Fundamental Research on Renewable Energy Systems

at the interface between engineering + mathematics + physics

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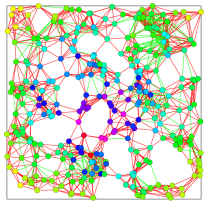
(1) 100% Renewable Energy Systems

(2) Complex Networks



(3) Wind-farm Modeling + Optimization

G Andresen	(PostDoc)
R Rodriguez	(PhD)
B Sairanen	(Master)
A Thomsen	(Master)
M Dahl	(Master)
B Tranberg	(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)

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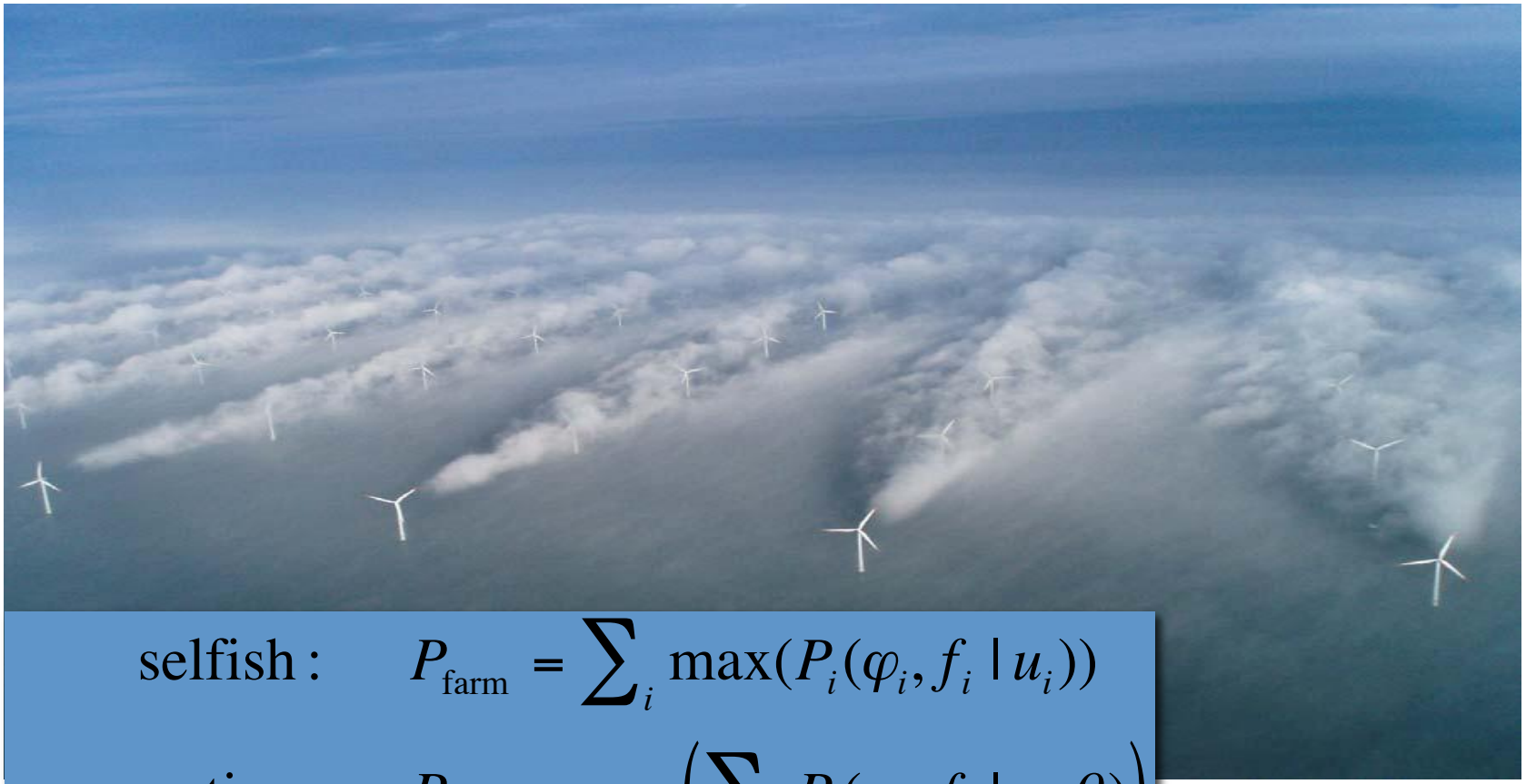
Wind-farm modeling + optimization + control



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

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

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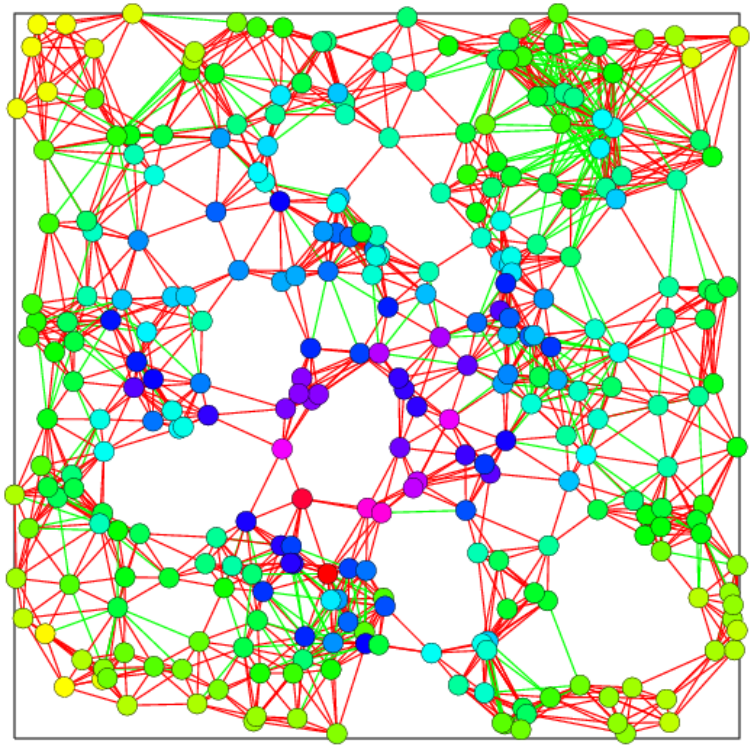
Physics of Complex Networks



Communication networks (Internet),

Biological networks (gene interactions),

Social network engineering,

Electricity networks, …

Structure, Dynamics, Function,

Robustness, Reliability,

Self-organization.

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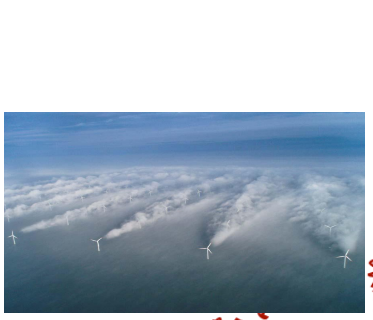
Design of
a highly renewable pan-European energy system



Challenges for:

system engineering, applied mathematics, and physics of complex networks

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

(Albert Einstein)

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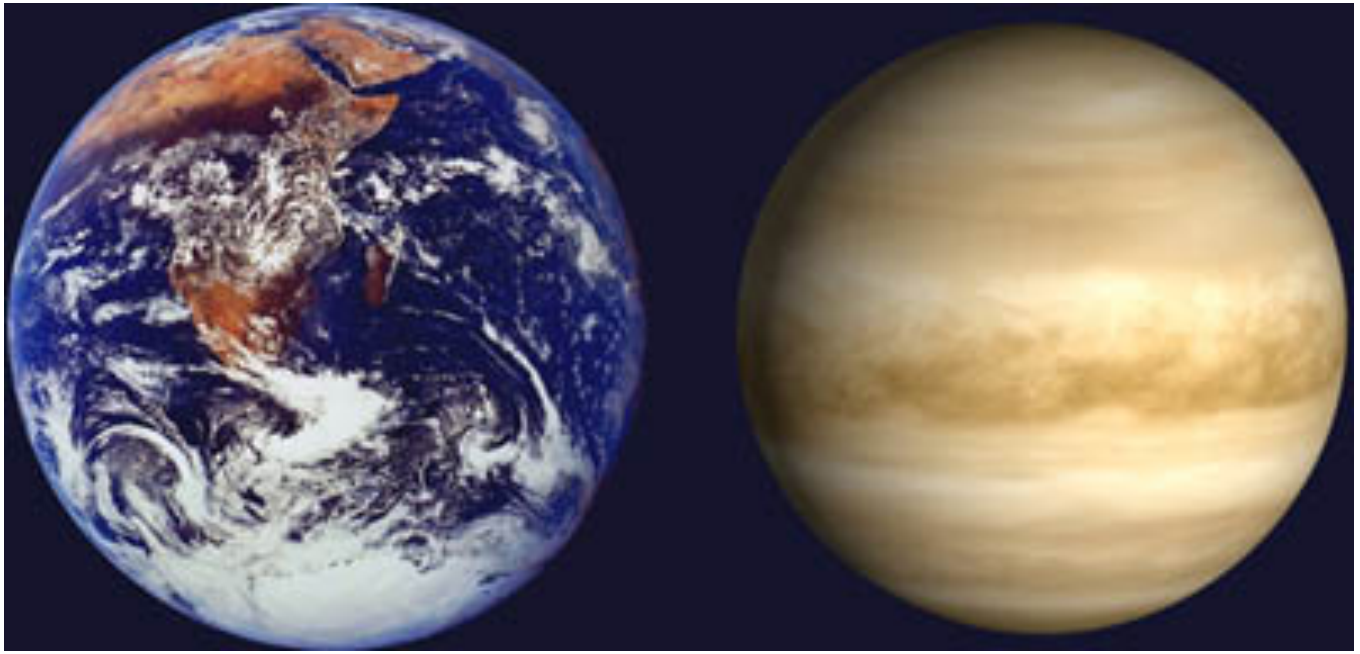

Venus to Earth: „My friend, you look really sick.“

Earth: „This fever is getting worse and worse.“

Venus: „Have you caught a virus?“

Earth: „My doctor says, I have Homo Sapiens.“

Venus: „Hmmmm ... don‘t worry, this vanishes.“

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

Think backwards!
2050→2020

Let the weather decide!

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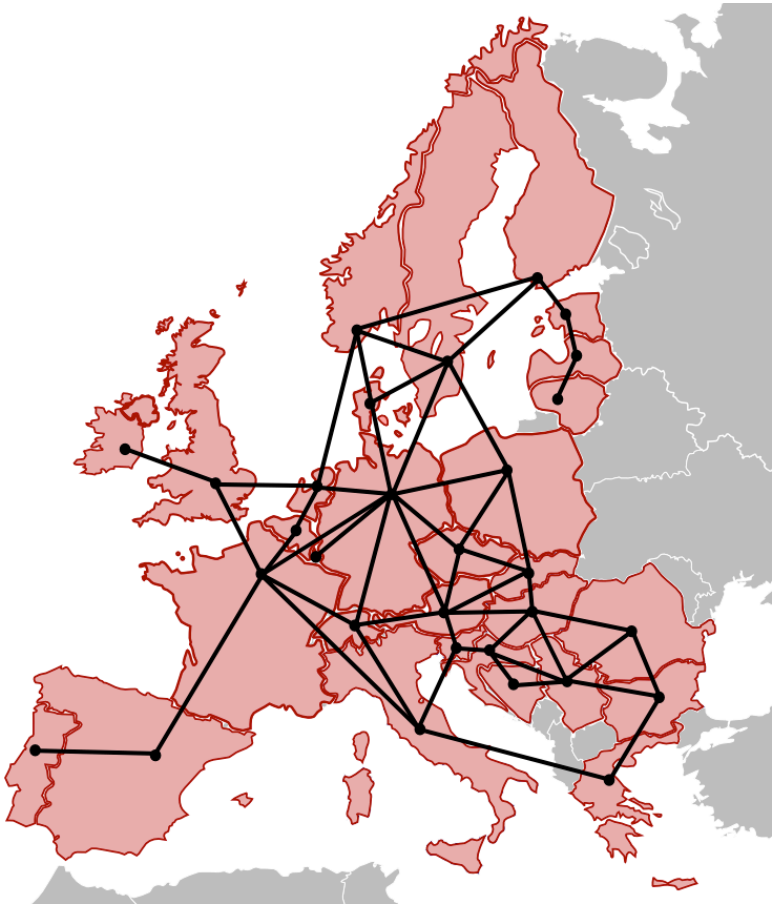


Let the weather decide!

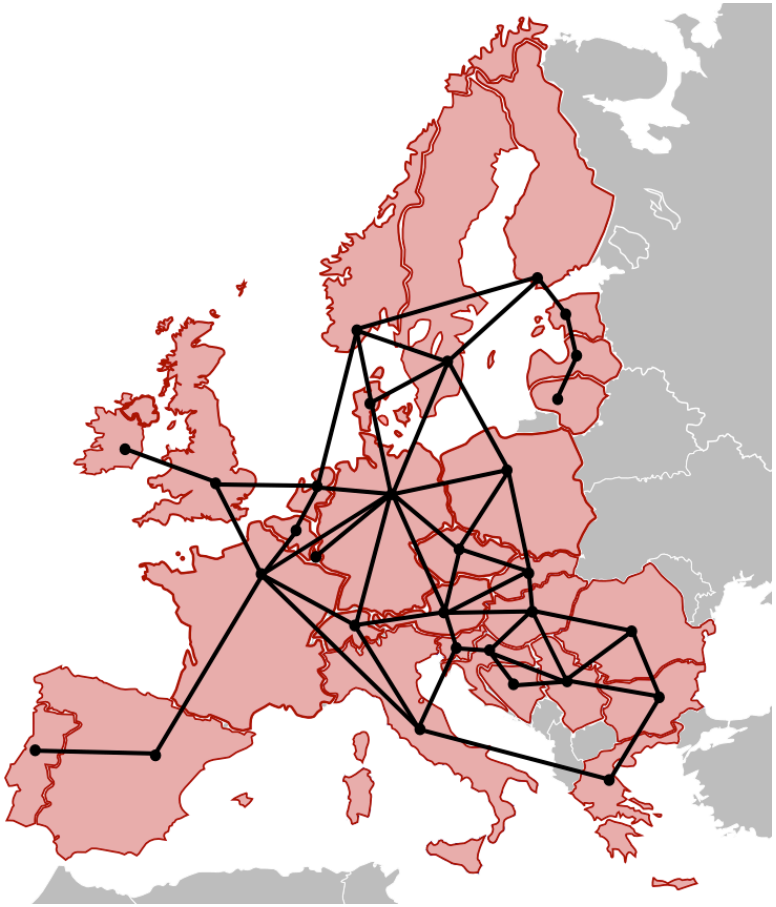
$$G_n^W(t) + G_n^S(t) + B_n(t) + \sum_{ngb(n)} F_{\rightarrow n} + S_n^- = L_n(t) + C_n(t) + \sum_{ngb(n)} F_{n\rightarrow} + S_n^+$$

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

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

actio = reactio

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



Let the weather decide!

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

$$L_n(t)$$

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

historical load (detrended)

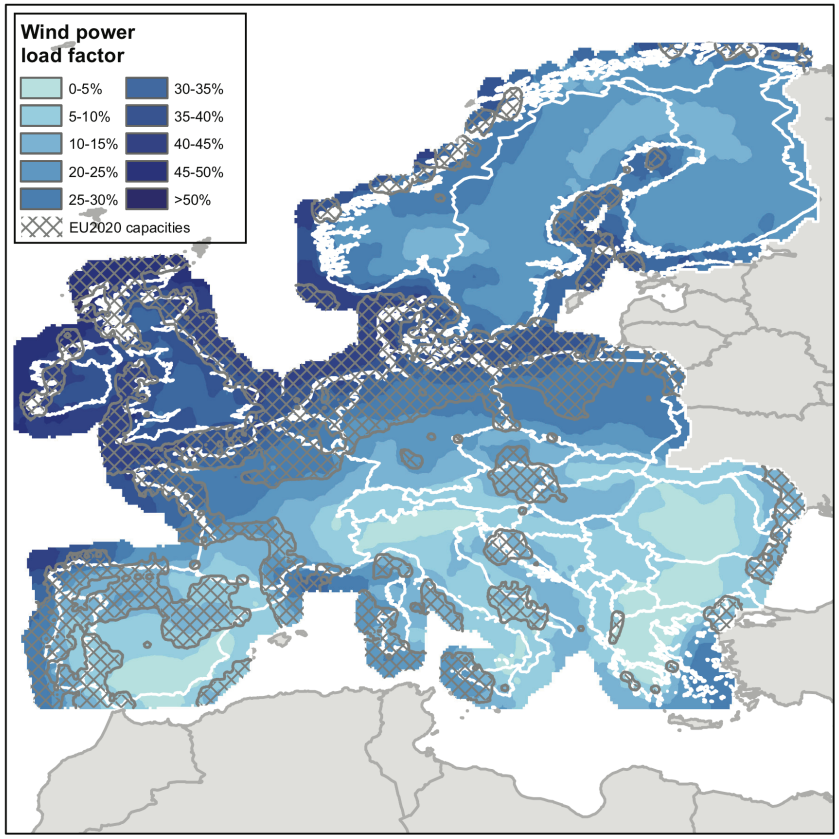
$$\left\langle G_n^W + G_n^S \right\rangle = \gamma_n \left\langle L_n \right\rangle$$

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

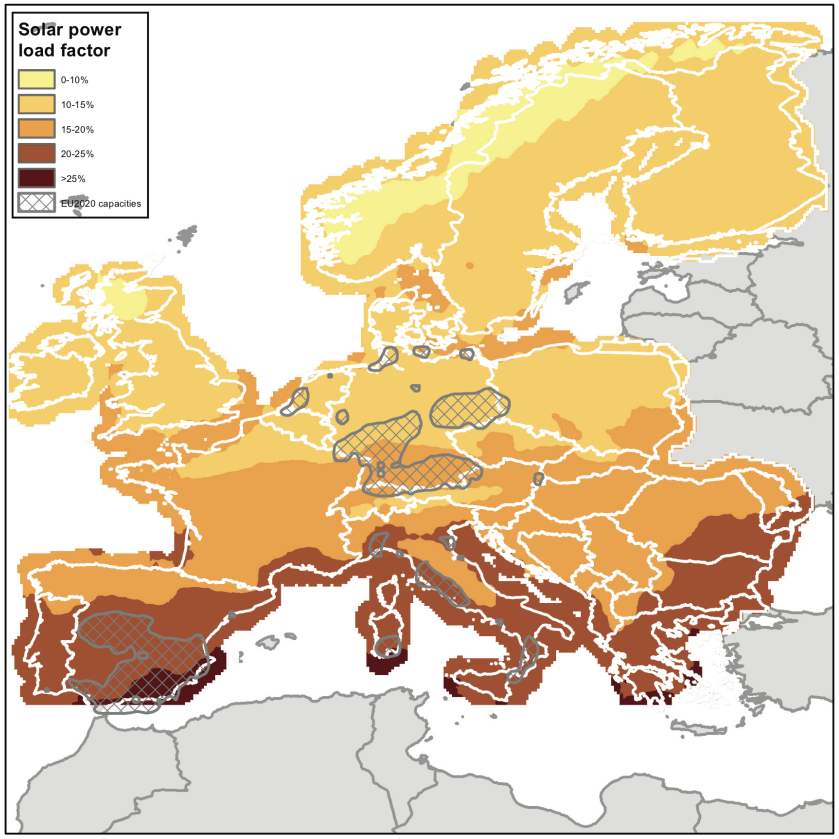
actio = reactio

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

wind-power



solar-power



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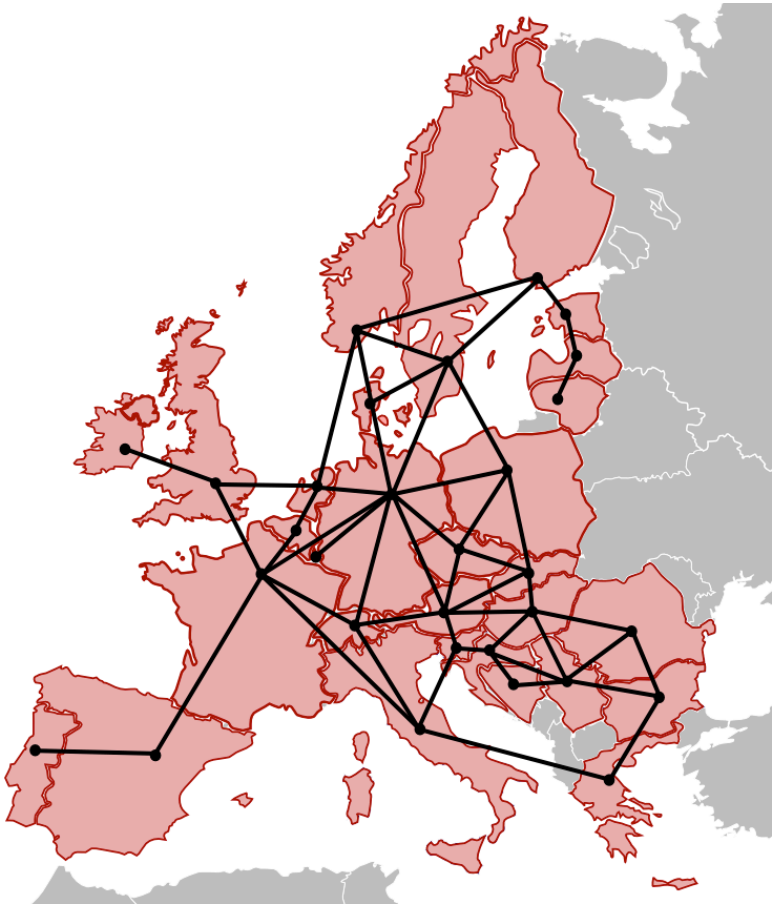

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$$G_n^{RES}(t) = G_n^W(t) + G_n^S(t)$$

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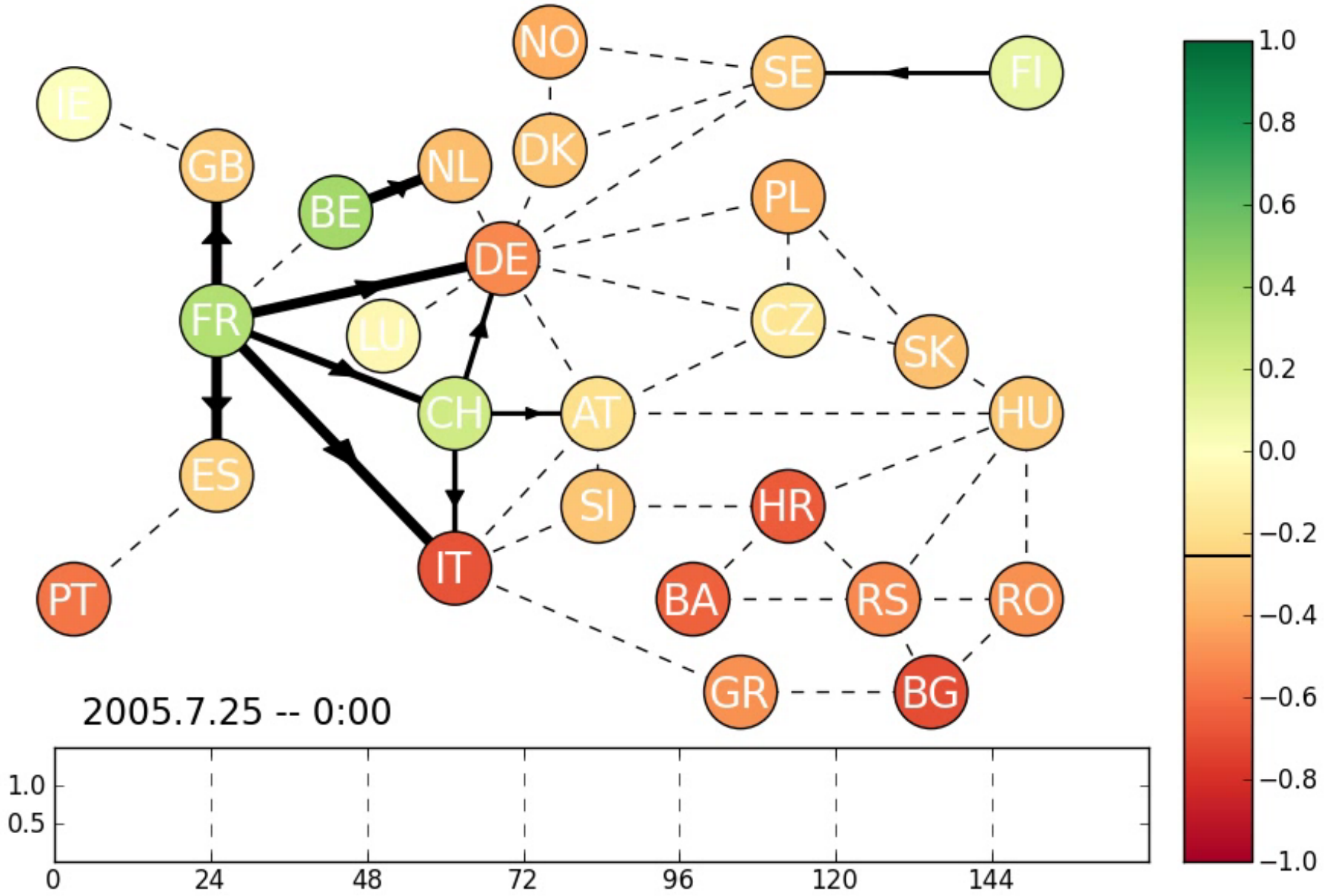
actio = reactio

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



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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?
... coupling of energy sectors?

and what about
... transition 2050 → 2014?
... future markets

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

① only Backup

② only Storage

③ Backup + Storage

④ 2015 ←→ 2050

⑤ Transmission + Backup

⑥ Economics

⑦ outlook: CONSENSYS

How much wind + solar power?

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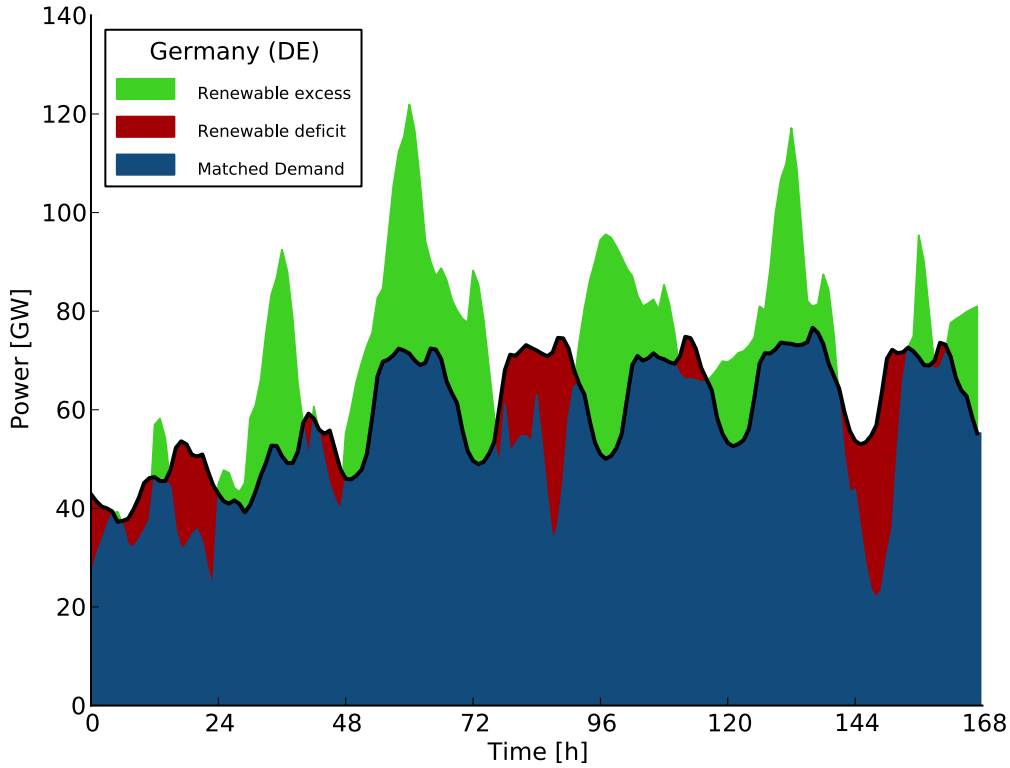
Mismatch distribution (Germany)

