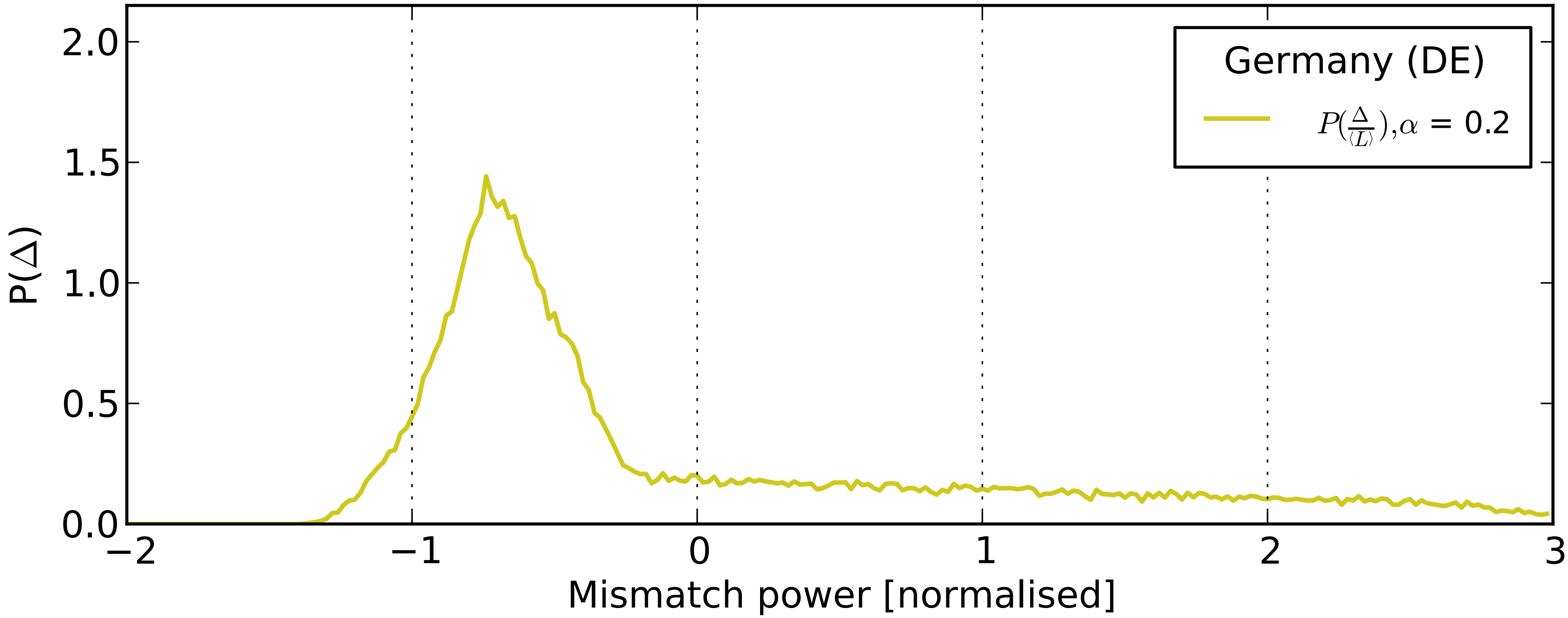
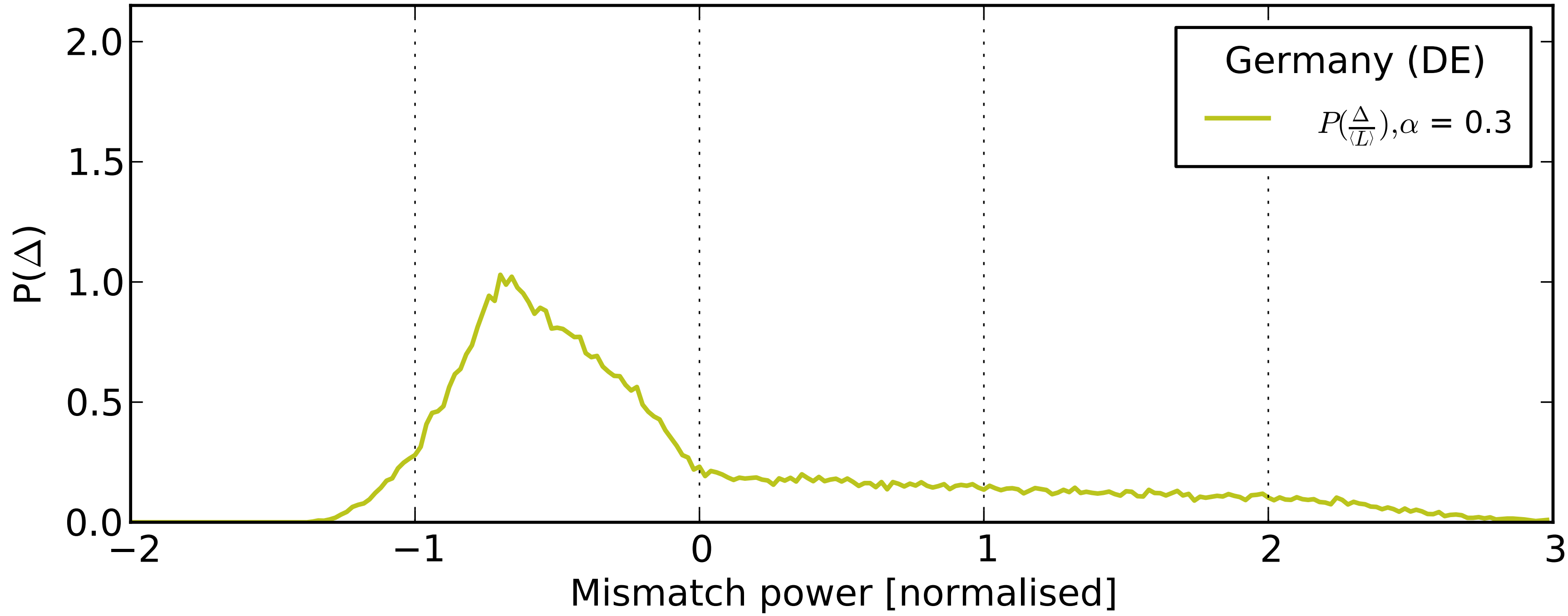


Germany (DE)
$P(\frac{\Delta}{\langle L \rangle})$,$\alpha$ = 0.2
P(Δ)
2.0
1.5
1.0
0.5
0.0
−2
−1
0
1
2
3
Mismatch power [normalised]



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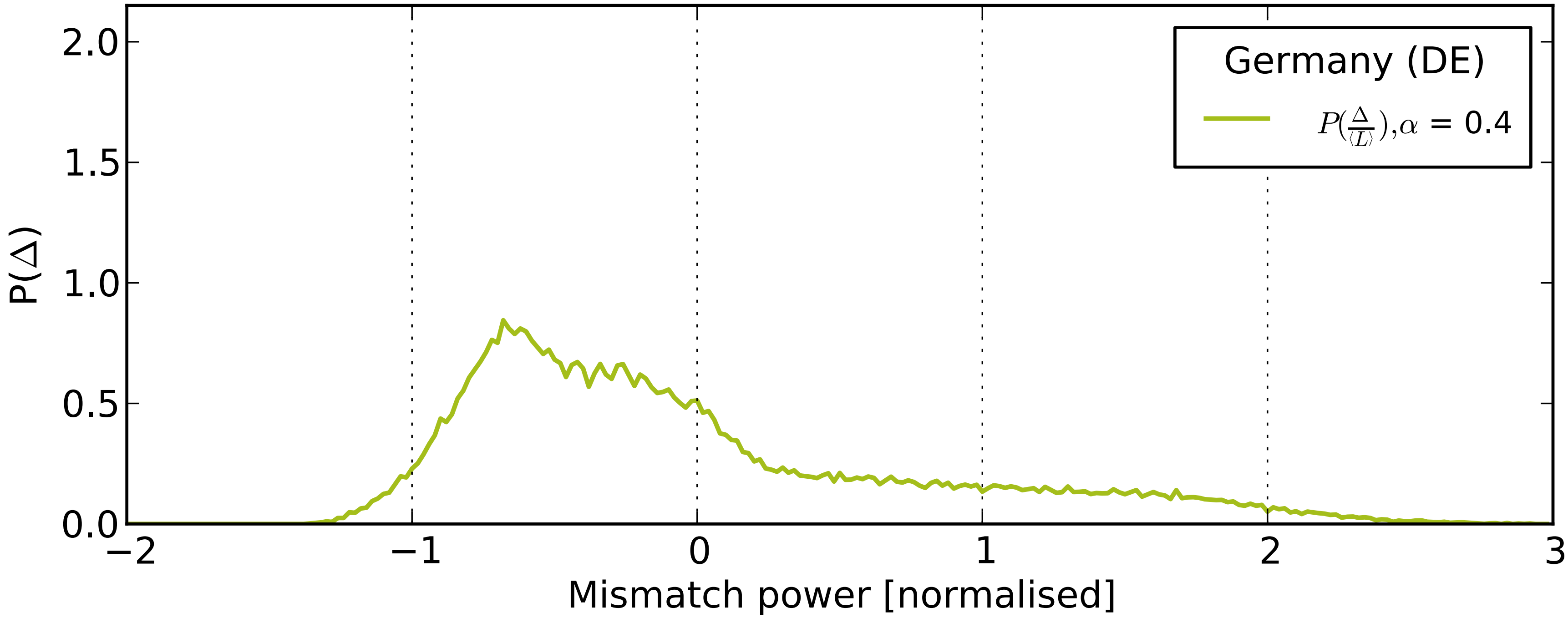
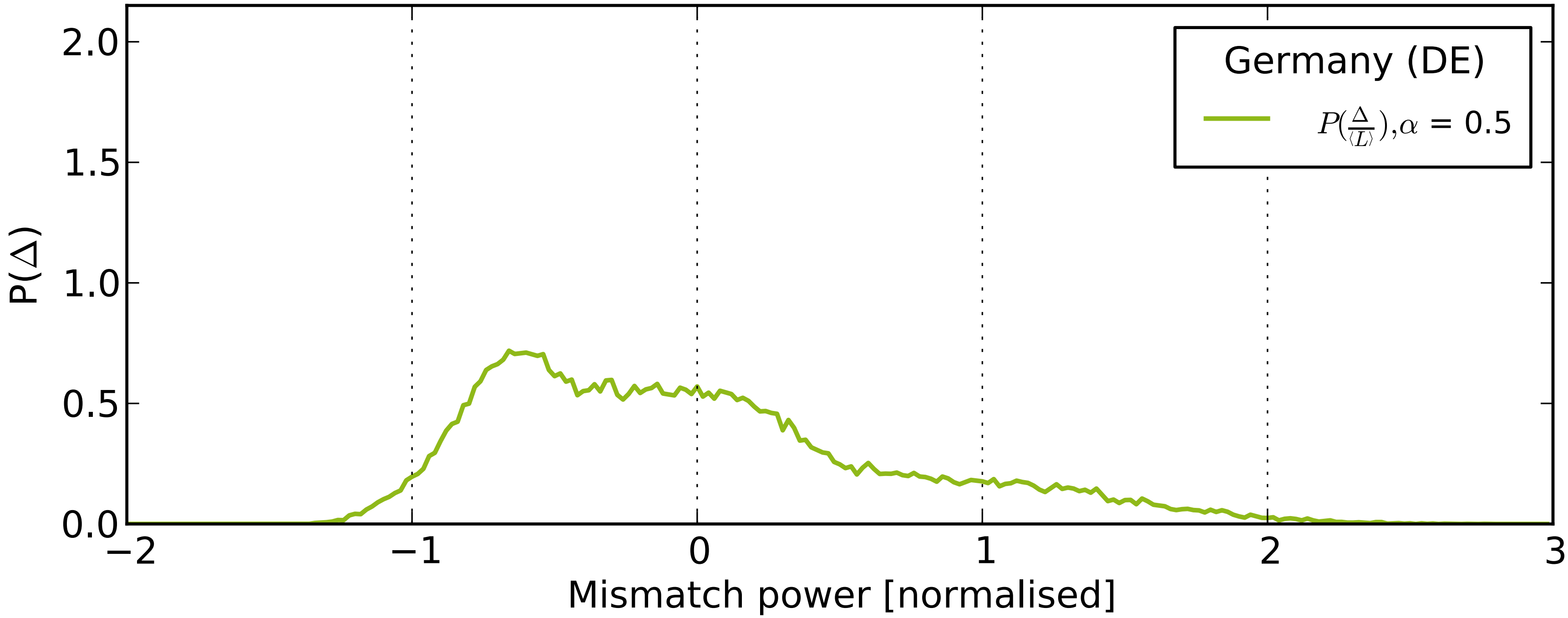

