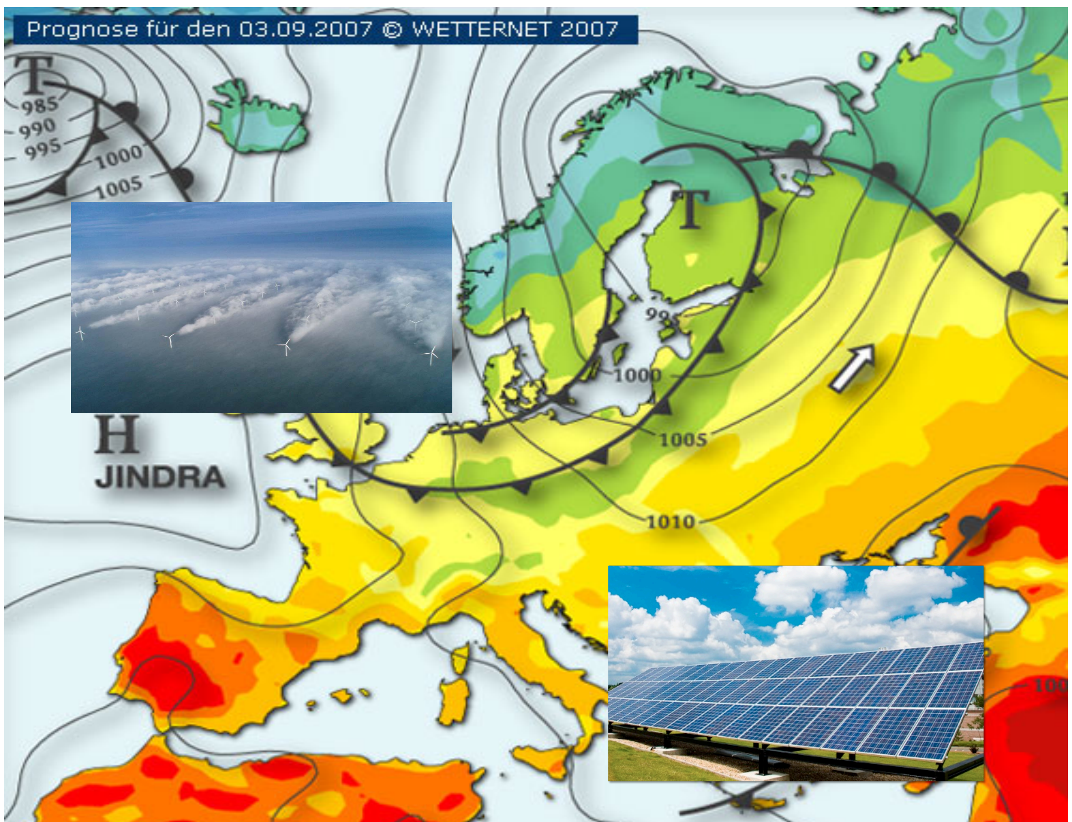
Mehr als die Vergangenheit und die Gegenwart
interessiert mich die Zukunft,
denn in ihr gedenke ich zu leben.

(Albert Einstein)

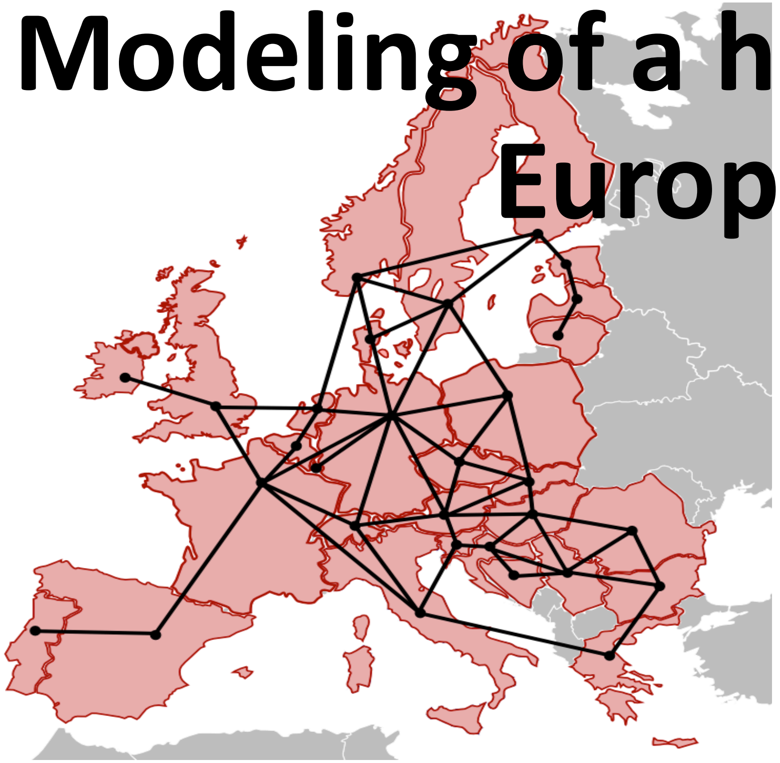
Technical and economic design of a simplified highly renewable European electricity system



Let the weather decide!

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

Modeling of a highly renewable European electricity system



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

actio = reactio

$$G_n^R(t) = G_n^W(t) + G_n^S(t)$$

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

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

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

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

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

$$F_l(t) = \sum_n PTDF_{ln} P_n(t)$$

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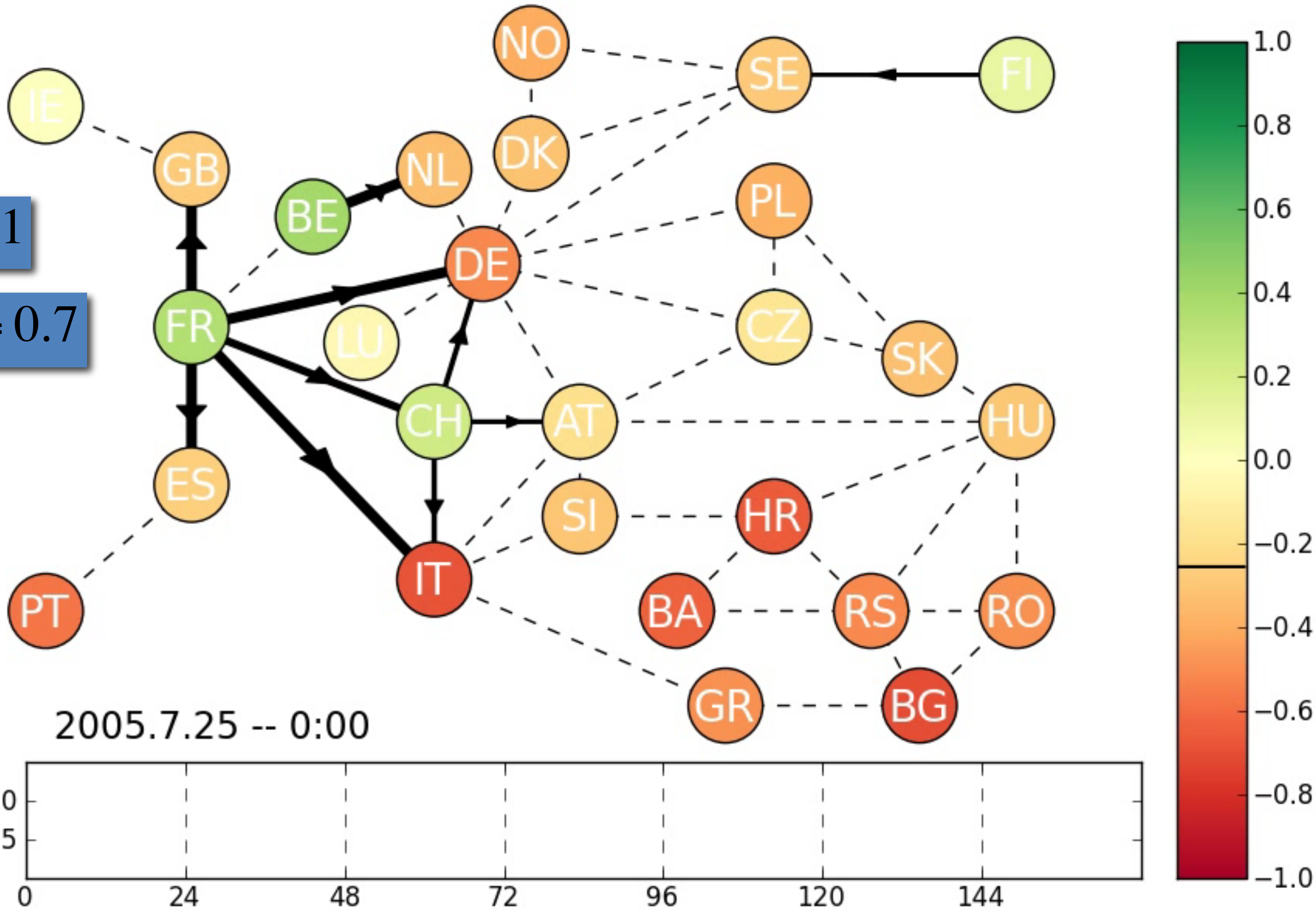
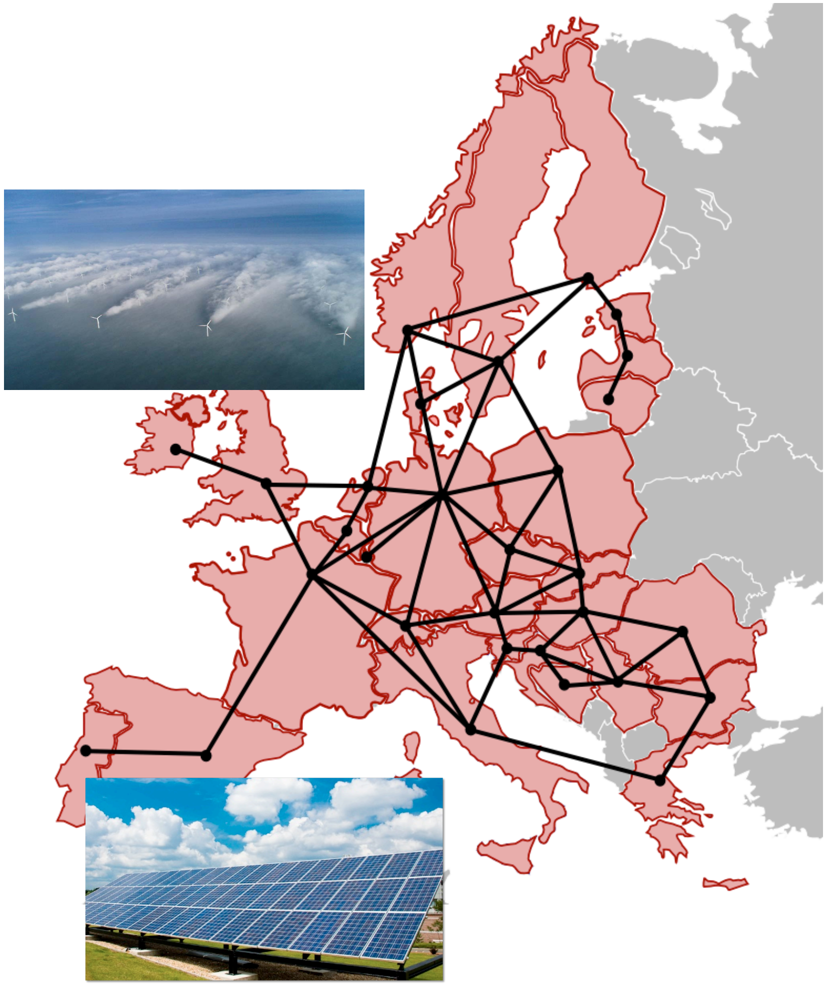
$$G_n^R(t) - L_n(t) = B_n(t) + P_n(t)$$

$\gamma_n = 1$

$\alpha_n = 0.7$





How much …

… wind energy?

… solar PV energy?

… backup energy + power?

… transmission?

… storage?

What are important temporal and spatial scales?