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

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



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

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

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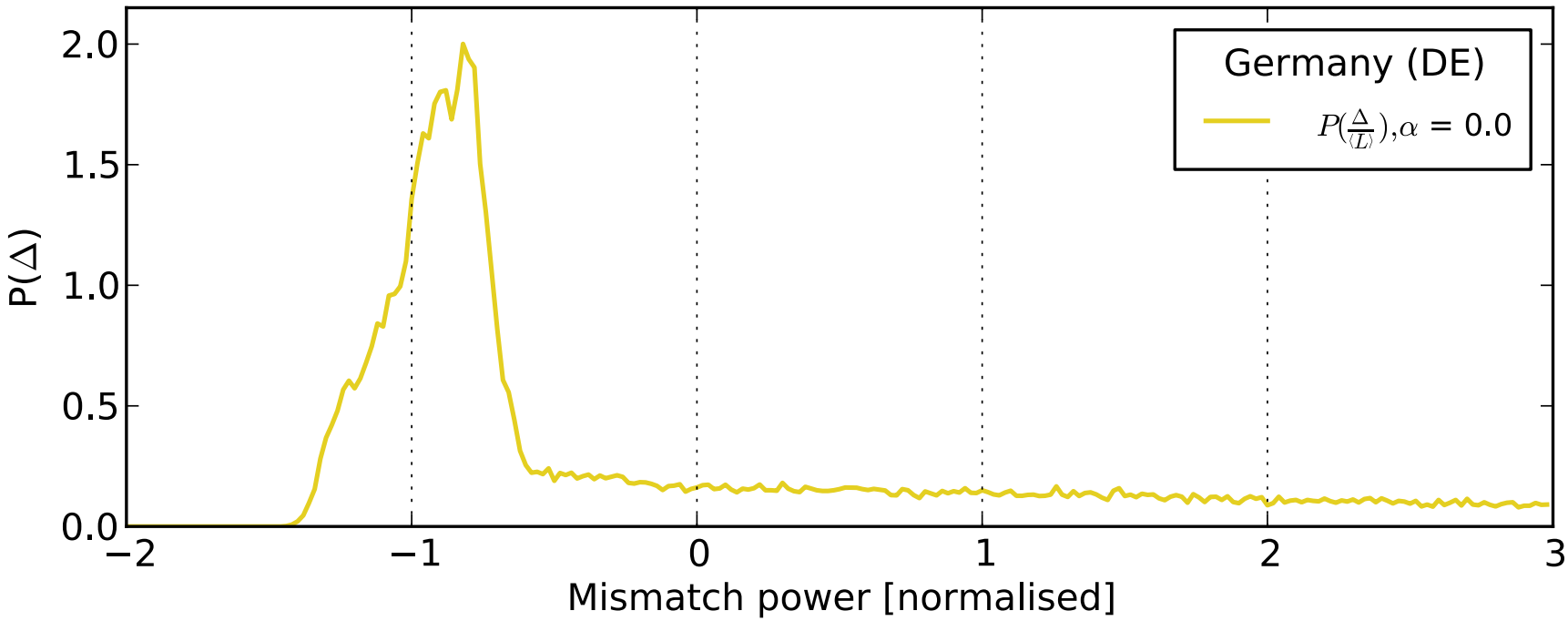
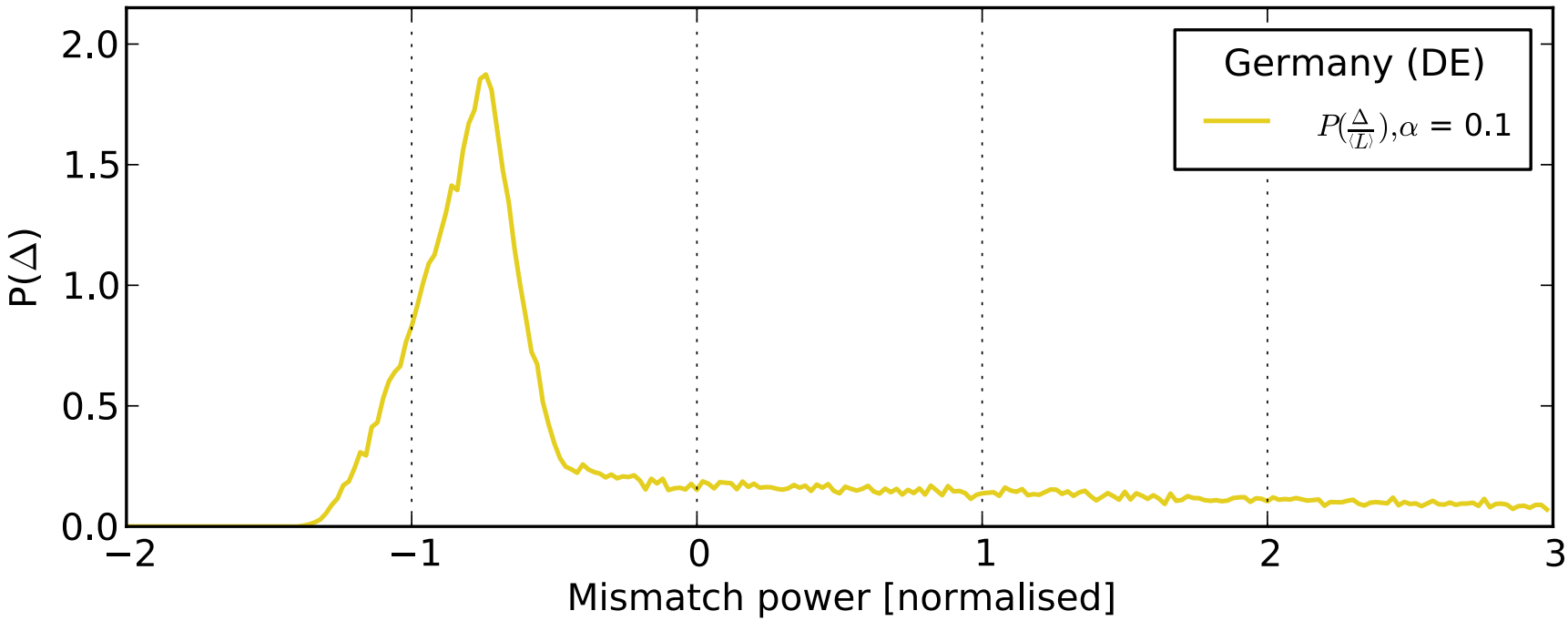
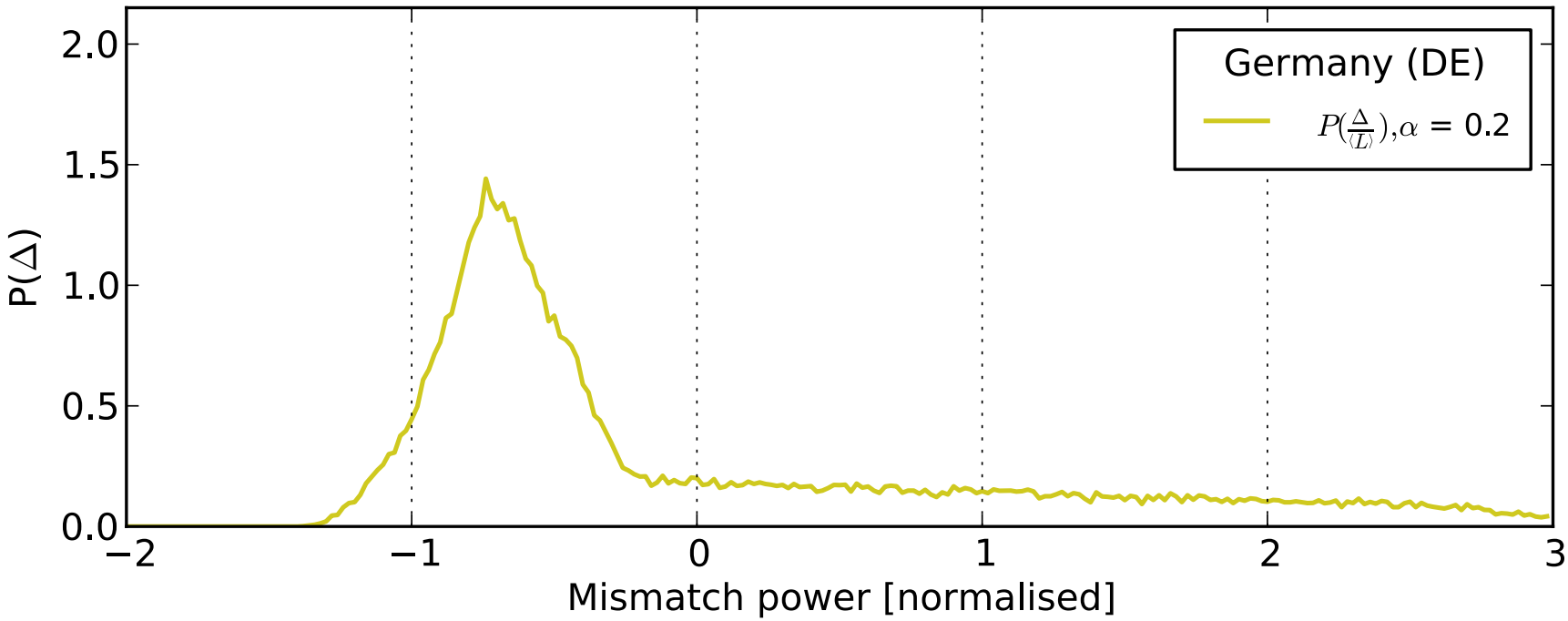
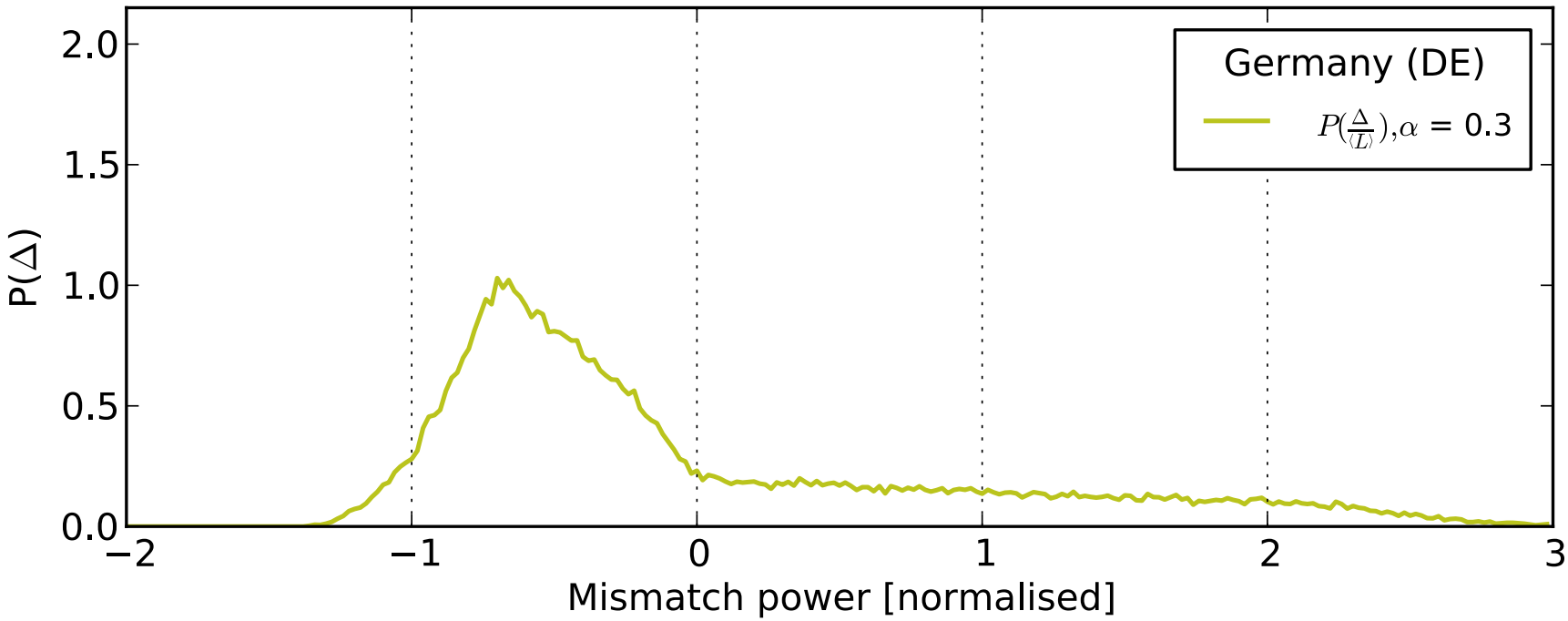
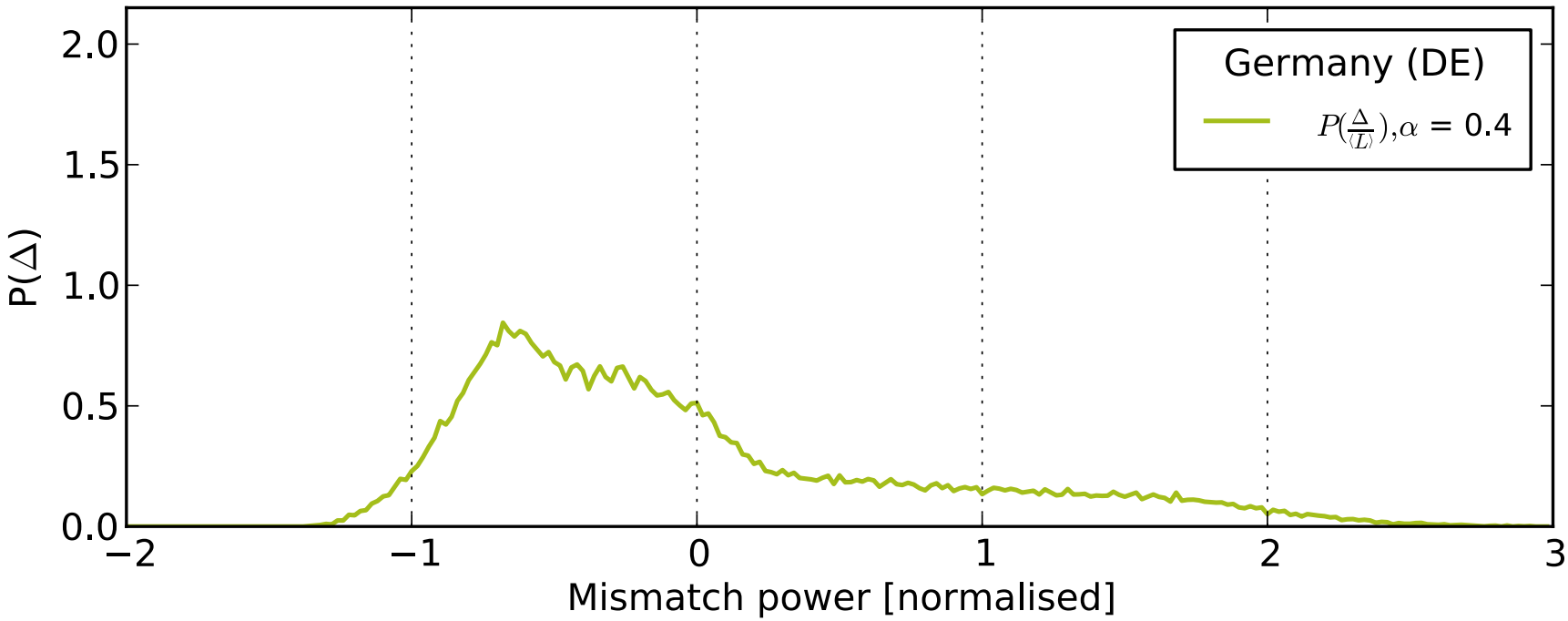
$$\alpha_n = \frac{\left\langle G_n^W \right\rangle}{\left\langle G_n^{RES} \right\rangle}$$

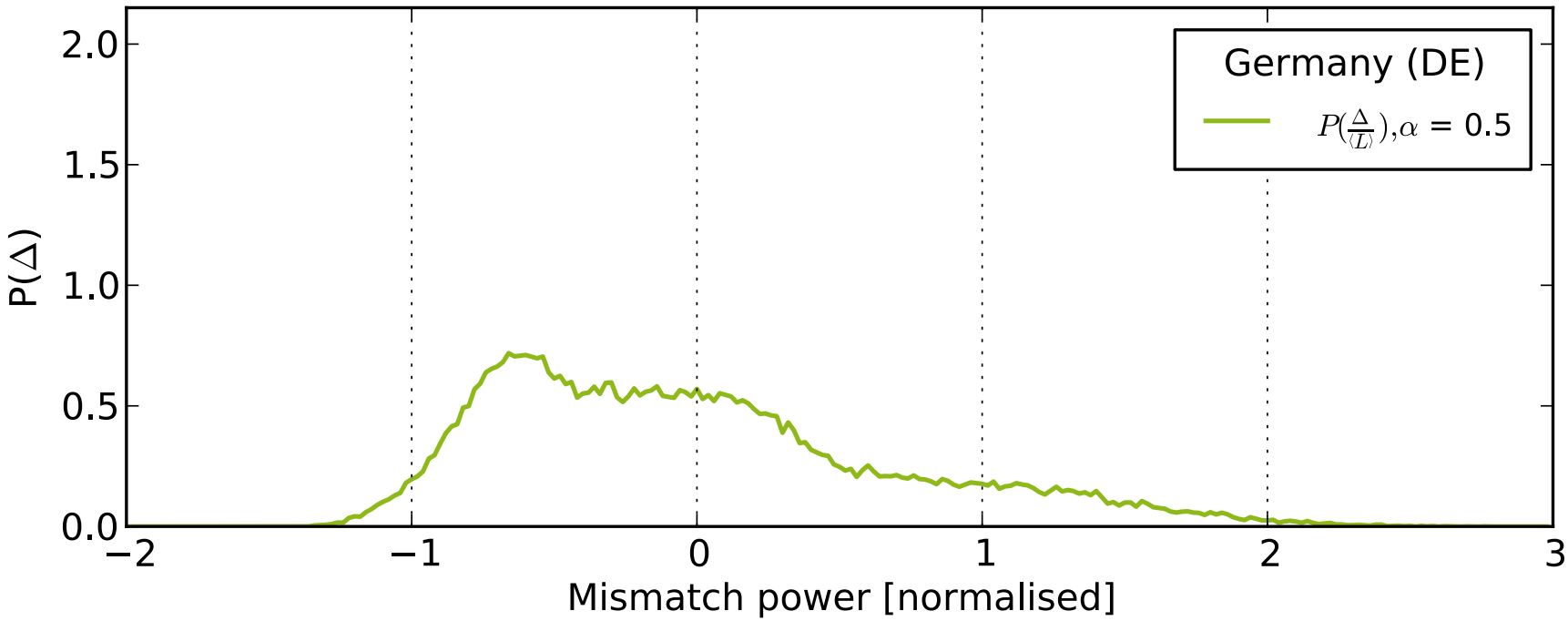


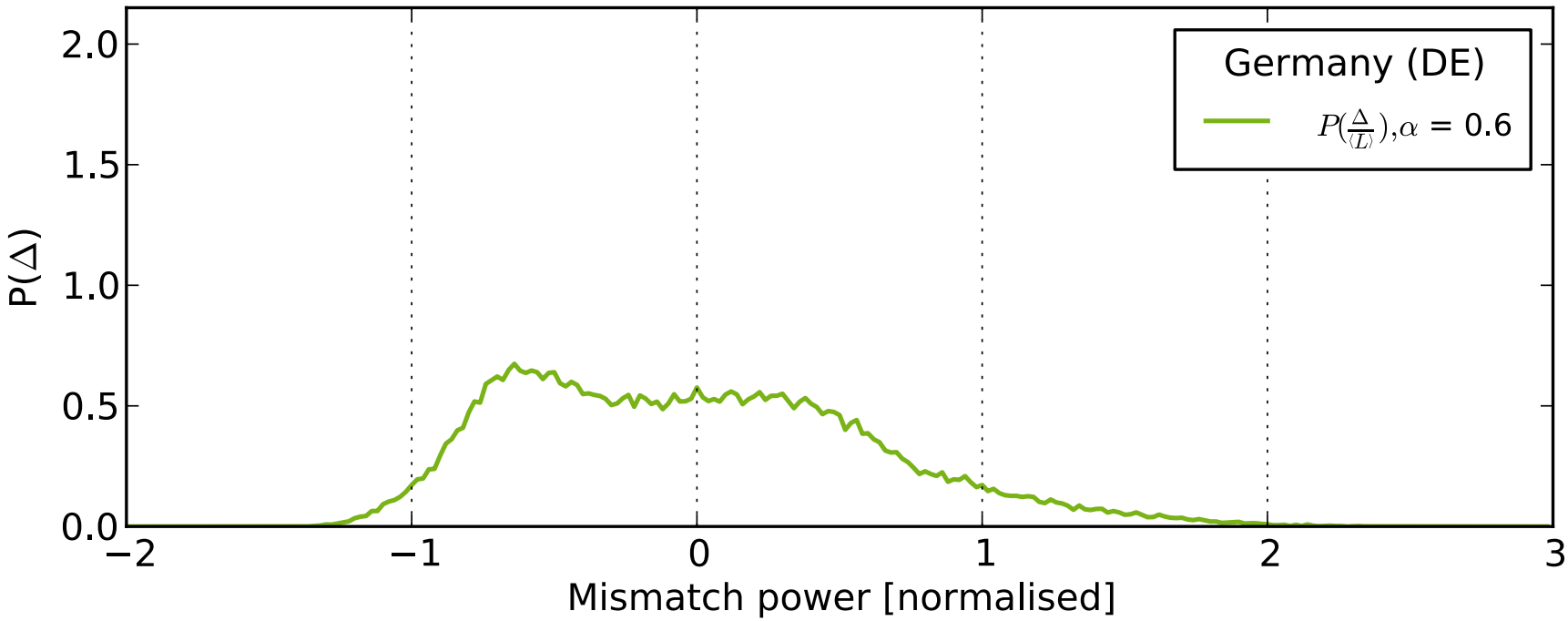

Germany (DE)
$P(\frac{\Delta}{\langle L \rangle}), \alpha$ = 0.1
P(Δ)
2.0
1.5
1.0
0.5
0.0
−2
−1
0
1
2
3
Mismatch power [normalised]

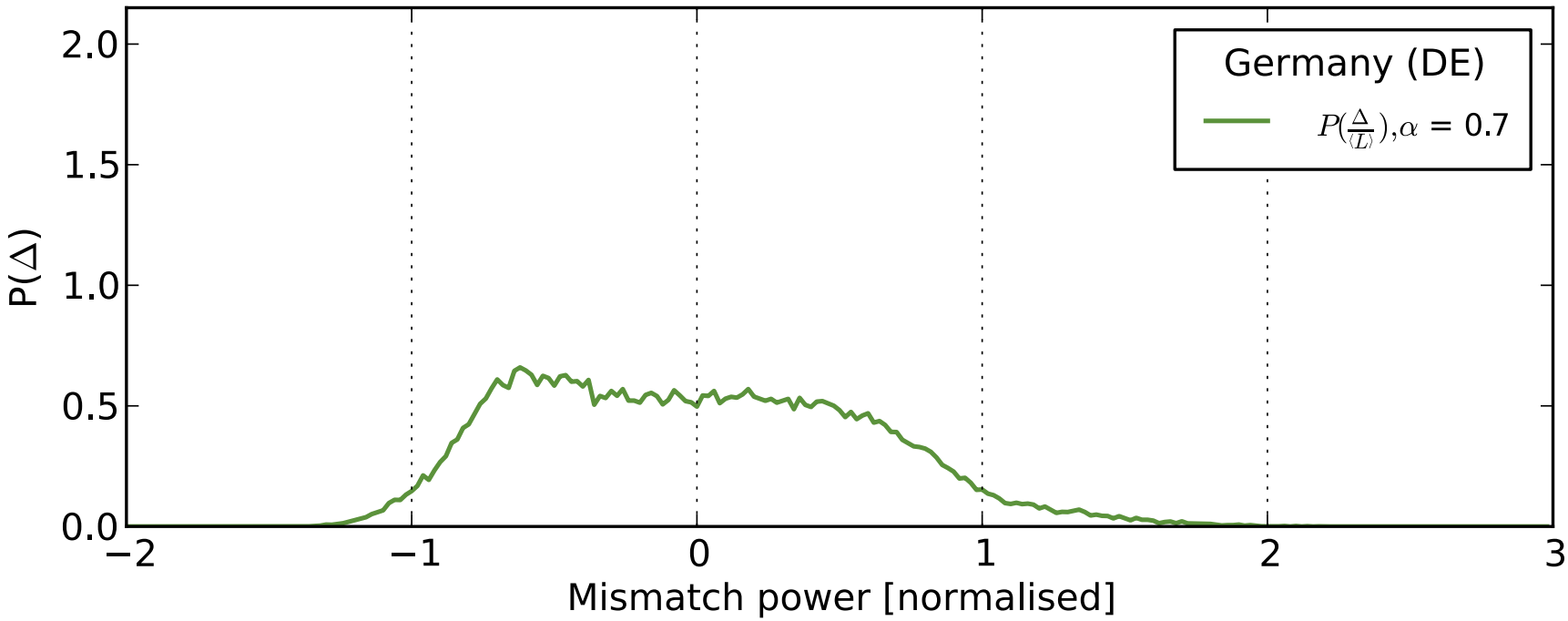

Germany (DE)
$P(\frac{\Delta}{\langle L \rangle}), \alpha$ = 0.2
P(Δ)
2.0
1.5
1.0
0.5
0.0
−2
−1
0
1
2
3
Mismatch power [normalised]

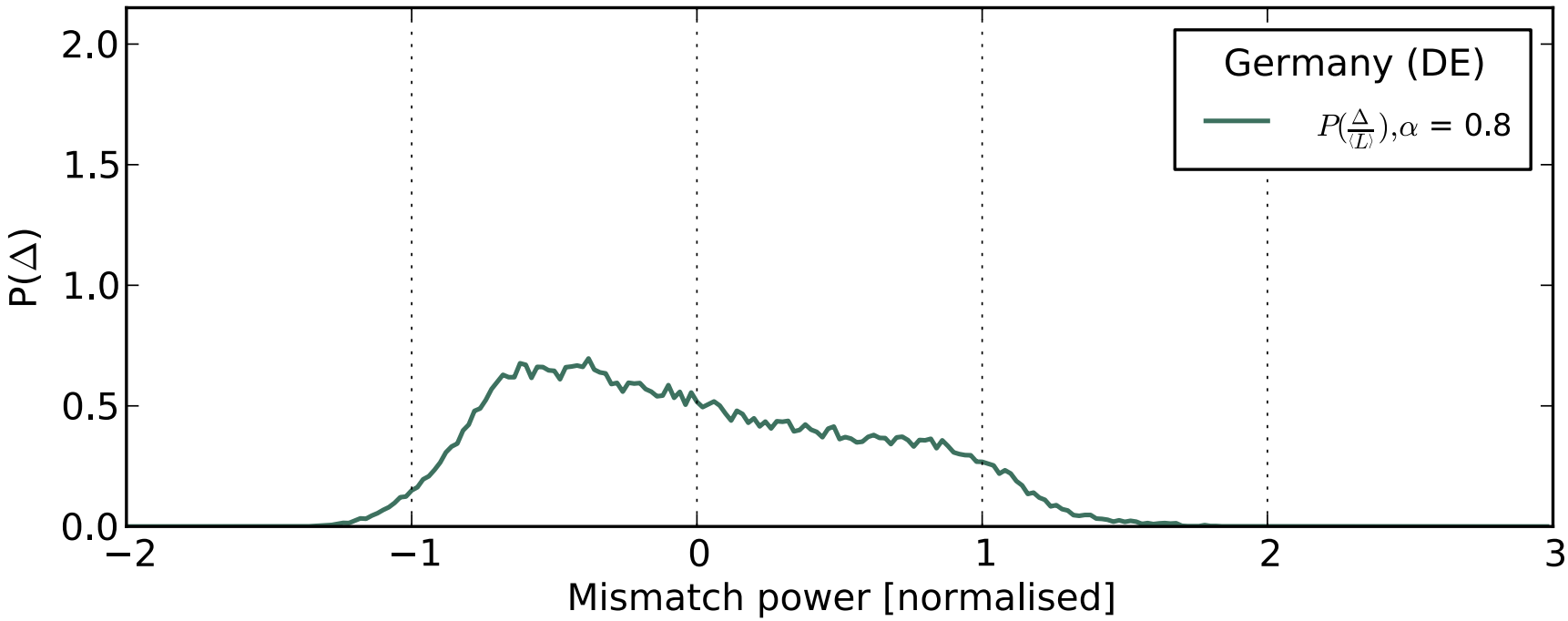

Germany (DE)
$P(\frac{\Delta}{\langle L \rangle}), \alpha$ = 0.3
P(Δ)
2.0
1.5
1.0
0.5
0.0
−2
−1
0
1
2
3
Mismatch power [normalised]

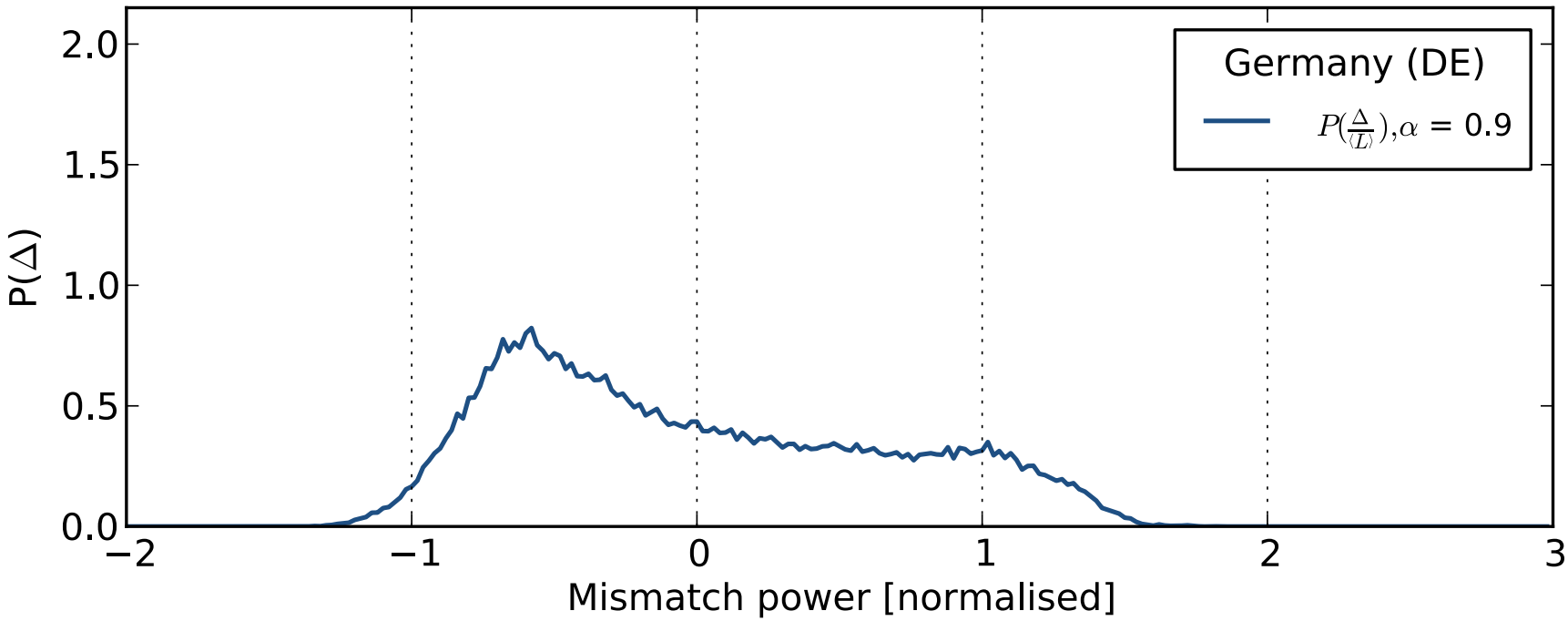

Germany (DE)
$P(\frac{\Delta}{\langle L \rangle}), \alpha$ = 0.4
P(Δ)
2.0
1.5
1.0
0.5
0.0
−2
−1
0
1
2
3
Mismatch power [normalised]

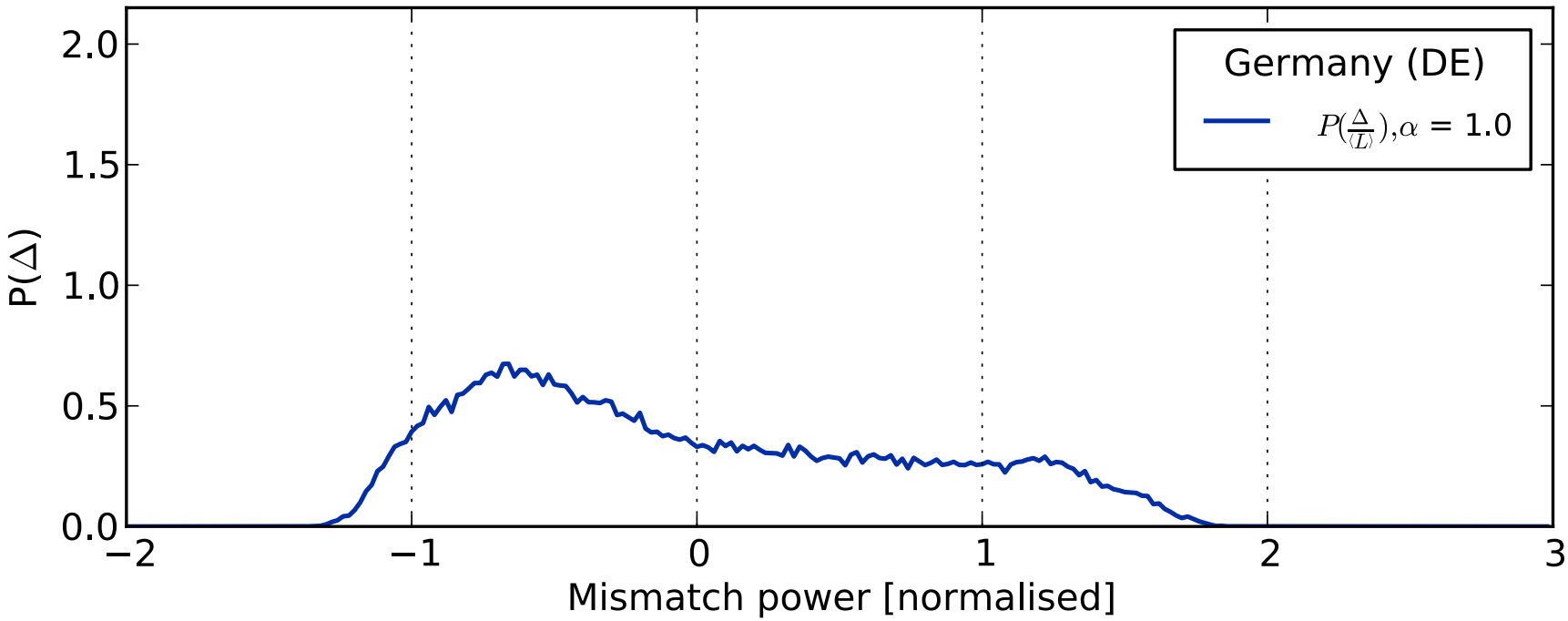

Germany (DE)
$P(\frac{\Delta}{\langle L \rangle}), \alpha$ = 0.5
P(Δ)
2.0
1.5
1.0
0.5
0.0
−2
−1
0
1
2
3
Mismatch power [normalised]


Germany (DE)
$P(\frac{\Delta}{\langle L \rangle}), \alpha$ = 0.6
P(Δ)
2.0
1.5
1.0
0.5
0.0
−2
−1
0
1
2
3
Mismatch power [normalised]


Germany (DE)
$P(\frac{\Delta}{\langle L \rangle}), \alpha$ = 0.7
P(Δ)
2.0
1.5
1.0
0.5
0.0
−2
−1
0
1
2
3
Mismatch power [normalised]


