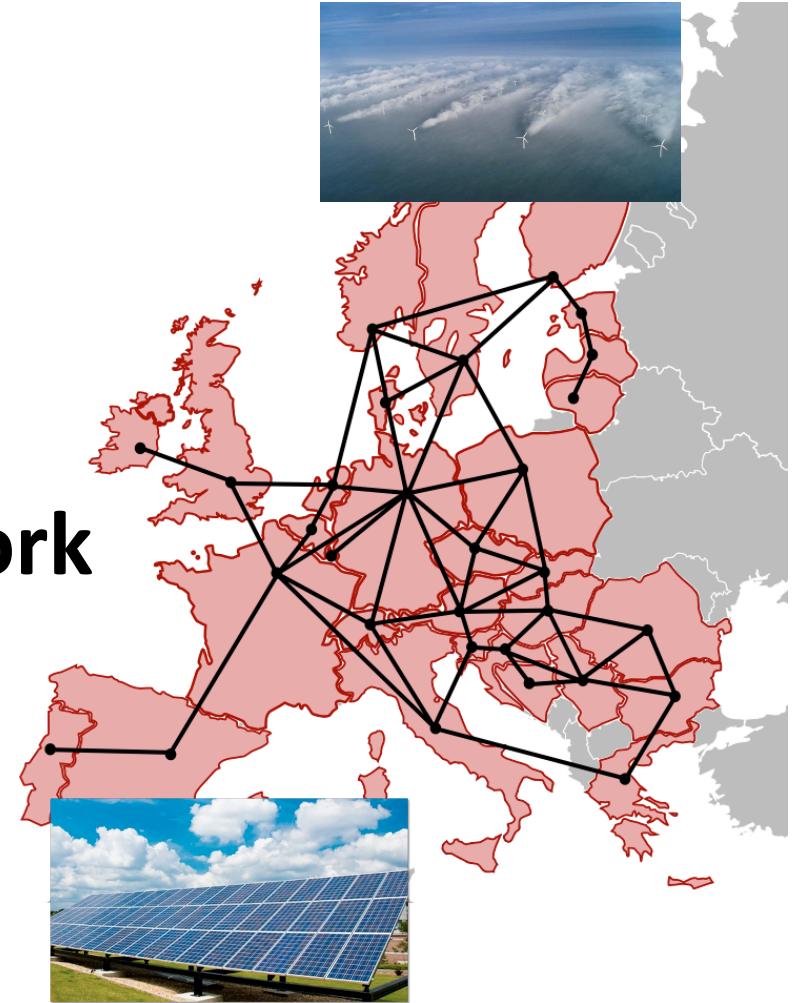


# System design of a simplified highly renewable European electricity network



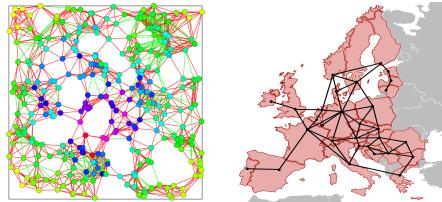
„Mehr als die Vergangenheit  
interessiert mich die Zukunft,  
denn in ihr gedenke ich zu leben.“

(Albert Einstein)



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Martin Greiner, Aarhus University  
[greiner@eng.au.dk](mailto:greiner@eng.au.dk)

- (1) Highly Renewable Energy Systems
- (2) Complex Networks 
- (3) Wind-farm Modeling + Optimization
- (4) Turbulence 

M Therkildsen (Master)  
P Nybroe (Master)  
J Otten (Master)  
J Bjerre (Master)  
J Herp (Master)  
U Poulsen (Assist Prof)

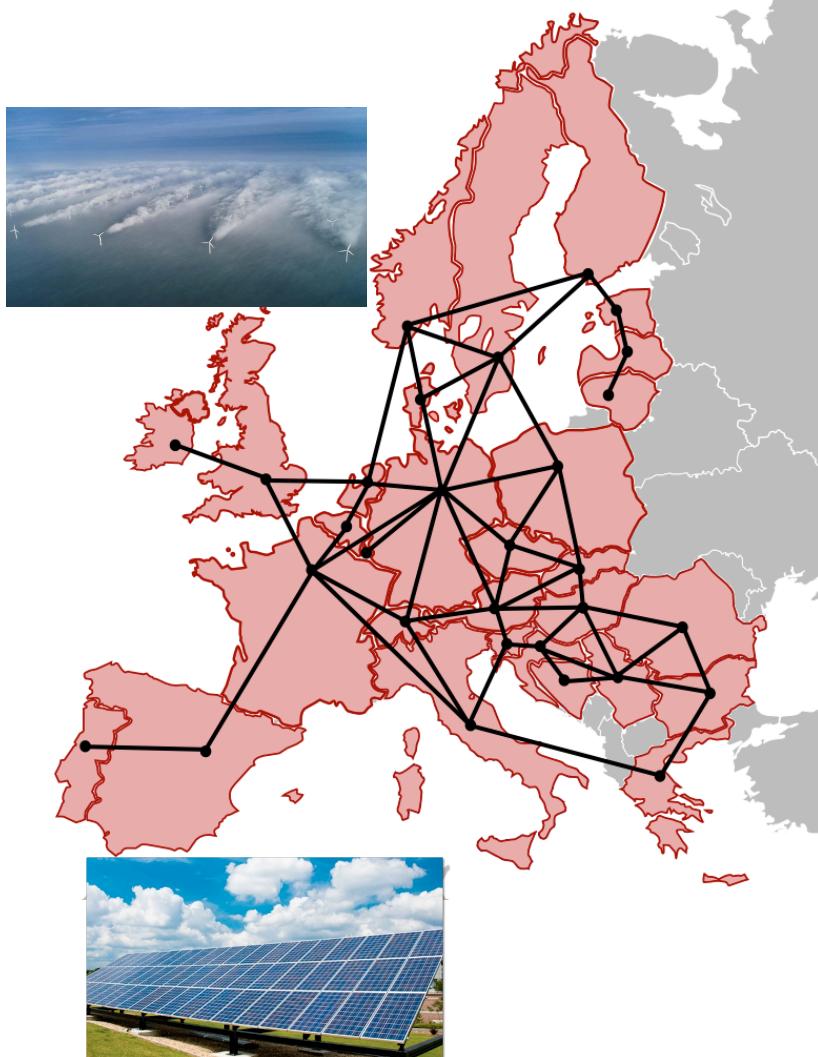
G Andresen	(Assit Prof)
N Skou-Nielsen	(Master)
C Poulsen	(Master)
M Raunbak	(Master)
A Ashfaq	(Master)
M Hansen	(Master)
K Holm	(Master)
M Rasmussen	(PostDoc)
R Rodriguez	(PhD)
B Tranberg	(Master)
E Eriksen	(Master)
S Kozarcanin	(Master)
M Dahl	(Master)
A Thomsen	(Master)
B Sairanen	(Master)
T Zeyer	(Master)
T Jensen	(Master)
A Søndergaard	(Master)
D Schlachtberger	(FIAS PhD)
J Hörsch	(FIAS PhD)
M Schäfer	(FIAS)
S Schramm	(FIAS)
S Becker	(FIAS PhD)
D Heide	(FIAS PhD)
A Kies	(U Oldenburg PhD)
L von Bremen	(ForWind)
C Hoffmann	(IWES)



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# Technical + economical design of a highly renewable European electricity system



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

How much ...

... wind energy? ... solar PV energy?  
... backup energy + power?  
... transmission? ... storage?

and what about ...

... coupling of energy sectors?  
... future market design?  
... transition 2050 → 2020?

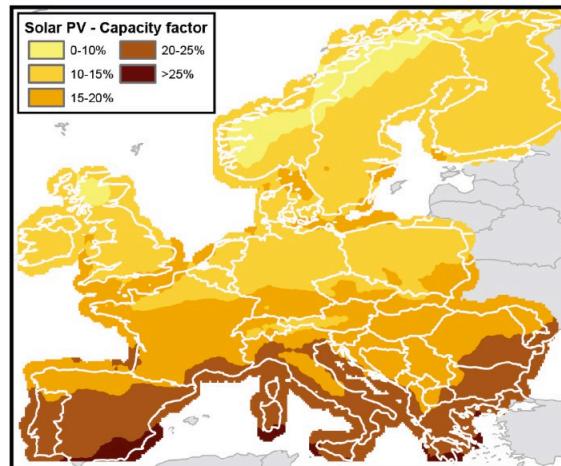
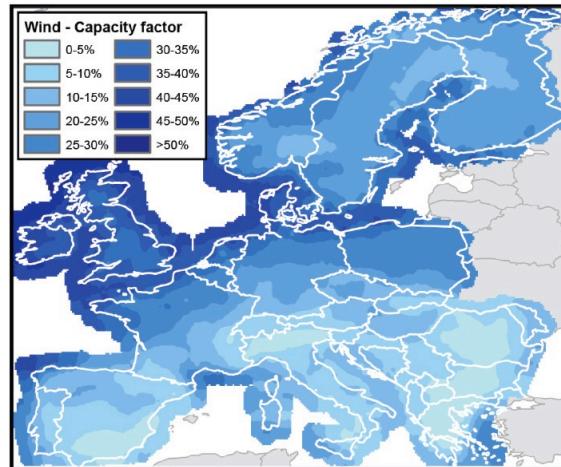
**Let the weather decide!**



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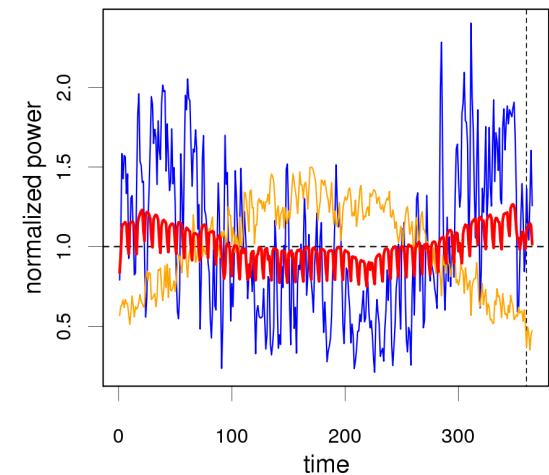
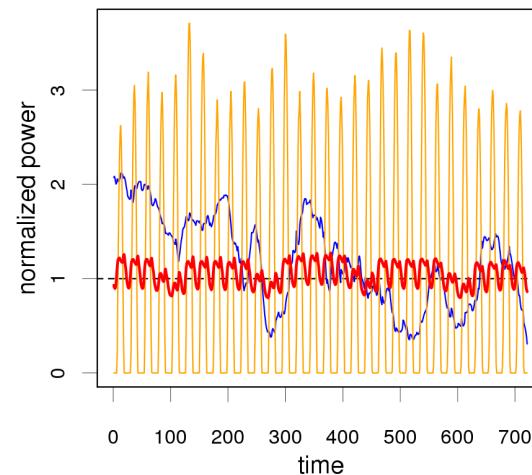
# Weather-driven electricity generation



## Renewable Energy Atlas

2000 – 2007: 1h, 45x45km<sup>2</sup>

1980 – 2014: 1h, 30x30km<sup>2</sup>



3 TIME SCALES:

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

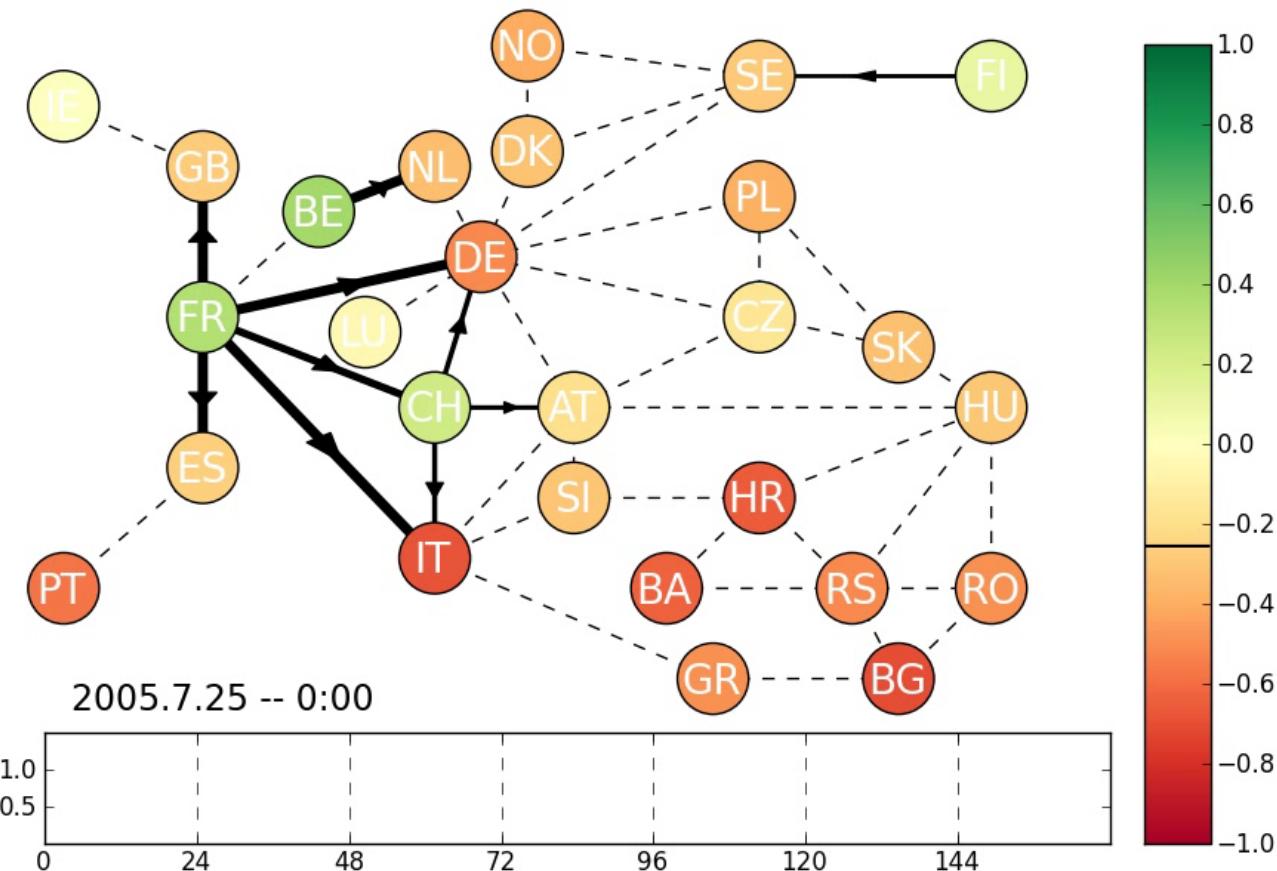


$$\underbrace{G_n^R(t) - L_n(t)}_{\text{actio}} = \underbrace{B_n(t) + P_n(t) + \dots}_{\text{reactio}}$$

