Fundamental Research on Renewable Energy Systems

at the interface between engineering + mathematics + physics

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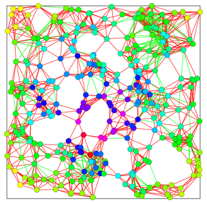
(1) 100% Renewable Energy Systems

(2) Complex Networks



(3) Wind-farm Modeling + Optimization

G Andresen (PostDoc)
R Rodriguez (PhD)
M Dahl (Master)
B Tranberg (Master)
E Eriksen (Master)
S Kozarcanin (Master)
M Therkildsen (Master)

S Becker (FIAS PhD)
T Jensen (DTU PhD)
J Herp (SDU PhD)

U Poulsen (Assist Prof)
M Rasmussen (PostDoc)
D Heide (PhD)
A Søndergaard (Master)
T Zeyer (Master)
A Thomsen (Master)
B Sairanen (Master)

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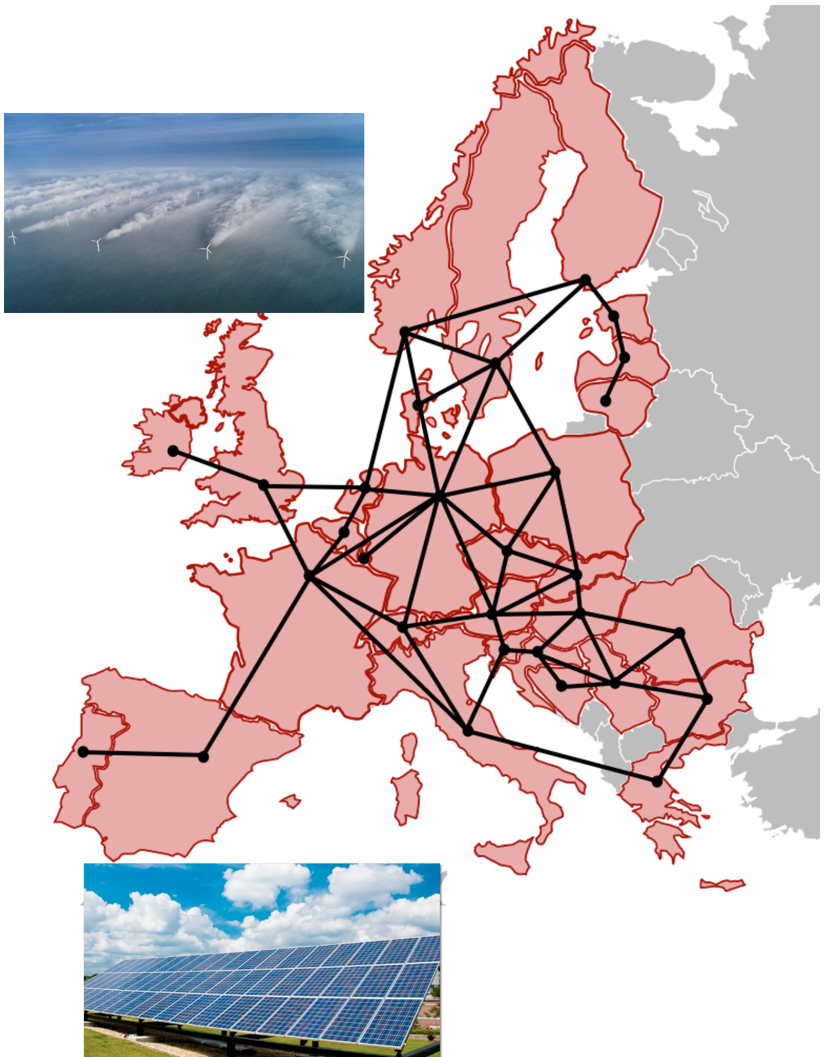
Design of
a highly renewable pan-European energy system



„Mehr als die Vergangenheit interessiert mich die Zukunft, denn in ihr gedenke ich zu leben.“

(Albert Einstein)

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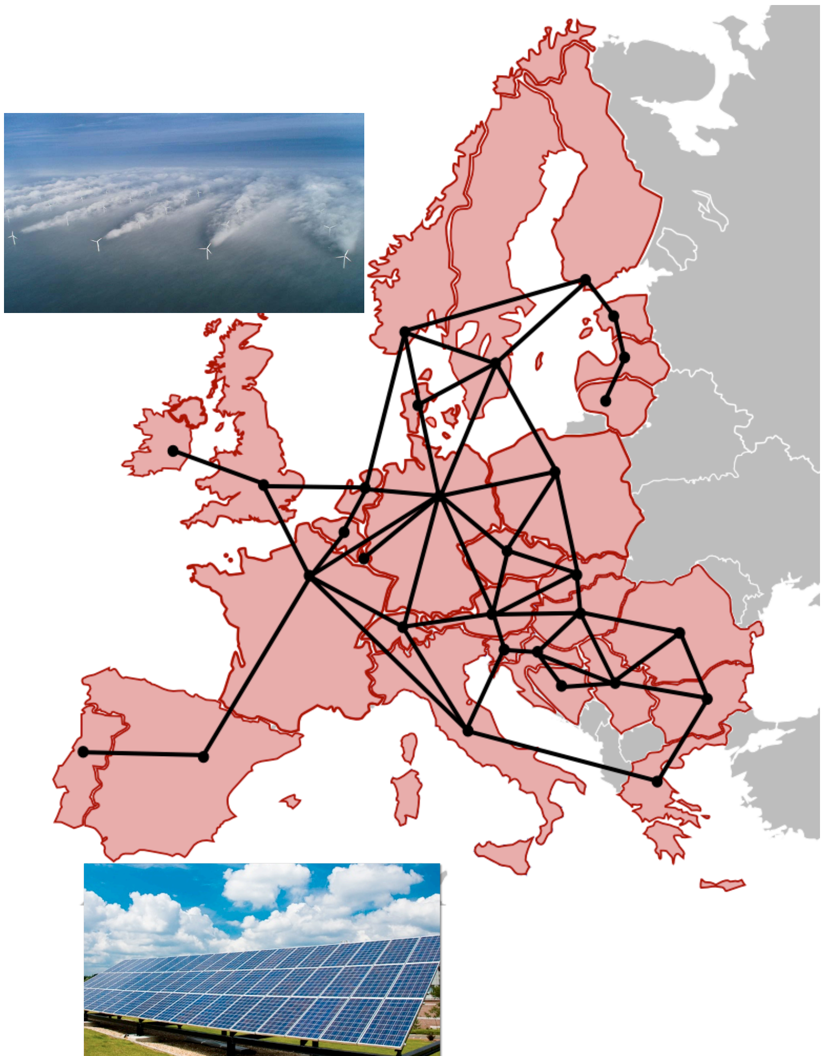
Design of
a highly renewable pan-European energy system



More + more + … renewables:
what is the end of the story?

Anticipate the future!
Think backwards: 2050 →2020!

Let the weather decide!

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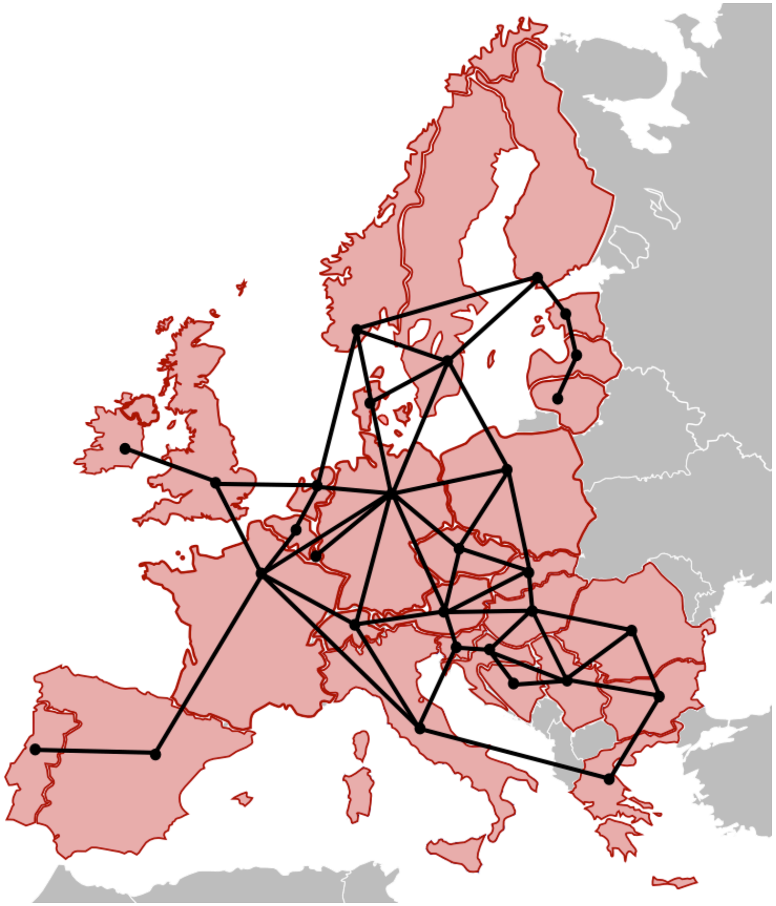


Let the weather decide!

$$G_n^W(t)+G_n^S(t)+B_n(t)+\sum_{ngb(n)} F_{\to n}+S_n^- = L_n(t)+C_n(t)+\sum_{ngb(n)} F_{n\to}+S_n^+$$

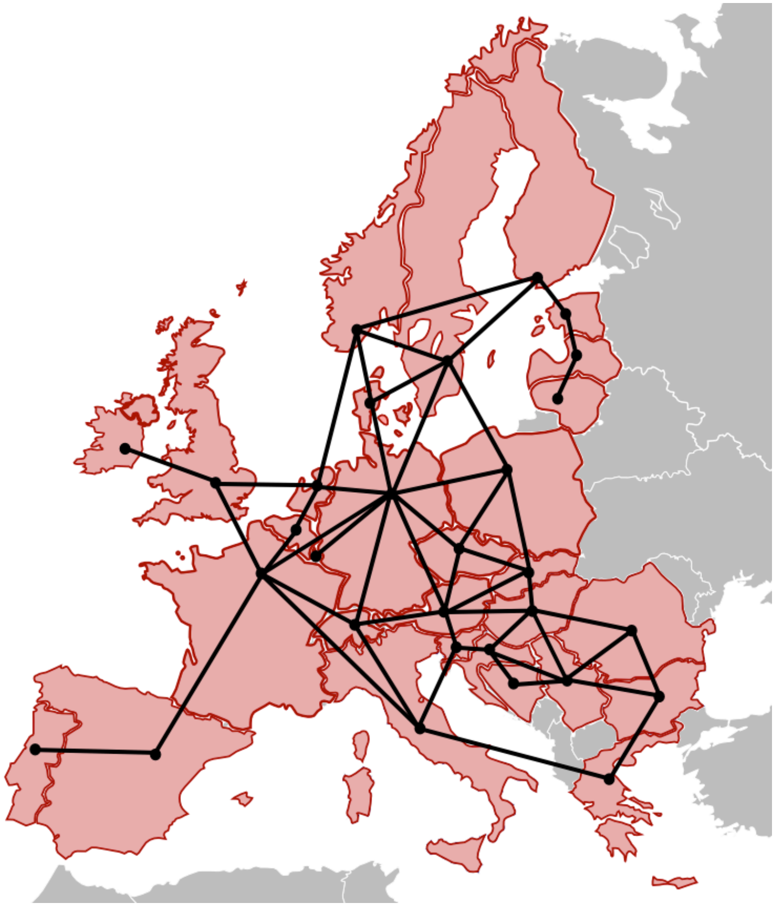
$$\left\langle G_n^W+G_n^S\right\rangle=\gamma_n\left\langle L_n\right\rangle$$

$$\left\langle G_n^W\right\rangle=\alpha_n\gamma_n\left\langle L_n\right\rangle \qquad \left\langle G_n^S\right\rangle=\left(1-\alpha_n\right)\gamma_n\left\langle L_n\right\rangle$$

actio = reactio

$$G_n^W(t)+G_n^S(t)-L_n(t)=C_n(t)-B_n(t)+\sum_{ngb(n)}\left(F_{n\to}-F_{\to n}\right)+\left(S_n^+-S_n^-\right)$$

Let the weather decide!



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

Renewable Energy Atlas

2000 – 2007: 1h, 45x45km²

1980 – 2014: 1h, 30x30km²

$$L_n(t)$$

historical load (detrended)

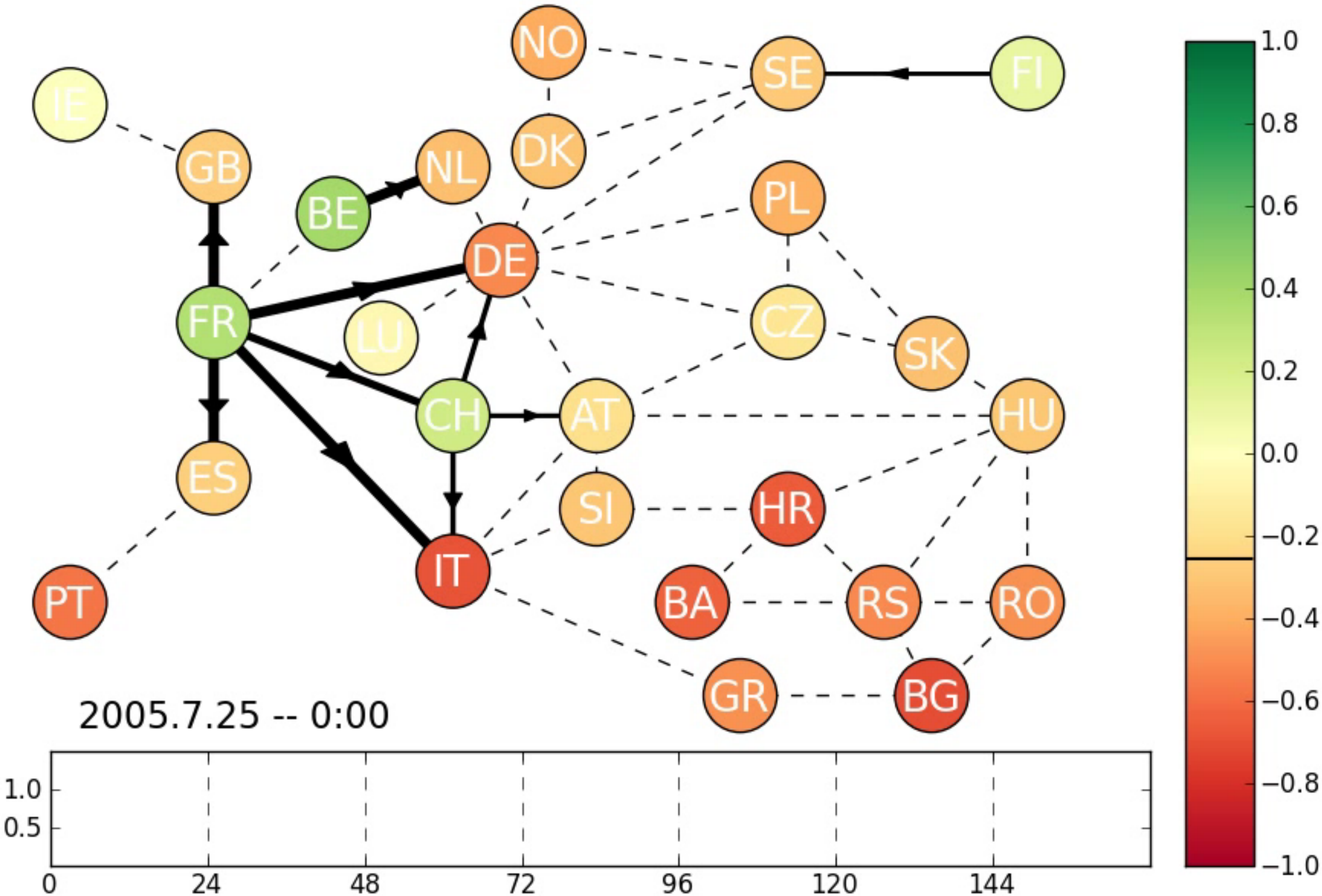
$$\left\langle G_n^W + G_n^S \right\rangle = \gamma_n \left\langle L_n \right\rangle$$

$$\left\langle G_n^W \right\rangle = \alpha_n \gamma_n \left\langle L_n \right\rangle$$

$$\left\langle G_n^S \right\rangle = \left(1 - \alpha_n\right) \gamma_n \left\langle L_n \right\rangle$$

actio = reactio

$$G_n^W(t) + G_n^S(t) - L_n(t) = C_n(t) - B_n(t) + \sum_{ngb(n)} \left(F_{n\rightarrow} - F_{\rightarrow n}\right) + \left(S_n^+ - S_n^-\right)$$



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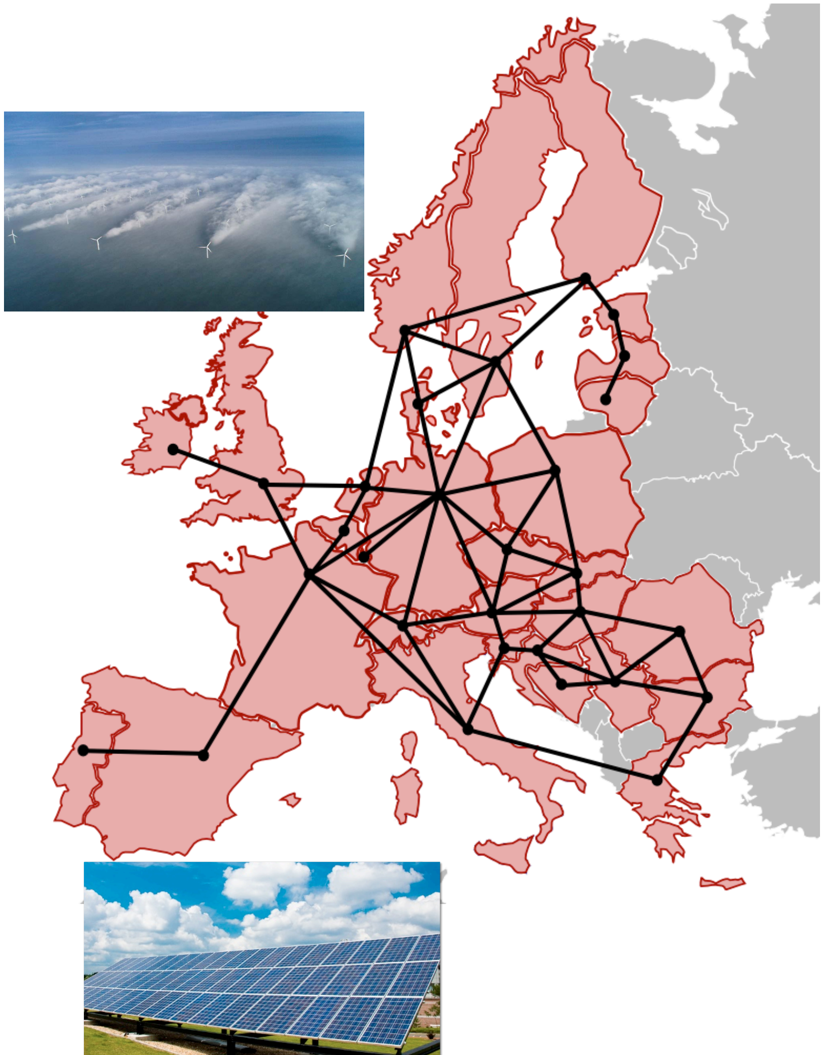
Technical + economical design of a highly renewable pan-European energy system



How much ...

... wind energy?

... solar PV energy?

... backup energy + power?

... transmission?

... storage?

and what about

... transition 2050 → 2020?

... future markets

... coupling of energy sectors?

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How much backup?

How much wind + solar power?