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

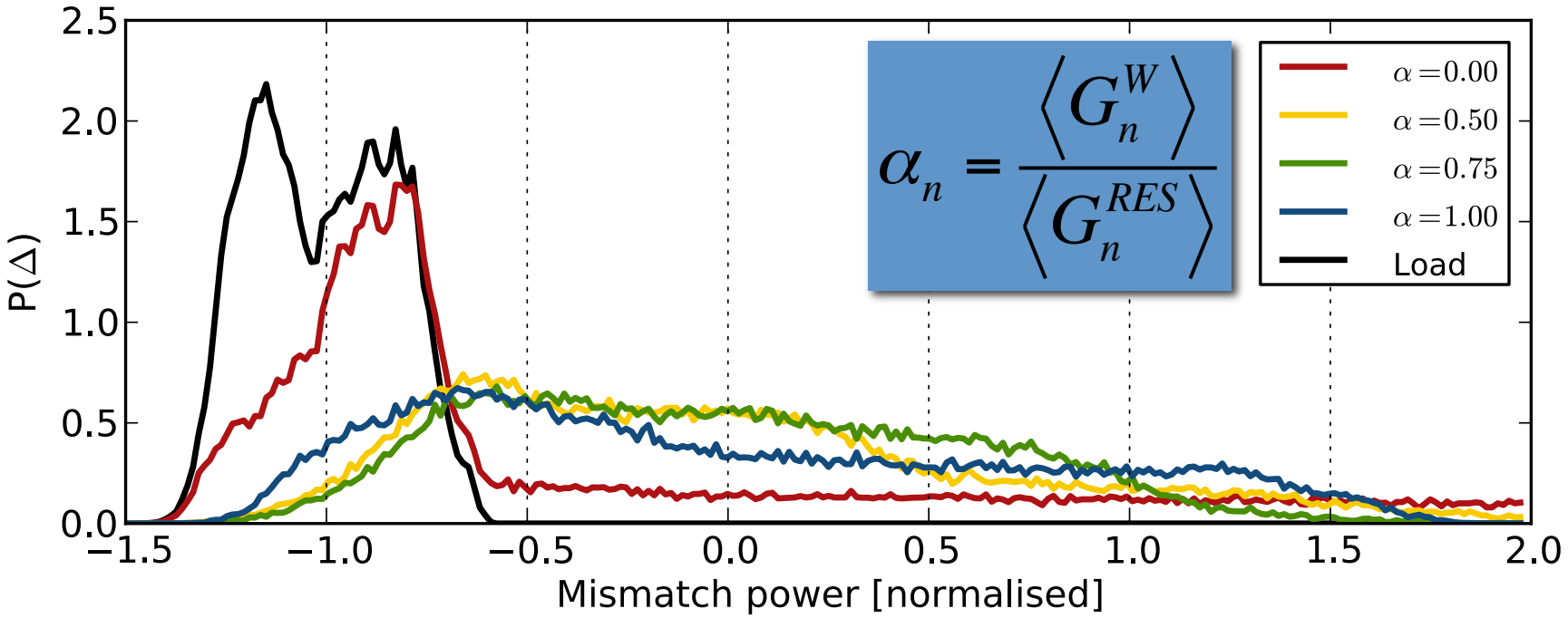

Germany (DE)
$P(\frac{\Delta}{\langle L \rangle}), \alpha$ = 0.9
P(Δ)
2.0
1.5
1.0
0.5
0.0
−2
−1
0
1
2
3
Mismatch power [normalised]


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

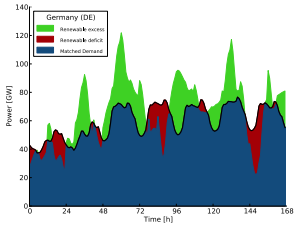
Mismatch distribution (Germany)

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

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

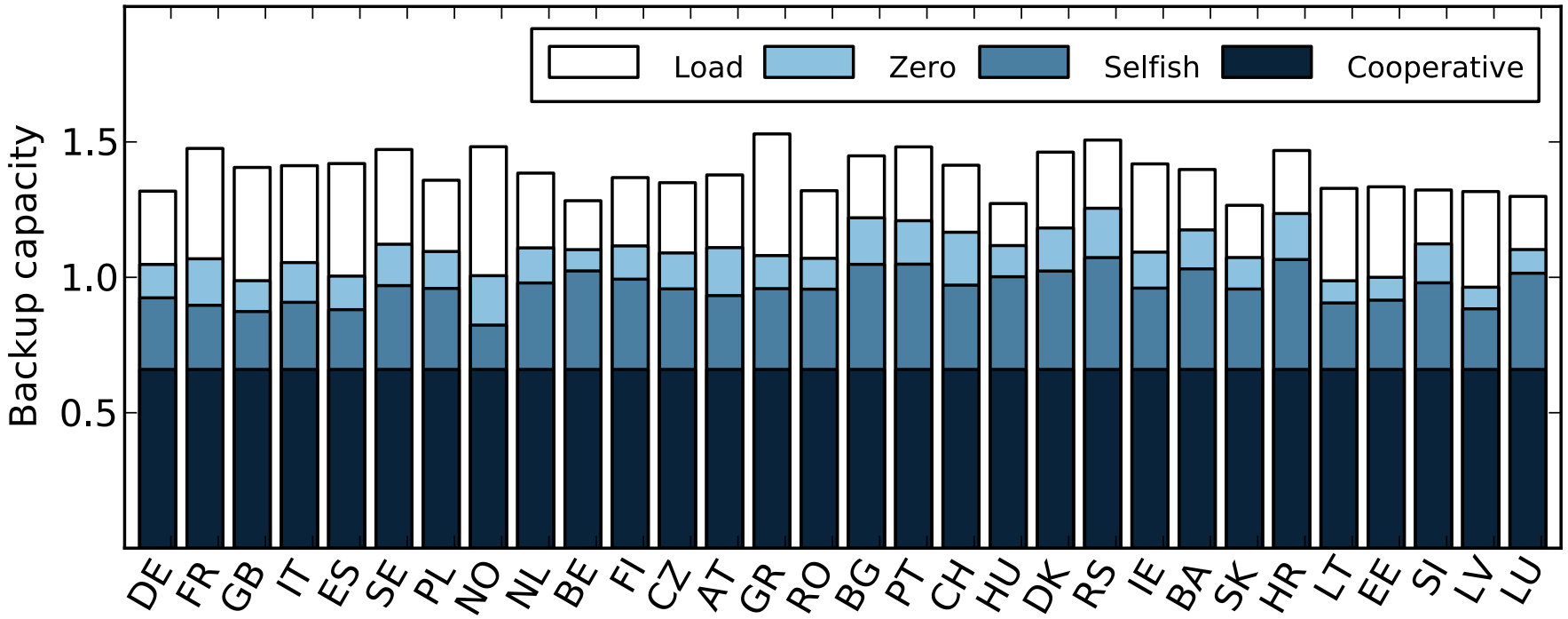


$$B_n(t) = -\min\left(\Delta(t), 0\right)$$



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

BACKUP CAPACITY of EU countries (zero transmission)



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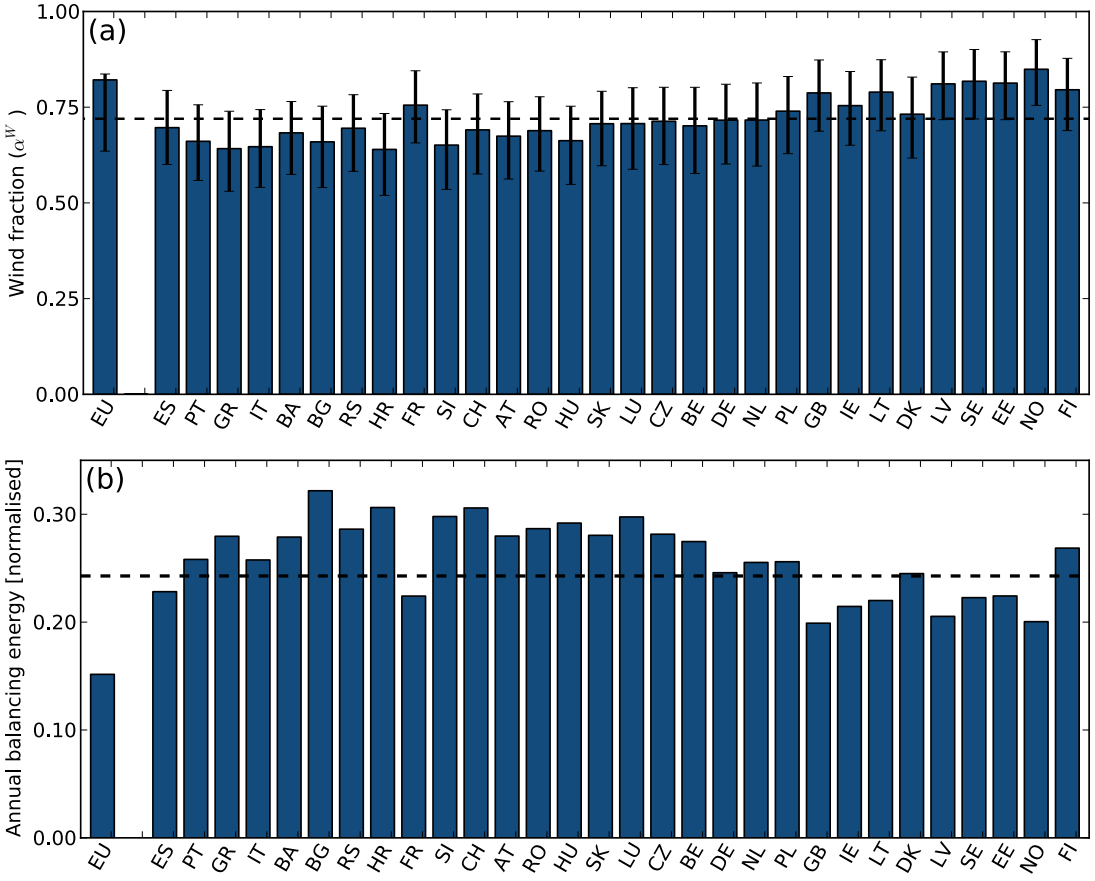
BACKUP ENERGIES of EU countries (zero transmission)



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

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

Mismatch distribution (Europe)

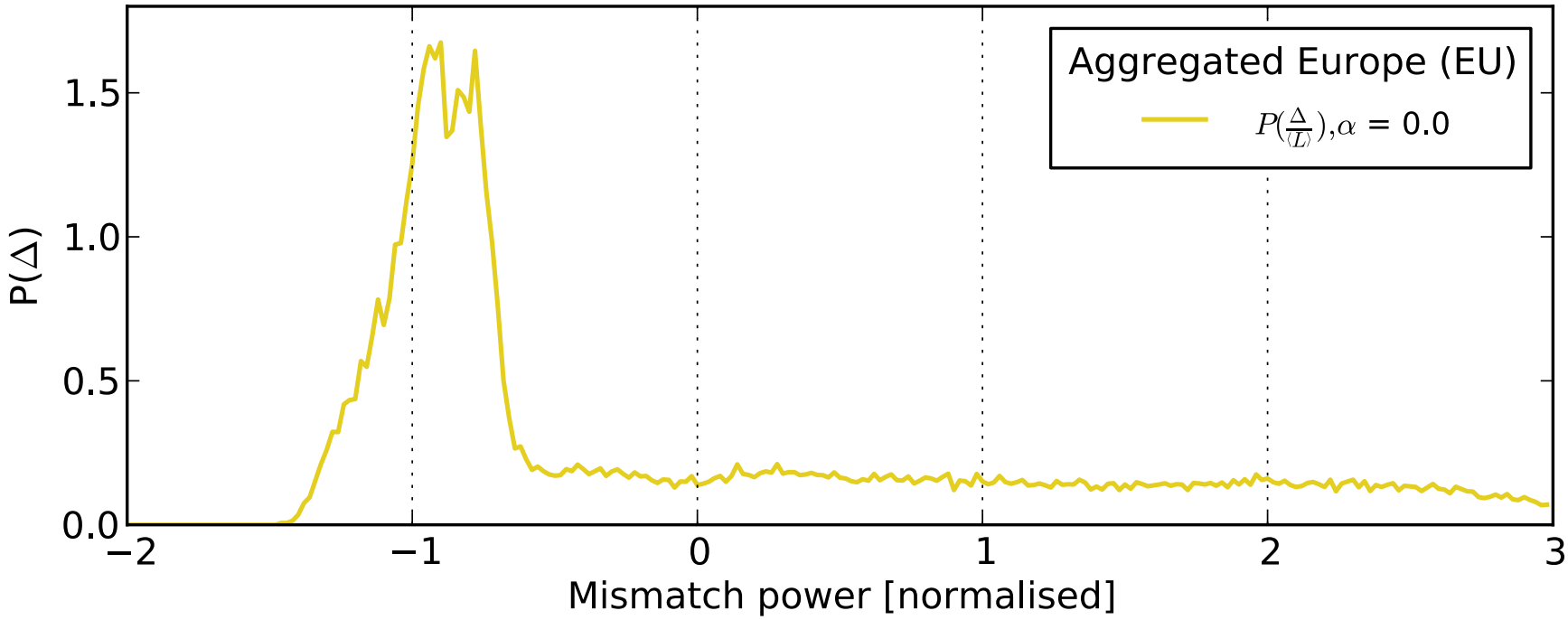
$$G_n^{RES}(t) - L_n(t) = C_n(t) - B_n(t) + \sum_{ngb(n)} \left(F_{n\rightarrow} - F_{\rightarrow n} \right)$$

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

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

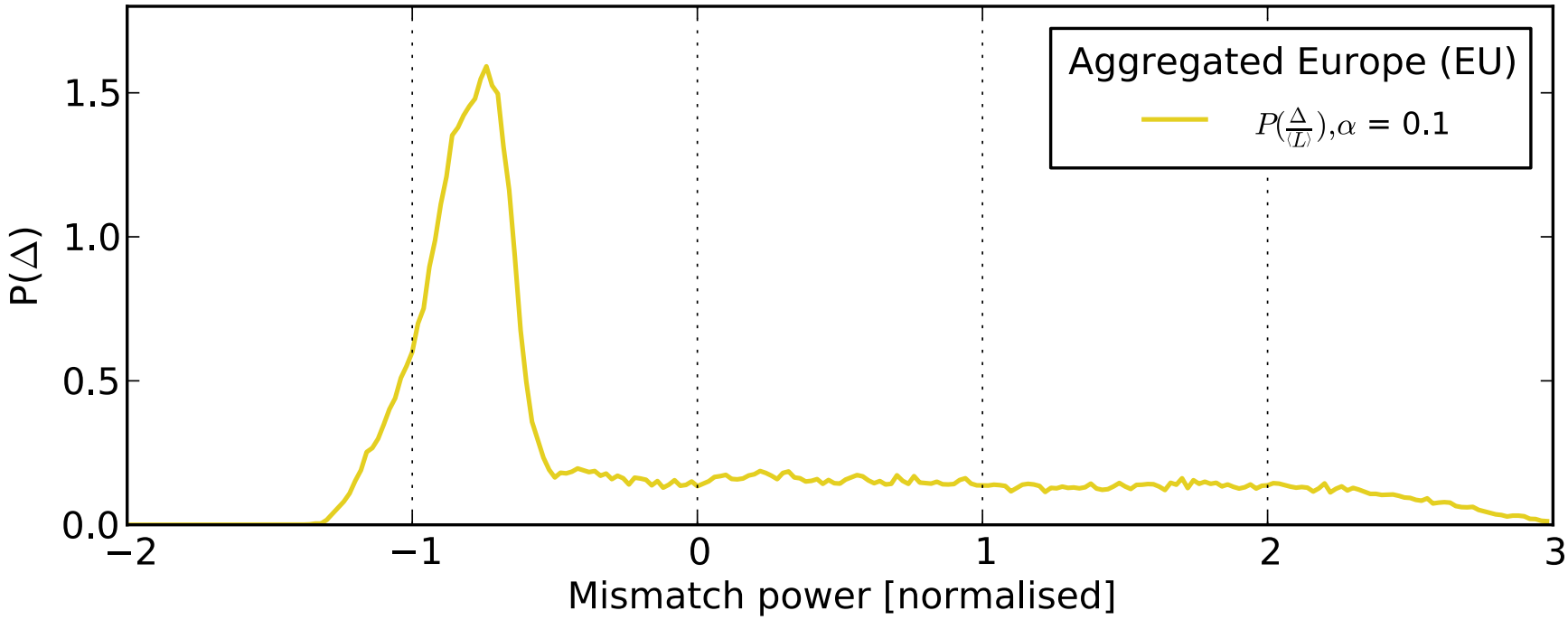
Mismatch distribution (Europe)

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



Mismatch distribution (Europe)

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



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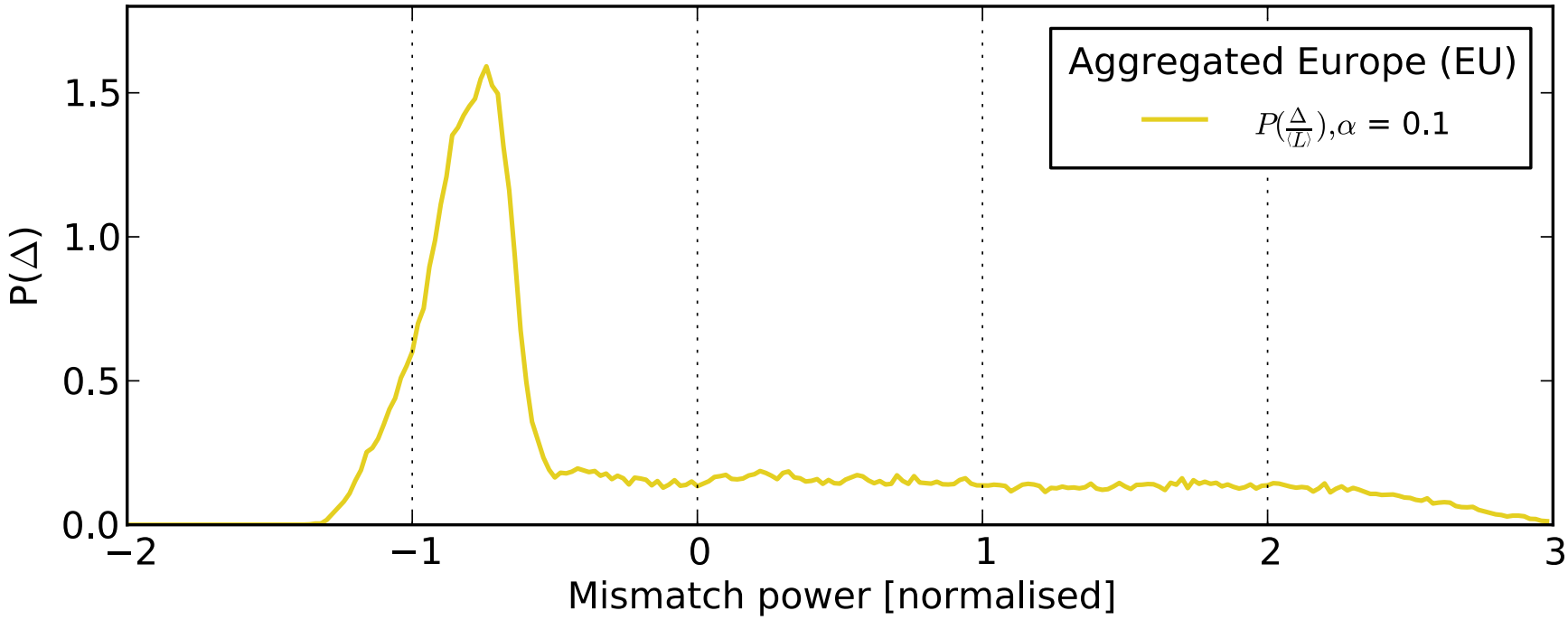

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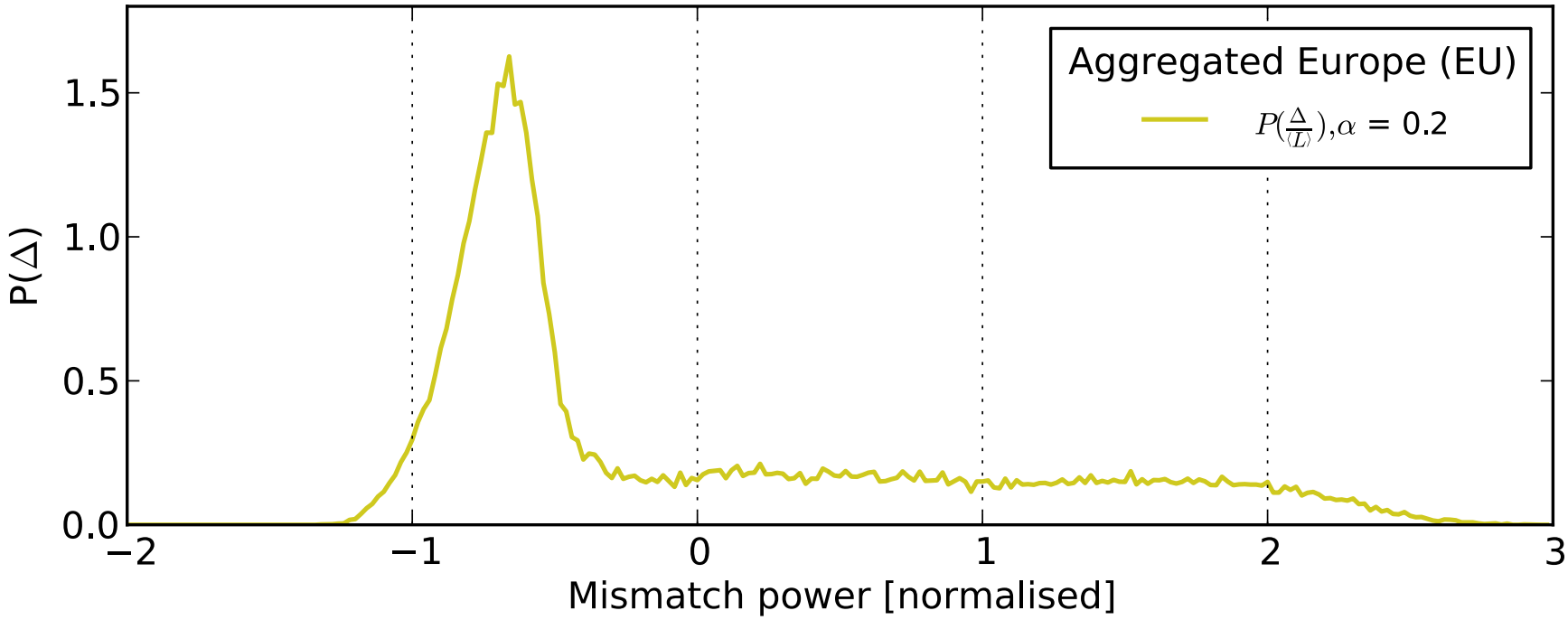

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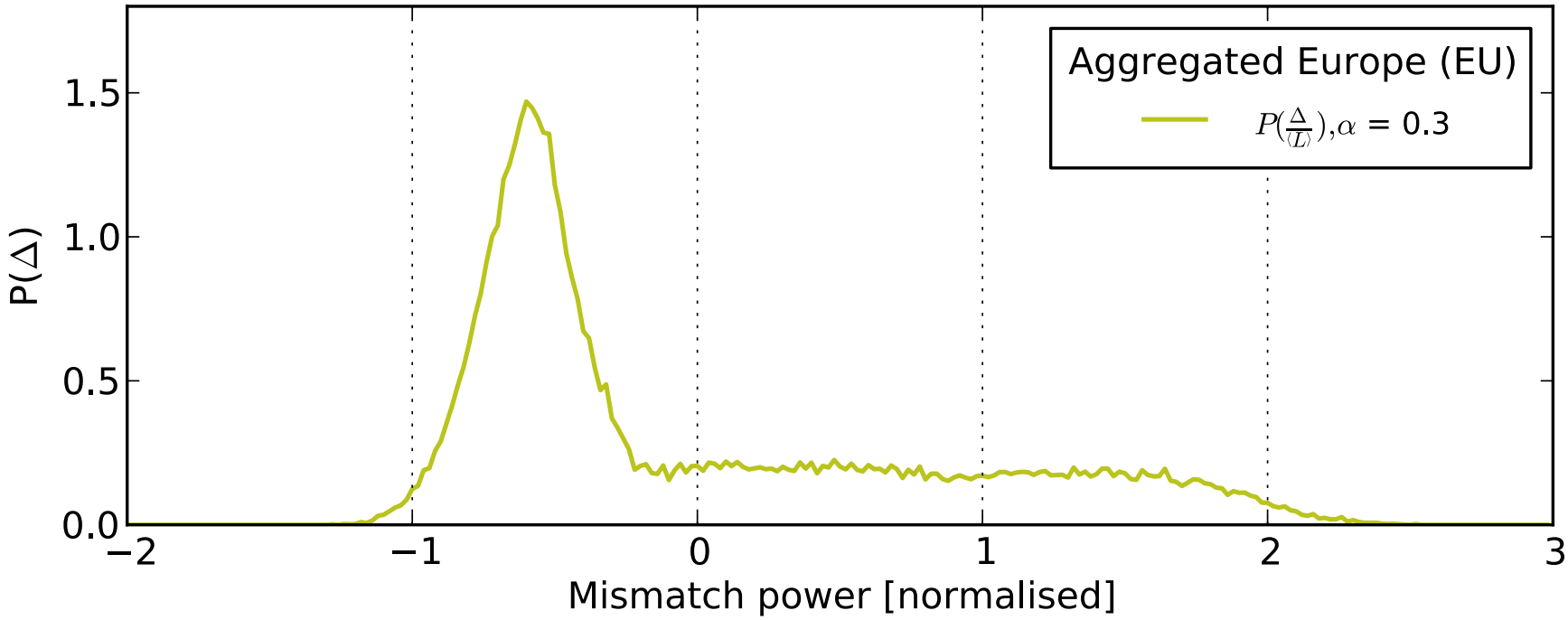
$$\Delta_{EU}(t) = G_{EU}^{RES}(t) - L_{EU}(t)$$



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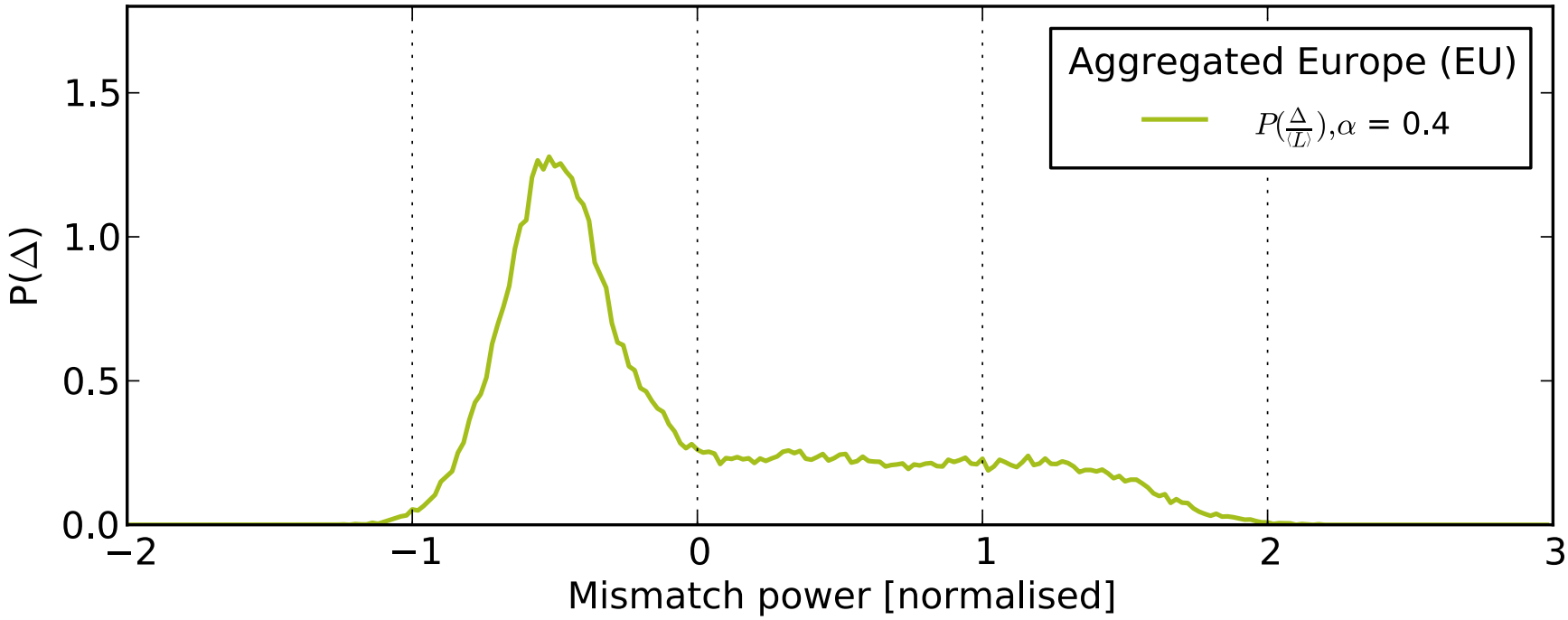

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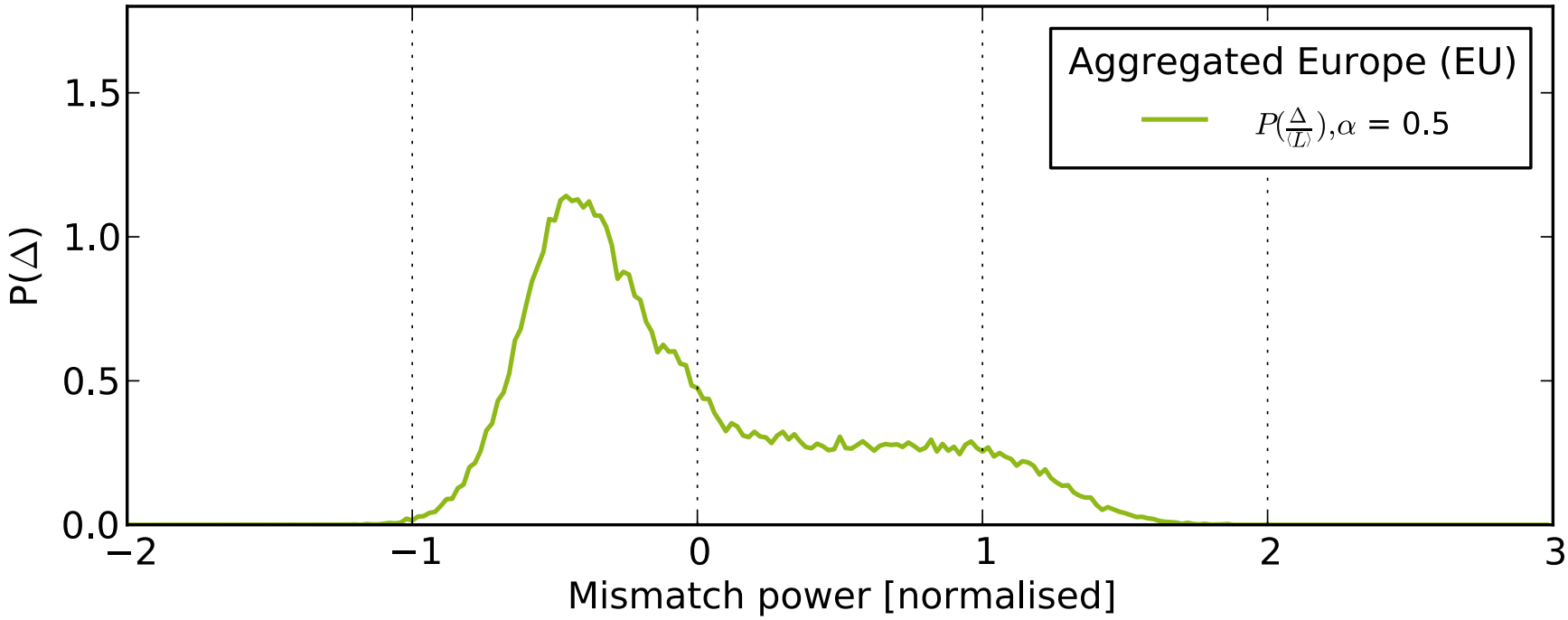