$$\langle G_n^R \rangle = \gamma_n \langle L_n \rangle$$

$$\langle G_n^W \rangle = \alpha_n \langle G_n^R \rangle$$

$$\langle G_n^S \rangle = (1 - \alpha_n) \langle G_n^R \rangle$$



$$\gamma_n = 1$$

$$\alpha_n = 0.7$$



**How much backup?**

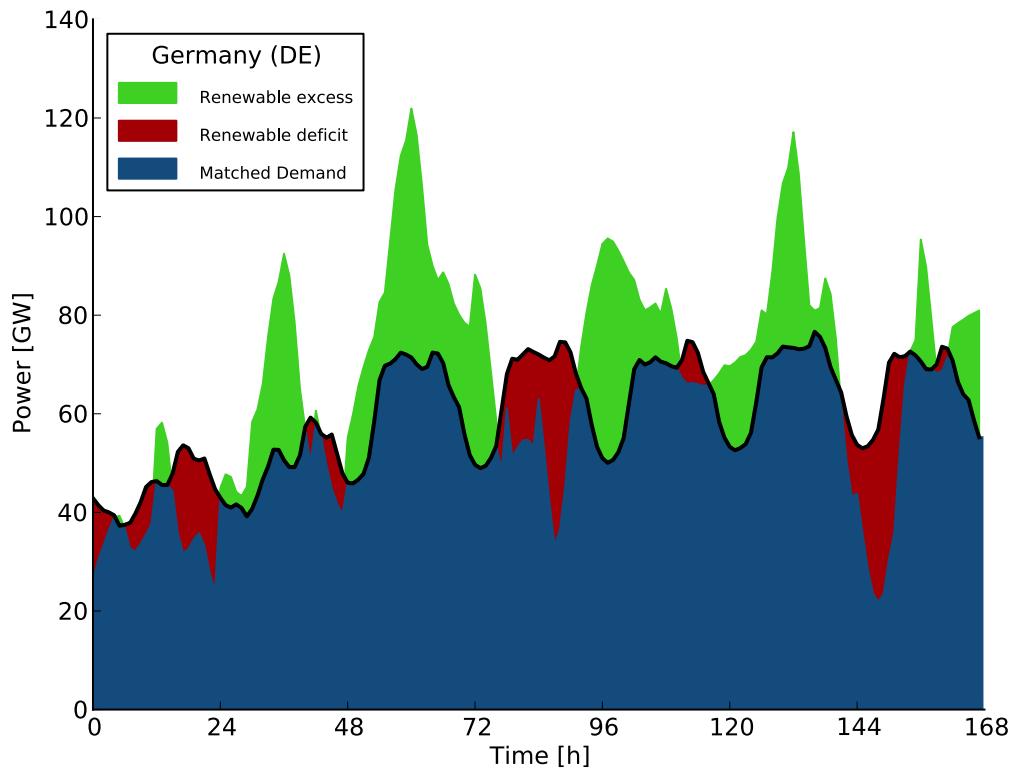
**How much wind + solar power?**

(no transmission)

# Mismatch distribution (Germany)

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

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



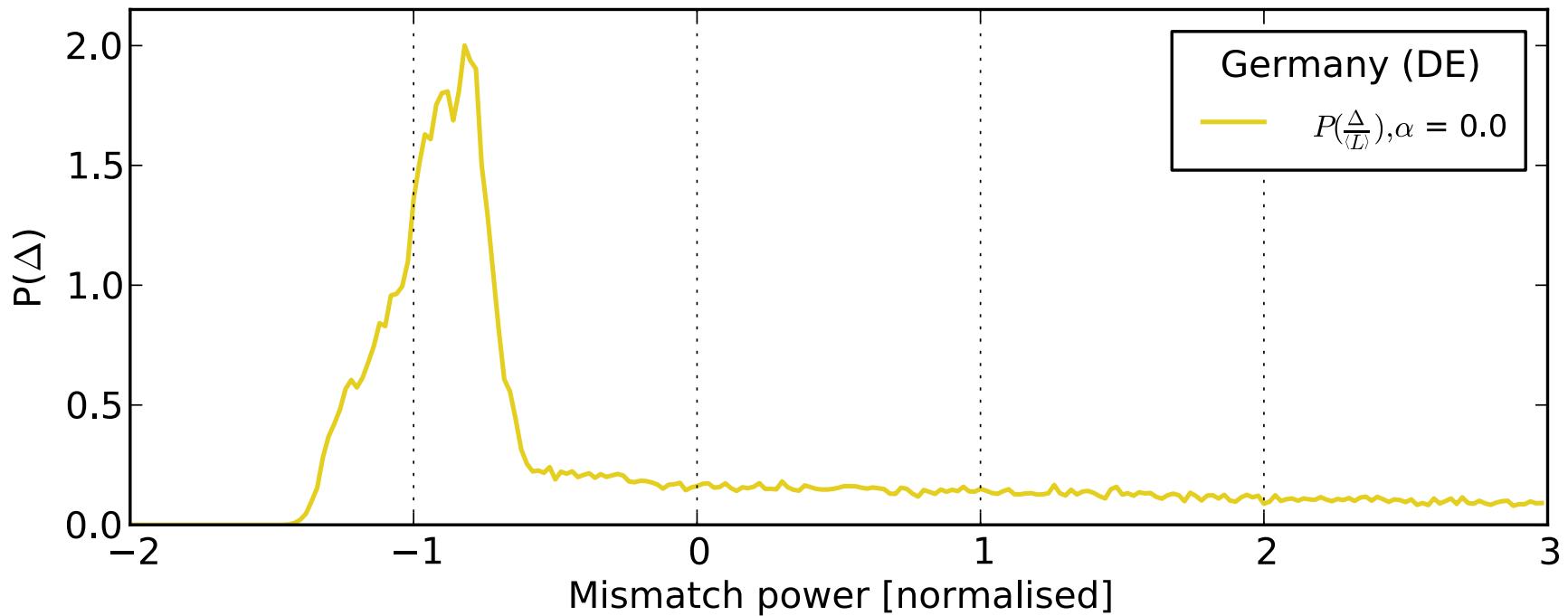
$$C_n(t) = \max(B_n(t), 0)$$

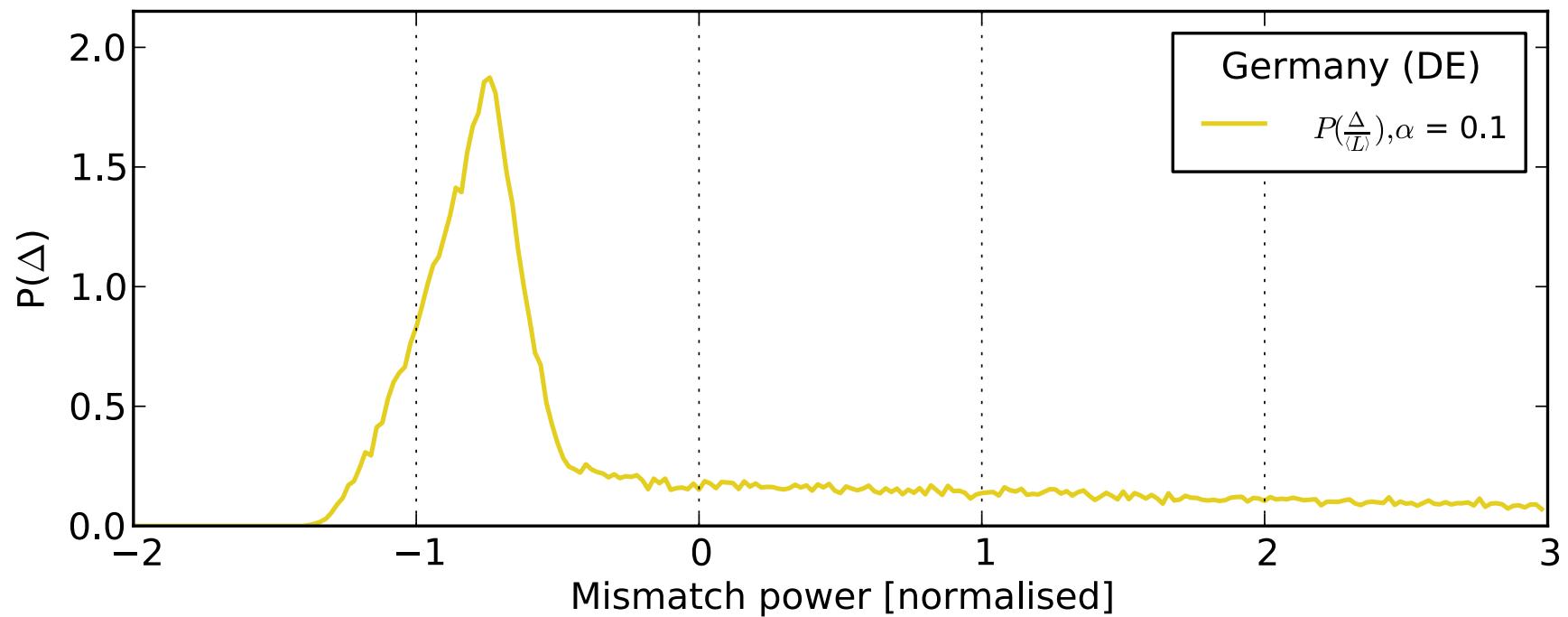
$$G_n^B(t) = -\min(B_n(t), 0)$$



$$\gamma_n = 1$$

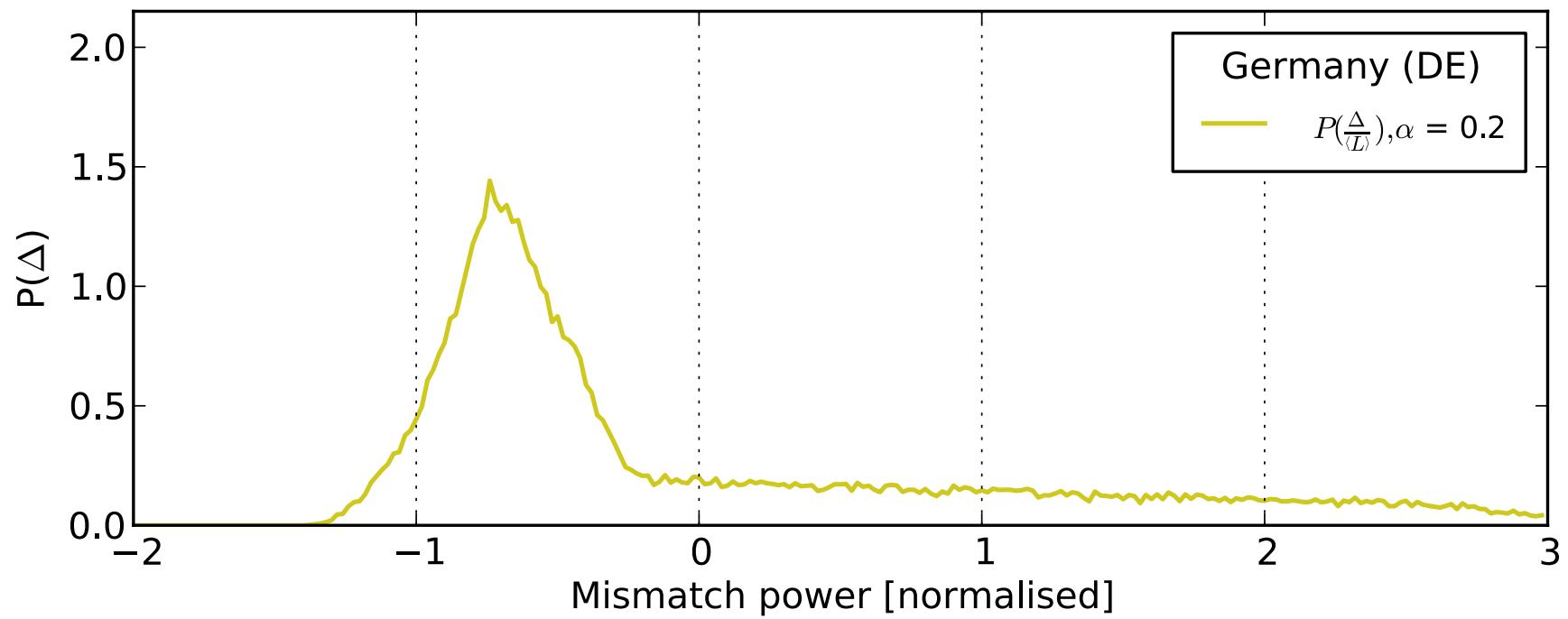
$$\alpha_n = \frac{\langle G_n^W \rangle}{\langle G_n^{RES} \rangle}$$

