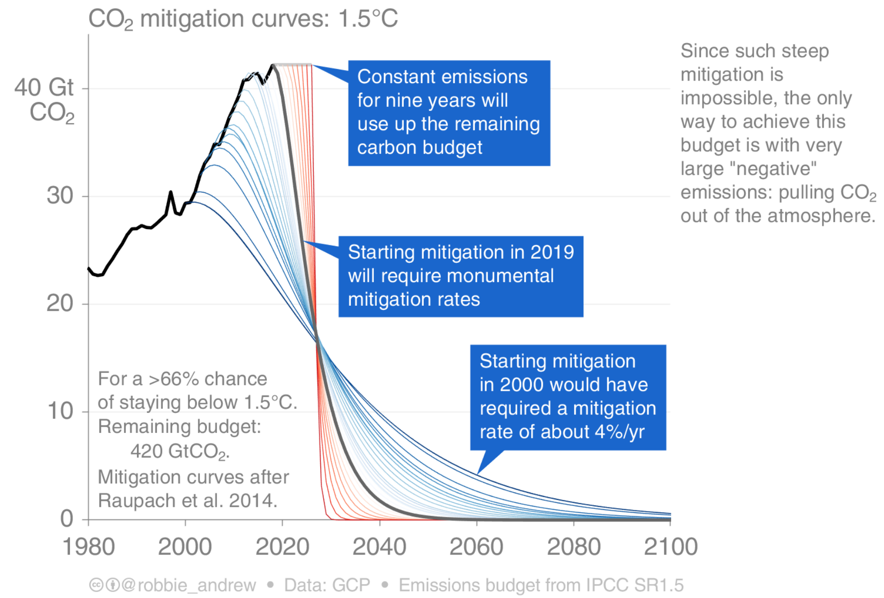
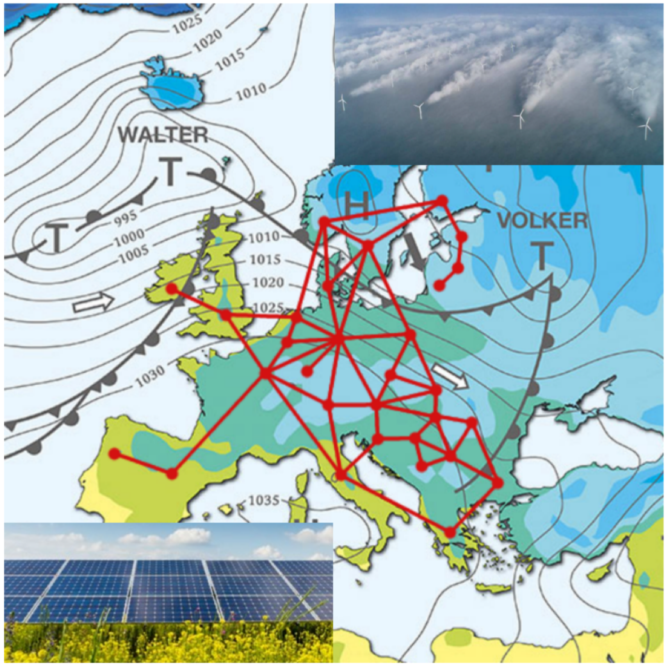
Decarbonisation of the networked European Energy System



I. **simple modeling: Renewable European electricty network**
- **weather-driven optimal design**
- **value of cooperation**

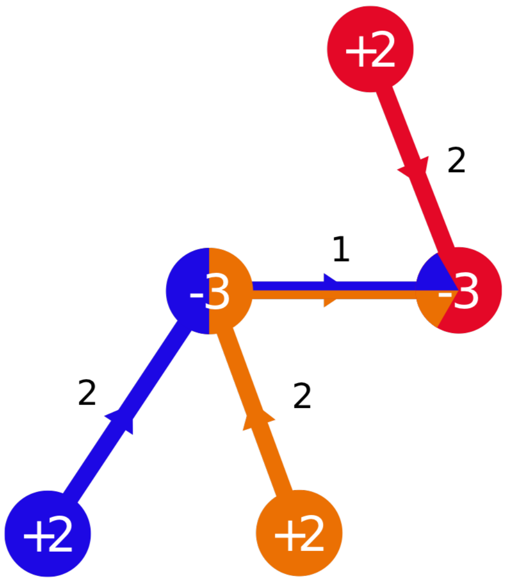
II. **advanced modeling:**
electricity → energy network
- **constraints**
  + (unavoidable) consequences

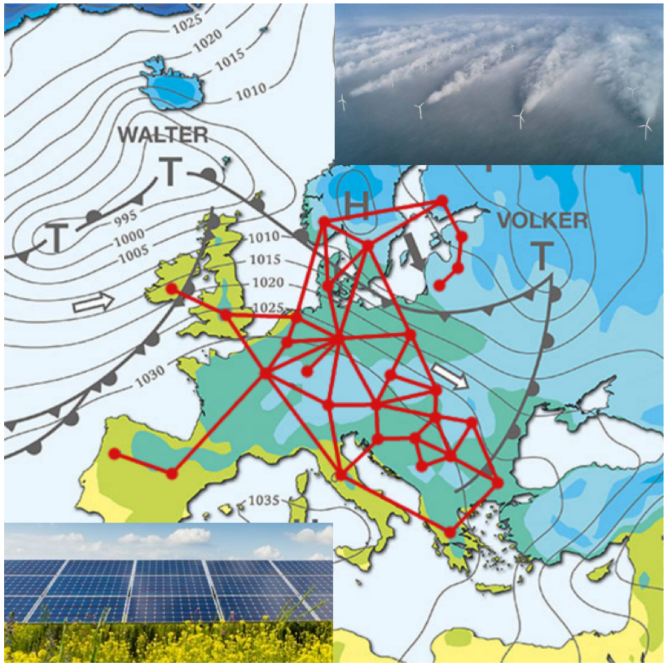


Flow tracing and nodal cost allocation in renewable energy networks

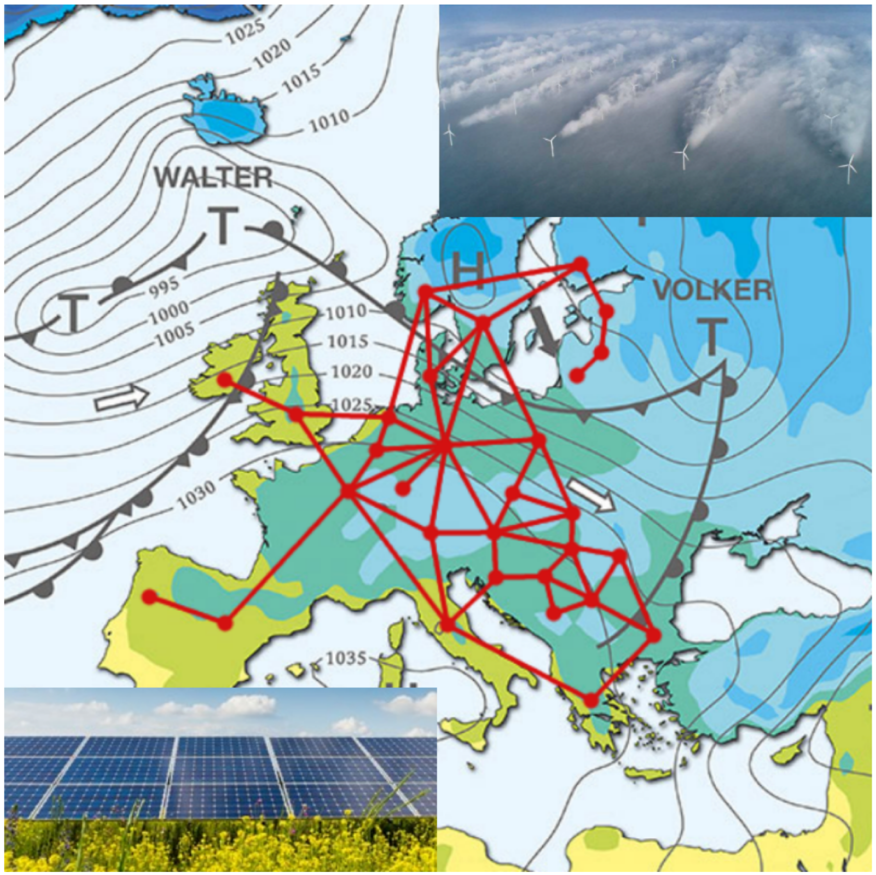
E Eriksen, L Schwenk-Nebbe, B Tranberg, T Brown, M Greiner:
Optimal heterogeneity in a simplified highly renewable European electricity system
Energy 133 (2017) 913-28.

B Tranberg, L Schwenk-Nebbe, M Schäfer, J Hörsch, M Greiner:
Flow-based nodal cost allocation in a heterogeneous highly renewable European electricity system
Energy 150 (2018) 122-33.





I. Simple Modeling:
Renewable European electricity network



Design of energy systems with a high share of renewables:

Let the weather decide!