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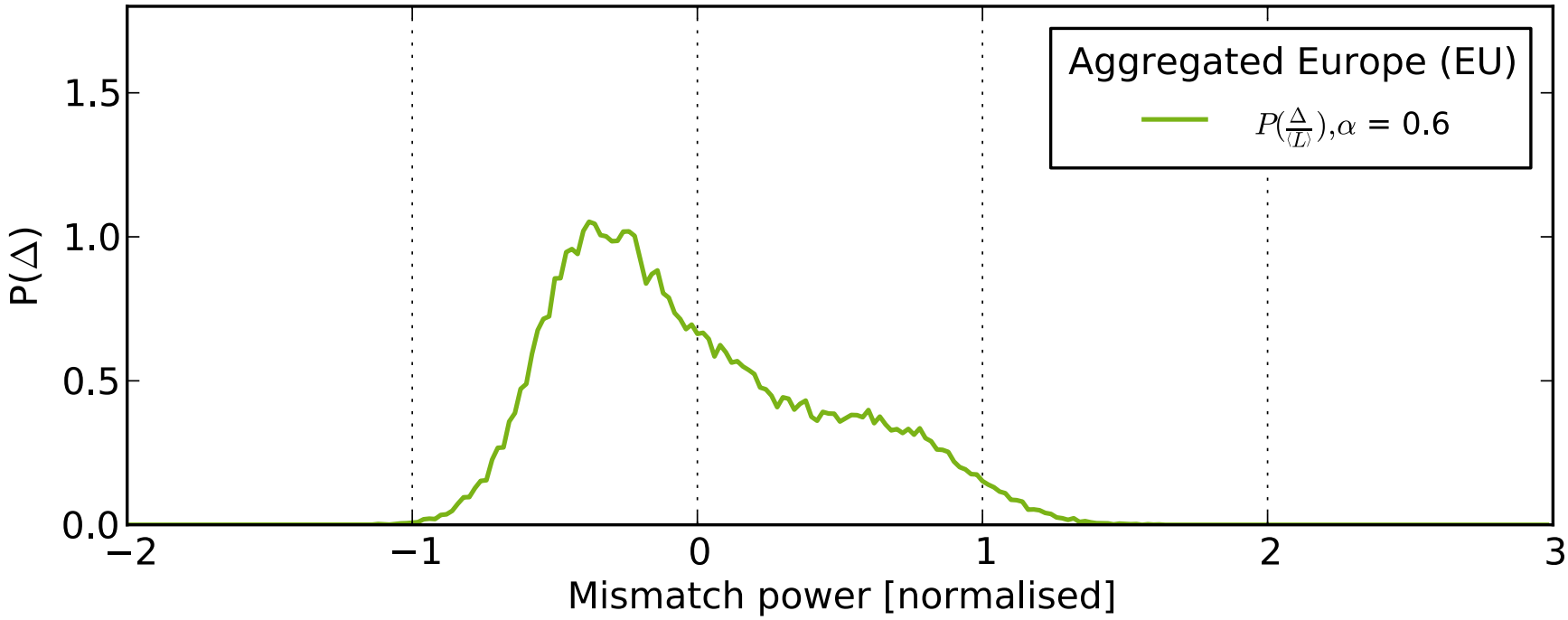
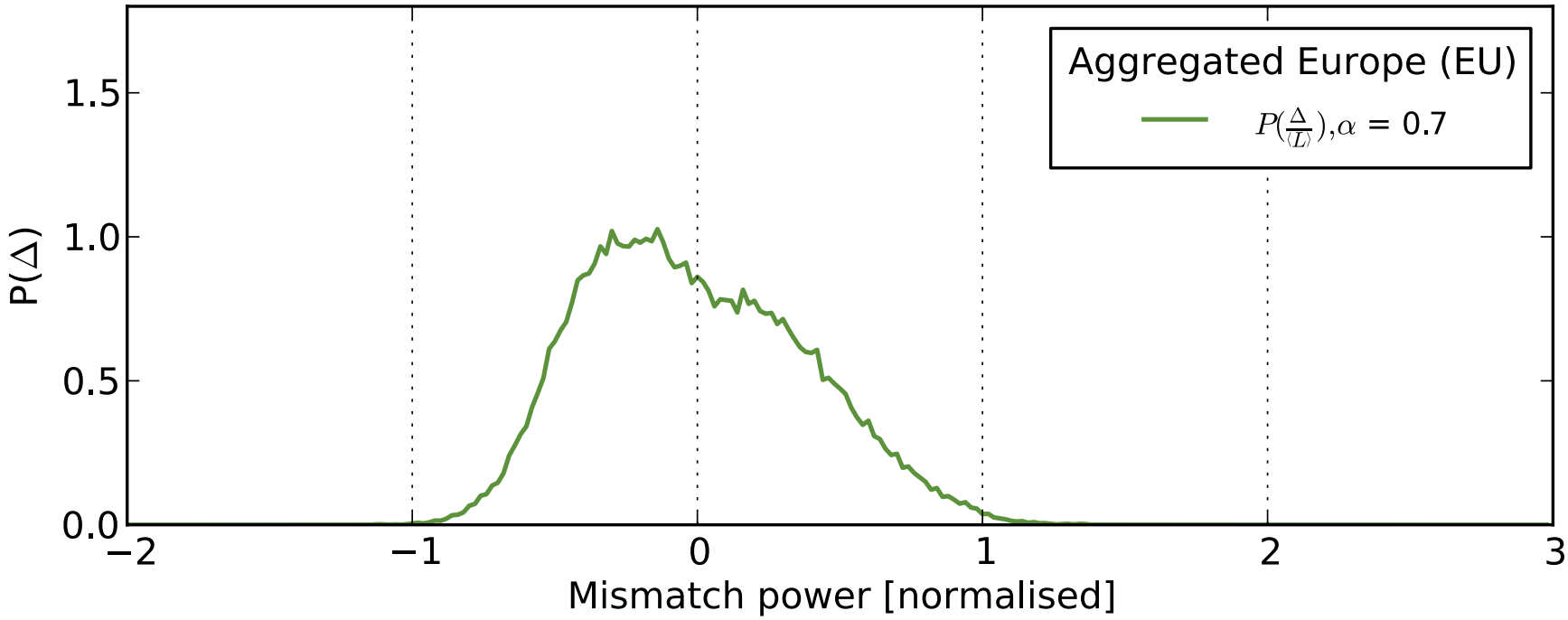
$$\Delta_{EU}(t) = G_{EU}^{RES}(t) - L_{EU}(t)$$



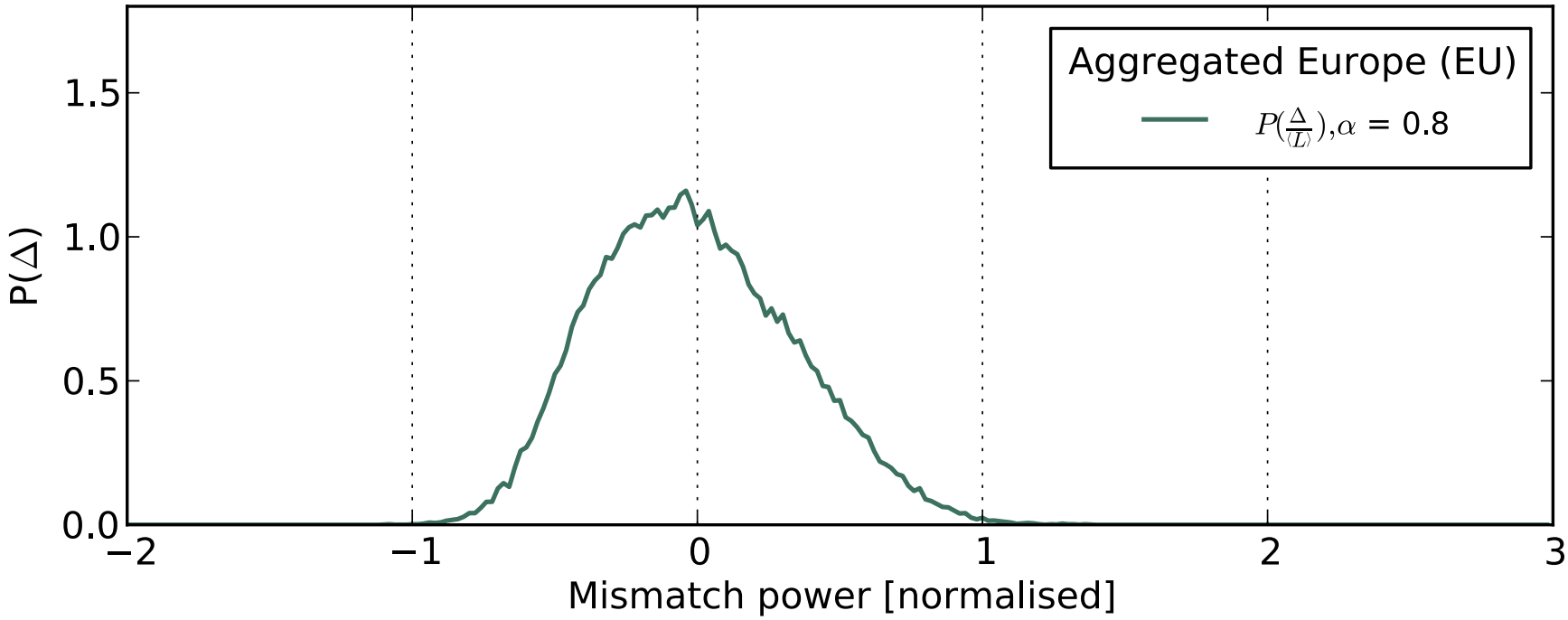
Mismatch distribution (Europe)

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



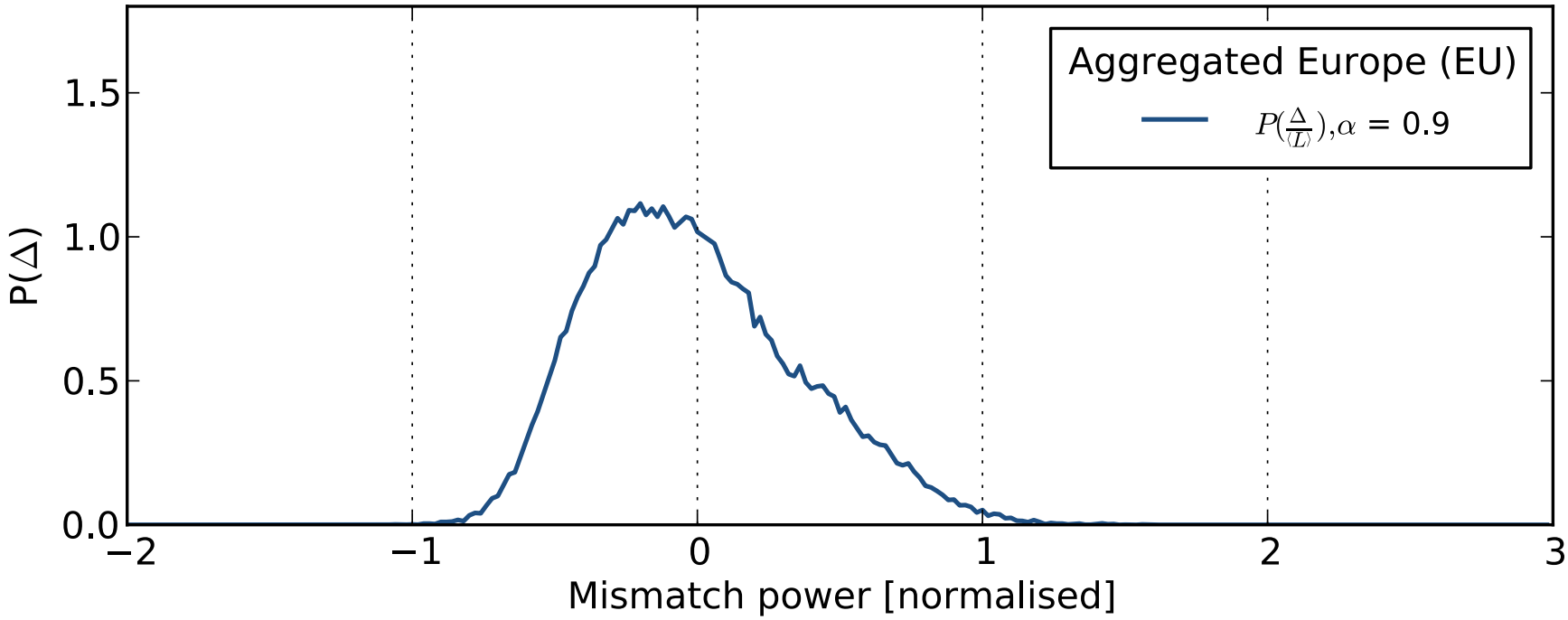
Mismatch distribution (Europe)

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



Mismatch distribution (Europe)

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



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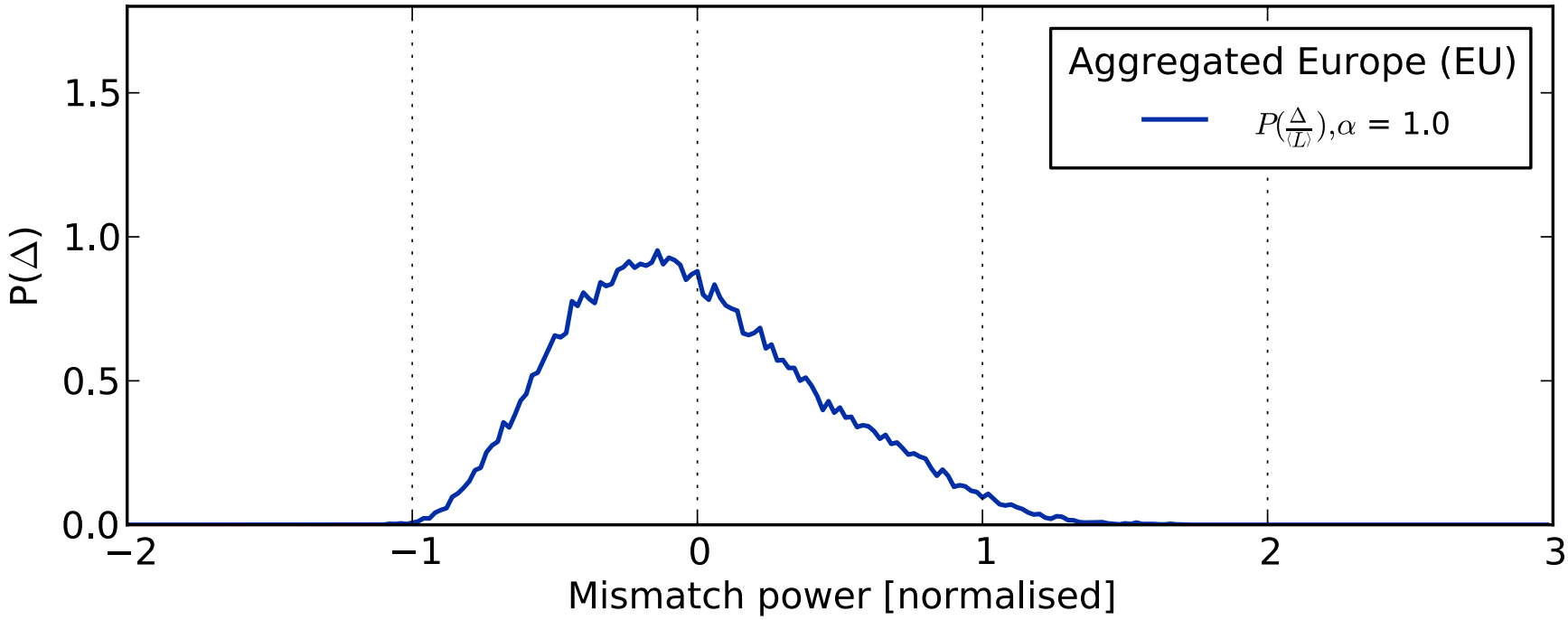
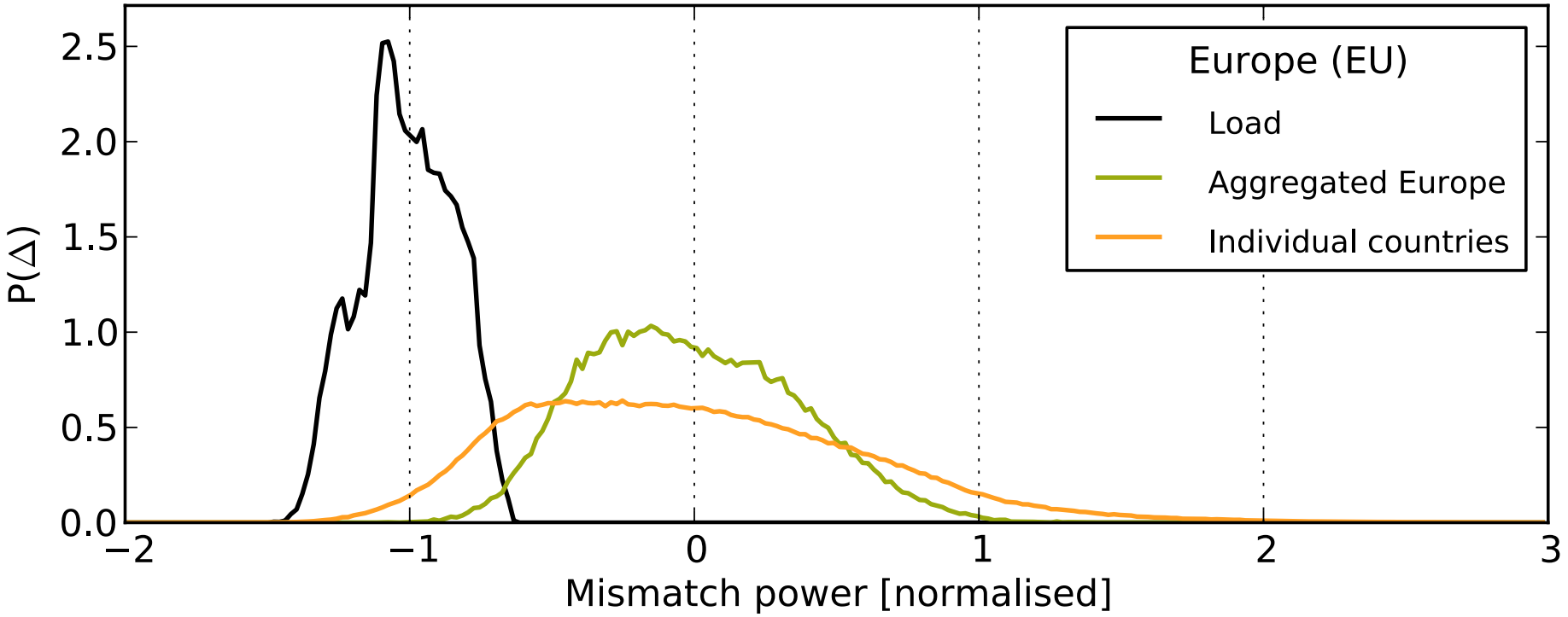
Mismatch distribution (Europe)

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

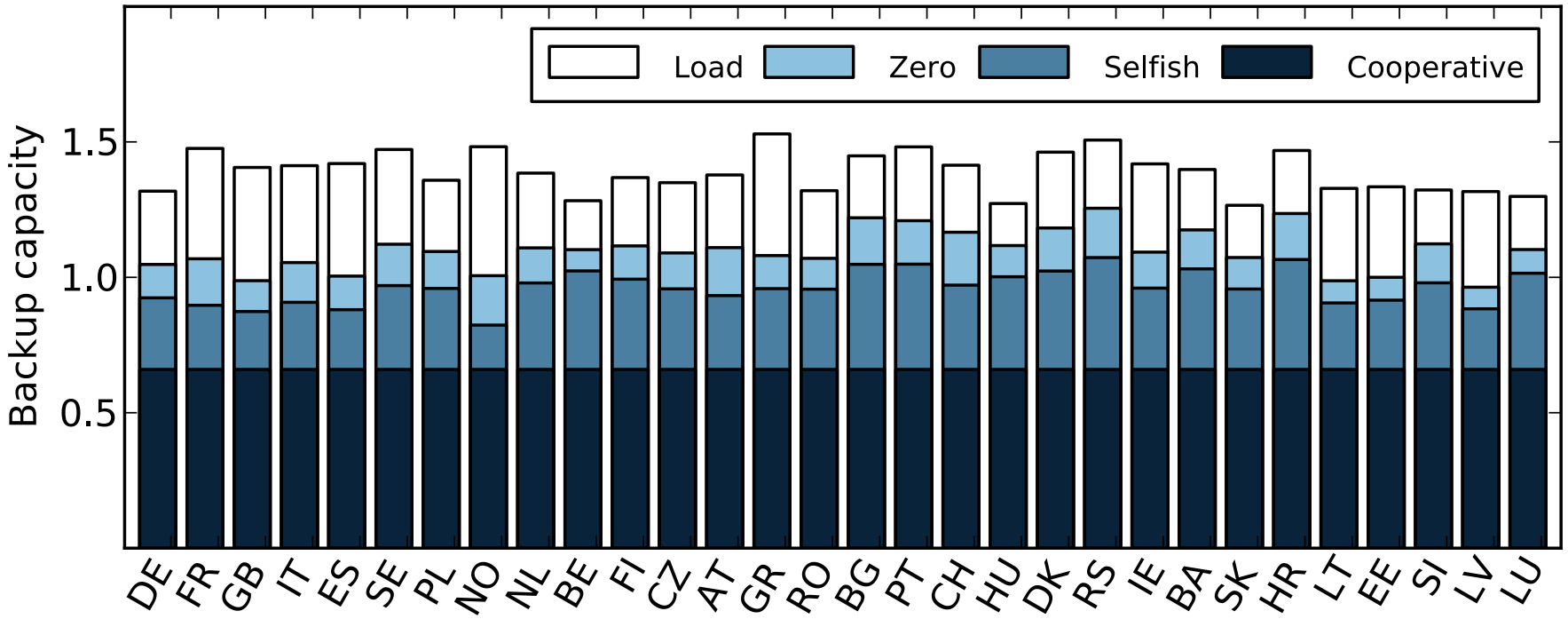


Mismatch distribution: Germany vs. Europe

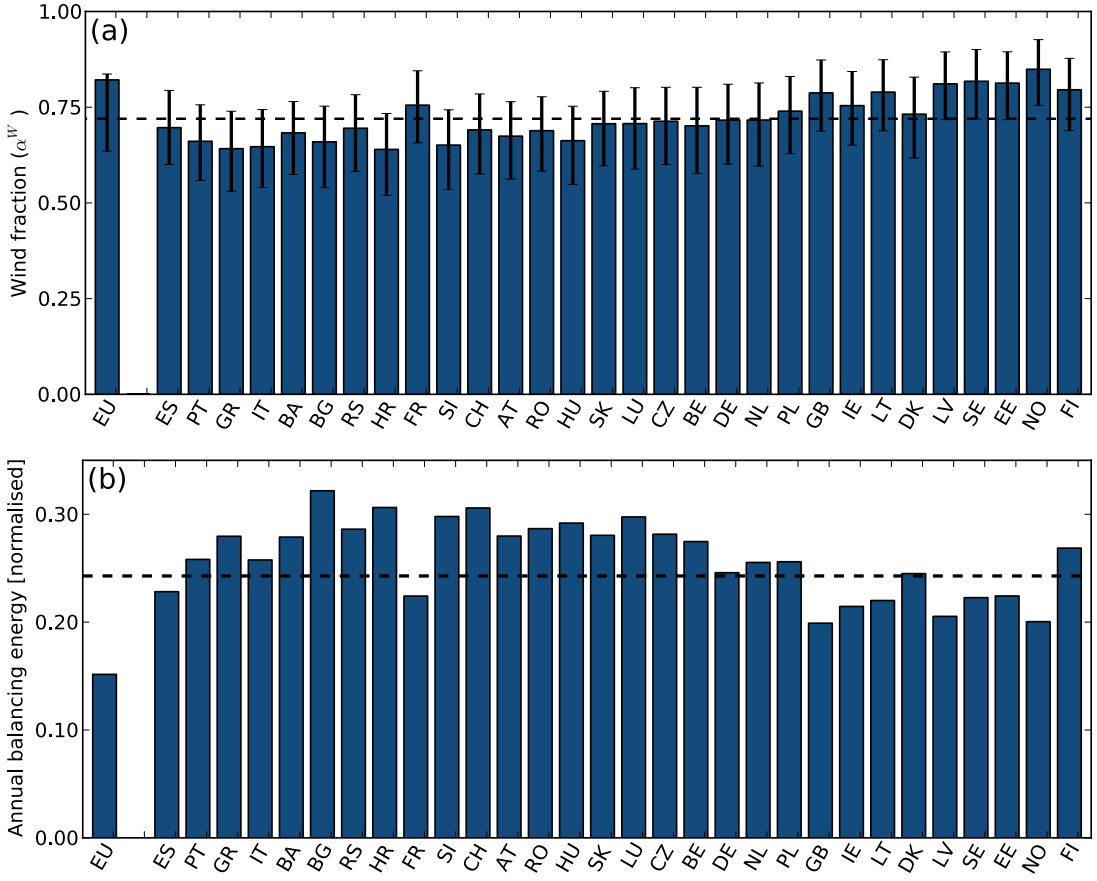


Mismatch without / with Transmission

BACKUP CAPACITY of EU countries (without/with transmission)



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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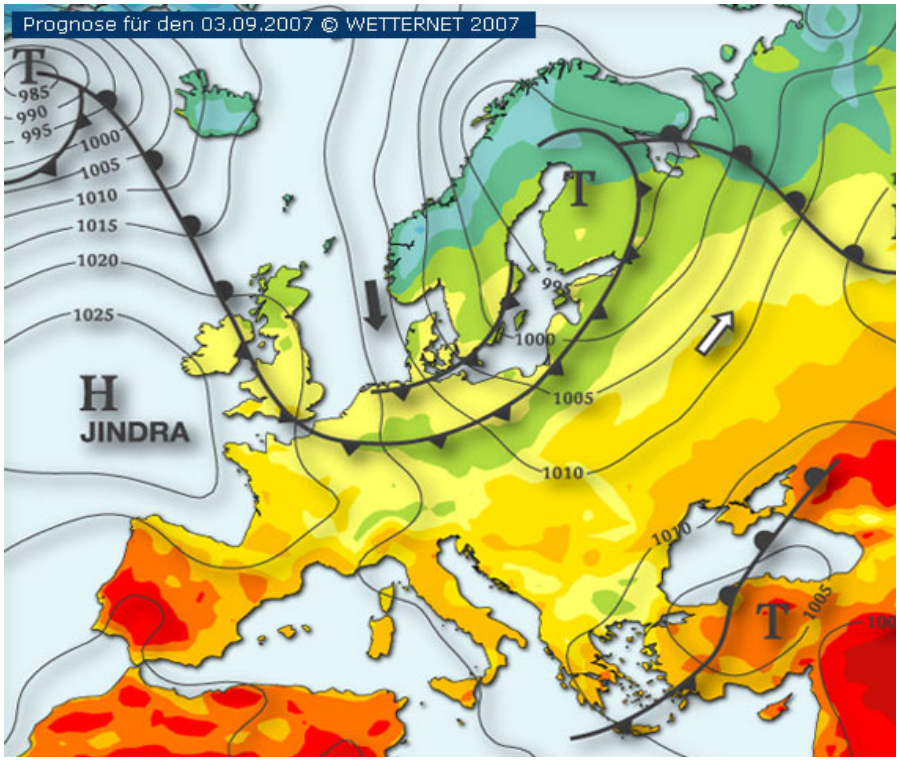
wind and solar power capacities



annual consumption (2009)
= 3360 TWh

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

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

so far: only backup

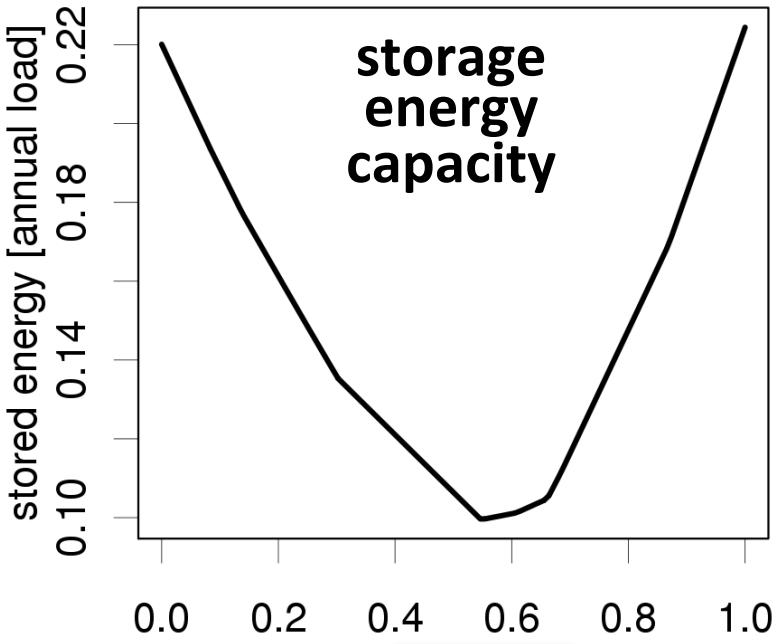
now: what about storage?

