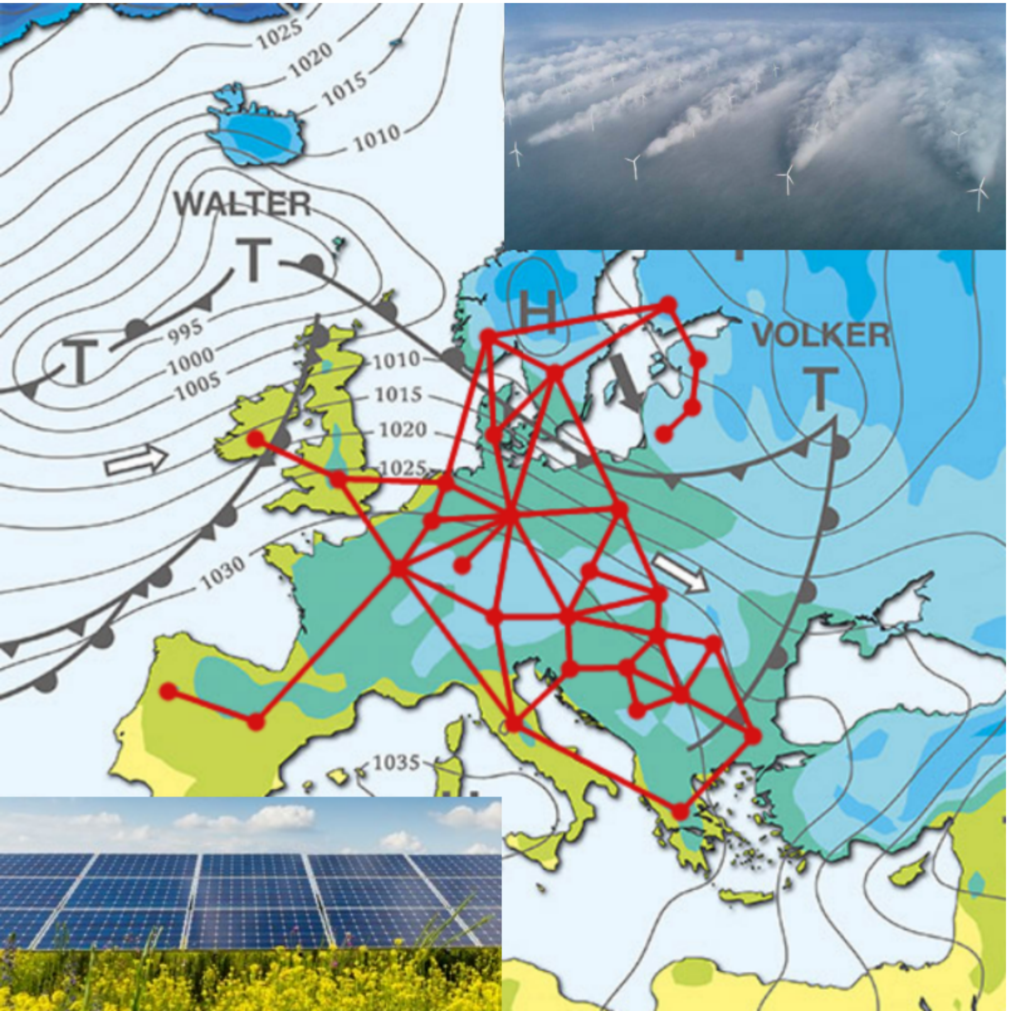
Mehr als die Vergangenheit und die Gegenwart
interessiert mich die Zukunft,
denn in ihr gedenke ich zu leben.

(Albert Einstein)

Renewable Energy Networks

a playground for Applied Theoretical Physics



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

How much …
… wind energy?
… solar PV energy?
… backup energy + power?
… transmission?
… storage?
… costs?
… energy sector coupling?