Germany (DE)
$P(\frac{\Delta}{\langle L \rangle})$,$\alpha$ = 0.4
P(Δ)
2.0
1.5
1.0
0.5
0.0
−2
−1
0
1
2
3
Mismatch power [normalised]



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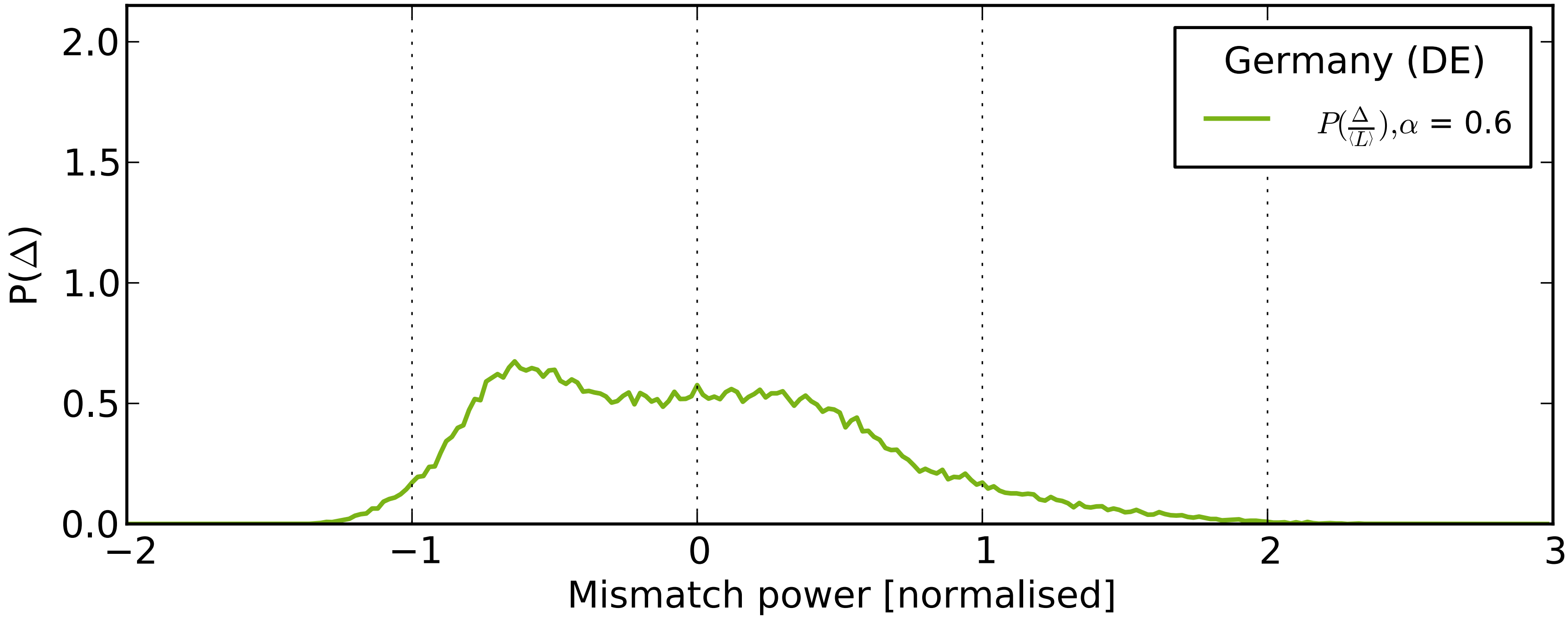

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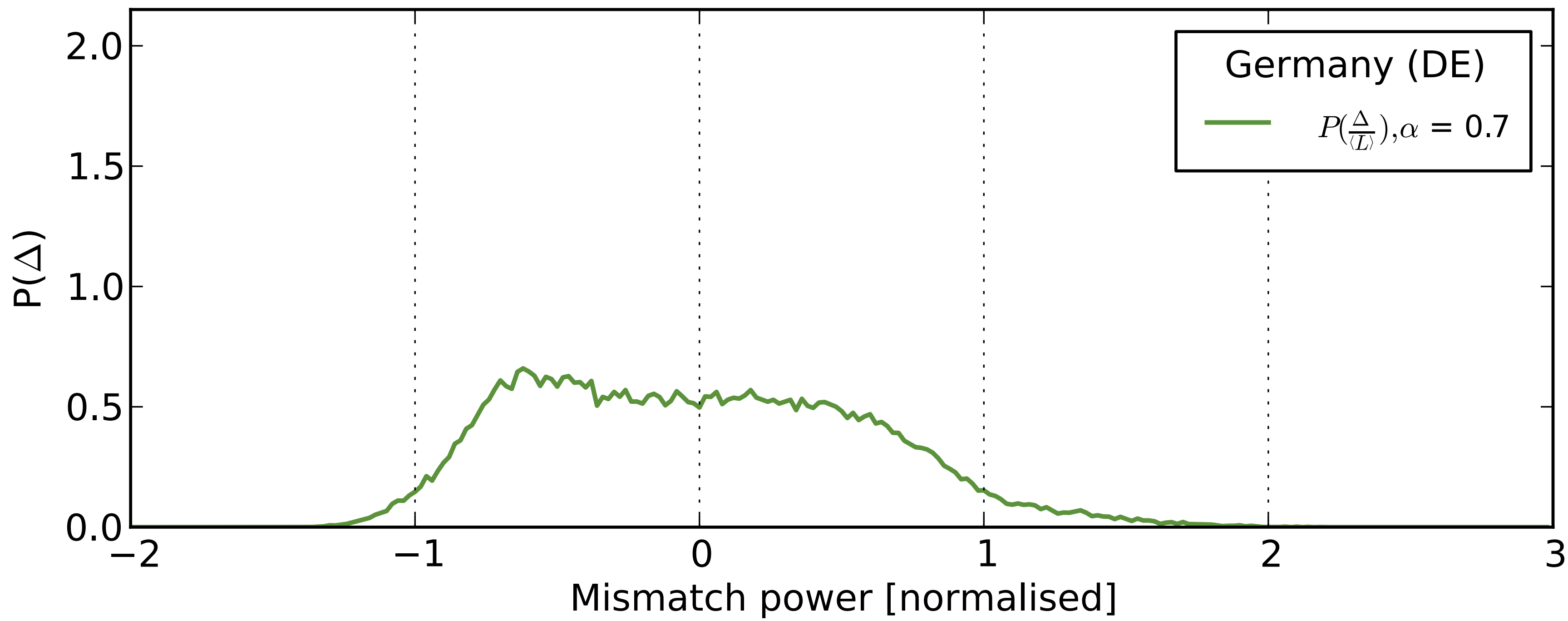

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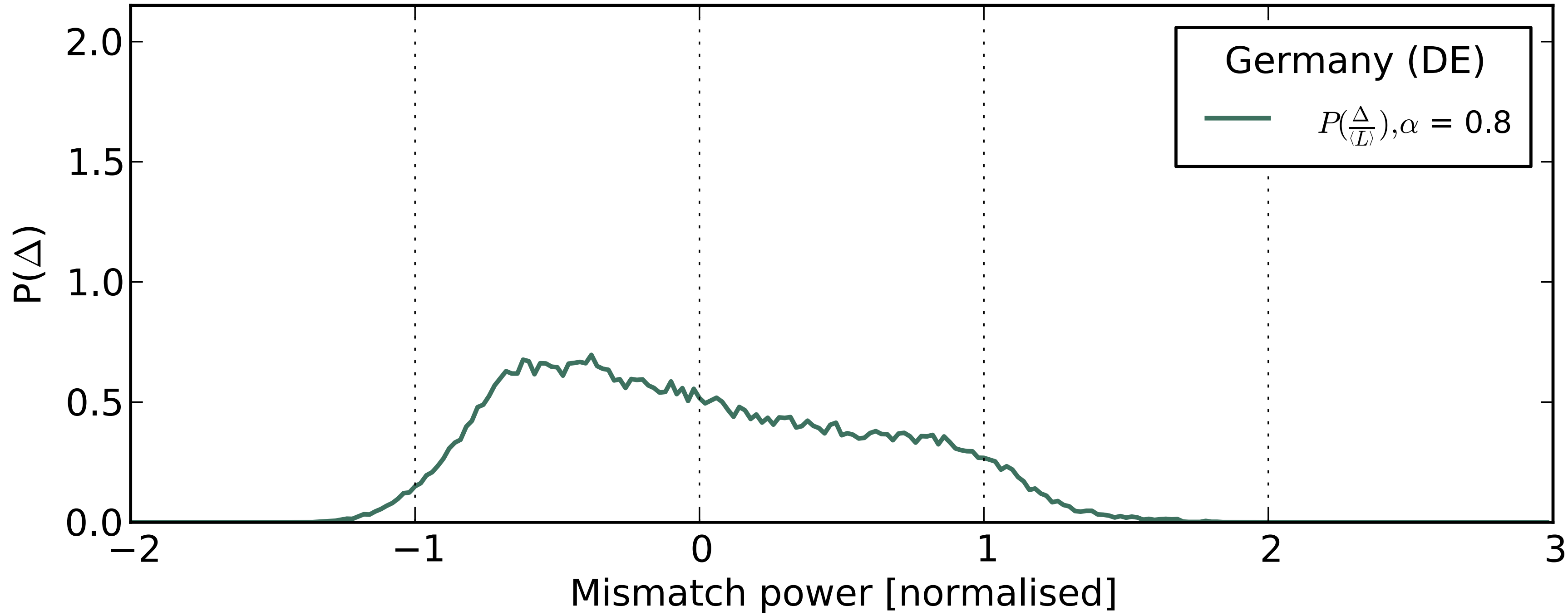