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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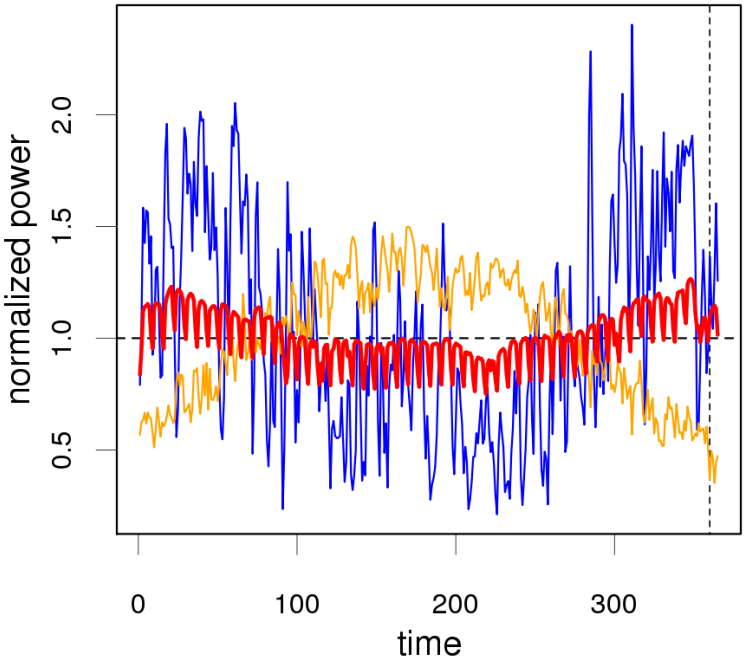
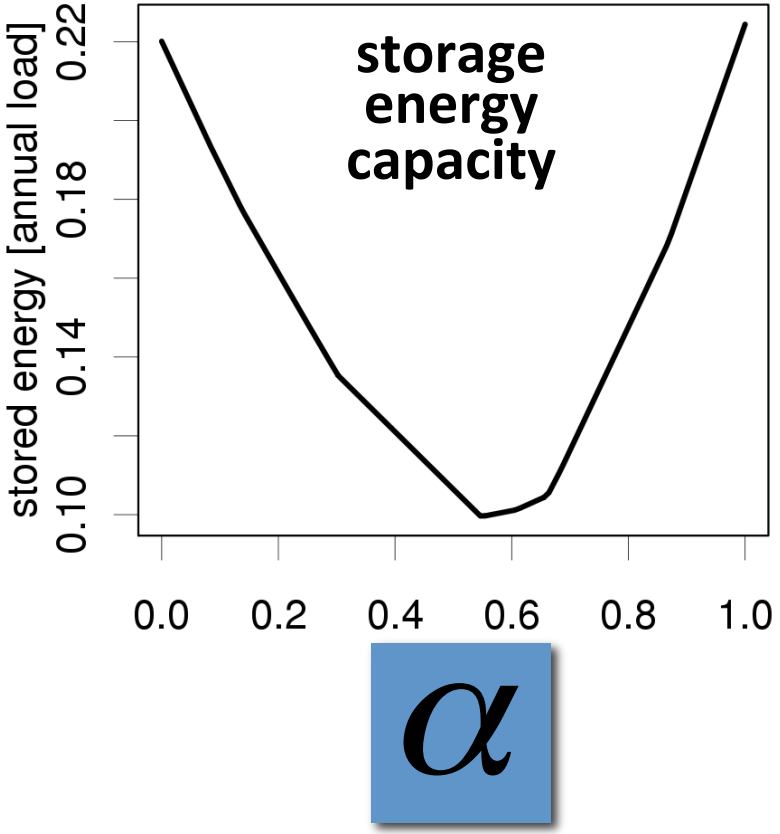
How much storage? @ 100% penetration in EU





Seasonal optimal mix

= 60% wind power

+ 40% solar power

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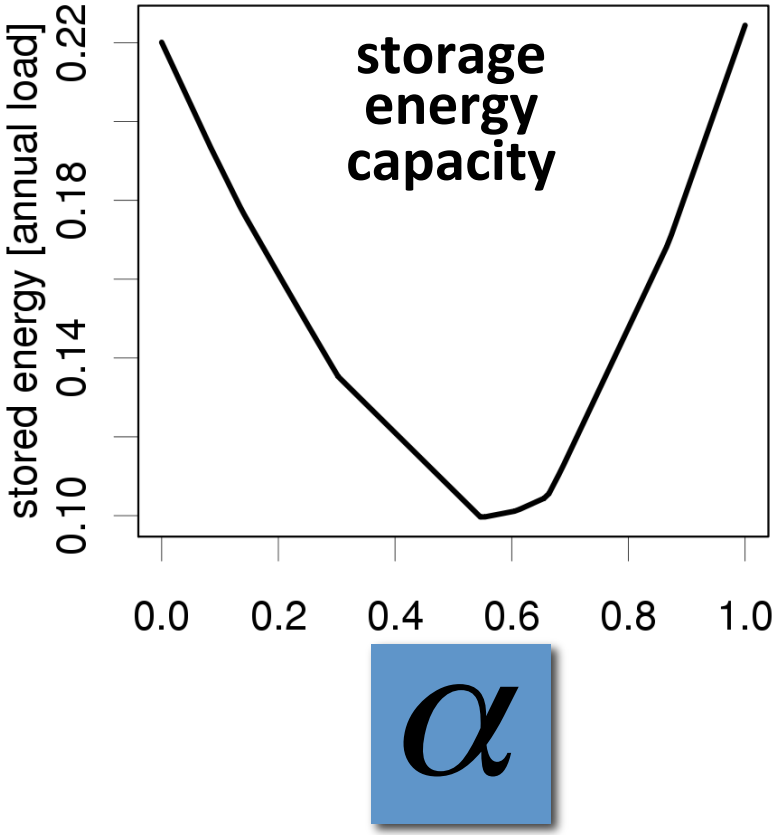
How much storage? @ 100% penetration in EU

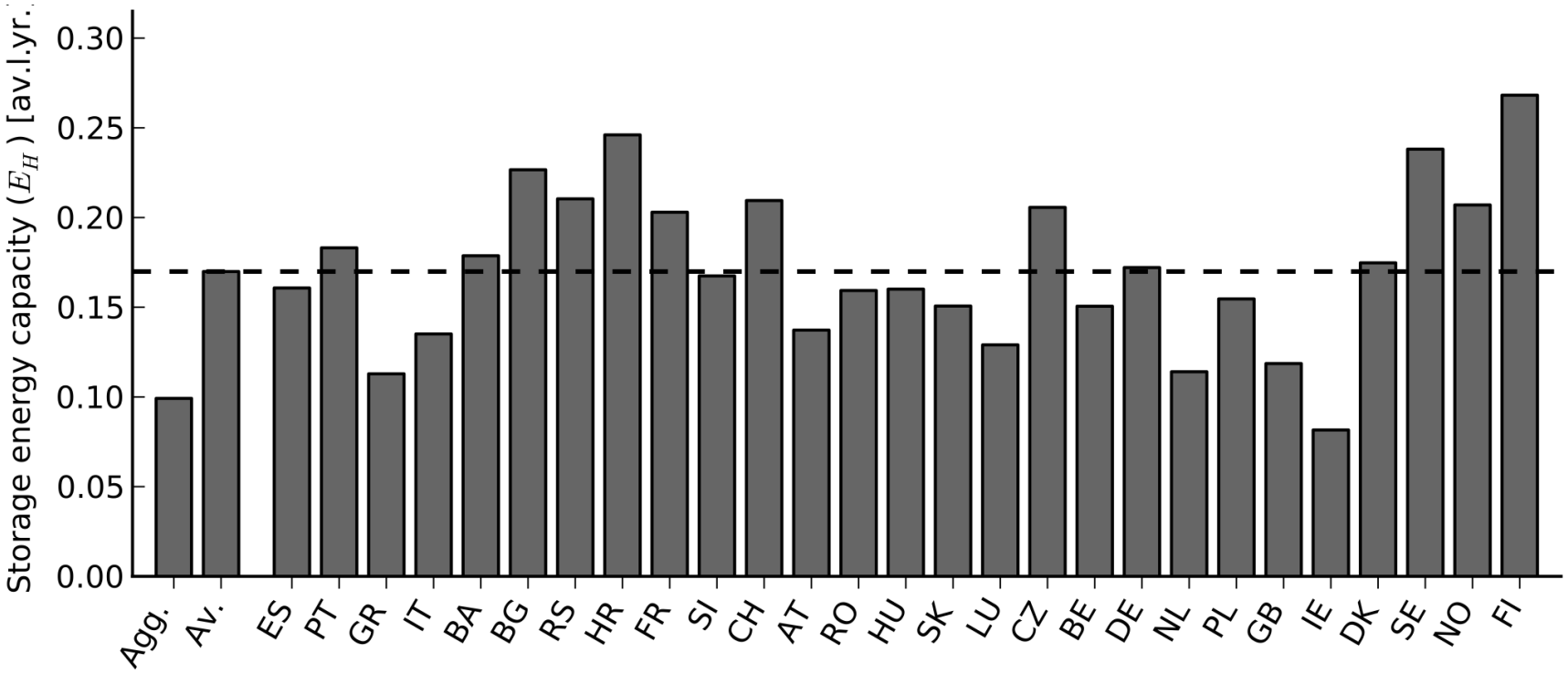
$$C_S = 10\% \langle L \rangle_{\text{annual}} = 340 \text{ TWh}$$

NOT POSSIBLE:
Pumped Hydro,
Compressed Air

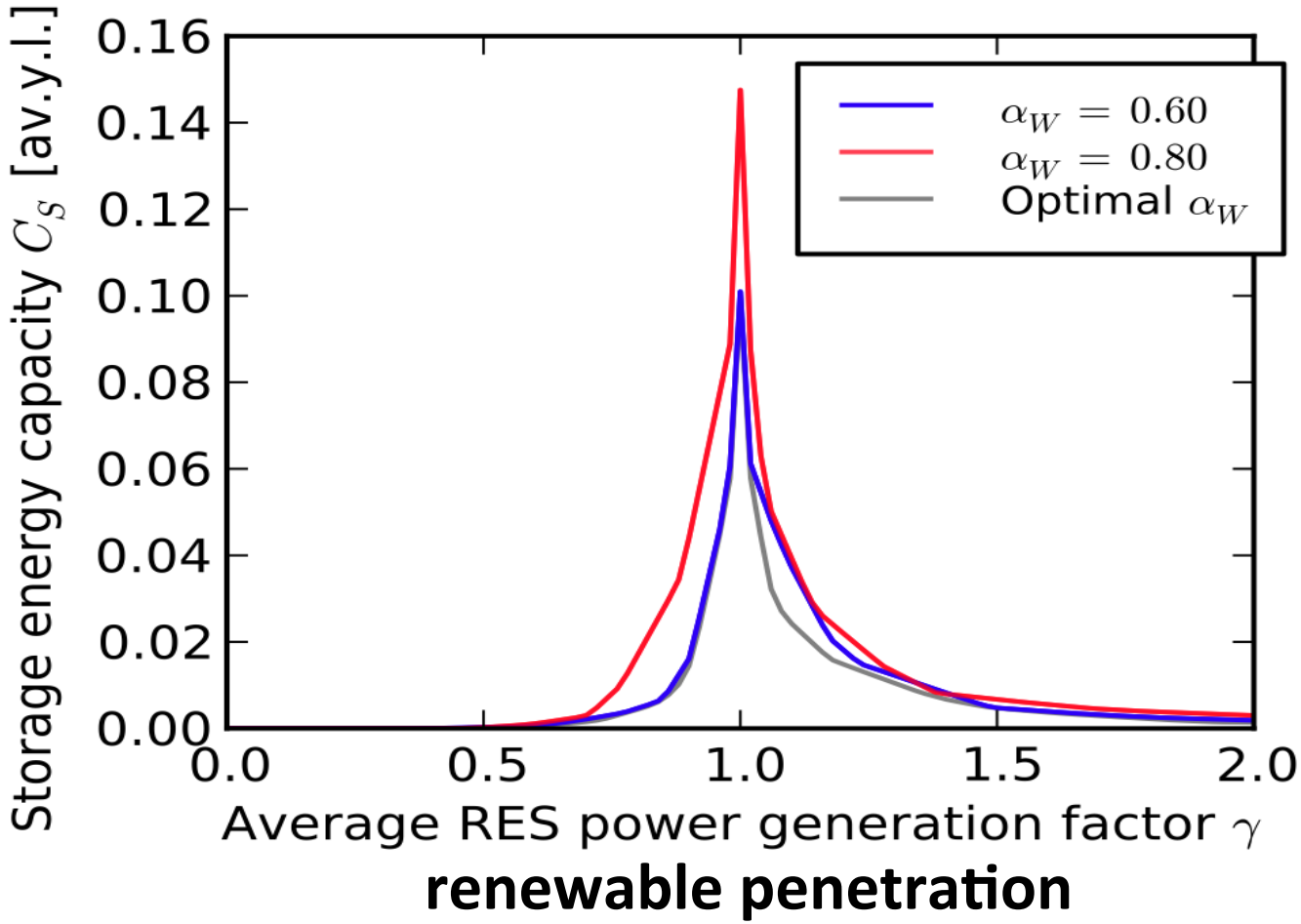
POSSIBLE:
H2 storage
25 TWh = 0.008 av.y.l.
6h "battery" storage
2.2 TWh = 0.0007 av.y.l



Country storage needs

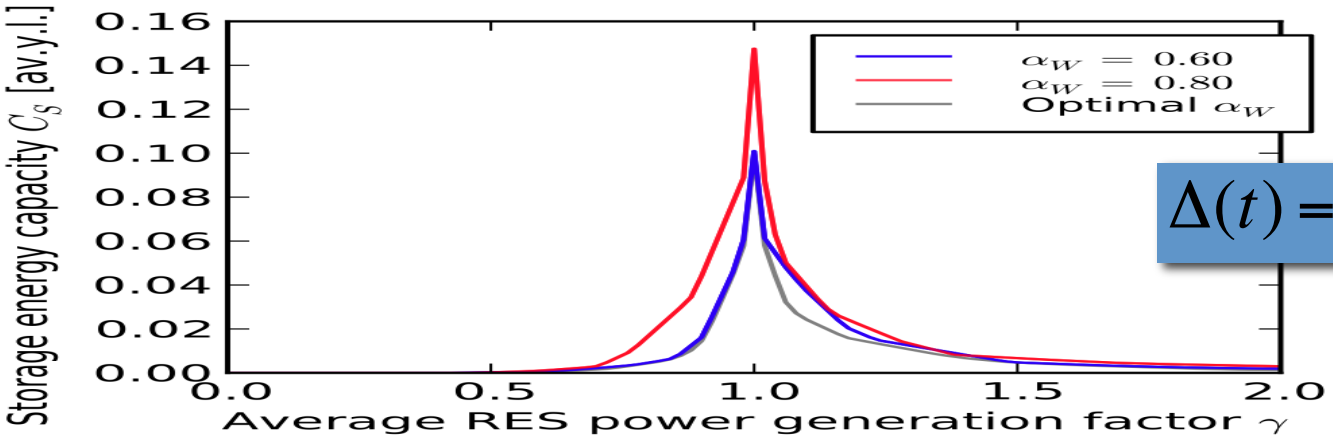


Storage Singularity



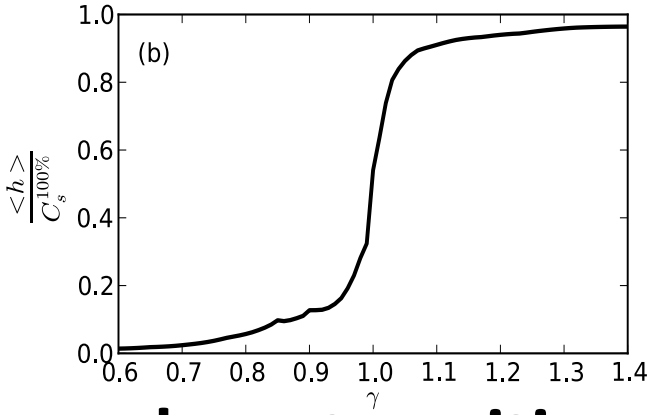
renewable penetration

Storage Singularity

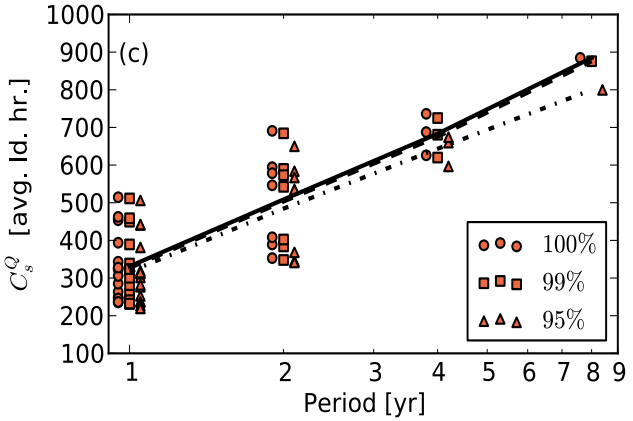


$$\Delta(t) = \gamma\, G_{RES}(t) - L(t)$$

γ = renewable penetration



phase transition



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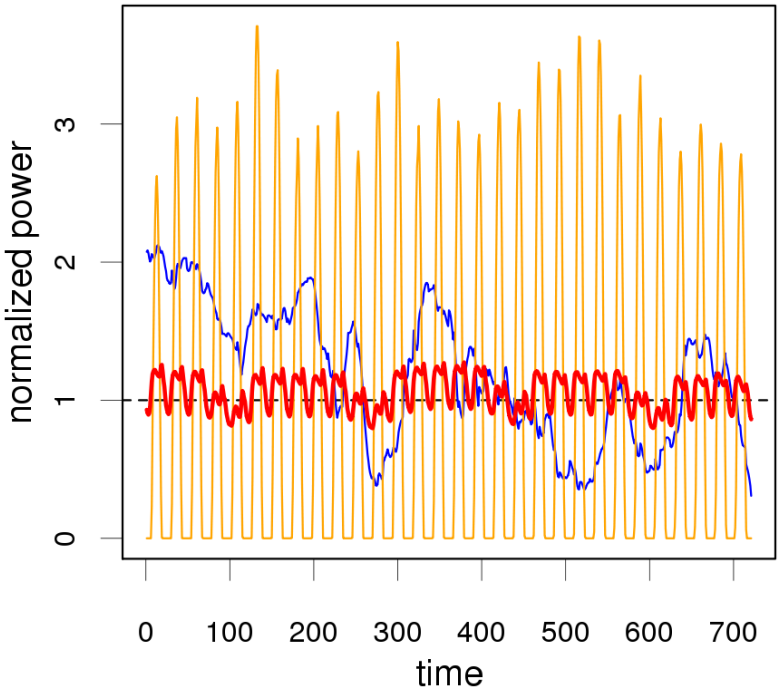
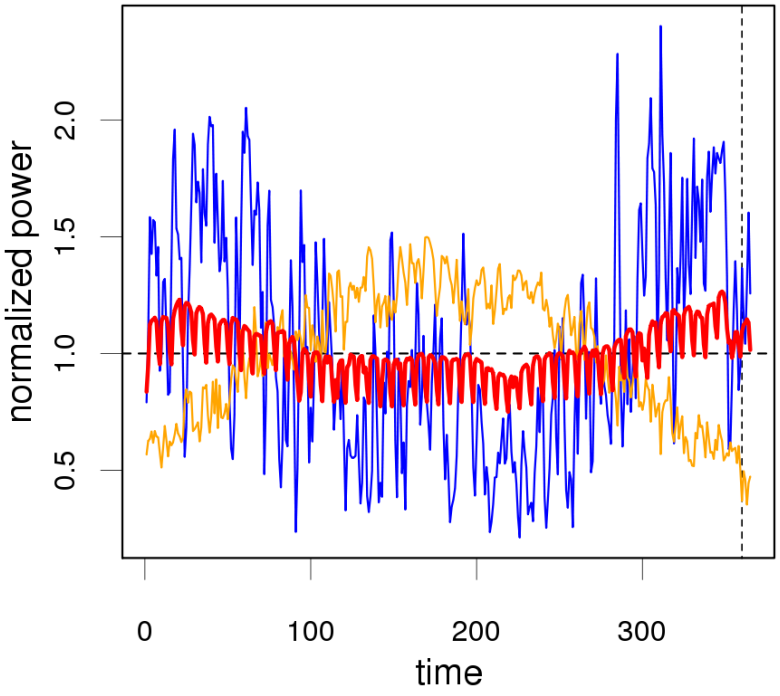
European aggregation:
Wind + Solar power generation + Load





3 TIME SCALES:

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

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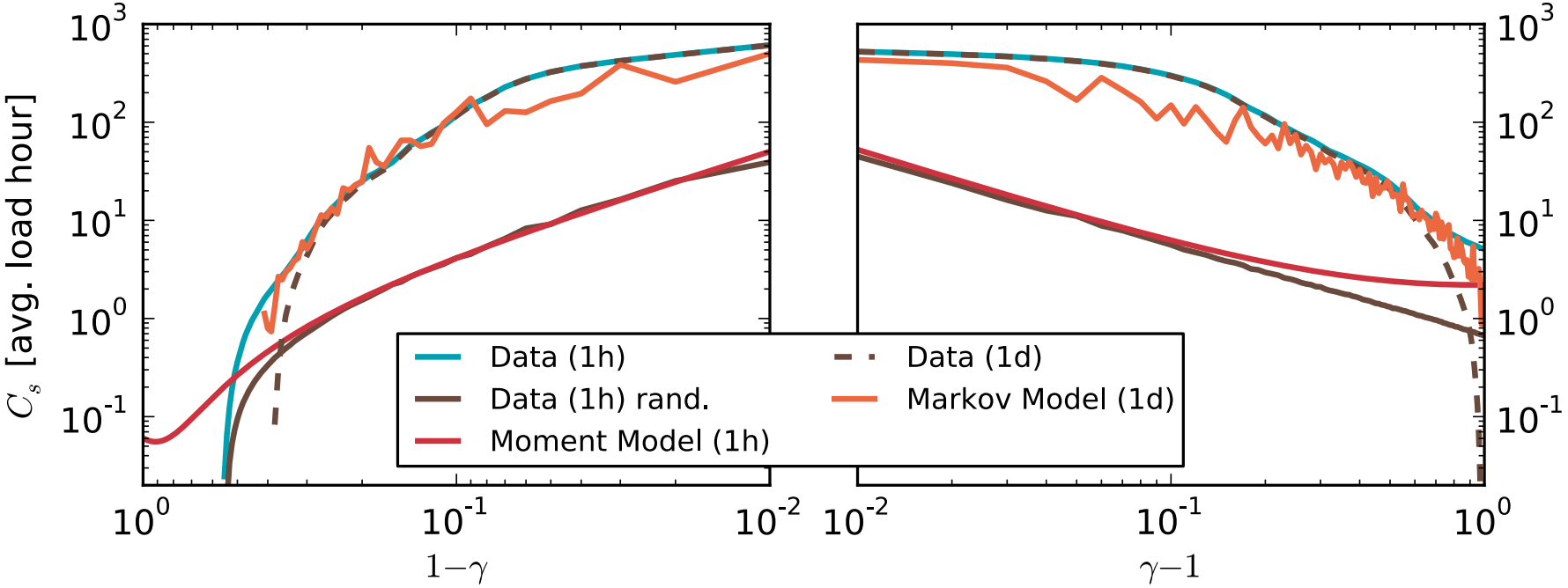
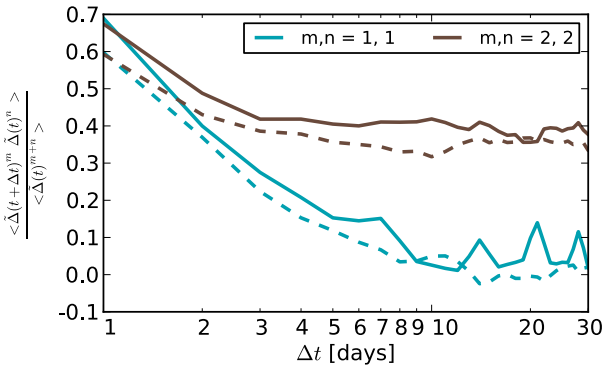
Storage Singularity



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!



Break?

Welcome back!

① only Backup

② only Storage

③ Backup + Storage

④ 2015 ←→ 2050

⑤ Transmission + Backup

⑥ Economics

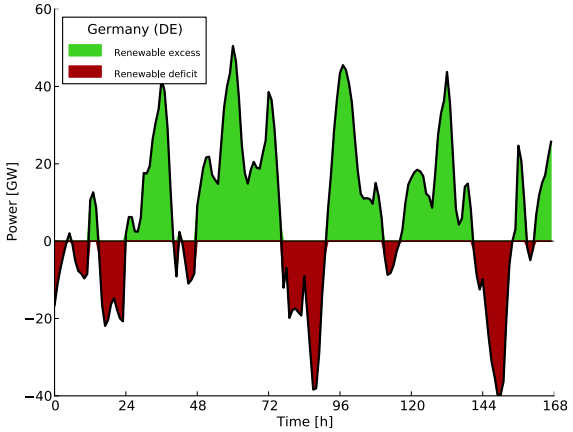
⑦ outlook: CONSENSYS

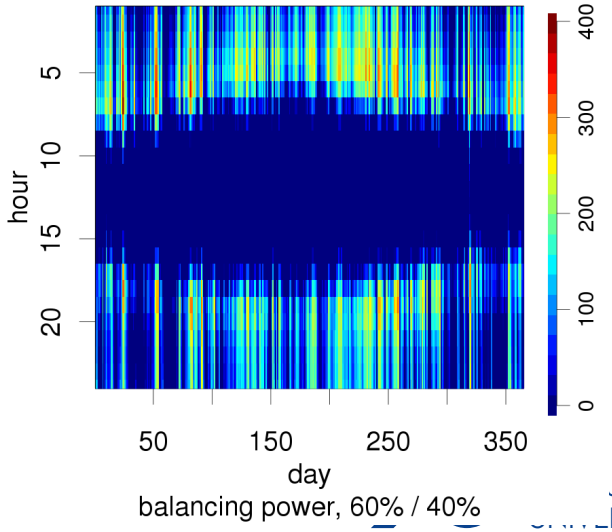
What about synergies: balancing + storage?

"hydro/bio" balancing **(150 TWh)**

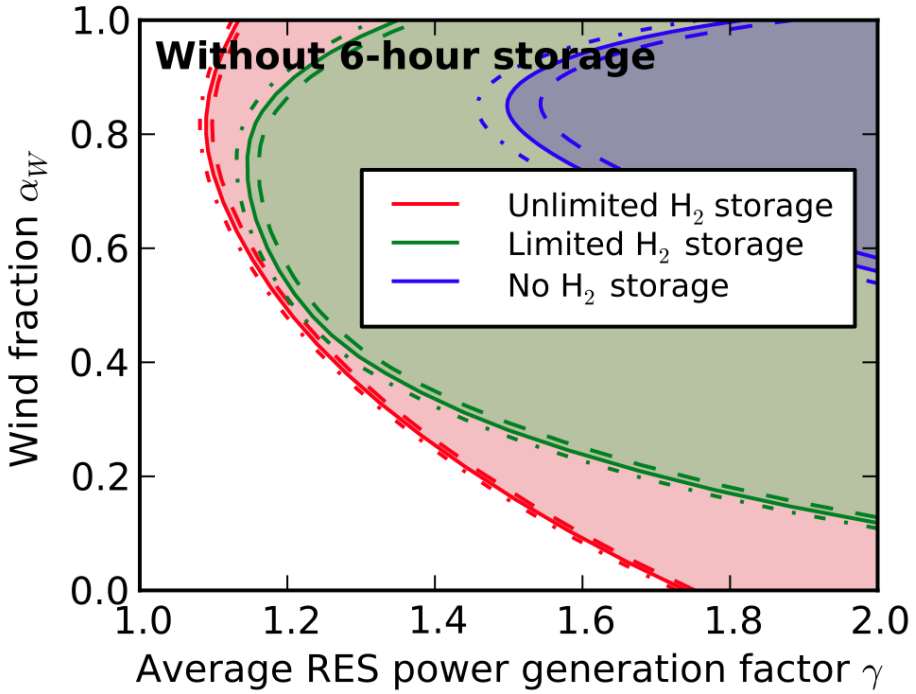
+ 6h "battery" storage **(2.2 TWh, η=1.0)**

+ seasonal H2 storage **(25 TWh, η=0.6)**





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



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

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

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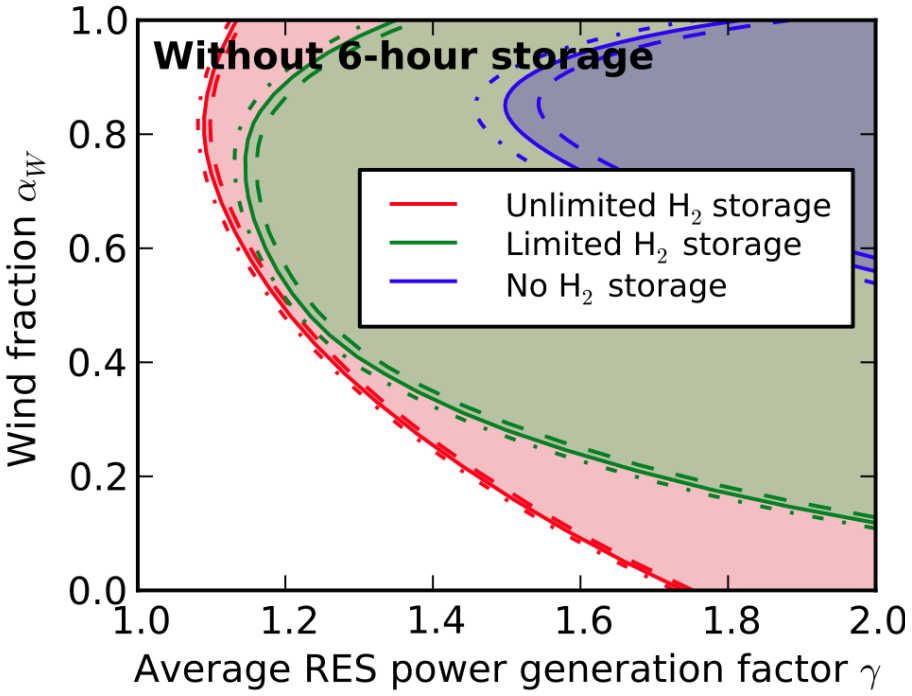
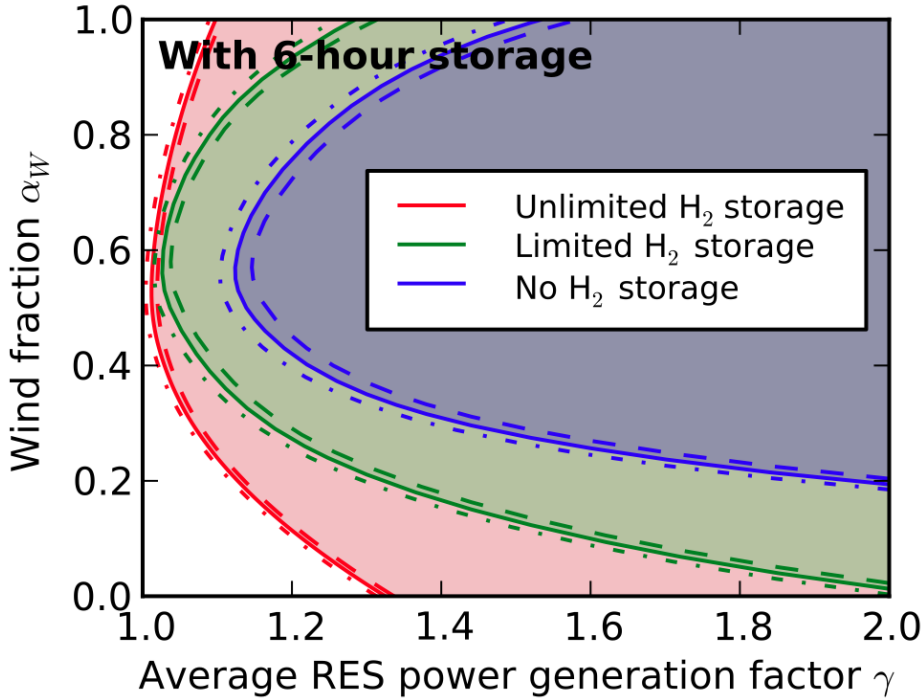
6h “battery” storage (2.2 TWh, η=1.0)
+ seasonal H2 storage (25 TWh, η=0.6)
+ “hydro/bio” balancing (150 TWh)