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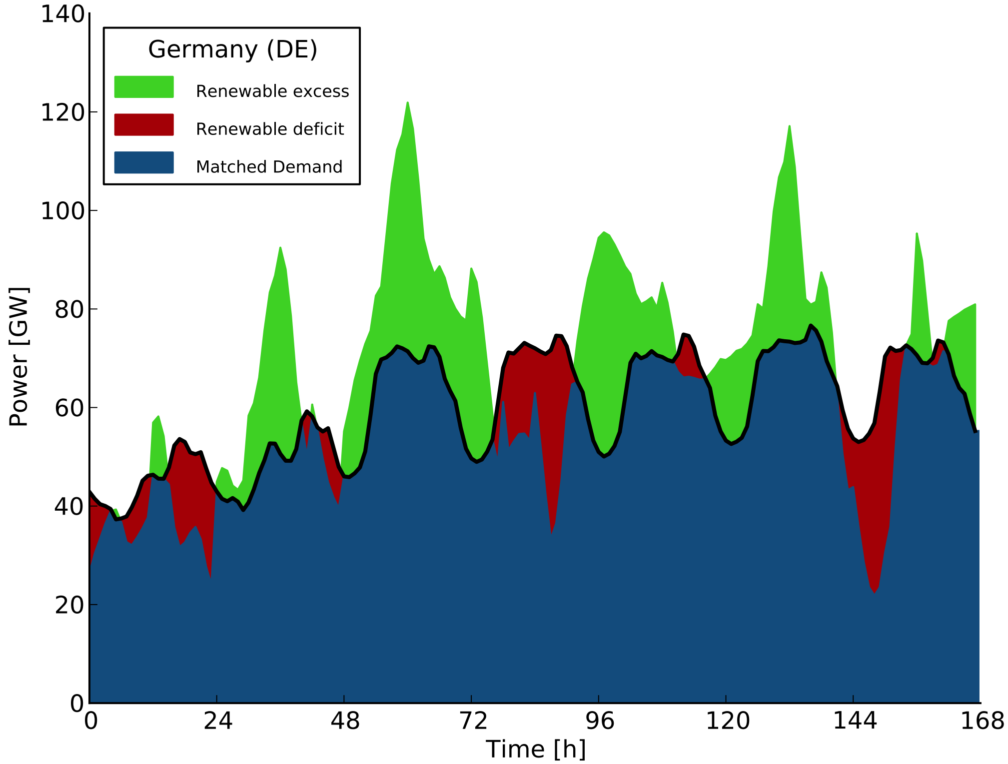
Mismatch distribution (Germany)

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

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



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

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

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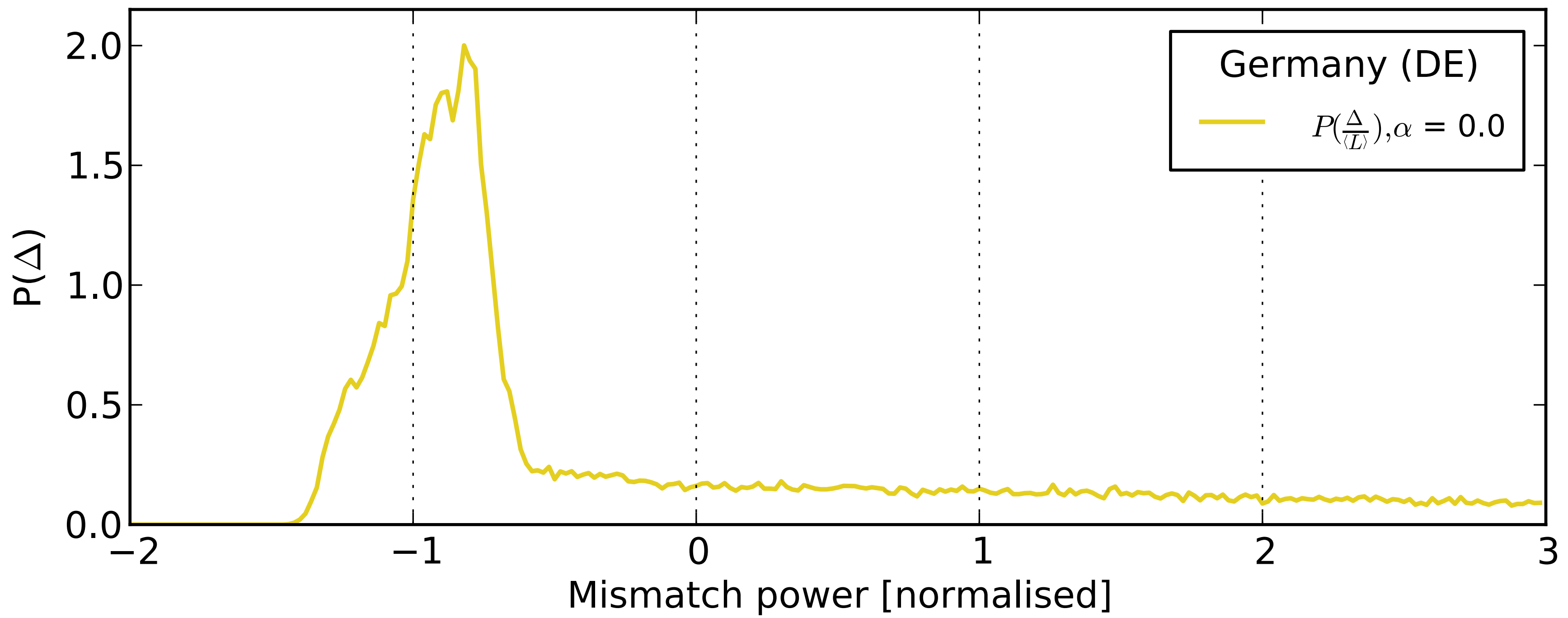
$$\alpha_n = \frac{\left\langle G_n^W \right\rangle}{\left\langle G_n^{RES} \right\rangle}$$



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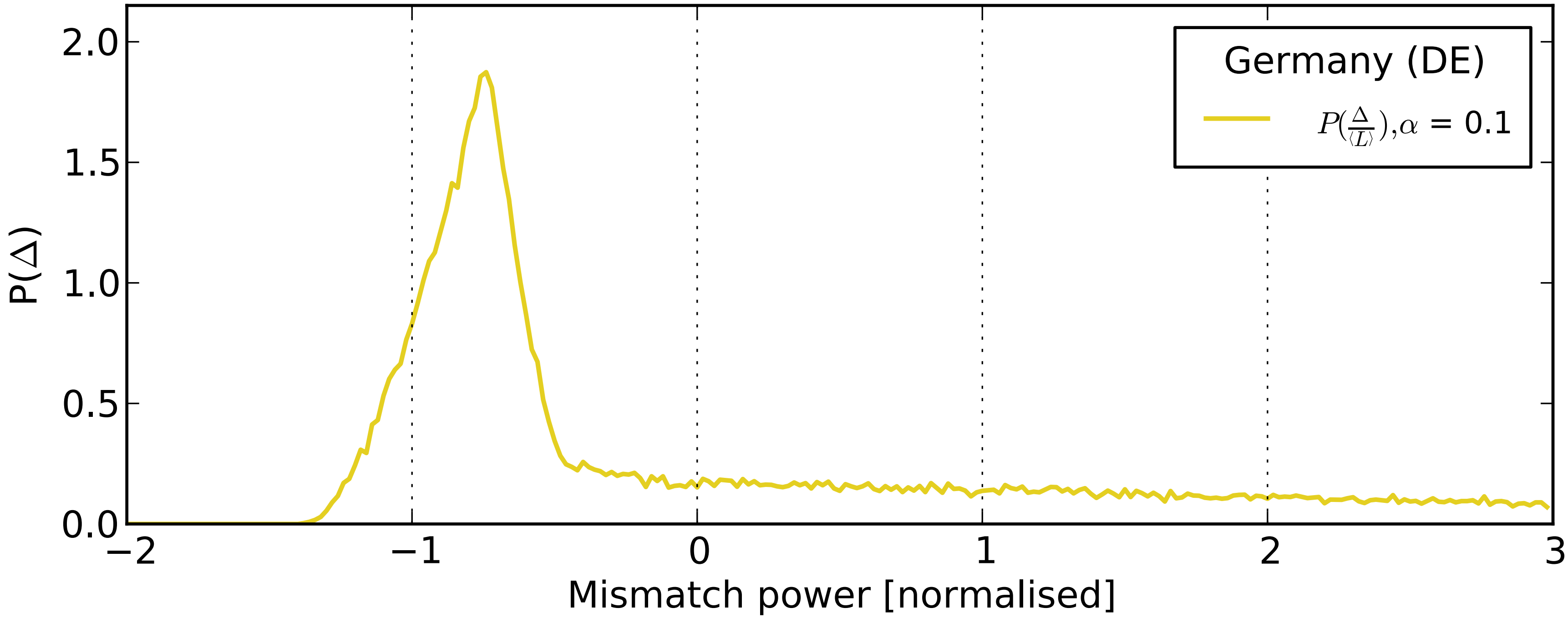

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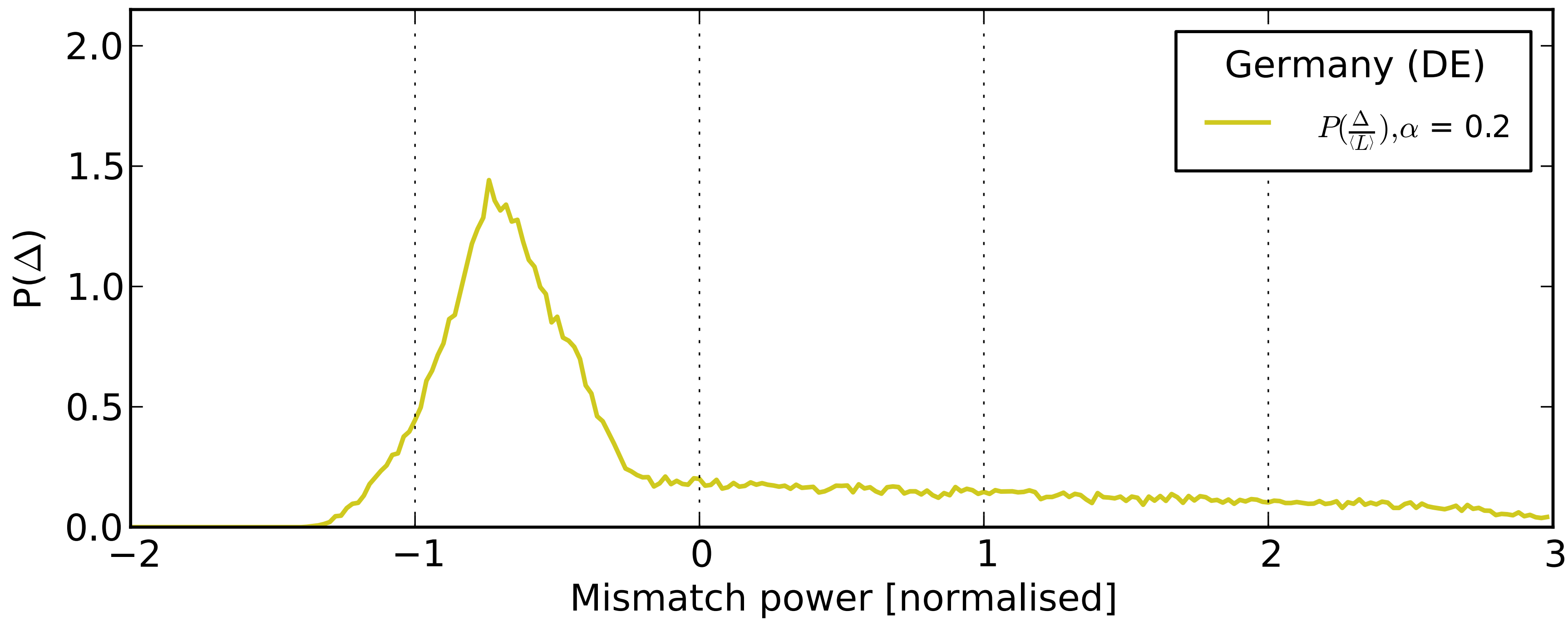

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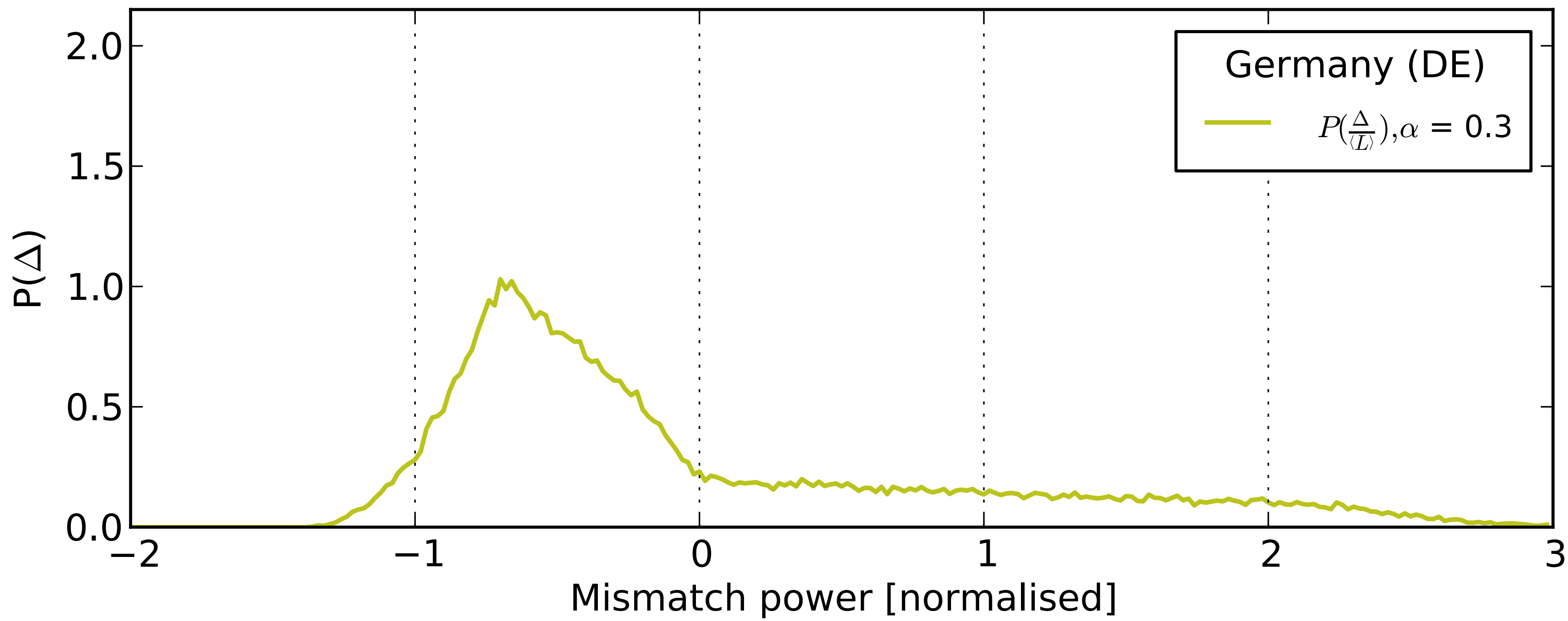

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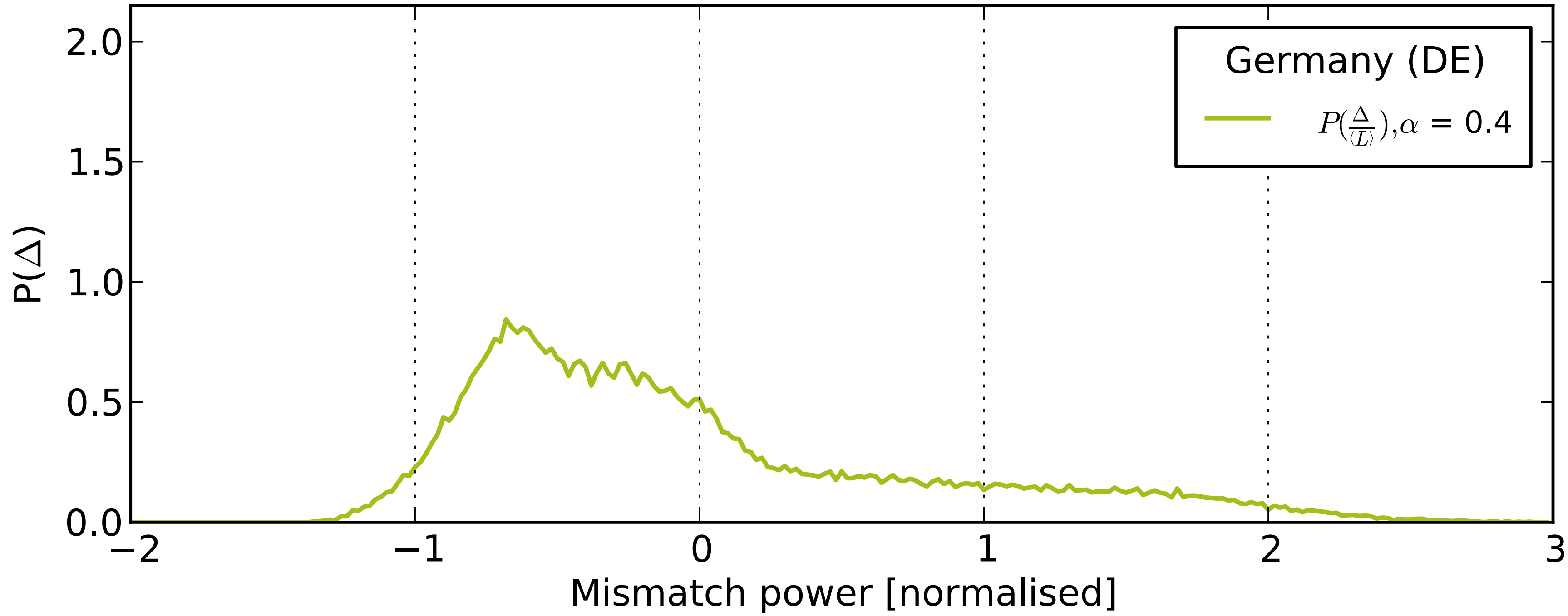

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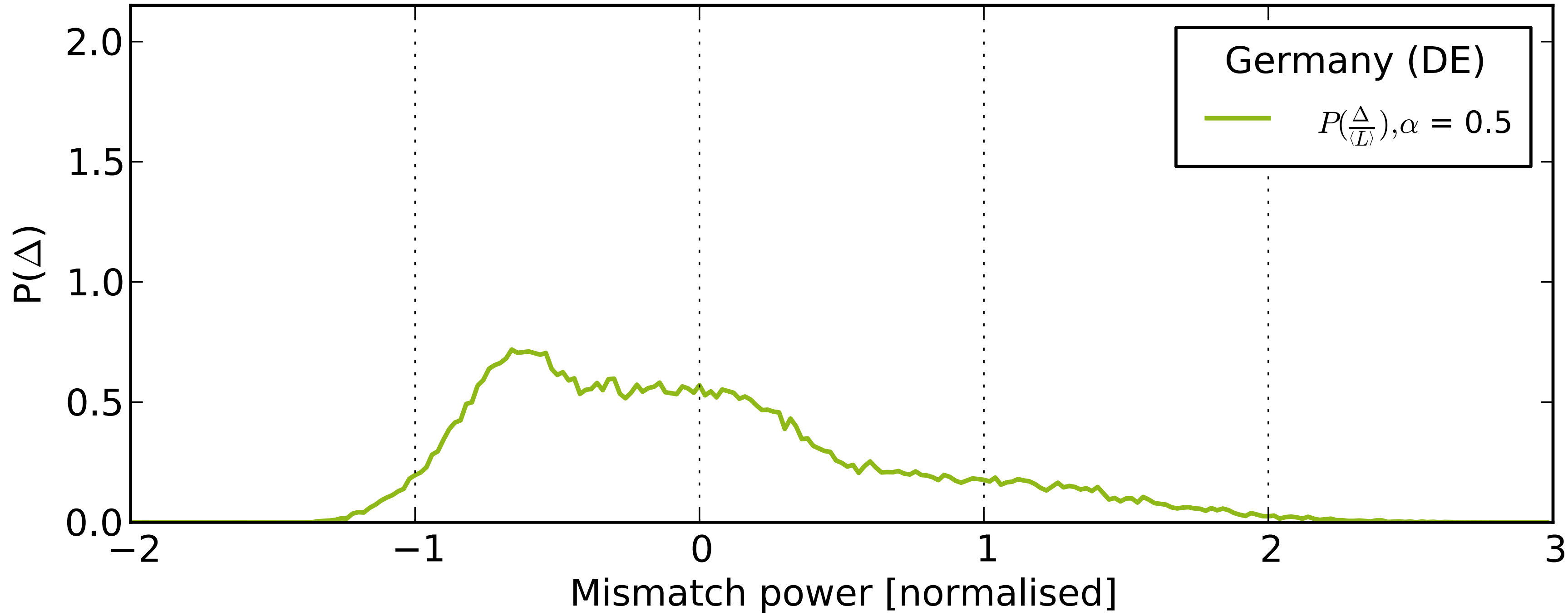

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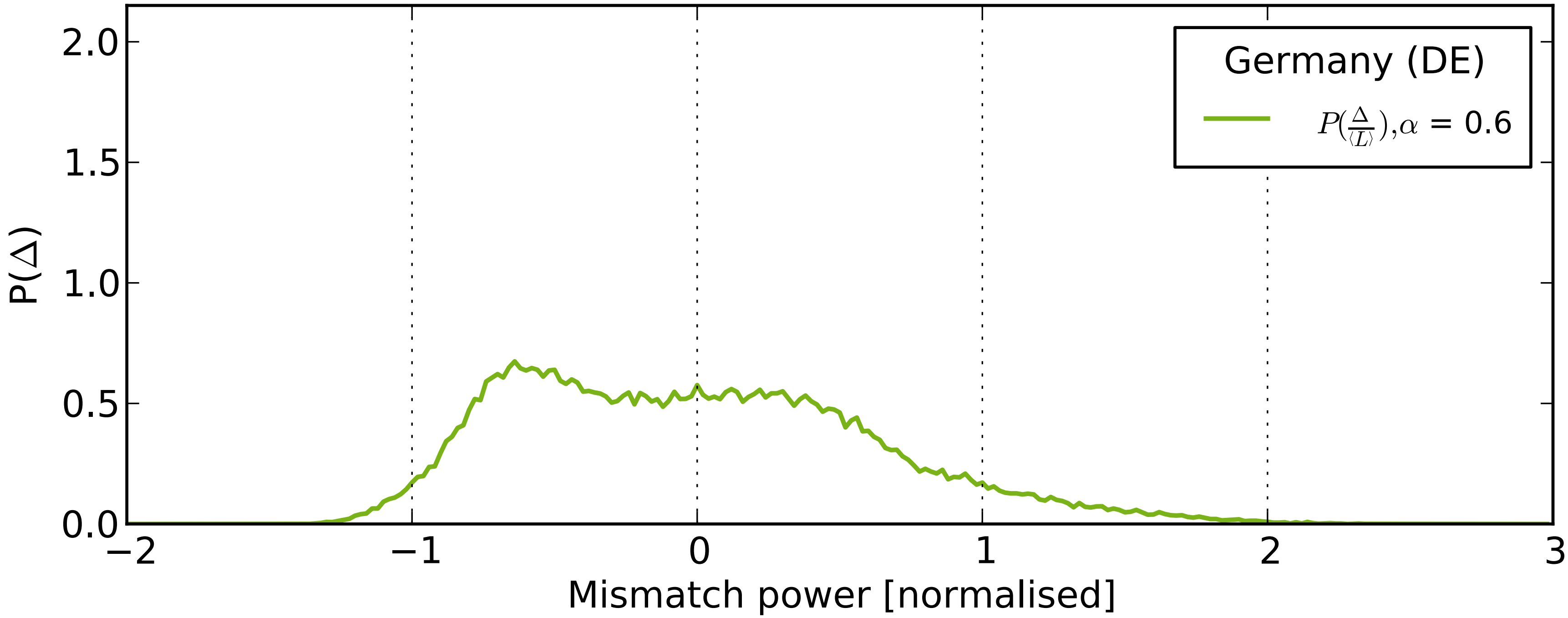