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Renewable European electricity network + fluctuating „weather forces“

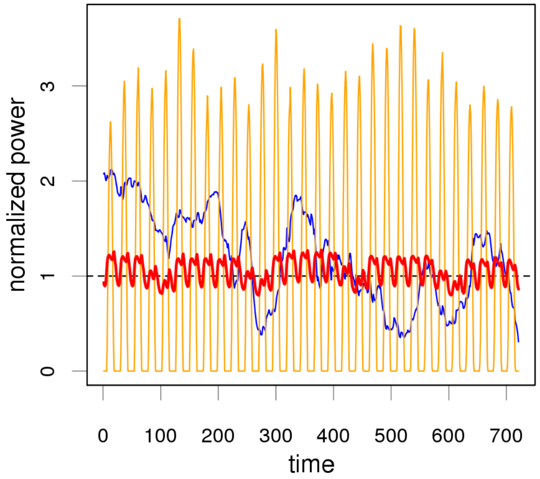
$$G_n^R(t) = G_n^W(t) + G_n^S(t)$$

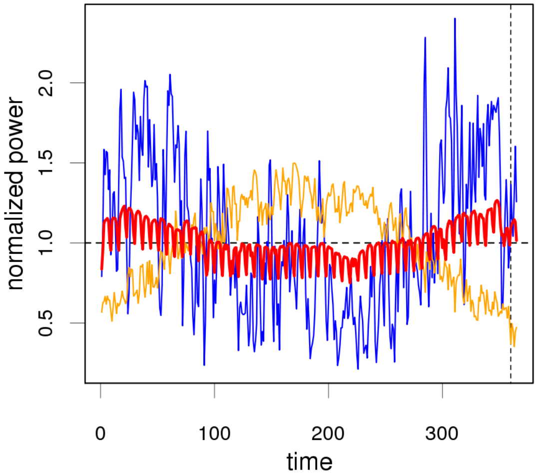
$$\langle G_n^R \rangle = \gamma_n \langle L_n \rangle$$

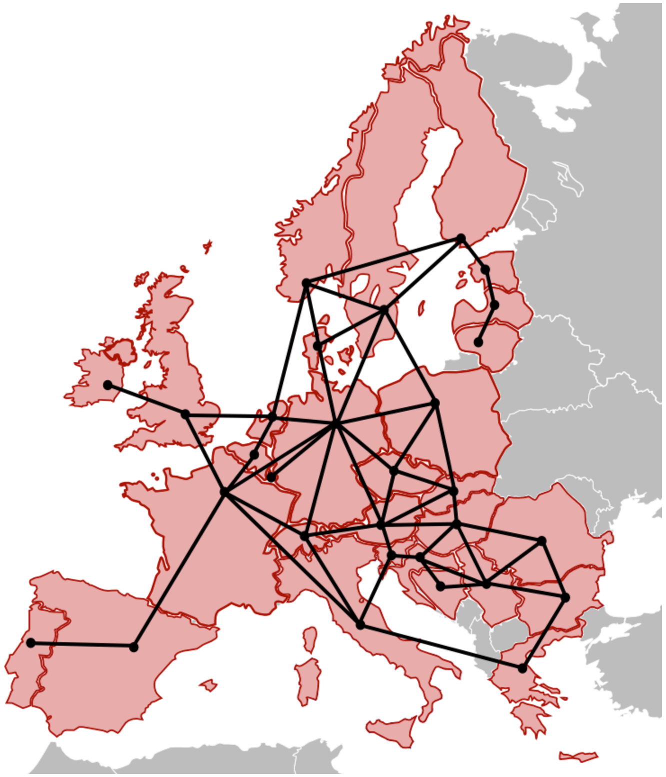
$$\langle G_n^W \rangle = \alpha_n \langle G_n^R \rangle$$

Let the weather decide!