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Renewable European electricity network + fluctuating „weather forces“

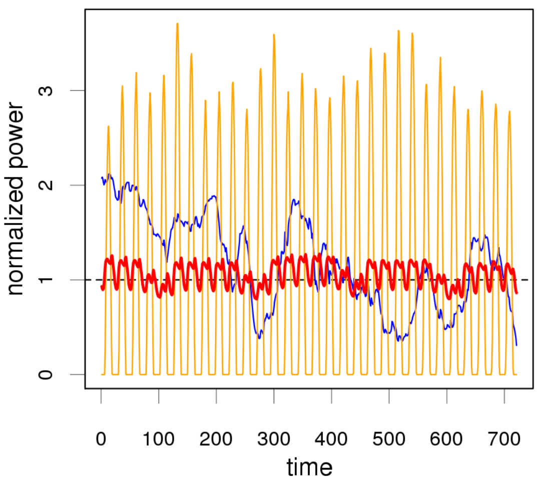
$$G_n^R(t) = G_n^W(t) + G_n^S(t)$$

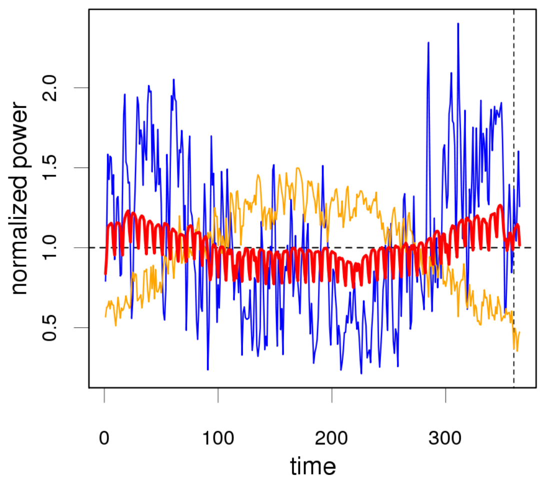
$$\langle G_n^R \rangle = \gamma_n \langle L_n \rangle$$

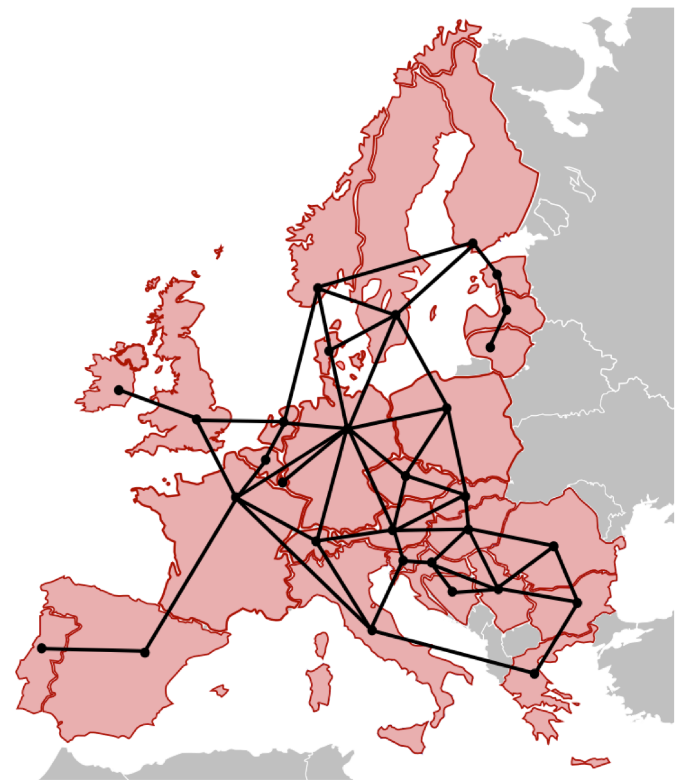
$$\langle G_n^W \rangle = \alpha_n \langle G_n^R \rangle$$

1980 – 2018: 1h, 30x30km²

Renewable Energy Atlas







3 TIME SCALES:	**diurnal**	**(1h-1d)**
	synoptic	**(2-10d)**
	seasonal	**(1y)**

Renewable European electricity network + fluctuating „weather forces“

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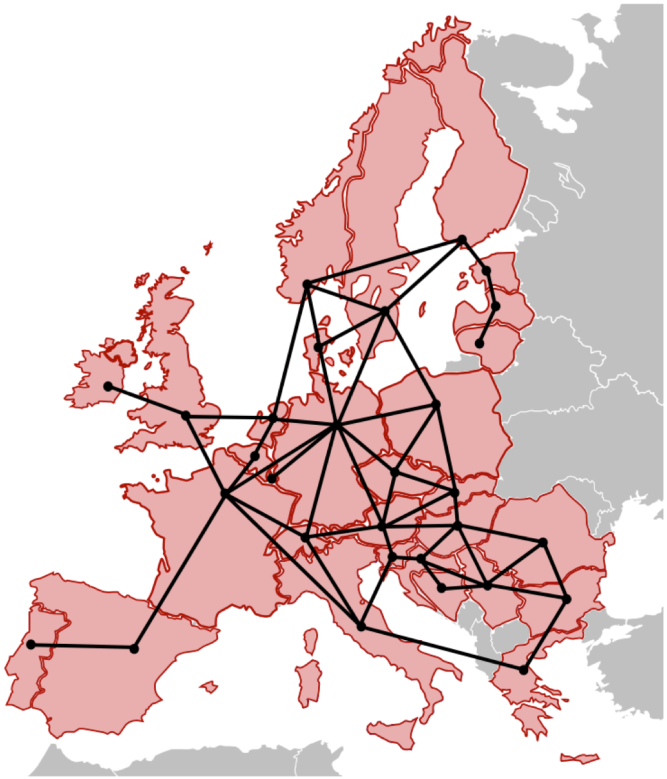
$$\langle G_n^W \rangle = \alpha_n \langle G_n^R \rangle$$

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



Renewable European electricity network + fluctuating „weather forces“

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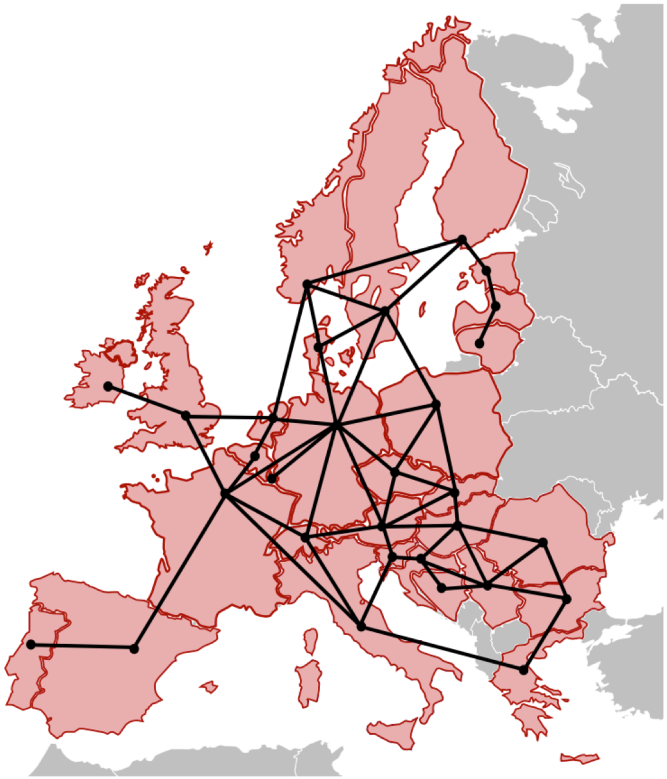
$$G_n^R(t) - L_n(t) = B_n(t) + P_n(t) + \cdots$$

$$G_n^B(t) = \big(B_n(t)\big)_-$$

$$C_n(t) = \big(B_n(t)\big)_+$$



Renewable European electricity network + fluctuating „weather forces“

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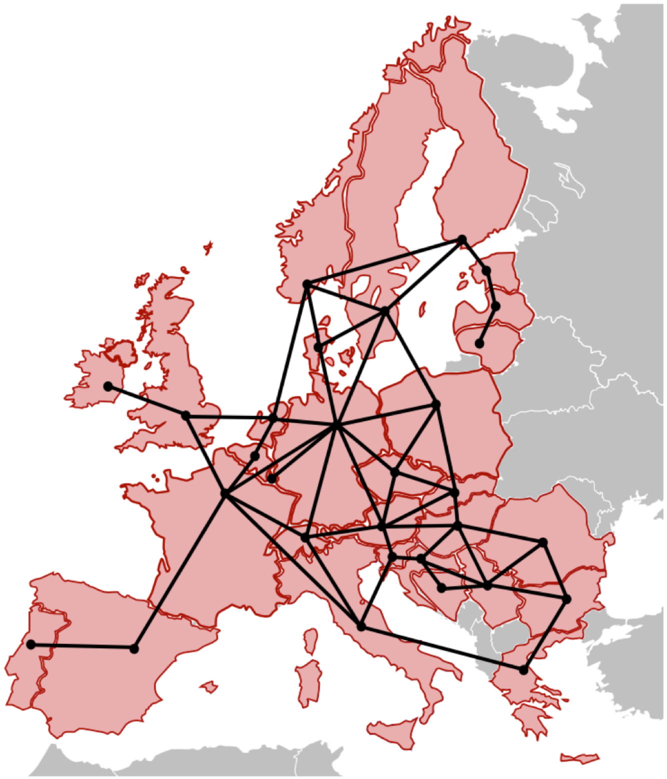
$$G_n^R(t) - L_n(t) = B_n(t) + P_n(t) + \cdots$$

$$G_n^B(t) = \left(B_n(t)\right)_-$$

$$C_n(t) = \left(B_n(t)\right)_+$$

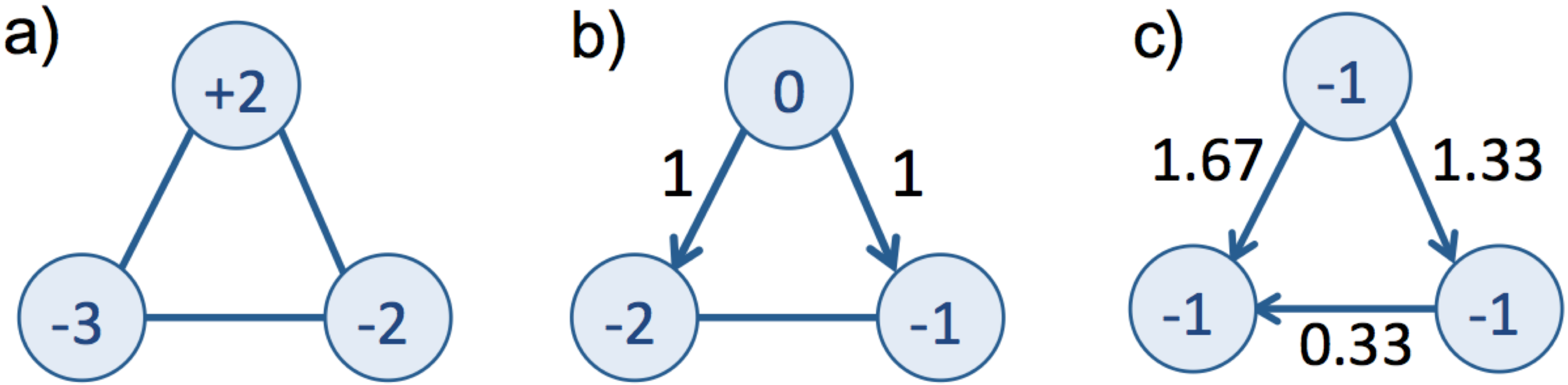
$$\sum_n P_n(t) = 0$$

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



“interactions”: balancing ⟺ transmission

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



zero flow	localized flow	synchronized balancing
$P_n(t) = 0$	$\min\left(\sum_n G_n^B(t)\right)$	$B_n(t) = \beta(t)\langle L_n \rangle$
	$\min\left(\sum_l F_l^2(t)\right)$	$\beta(t) = \frac{\sum_n \Delta_n(t)}{\sum_n \langle L_n \rangle}$