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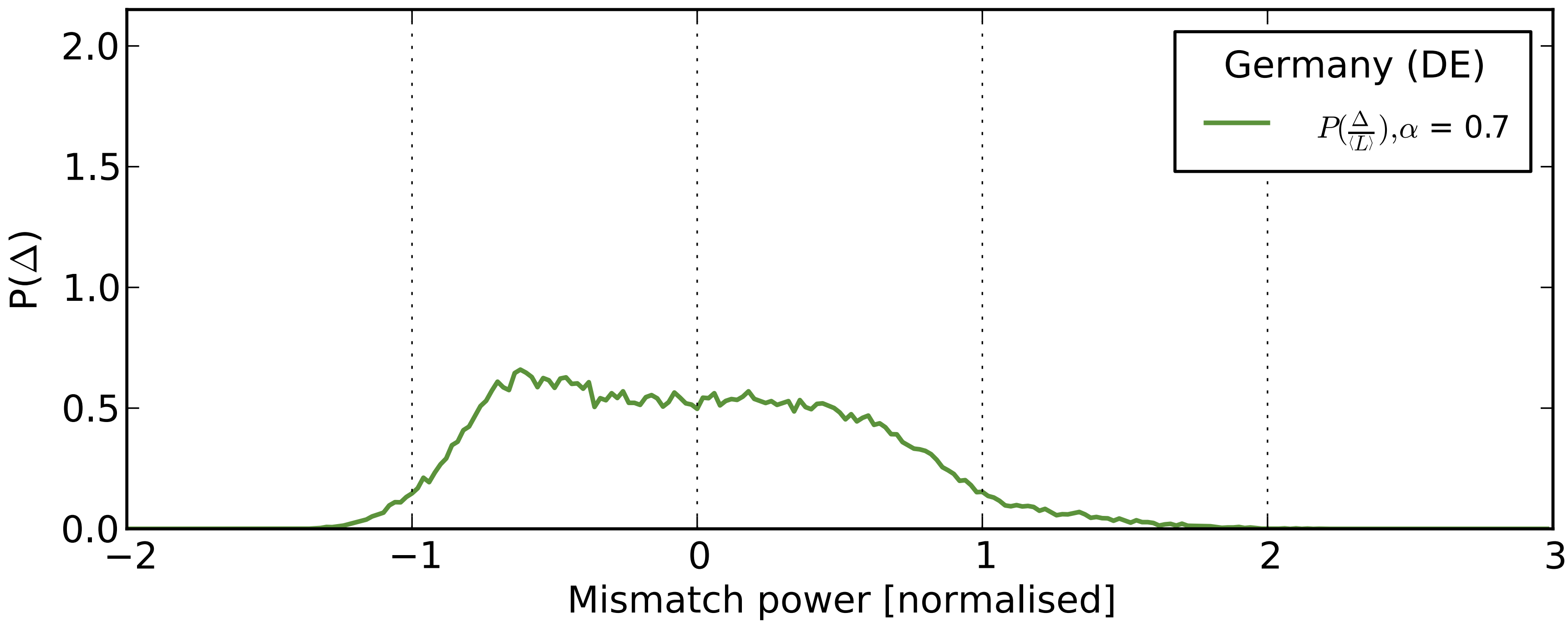

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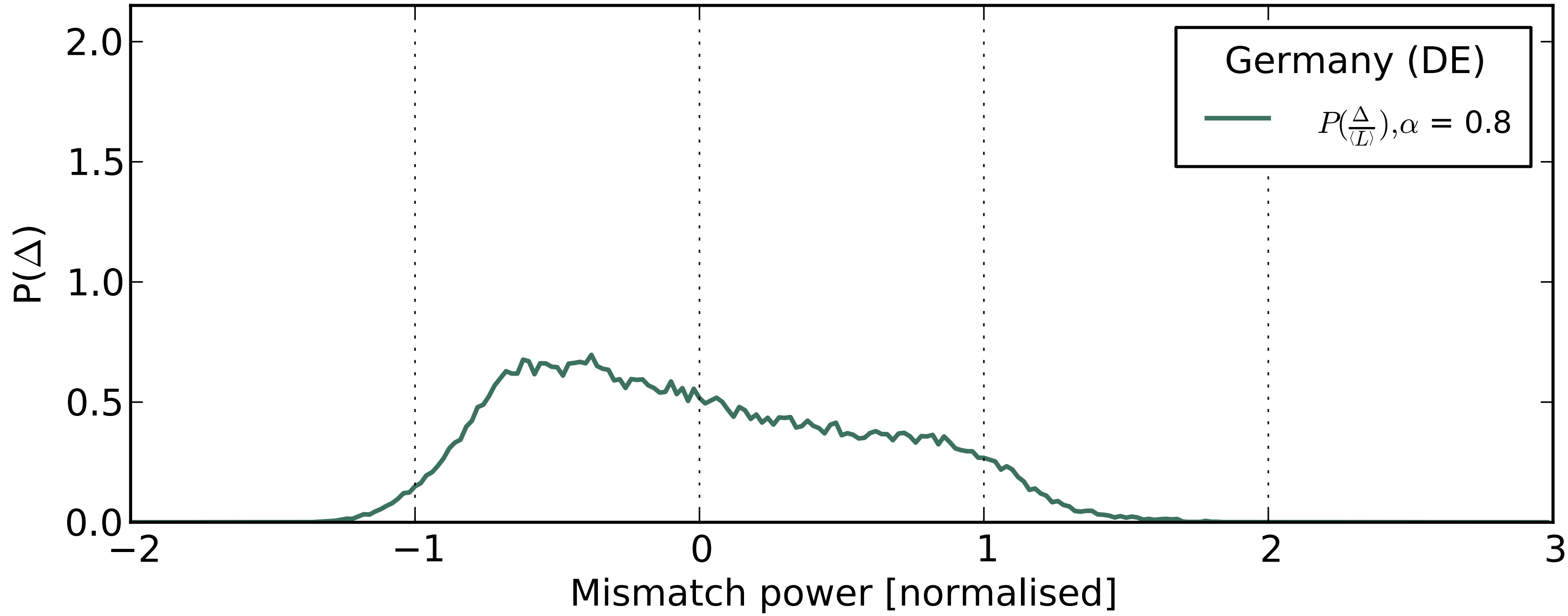
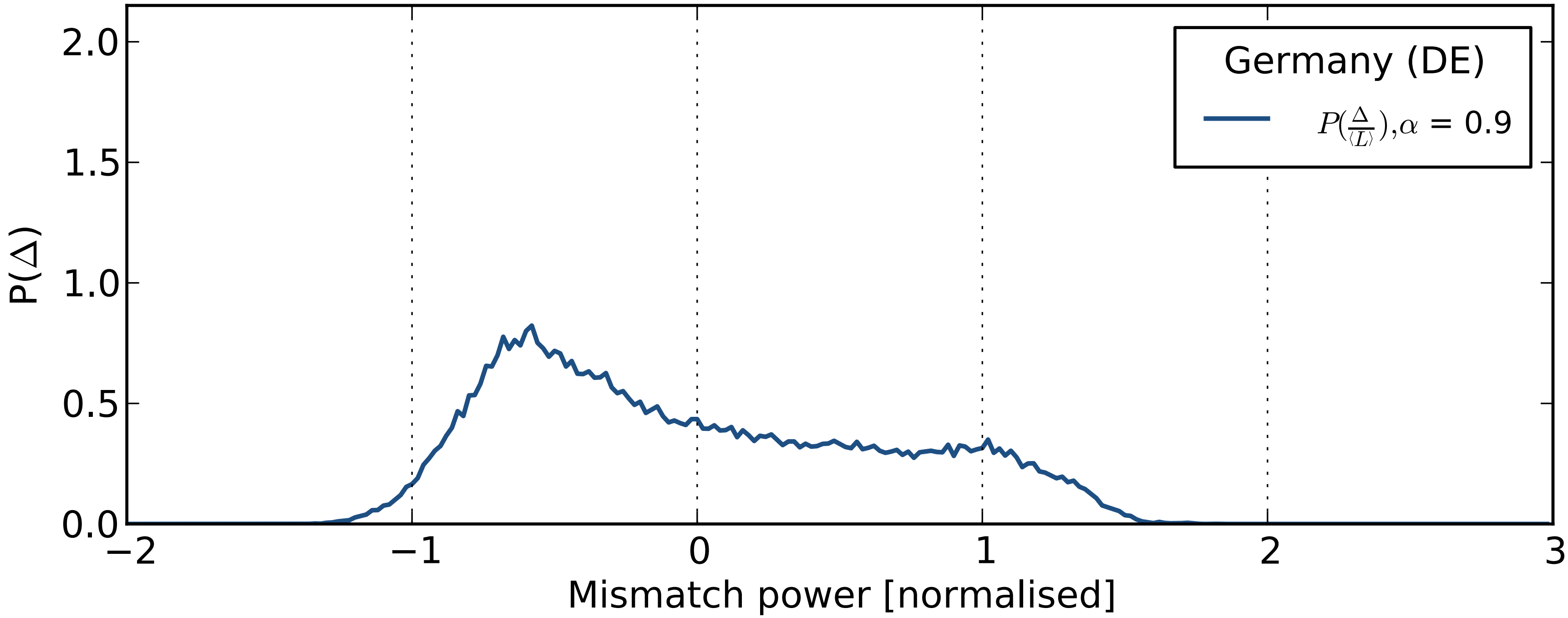
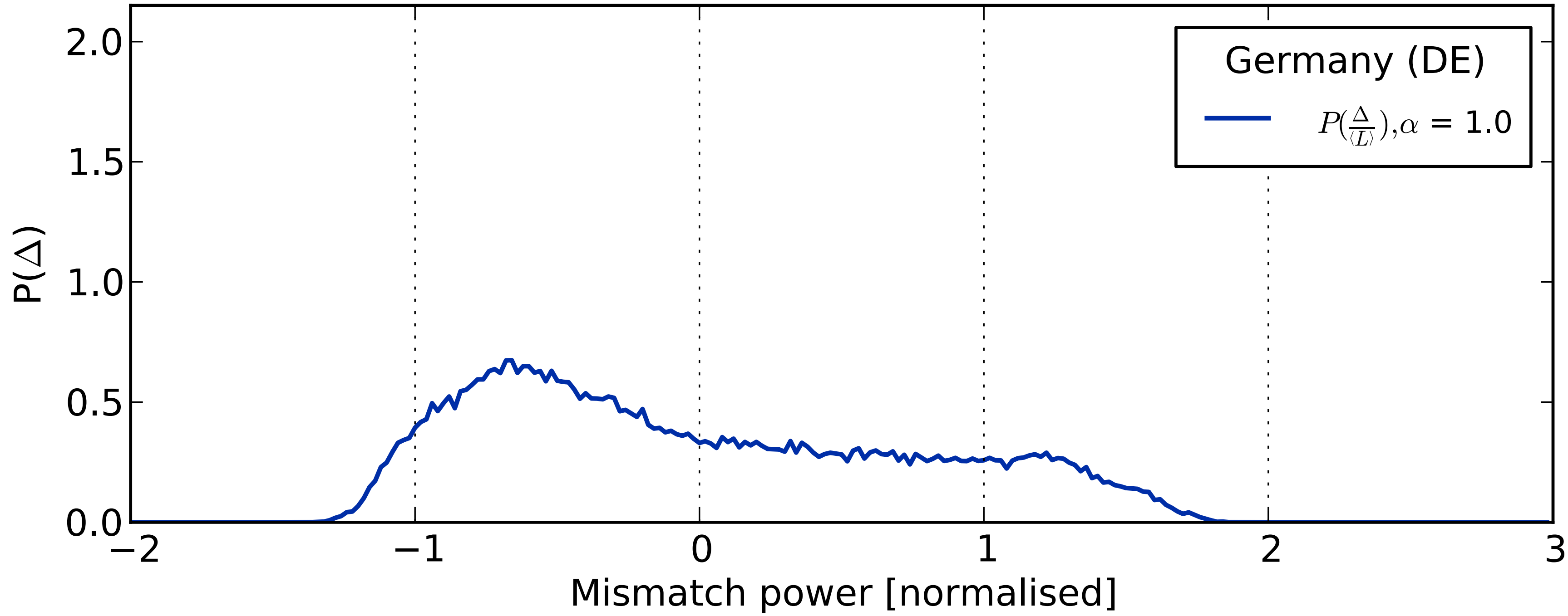

Germany (DE)
$P(\frac{\Delta}{\langle L \rangle})$,$\alpha$ = 0.8
P(Δ)
2.0
1.5
1.0
0.5
0.0
−2
−1
0
1
2
3
Mismatch power [normalised]



Germany (DE)
$P(\frac{\Delta}{\langle L \rangle}), \alpha$ = 0.9
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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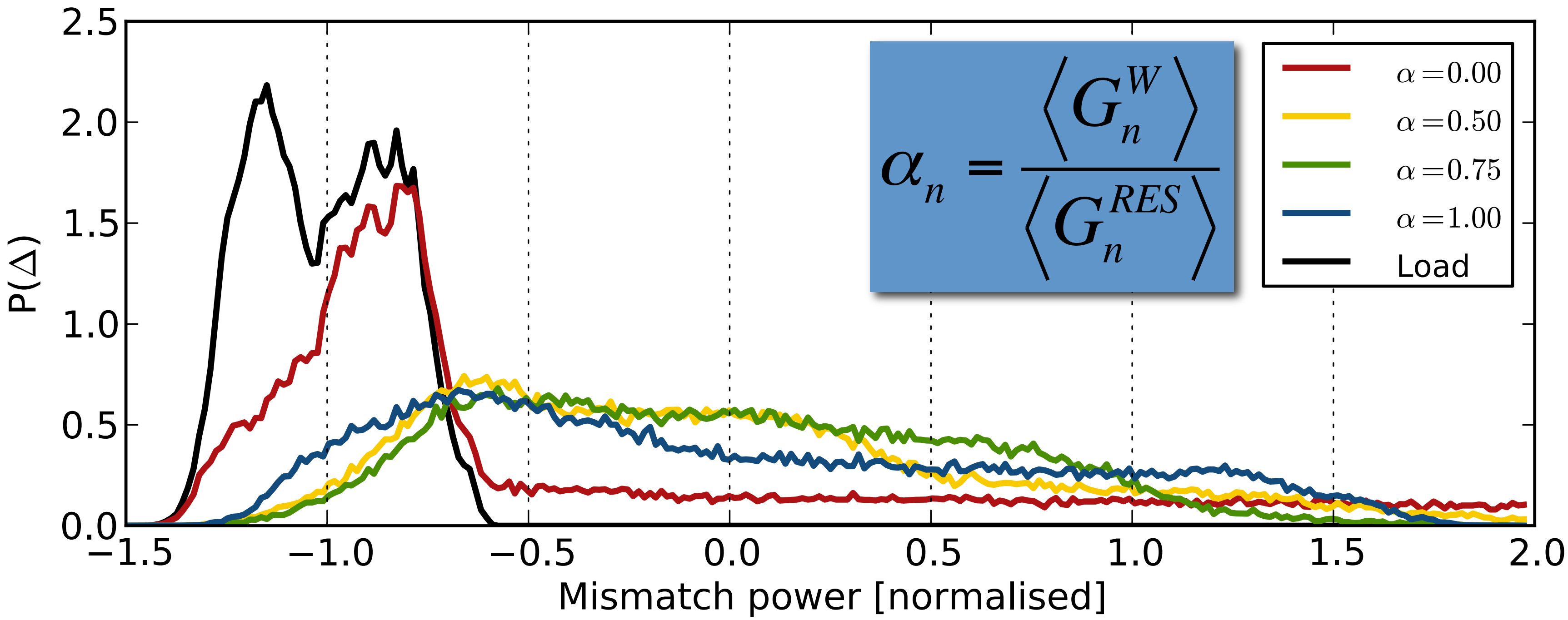
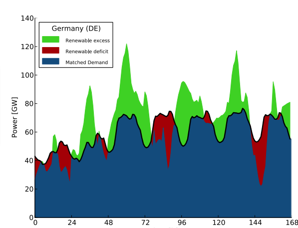
Mismatch distribution (Germany)

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

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



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



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

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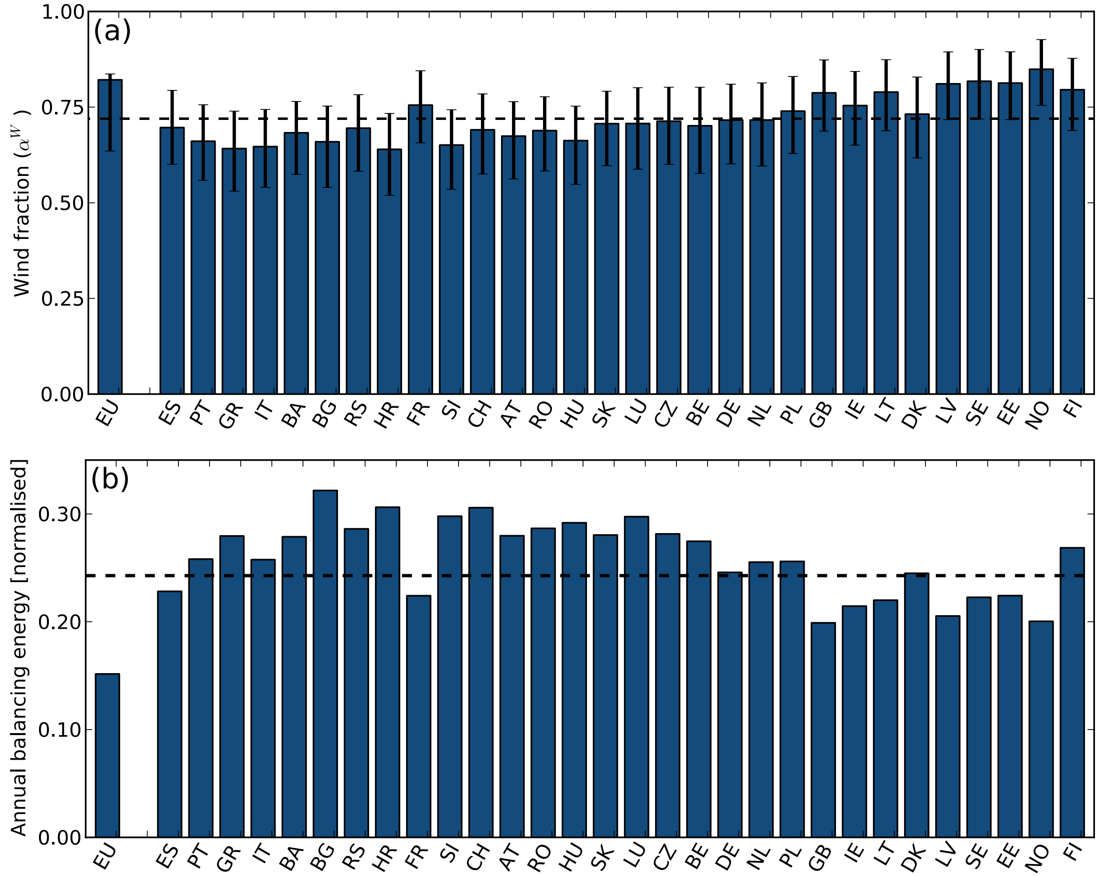
BACKUP ENERGIES of EU countries (zero transmission)



$$\alpha_{\min} \approx 0.70$$

$$\langle B_n \rangle \approx 0.24$$

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Mismatch distribution (Europe)

$$G_n^{RES}(t) - L_n(t) = C_n(t) - B_n(t) + \sum_{ngb(n)} \left(F_{n\rightarrow} - F_{\rightarrow n} \right)$$

$$\Delta_{EU}(t) = \sum_n G_n^{RES}(t) - \sum_n L_n(t) \qquad = G_{EU}^{RES}(t) - L_{EU}(t)$$

$$= \sum_n \left(C_n(t) - B_n(t) \right) + \underbrace{\sum_n \sum_{ngb(n)} \left(F_{n\rightarrow} - F_{\rightarrow n} \right)}_{=0} \qquad = C_{EU}(t) - B_{EU}(t)$$

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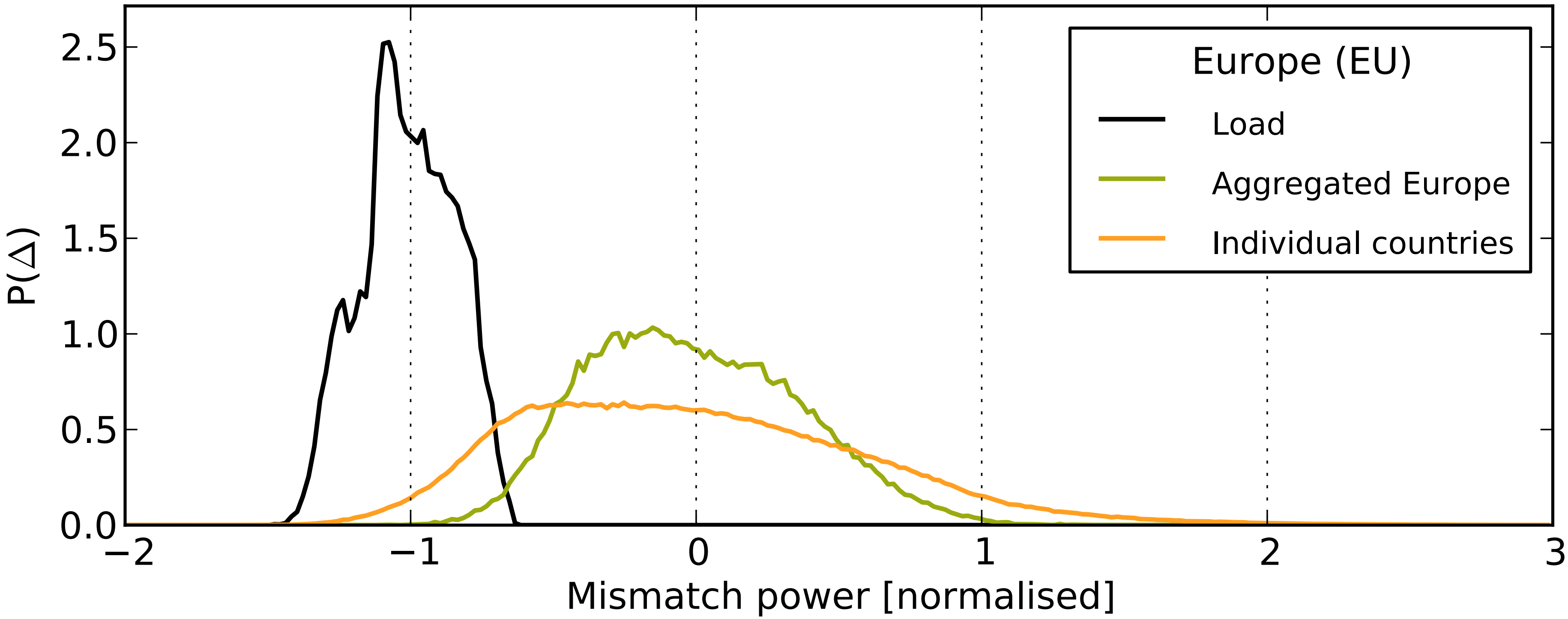
Mismatch distribution: Germany vs. Europe