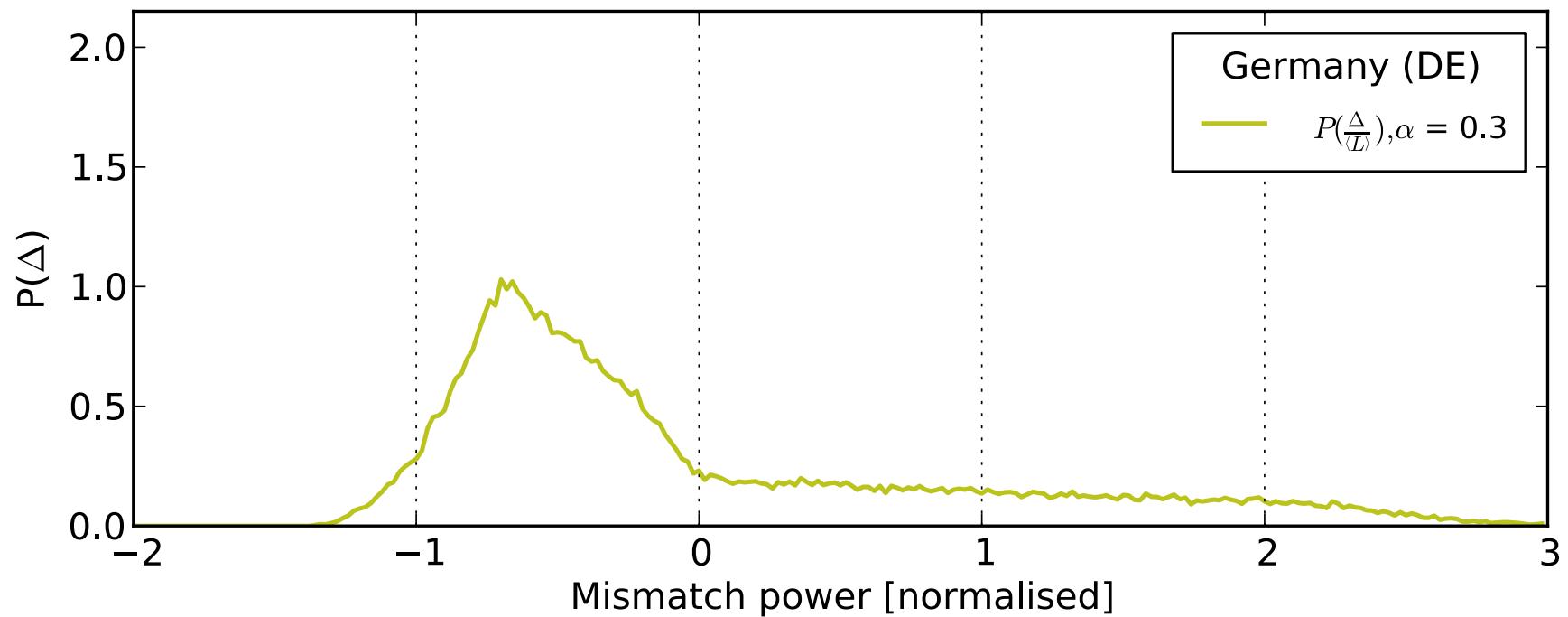


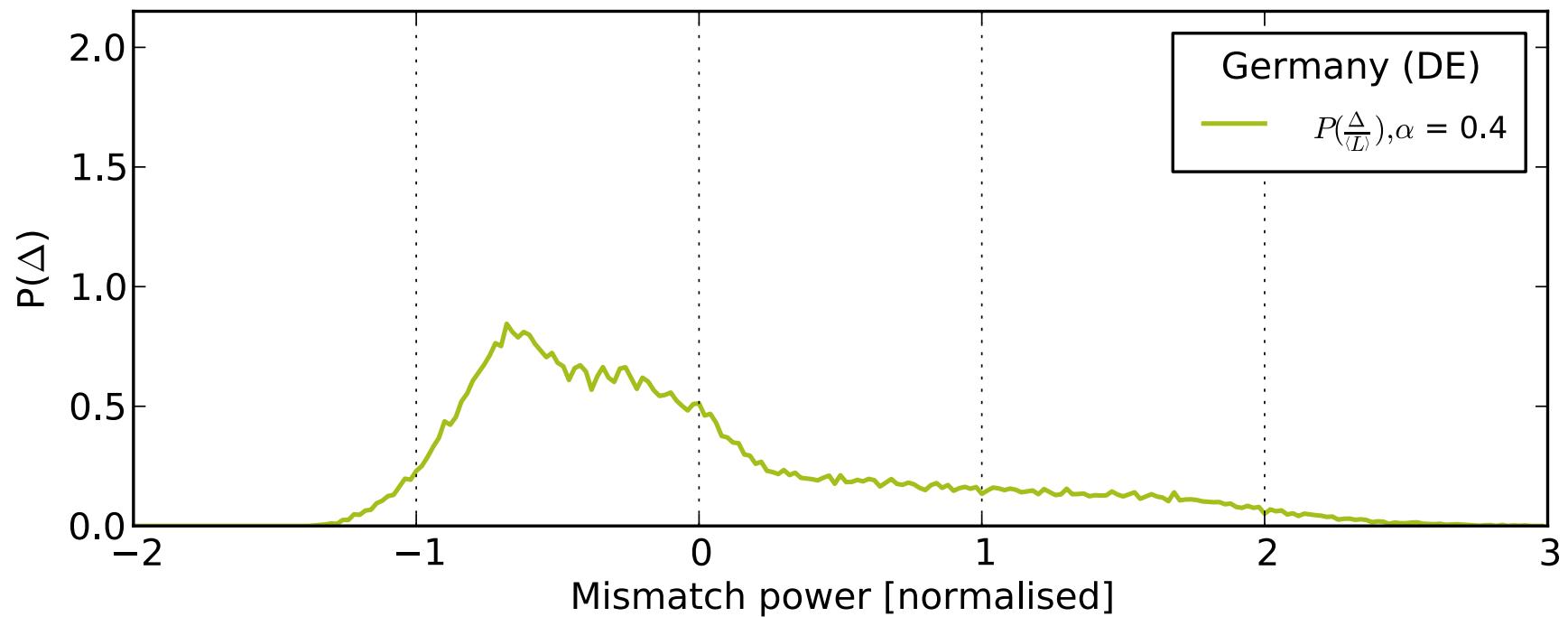


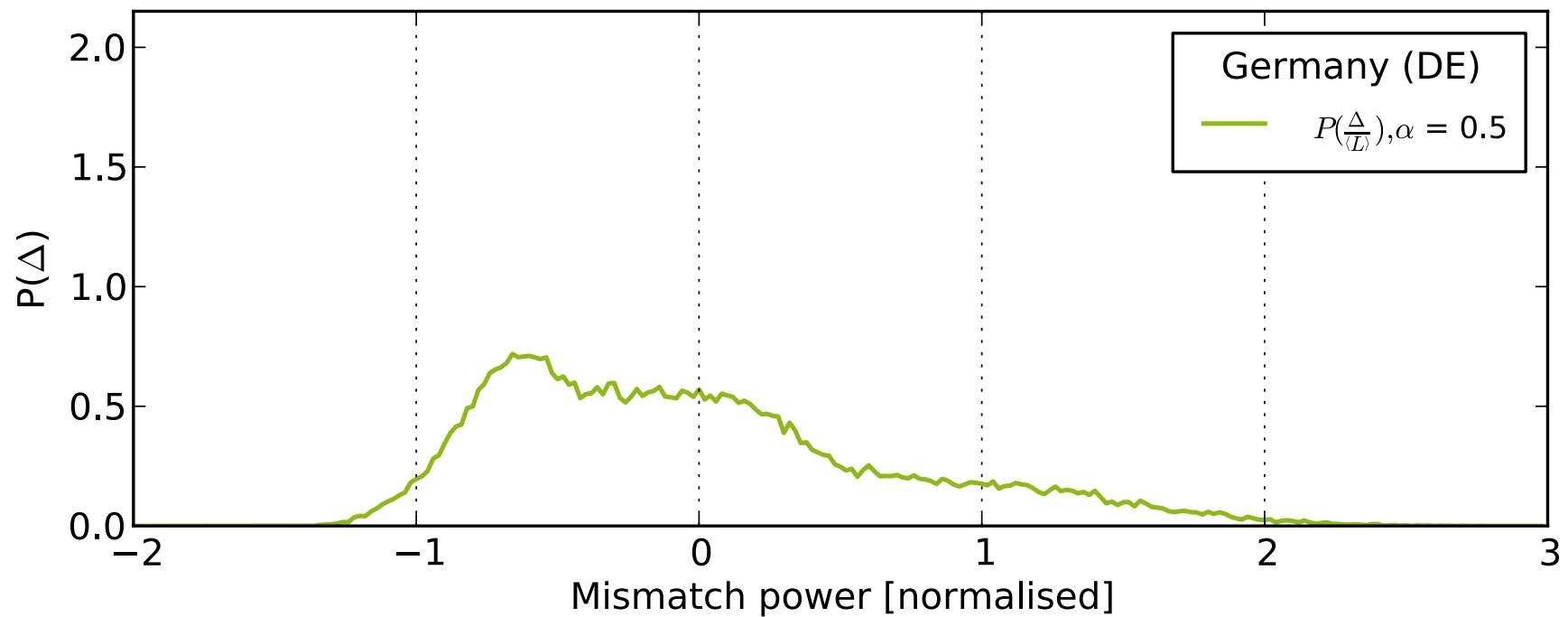
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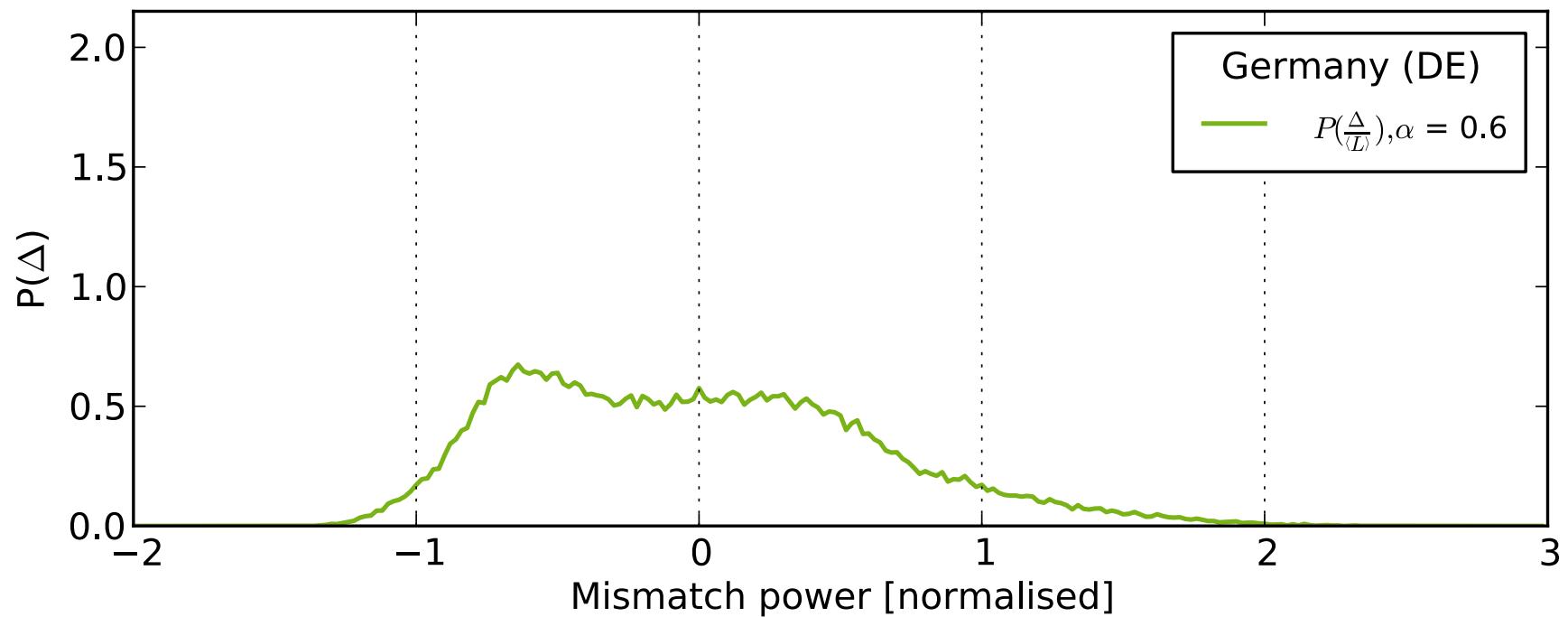
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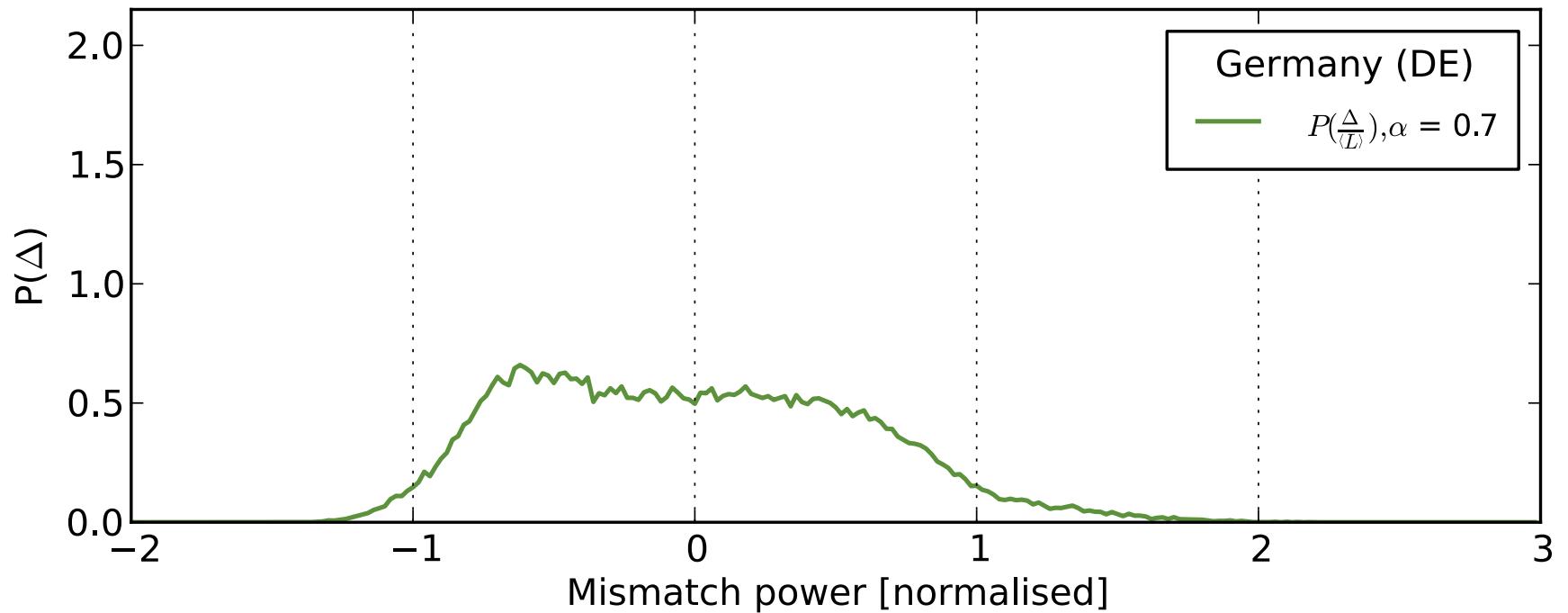