Renewable European electricity network + fluctuating „weather forces“

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

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

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

$$G_n^B(t) = \big(B_n(t)\big)_-$$

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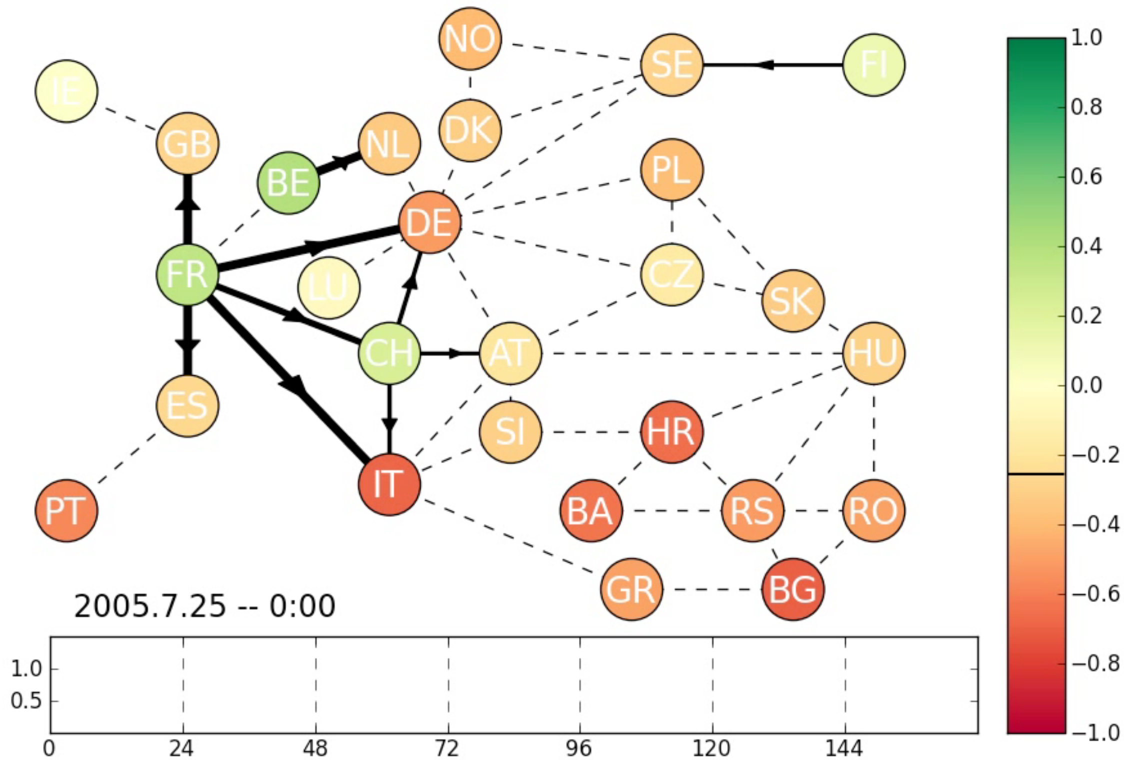
$$\sum_n P_n(t) = 0$$

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

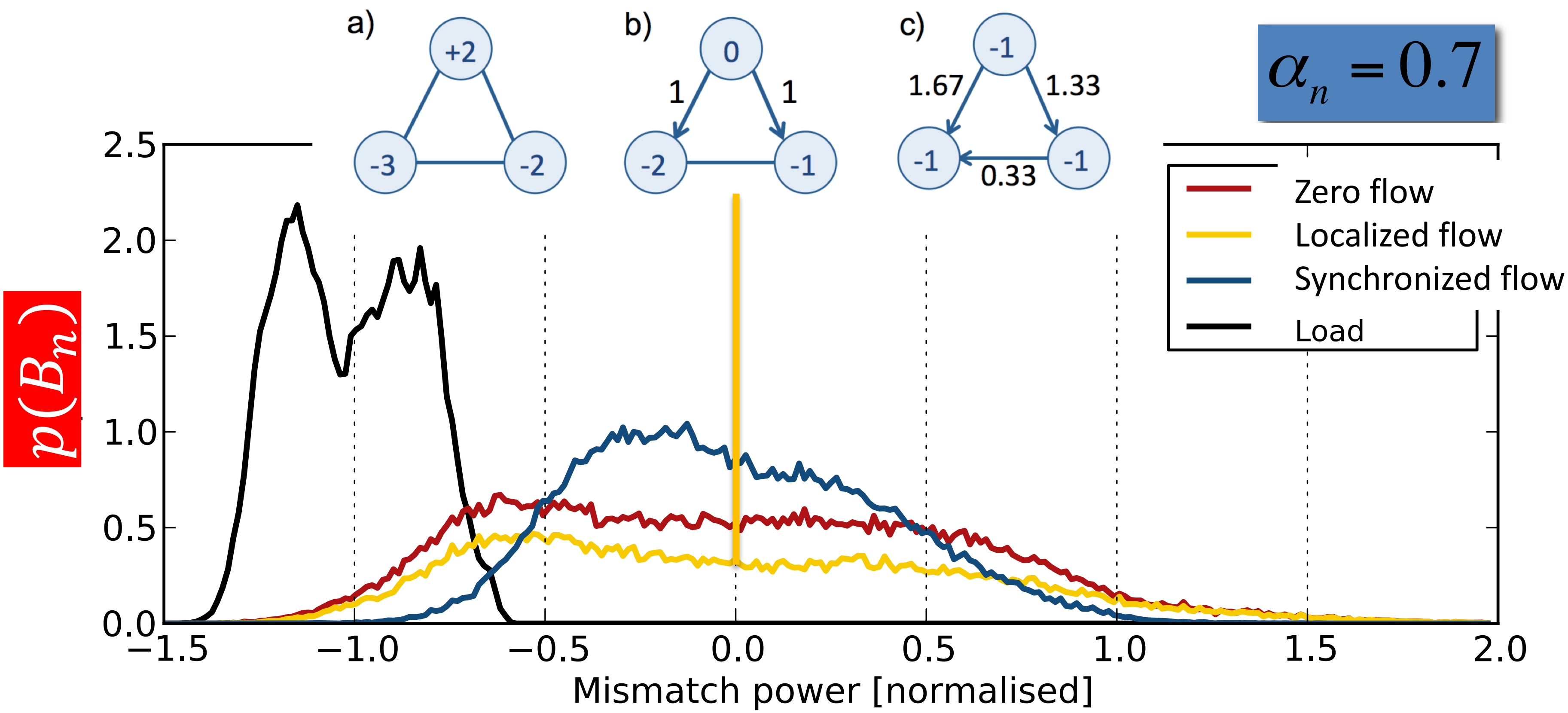


Balancing distribution (Germany)

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

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

$$\alpha_n = 0.7$$



$$G_n^B(t) = (B_n(t))_-$$

$$C_n(t) = (B_n(t))_+$$

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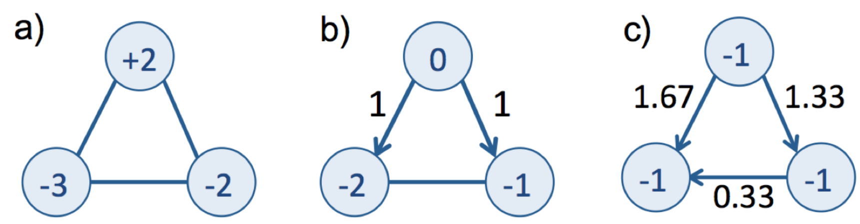
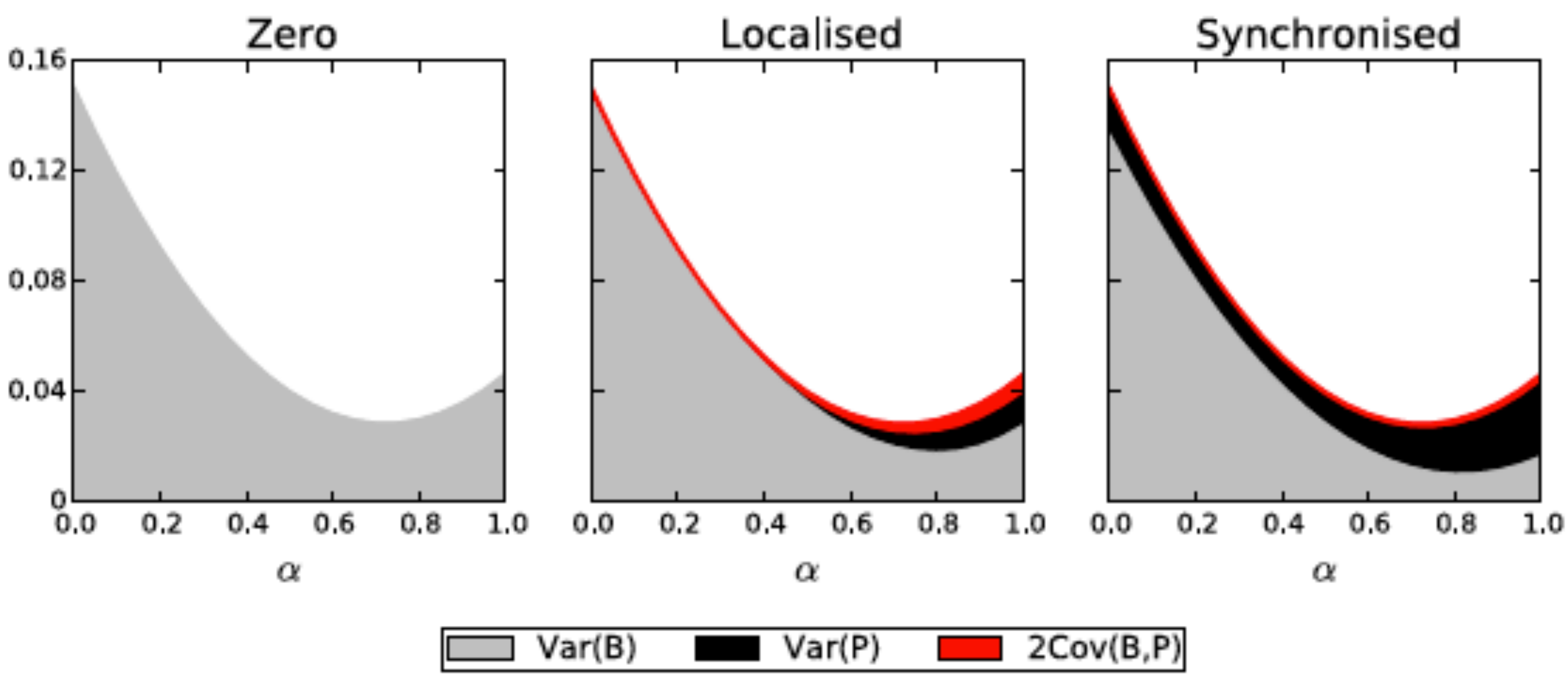
variance: balancing ⟺ transmission