Mismatch without / with Transmission

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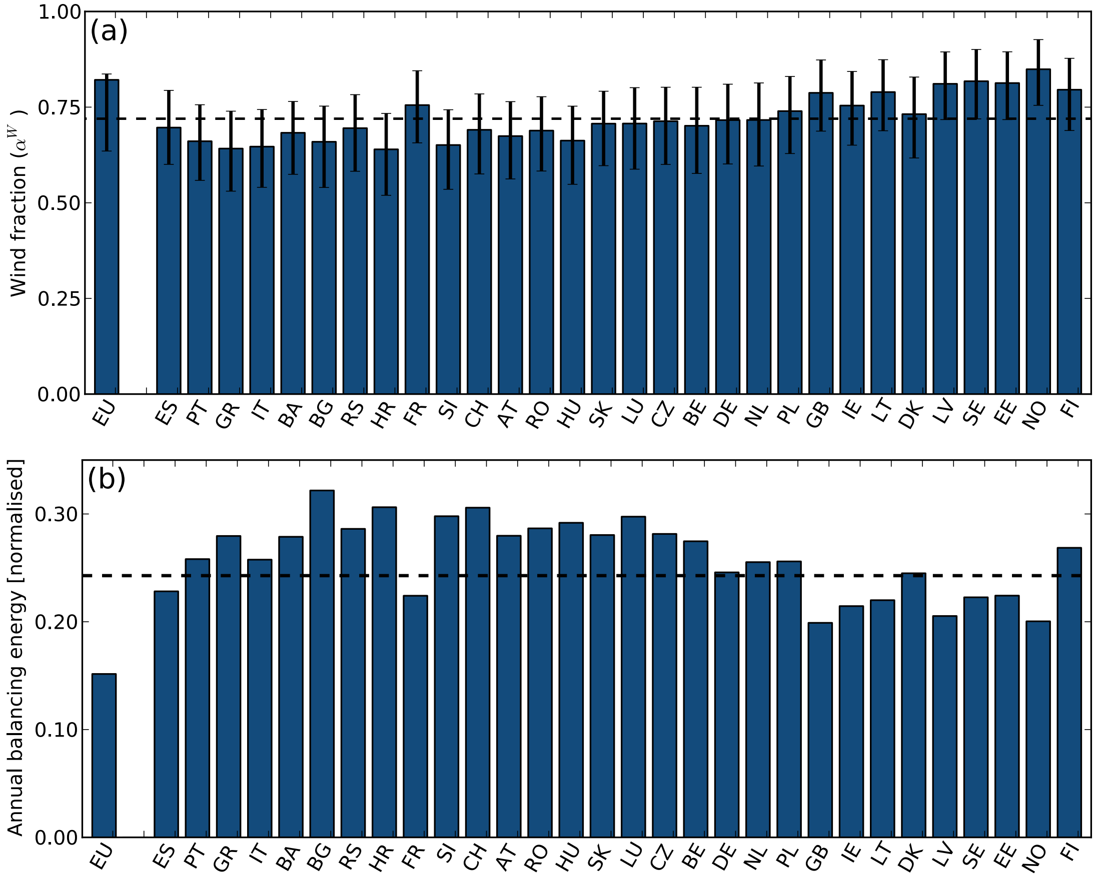
BACKUP ENERGIES of EU countries (with/without transmission)



$$\alpha_n^{\min} \approx 0.70$$

$$\alpha_{EU} \approx 0.80$$

$$\langle B_n \rangle \approx 0.24$$

$$\langle B_{EU} \rangle \approx 0.15$$

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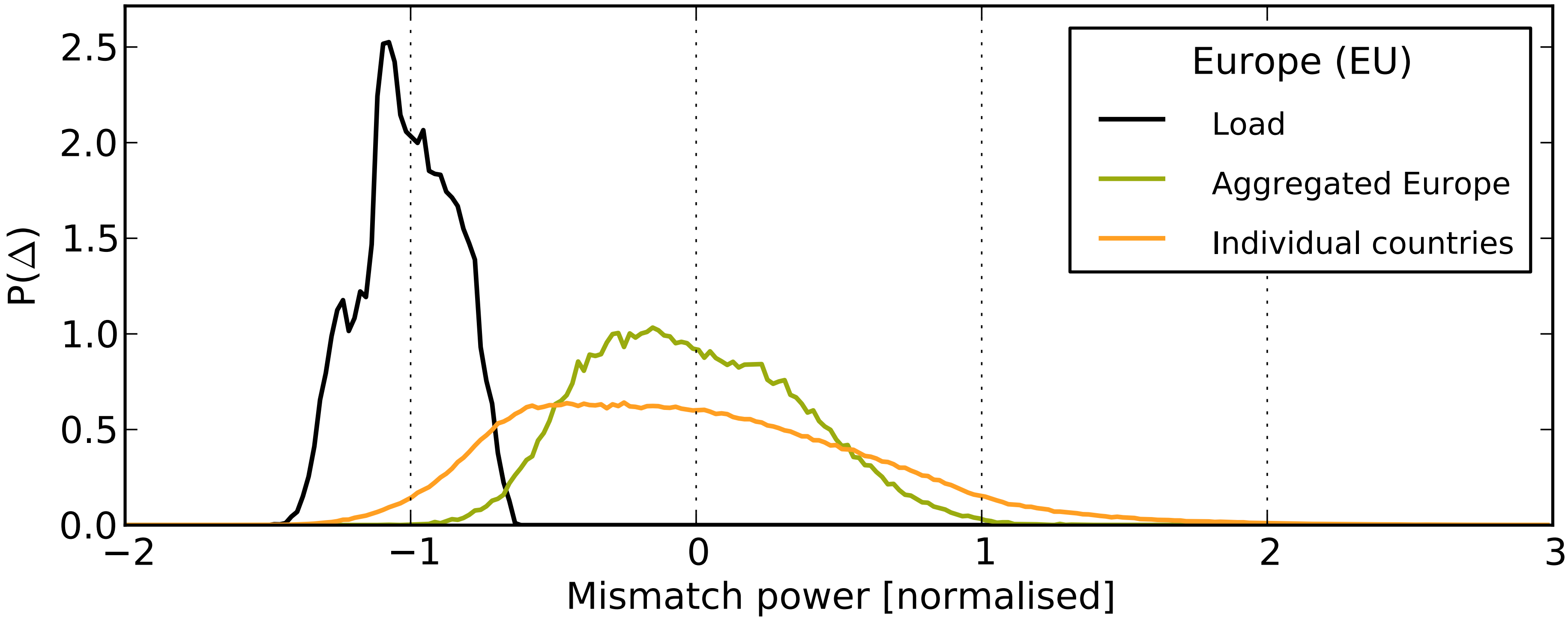
Mismatch distribution: Germany vs. Europe



Mismatch without / with Transmission

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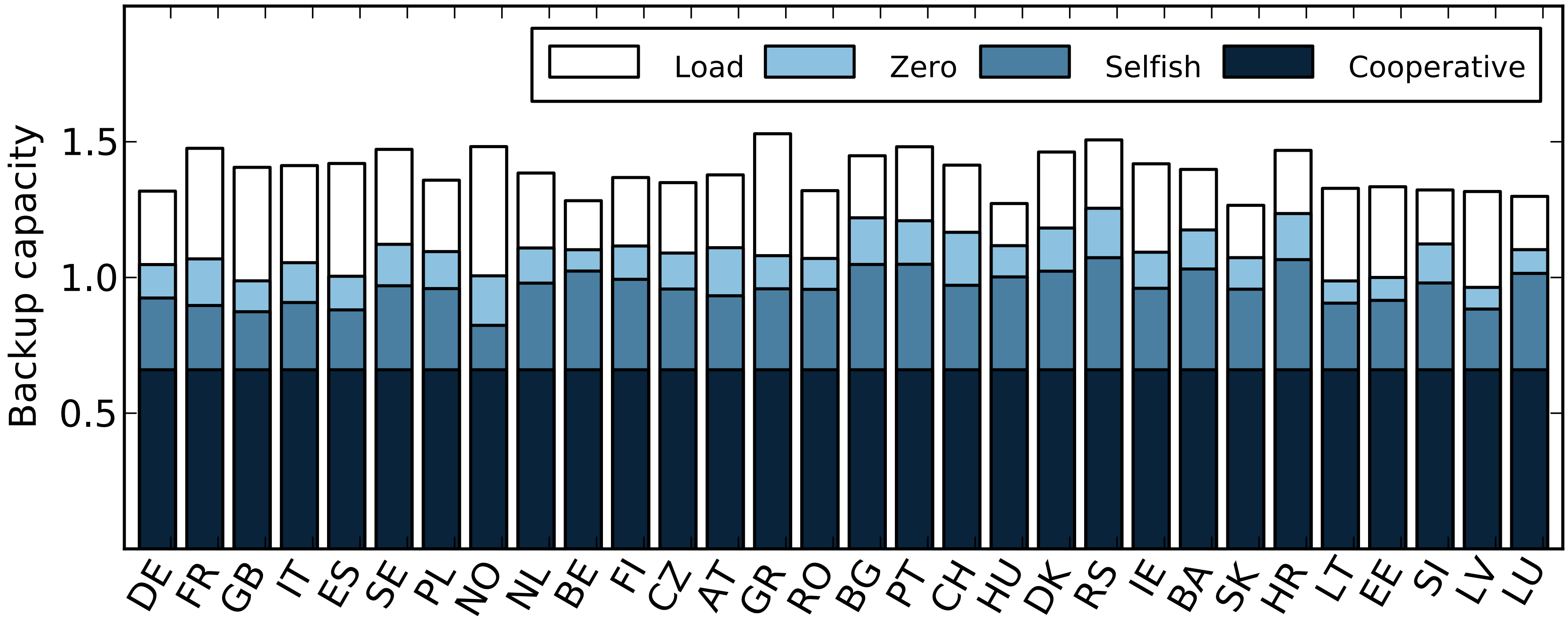
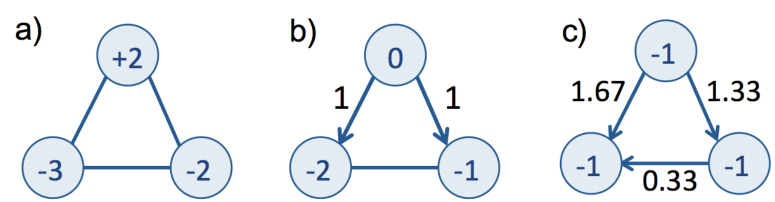
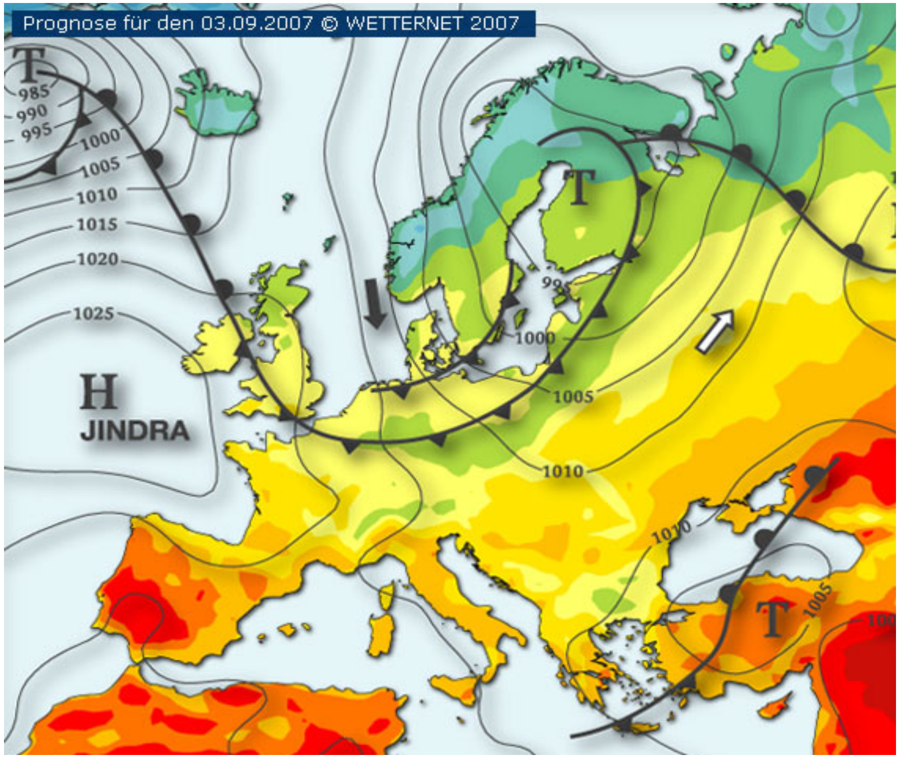
BACKUP CAPACITY of EU countries (without/with transmission)





wind and solar power capacities



annual consumption (2009)
= 3360 TWh

70% wind power generation
= 875 GW installed capacity
= 175.000 x 5 MW turbines
= 4350 x 200 MW wind farms
≈ 115000 km²

30% solar PV power generation
= 550 GW installed capacity
≈ 3500 - 7500 km²

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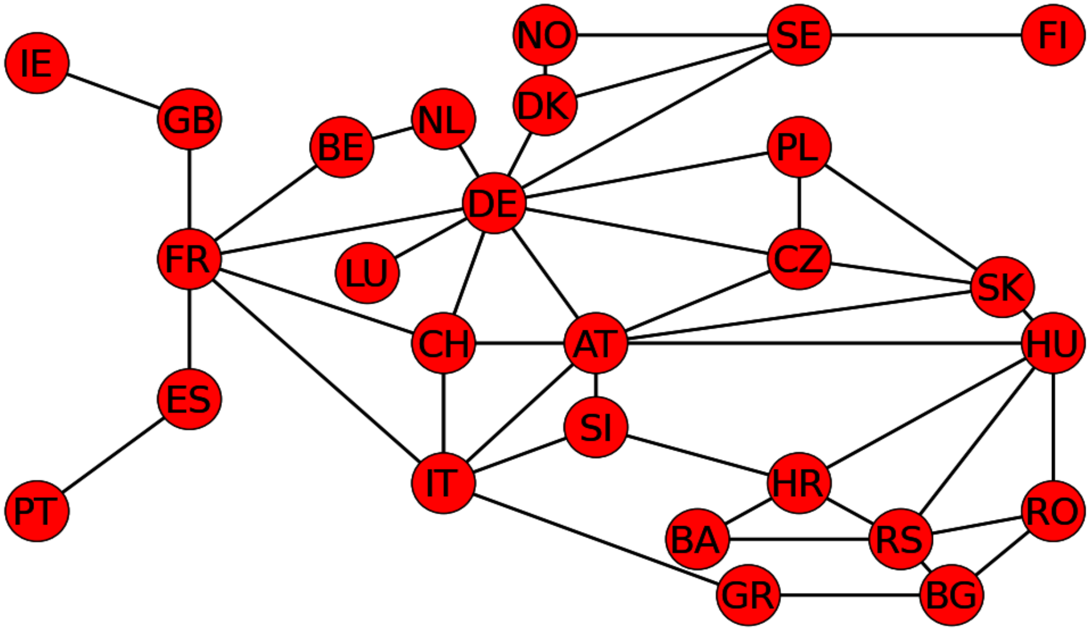
How much transmission?



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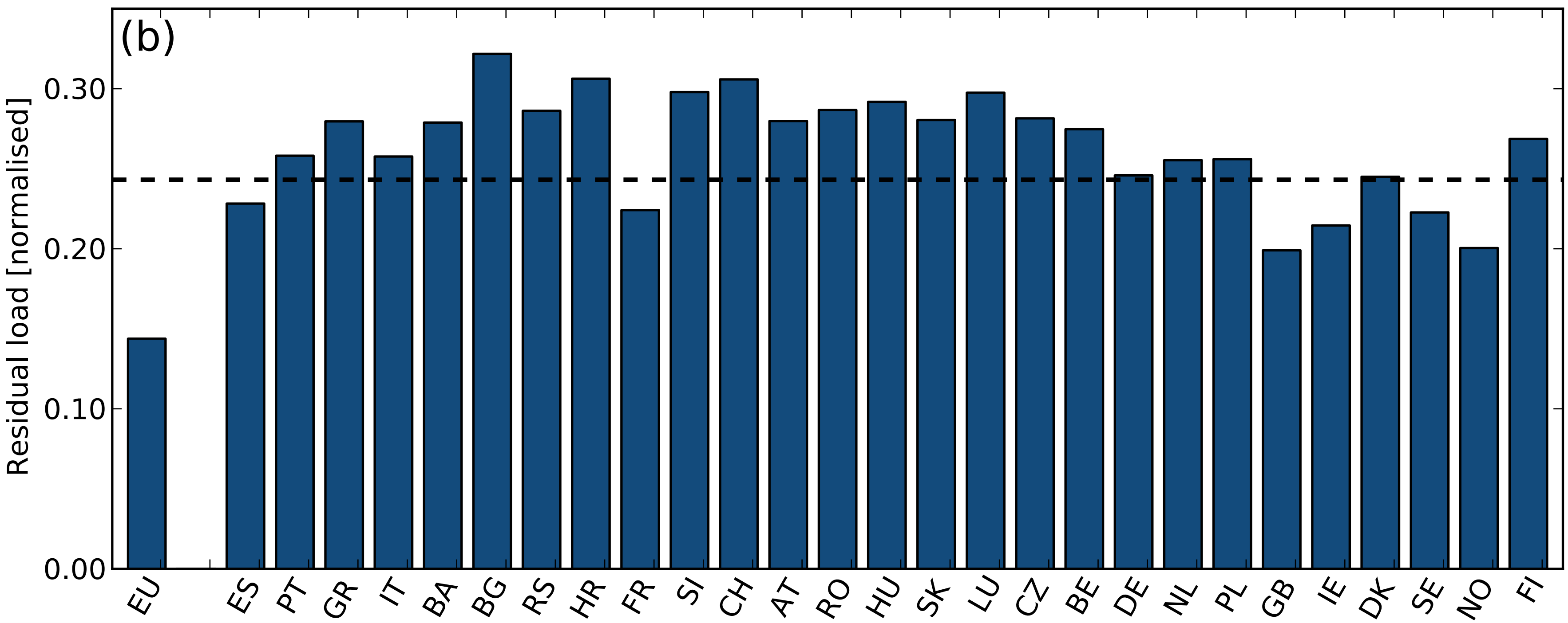
29

transmission calculation without transmission

$\gamma = 1$ $\alpha \approx 0.7$

minimum backup energy at optimal wind / solar mix



$B_{EU} = 0.15$ **vs.** $\sum_n B_n = 0.24$

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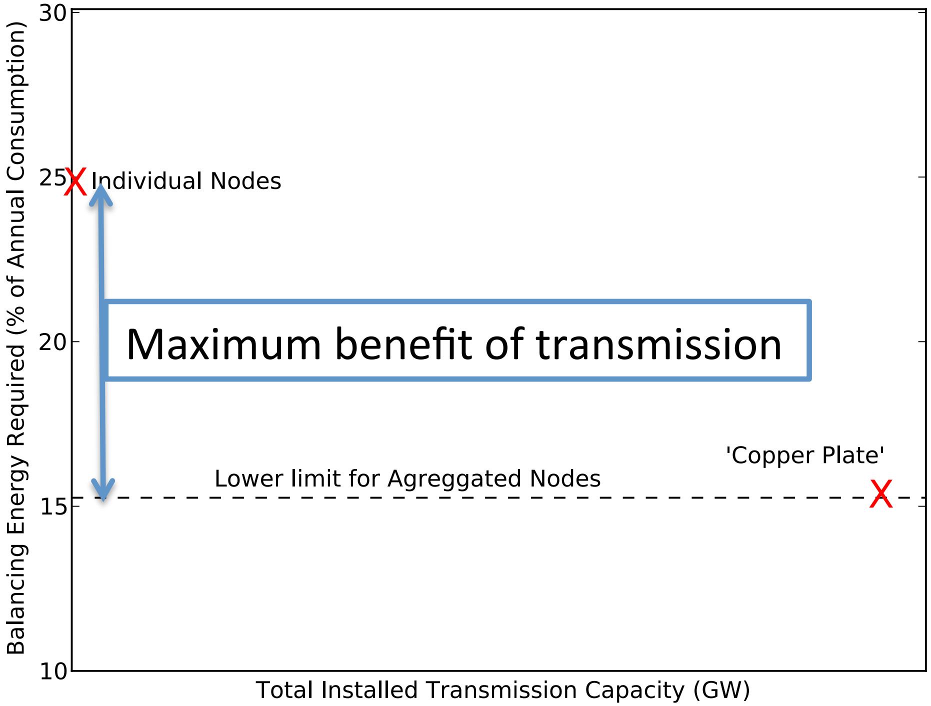
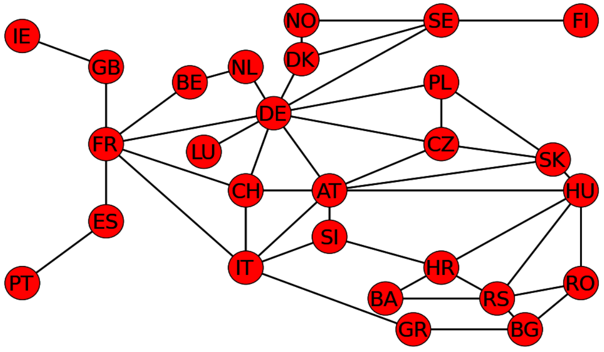
transmission calculation without transmission





The MAXIMUM BENEFIT OF TRANSMISSION quantifies how much balancing/surplus can be reduced by sharing local surplus wind and solar power in an unconstrained pan-European transmission network.

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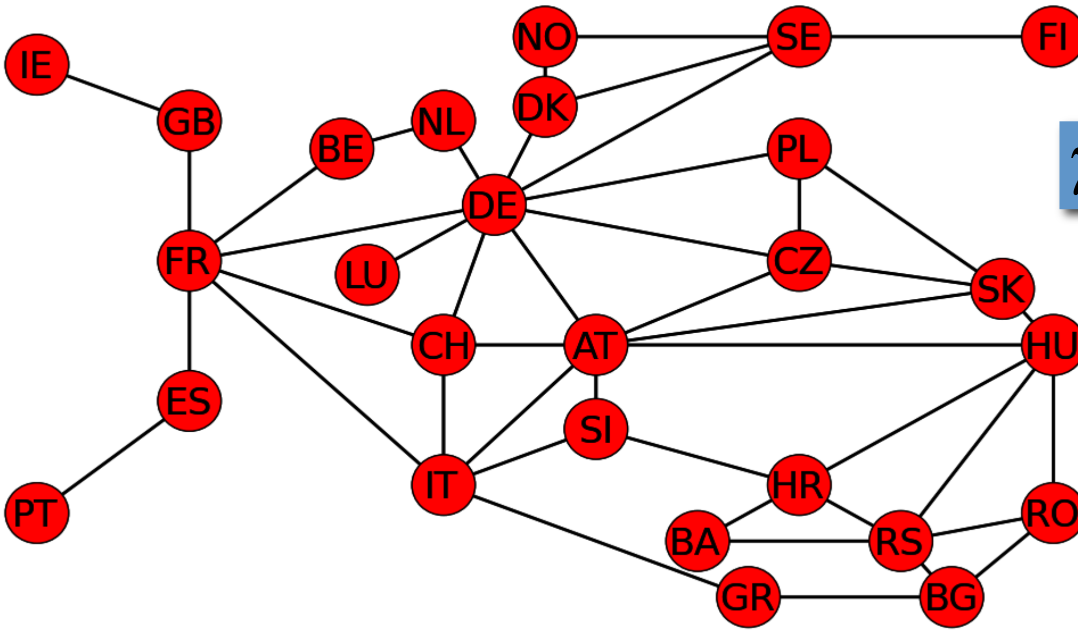
How much transmission?