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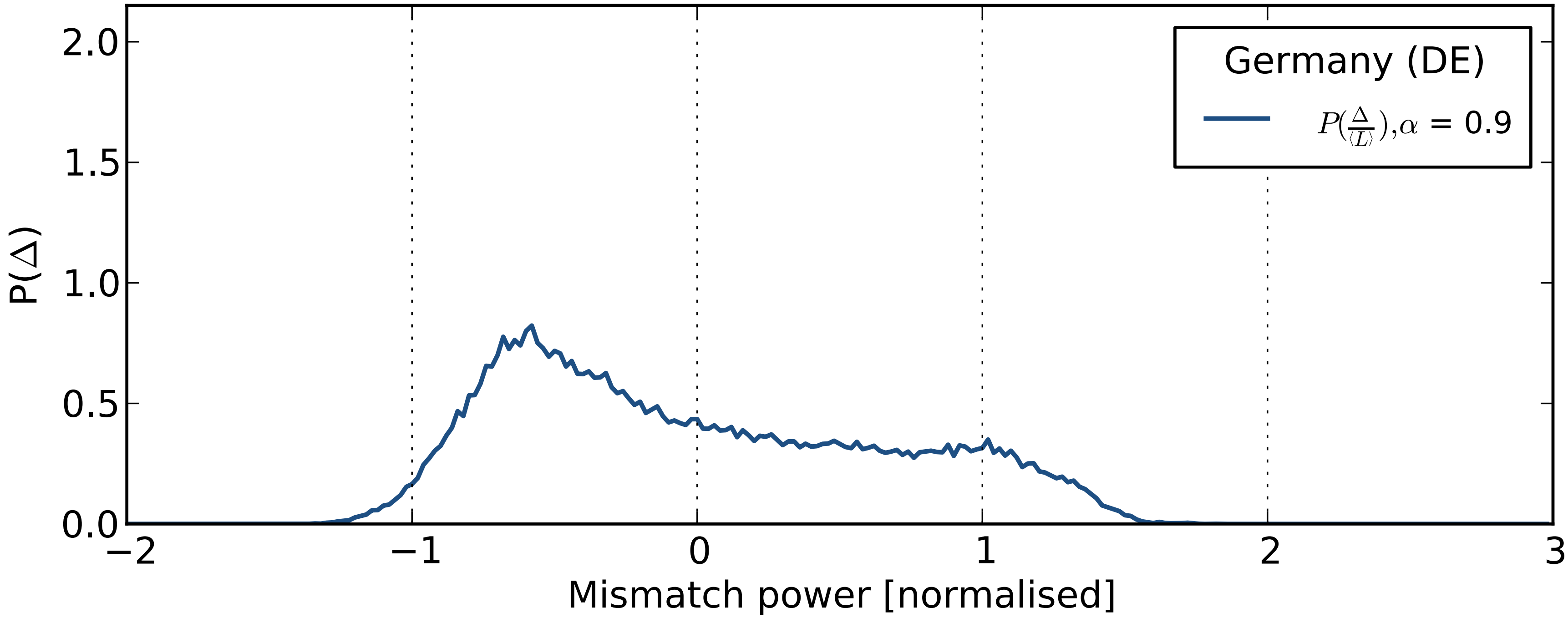

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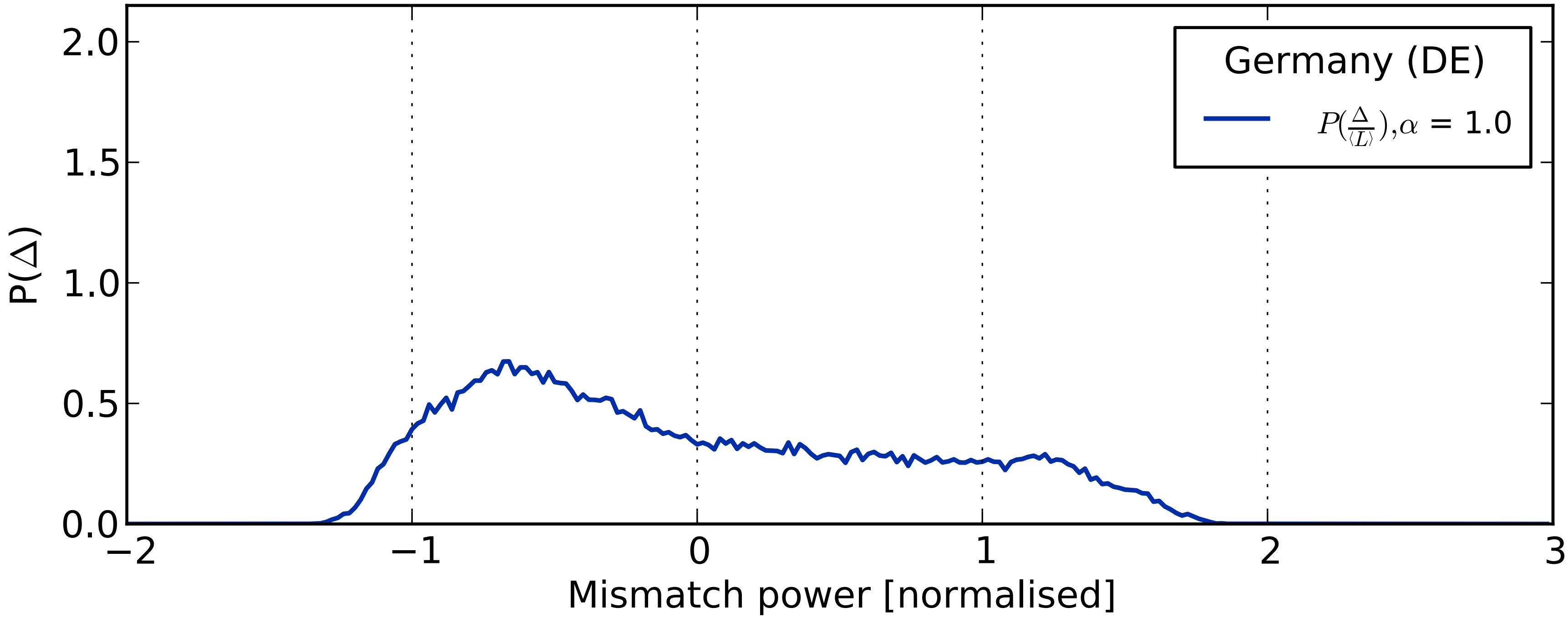

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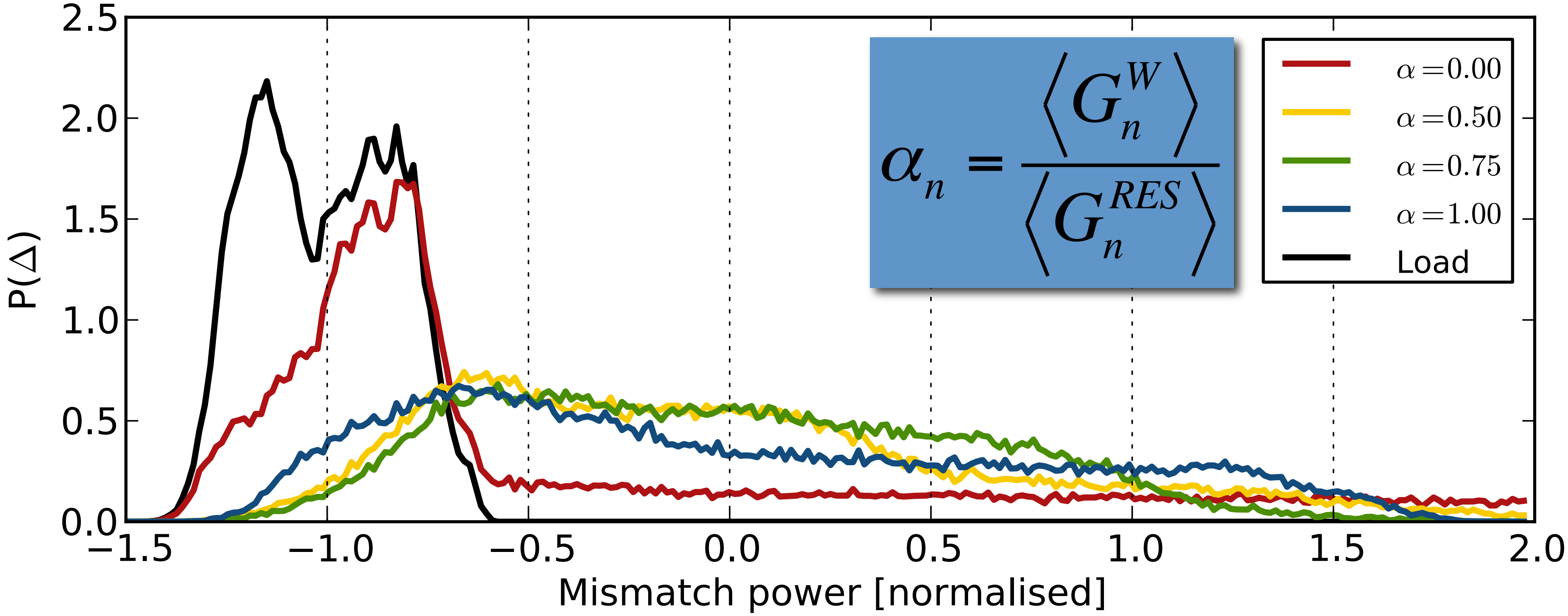
Mismatch distribution (Germany)