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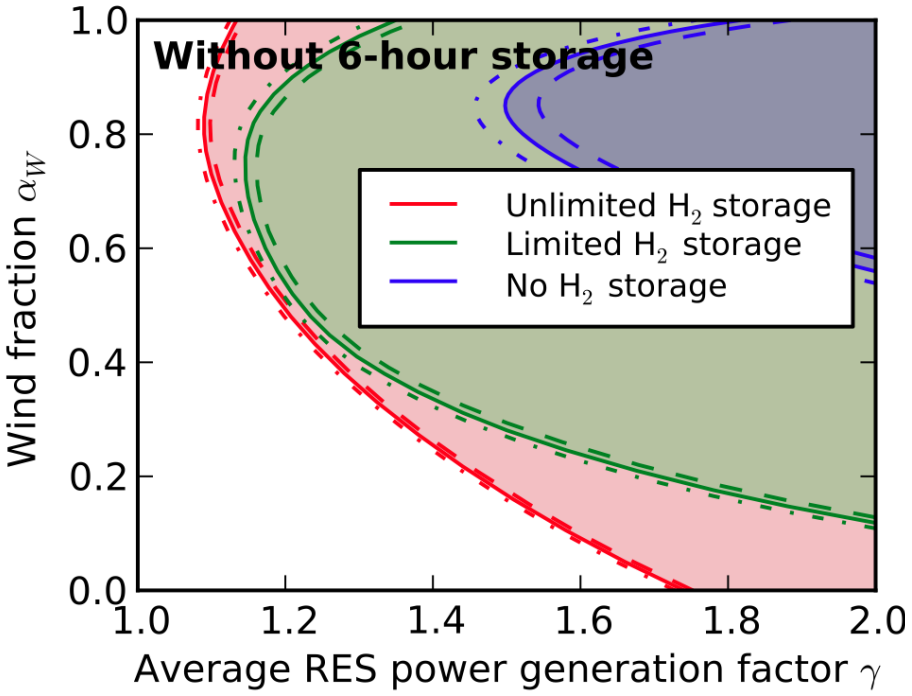
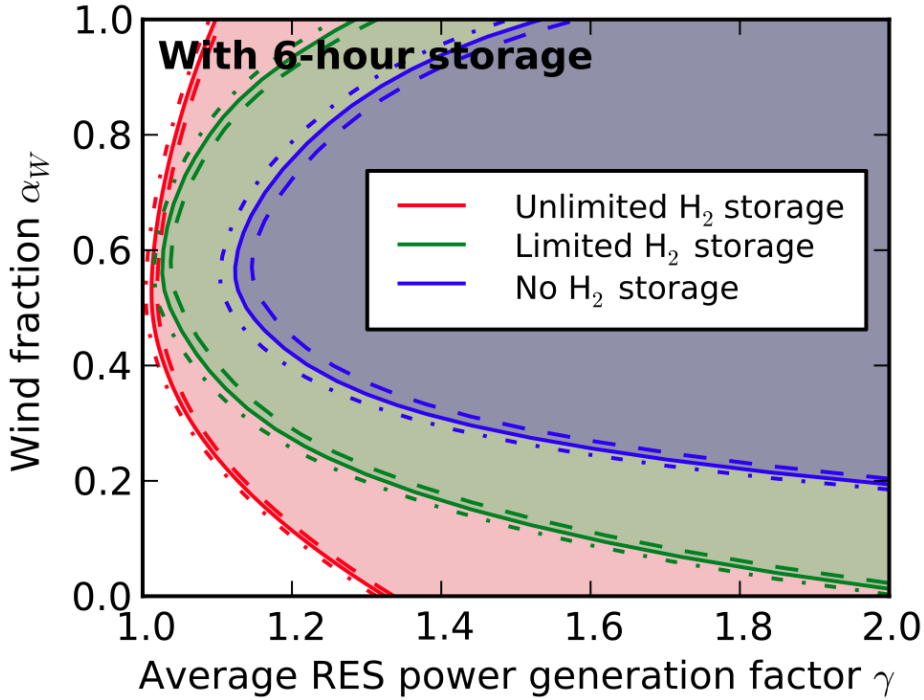
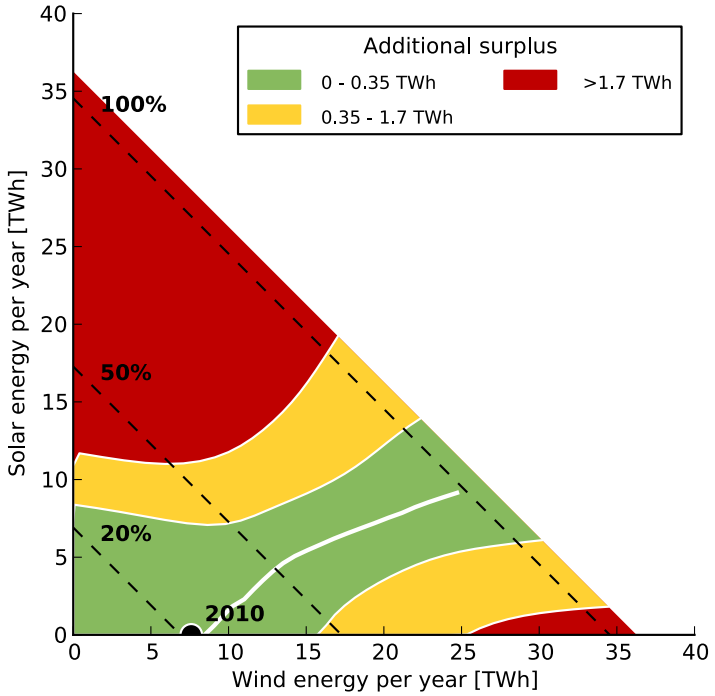
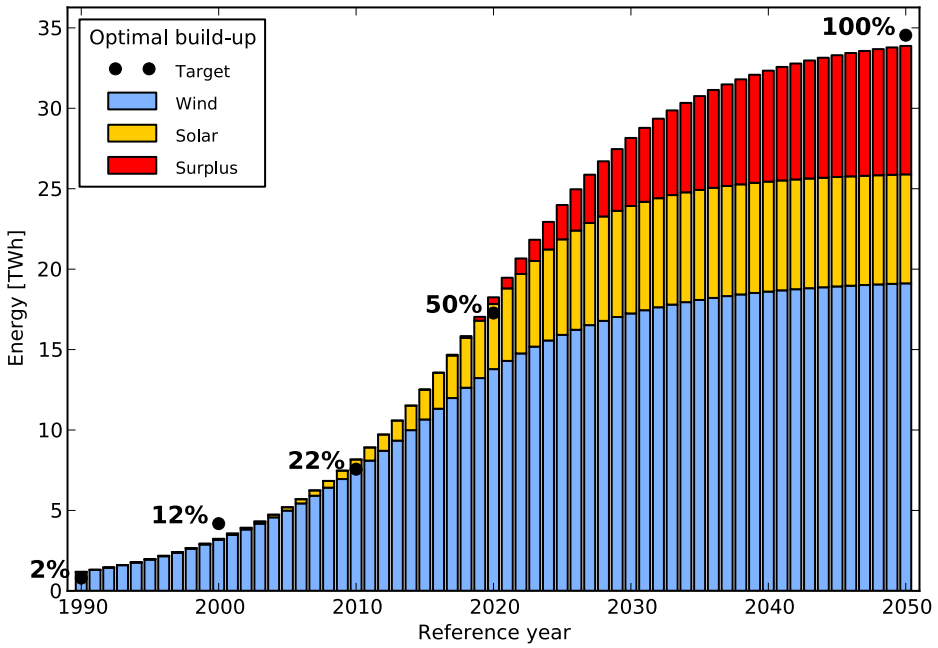




2015 ←→ 2050

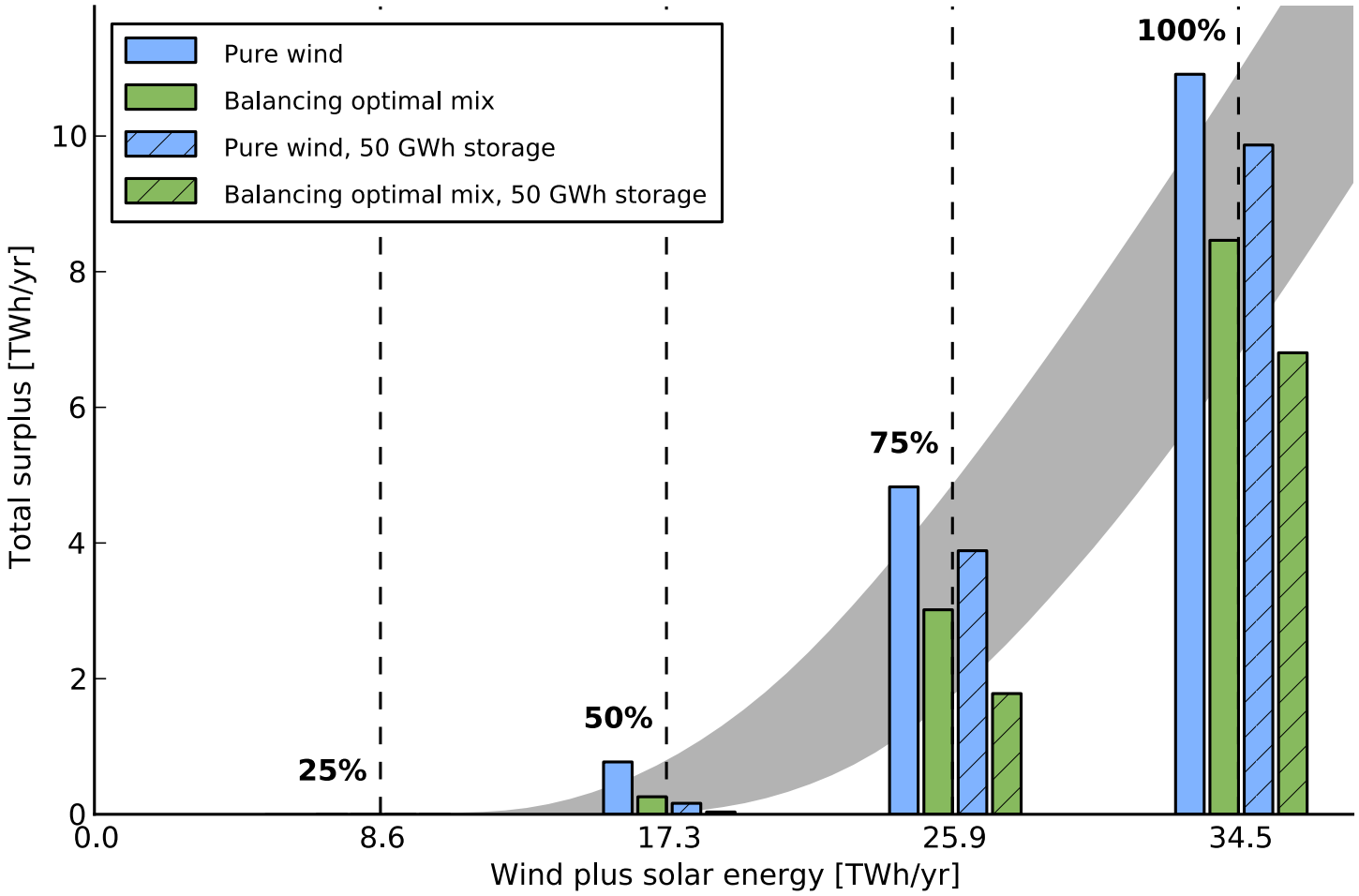
Transition 0% → 100% renewables
Case: Denmark (without storage)





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

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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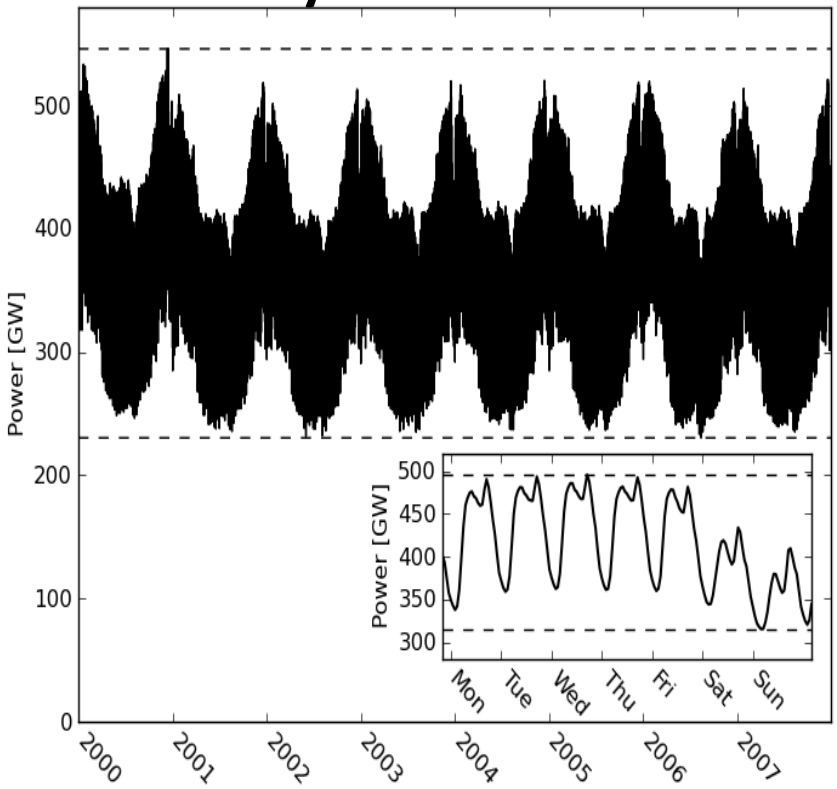
Transition 0% → 100% renewables

with highly / medium /slowly flexible conventionals

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

Derived power capacities (2007 values)

Country	Derived power capacities (GW) Seasonal	Intra-week	Intra-day	Total
Austria (AT)	4.05 (43%)	2.29 (24%)	3.08 (33%)	9.42 (100%)
Belgium (BE)	7.21 (50%)	3.64 (25%)	3.60 (25%)	14.45 (100%)
Bulgaria (BG)	4.27 (48%)	2.13 (24%)	2.57 (29%)	8.98 (100%)
Bosnia and Herzegovina (BA)	2.75 (54%)	0.58 (12%)	1.72 (34%)	5.05 (100%)
Czech Republic (CZ)	5.45 (53%)	2.54 (25%)	2.36 (23%)	10.35 (100%)
Switzerland (CH)	4.47 (54%)	1.73 (21%)	2.01 (24%)	8.21 (100%)
Germany (DE)	34.15 (41%)	23.46 (28%)	25.80 (31%)	83.41 (100%)
Denmark (DK)	2.50 (37%)	1.56 (23%)	2.67 (40%)	6.73 (100%)
Spain (ES)	15.88 (38%)	12.44 (30%)	13.70 (33%)	42.01 (100%)
France (FR)	56.80 (60%)	17.36 (18%)	19.87 (21%)	94.03 (100%)
Finland (FI)	8.46 (59%)	3.17 (22%)	2.69 (19%)	14.31 (100%)
Great Britain (GB)	29.93 (48%)			
Greece (GR)	4.80 (45%			
Hungary (HU)	3.39 (51%			

Minimum peak capacities (Total):

- **Intra-day: 165 GW (29%)**
- **Intra-week: 133 GW (23%)**
- **Seasonal: 273 GW (48%)**

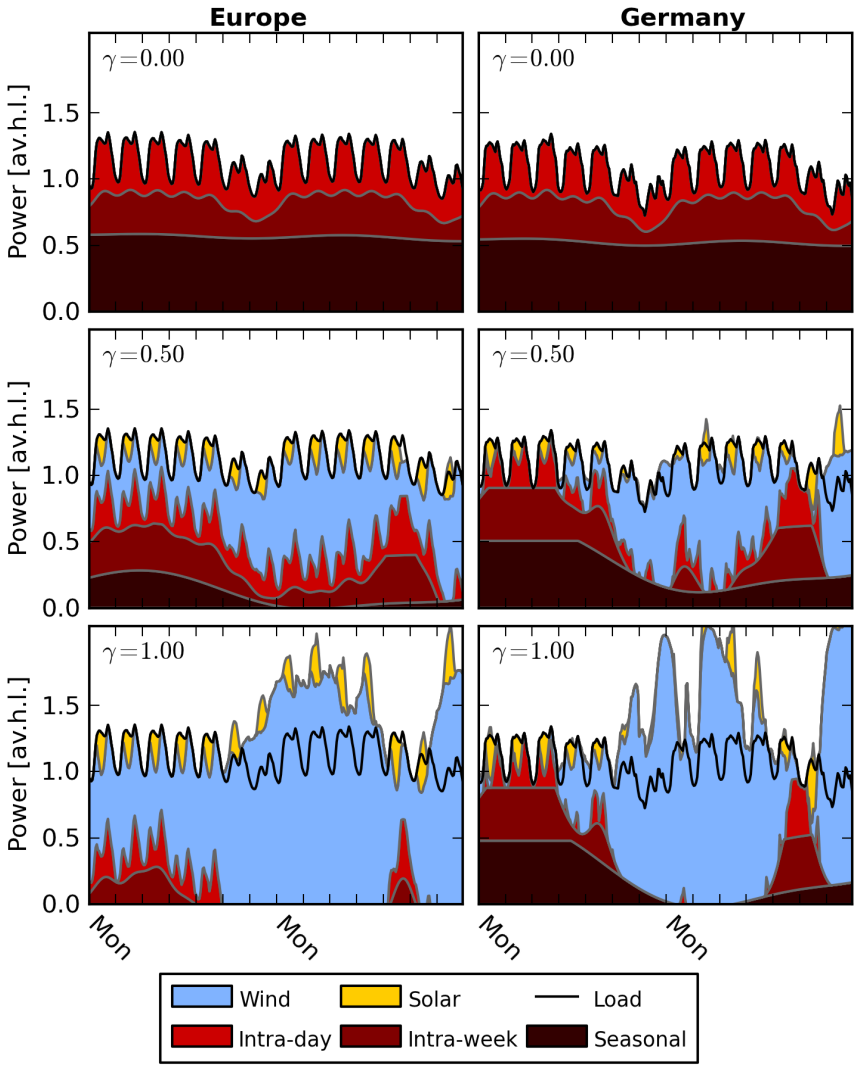
Power dispatch

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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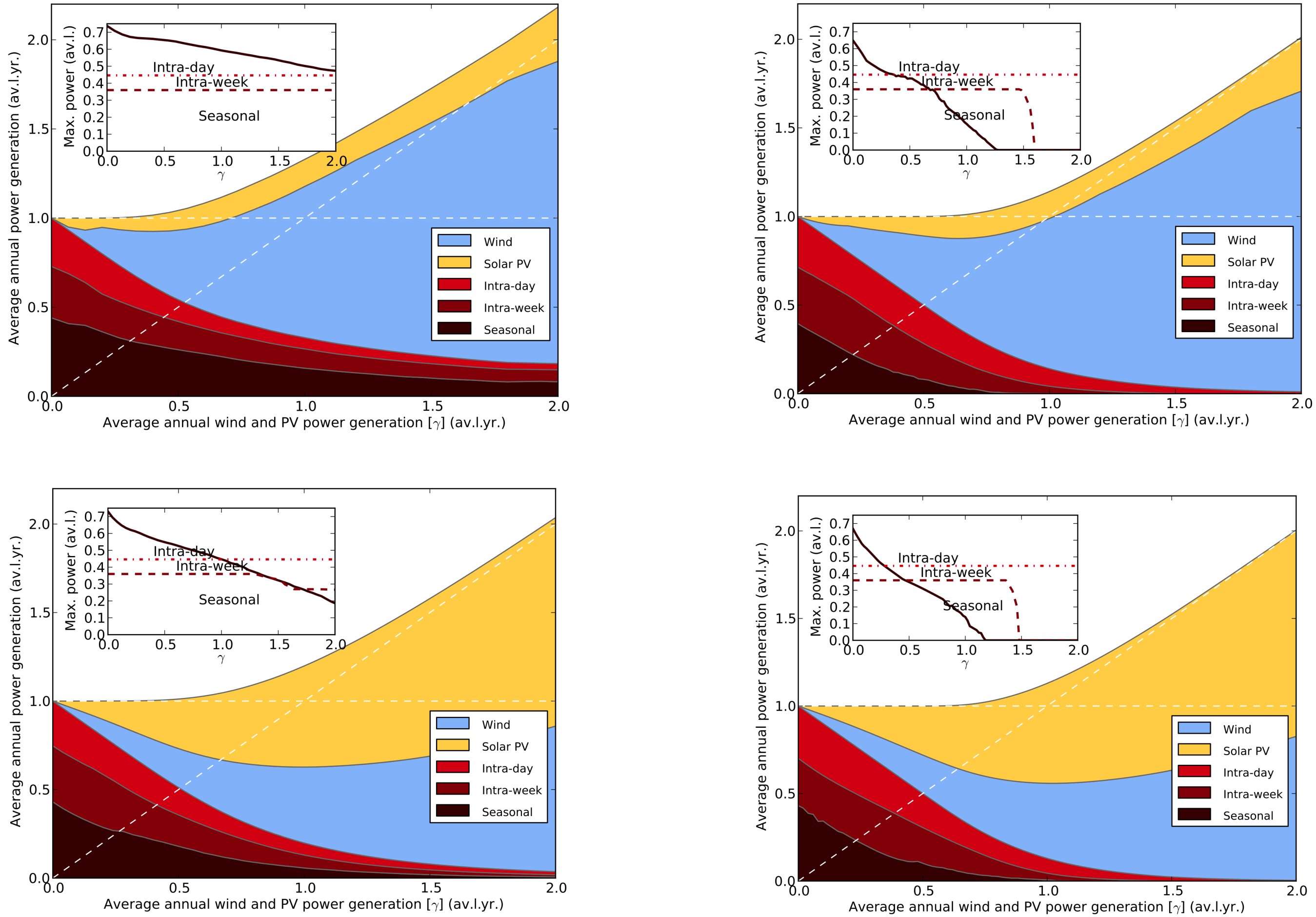
Transition: 0% → 100% renewables

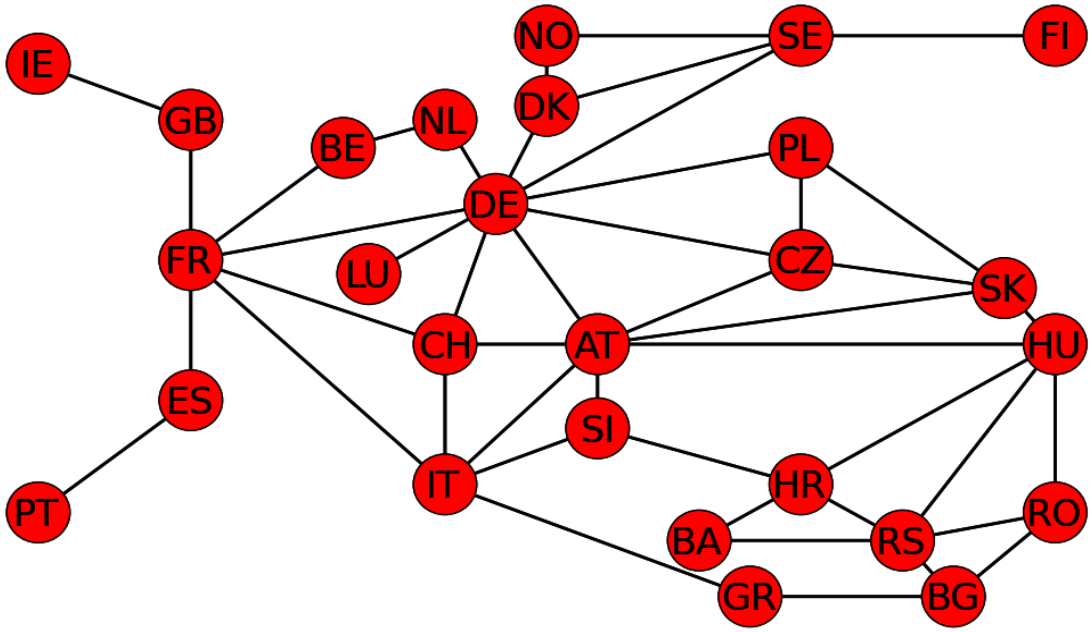
no … cross-border transmission … yes

yes…short-term storage…no



PRELIMINARY

How much transmission?



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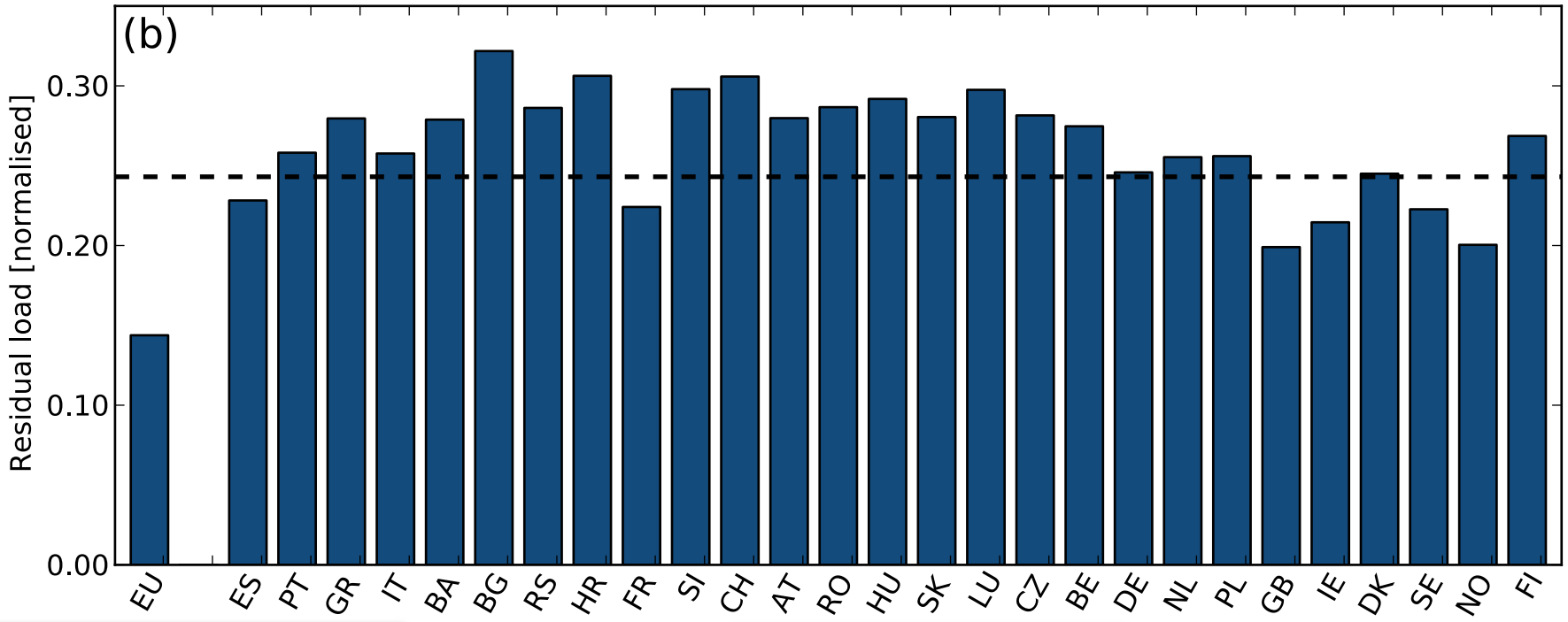
transmission calculation without transmission

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

minimum backup energy at optimal wind / solar mix



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

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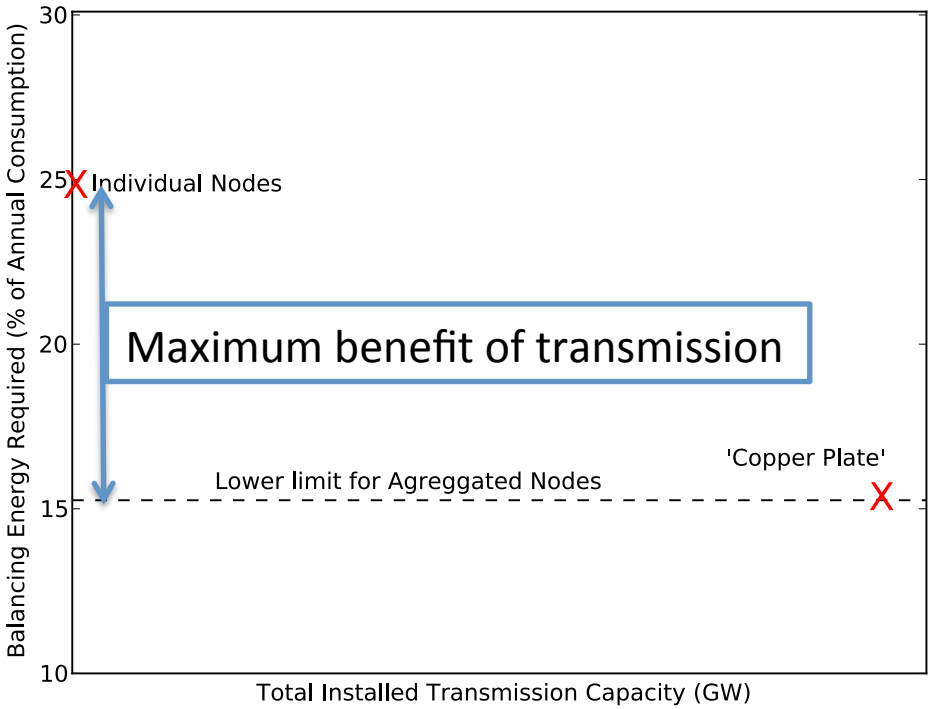
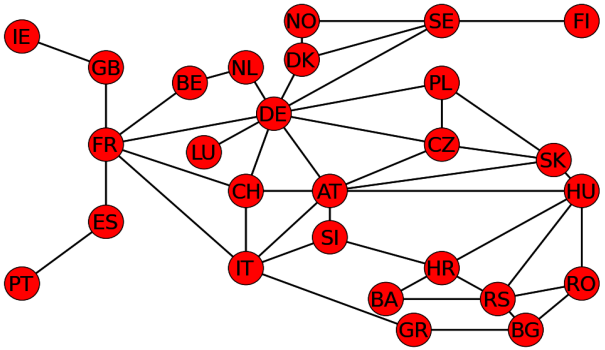
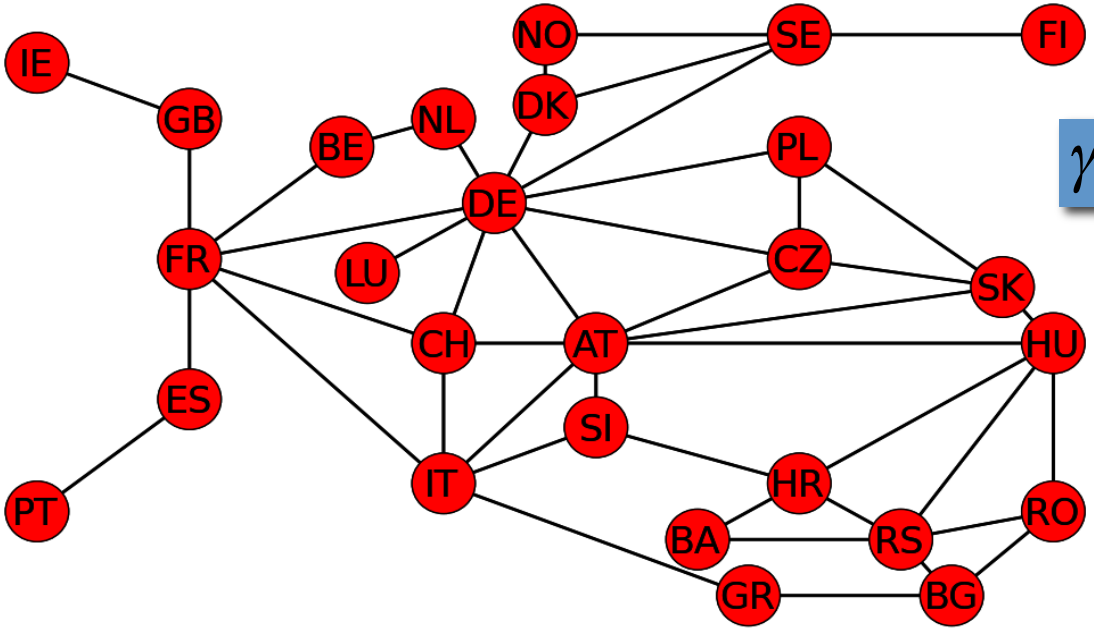
transmission calculation without transmission





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.

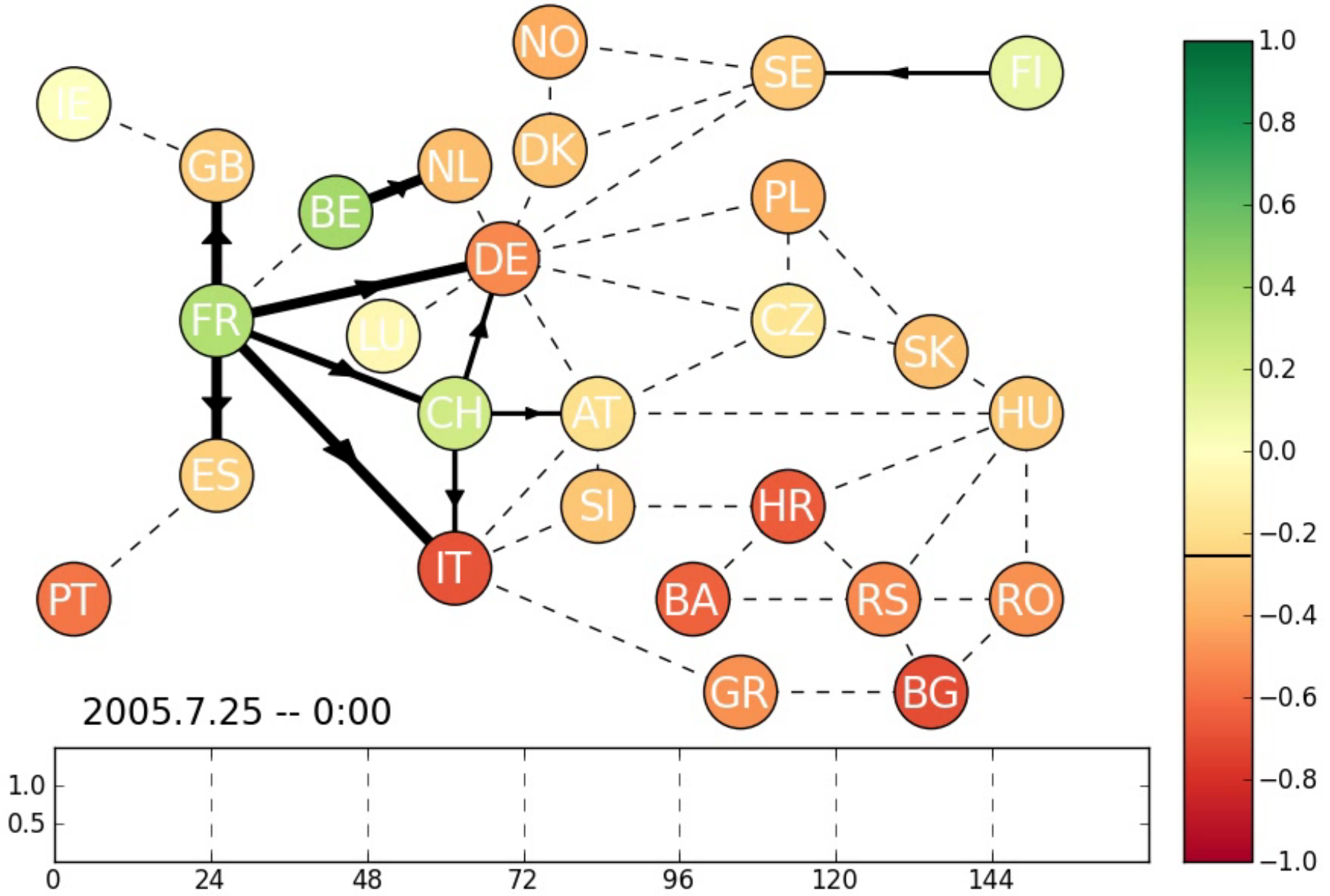
How much transmission?