$\gamma = 1, \quad \alpha \approx 0.7$

$$\min \sum_n B_n$$

$$\min \sum_l F_l^2$$

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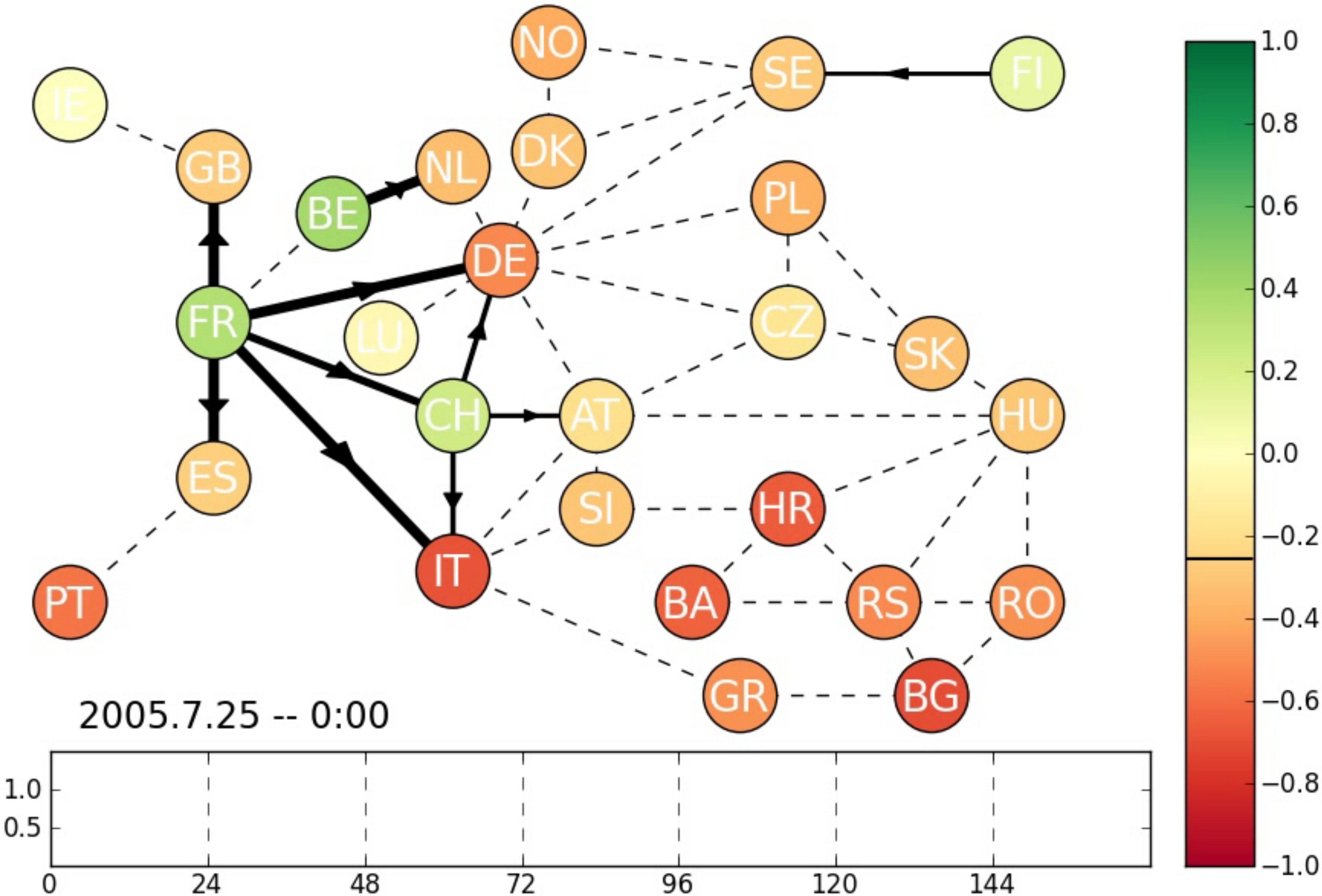

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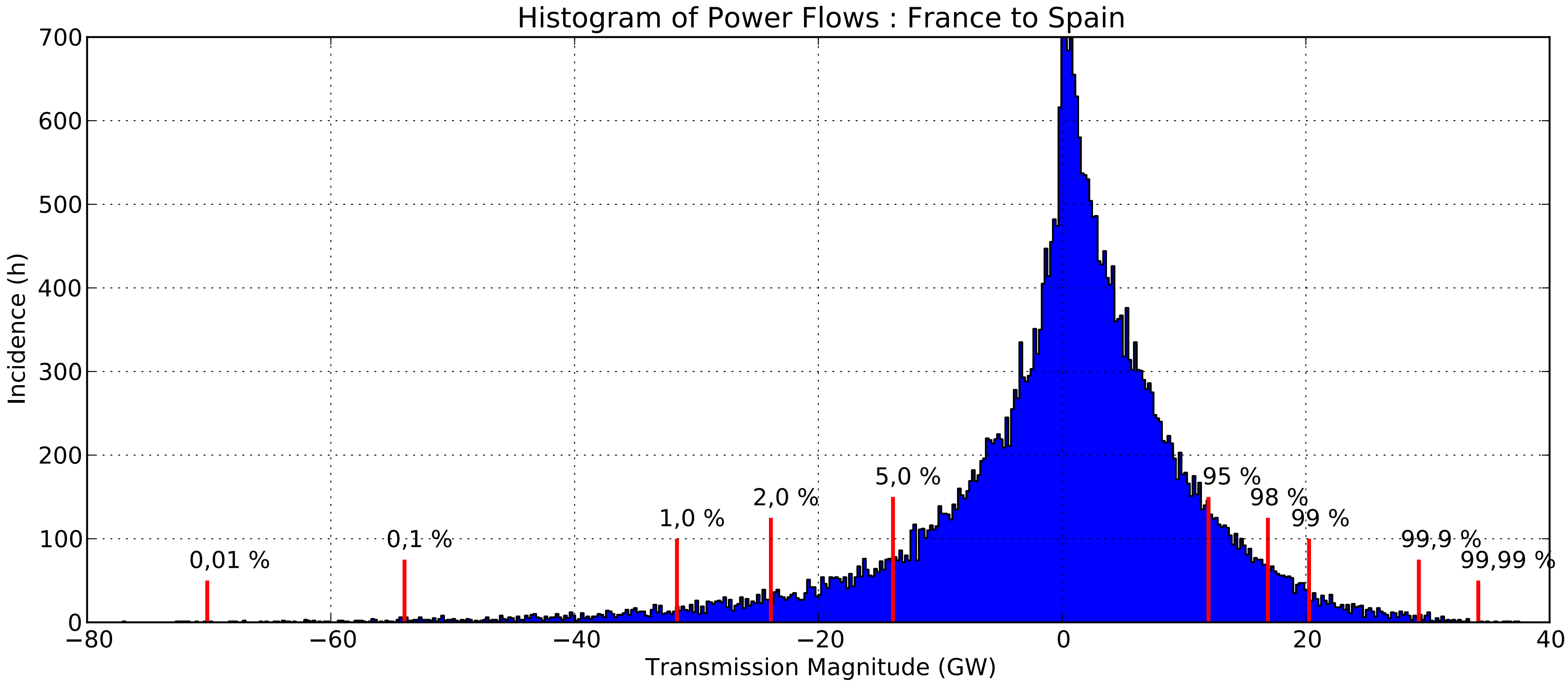
−0.4
−0.6
−0.8
−1.0



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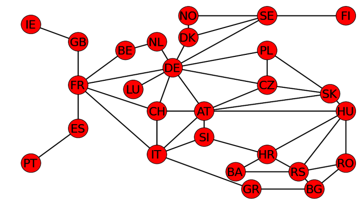
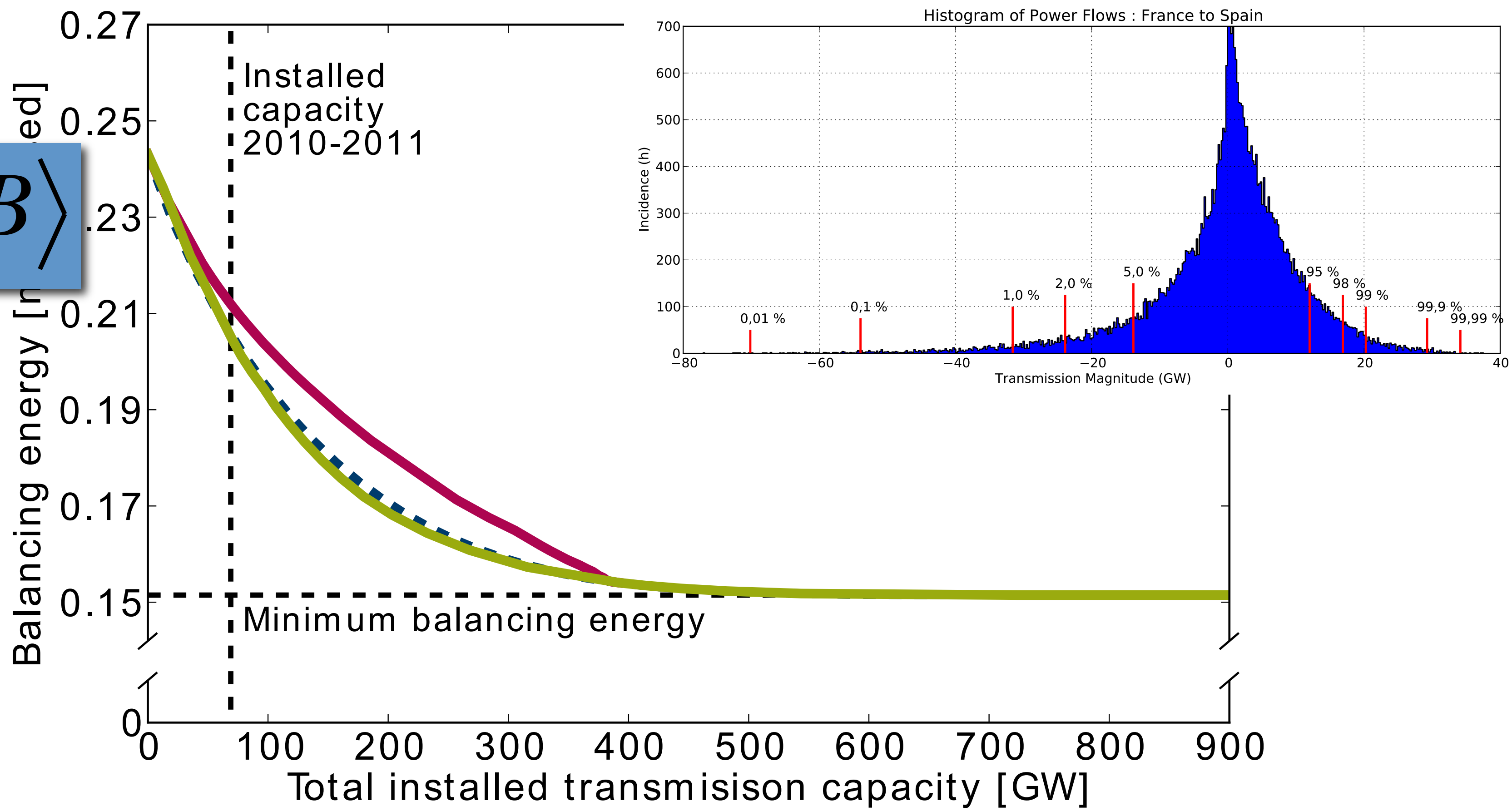
Backup vs. Transmission



$\langle B \rangle$



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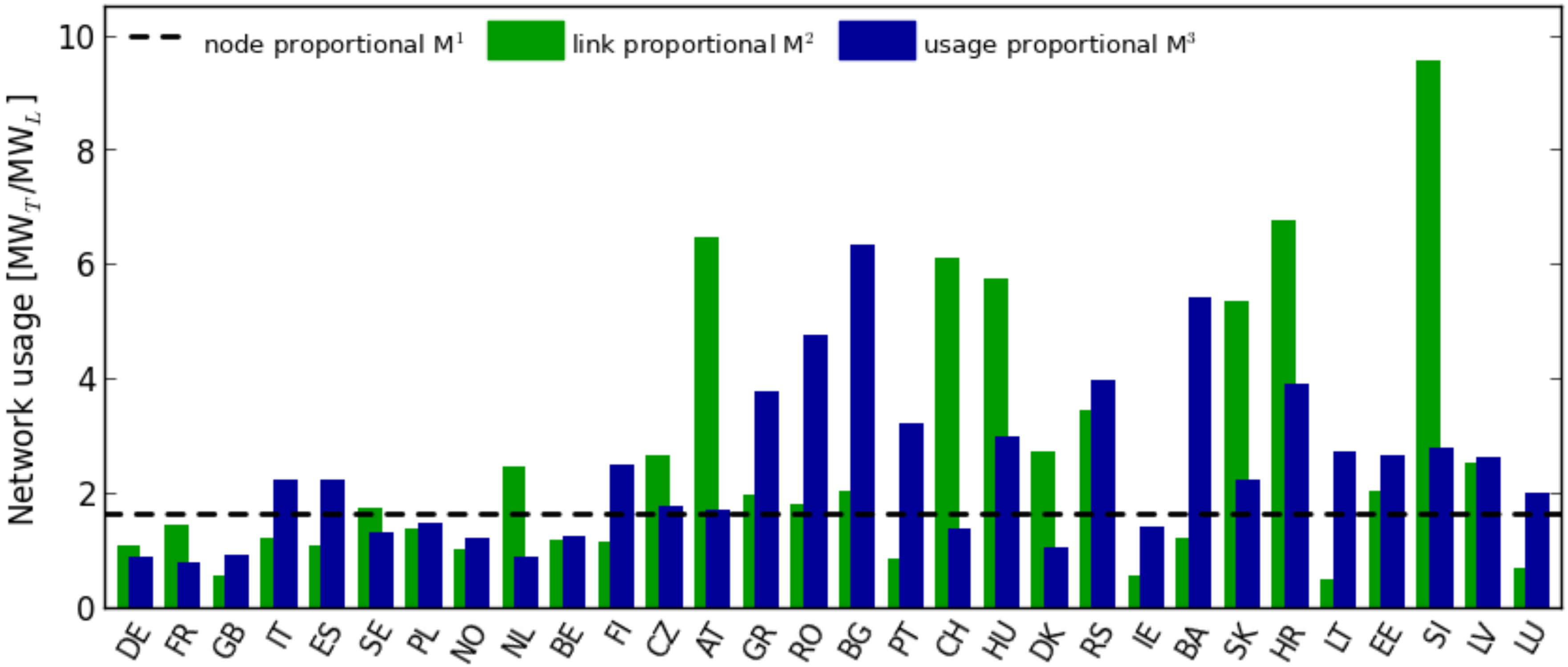
Who pays for the transmission capacity?



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

$$\sum_{l(n)} \frac{T_l^{2050}}{2}$$

$$\sum_l T_{l\leftarrow \mathrm{export}(n)}^{2050}$$

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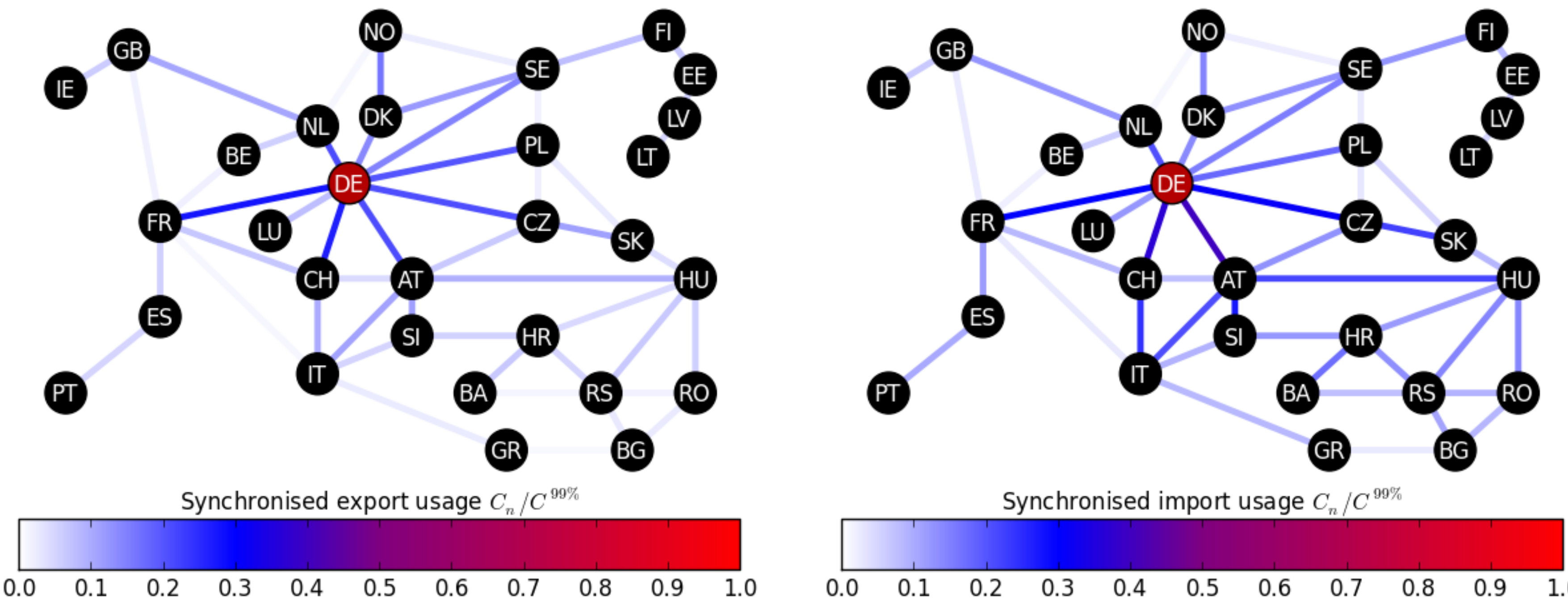
Who pays for the transmission capacity?



export flow tracing

import flow tracing

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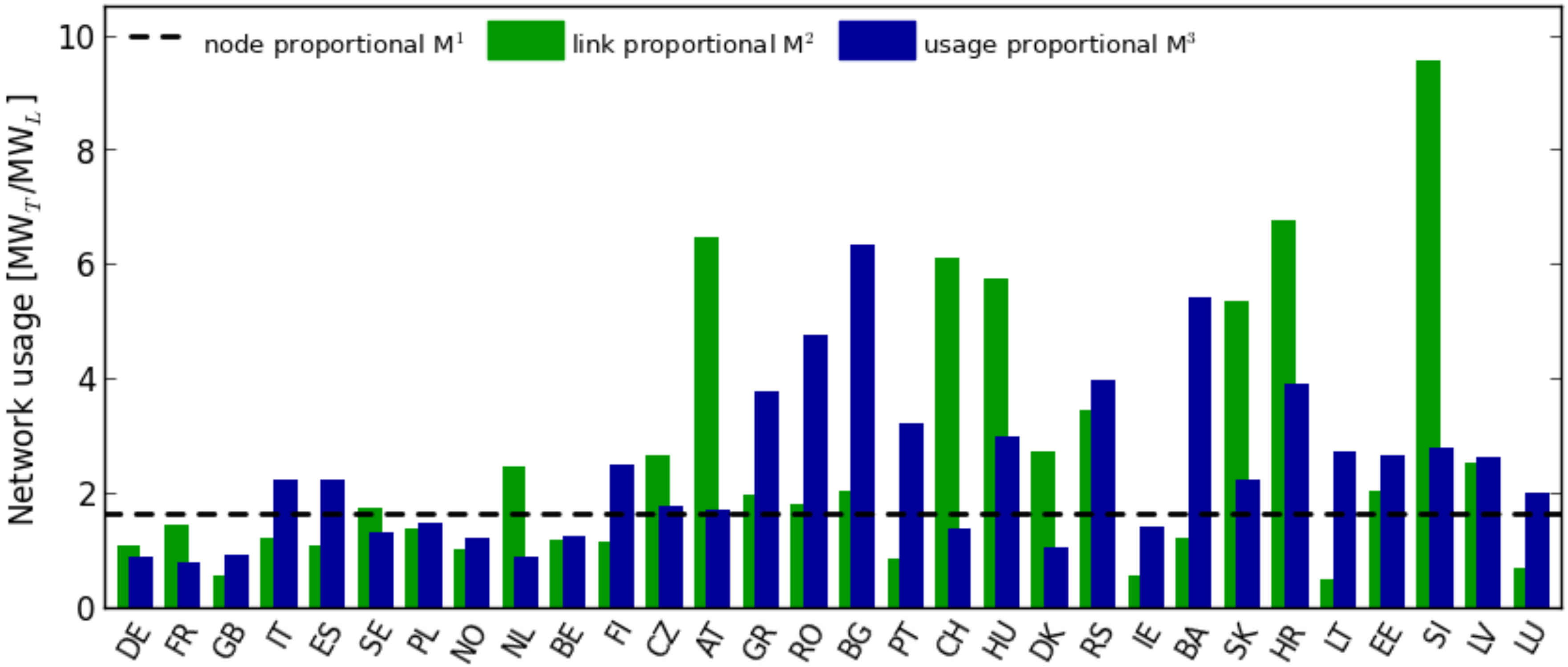
Who pays for the transmission capacity?