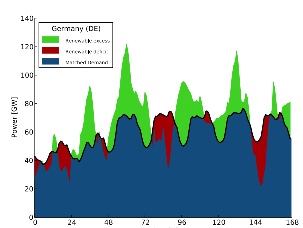
$$\Delta_n(t) = G_n^{RES}(t) - L_n(t) - T_n(t)$$

$$T_n(t) = 0$$

$$\langle G_n^{RES} \rangle = \langle L_n \rangle$$



$$B_n(t) = -\min\left(\Delta(t), 0\right)$$



$$C_n(t) = \max\left(\Delta(t), 0\right)$$

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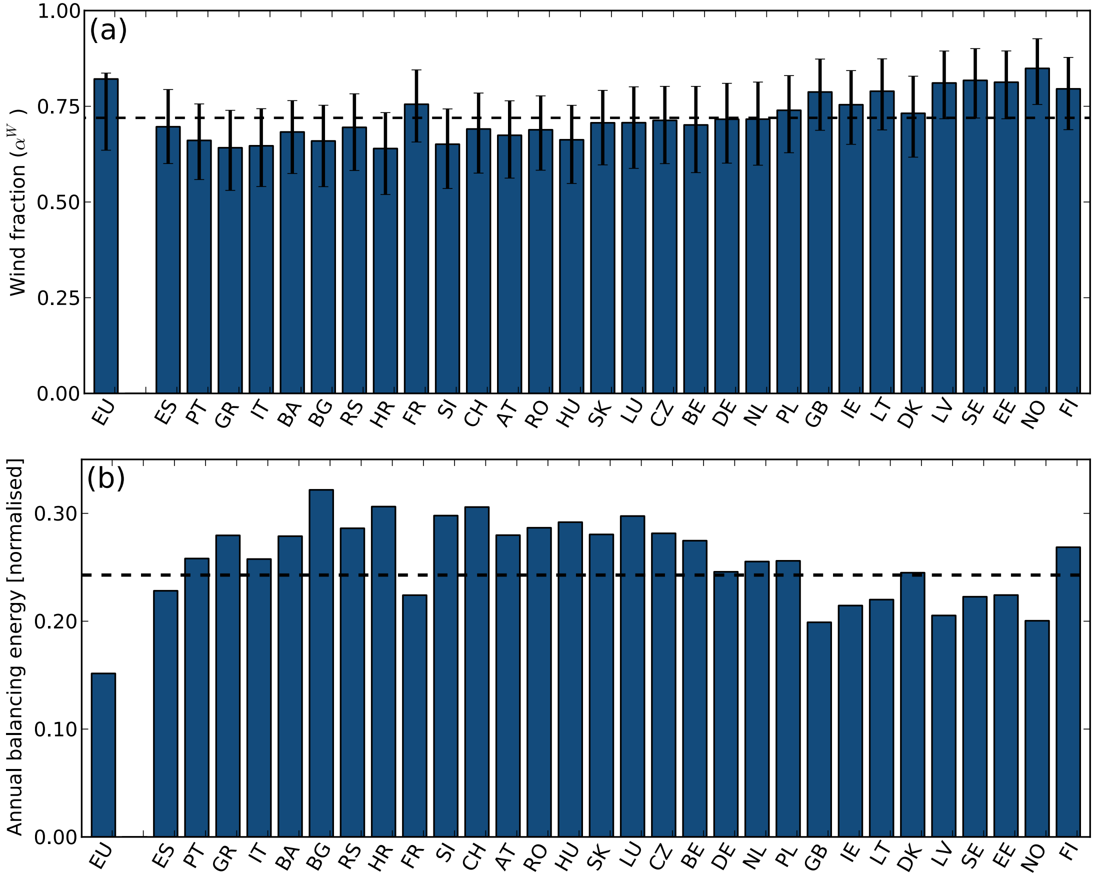
BACKUP ENERGY: European countries



$\alpha_{\min}$

$\langle B_n \rangle \approx 0.24$

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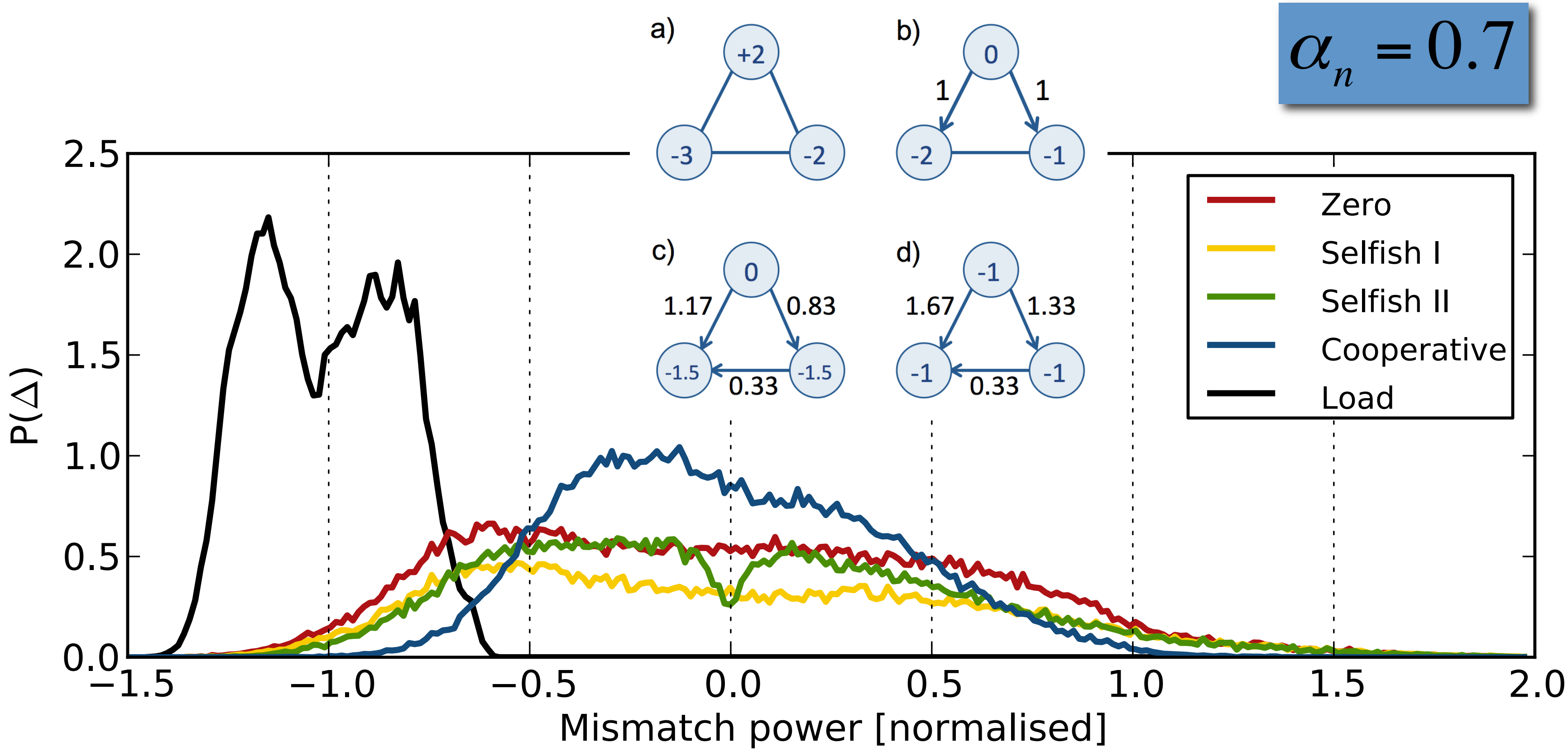
Mismatch distribution (Germany)

$$\Delta_n(t) = G_n^{RES}(t) - L_n(t) - T_n(t)$$

$$\langle G_n^{RES} \rangle = \langle L_n \rangle$$

$$\alpha_n = 0.7$$



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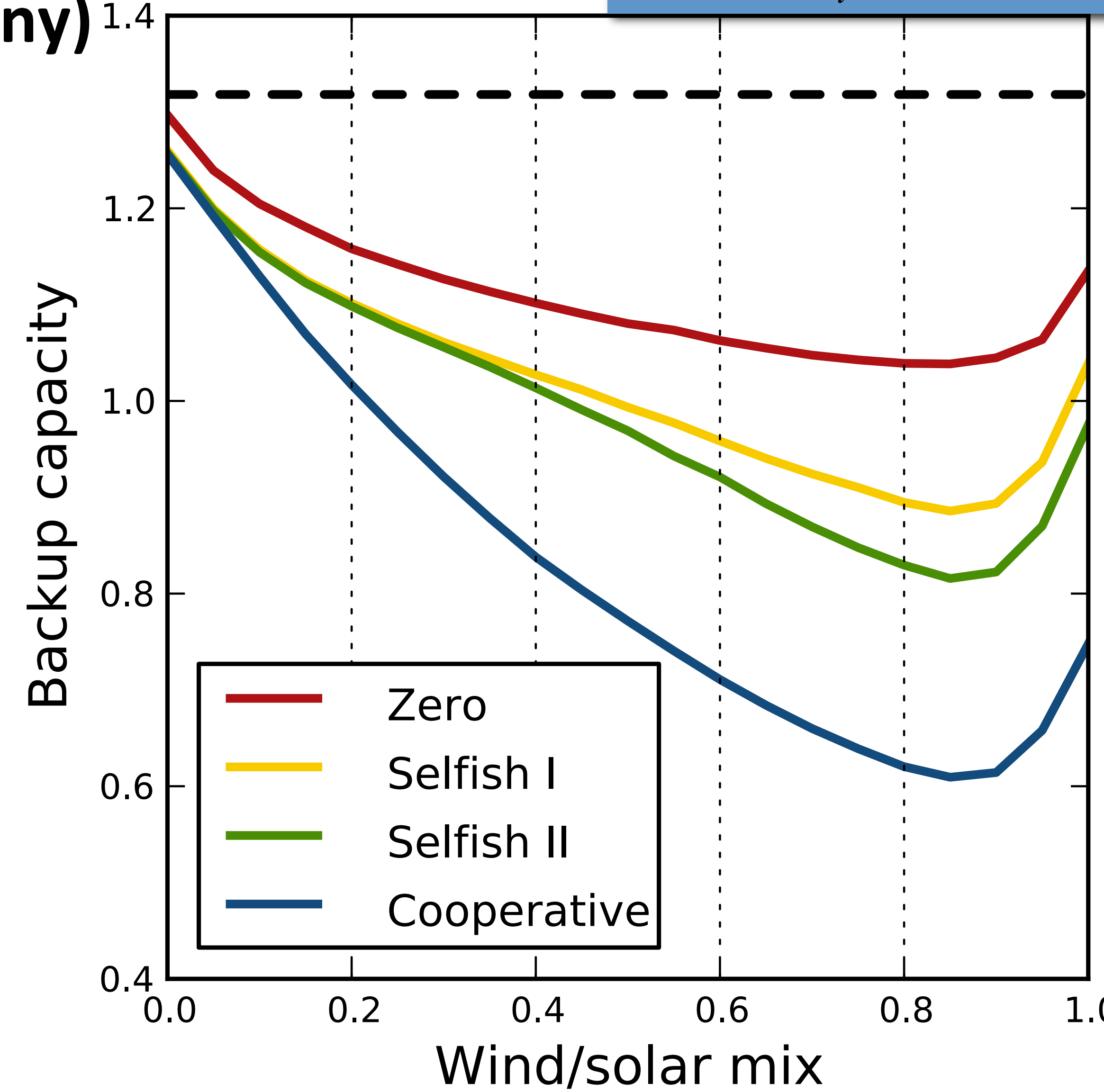
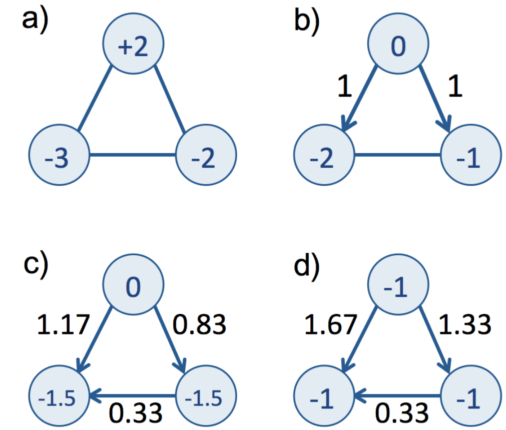
Backup Capacity
(Germany)