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

$$\min \sum_n B_n$$

$$\min \sum_l F_l^2$$



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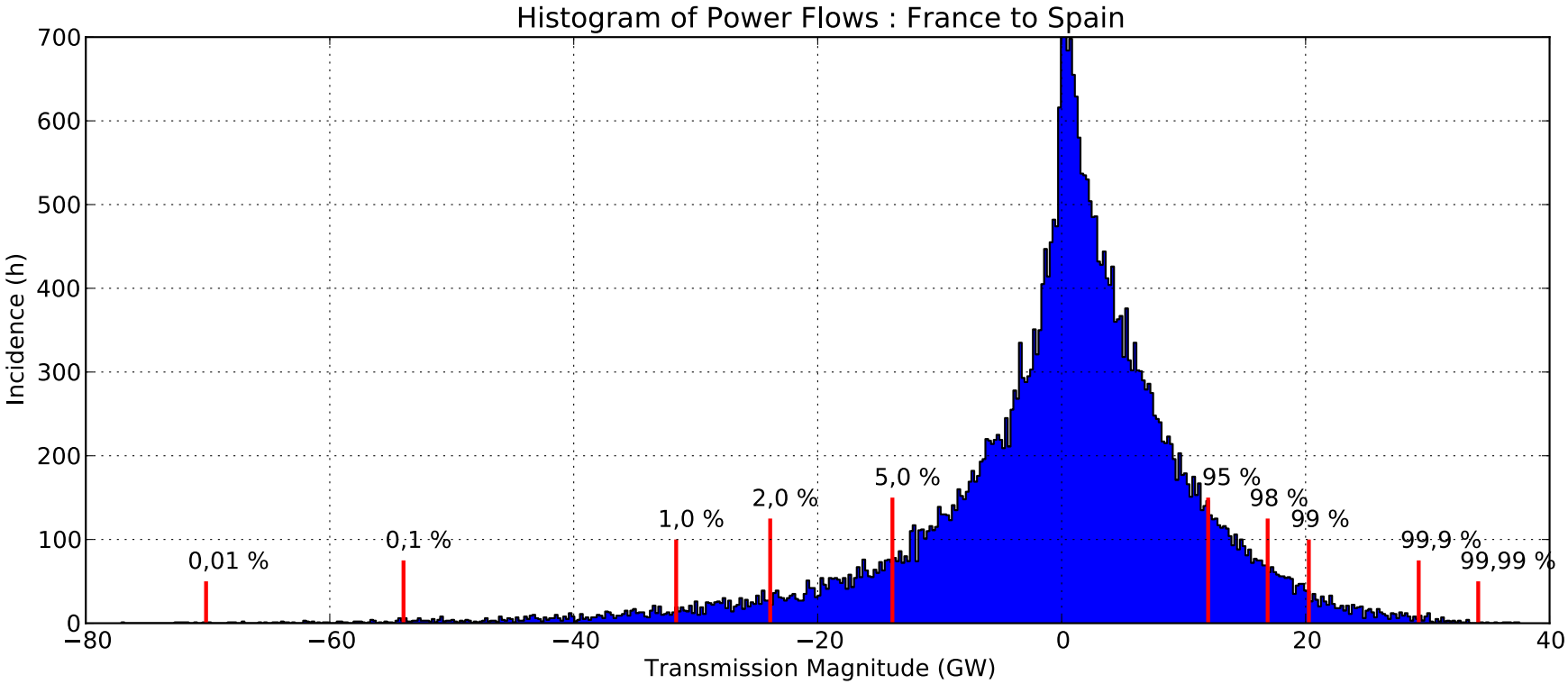

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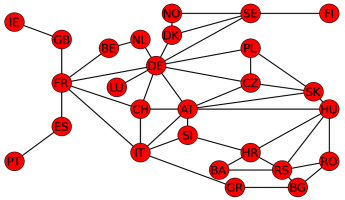
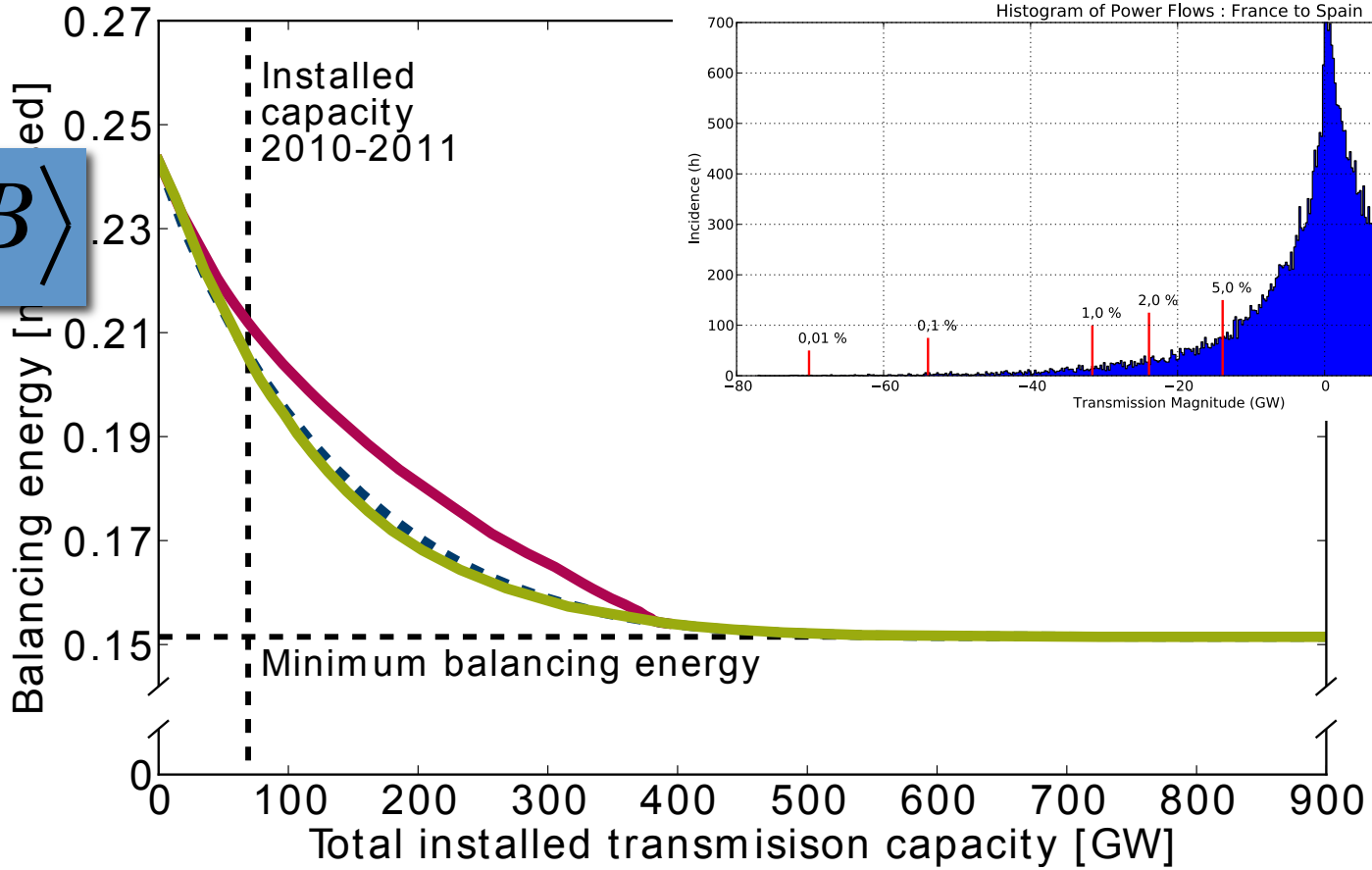
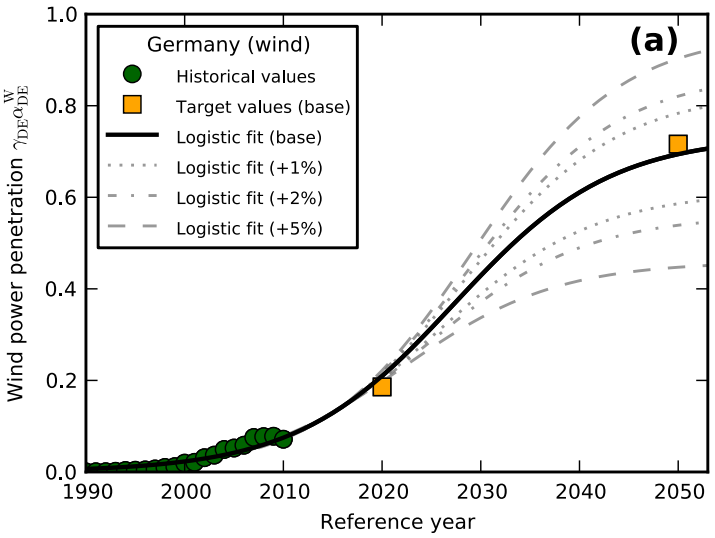
Backup vs. Transmission

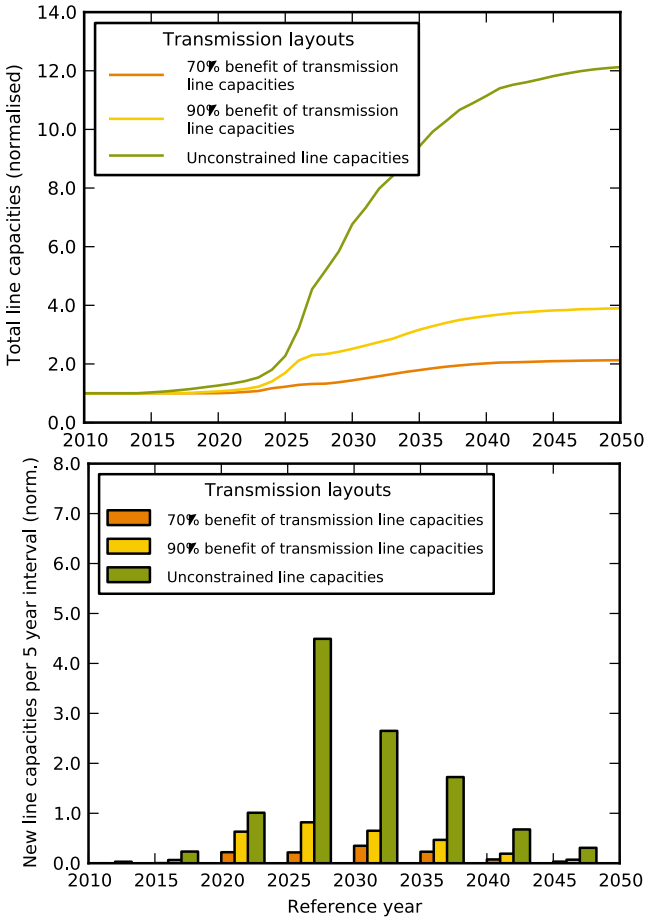


$\langle B \rangle$



Pan-European Transmission 2014 → 2050





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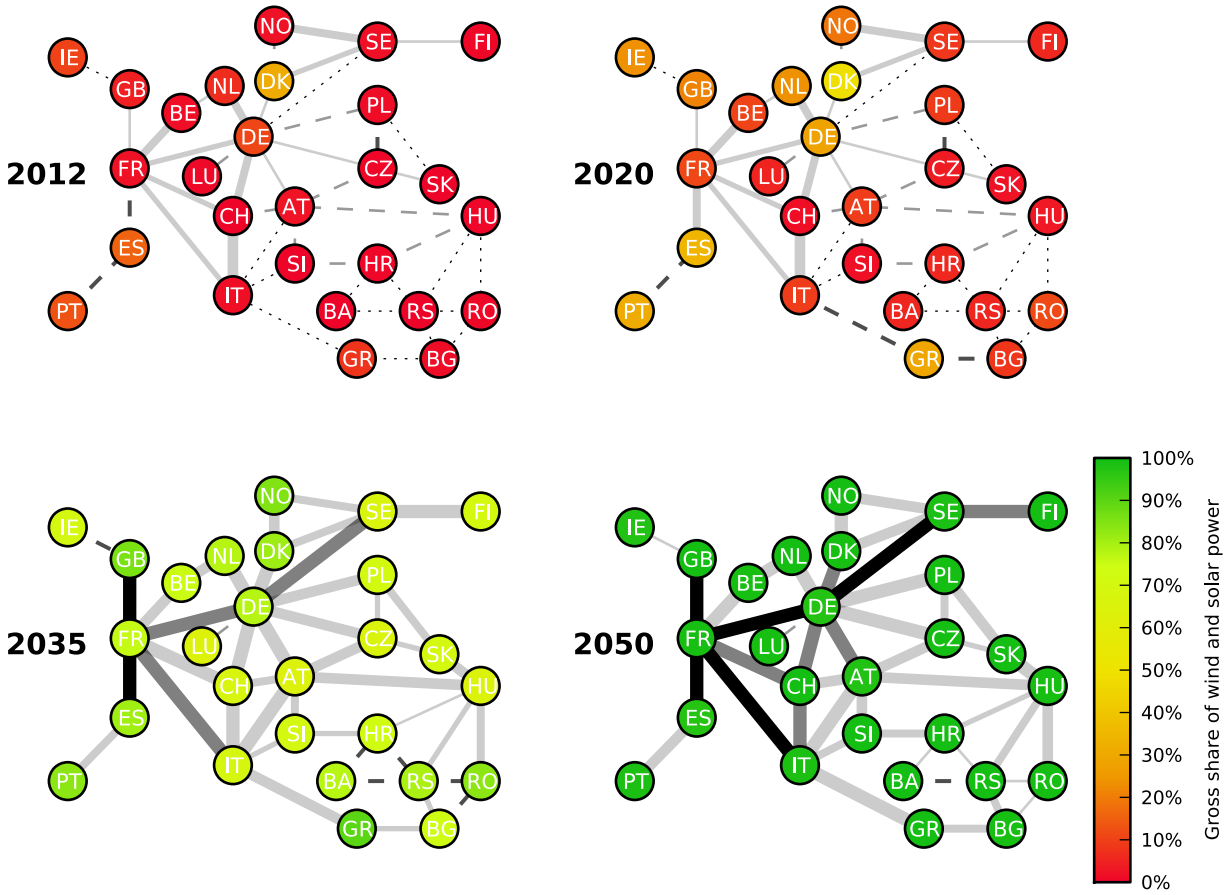
Pan-European Transmission 2014 → 2050



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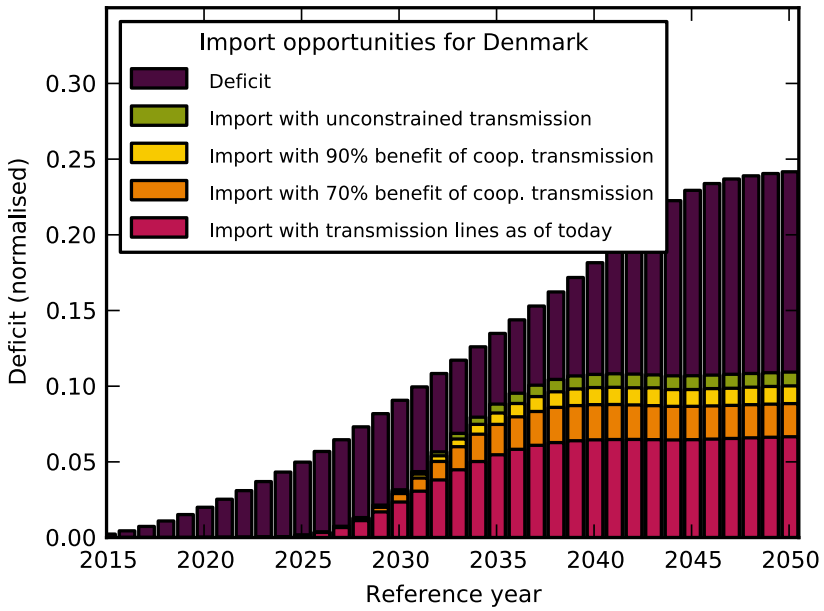
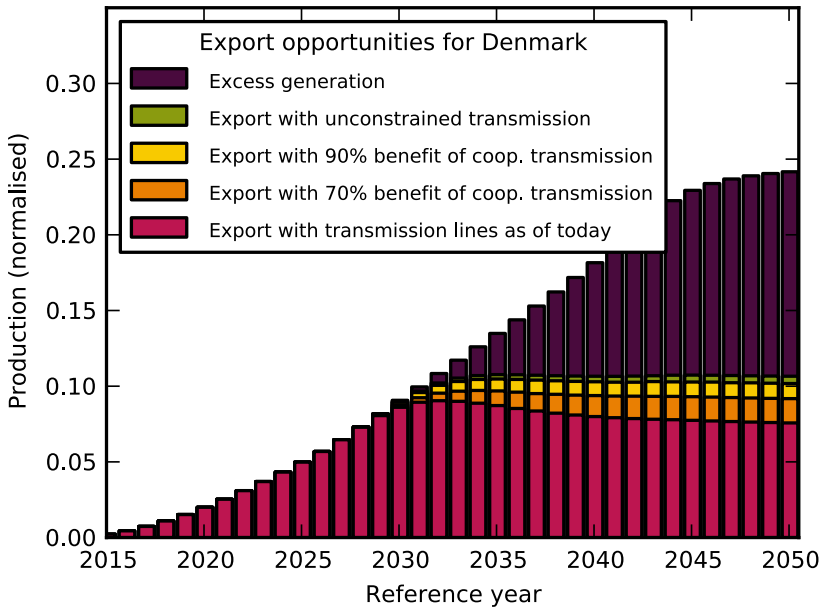
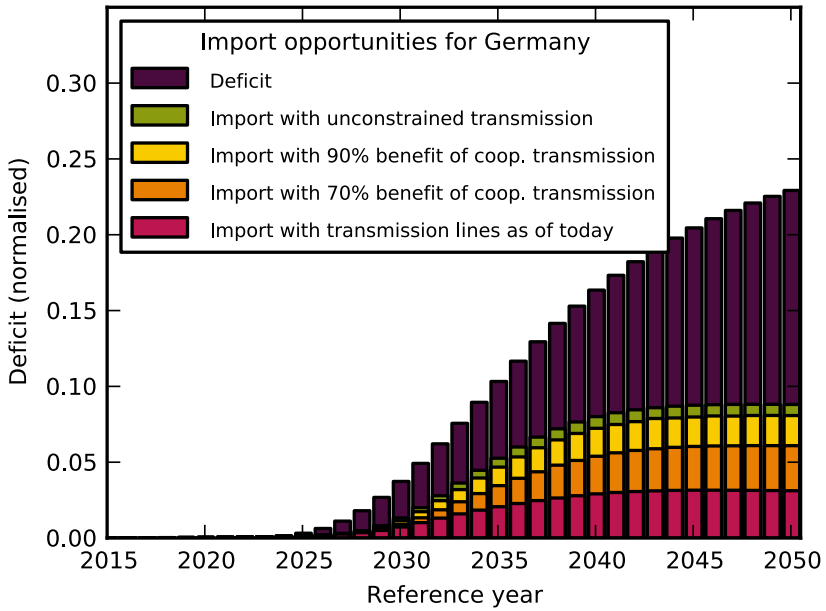
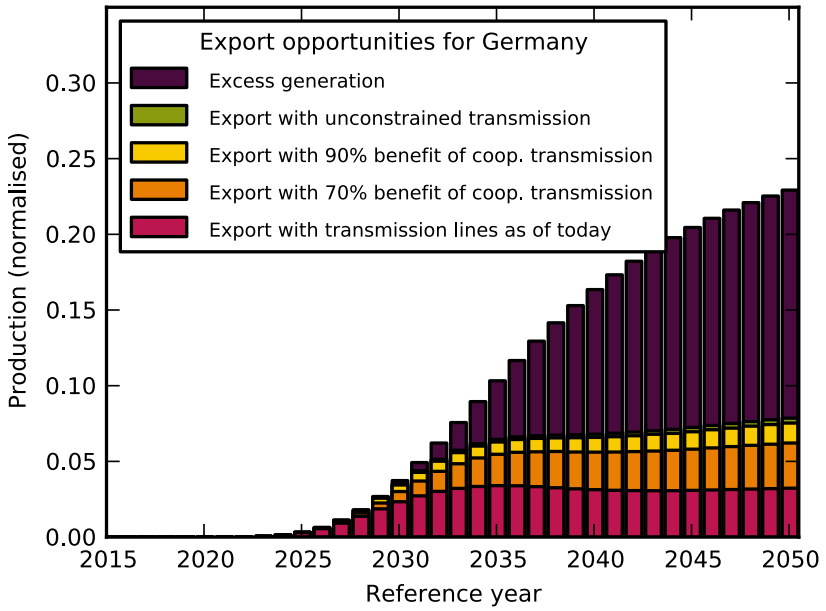
Denmark 2014 → 2050:
Import / Export opportunities



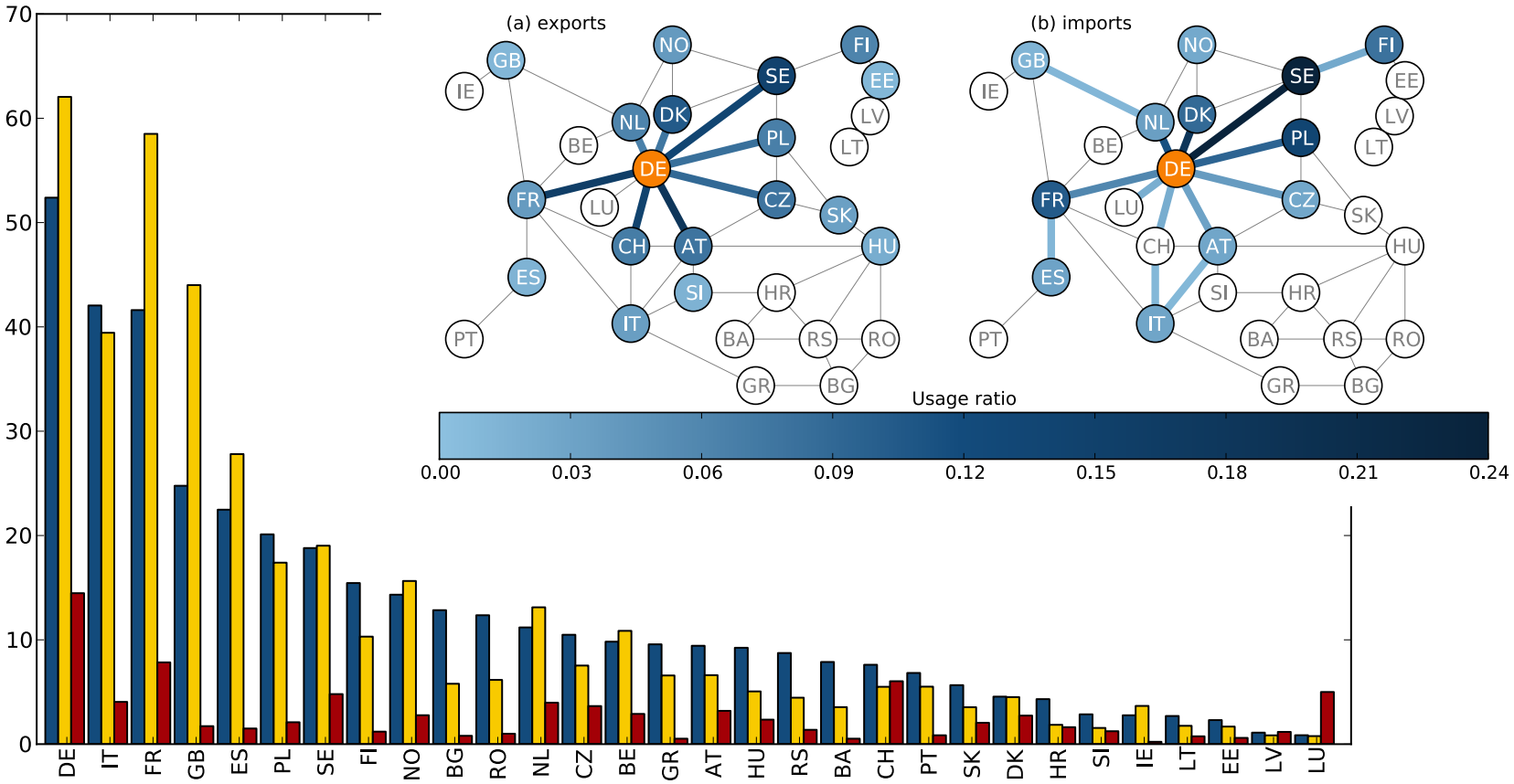


Germany 2014 → 2050:
Import / Export opportunities





Who pays for the transmission capacity?

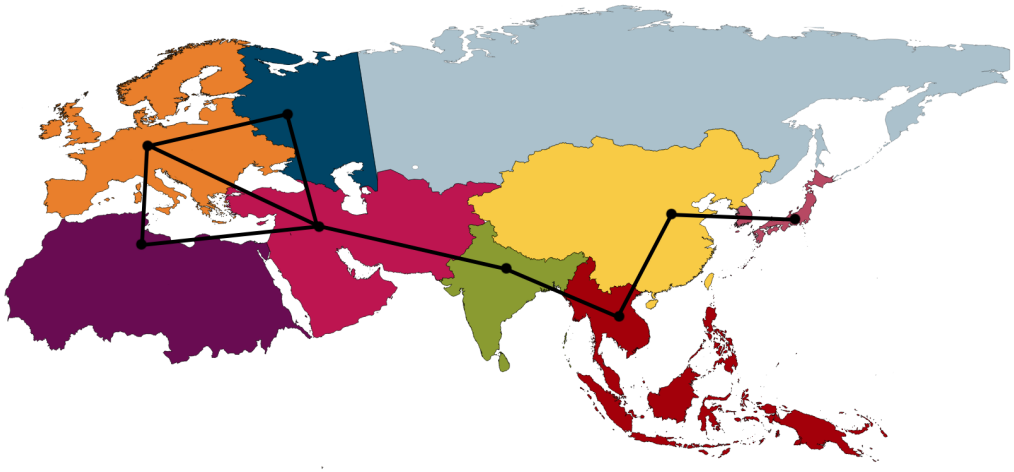


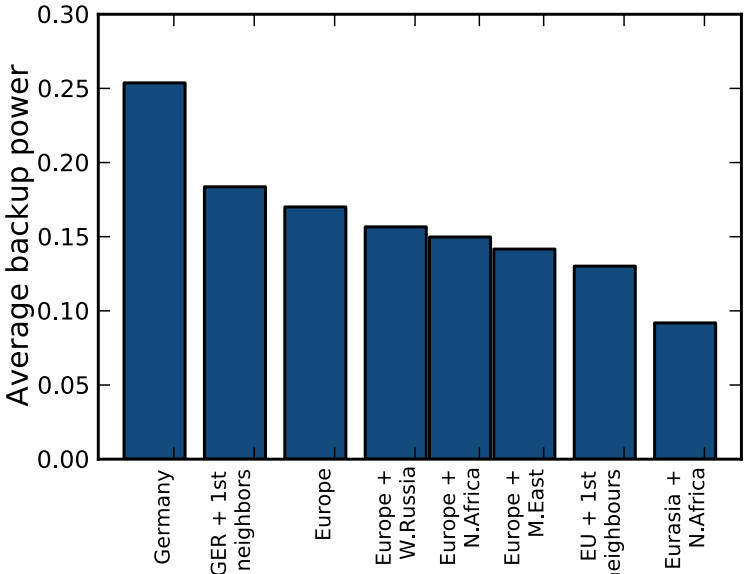
$$\sum_l \frac{\langle e_{nl} \rangle + \langle i_{ln} \rangle}{2\langle |f_l| \rangle} T_l^{2050}$$

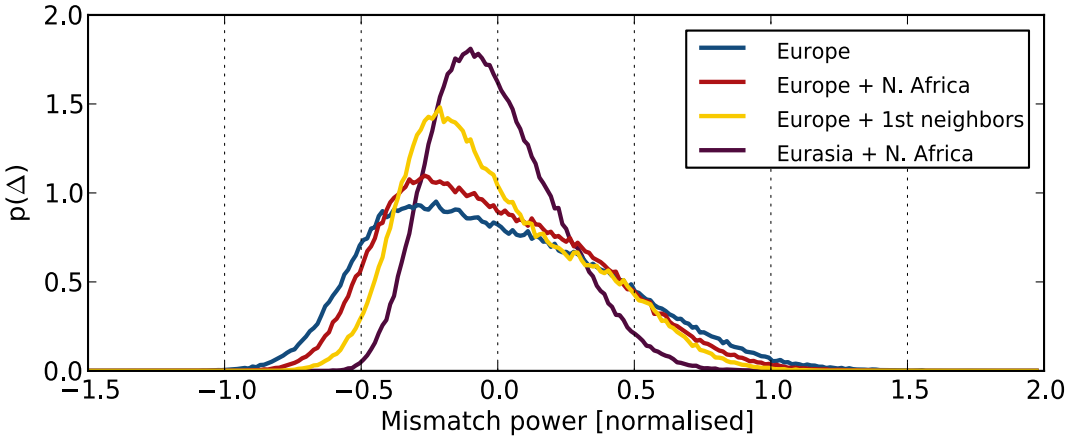
$$\left(\sum_l T_l^{2050}\right) \frac{\langle L_n \rangle}{\sum_m \langle L_m \rangle}$$

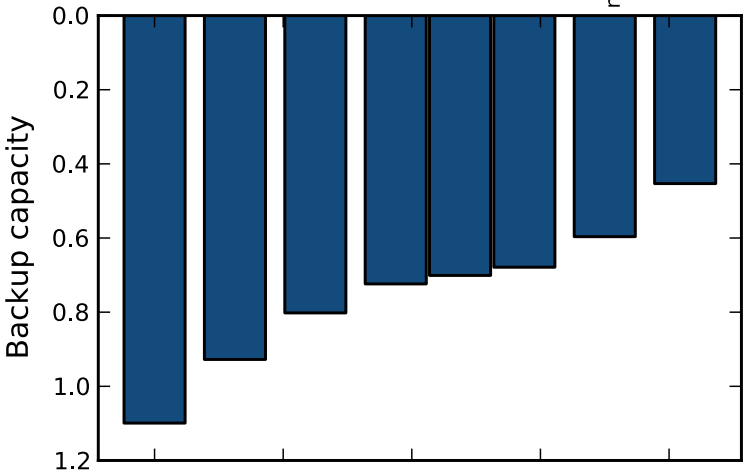
$$\sum_{l(n)} \frac{T_l^{today}}{2}$$

Transmission beyond EU









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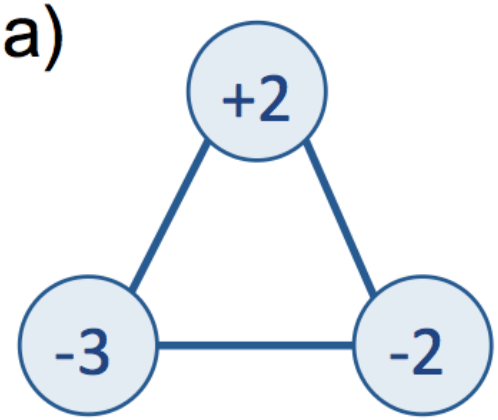
Levelized Cost of SYSTEM Energy