I. Time scales: storage
II. Spatial scales: backup + transmission
III. Costs
IV. Outlook

I. Time scales: how much storage?

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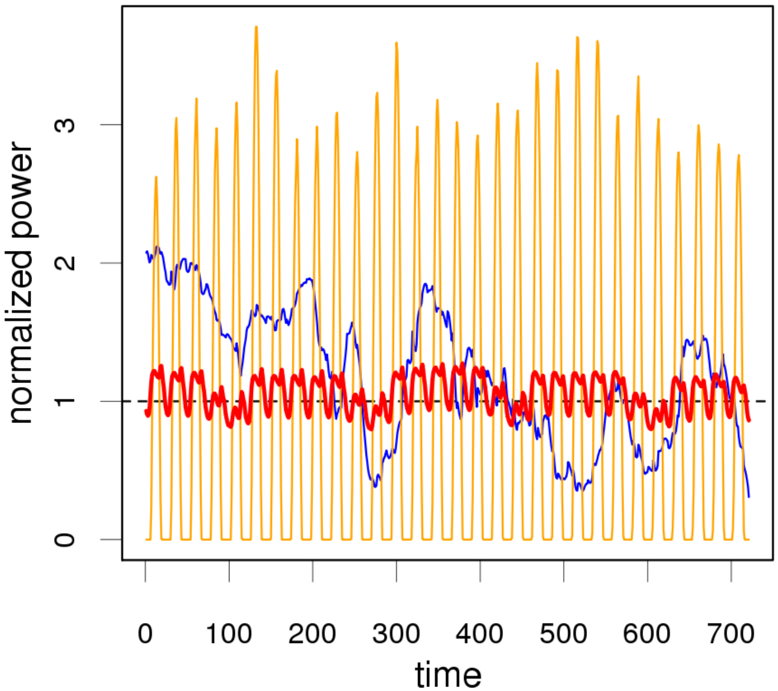
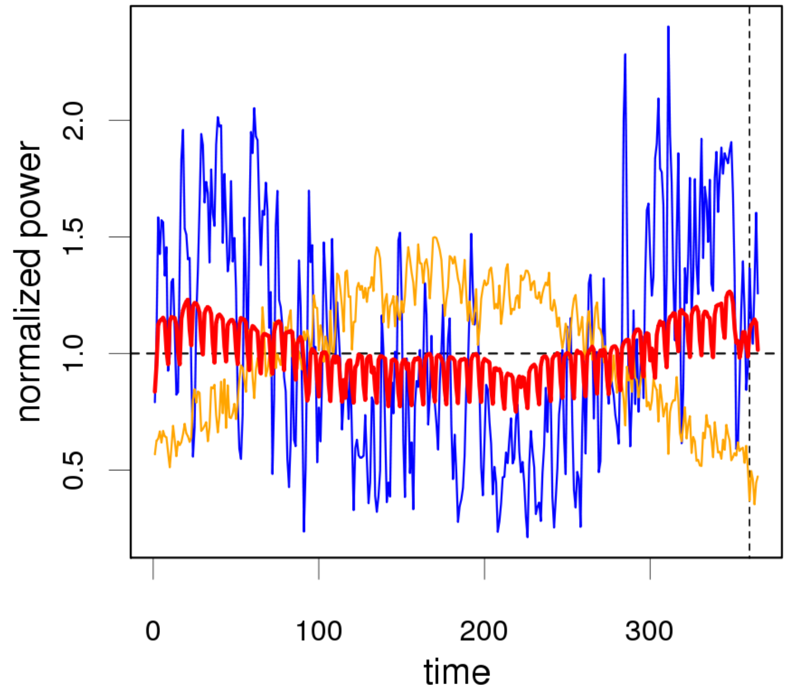
European aggregation:
Wind + Solar power generation + Load





3 TIME SCALES:

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

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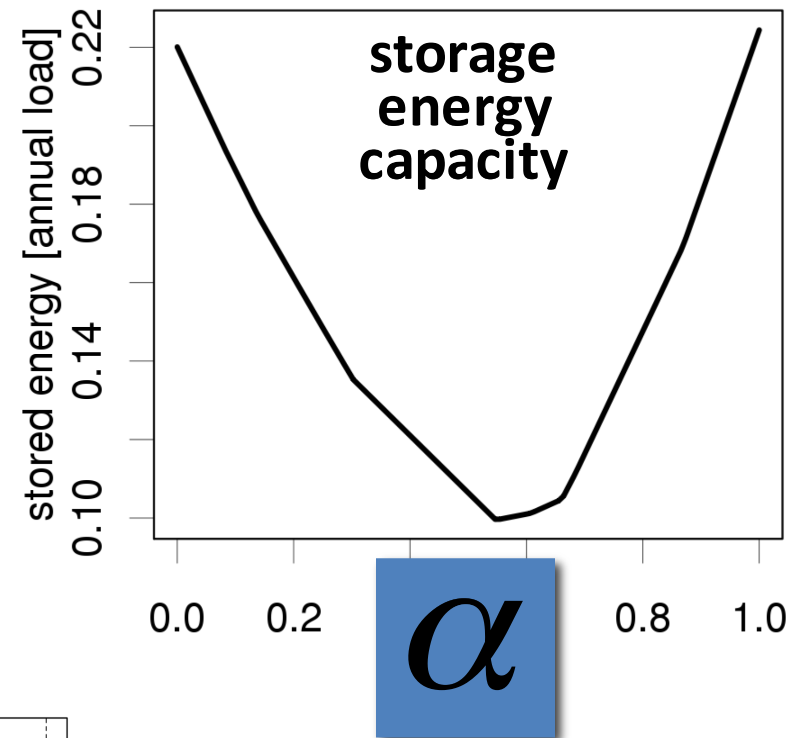
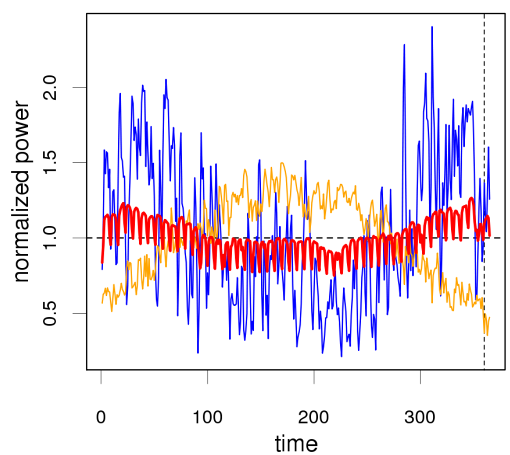
How much storage? @ 100% penetration in EU

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

$$C_E = \max_t S(t) - \min_t S(t)$$

$\eta_{in} = \eta_{out} = 1$



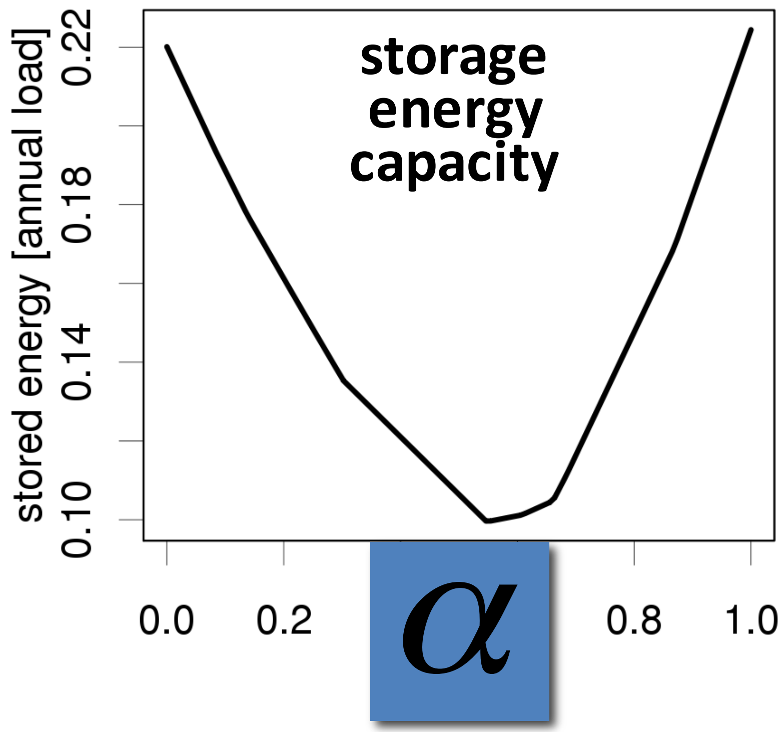


Seasonal optimal mix
= 60% wind power
+ 40% solar power

How much storage? @ 100% penetration in EU

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

$$= 340 \text{ TWh}$$



NOT POSSIBLE:
Pumped Hydro,
Compressed Air

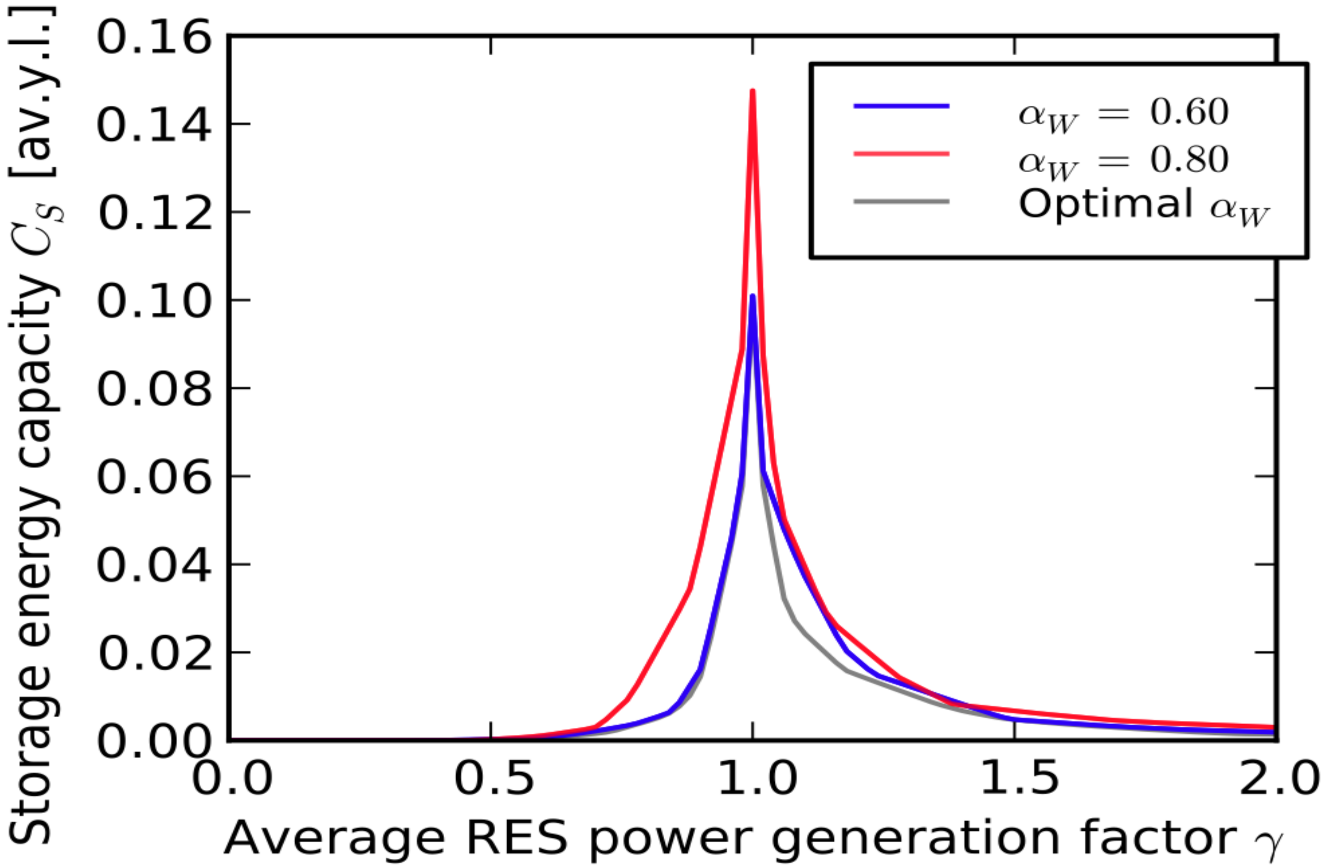
POSSIBLE:
H_2 storage
25 TWh = 0.008 av.y.l.
6h “battery” storage
2.2 TWh = 0.0007 av.y.l