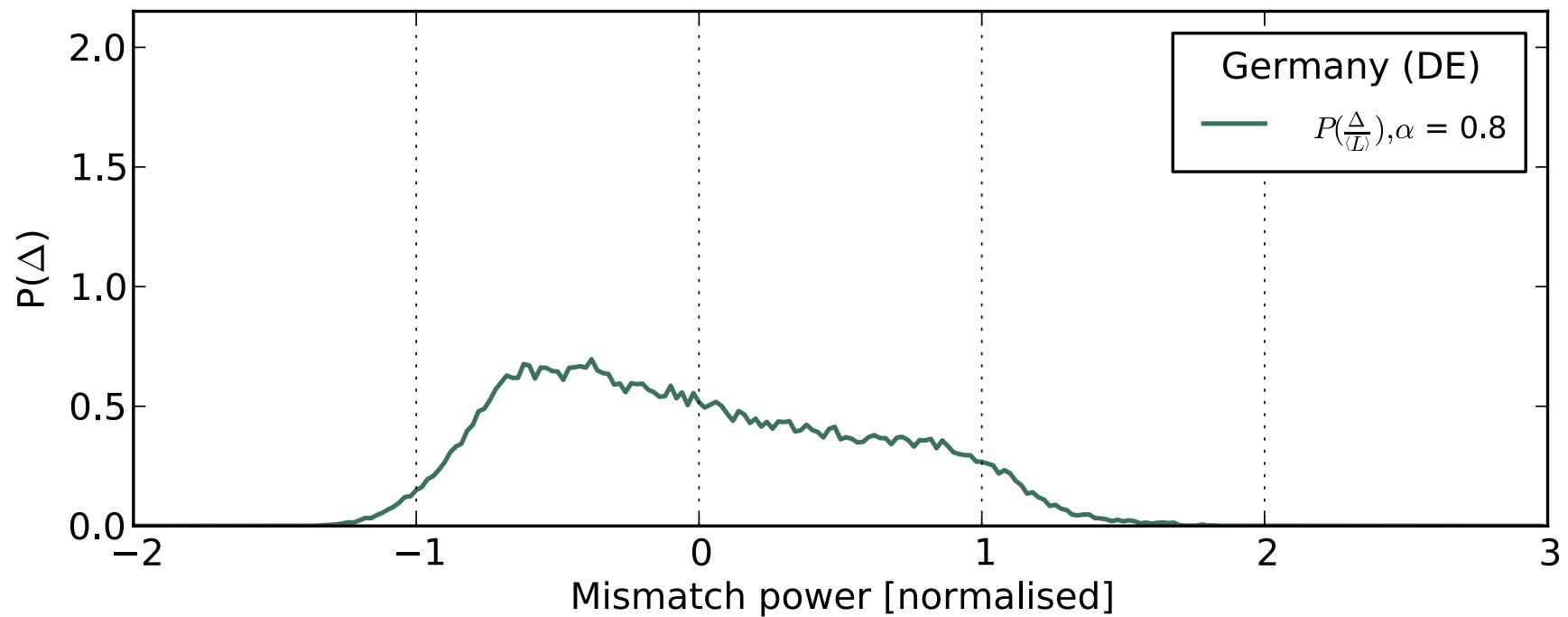


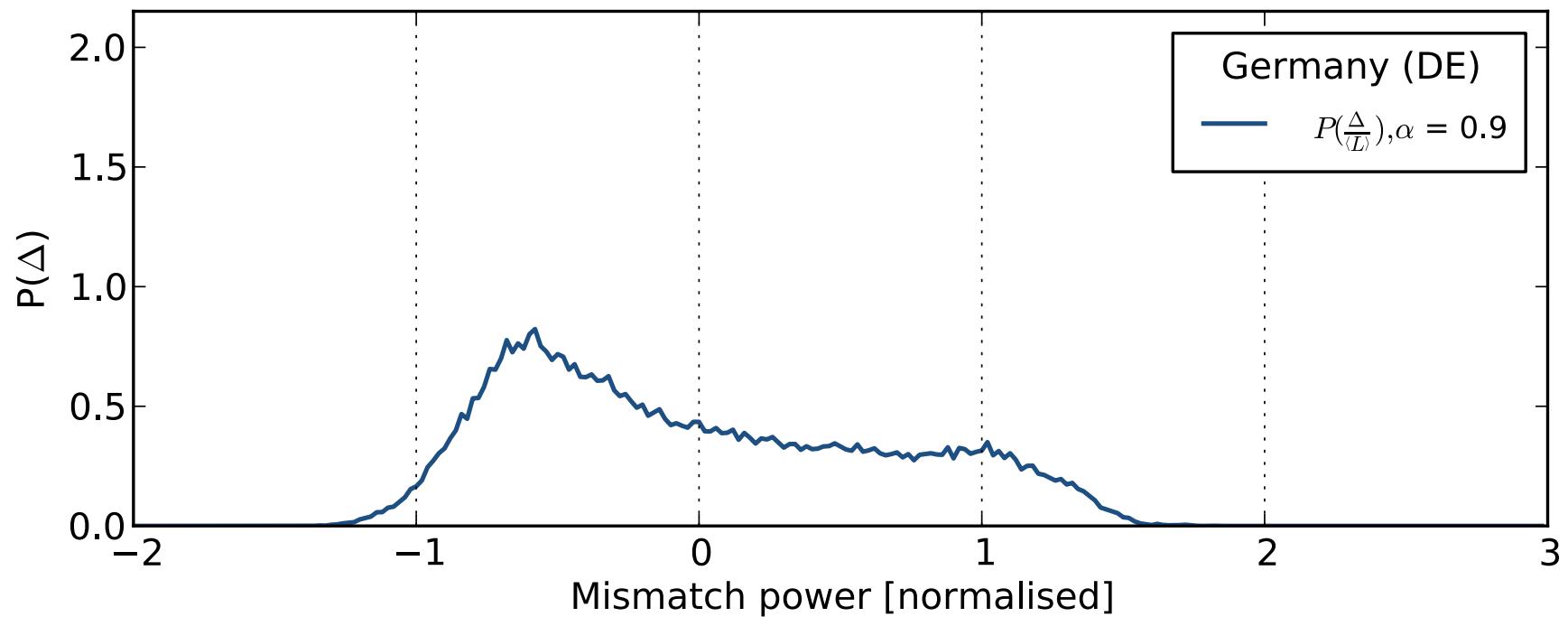


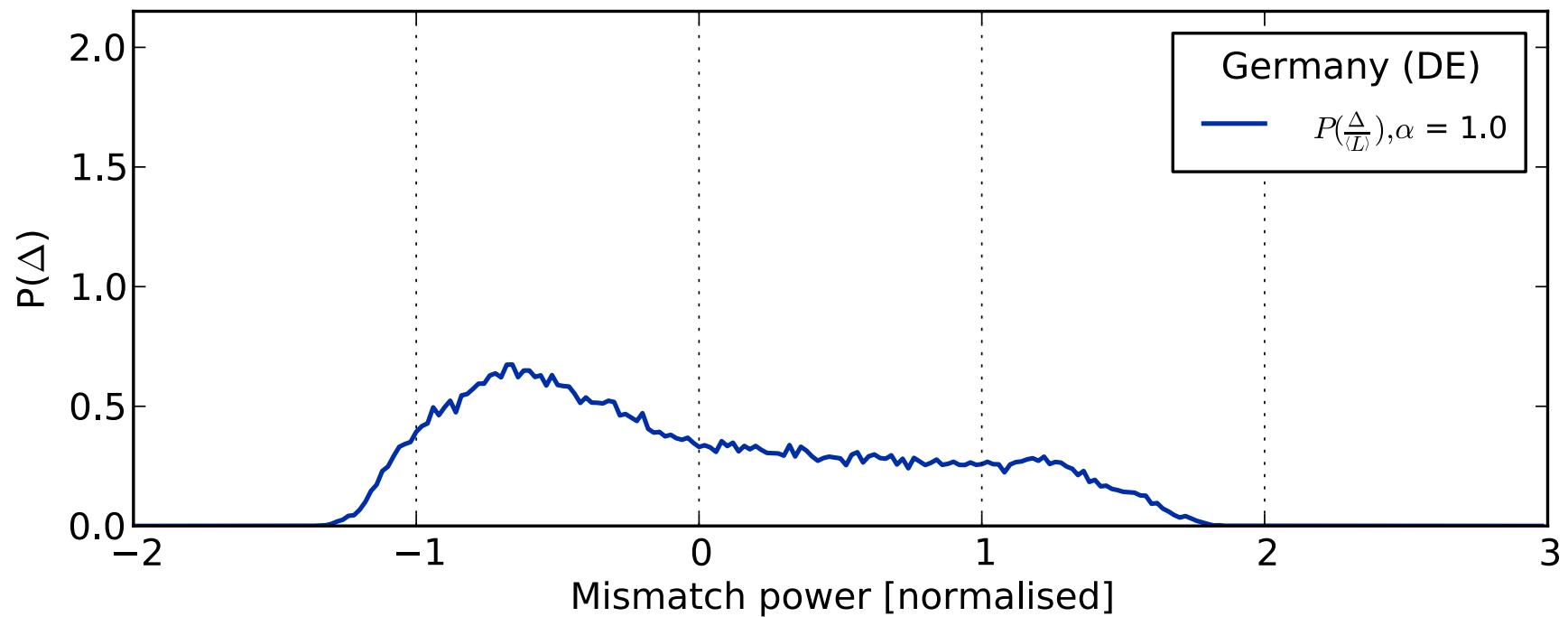








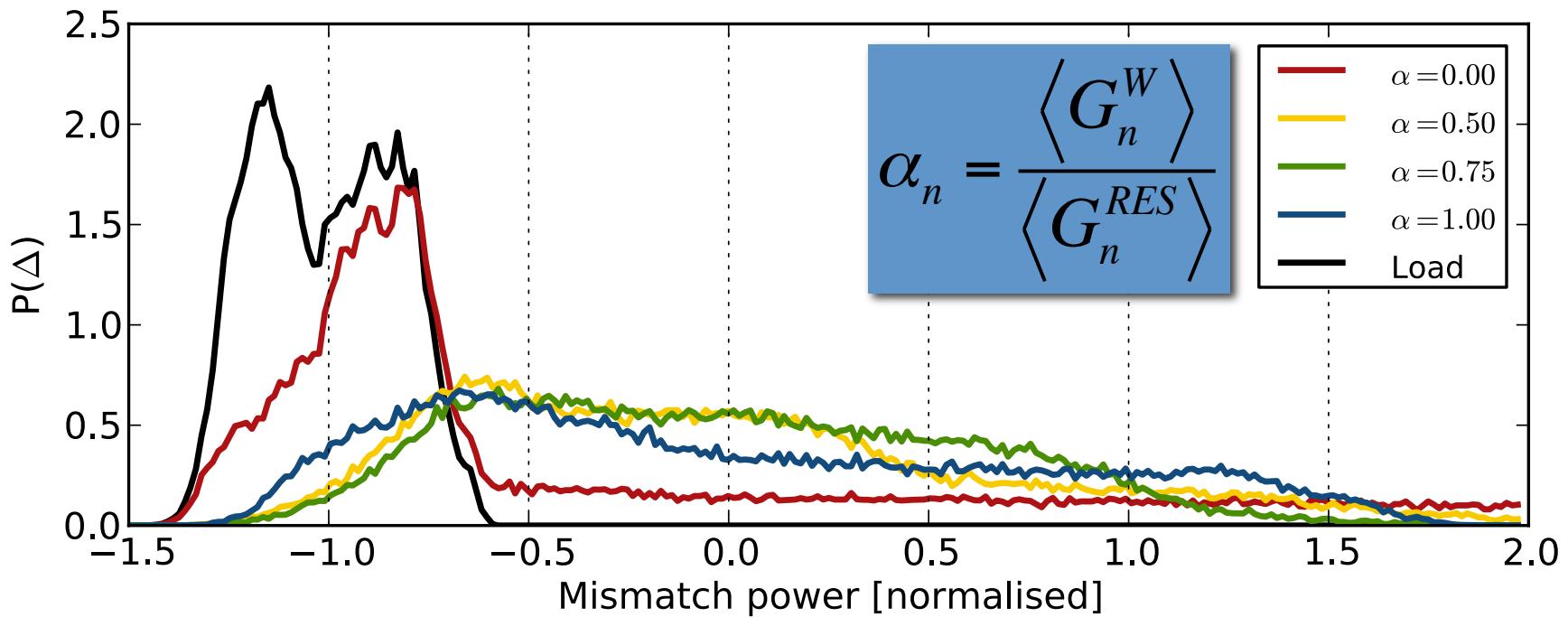




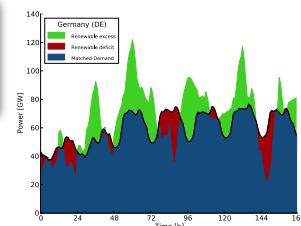
# Mismatch distribution (Germany)