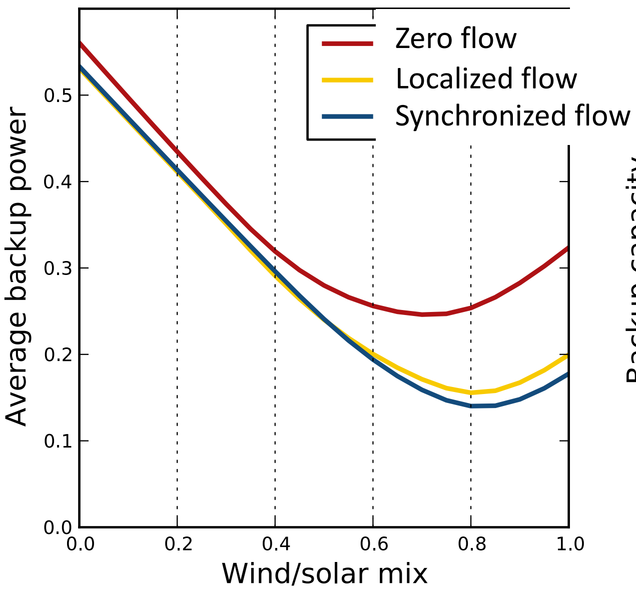
$$\Delta_n(t) =$$
$$= G_n^R(t) - L_n(t)$$
$$= B_n(t) + P_n(t)$$





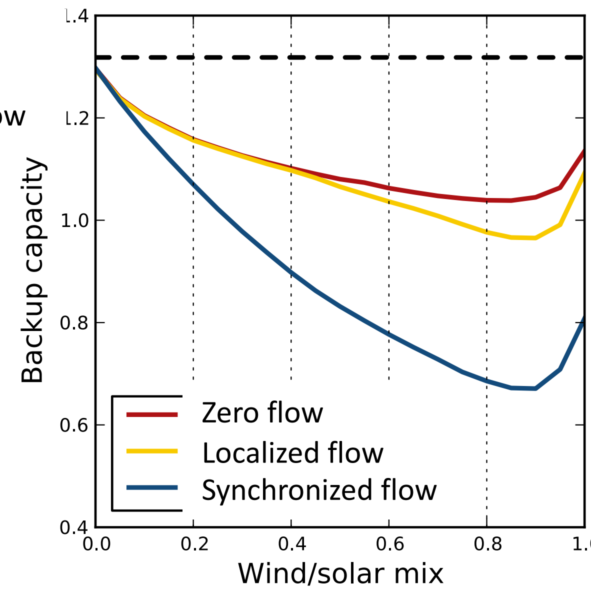
backup energy

$\langle G_n^B \rangle$



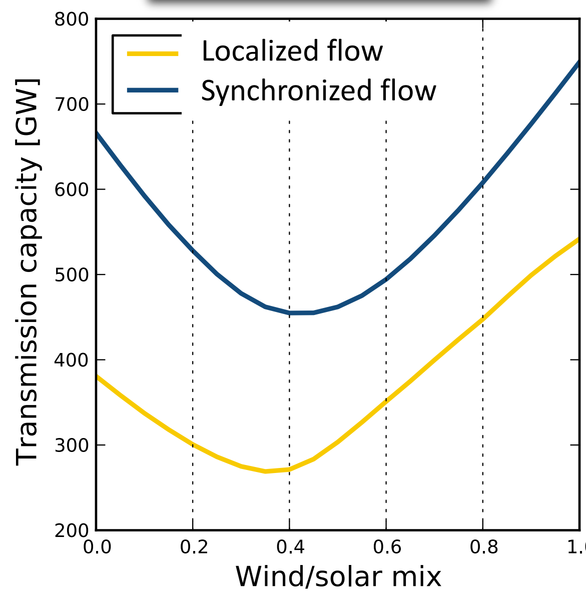
backup capacity

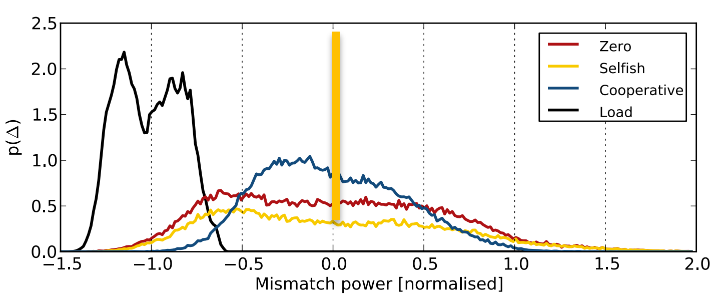
$max_q(G_n^B)$

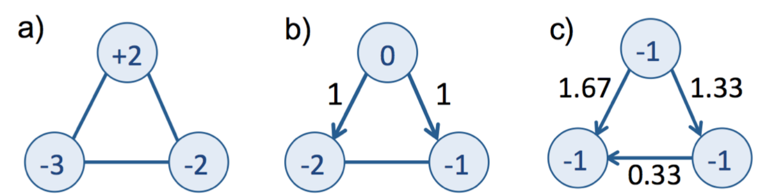


transmission capacity

$\sum_l \max_q |F_l|$







Infrastructure measures

backup energy $E_n^B = \langle G_n^B \rangle$

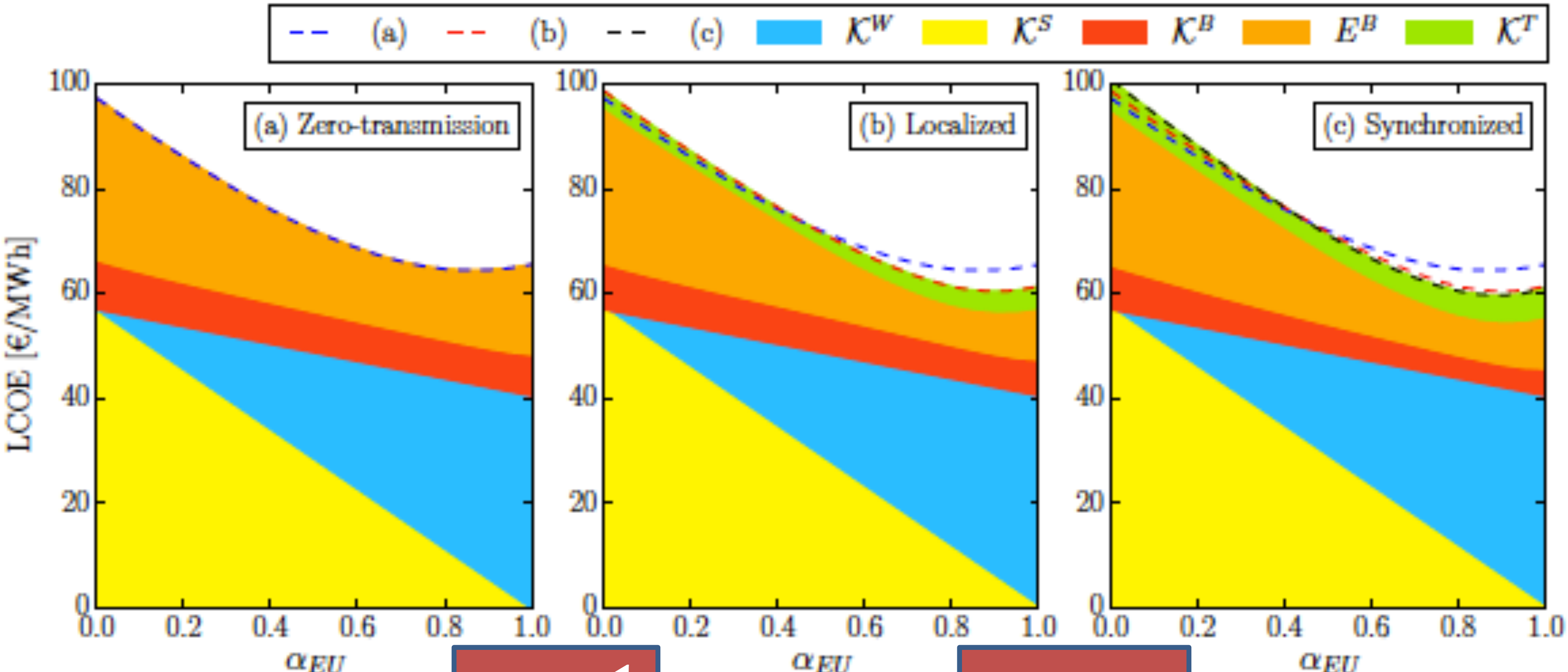
backup capacity $K_n^B = max_q (G_n^B)$

transmission capacity $K_l^T = max_q |F_l| \cdot d_l$

wind capacity $K_n^W = \frac{\alpha_n \gamma_n \langle L_n \rangle}{CF_n^W}$

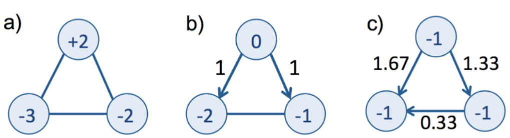
solar capacity $K_n^S = \frac{(1-\alpha_n)\gamma_n \langle L_n \rangle}{CF_n^S}$