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

$$\sum_{l(n)} \frac{T_l^{2050}}{2}$$

$$\sum_l T_{l\leftarrow \mathrm{export}(n)}^{2050}$$

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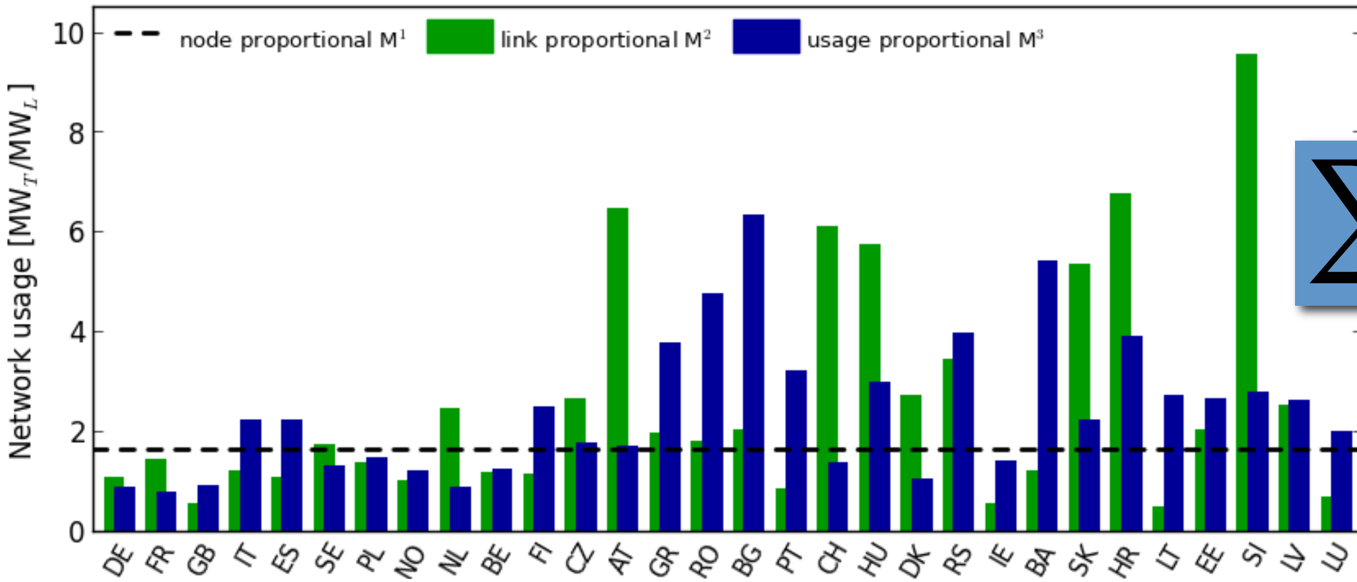
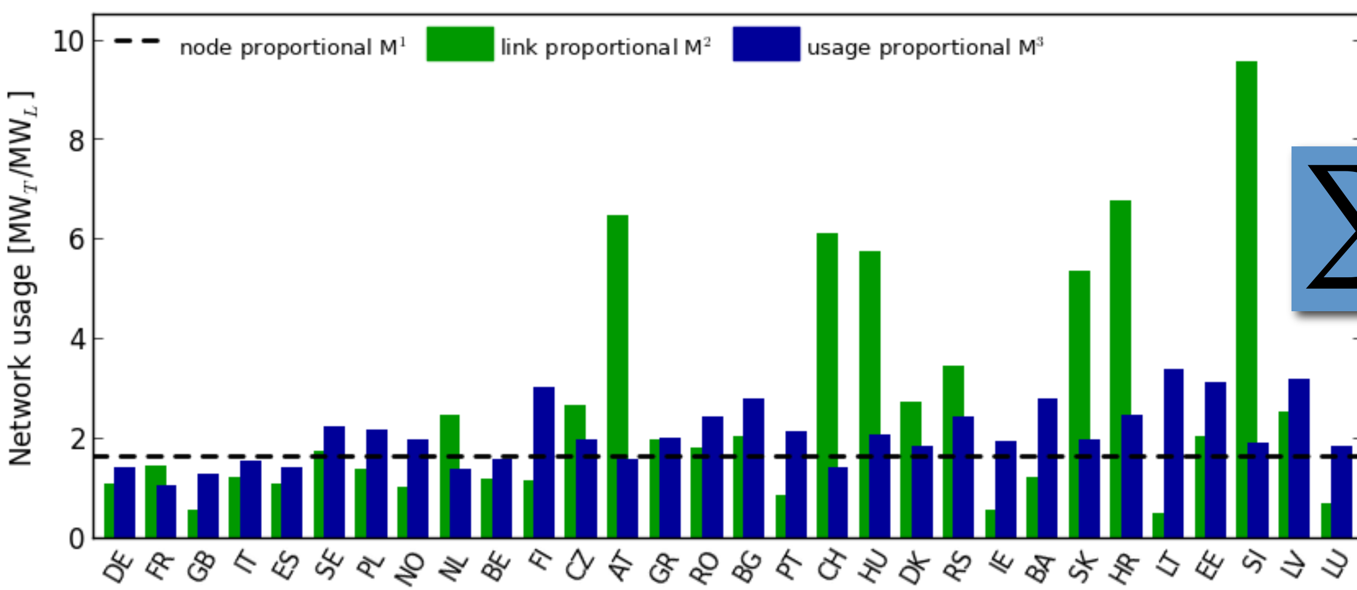
Who pays for the transmission capacity?



$$\sum_l T_{l \leftarrow \mathrm{export}(n)}^{2050}$$



$$\sum_l T_{l \leftarrow \mathrm{import}(n)}^{2050}$$

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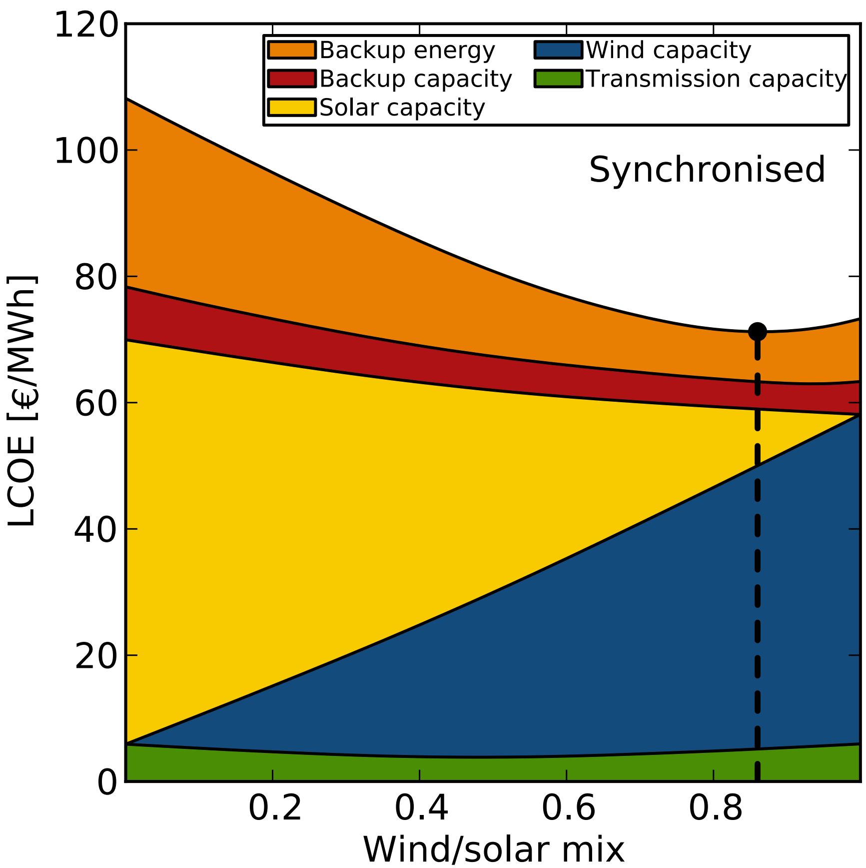
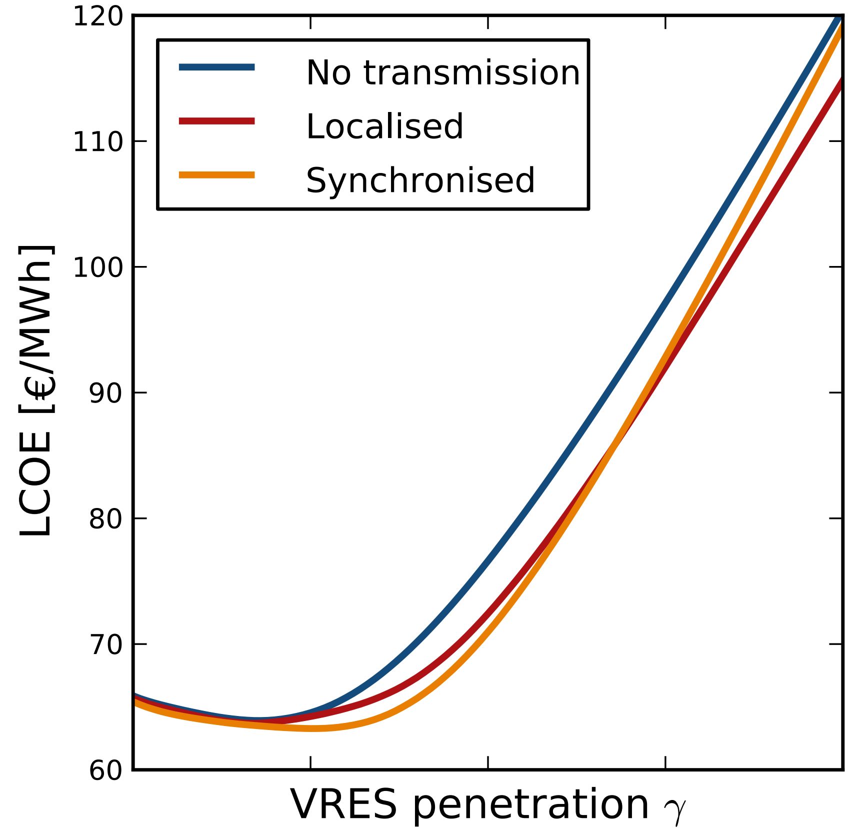
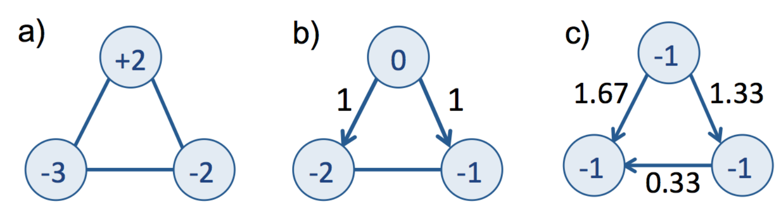
Levelized Cost of SYSTEM Energy

Levelized Cost of SYSTEM Energy

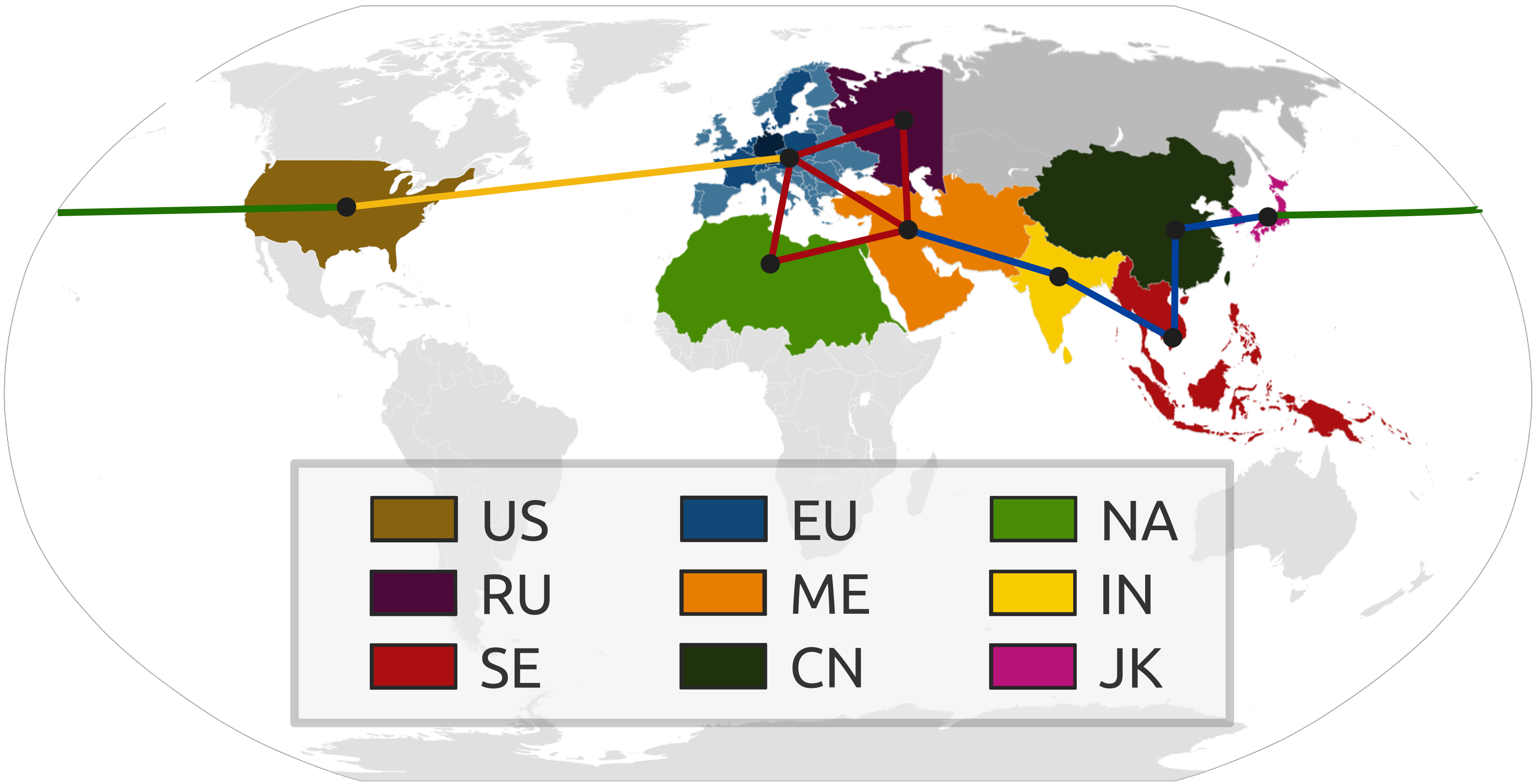




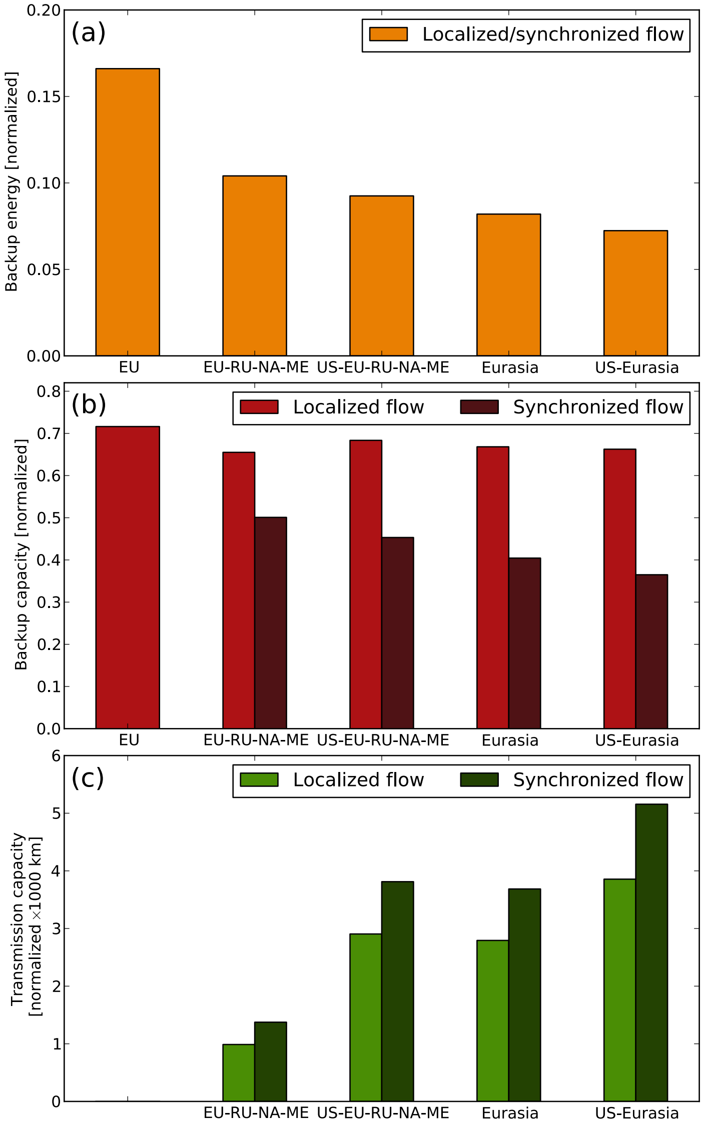
$$\left\langle G_n^{RES} \right\rangle = \left\langle L_n \right\rangle$$

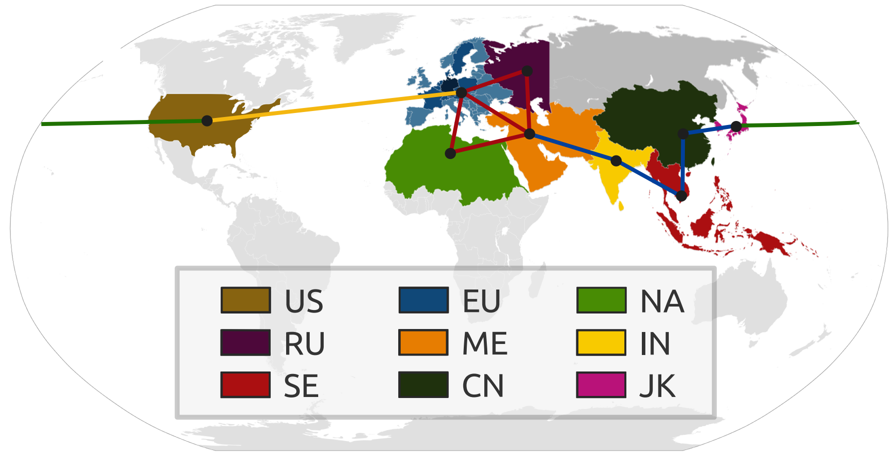


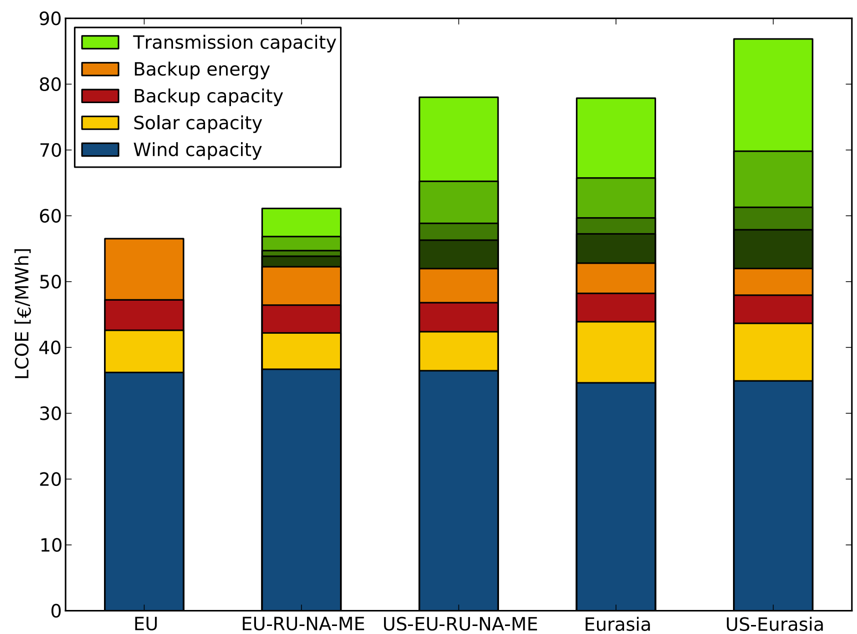
beyond EU: world-wide grid



beyond EU: world-wide grid







so far: backup + transmission

now: what about storage?

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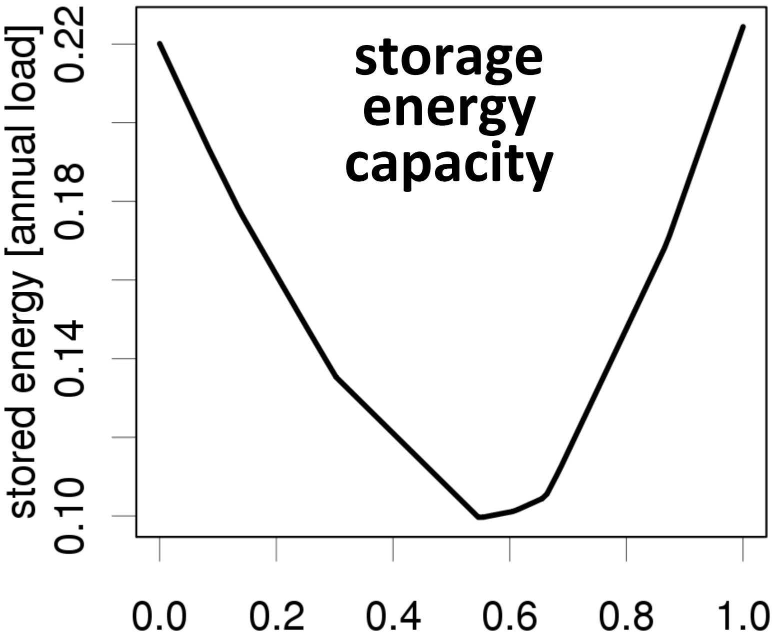
How much storage? @ 100% penetration in EU

$$G_n^W(t) + G_n^S(t) - L_n(t) = \sum_{ngb(n)} \left(F_{n\rightarrow} - F_{\rightarrow n}\right) + \left(S_n^+ - S_n^-\right)$$

$$\Delta_{EU}(t) = G_{EU}^{RES}(t) - L_{EU}(t)$$

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



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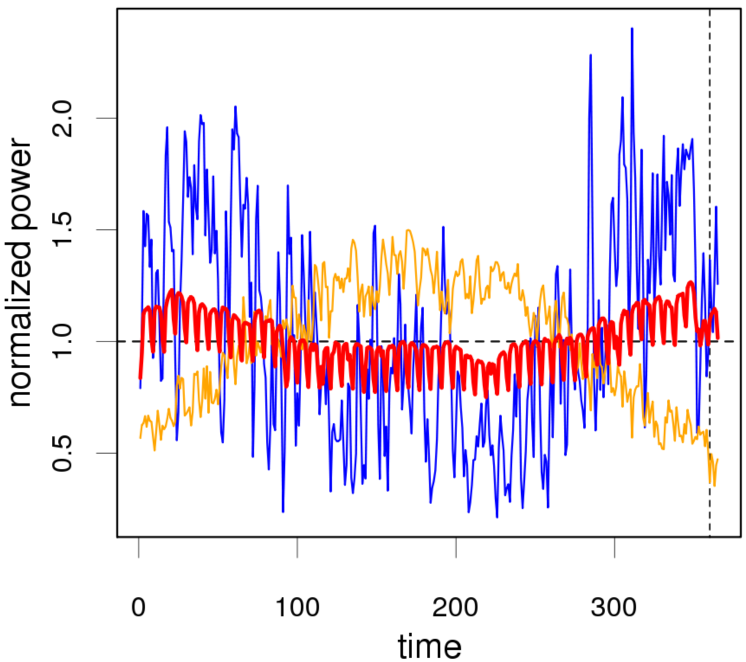
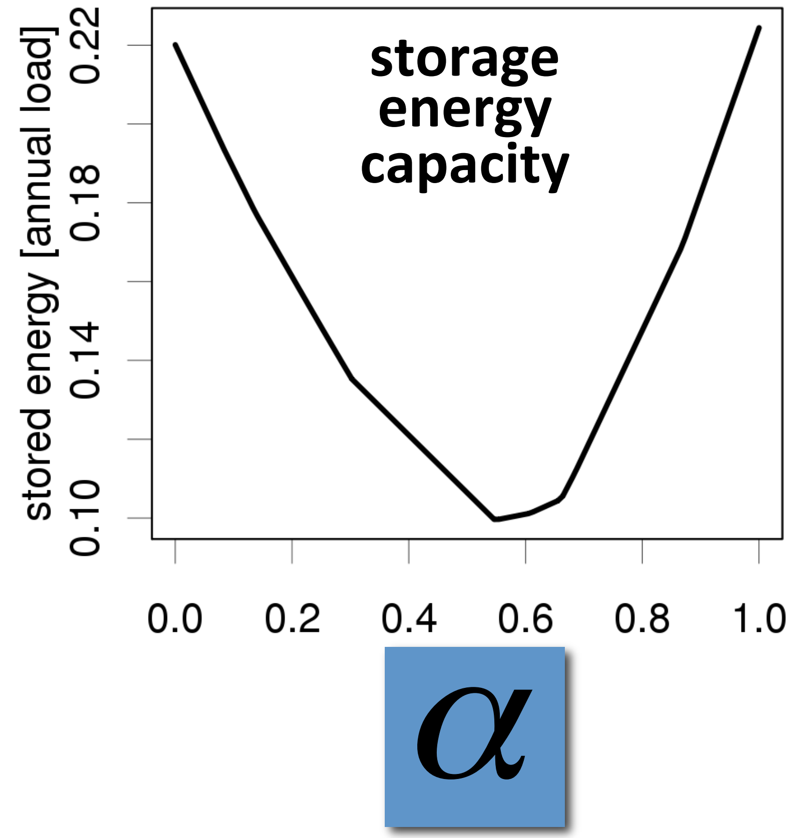
How much storage? @ 100% penetration in EU