annual consumption (2009) = 3360 TWh

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

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

Storage Singularity



renewable penetration

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

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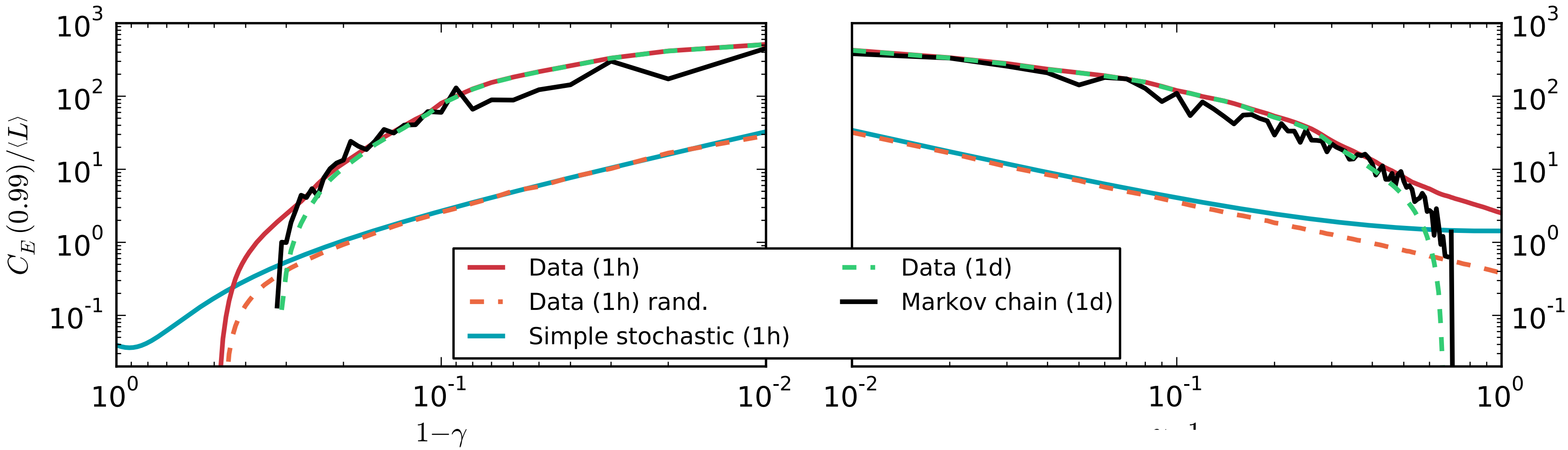
Storage Singularity



$$C_E(\text{random}) << C_E(\text{original})$$

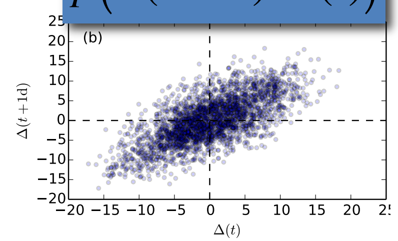
$$C_E(\text{random}) \propto \frac{1}{|\gamma - 1|^{\delta}}$$

$$\delta = 1$$

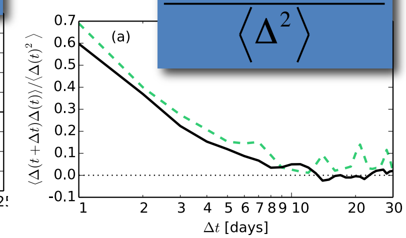
$$C_E(1\text{h}) \approx C_E(1\text{d})$$

temporal correlations

$$p\big(\Delta(t+1\text{d}) \,|\, \Delta(t)\big)$$

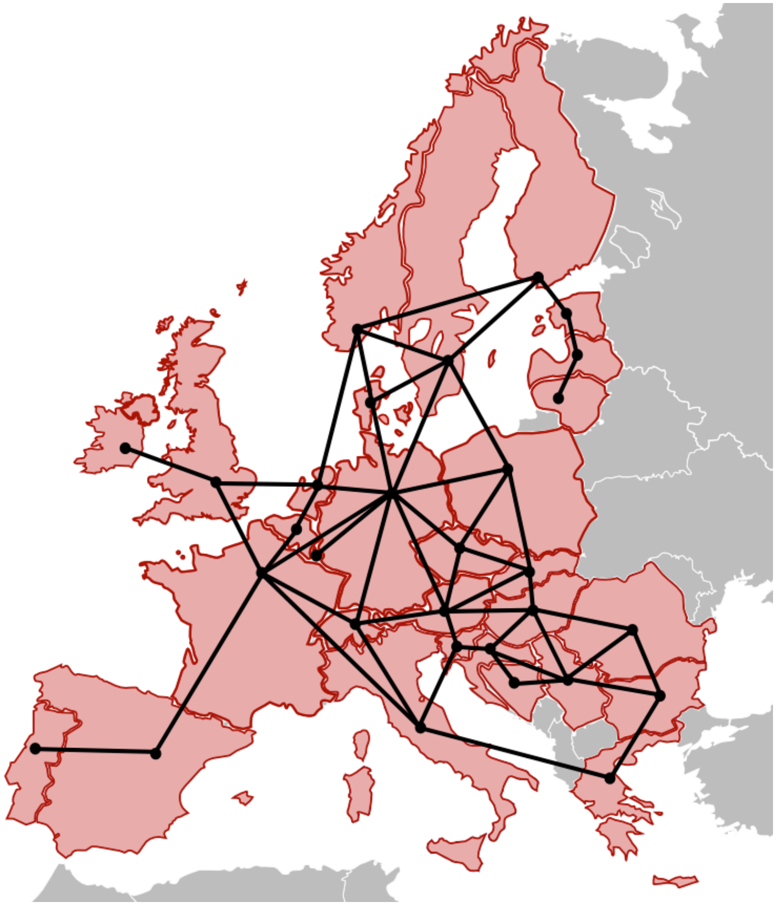


$$\frac{\langle \Delta(t+\tau)\, \Delta(t) \rangle}{\langle \Delta^2 \rangle}$$



synoptic time scale

II. Spatial scales: how much backup + transmission?



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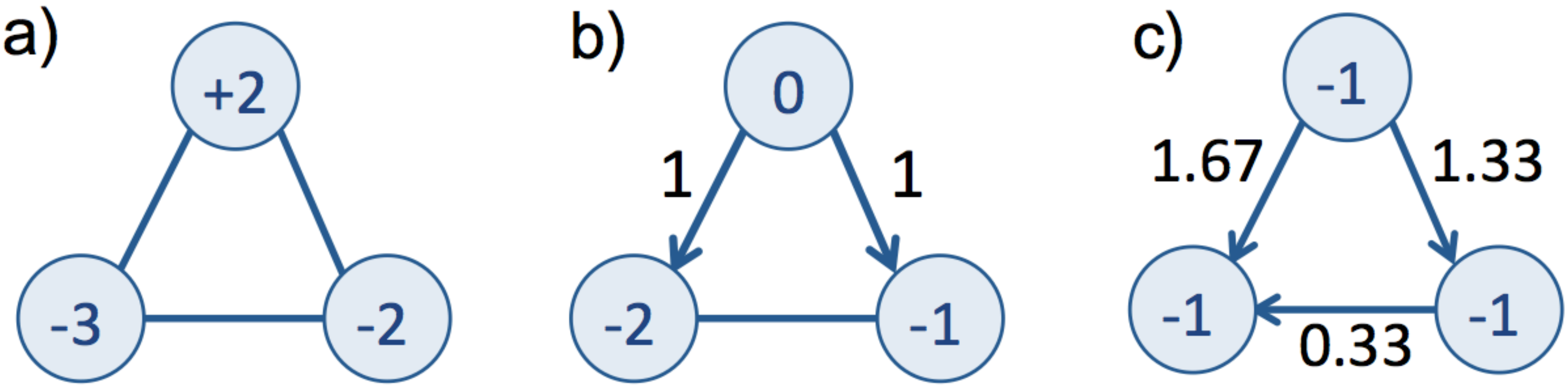
Coupling schemes between transmission and backup

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



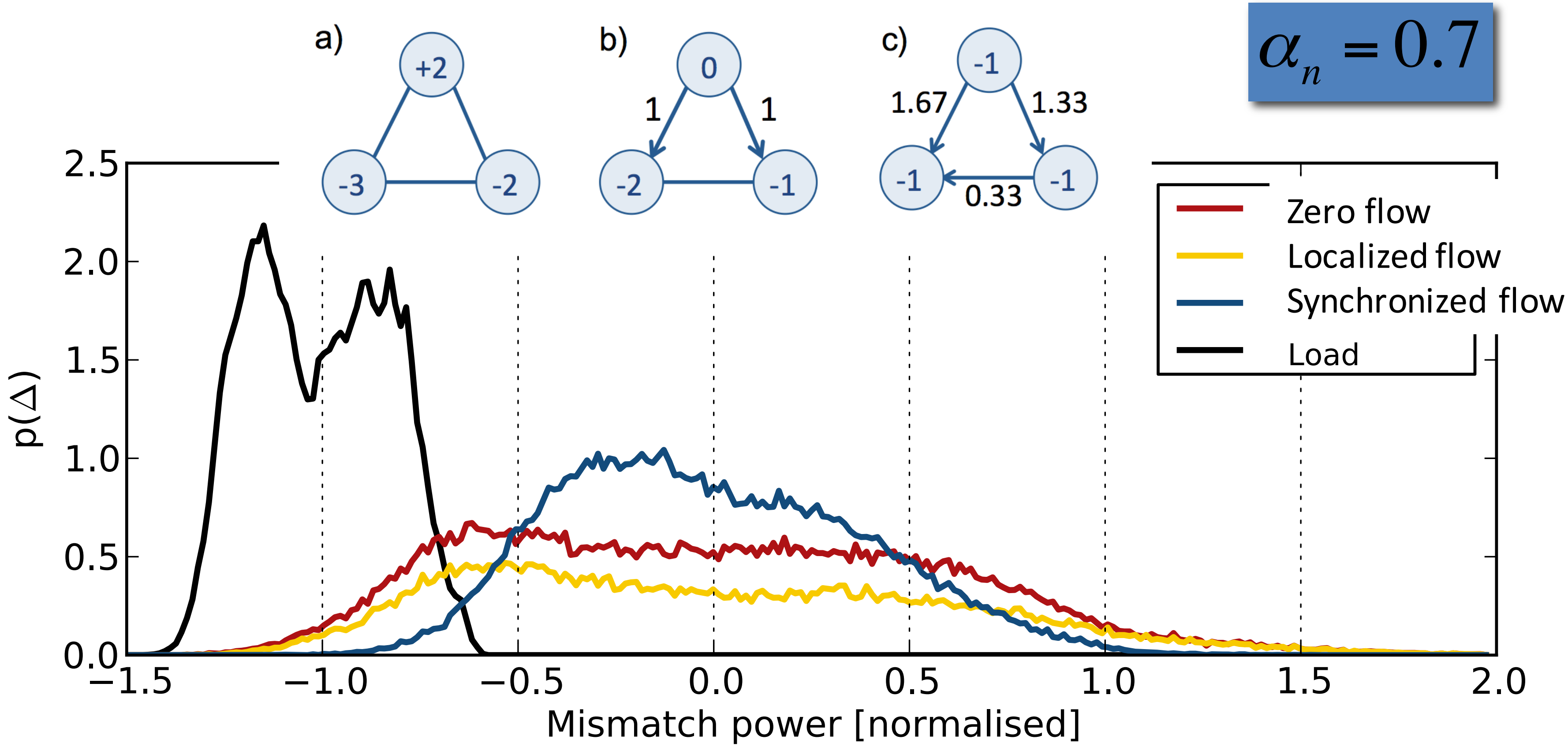
a)	b)	c)
$P_n(t) = 0$	$\min\left(\sum_n G_n^B(t)\right)$	$B_n(t) = \beta(t)\langle L_n \rangle$
	$\min\left(\sum_l F_l^2(t)\right)$	$\beta(t) = \dfrac{\sum_n \Delta_n(t)}{\sum_n \langle L_n \rangle}$
Zero flow	**Localized flow**	**Flow with synchronized balancing**

Balancing distribution (Germany)