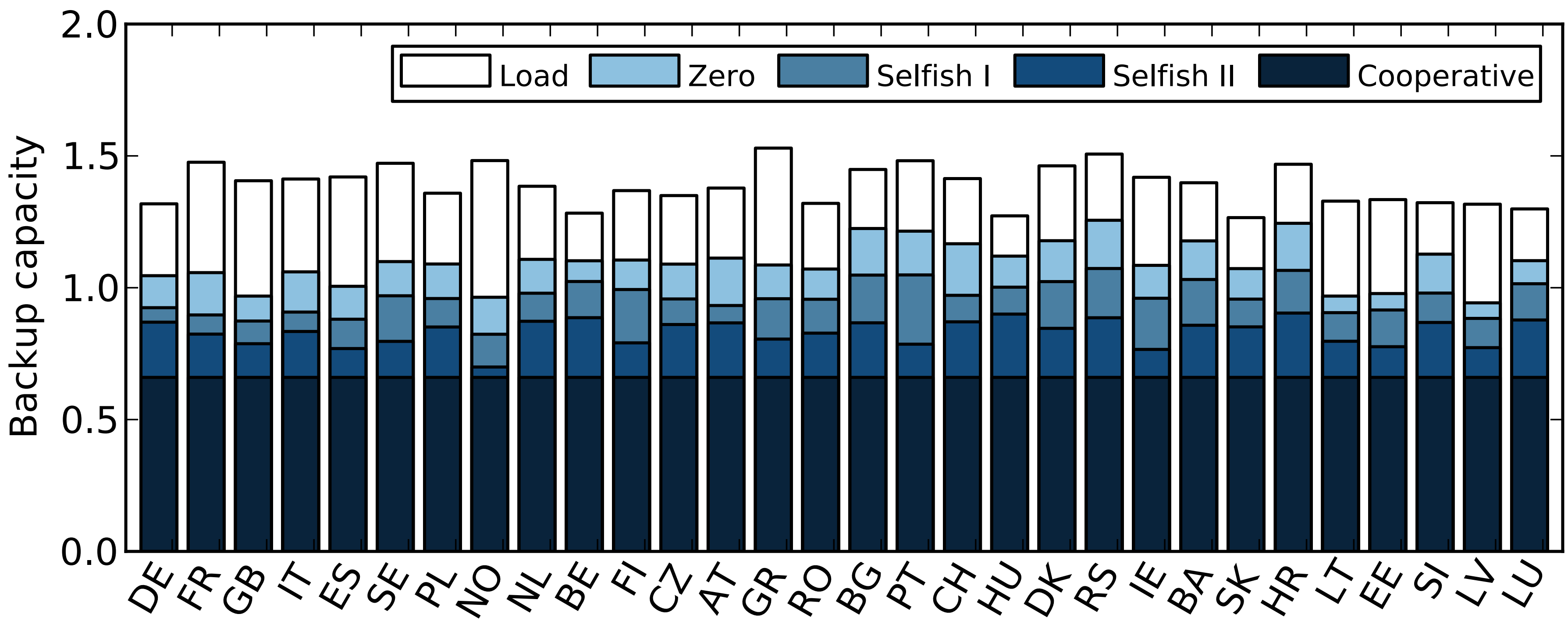
$$B_n^C = -\min_t \left(G_n^{RES}(t) - L_n(t) - T_n(t) \right)$$



$$\alpha_n = \frac{\left\langle G_n^W \right\rangle}{\left\langle G_n^{RES} \right\rangle}$$

Backup Capacity





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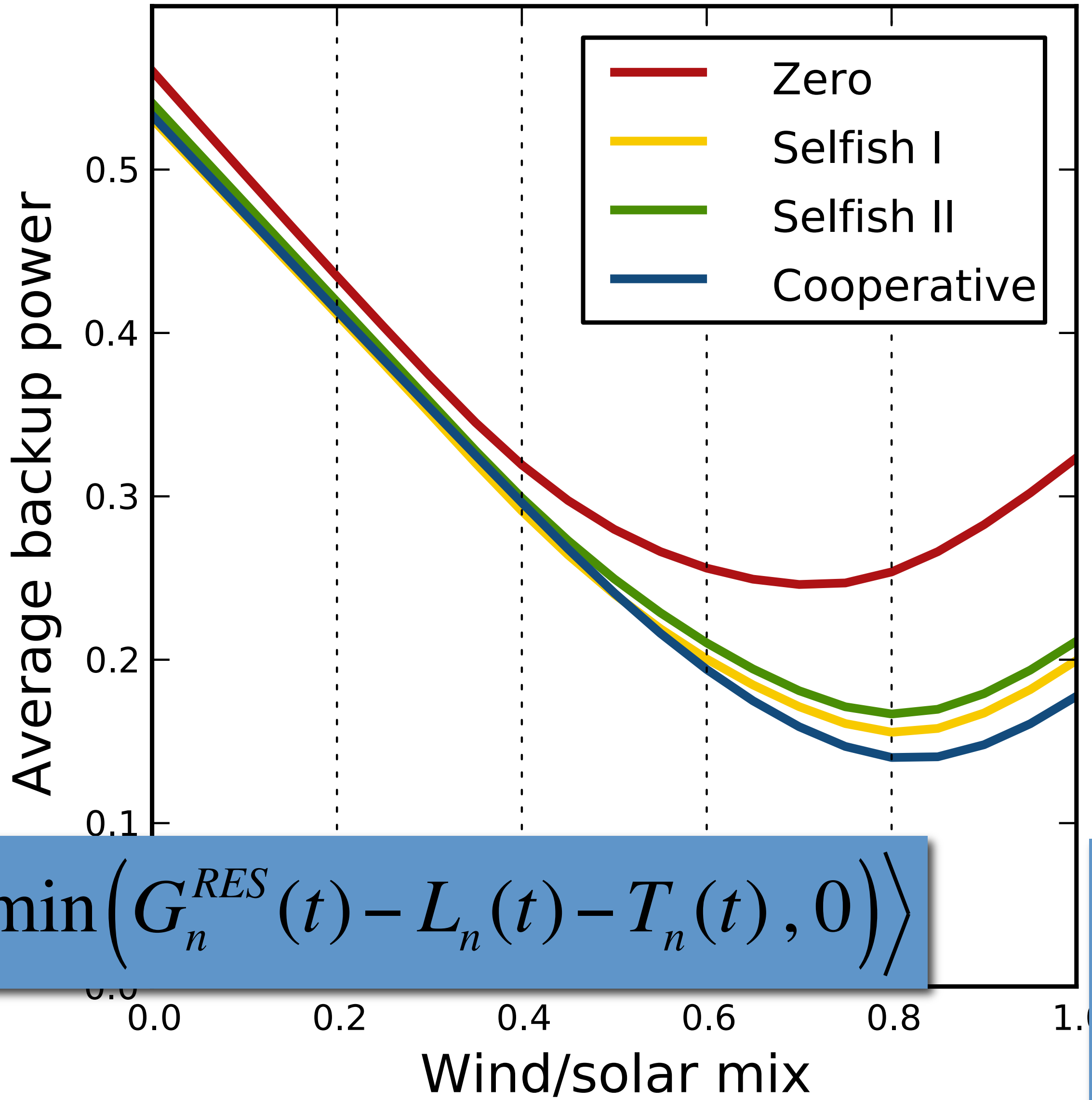
Average Backup Power (Germany)



$$\langle B_n \rangle = -\left\langle \min\left(G_n^{RES}(t) - L_n(t) - T_n(t), 0\right) \right\rangle$$

$$\alpha_n = \frac{\langle G_n^{W} \rangle}{\langle G_n^{RES} \rangle}$$

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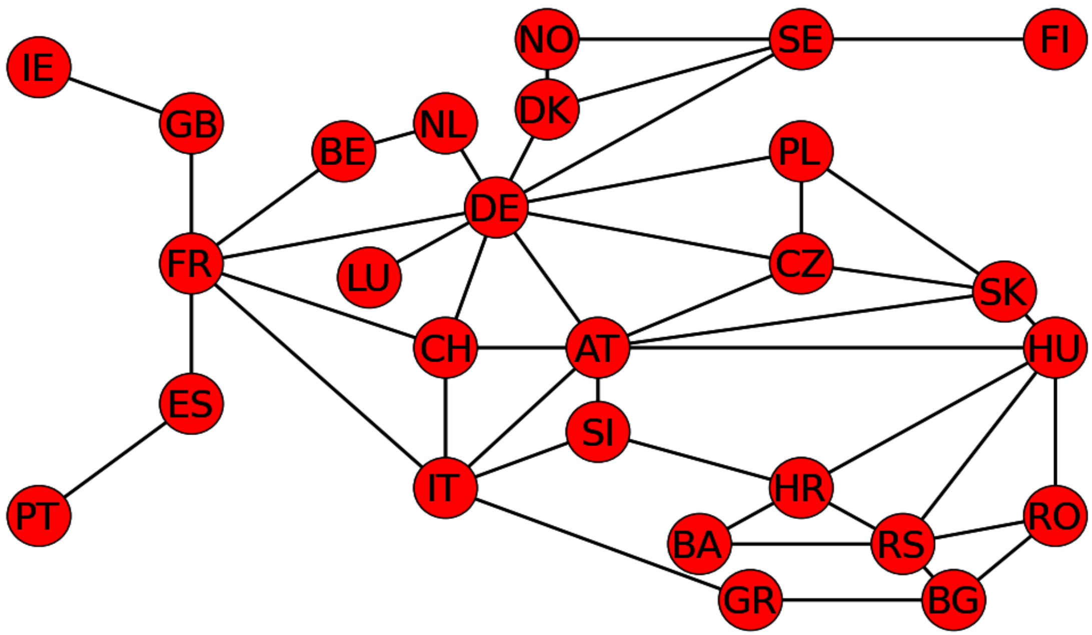
How much transmission?