Levelized Cost of SYSTEM Energy



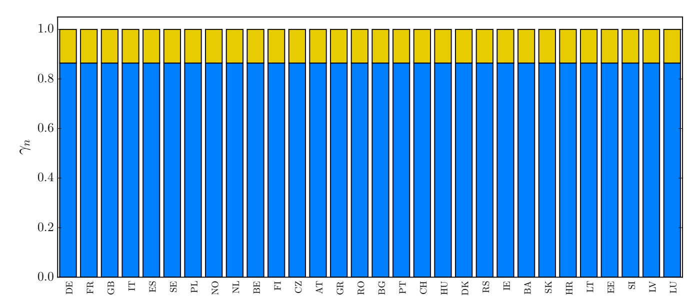
$\gamma_n = 1$

$\alpha_n = \alpha$

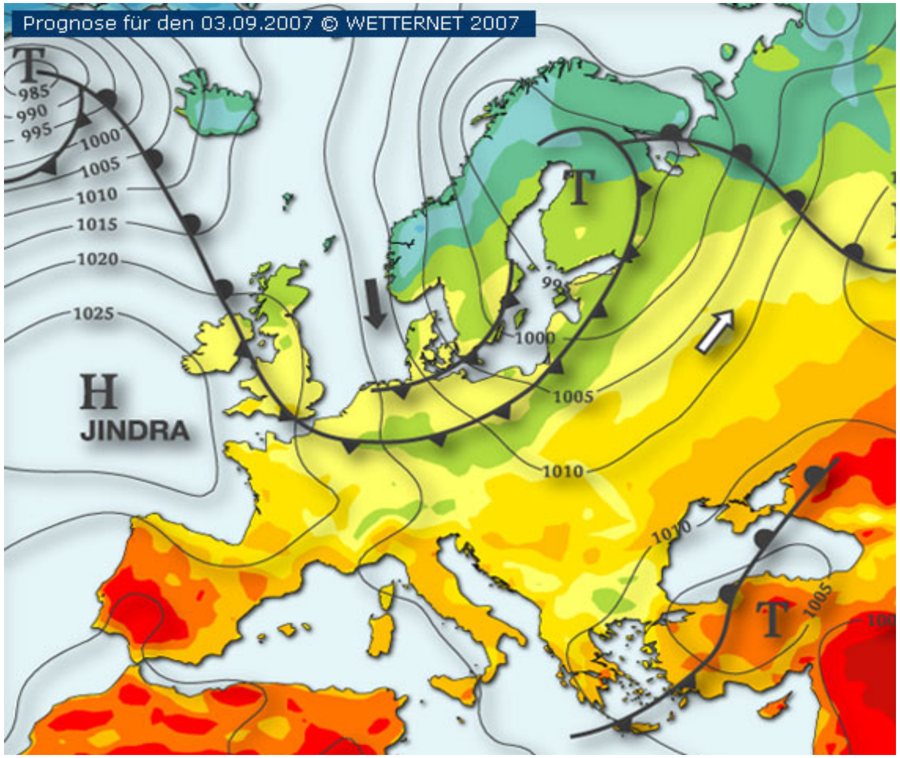


Coupling objectives: B ⟺ P

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



wind and solar power capacities



annual consumption (2009)
= 3400 TWh

80% wind power generation
= 1000 GW installed capacity
= 200.000 x 5 MW turbines
= 5000 x 200 MW wind farms
≈ 130000 km²

20% solar PV power generation
= 370 GW installed capacity
≈ 2500 - 5000 km²

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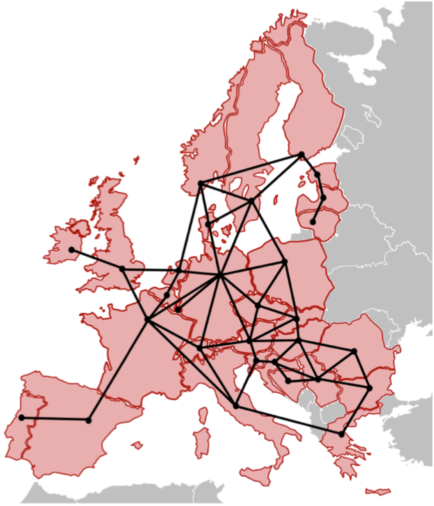
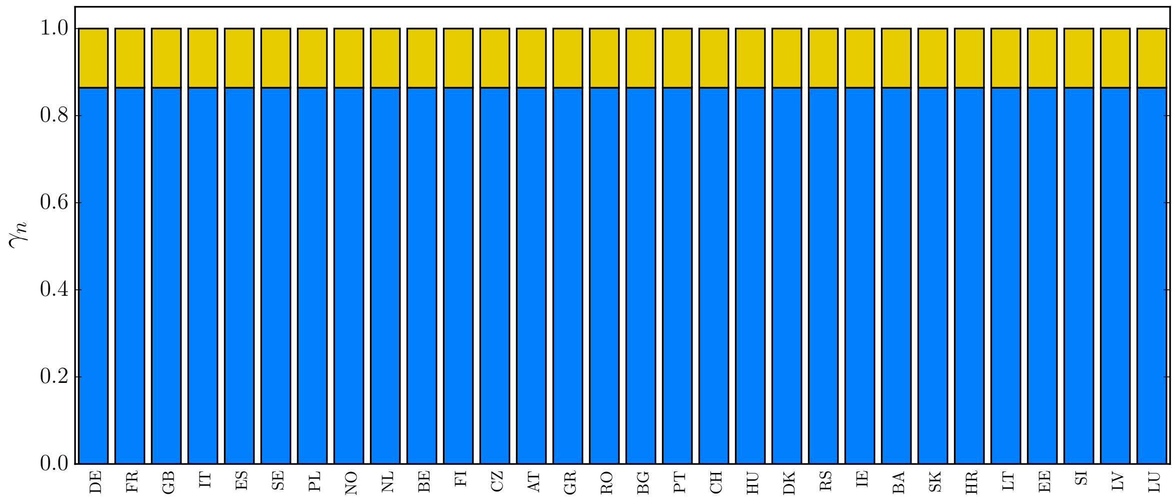
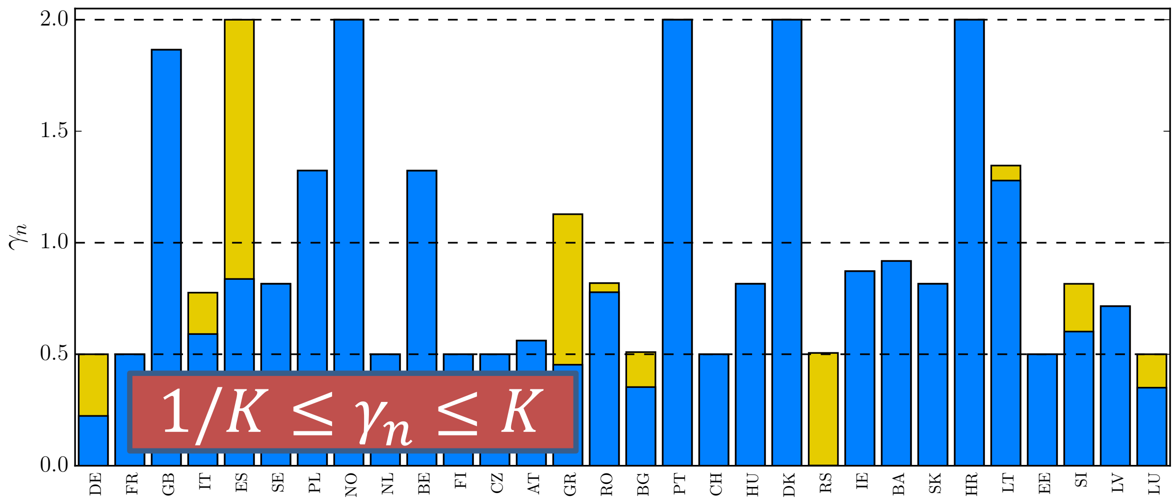
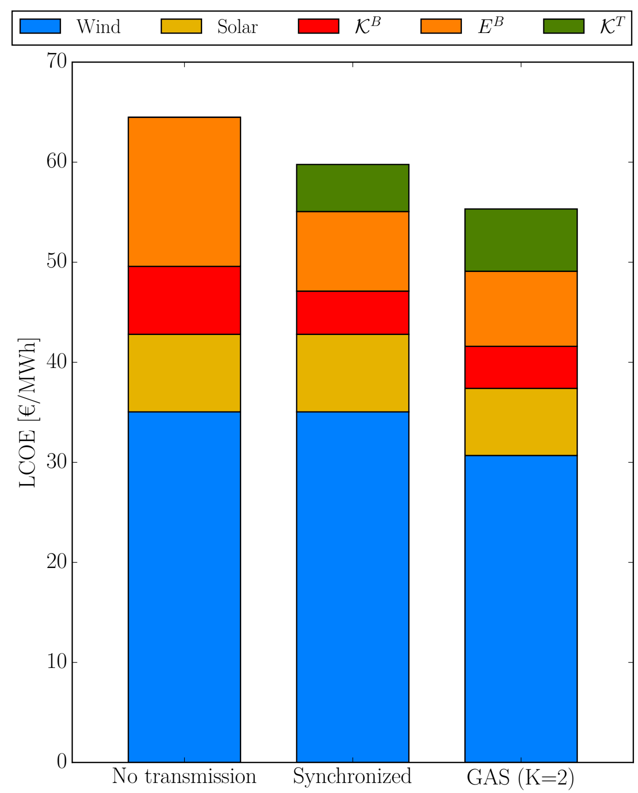
Breaking homogeneity: cost-optimal heterogeneity







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



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

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

Back-on-the-envelop estimate

OPT-HOM-noT(K=1):	64.5 €/MWh
OPT-HOM(K=1):	56.6 €/MWh
OPT-HET(K=2):	53.8 €/MWh

EU cost reduction / y

= 3500 TWh/y x 10 €/MWh

= 35 x 10^9 €/y

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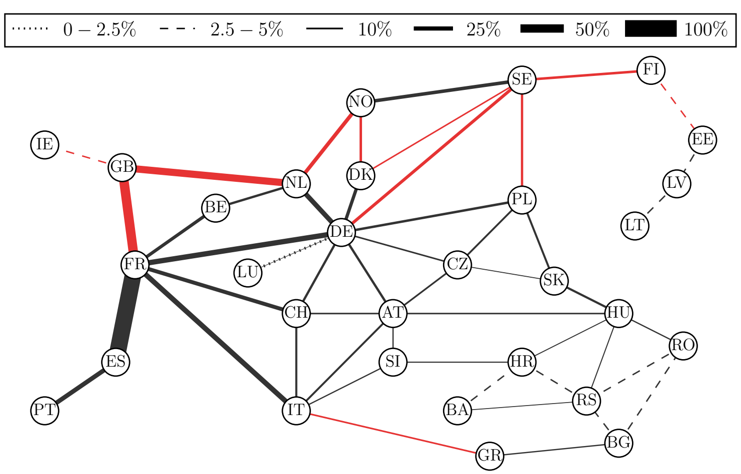
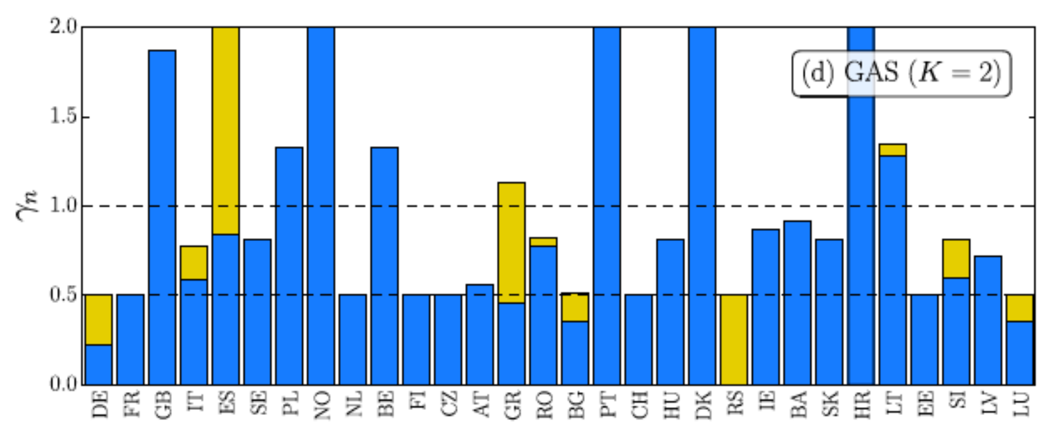
30 European friends you have to be!