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

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

$$\alpha_n = 0.7$$



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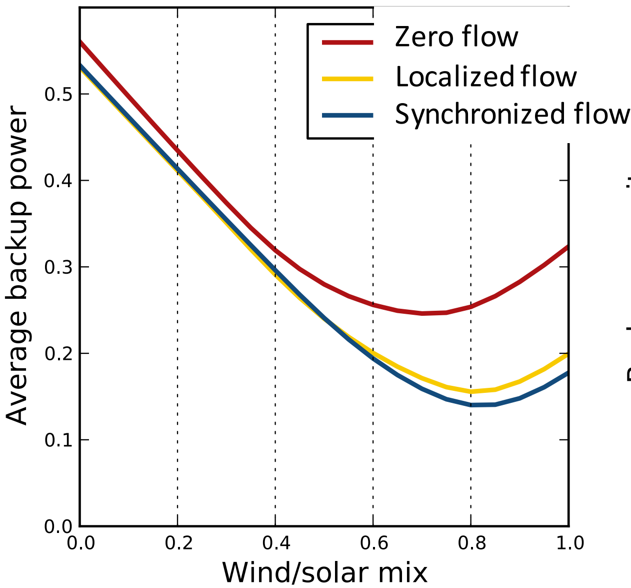
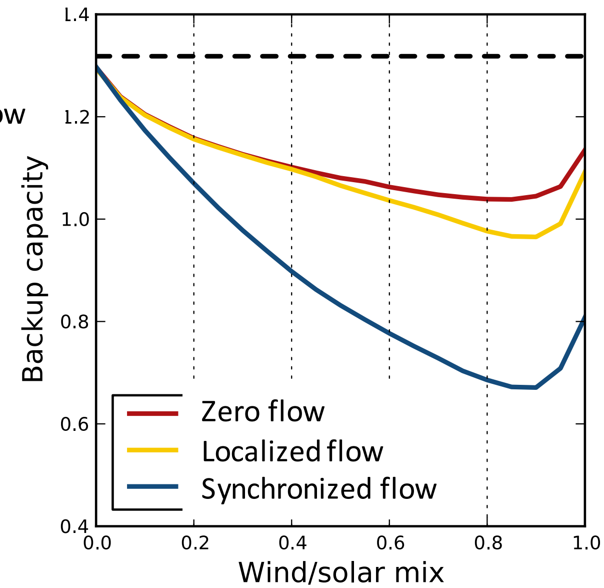
backup energy

$$\langle G_n^B \rangle$$



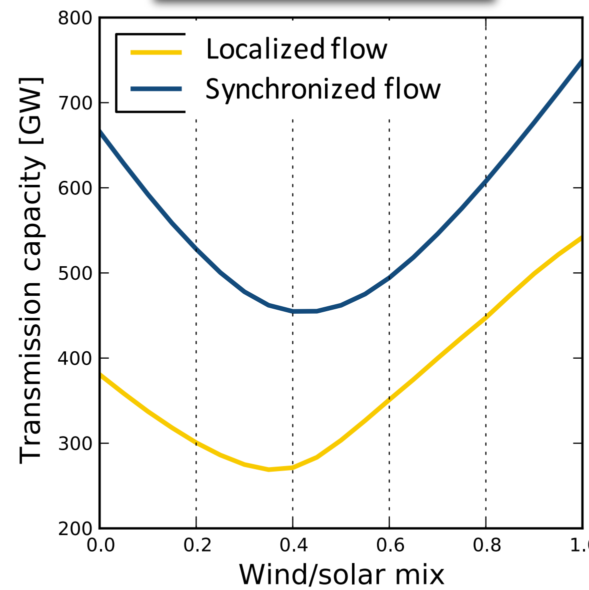
backup capacity

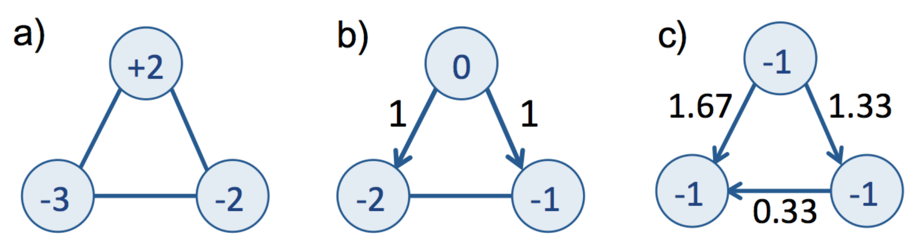
$$max_q (G_n^B)$$



transmission capacity

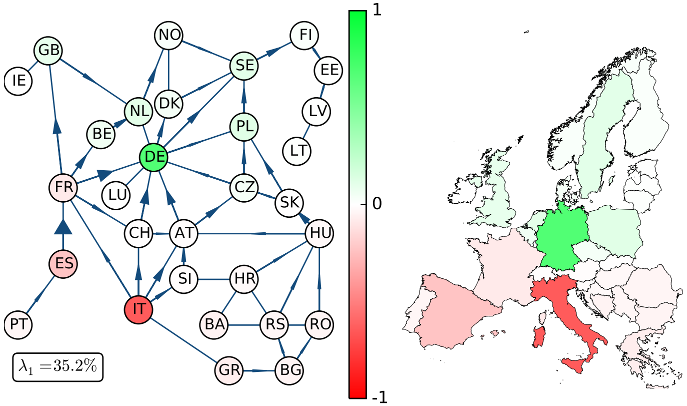
$$\sum_l \max_q |F_l|$$

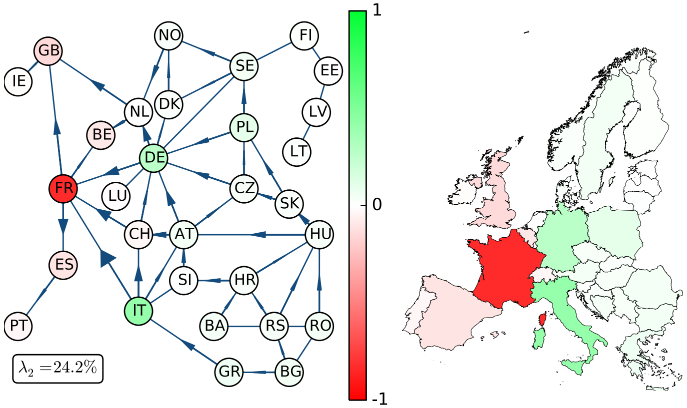


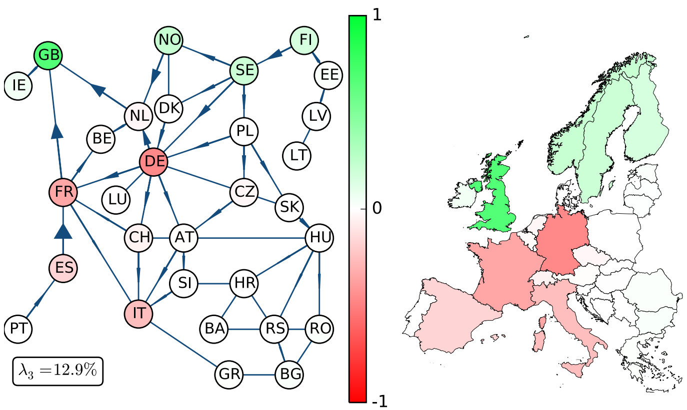


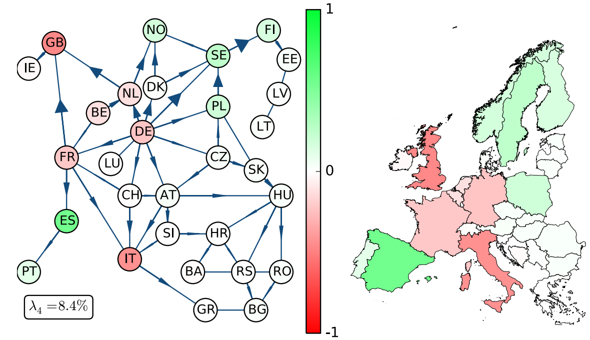
$$\left\langle G_n^{RES} \right\rangle = \left\langle L_n \right\rangle$$

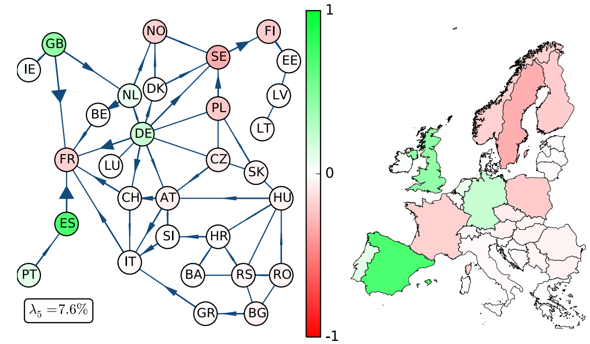
Principal flow patterns

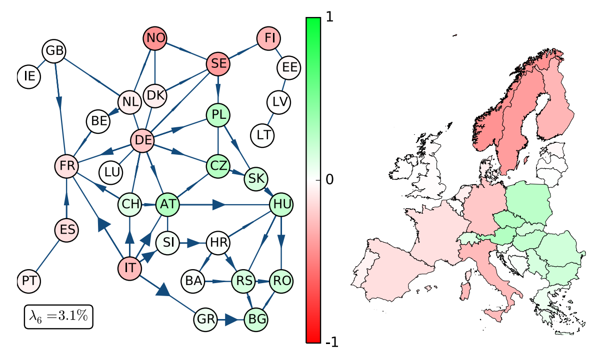






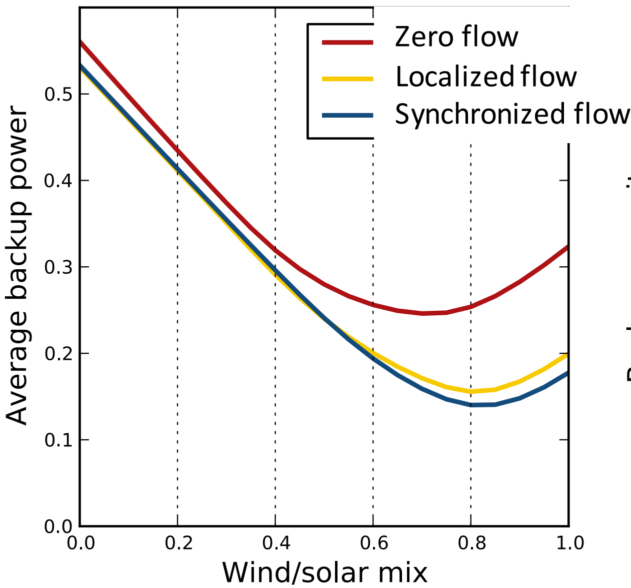






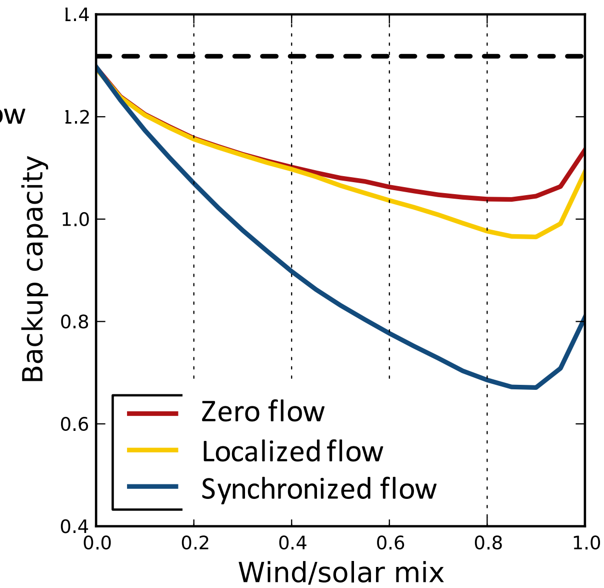
backup energy

$\langle G_n^B \rangle$



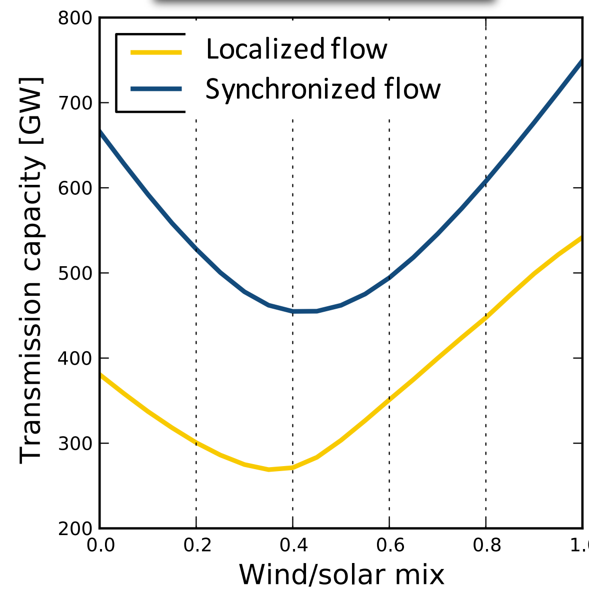
backup capacity

$max_q(G_n^B)$



transmission capacity

$\sum_l \max_q |F_l|$



Zero flow

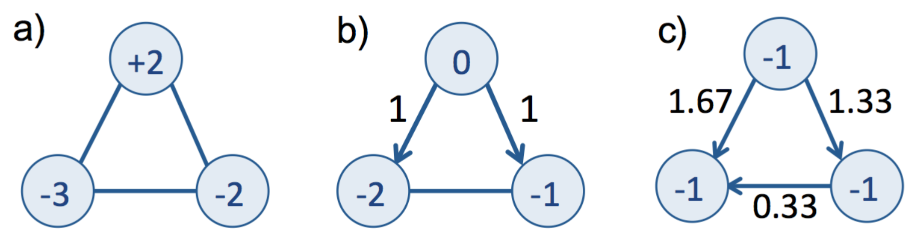
$\langle G_n^B \rangle \approx 0.24$

$\alpha_n \approx 0.70$

Flow with synch. bal.