$$\min \sum_n B_n$$

$$\min \sum_l F_l^2$$

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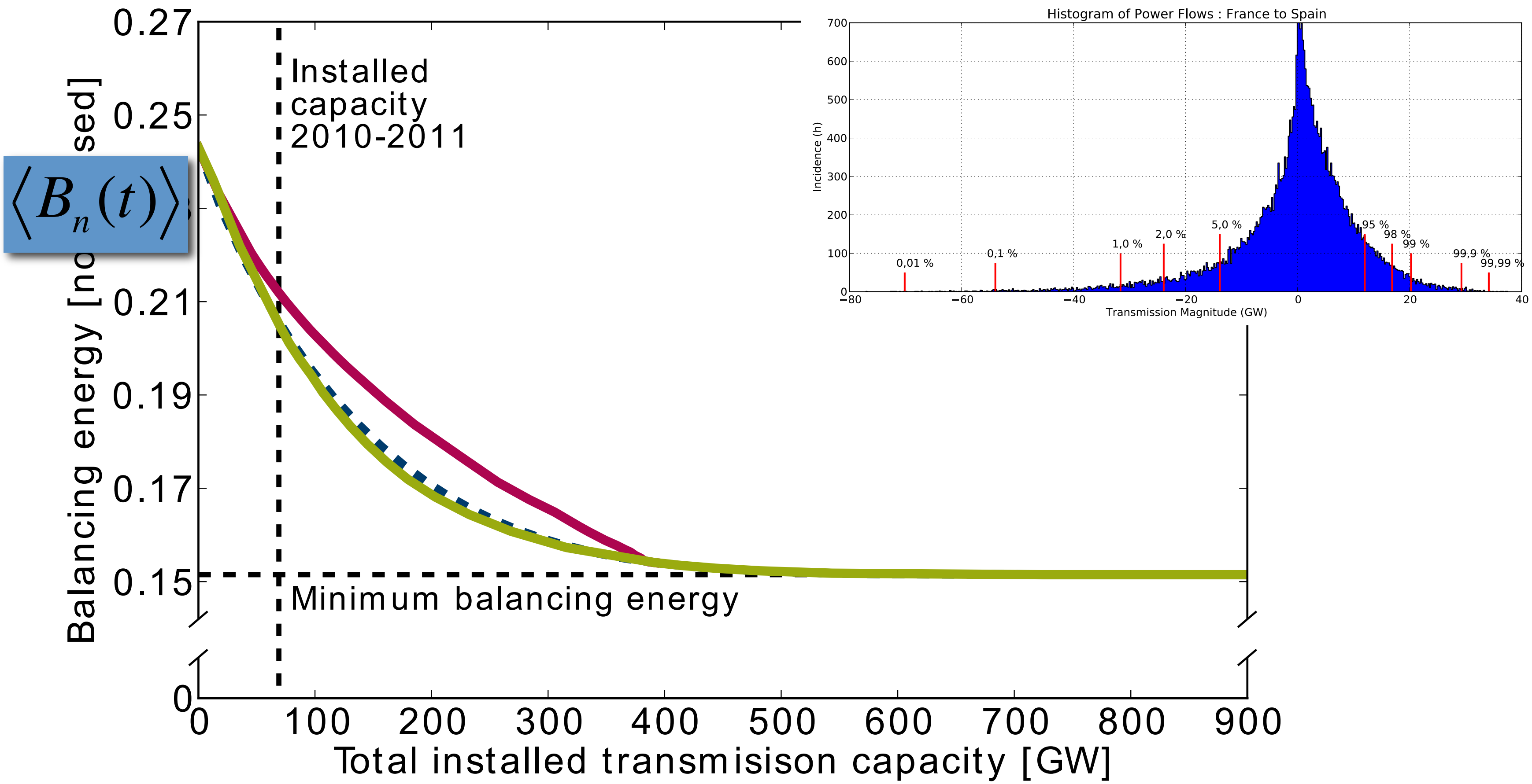
Backup vs. Transmission



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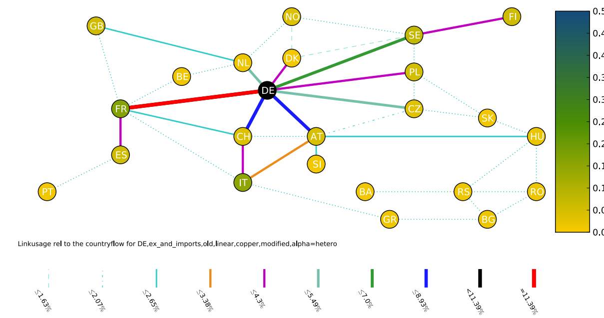
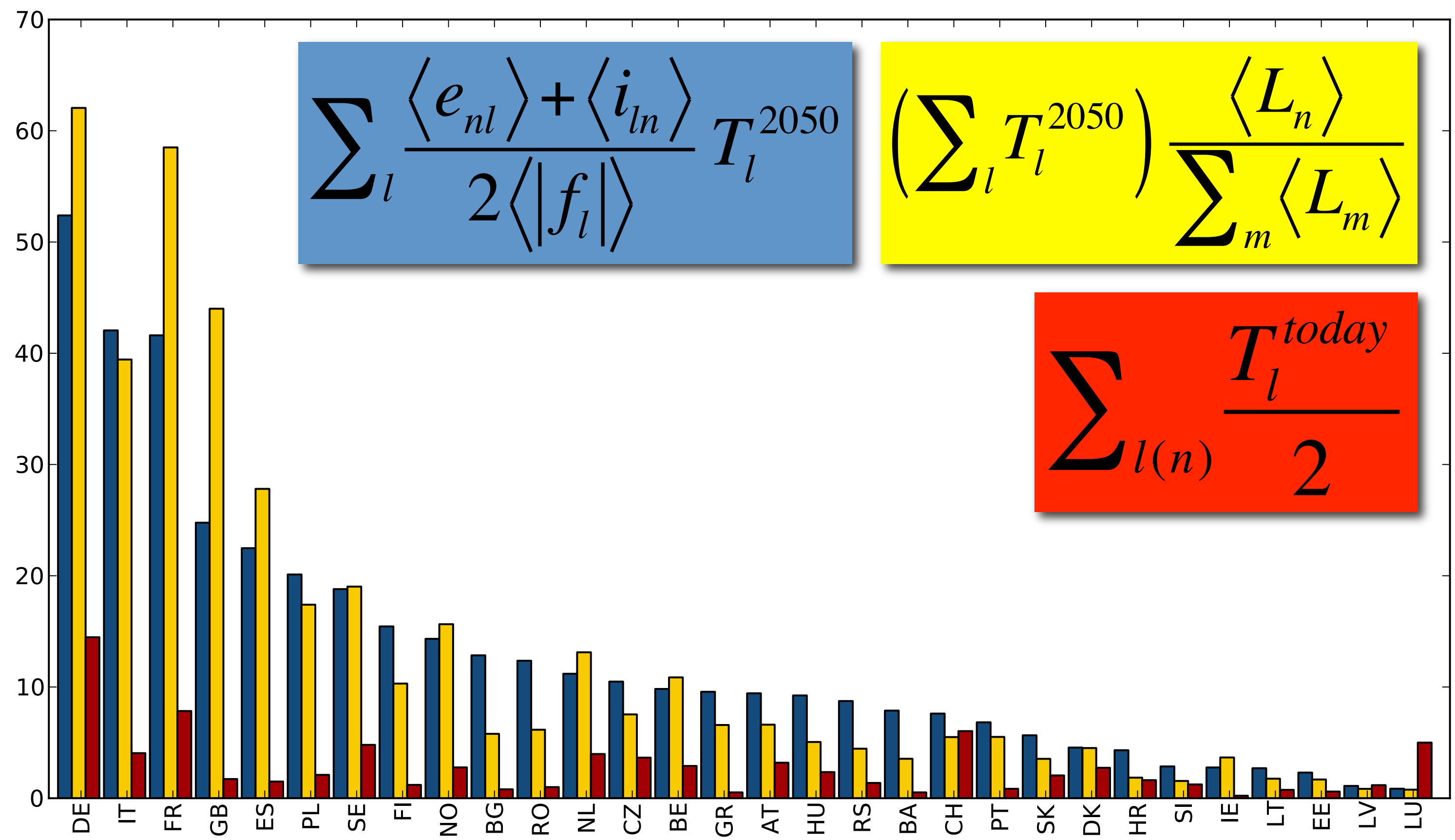
Who pays the transmission bill?

…………… Flow tracing ……………





$$\sum_l \frac{\langle e_{nl} \rangle + \langle i_{ln} \rangle}{2\langle |f_l| \rangle} T_l^{2050}$$

$$\left(\sum_l T_l^{2050} \right) \frac{\langle L_n \rangle}{\sum_m \langle L_m \rangle}$$

$$\sum_{l(n)} \frac{T_l^{today}}{2}$$

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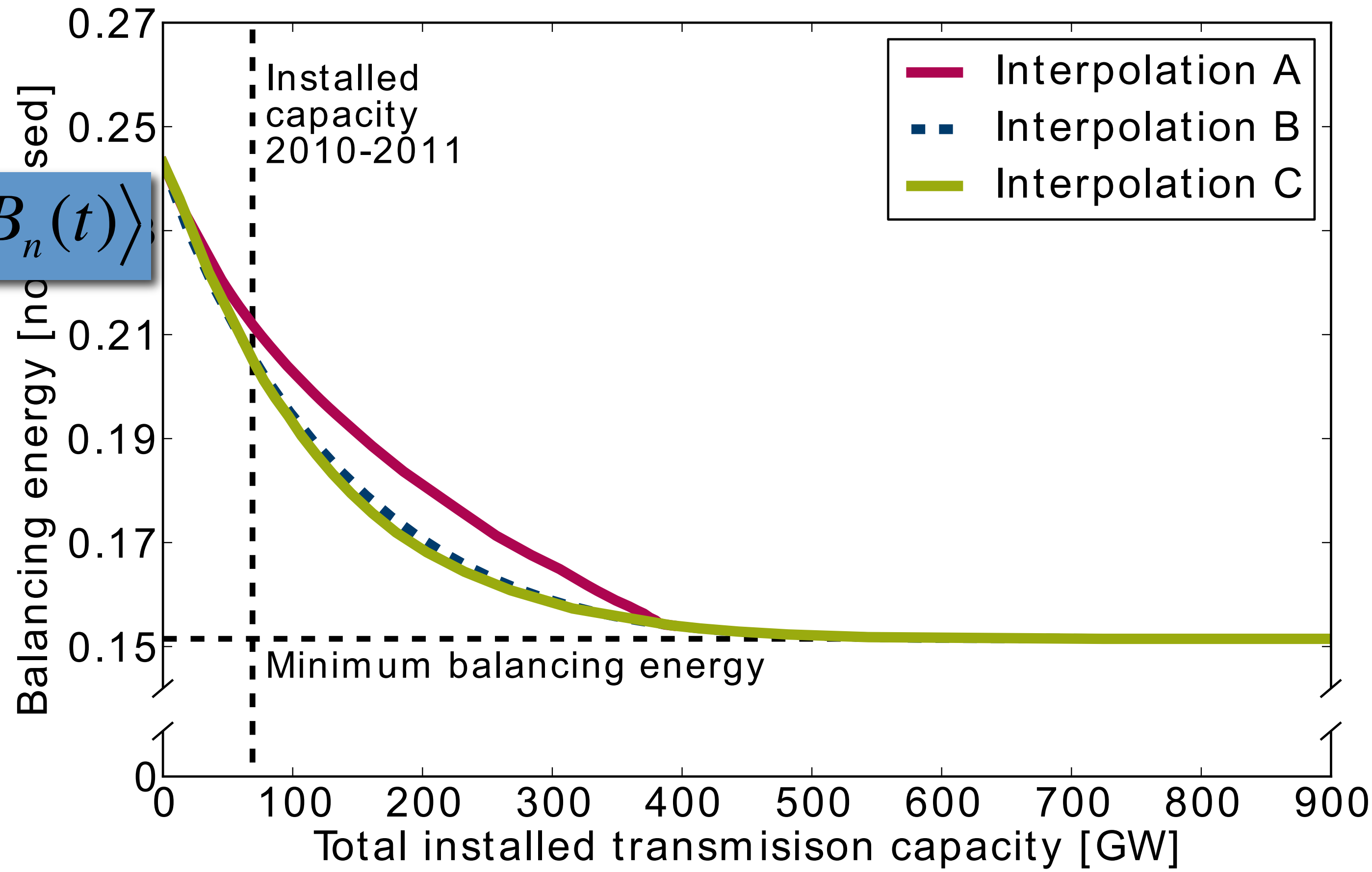
More reduction of backup?