but …… who pays for …

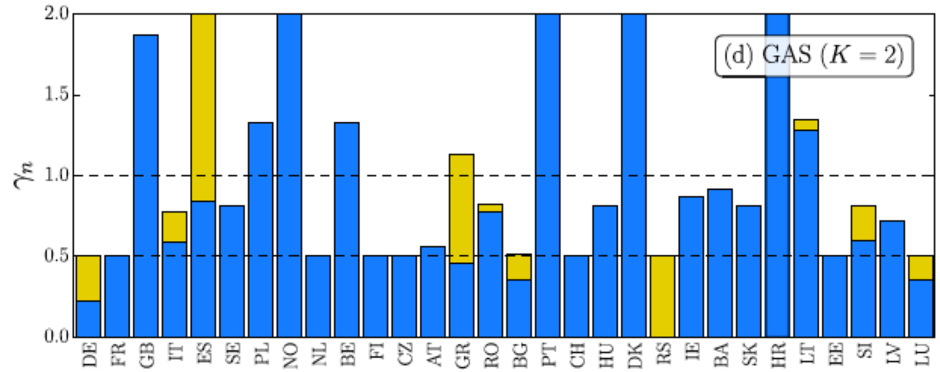
…… the heterogeneity?

…… the transmission grid?

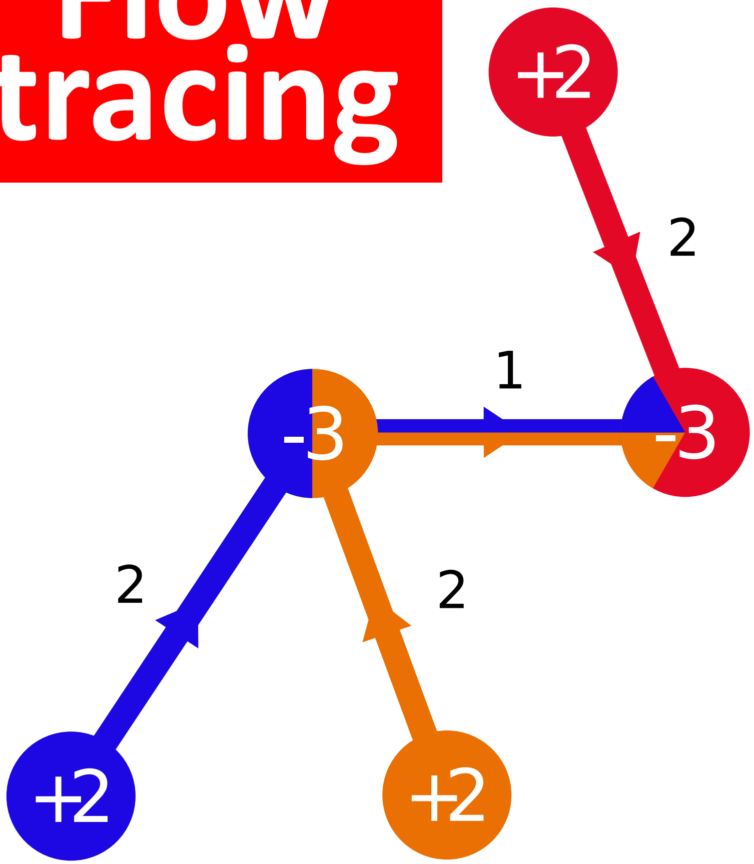




Who pays for the heterogeneity?



Flow tracing



$$K_n^{\mu} = K_{nn}^{\mu} + \sum_{m \neq n} K_{nm}^{\mu}$$

$$\widetilde{K}_n^{\mu} = K_{nn}^{\mu} + \sum_{m \neq n} K_{mn}^{\mu}$$

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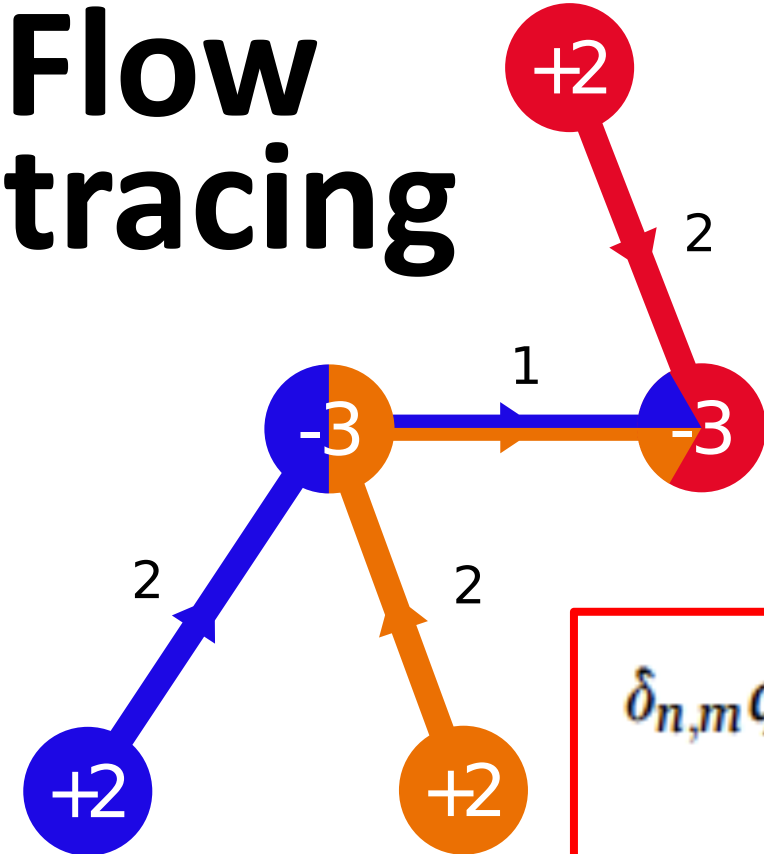
Flow tracing



$$\delta_{n,m} q^{\text{in}}_{(n,\mu)} P^{+}_{n} + \sum_{k} q_{k\to n,(m,\mu)} F_{k\to n} = q^{\text{out}}_{n,(m,\mu)} P^{-}_{n} + \sum_{k} q_{n\to k,(m,\mu)} F_{n\to k},$$

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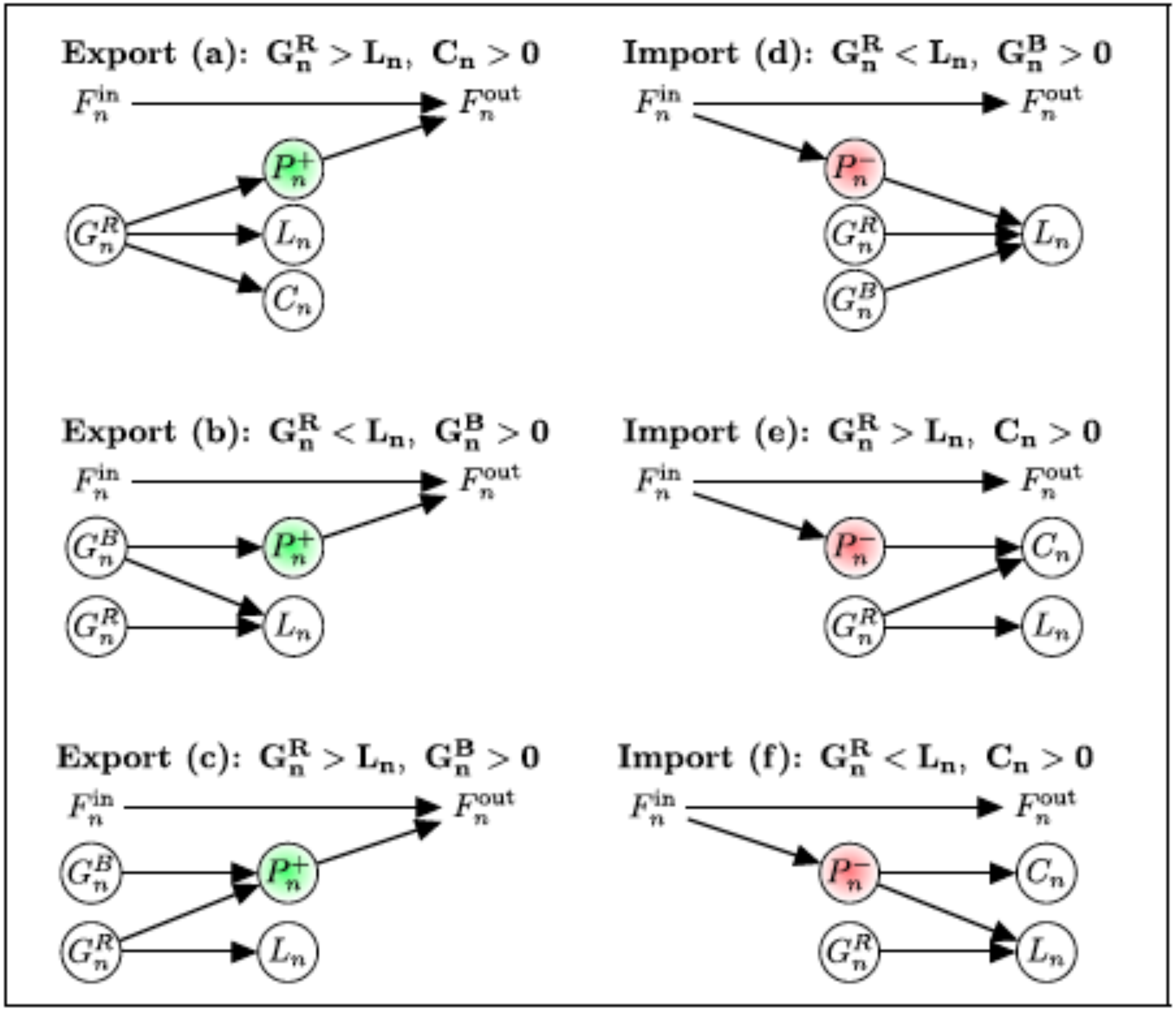
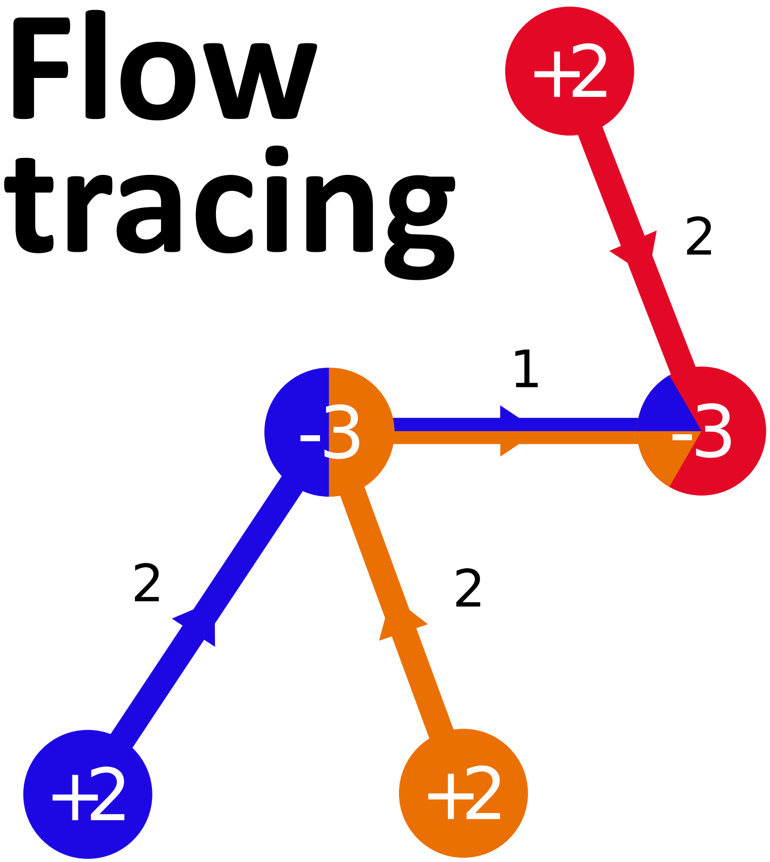