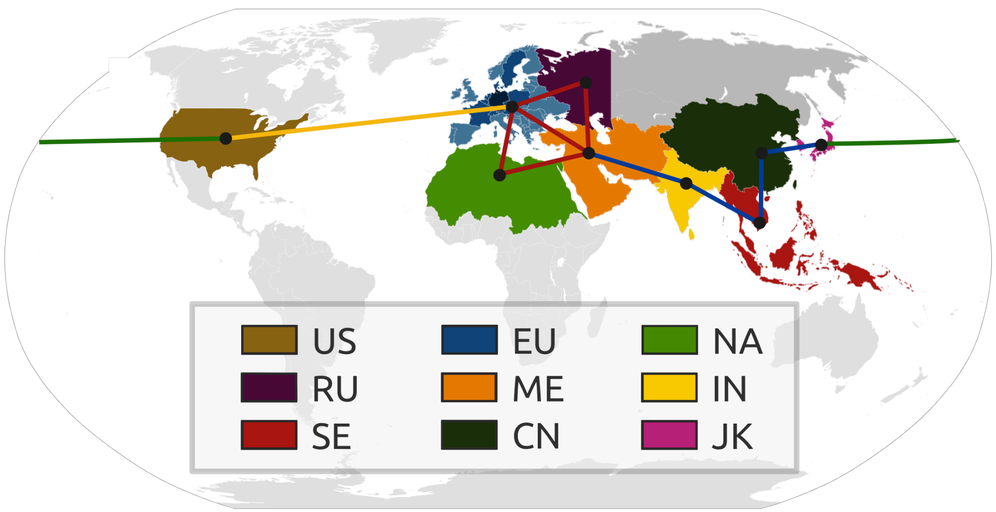
$\langle G_{EU}^B \rangle \approx 0.15$

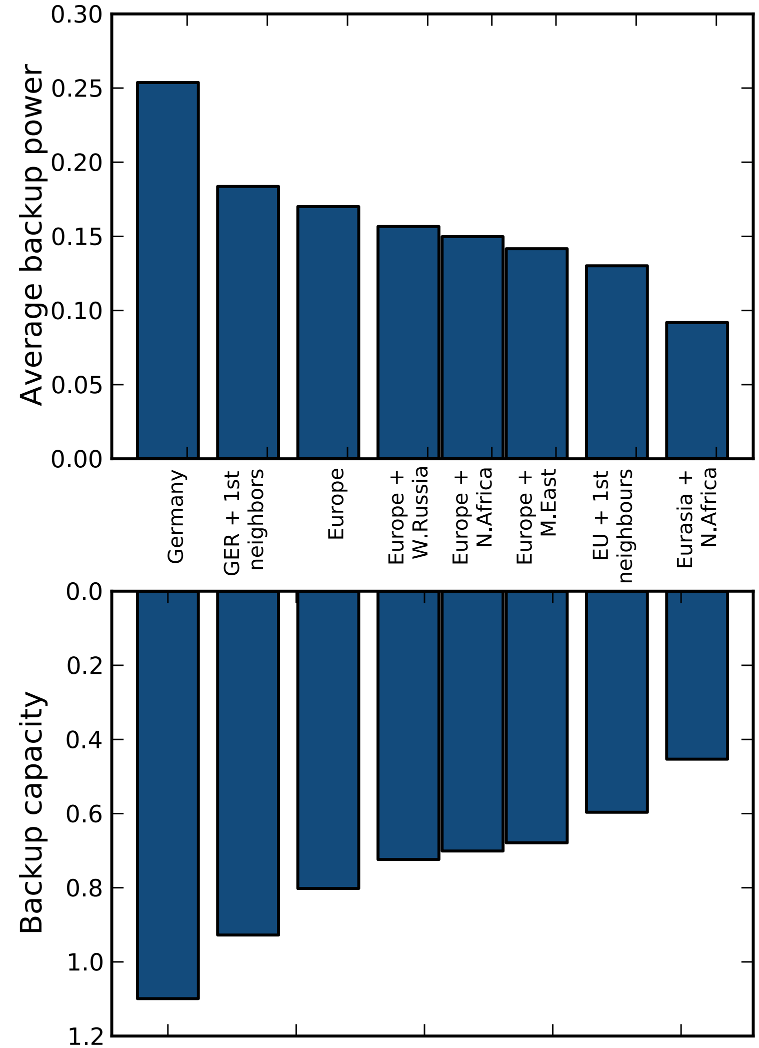
$\alpha_{EU} \approx 0.80$

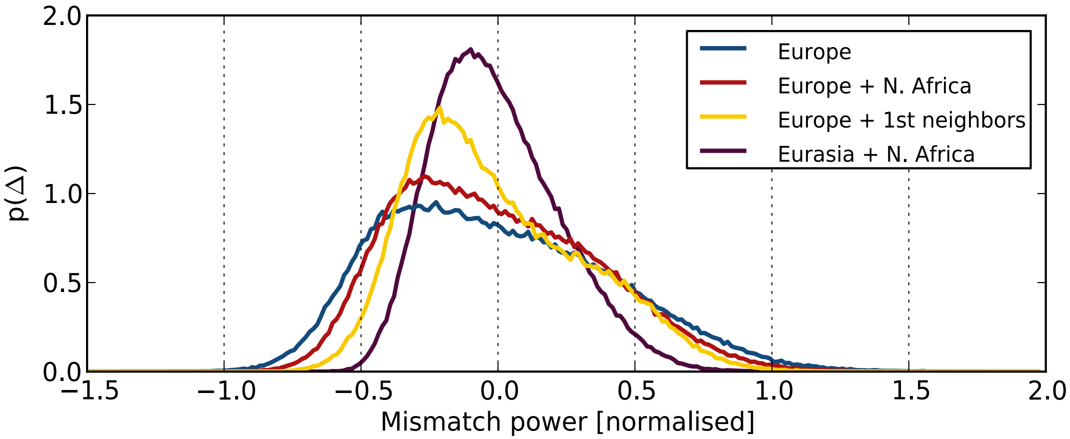


$\langle G_n^{RES} \rangle = \langle L_n \rangle$

beyond EU: world-wide grid







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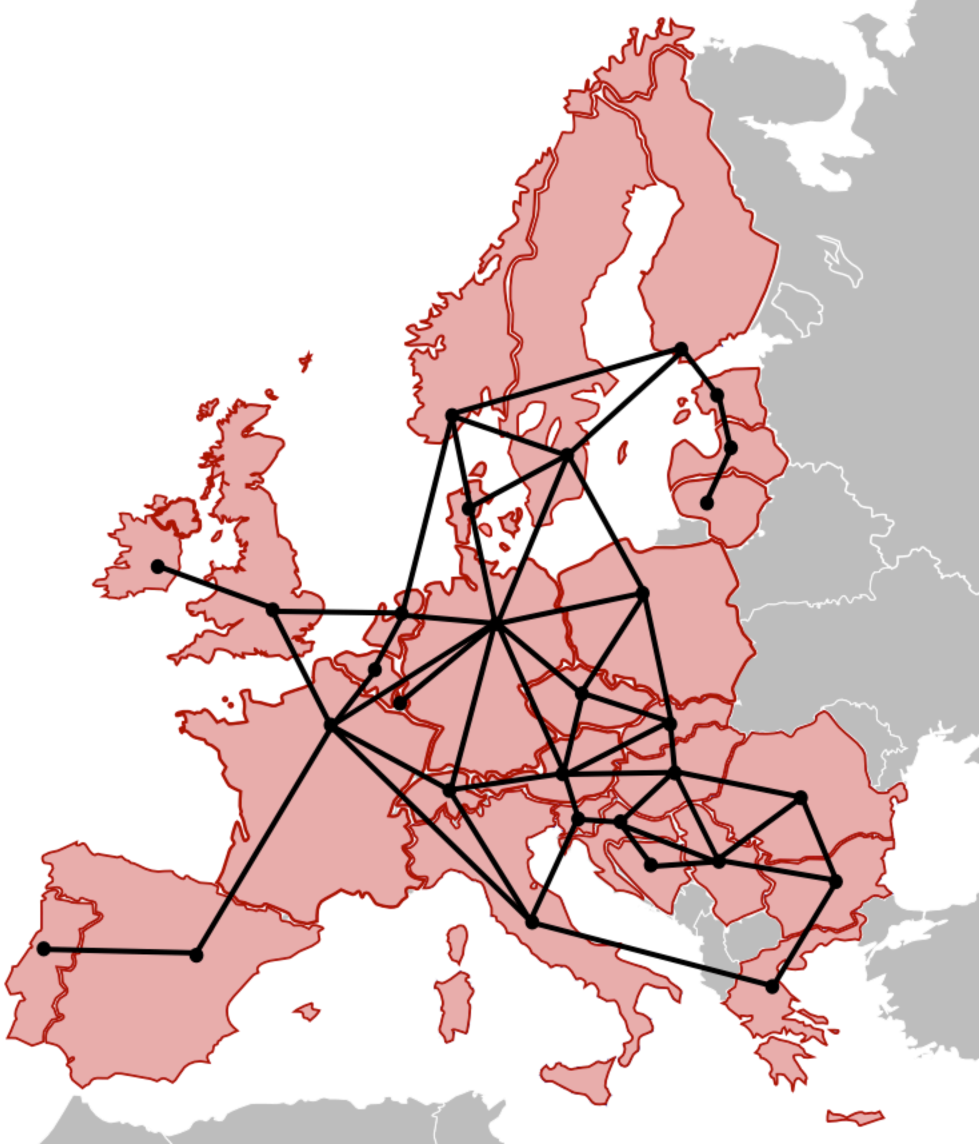
III. Costs



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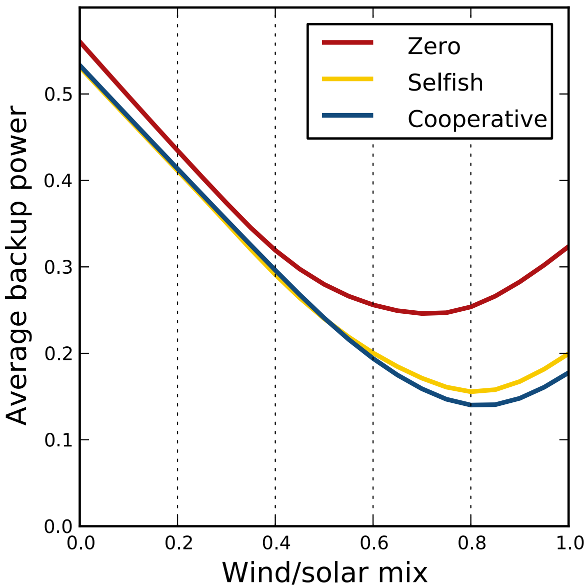
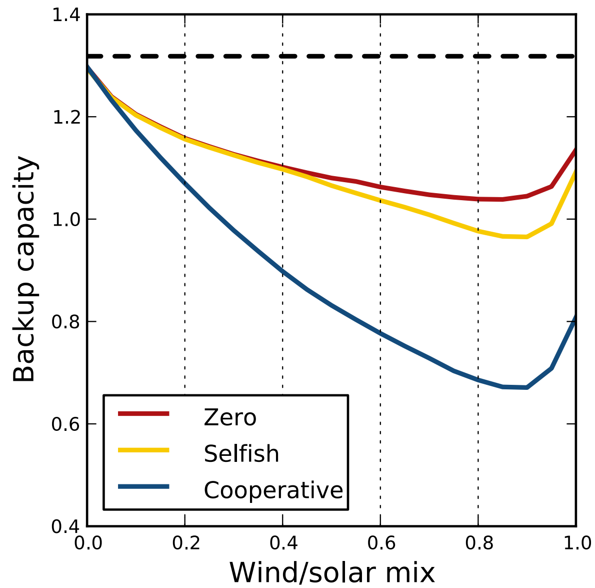
backup energy