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

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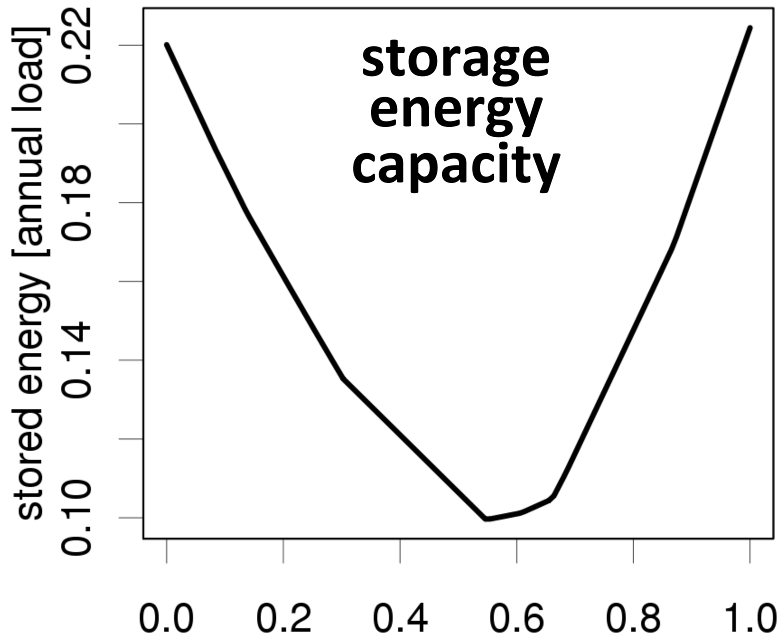
How much storage? @ 100% penetration in EU

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

NOT POSSIBLE:
Pumped Hydro,
Compressed Air

POSSIBLE:
H2 storage
25 TWh = 0.008 av.y.l.
6h "battery" storage
2.2 TWh = 0.0007 av.y.l



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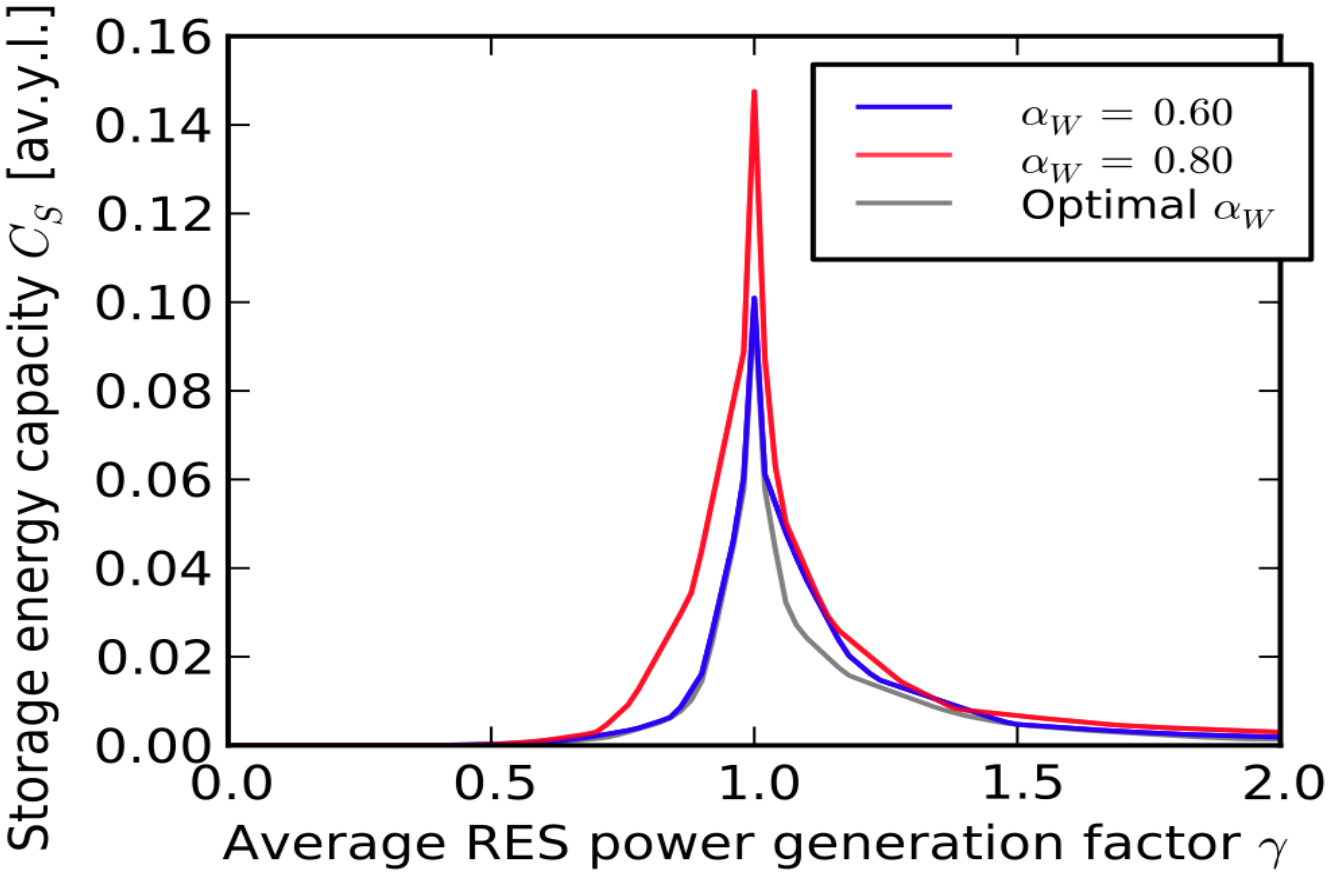
Storage Singularity



renewable penetration

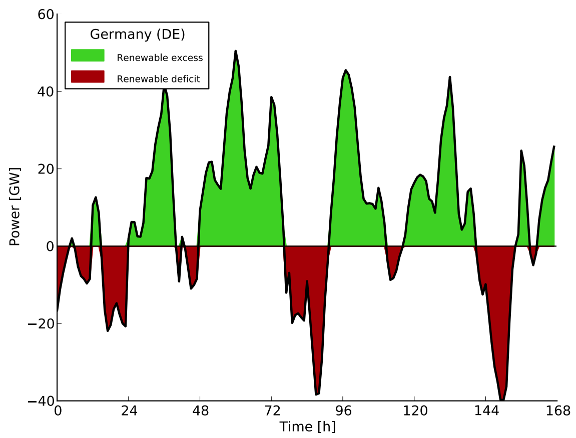
Temporal correlations on the synoptic time scale cause the extremely enhanced need for storage energy capacity.

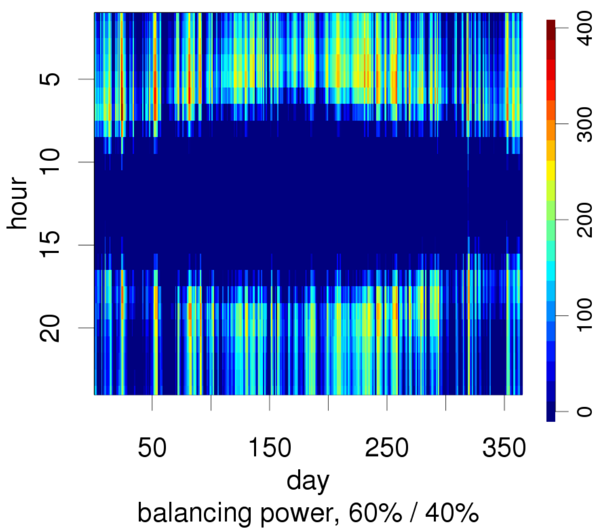
Beyond a penetration of γ > 60% a 6h storage (load flexibility, smart grid, v2g) is no longer sufficient!

What about synergies: balancing + storage?

“hydro/bio” balancing (150 TWh)

+ 6h “battery” storage (2.2 TWh, η=1.0)
+ seasonal H2 storage (25 TWh, η=0.6)





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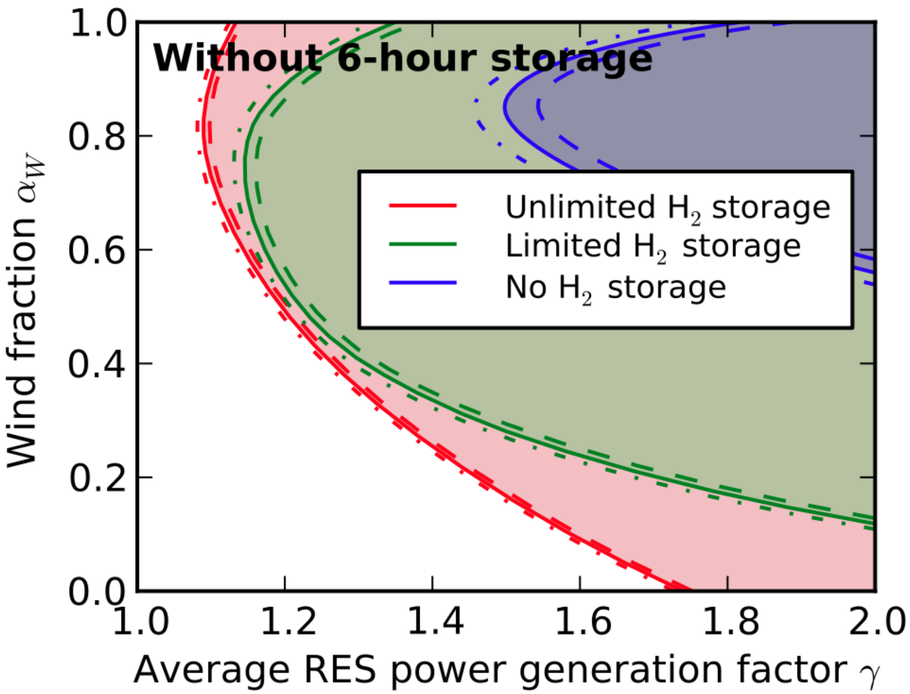
6h "battery" storage (2.2 TWh, η=1.0)
+ seasonal H2 storage (25 TWh, η=0.6)
+ "hydro/bio" balancing (150 TWh)



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

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

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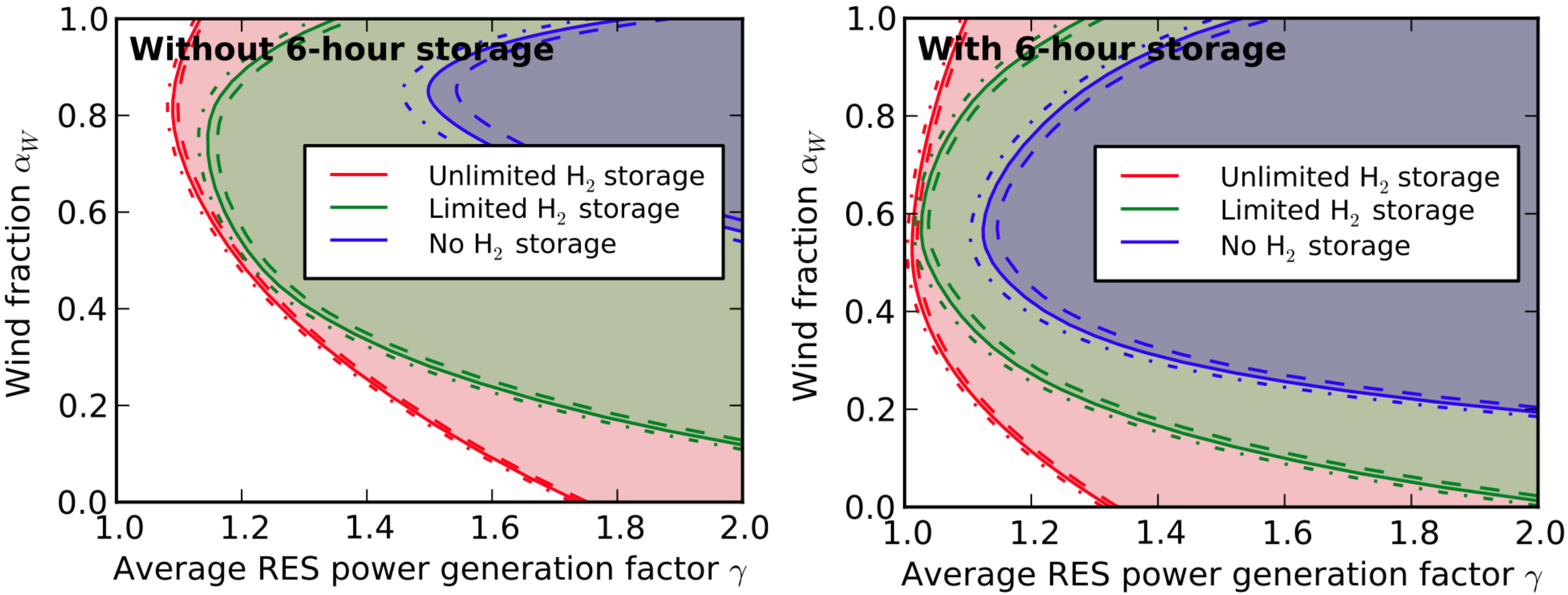
6h “battery” storage (2.2 TWh, η=1.0)
+ seasonal H2 storage (25 TWh, η=0.6)
+ “hydro/bio” balancing (150 TWh)



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6h "battery" storage (2.2 TWh, η=1.0)
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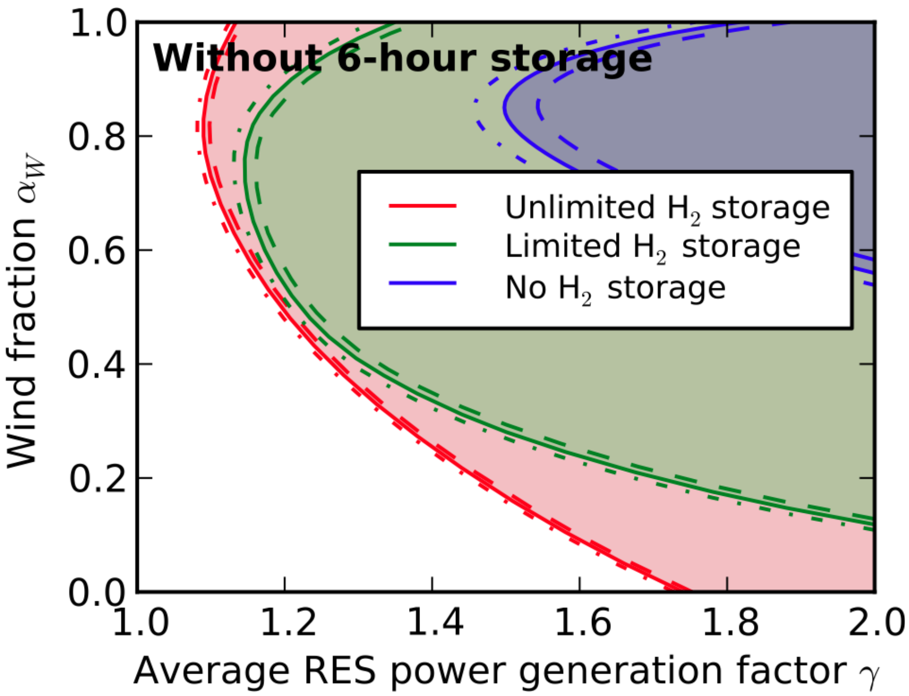

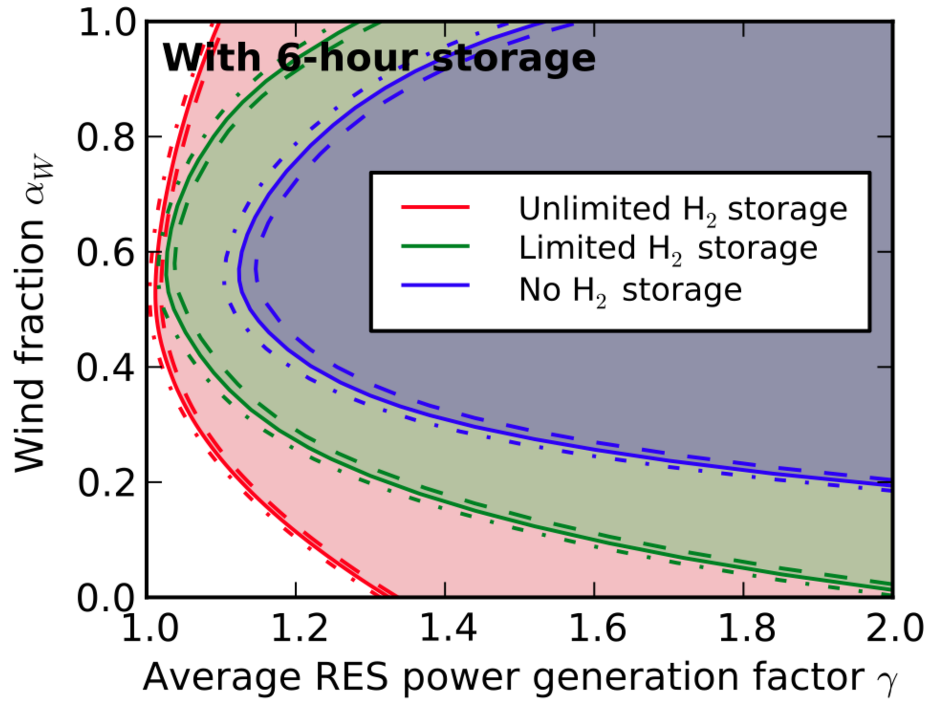

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2015 ←→ 2050

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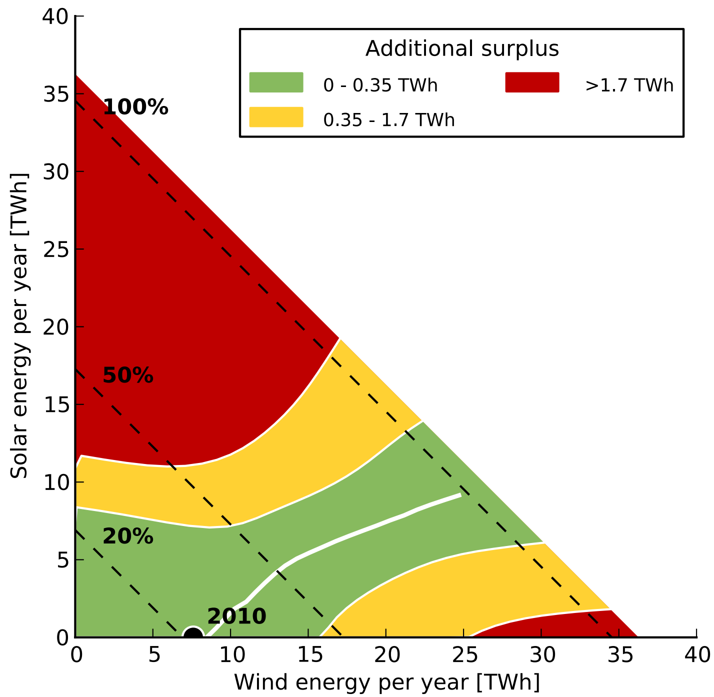
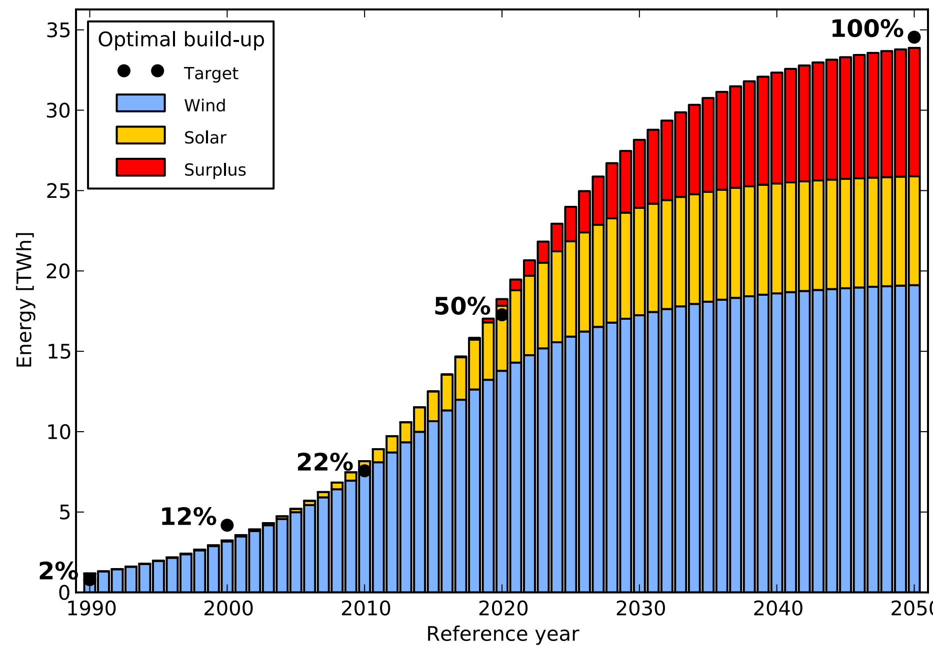
Transition 0% → 100% renewables
Case: Denmark (without storage)