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

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



$$G_n^B(t) = -\min(B(t), 0)$$

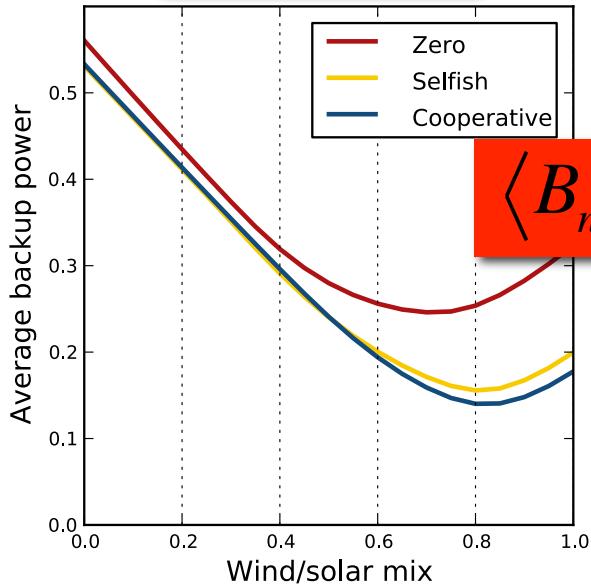


$$C_n(t) = \max(B_n(t), 0)$$



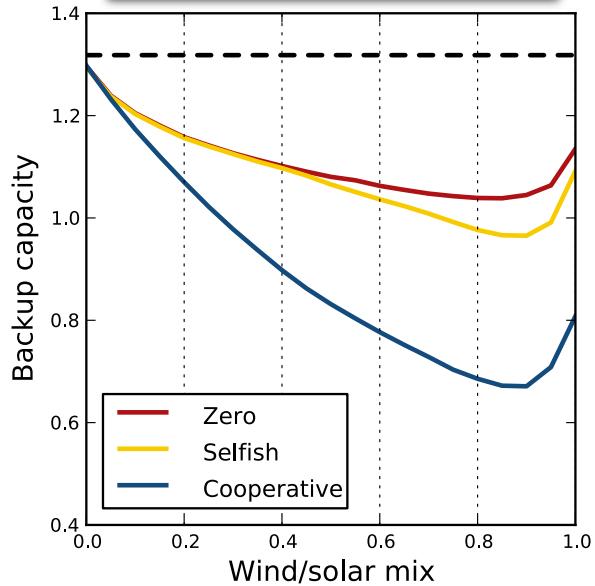
# backup energy

$$\langle G_n^B \rangle / \langle L_n \rangle$$



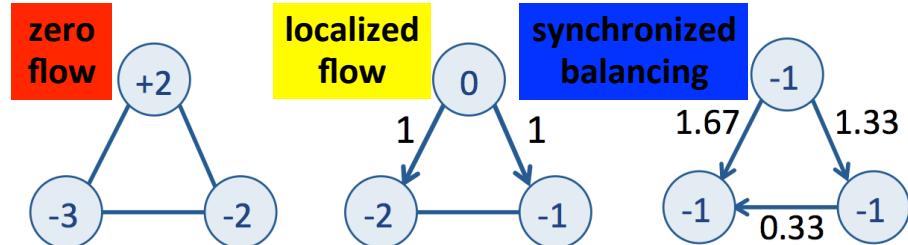
# backup capacity

$$\max_q \langle G_n^B \rangle / \langle L_n \rangle$$



$$\alpha_n = \langle G_n^W \rangle / \langle G_n^R \rangle$$

$$\gamma_n = 1$$



**How much backup?**

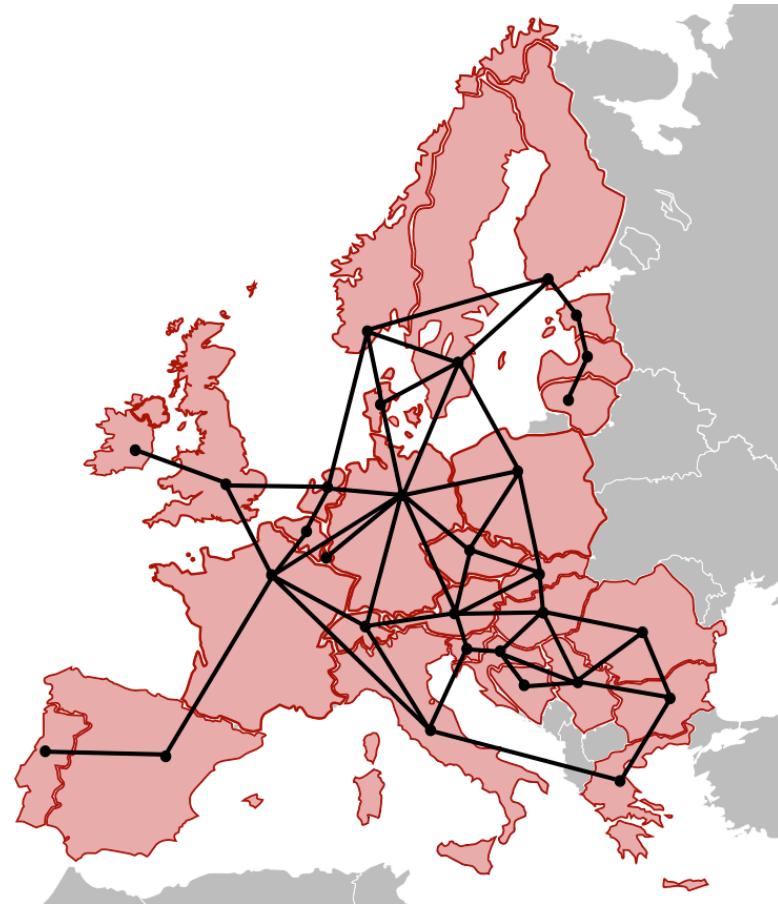
**How much transmission?**

$$\underbrace{G_n^R(t) - L_n(t)}_{\text{actio}} = \underbrace{B_n(t) + P_n(t) + \dots}_{\text{reactio}}$$

$$\langle G_n^R \rangle = \gamma_n \langle L_n \rangle$$

$$\langle G_n^W \rangle = \alpha_n \langle G_n^R \rangle$$

$$\langle G_n^S \rangle = (1 - \alpha_n) \langle G_n^R \rangle$$

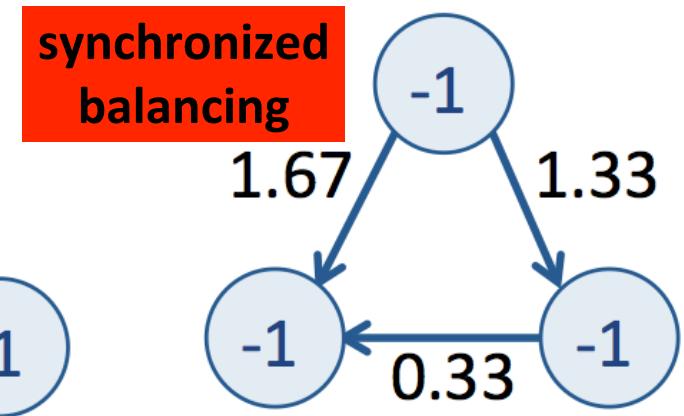
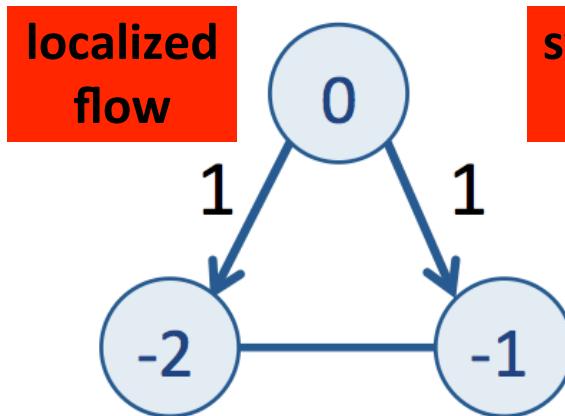
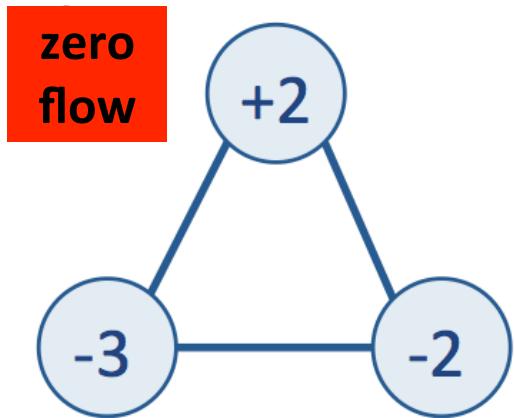


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# Coupling schemes between balancing and transmission