$\langle G_n^B \rangle$



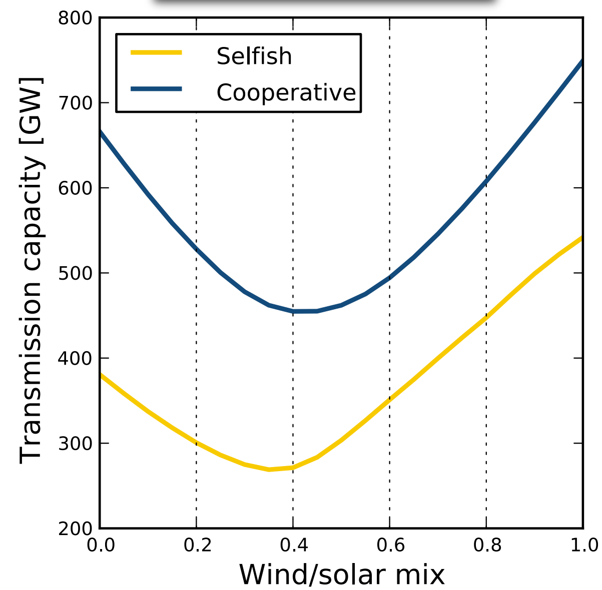
backup capacity

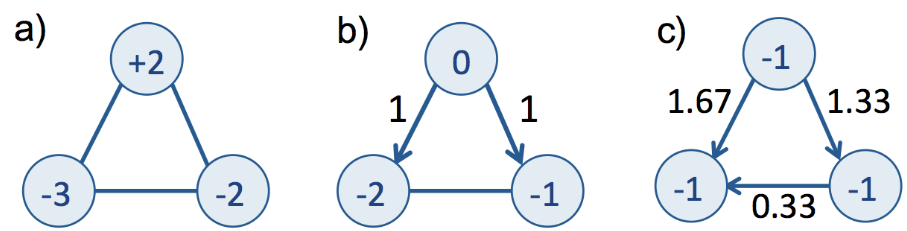
$max_q (G_n^B)$



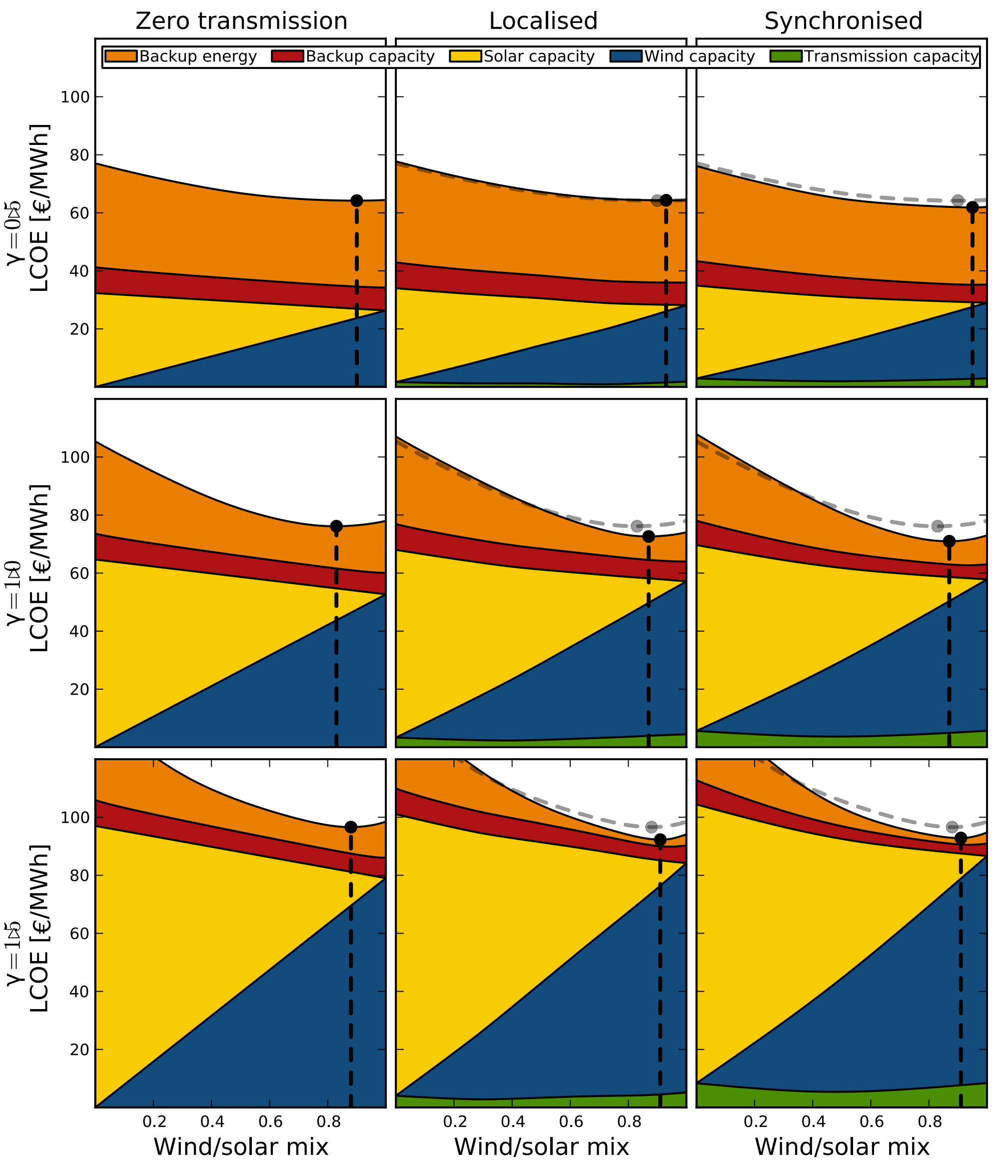
transmission capacity

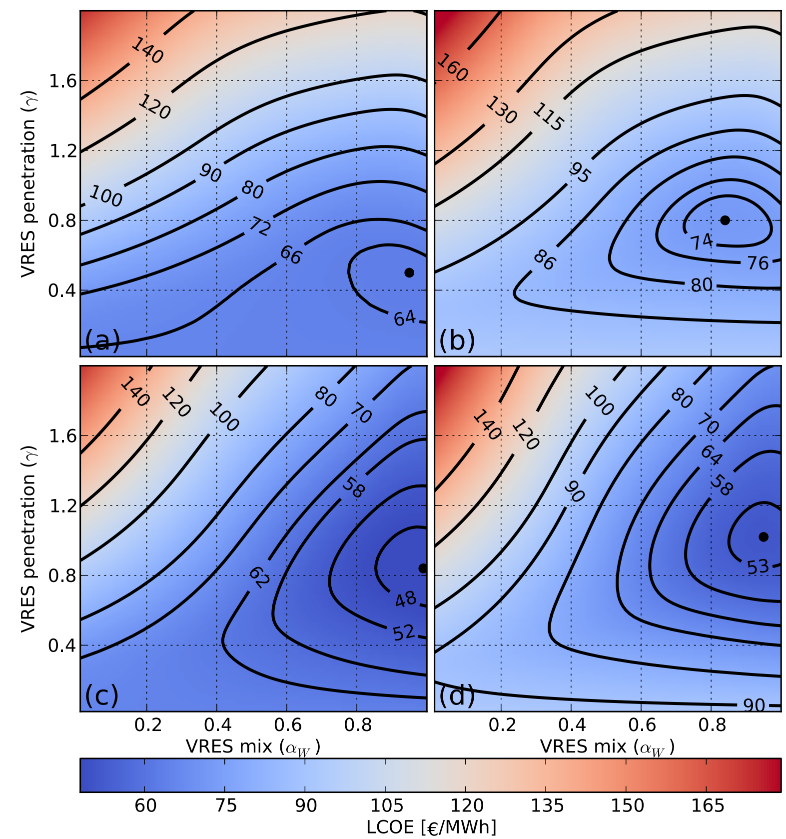
$\sum_l \max_q |F_l|$

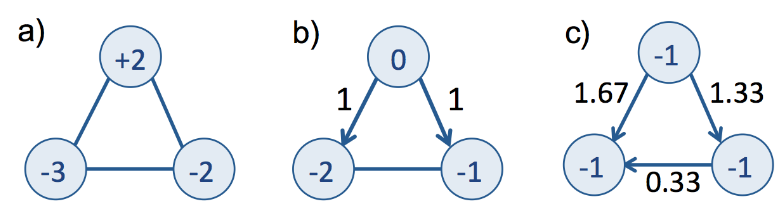


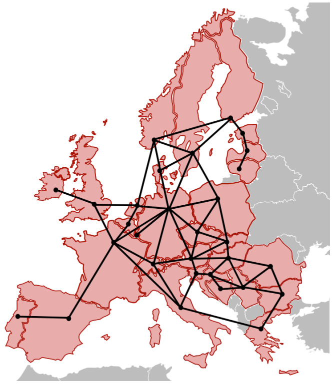


Levelized Cost of SYSTEM Energy

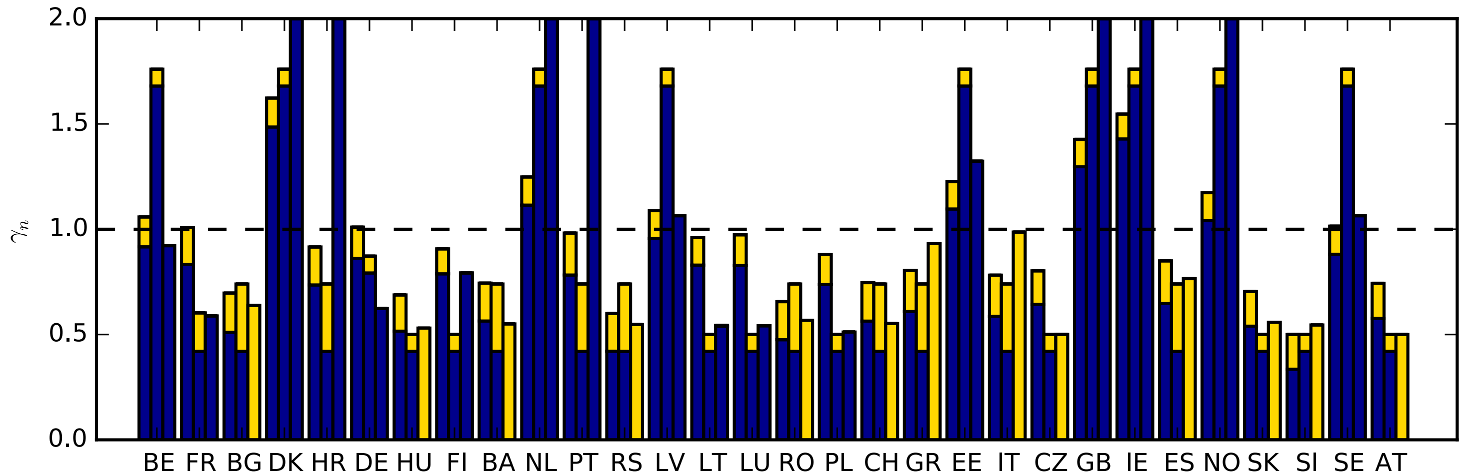


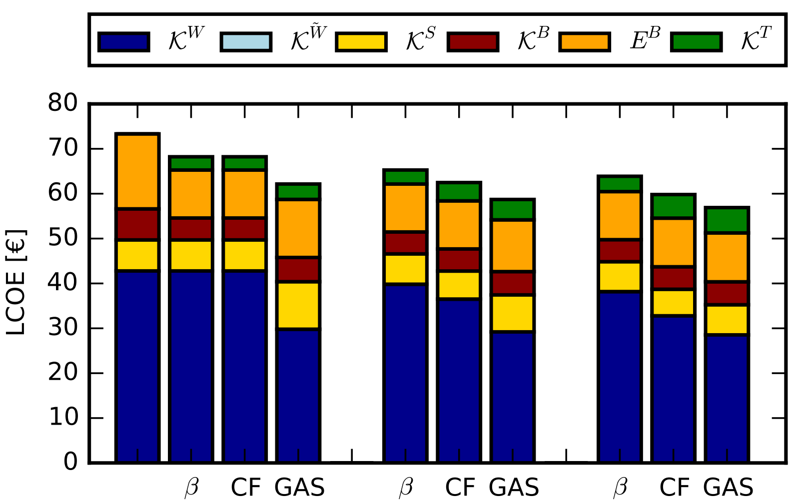