Export (a): $\mathbf{G_n^R > L_n,\ C_n > 0}$
F_n^{in}
F_n^{out}
P_n^+
G_n^R
L_n
C_n
Import (d): $\mathbf{G_n^R < L_n,\ G_n^B > 0}$
F_n^{in}
F_n^{out}
P_n^-
G_n^R
G_n^B
L_n
Export (b): $\mathbf{G_n^R < L_n,\ G_n^B > 0}$
F_n^{in}
F_n^{out}
G_n^B
P_n^+
G_n^R
L_n
Import (e): $\mathbf{G_n^R > L_n,\ C_n > 0}$
F_n^{in}
F_n^{out}
P_n^-
C_n
G_n^R
L_n
Export (c): $\mathbf{G_n^R > L_n,\ G_n^B > 0}$
F_n^{in}
F_n^{out}
G_n^B
P_n^+
G_n^R
L_n
Import (f): $\mathbf{G_n^R < L_n,\ C_n > 0}$
F_n^{in}
F_n^{out}
P_n^-
C_n
G_n^R
L_n

Flow tracing



$$\mathscr{E}^{\mu}_{m\to n} = \left\langle q^{\mathrm{out}}_{n,(m,\mu)} P^{-}_{n} \right\rangle .$$

$$\mathscr{K}^{\mu}_{m\to n} = \begin{cases} \left[\dfrac{\mathscr{E}^{\mu}_{m\to n}}{\langle G^{\mu}_{m}\rangle - \langle C^{\mu}_{m}\rangle}\right] \mathscr{K}^{\mu}_{m} & \text{if } m \neq n \\ \mathscr{K}^{\mu}_{m} - \sum_{s\neq m} \mathscr{K}^{\mu}_{m\to s} & \text{if } m = n. \end{cases}$$

$$K^{\mu}_{n} = K^{\mu}_{nn} + \sum\nolimits_{m\neq n} K^{\mu}_{nm}$$

$$\widetilde{K}^{\mu}_{n} = K^{\mu}_{nn} + \sum\nolimits_{m\neq n} K^{\mu}_{mn}$$

$$\begin{aligned} \delta_{n,m} q^{\mathrm{in}}_{(n,\mu)} P^{+}_{n} &+ \sum_{k} q_{k\to n,(m,\mu)} F_{k\to n} \\ &= q^{\mathrm{out}}_{n,(m,\mu)} P^{-}_{n} + \sum_{k} q_{n\to k,(m,\mu)} F_{n\to k}, \end{aligned}$$

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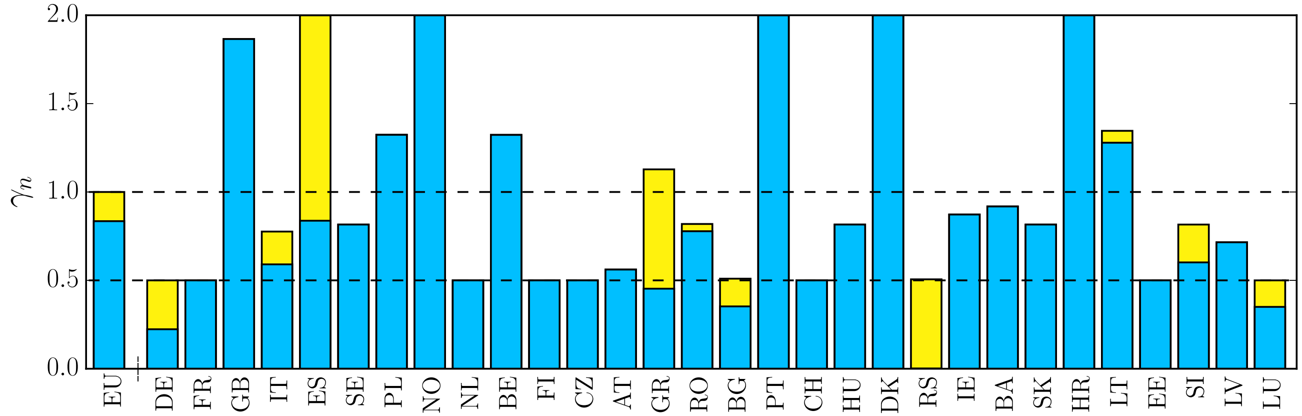
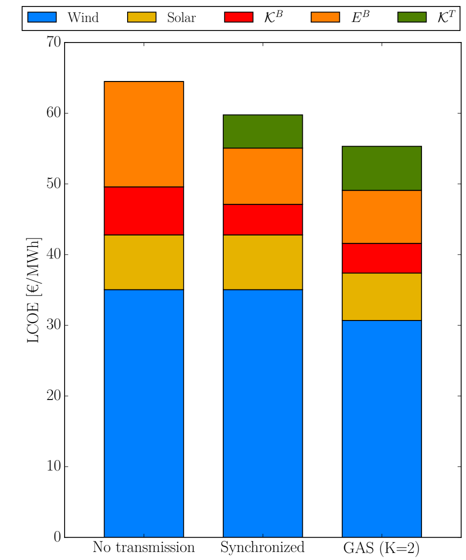
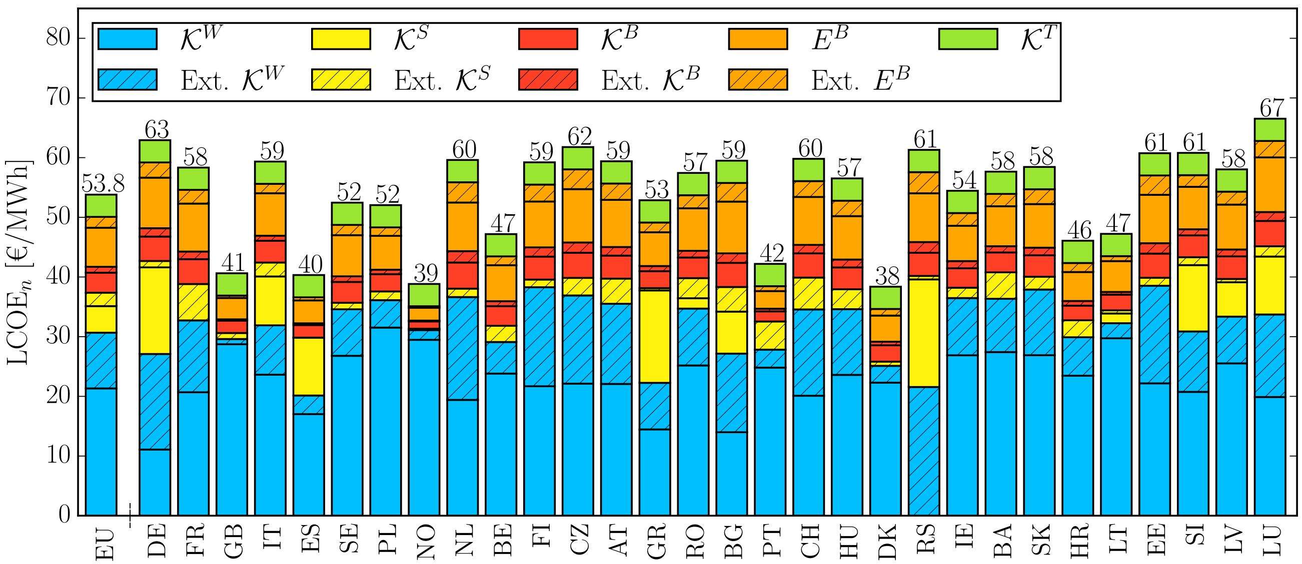
Benefit of cooperation