$\langle B_n(t) \rangle$

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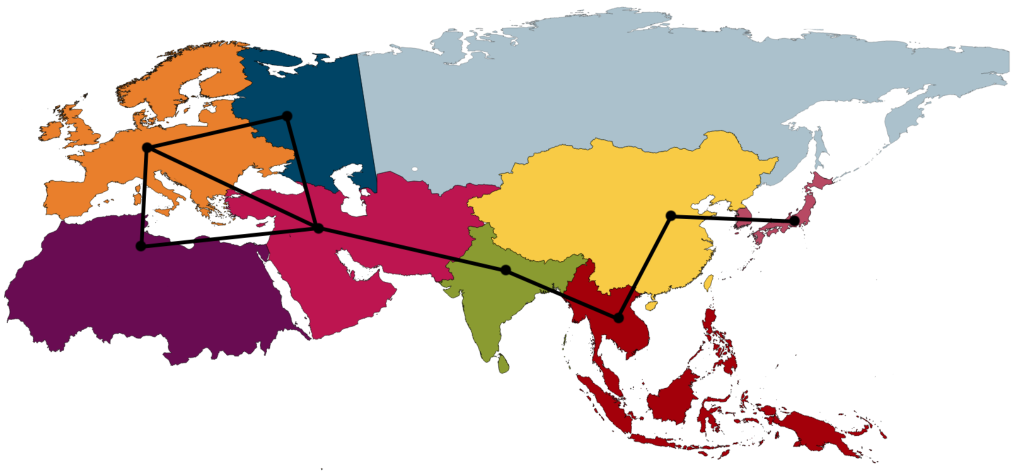
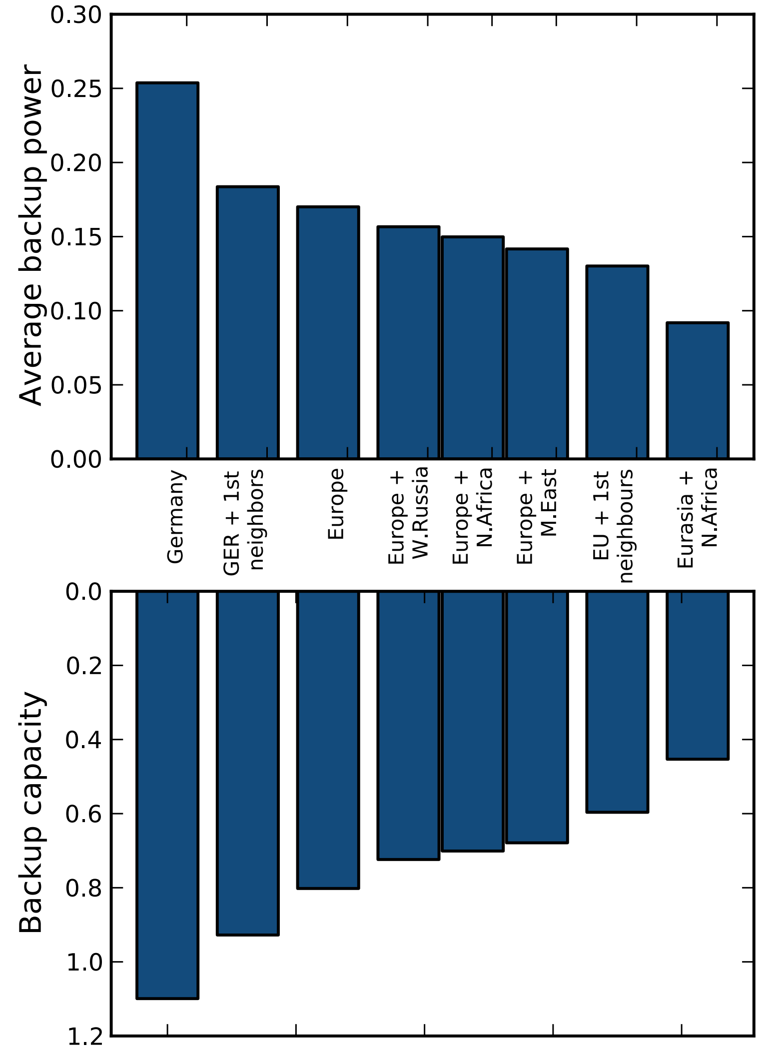
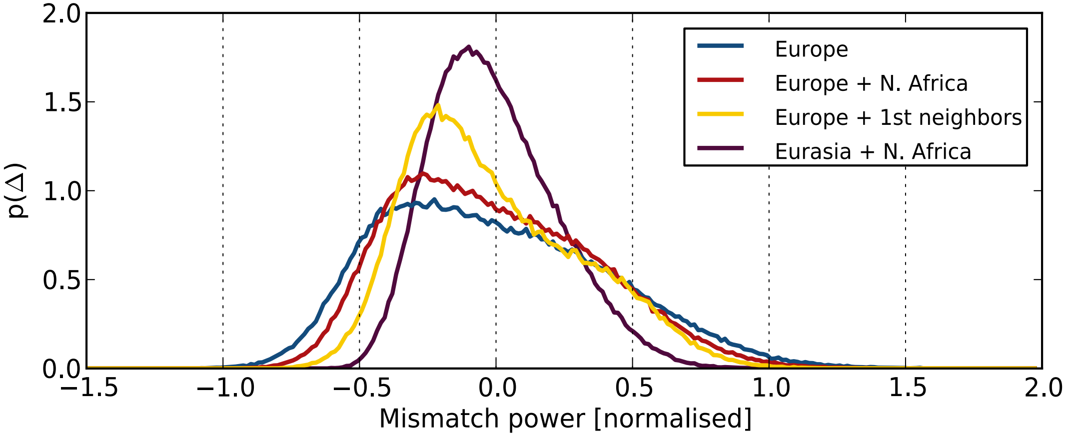
Answer 1: Transmission beyond EU







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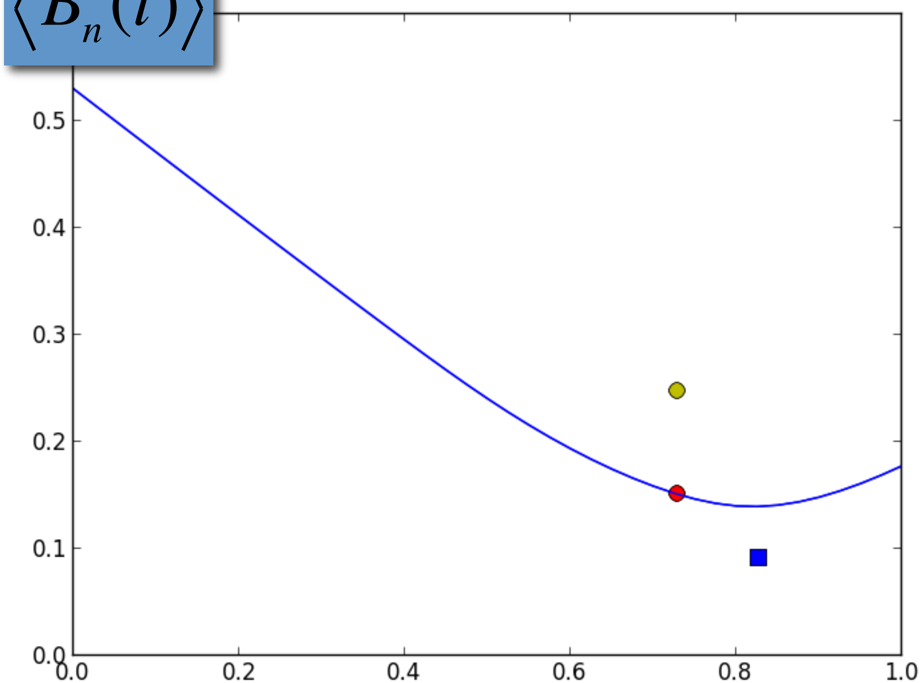
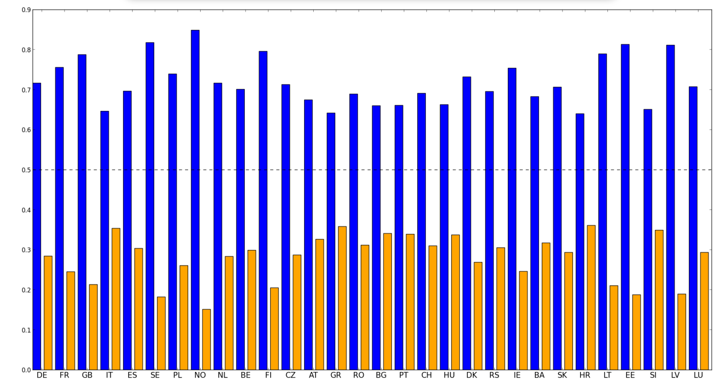
Answer 2: Optimization

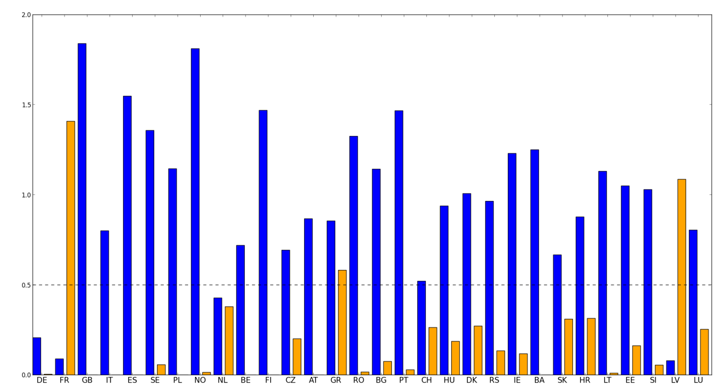
optimal portfolio theory, genetic optimization

$$\left\langle G_n^{RES} \right\rangle_t = \left\langle L_n \right\rangle_t$$

$$\left\langle B_n(t) \right\rangle$$





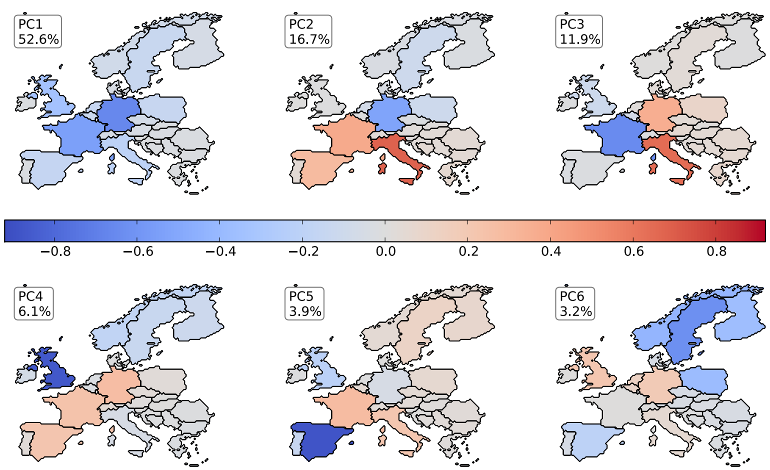


$$\sum_n \left\langle G_n^{RES} \right\rangle_t = \sum_n \left\langle L_n \right\rangle_t$$