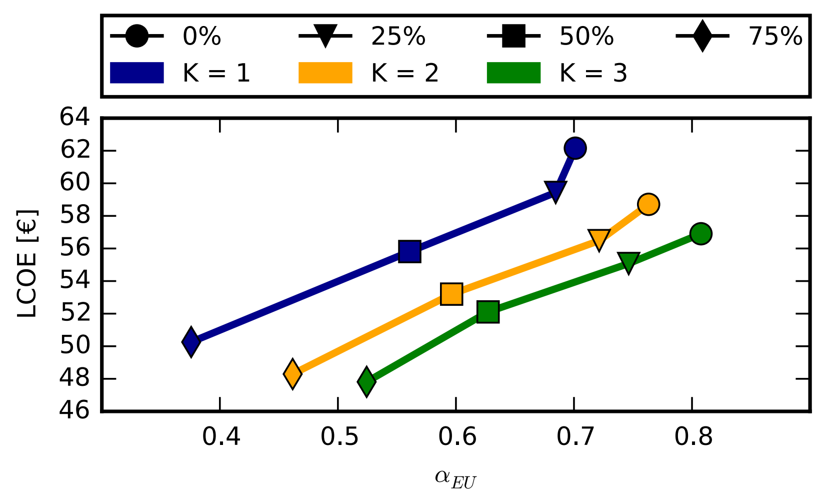




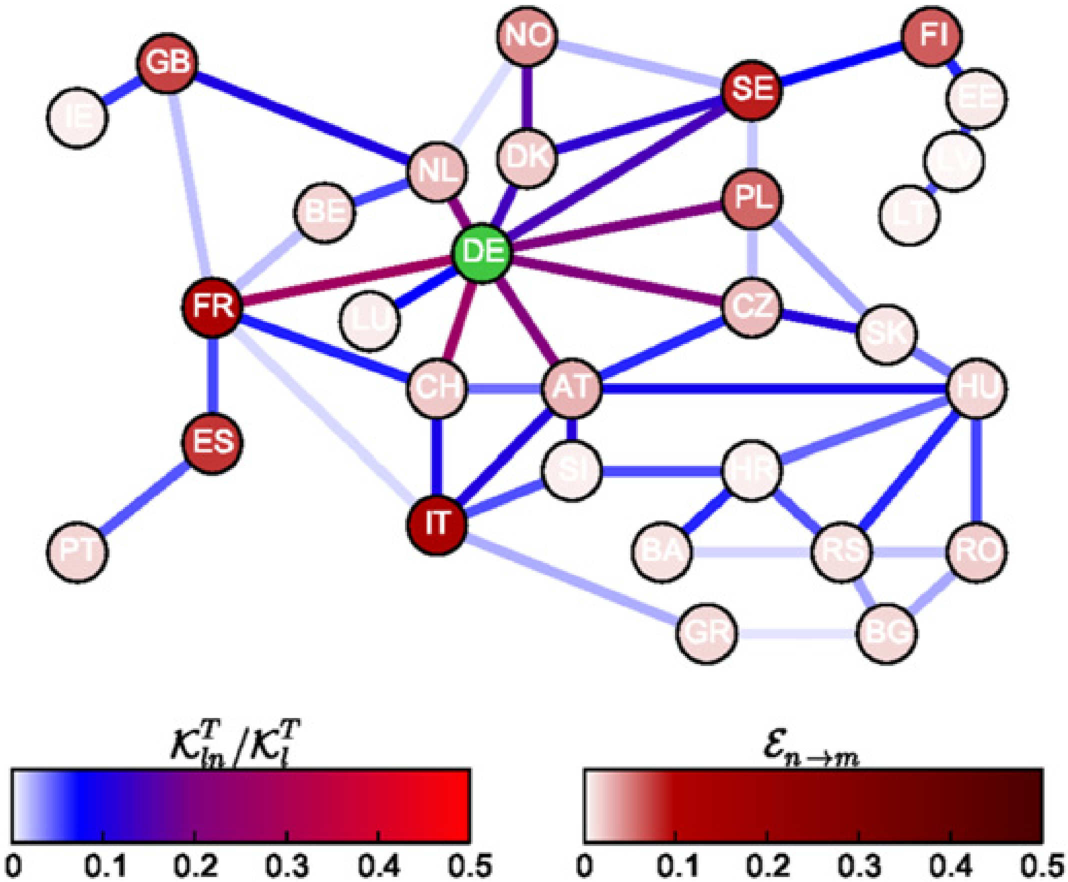
Heterogeneous renewable electricity networks







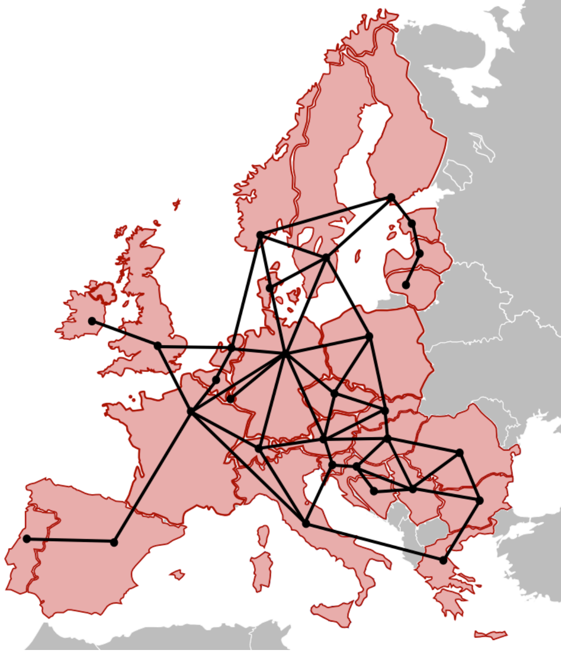
Who pays for the heterogeneity?



flow tracing

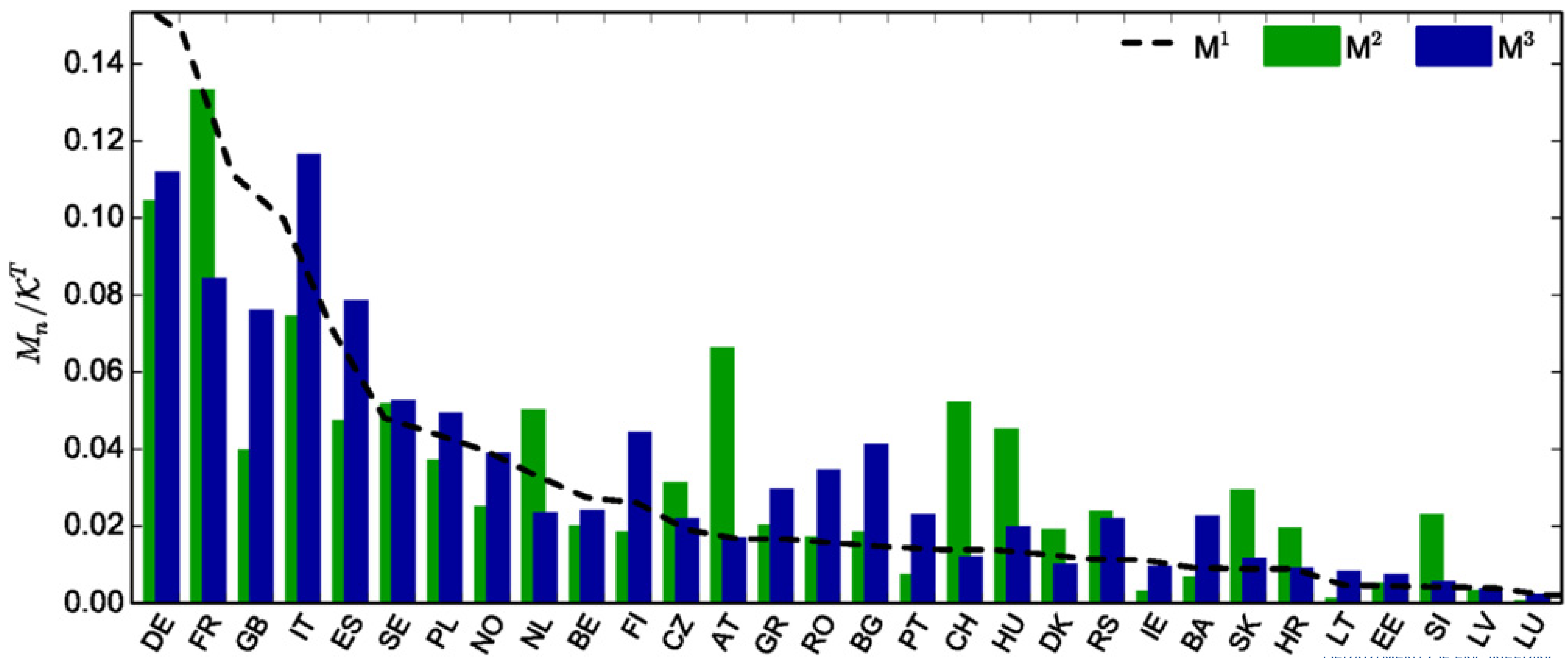
Challenge: cooperative 2020→2050 investments + markets

Flow tracing

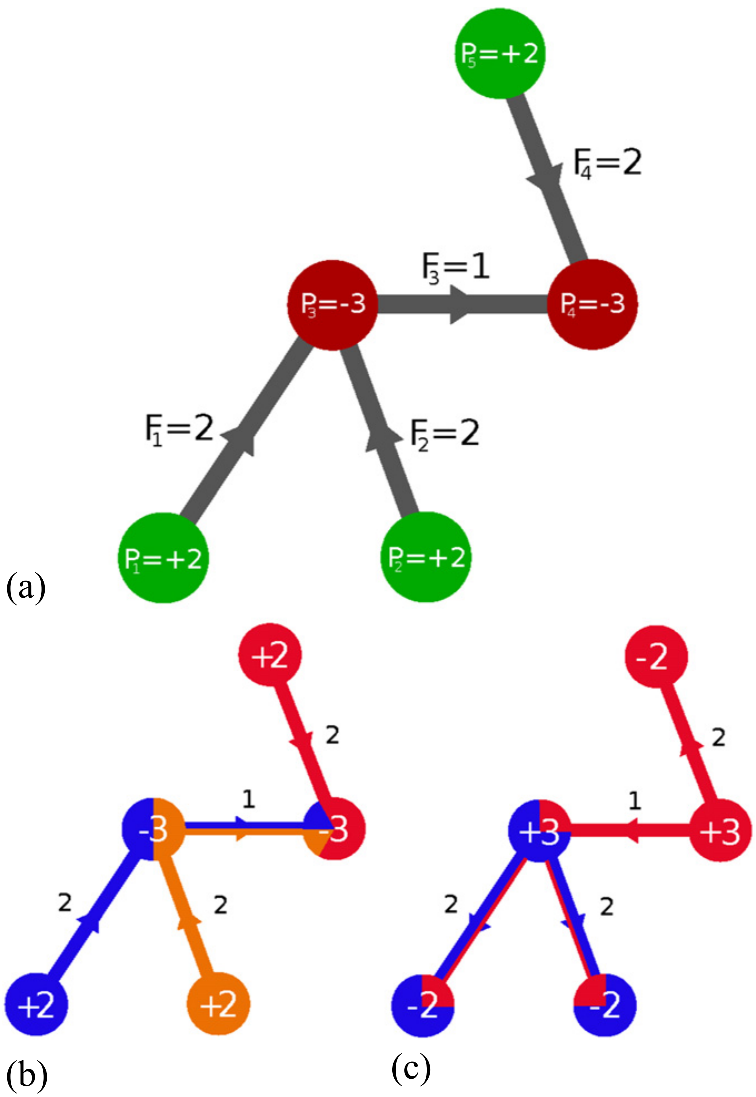


$$\mathcal{M}_n^{(1)} = \frac{\langle L_n \rangle}{\sum_m \langle L_m \rangle} \mathcal{K}^{\mathrm{T}}$$