$$G_n^R(t) - L_n(t) = B_n(t) + P_n(t)$$



$$P_n(t) = 0$$

$$\min \left( \sum_n G_n^B(t) \right)$$

$$\min \left( \sum_n \frac{B_n(t)^2}{\langle L_n \rangle} \right)$$

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

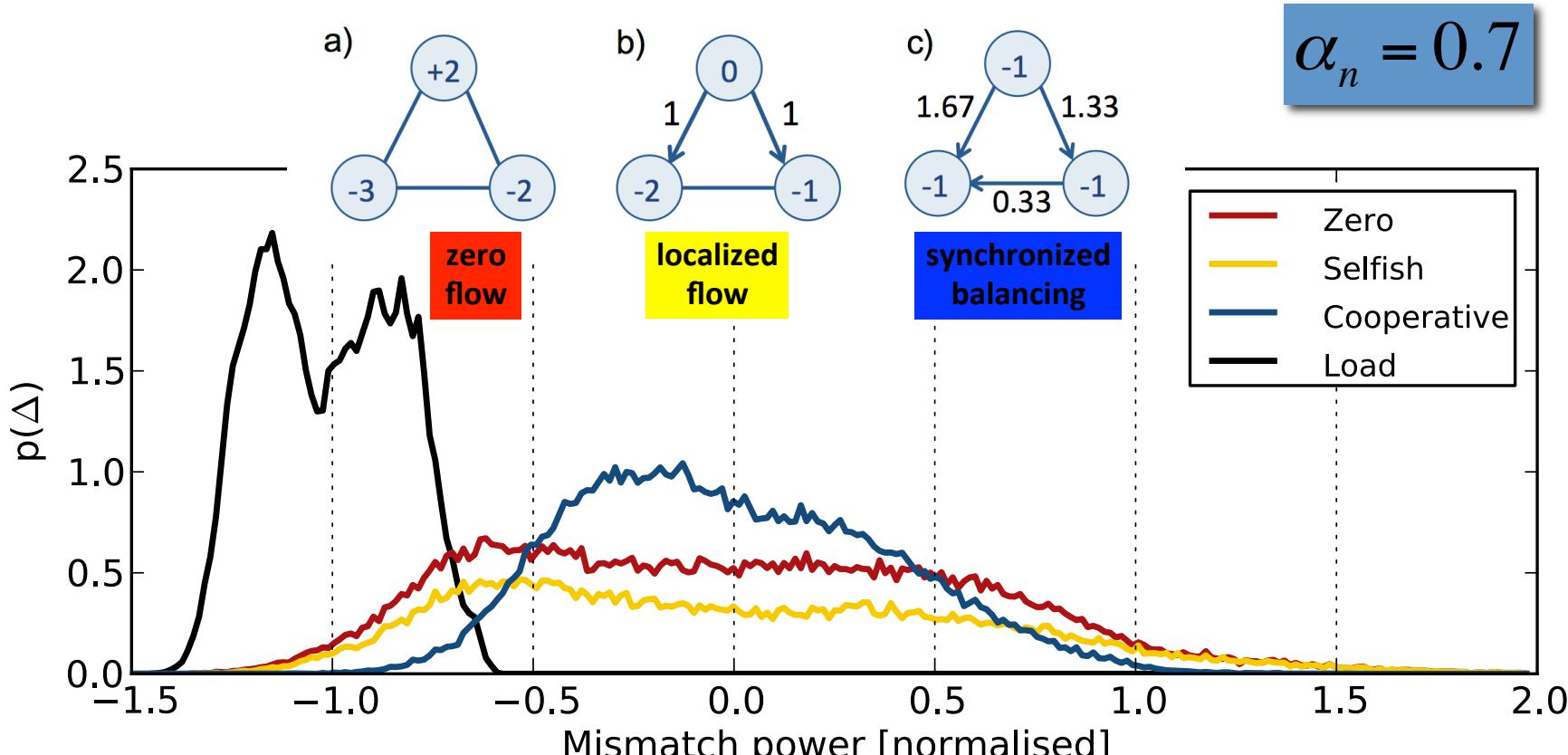
$$\min \left( \sum_l F_l^2(t) \right)$$



# Balancing distribution (Germany)

$$B_n(t) = G_n^R(t) - L_n(t) - P_n(t)$$

$$\langle G_n^R \rangle = \langle L_n \rangle$$



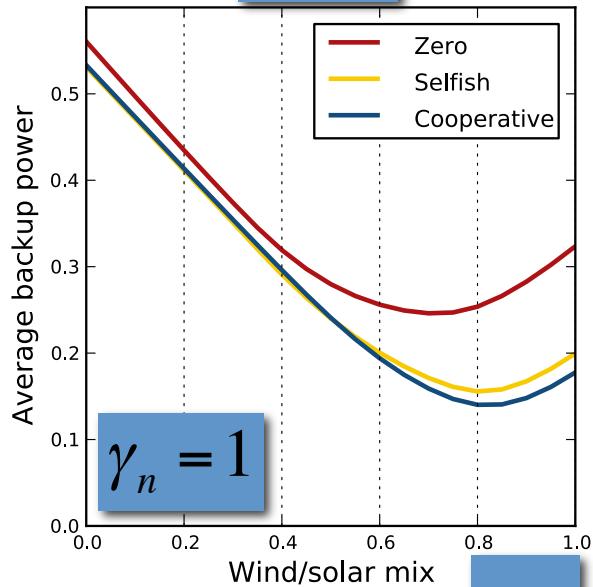
$$G_n^B(t) = -\min(B_n(t), 0)$$

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



# backup energy

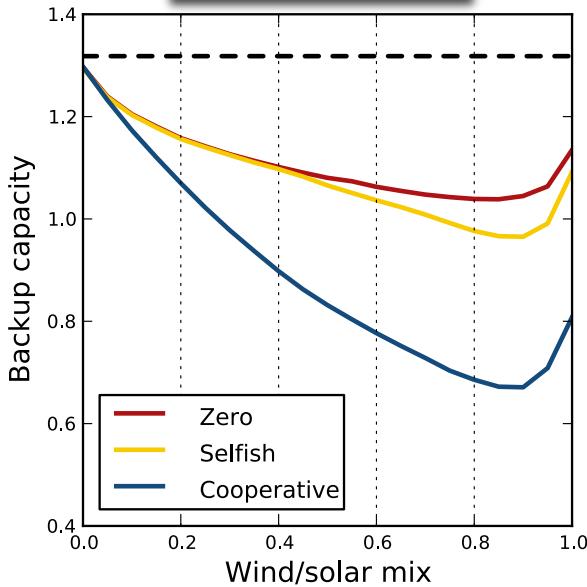
$$\langle G_n^B \rangle$$



$$\alpha_n$$

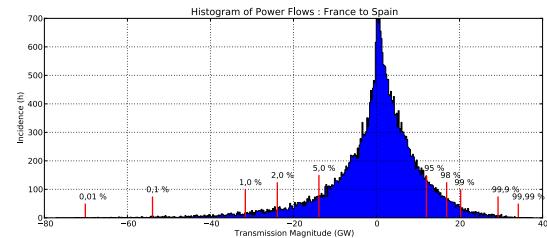
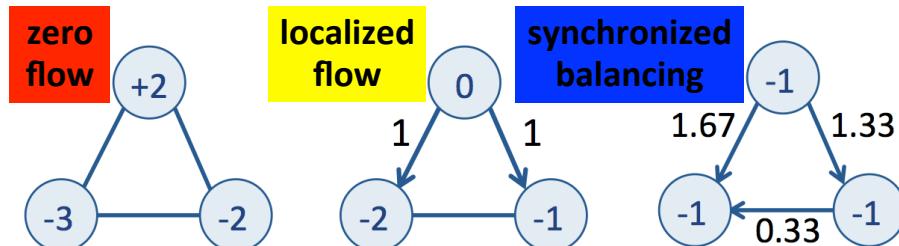
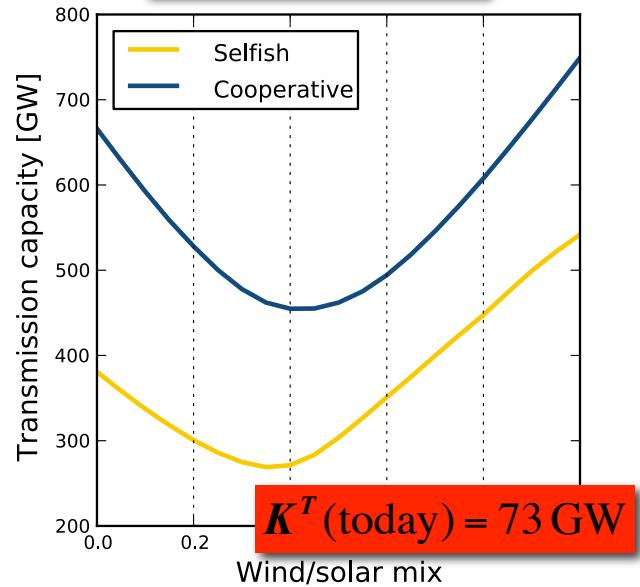
# backup capacity

$$\max_q(G_n^B)$$

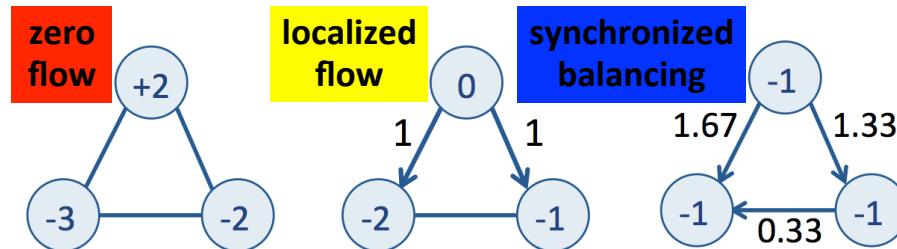
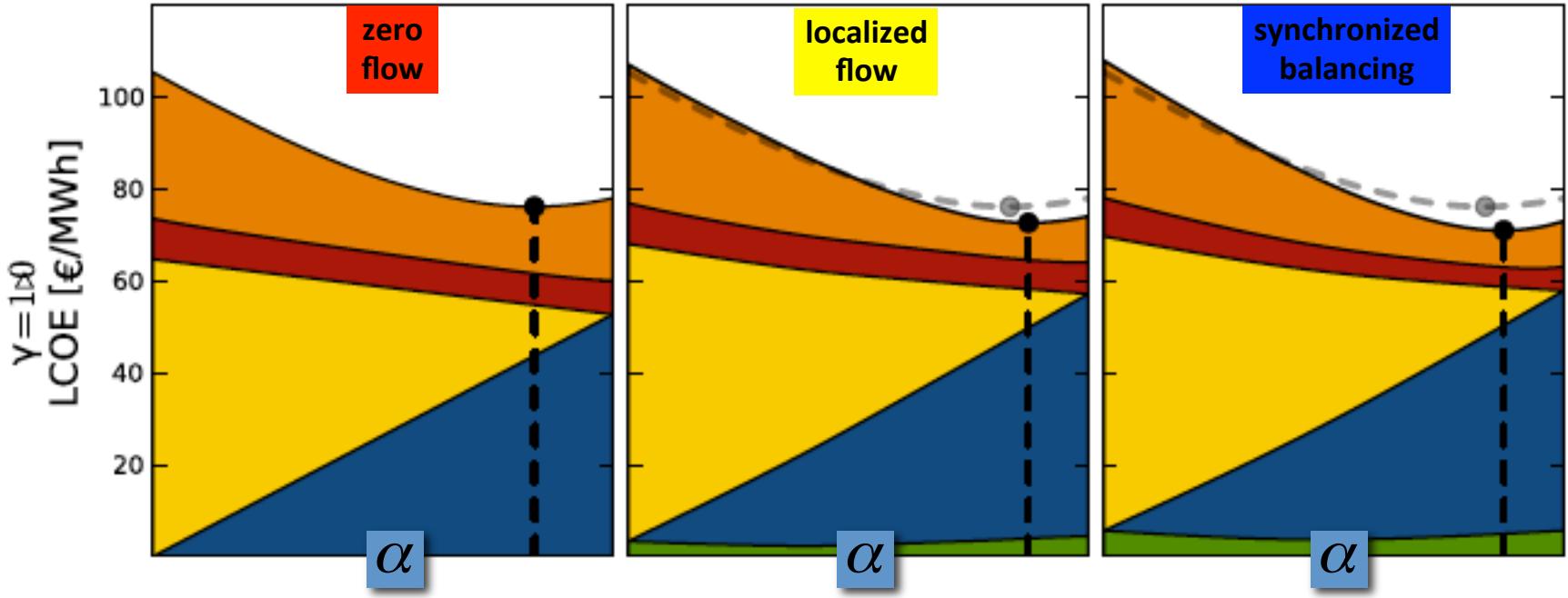


# transmission capacity

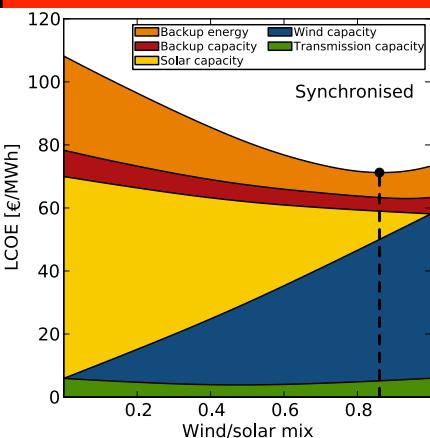
$$\sum_l \max_q |F_l|$$



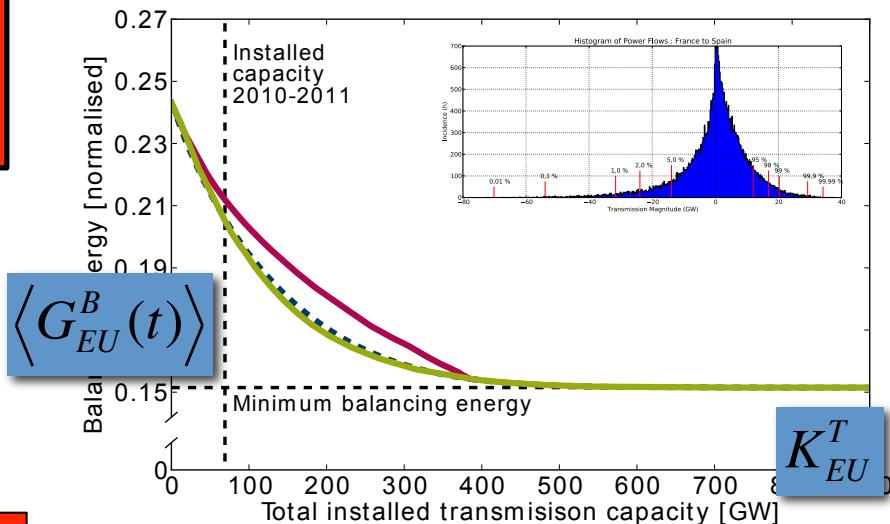
# Levelized SYSTEM Cost of Energy: CAPEX+OPEX **wind**, **solar**, **backup**, **transmission**



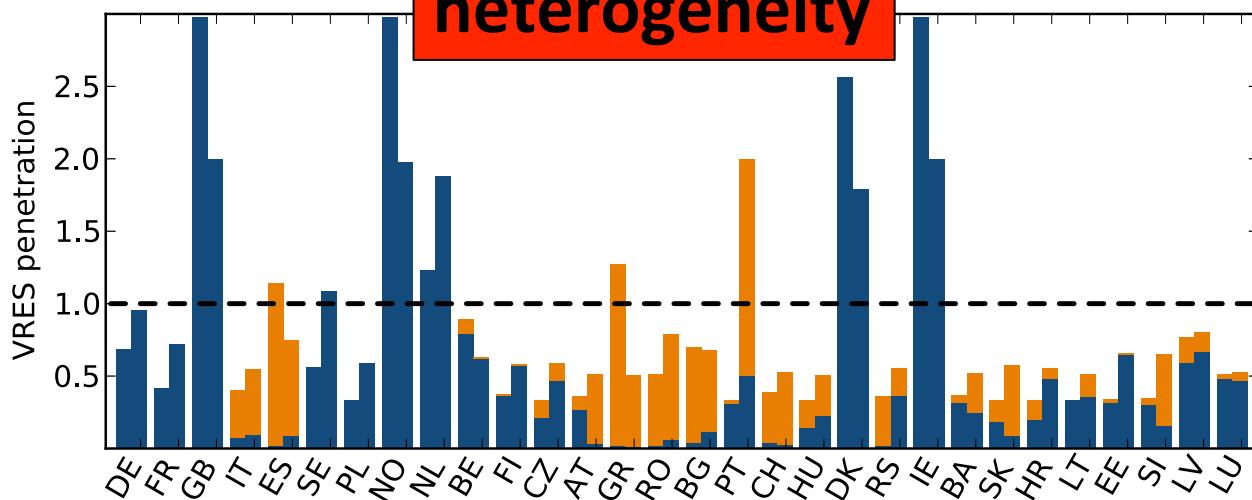
# SNEAK PREVIEW: further reductions of LsCOE



benefit of  
transmission



optimal  
heterogeneity



$$1/K \leq \gamma_n \leq K$$

$$\gamma_{EU} = 1$$

$$0 \leq \alpha_n \leq 1$$



# Outlook: current + next challenges

**Storage + transmission**

**Big networks**

**Flow tracing**

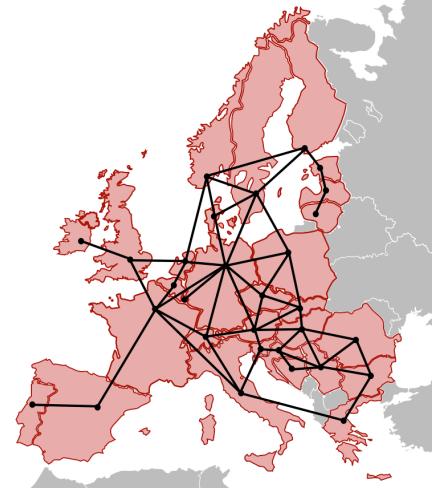
**Selforganizing power flows**

**Design → operation: balancing markets**

**Smart energy systems: coupling of  
electricity + heating + transportation**

**2050 ← 2020 investments:  
cooperative game theory + incentives**

**Climate change**



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

**D Heide et.al.:** Reduced storage and balancing needs in a fully renewable European power system with excess wind and solar power generation, **Renewable Energy 36 (2011) 2515-2523.**