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

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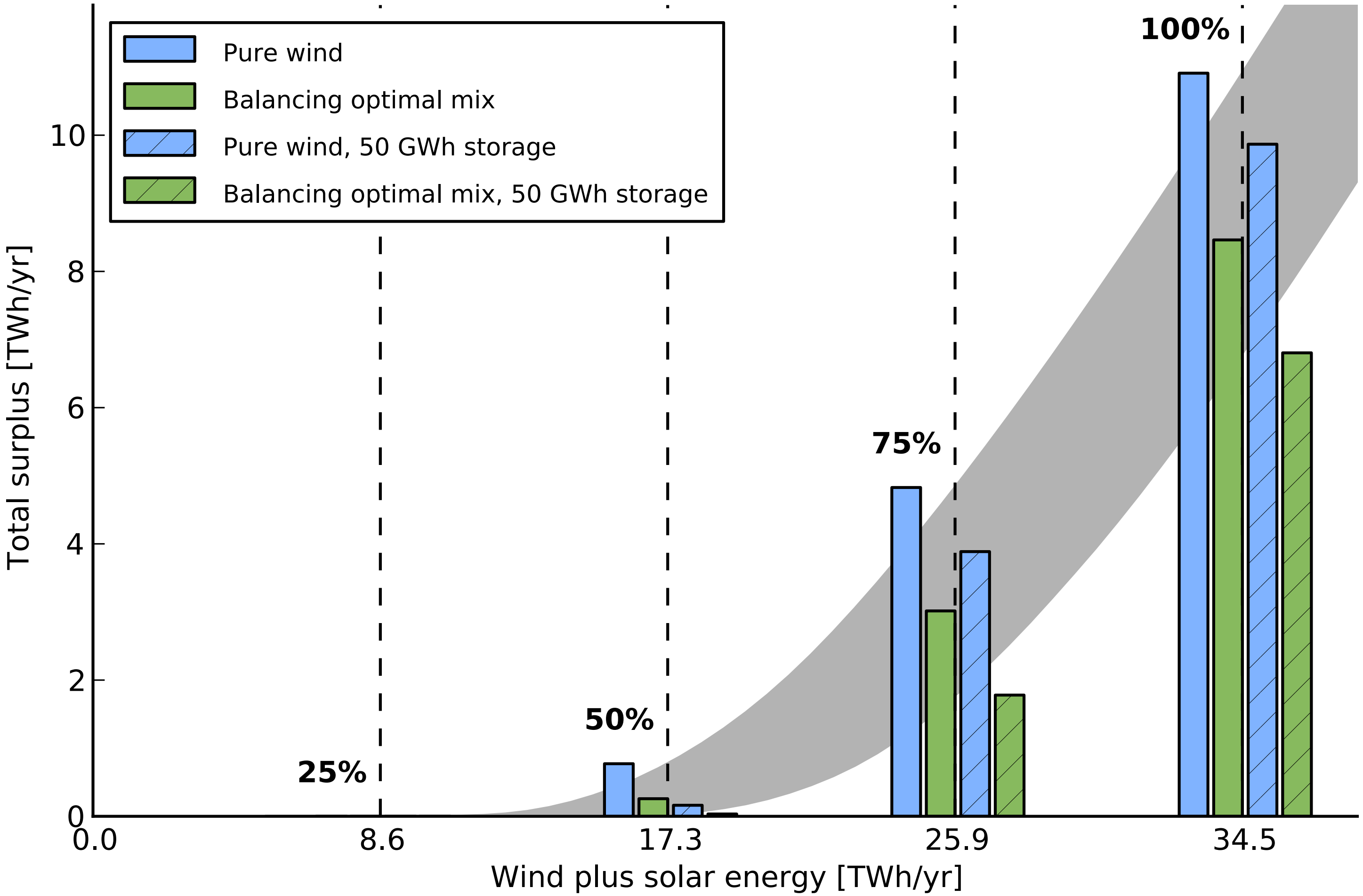
Excess generation:

$$\langle C_n(t) \rangle_t$$



$$G_n^W(t) + G_n^S(t) - L_n(t) = C_n(t) - B_n(t) + \left(S_n^+ - S_n^-\right)$$

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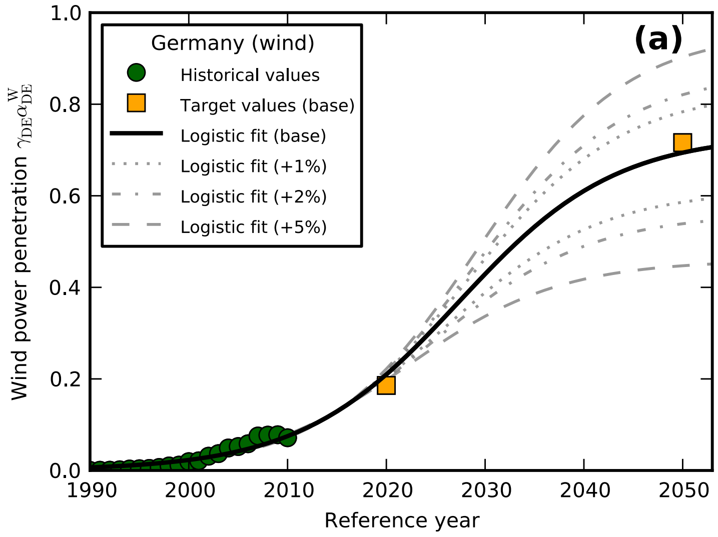
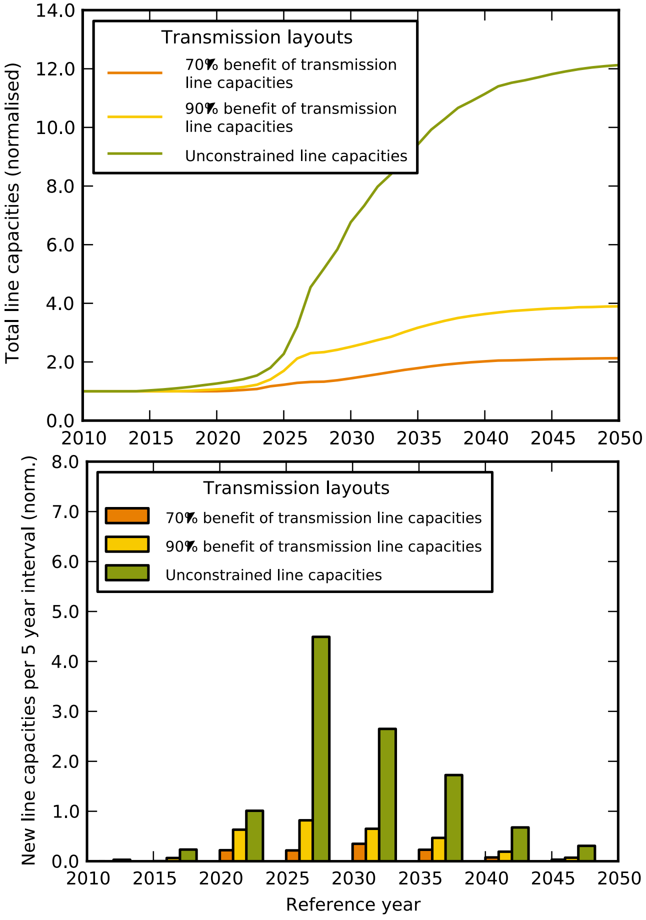
Pan-European Transmission 2014 → 2050





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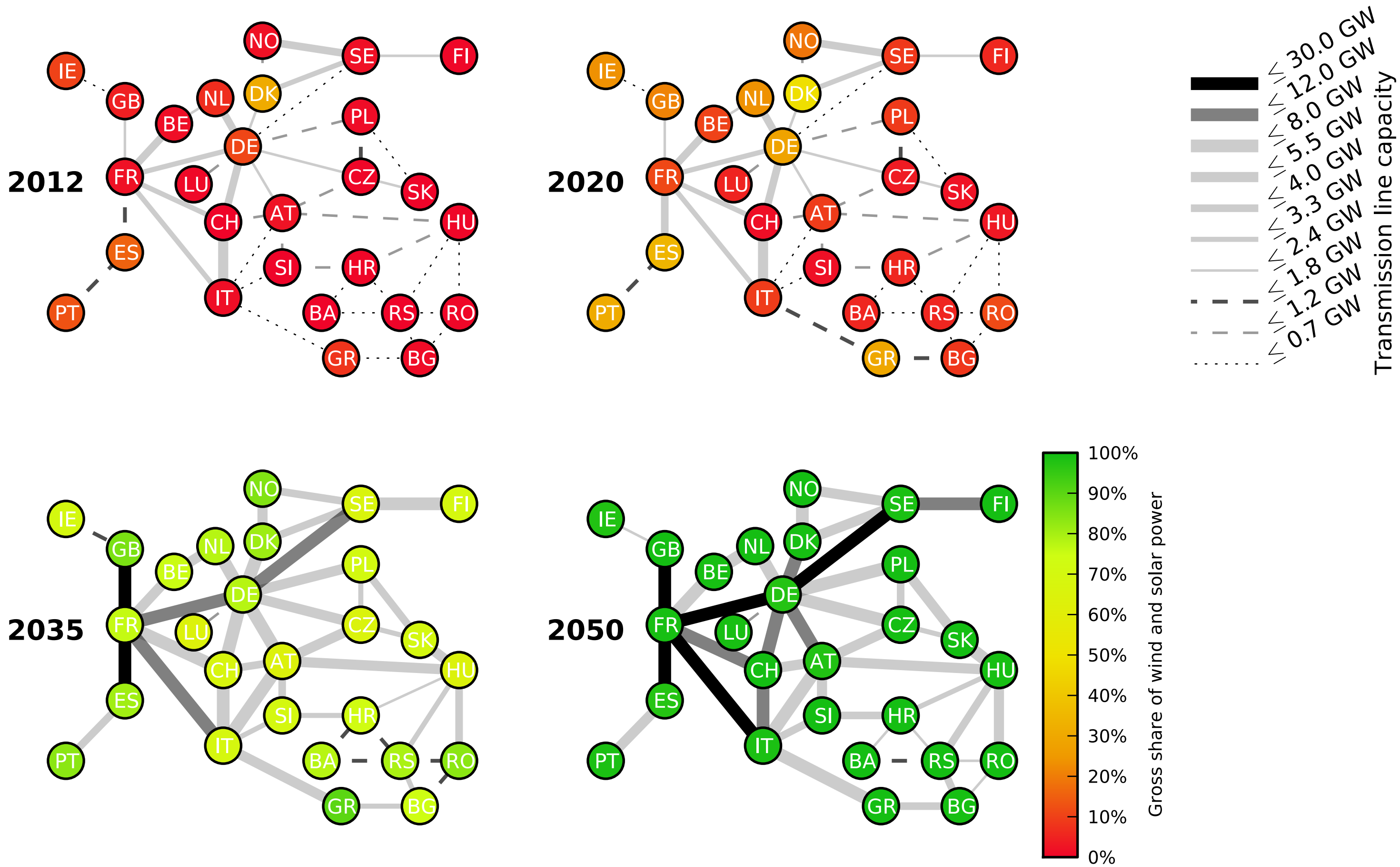
Pan-European Transmission 2014 → 2050



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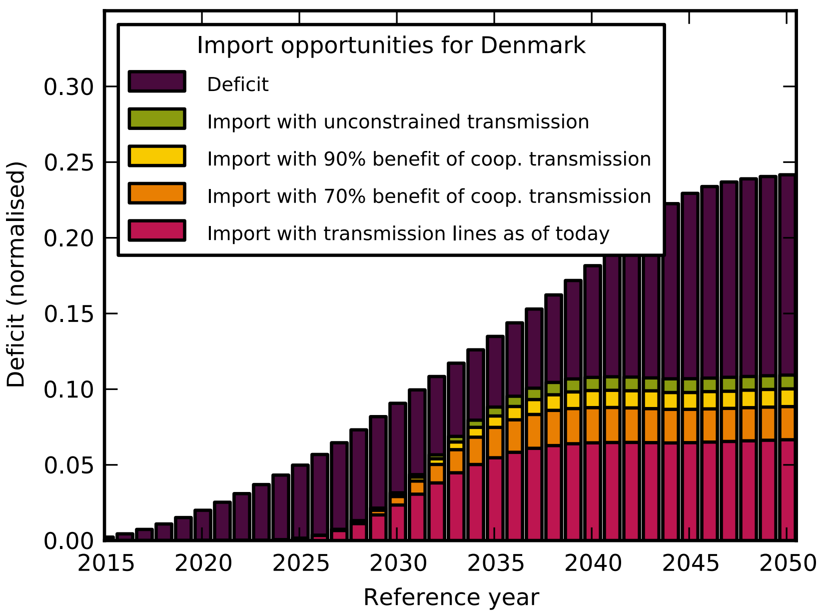
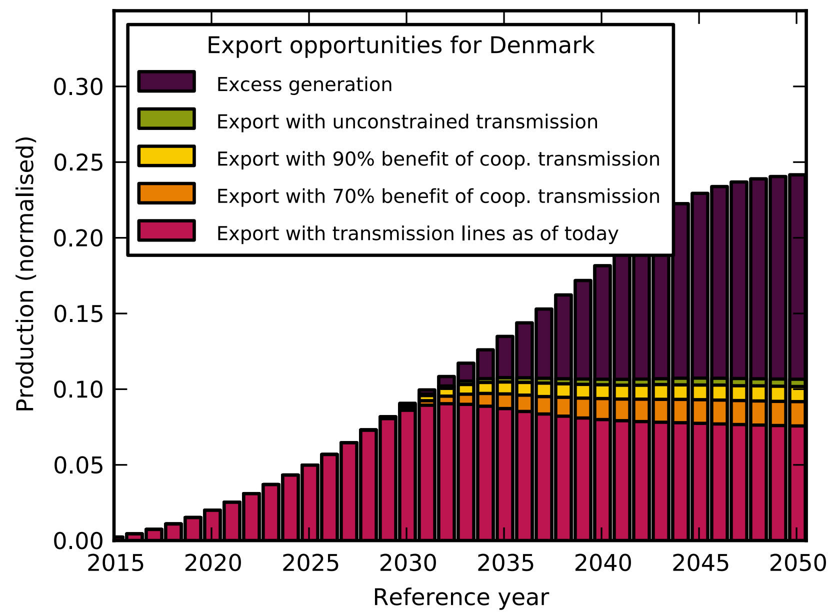
Denmark 2014 → 2050: Import / Export opportunities





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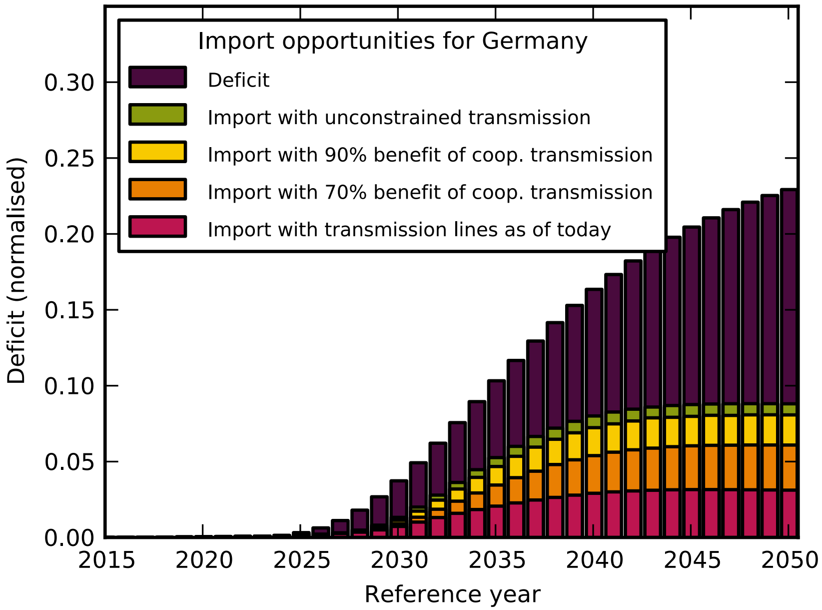
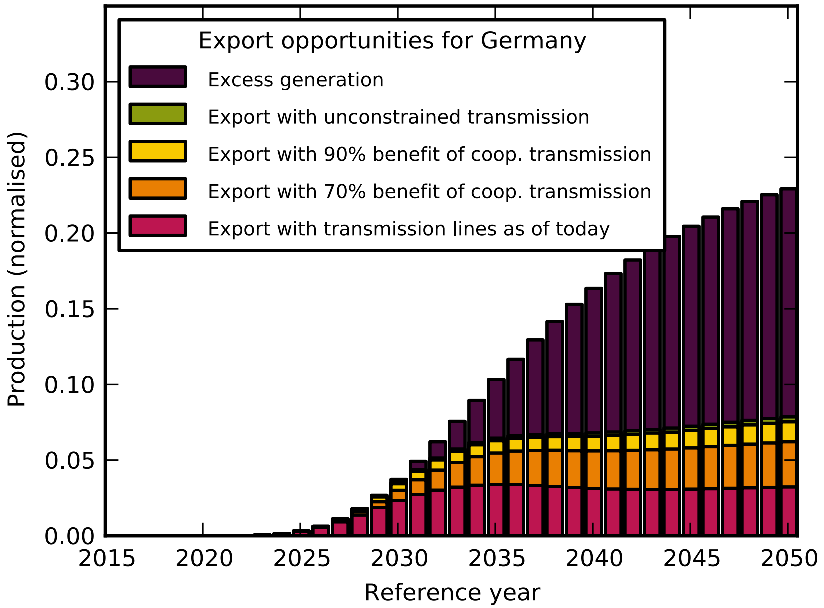
Germany 2014 → 2050: Import / Export opportunities





OUTLOOK

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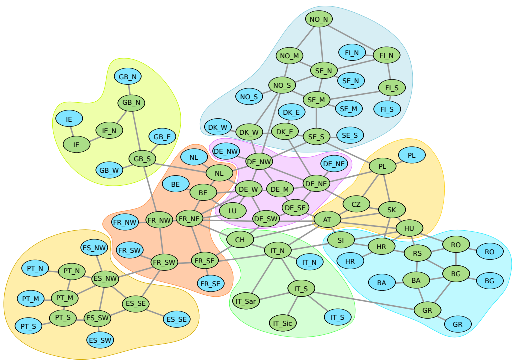
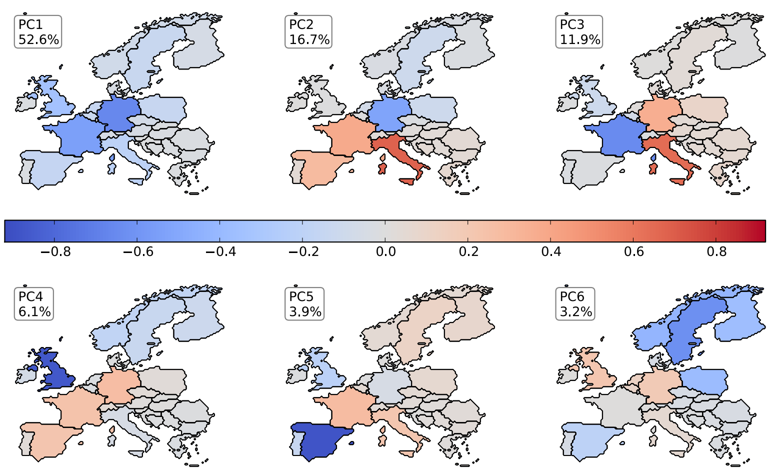
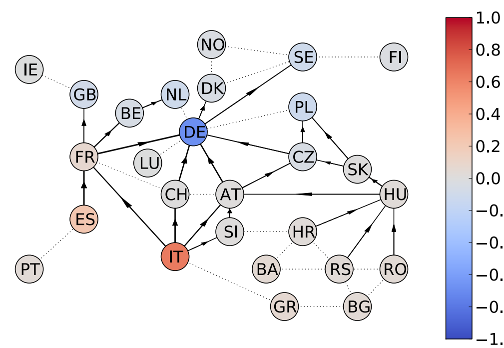
Fundamental Research on Renewable Energy Systems
at the interface between engineering + mathematics + physics

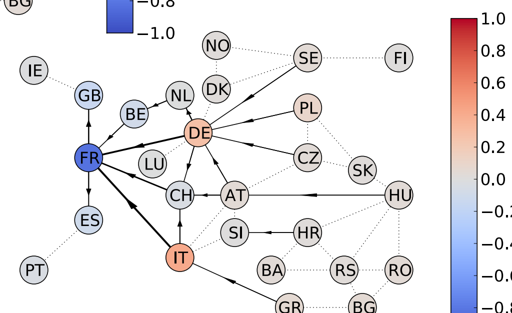


SOME FUNDAMENTAL CHALLENGES:

storage phase transition,
renormalisation scaling of power flows,
spatio-temporal flow pattern analysis,
flow tracing,
optimal heterogenity,
self-organizing power flows.

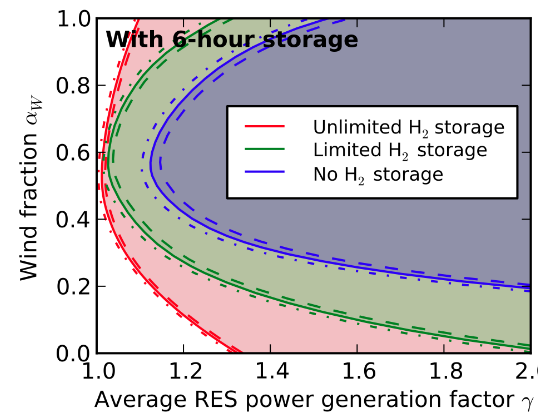






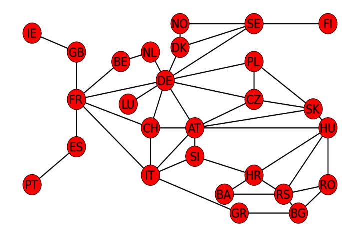
CONSENSYS

100% = 100+X%

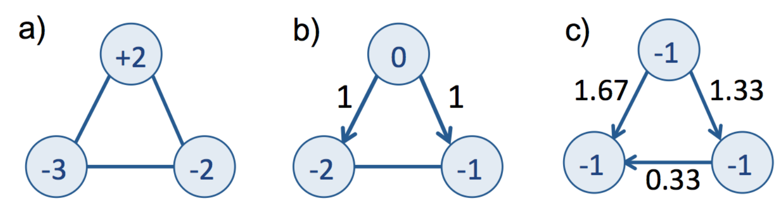


COMPLEX NETWORKS OF SMART ENERGY SYSTEMS

wind + solar + hydro + bio +
+ backup + transmission + storage,
electricity + heating + transportation



DESIGN OF FUTURE ENERGY MARKETS



OPTIMAL TRANSITION 2050 → 2020

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Thank you!

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(Aarhus University):
greiner@eng.au.dk

D Heide et.al.: Seasonable optimal mix of wind and solar power in a future, highly renewable Europe, **Renewable Energy 35 (2010) 2483-2489**.

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