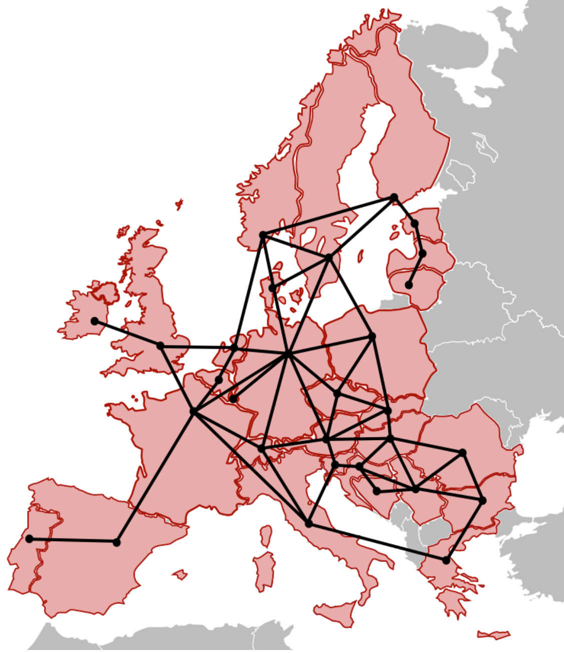
$$\mathcal{M}_n^{(2)} = \sum_{l(n)} \frac{\mathcal{K}_l^{\mathrm{T}}}{2}$$



Flow tracing



Flow tracing

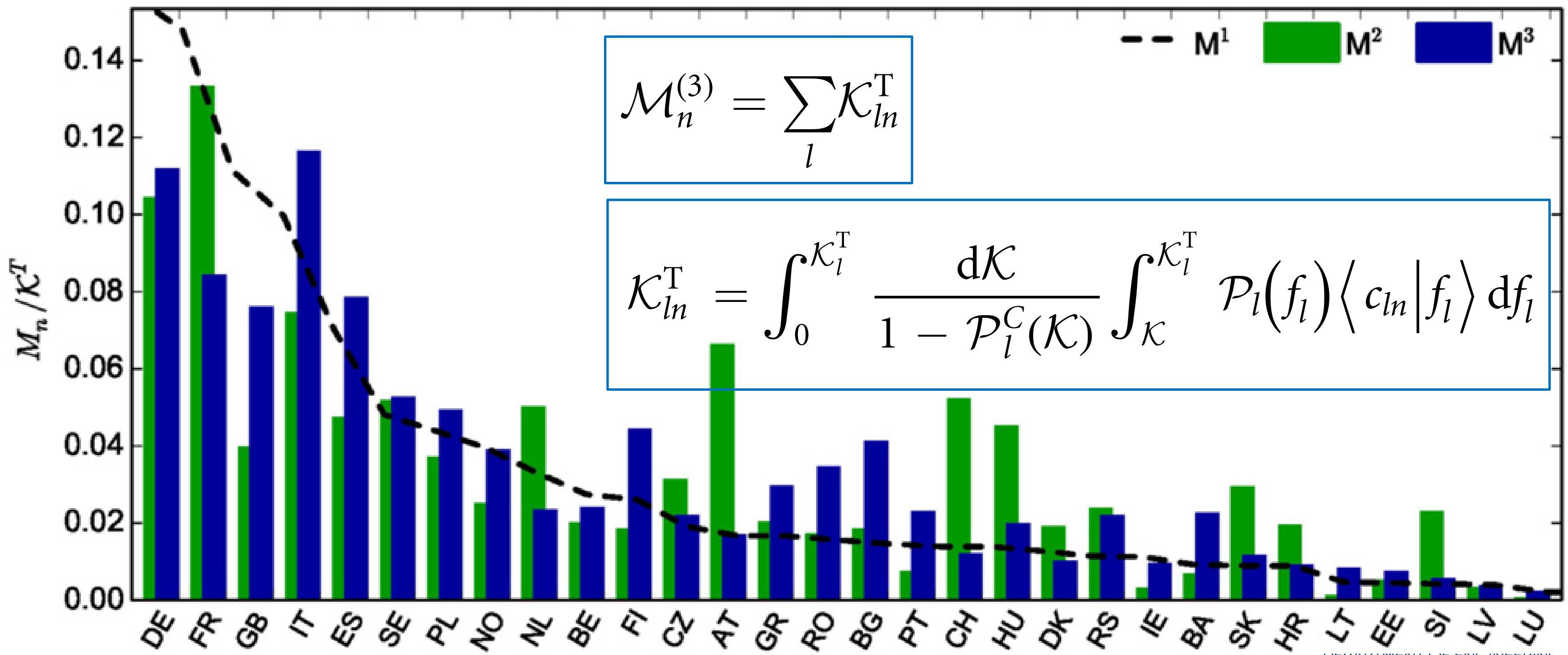


$$\mathcal{M}_n^{(1)} = \frac{\langle L_n \rangle}{\sum_m \langle L_m \rangle} \mathcal{K}^{\mathrm{T}}$$

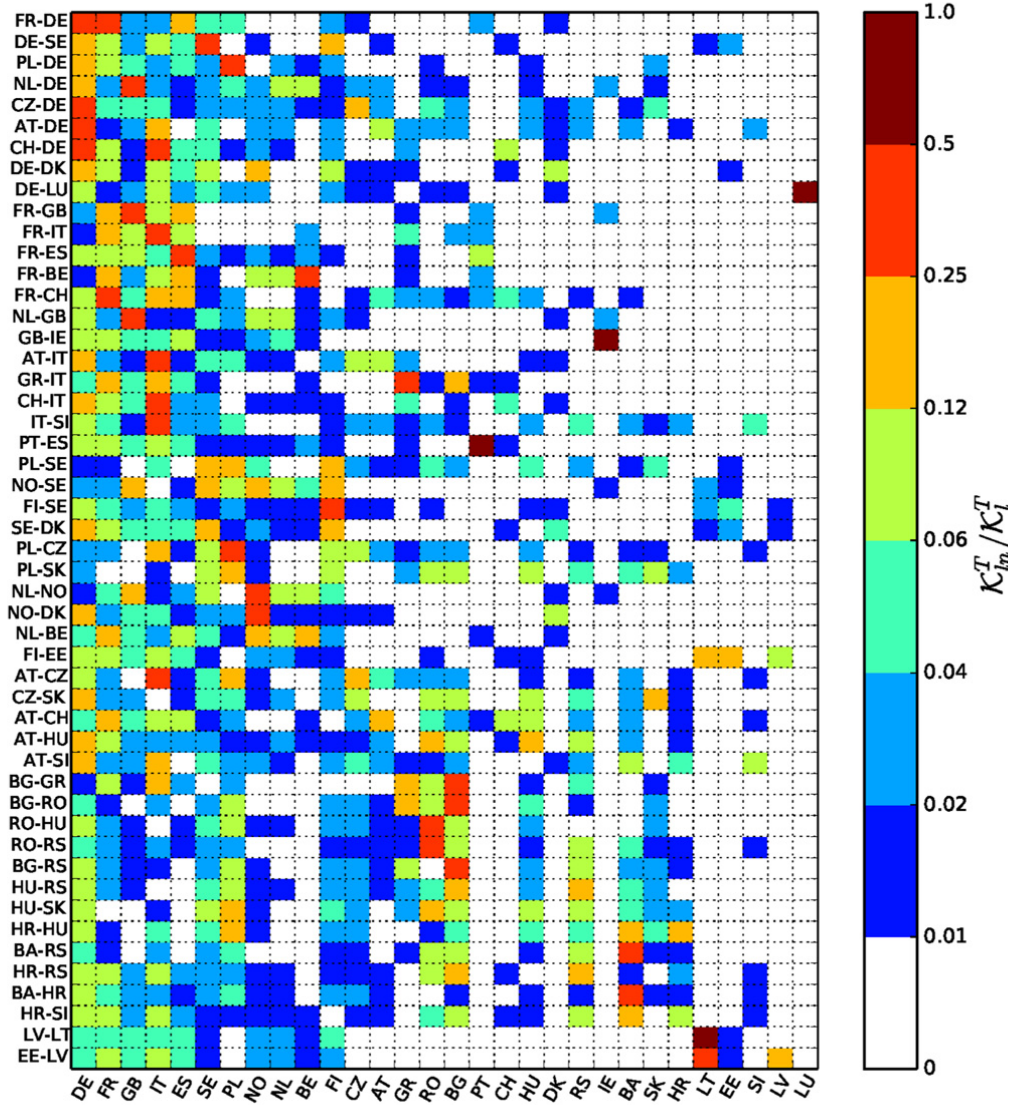
$$\mathcal{M}_n^{(2)} = \sum_{l(n)} \frac{\mathcal{K}_l^{\mathrm{T}}}{2}$$

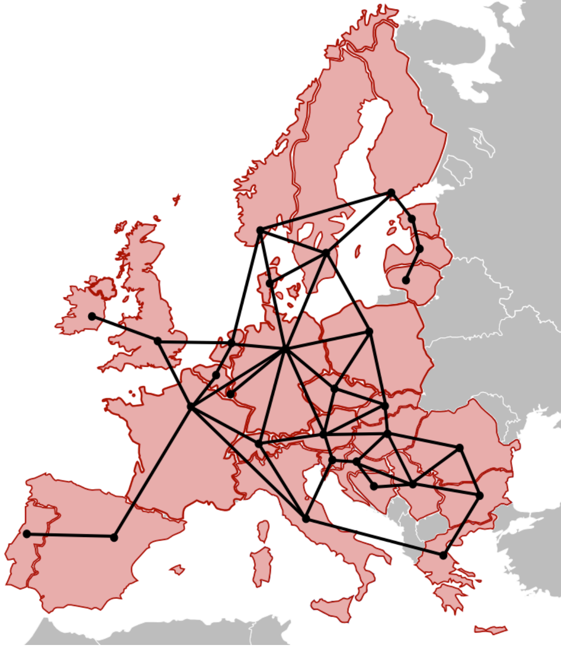
$$\mathcal{M}_n^{(3)} = \sum_l \mathcal{K}_{ln}^{\mathrm{T}}$$

$$\mathcal{K}_{ln}^{\mathrm{T}} = \int_0^{\mathcal{K}_l^{\mathrm{T}}} \frac{\mathrm{d}\mathcal{K}}{1 - \mathcal{P}_l^C(\mathcal{K})} \int_{\mathcal{K}}^{\mathcal{K}_l^{\mathrm{T}}} \mathcal{P}_l\left(f_l\right) \left\langle c_{ln} \middle| f_l \right\rangle \mathrm{d}f_l$$



Flow tracing





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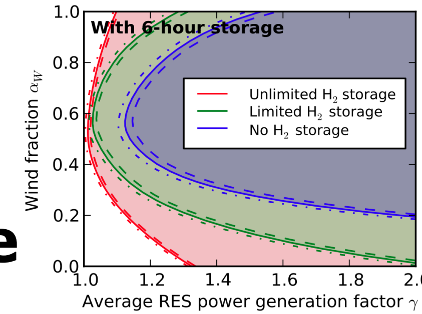
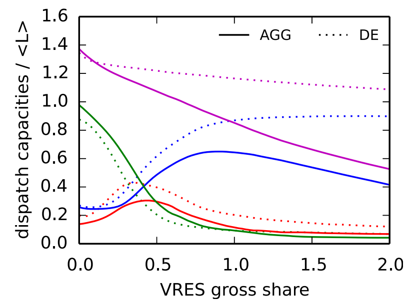
IV. More challenges



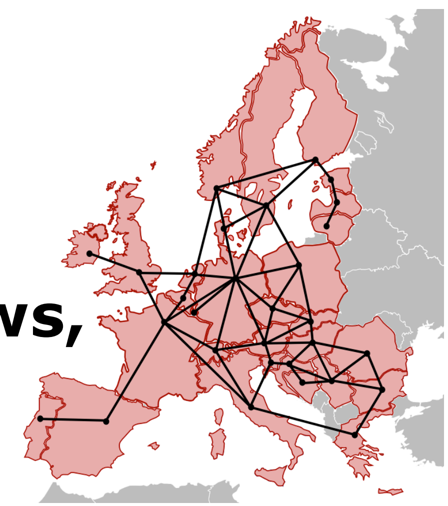
wind + solar + hydro + bio +
+ transmission + storage

coupling of electricity + heating + transportation.

backup flexibility classes



big networks:
renormalization scaling of power flows,
small-world AC/DC networks,
self-organizing power flows.



climate change + mesoscale turbulence

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FunRes Fundamental Research on Renewable Energy Systems

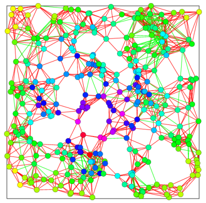
at the interface between engineering + physics + mathematics

Martin Greiner, Aarhus University

greiner@eng.au.dk

(1) Highly Renewable Energy Systems

(2) Complex Networks



(3) Wind-farm Modeling + Optimization

(4) Turbulence

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