**MG Rasmussen et.al.:** Storage and balancing synergies in a fully or highly renewable pan-European power system, **Energy Policy 51 (2012) 642-651.**

**RA Rodriguez et.al.:** Transmission needs across a fully renewable European power system, **Renewable Energy 63 (2014) 467-476.**

**S Becker et.al.:** Transmission grid extensions during the build-up of a fully renewable pan-European electricity supply, **Energy 64 (2014) 404-418.**

**TV Jensen et.al.:** Emergence of a phase transition for the required amount of storage in highly renewable electricity systems, **EPJ ST 223 (2014) 2475-2481.**

**S Becker et.al.:** Features of a fully renewable US electricity system – optimized mixes of wind and solar PV and transmission grid extensions, **Energy 72 (2014) 443-458.**

**GB Andresen et.al.:** The potential for arbitrage of wind and solar surplus power in Denmark, **Energy 76 (2014) 49-58.**

**S Becker et.al.:** Renewable build-up pathways for the US: Generation costs are not system costs”, **Energy 81 (2015) 437-445.**

**RA Rodriguez et.al.:** Cost-optimal design of a simplified, highly renewable pan-European electricity system, **Energy 83 (2015) 658-668.**

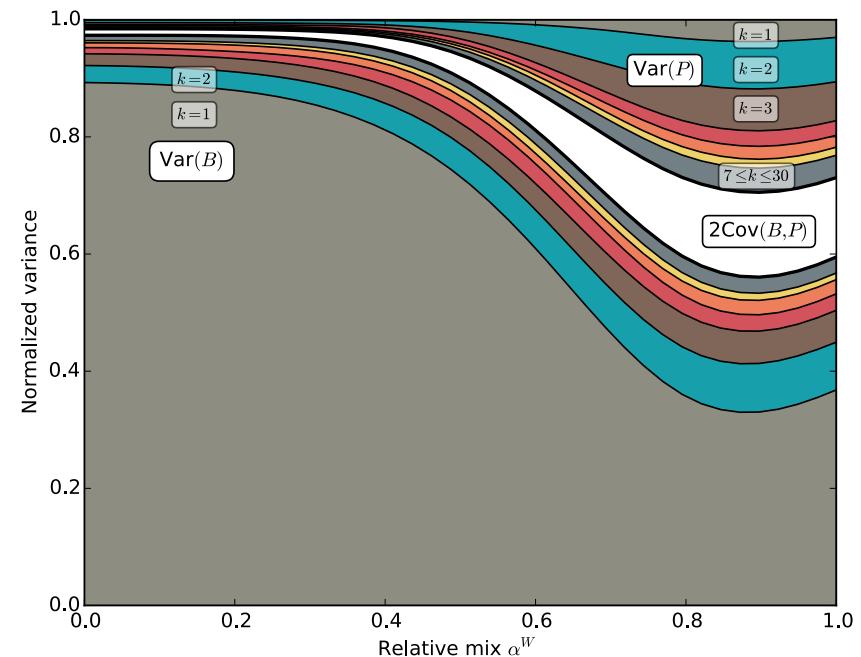
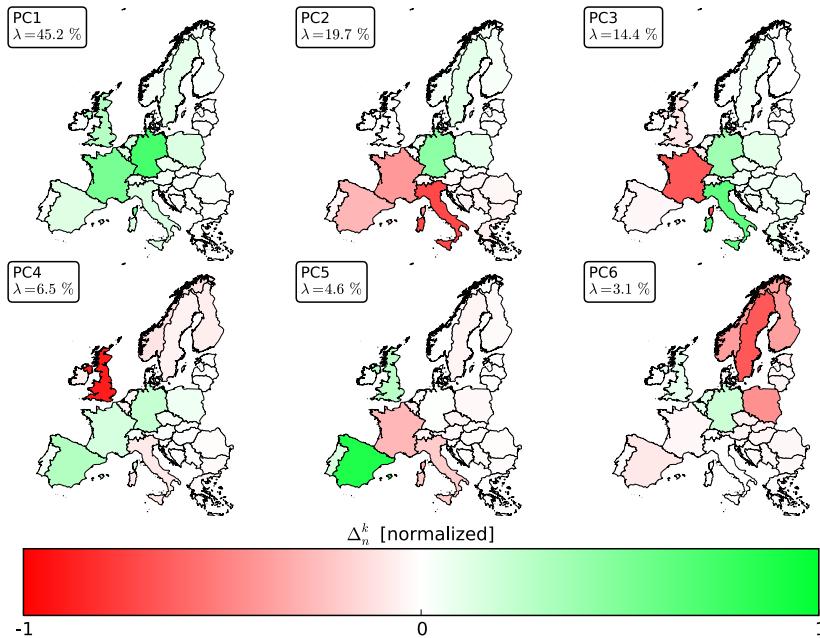
**RA Rodriguez et.al.:** Localized vs. synchronized exports across a highly renewable pan-European transmission network, **Energy, Sustainability & Society 5 (2015) 21.**

**B Tranberg et.al.:** Power flow tracing in a simplified highly renewable European electricity network, **New J. Phys. 17 (2015) 105002.**

**GB Andresen et.al.:** Validation of Danish wind time series from a new global renewable energy atlas for energy system analysis, **Energy (2015) accepted.**

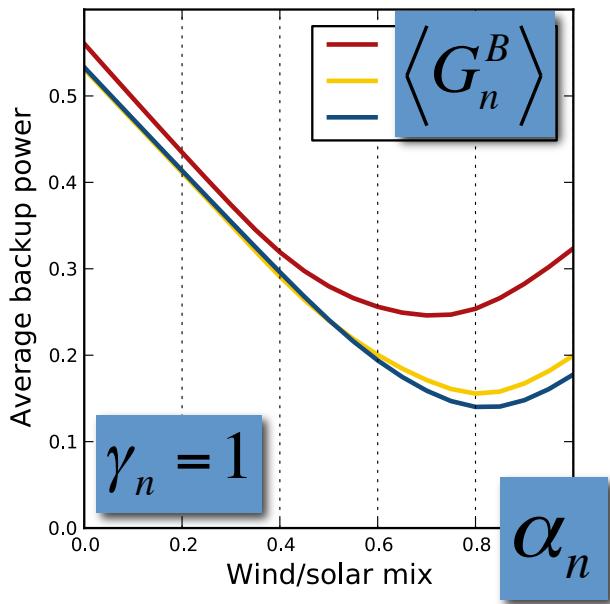
# SNEAK PREVIEW: principal component analysis

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

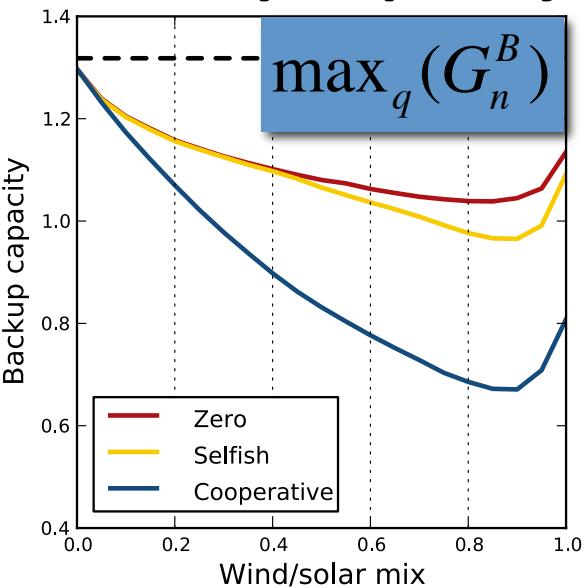


# SNEAK PREVIEW: an engineering approach to extreme backup values

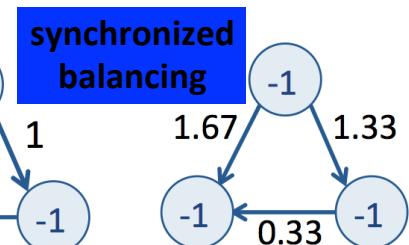
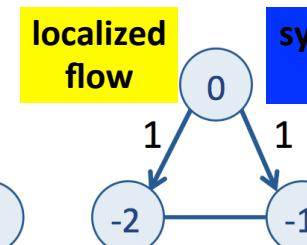
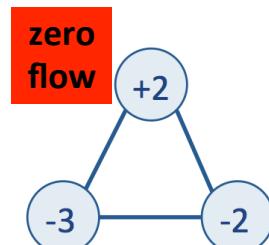
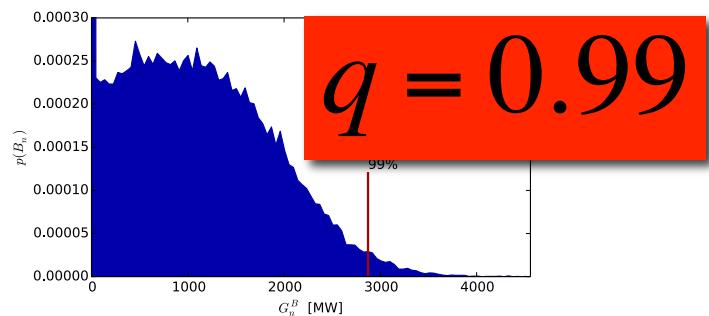
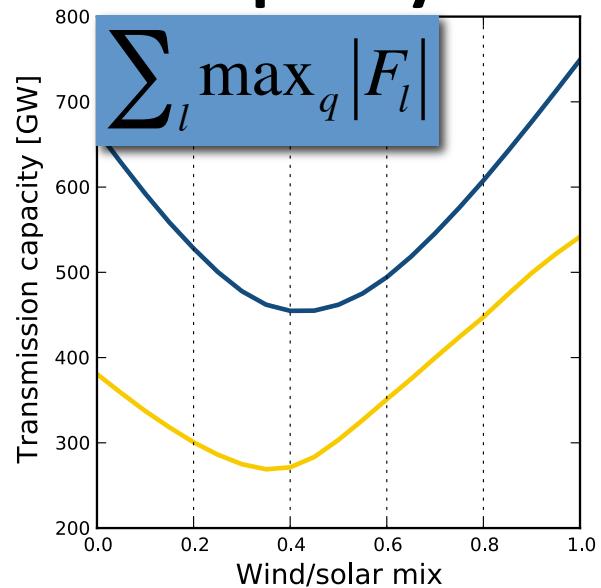
## backup energy



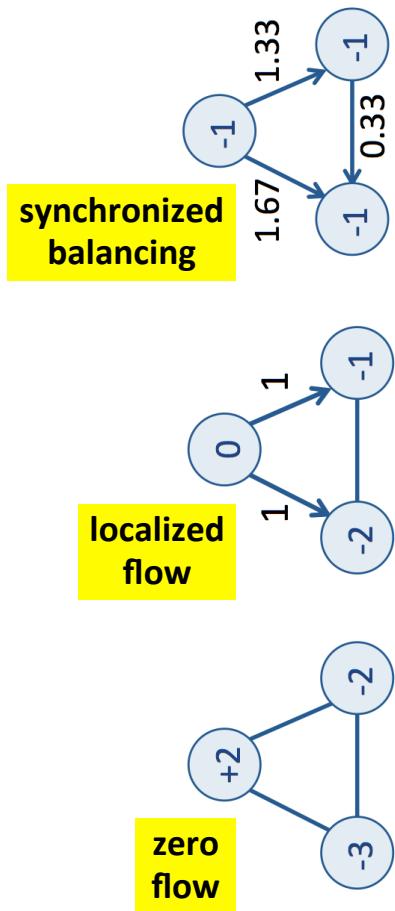
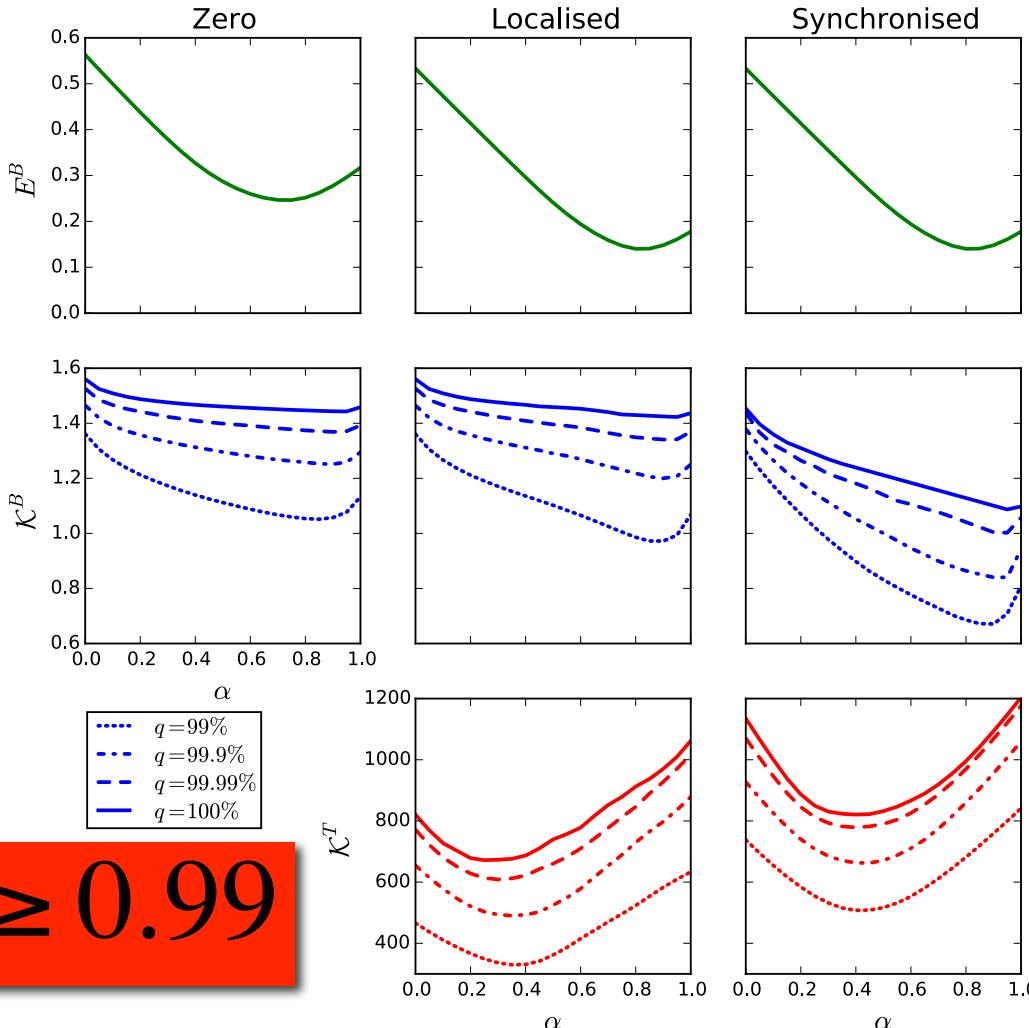
## backup capacity