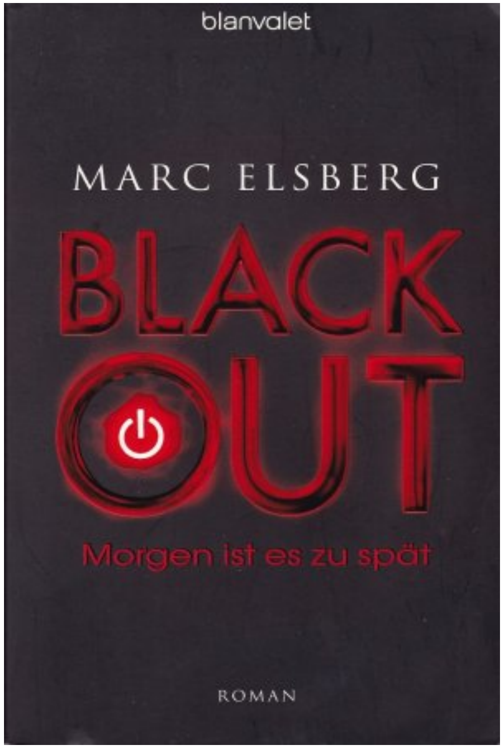


$$K_n^\mu = K_{nn}^\mu + \sum_{m\neq n} K_{nm}^\mu$$

$$\tilde{K}_n^\mu = K_{nn}^\mu + \sum_{m\neq n} K_{mn}^\mu$$

$$\forall\ n: \quad LCOE_n^{hom,noT} > LCOE_n^{hom,T} > LCOE_n^{het,T}$$

30 EU friends you have to be!



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“Gier” nach mehr Physik:

power-flow renormalization M Schäfer et.al., EPL 119 (2017) 38004

storage phase transition T Jensen + M Greiner, EPJ ST 223 (2014) 2475-81

principal spatio-temporal patterns
M Raunbak et.al., Energies 10 (2017) 2934
F Hofmann et.al., EPL 124 (2018) 18005

mesoscale turbulence + climate change
M Schlott, A Kies et.al., Applied Energy 230 (2018) 1645-59

flexibility classes D Schlachtberter et.al., Energy Conversion Management 125 (2016) 336-46

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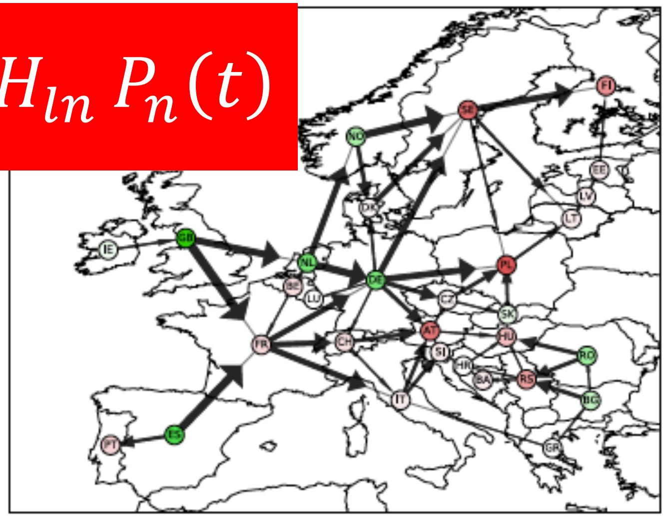
Decompositions of injection patterns for nodal flow allocation in renewable electricity networks

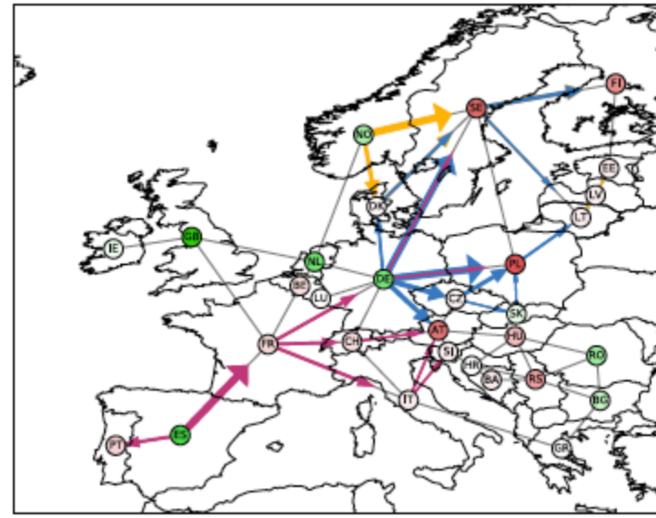
THE EUROPEAN PHYSICAL JOURNAL B

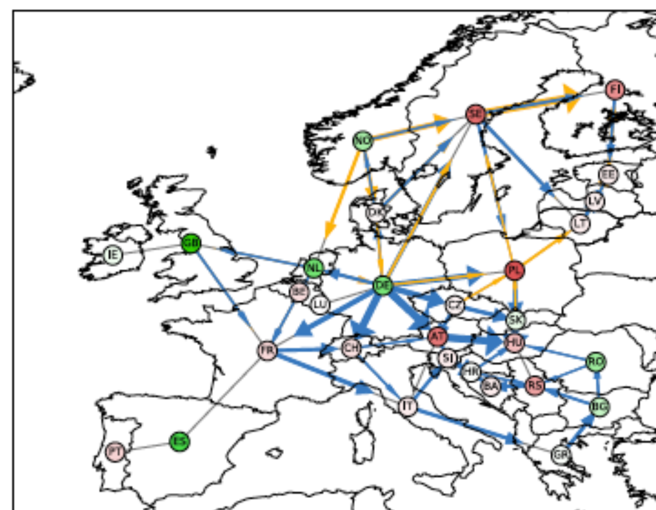
Mirko Schäfer[1,a], Bo Tranberg[1,2], Sabrina Hempel[3,b], Stefan Schramm[3], and Martin Greiner[1]

Eur. Phys. J. B (2017) 90: 144
DOI: 10.1140/epjb/e2017-80200-y

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







$$F_l^{(\alpha)}(t) = \sum_n H_{ln} P_n^{(\alpha)}(t)$$

$$\sum_n P_n^{(\alpha)}(t) = 0$$

$$\sum_\alpha P_n^{(\alpha)}(t) = P_n(t)$$

Sustainable Energy Systems

Gorm Andresen
Thermodynamics, District Heating

Marta Victoria
Solar Photovoltaics

Martin Greiner
Complex Networks

Mahdi Abkar
Wind-farm modelling + optimization, Turbulence
Computational Fluid Dynamics

Aarhus University
Department of Engineering

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Mirko Schäfer (U Freiburg)

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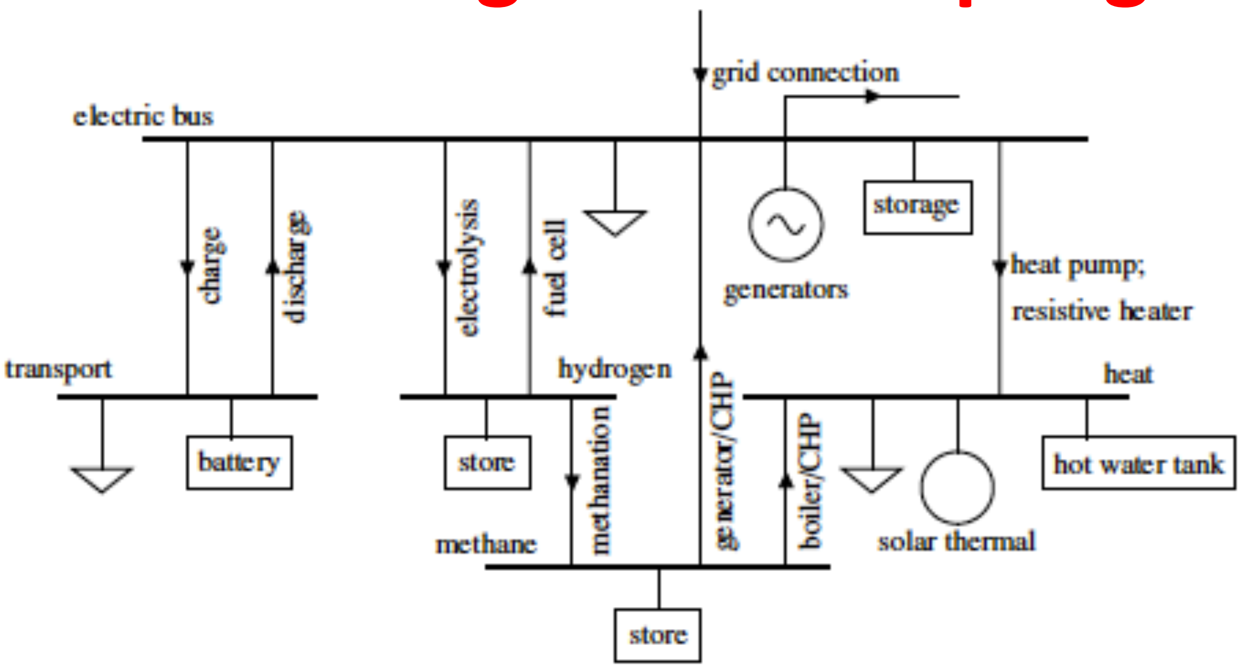
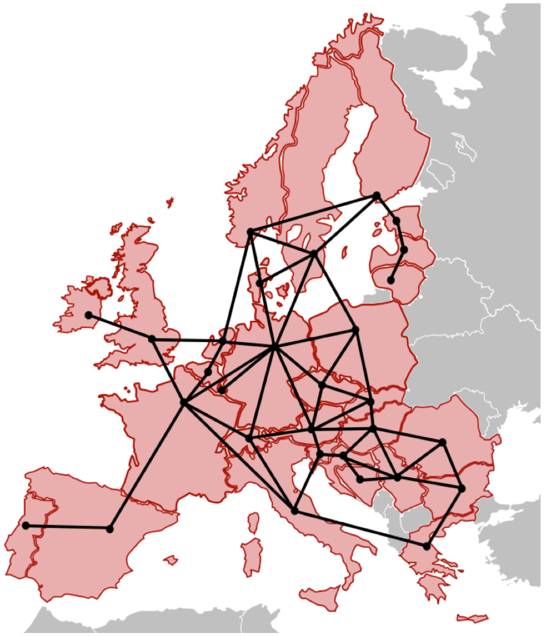
II. Advanced Modeling:
electricity → "smart" energy network

Decarbonization of the European energy system with strong sector couplings





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