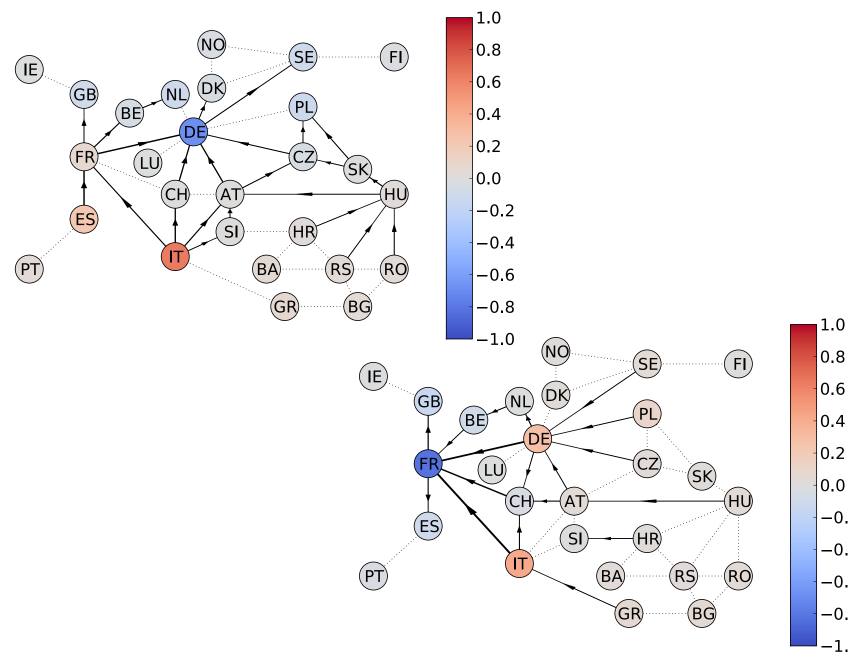
Fundamental Research on Renewable Energy Systems
at the interface between engineering + mathematics + physics

SOME FUNDAMENTAL CHALLENGES:

storage phase transition,
renormalisation scaling of power flows,
spatio-temporal flow pattern analysis,
self-organizing power flows,
emergence of socio-economic cooperation



b)



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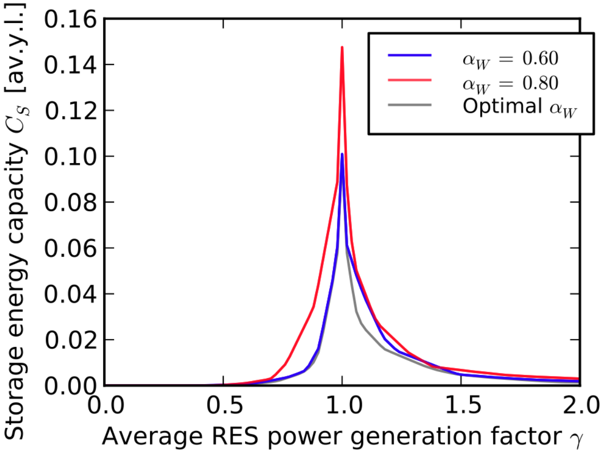

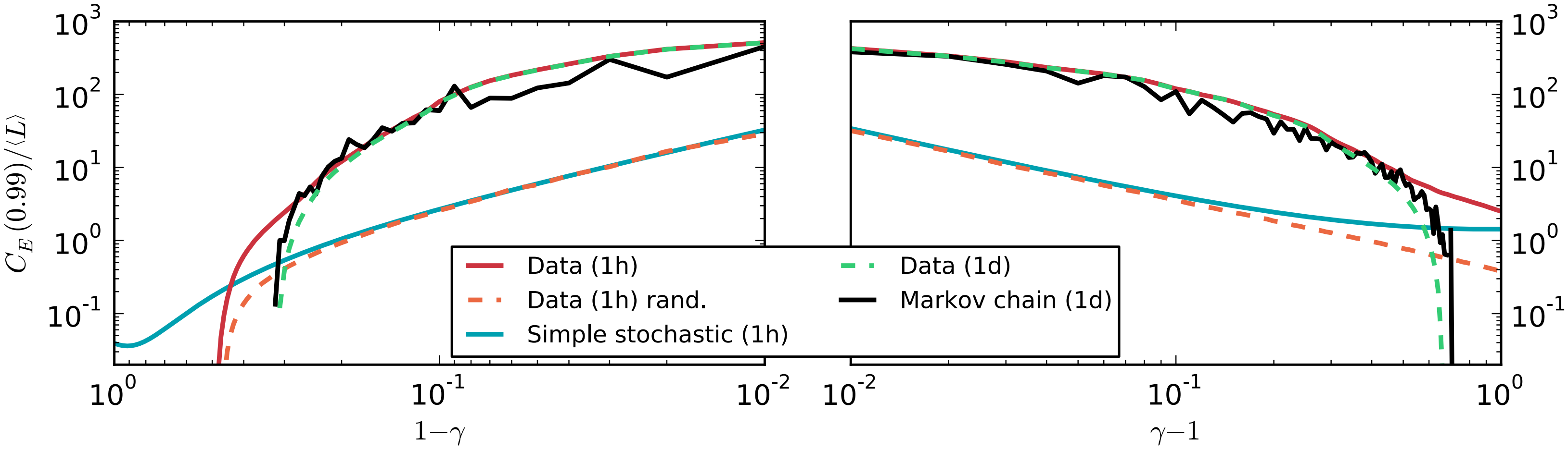

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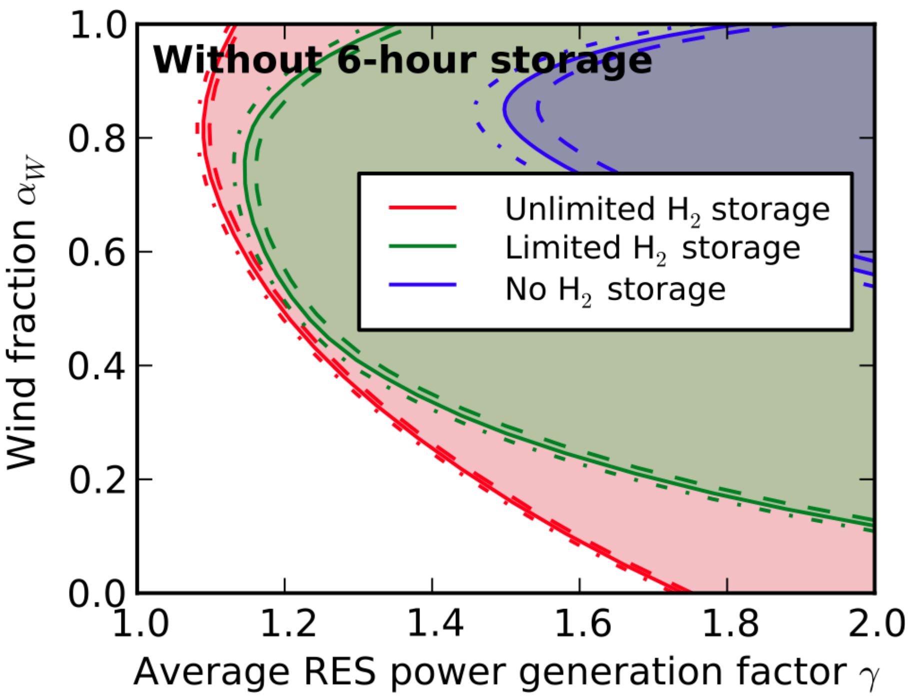
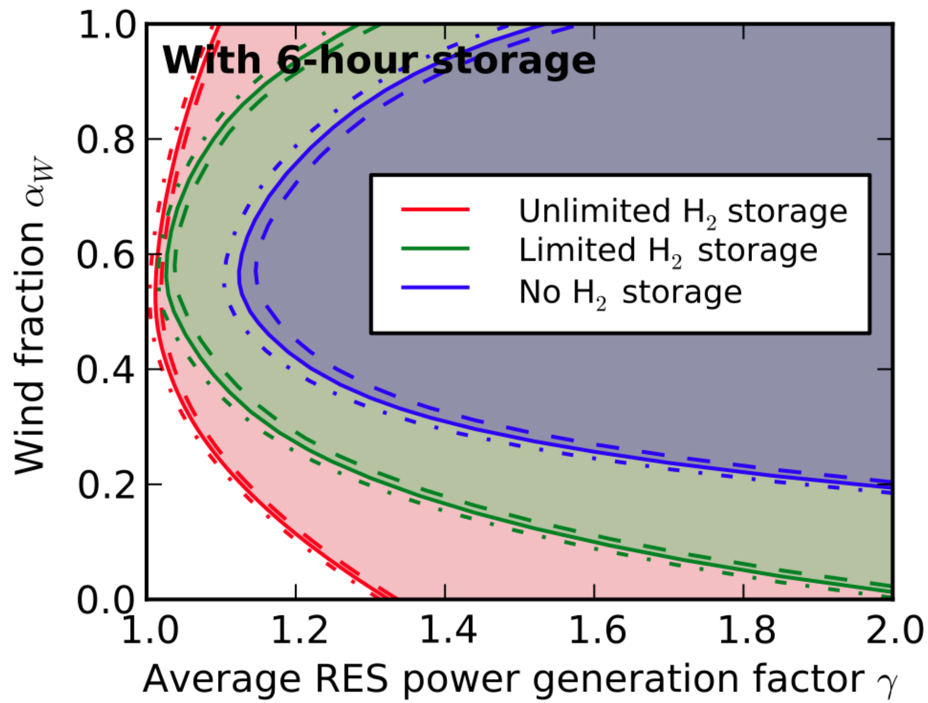
Synergies: balancing + storage

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





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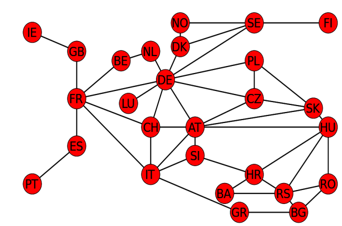
Fundamental Research on Renewable Energy Systems
at the interface between engineering + mathematics + physics

BIG SIMULATION: **100% = 100+X%**

COMPLEX NETWORKS OF SMART ENERGY SYSTEMS

all renewables + backup +
+ transmission + storage,
electricity + heating + transportation



DESIGN OF FUTURE ENERGY MARKETS

OPTIMAL TRANSITION 2050 → 2015

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Fundamental Research on Renewable Energy Systems

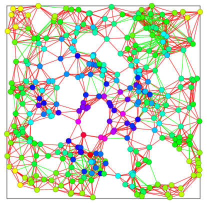
at the interface between engineering + mathematics + physics

Martin Greiner, Aarhus University

greiner@eng.au.dk

(1) 100% Renewable Energy Systems

(2) Complex Networks



(3) Wind-farm Modeling + Optimization

G Andresen	(PostDoc)
R Rodriguez	(PHD)
S Becker	(FIAS PhD)
B Sairanen	(Master)
A Thomsen	(Master)
M Dahl	(Master)
C Hoffmann	(IWES)
M Rasmussen	(PostDoc)
D Heide	(PhD)
T Jensen	(Master)
A Søndergaard	(Master)
T Zeyer	(Master)

U Poulsen	(Assistant Professor)
J Herp	(Master)

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