## transmission capacity

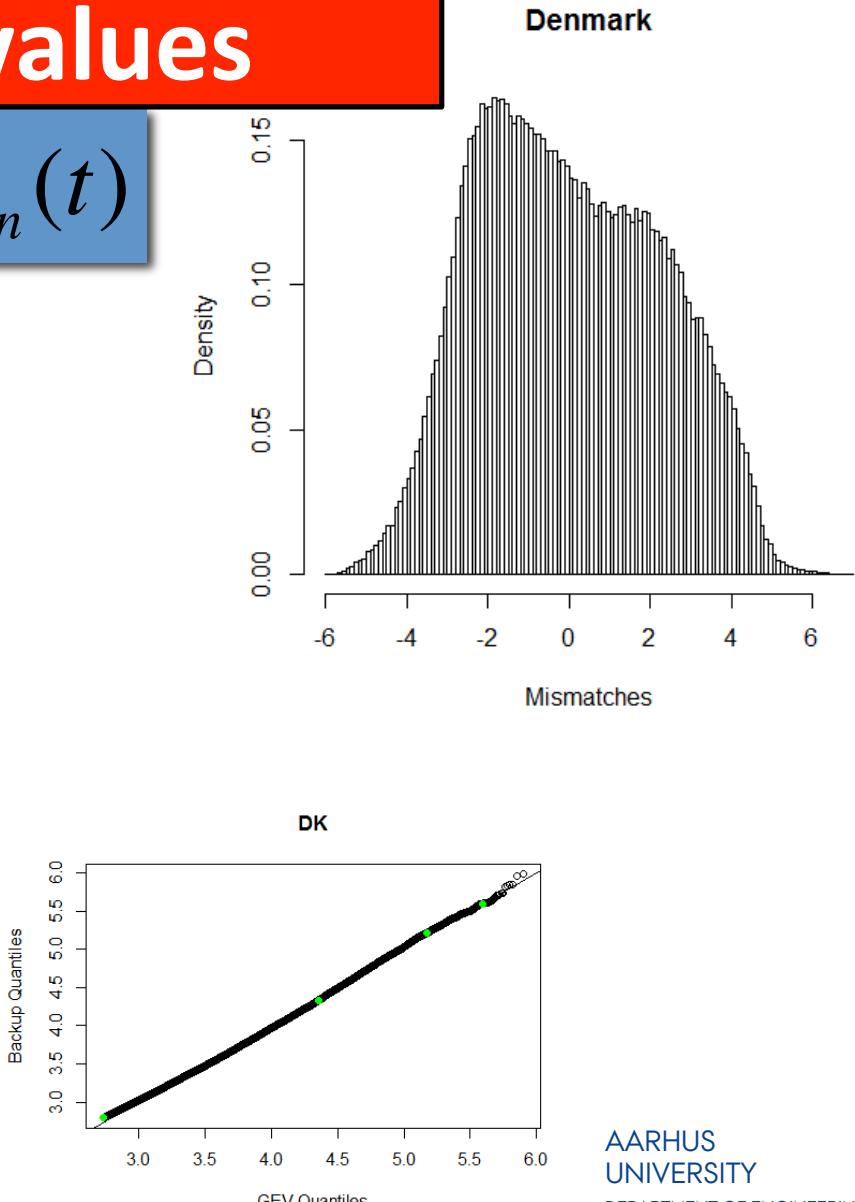
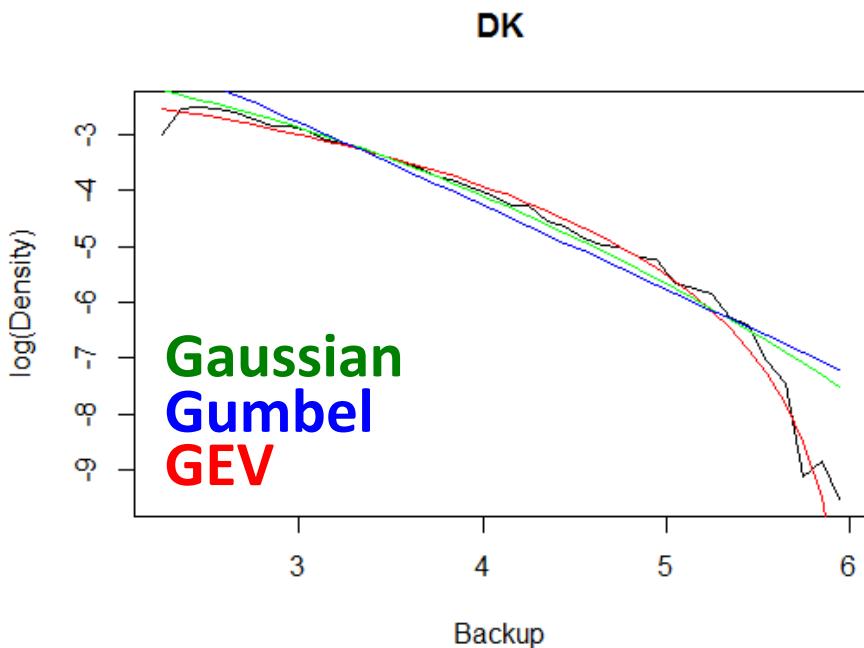


# SNEAK PREVIEW: an engineering approach to extreme backup values

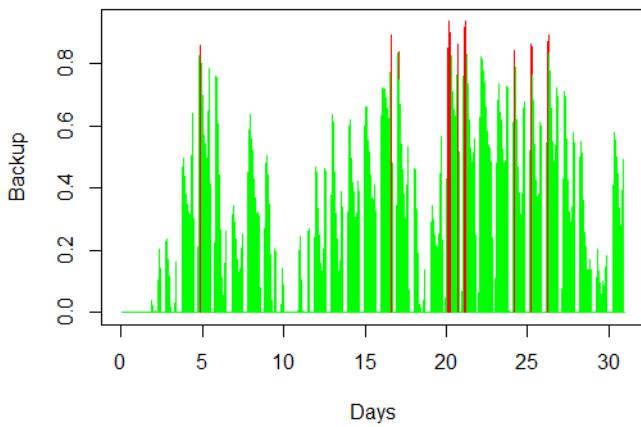


# SNEAK PREVIEW: an engineering approach to extreme backup values

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

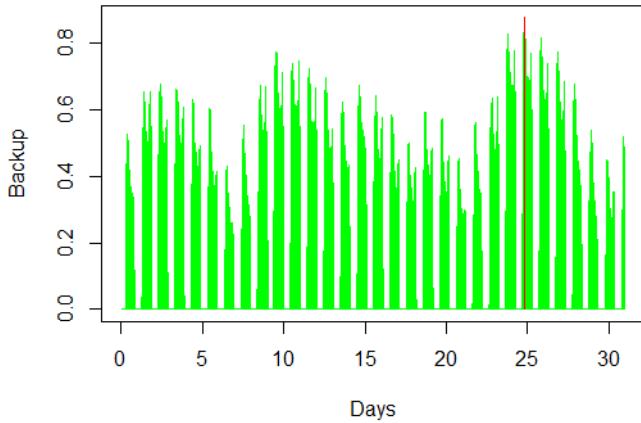


# SNEAK PREVIEW: an engineering approach to extreme backup values



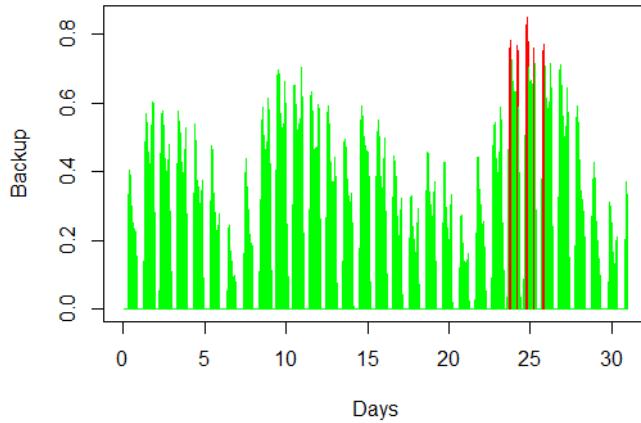
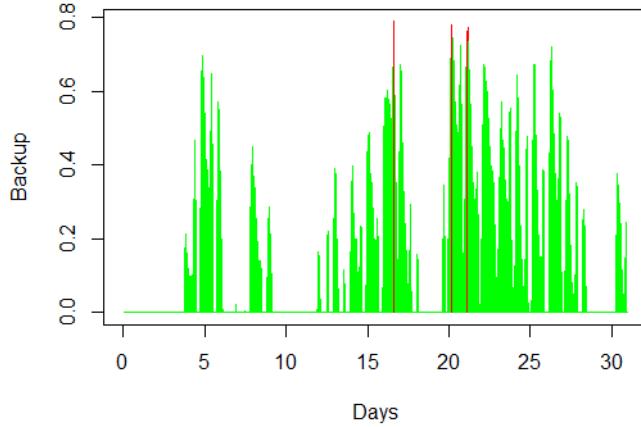
January

$$\alpha_{DK} = 0.6$$

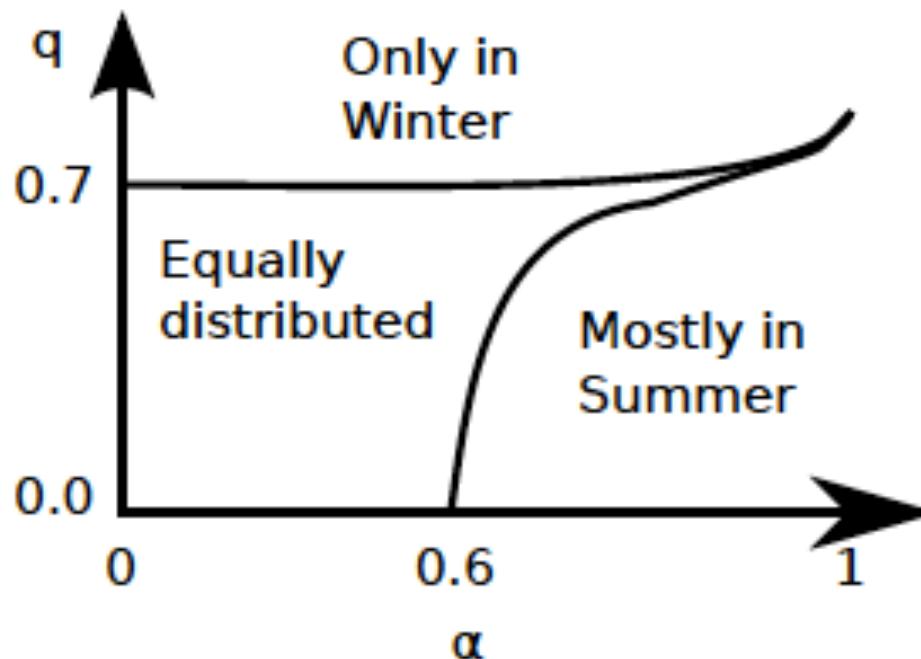


July

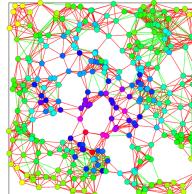
$$\alpha_{DK} = 0.8$$



# SNEAK PREVIEW: an engineering approach to extreme backup values



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[greiner@eng.au.dk](mailto:greiner@eng.au.dk)

- (1) Highly Renewable Energy Systems
- (2) Complex Networks  
- (3) Wind-farm Modeling + Optimization
- (4) Turbulence 

M Therkildsen (Master)  
P Nybroe (Master)  
J Otten (Master)  
J Bjerre (Master)  
J Herp (Master)  
U Poulsen (Assist Prof)

G Andresen	(Assit Prof)
N Skou-Nielsen	(Master)
C Poulsen	(Master)
M Raunbak	(Master)
A Ashfaq	(Master)
M Hansen	(Master)
K Holm	(Master)
M Rasmussen	(PostDoc)
R Rodriguez	(PhD)
B Tranberg	(Master)
E Eriksen	(Master)
S Kozarcanin	(Master)
M Dahl	(Master)
A Thomsen	(Master)
B Sairanen	(Master)
T Zeyer	(Master)
T Jensen	(Master)
A Søndergaard	(Master)
D Schlachtberger	(FIAS PhD)
J Hörsch	(FIAS PhD)
M Schäfer	(FIAS)
S Schramm	(FIAS)
S Becker	(FIAS PhD)
D Heide	(FIAS PhD)
A Kies	(U Oldenburg PhD)
L von Bremen	(ForWind)
C Hoffmann	(IWES)



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