Coupling schemes between transmission and backup

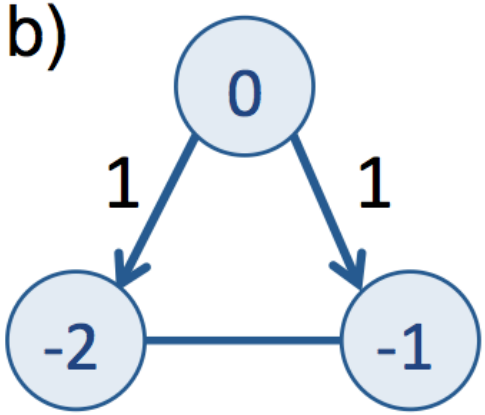
$$\Delta_n(t) = G_n^{RES}(t) - L_n(t) - T_n(t)$$

a)



$$T_n(t) = 0$$

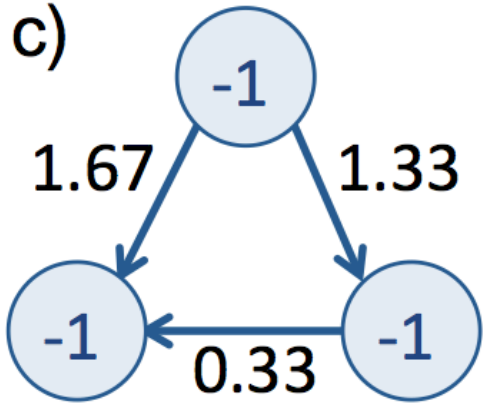
b)



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

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

c)



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

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

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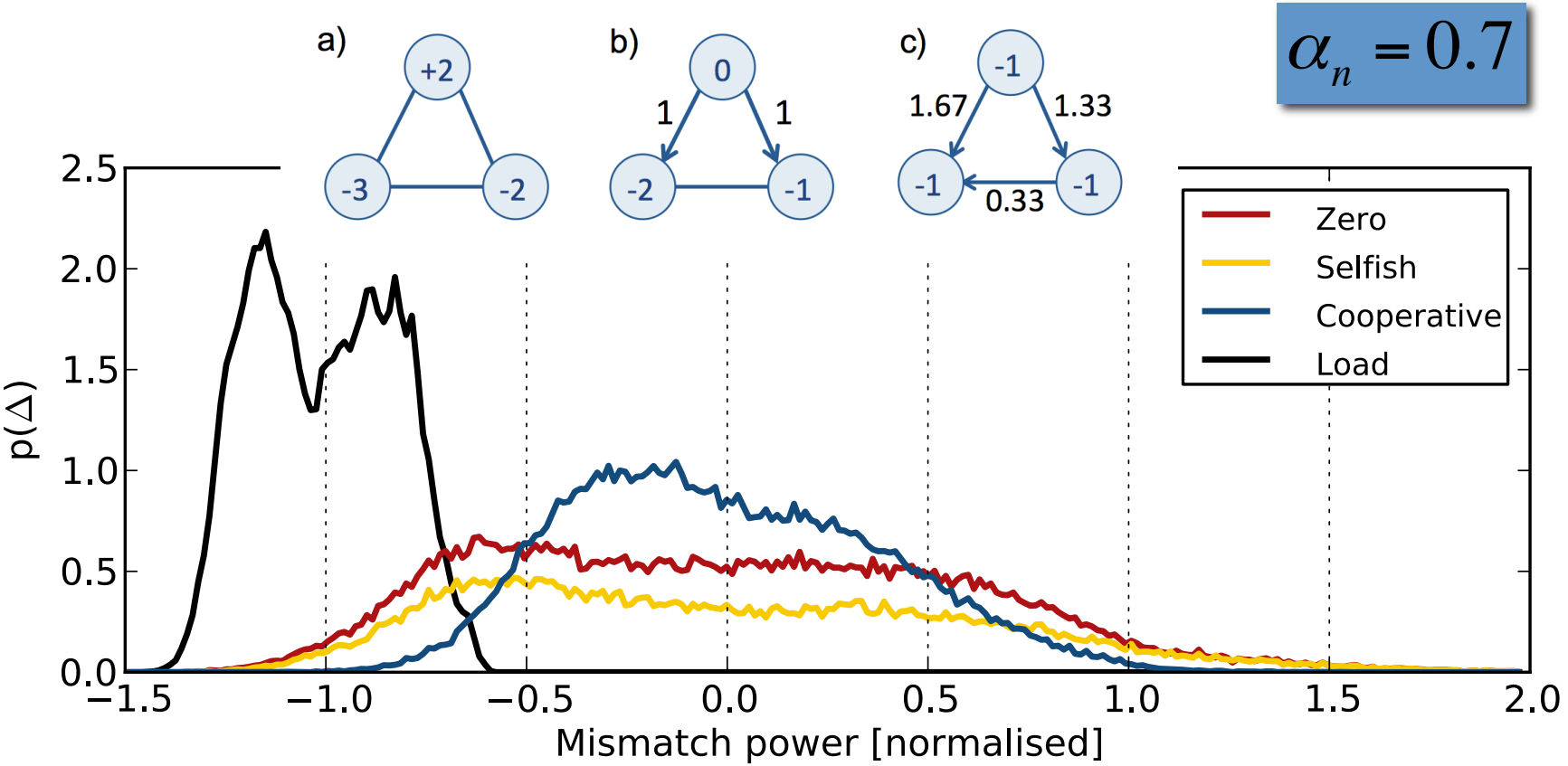
Mismatch distribution (Germany)

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

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

$$\alpha_n = 0.7$$



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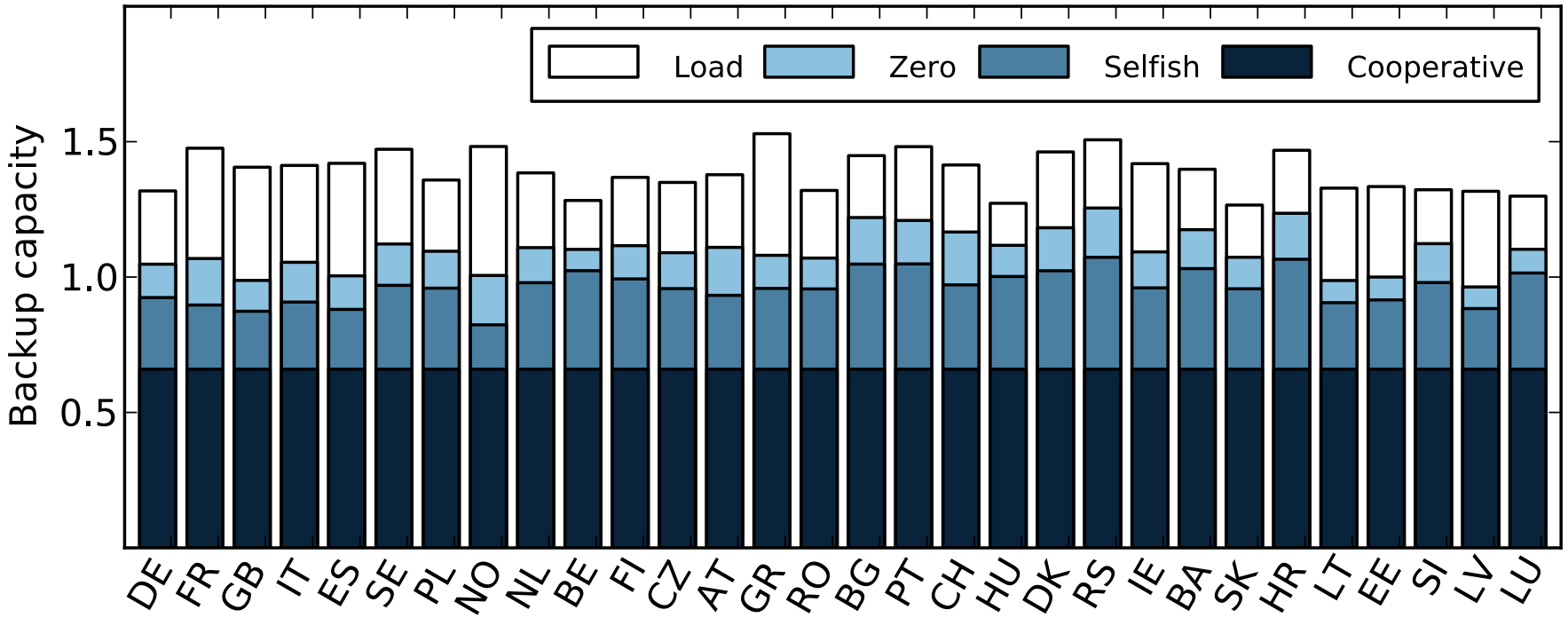
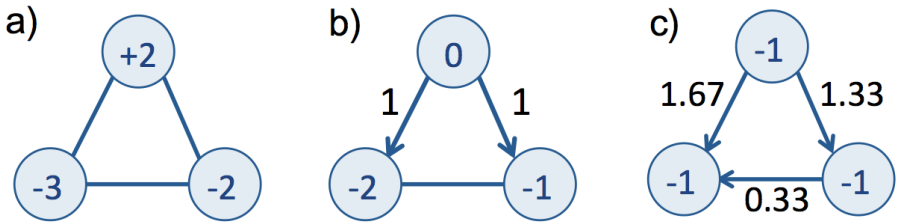
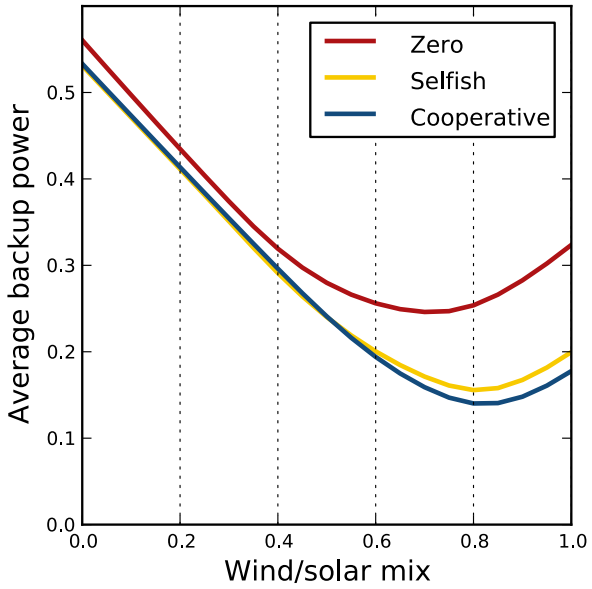
Who pays for the backup capacity?

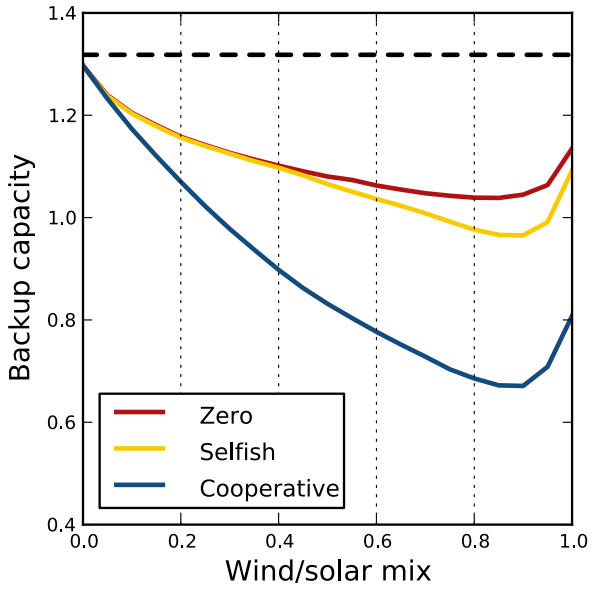




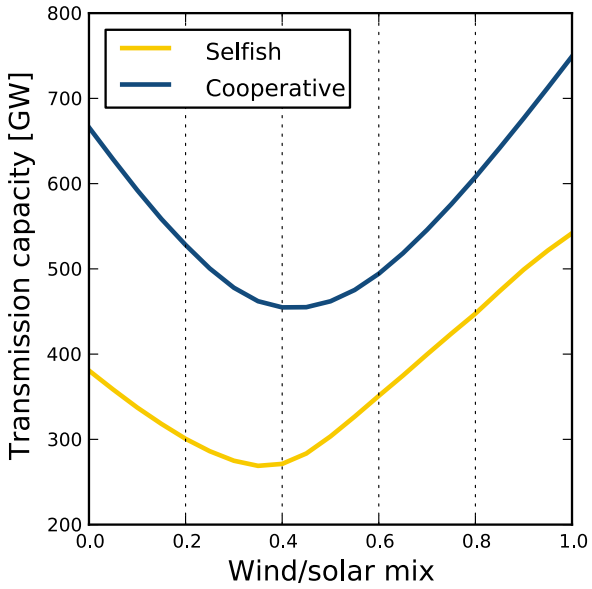
backup energy



backup capacity

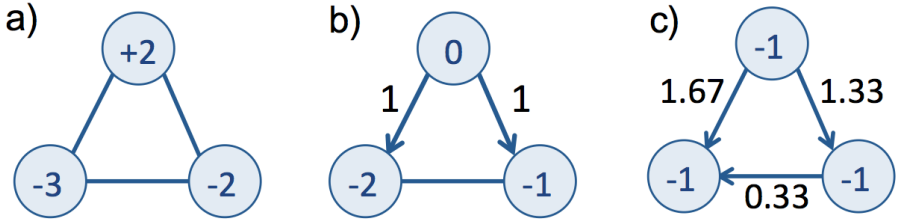


transmission capacity



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

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



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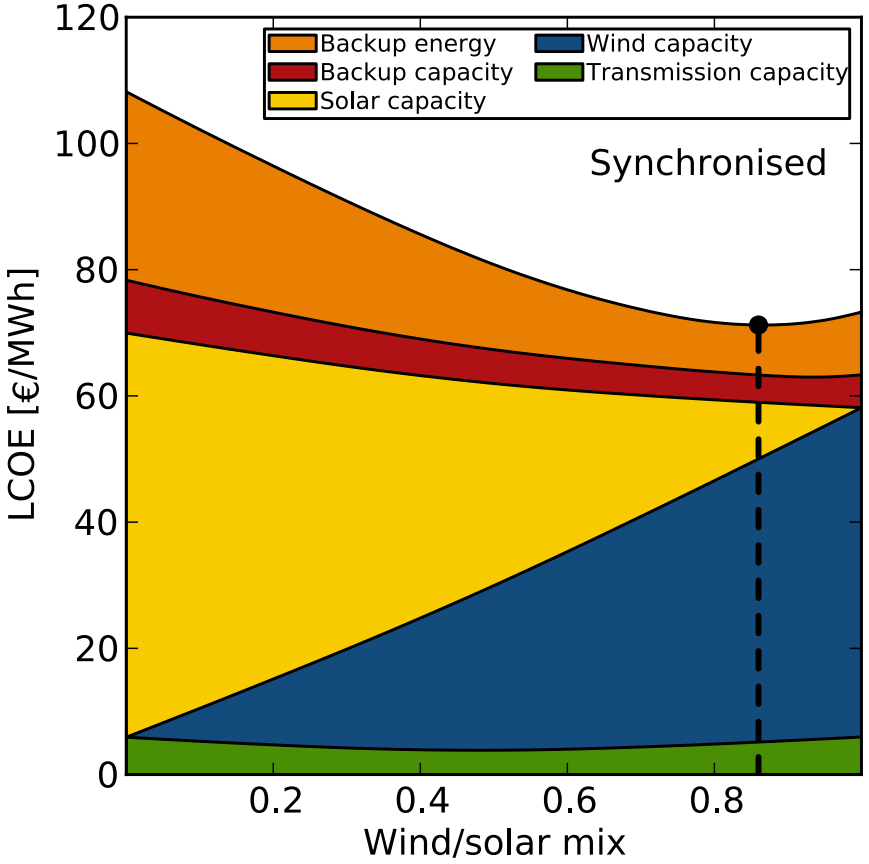
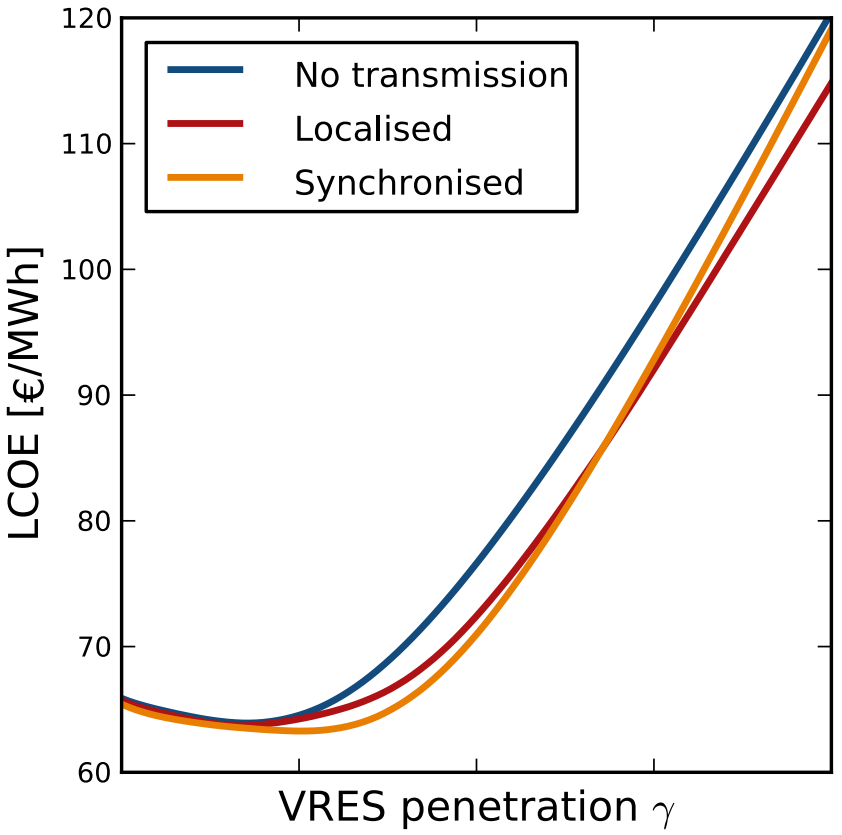
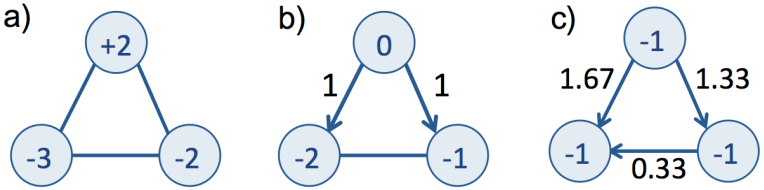
Levelized Cost of SYSTEM Energy





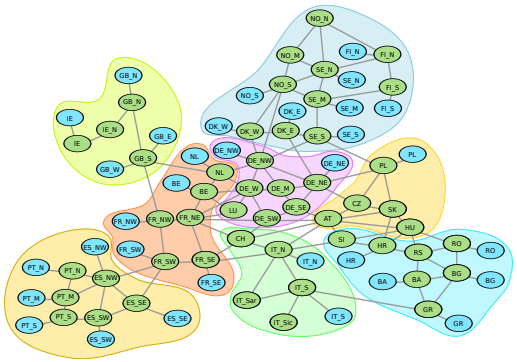
$$\left\langle G_n^{RES} \right\rangle = \left\langle L_n \right\rangle$$



OUTLOOK

Fundamental Research on Renewable Energy Systems

at the interface between engineering + mathematics + physics



SOME FUNDAMENTAL CHALLENGES:

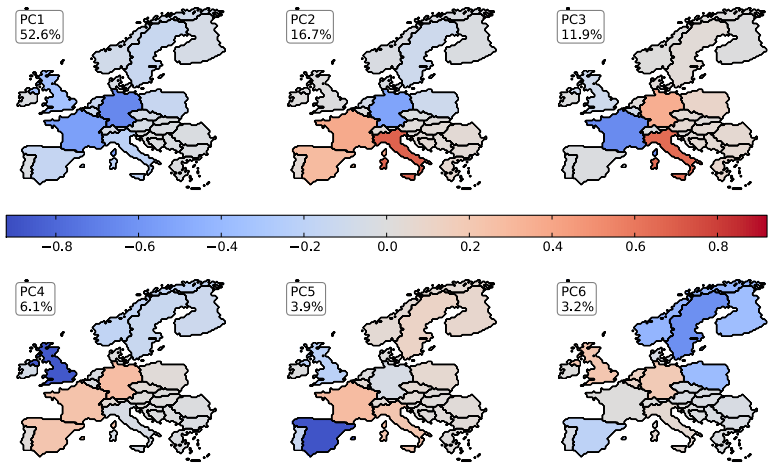
storage phase transition,

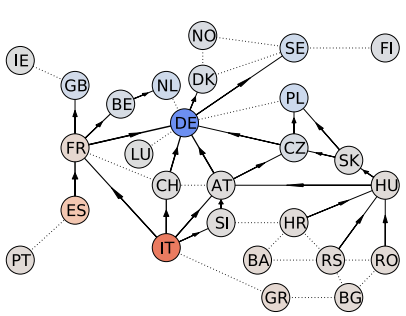
renormalisation scaling of power flows,

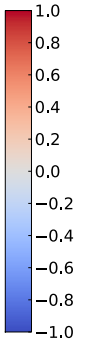
spatio-temporal flow pattern analysis,

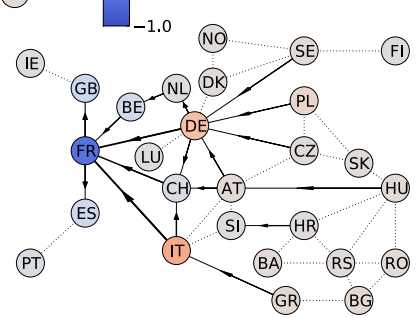
self-organizing power flows,

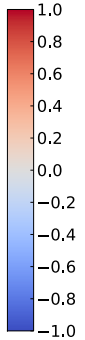
emergence of socio-economic cooperation







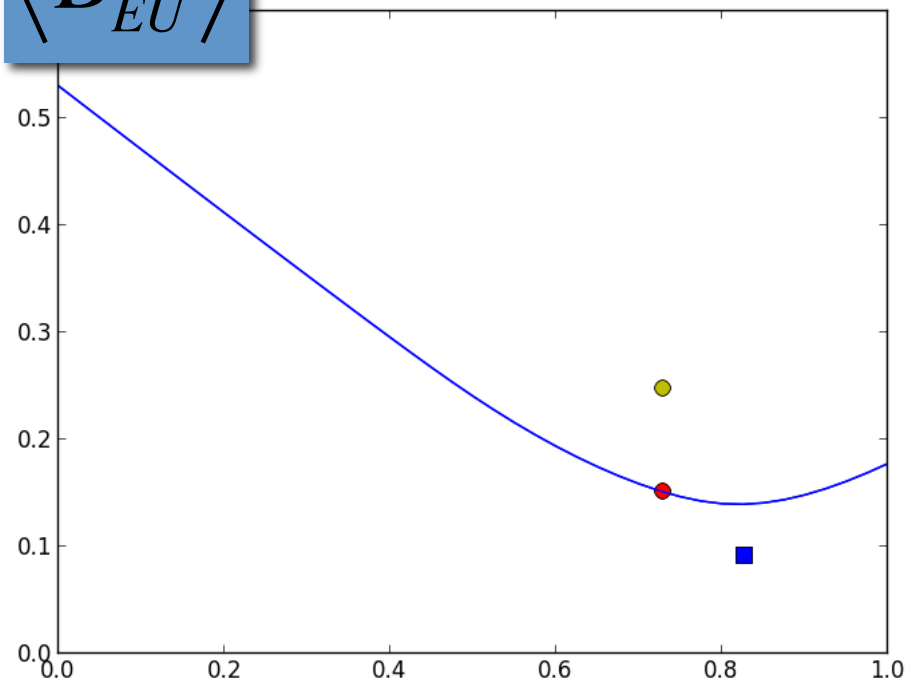


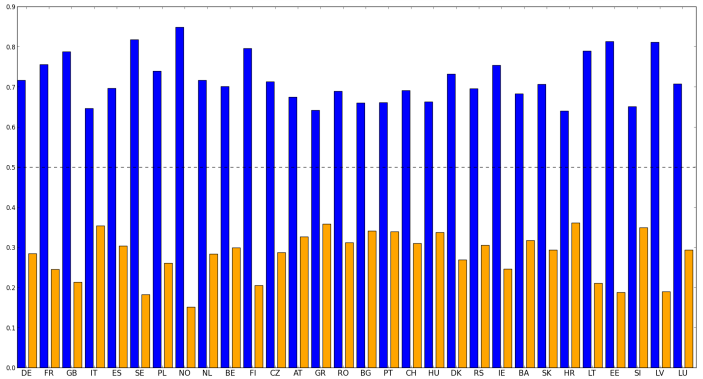


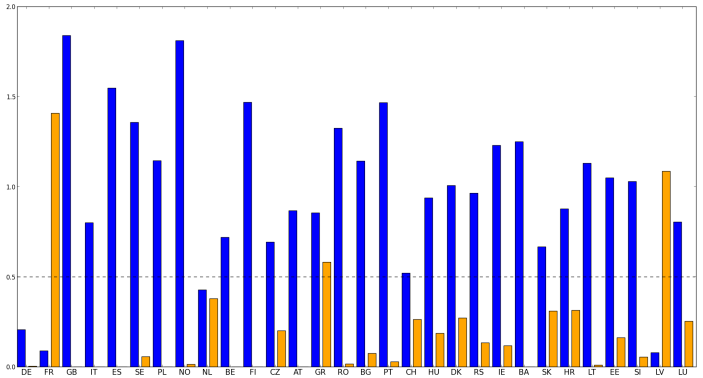
Optimal Portfolio Theory + Genetic Optimization

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

$\left\langle B_{EU} \right\rangle$





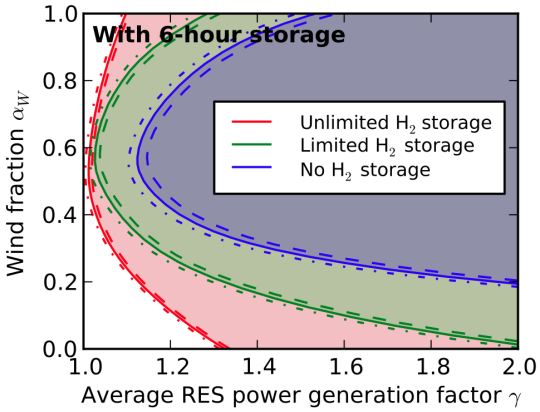


PRELIMINARY

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

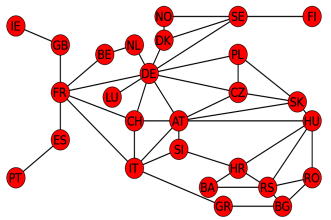
CONSENSYS

100% = 100+X%

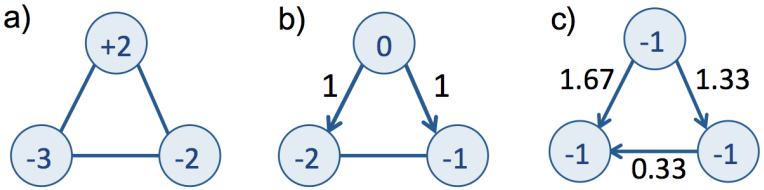


BIG DESIGN:
COMPLEX NETWORKS OF SMART ENERGY SYSTEMS

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



DESIGN OF FUTURE ENERGY MARKETS



OPTIMAL TRANSITION 2050 → 2015

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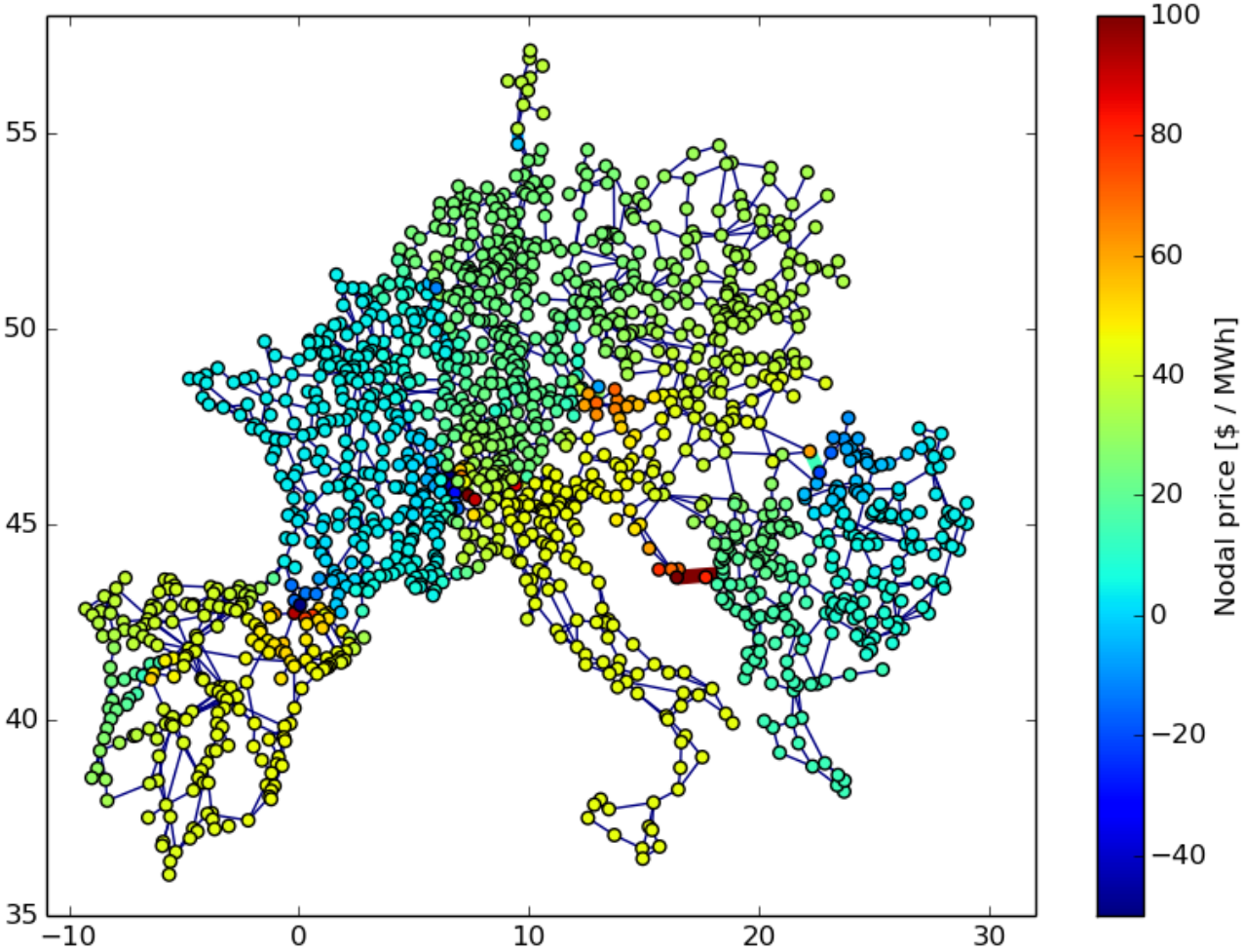
Tue Jensen (DTU, EU grant 5s – Future Electricity Markets)

Nodal vs. zonal pricing



Open access data set

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„Think beyond Wind Energy!“
„Think beyond Denmark!“
„Complex Networks of Smart Energy Systems!“

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

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R Rodriguez	(PhD)
B Sairanen	(Master)
A Thomsen	(Master)
M Dahl	(Master)
B Tranberg	(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)