1980 – 2014: 1h, 30x30km²
Renewable Energy Atlas







3 TIME SCALES:

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

Renewable European electricity network + fluctuating „weather forces“

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

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

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

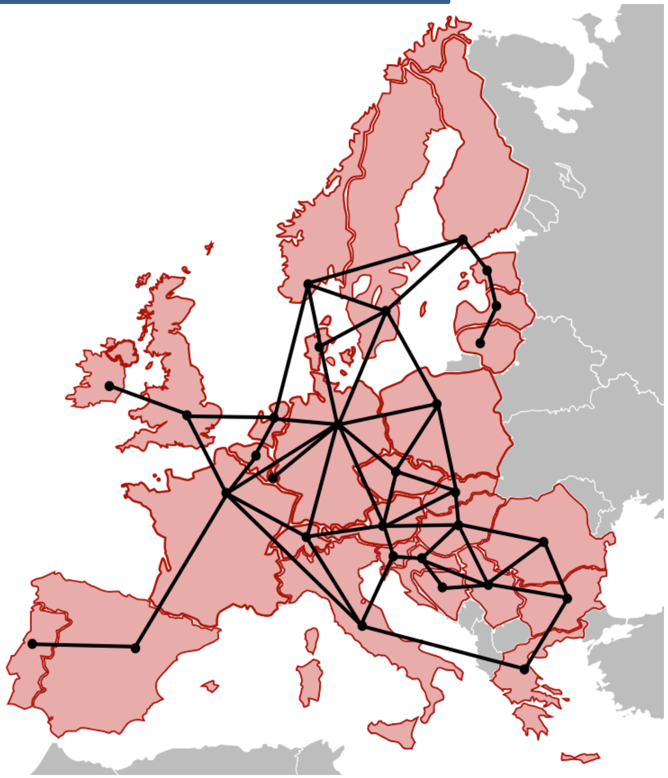
$$G_n^R(t) - L_n(t) = B_n(t) + P_n(t) + \cdots$$

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

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

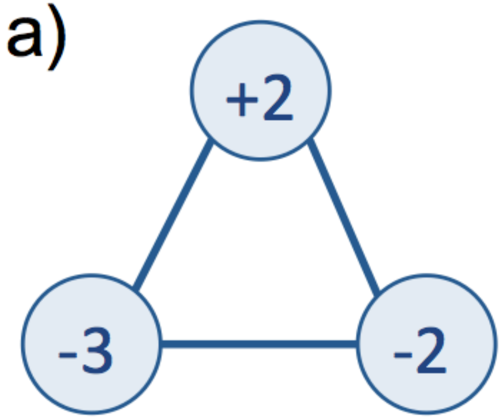
$$\sum_n P_n(t) = 0$$

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



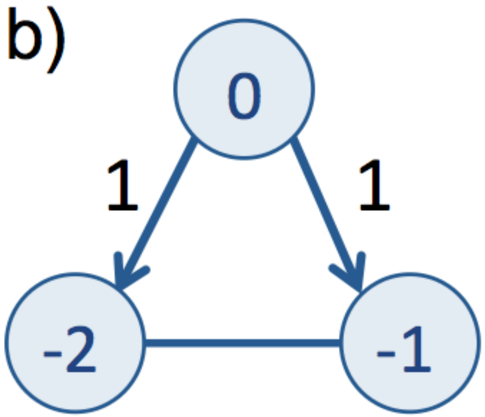
“interactions”: balancing ⟺ transmission

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



zero flow

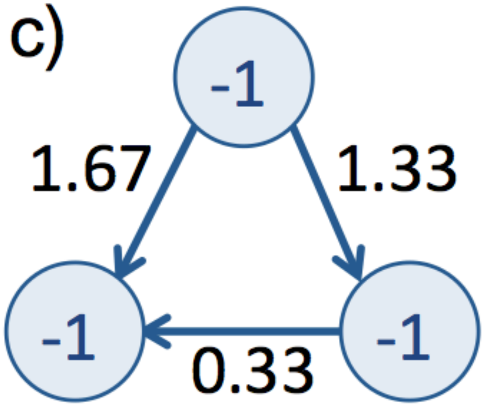
$$P_n(t) = 0$$



localized flow

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

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



synchronized balancing

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

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

Renewable European electricity network + fluctuating „weather forces“

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

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

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

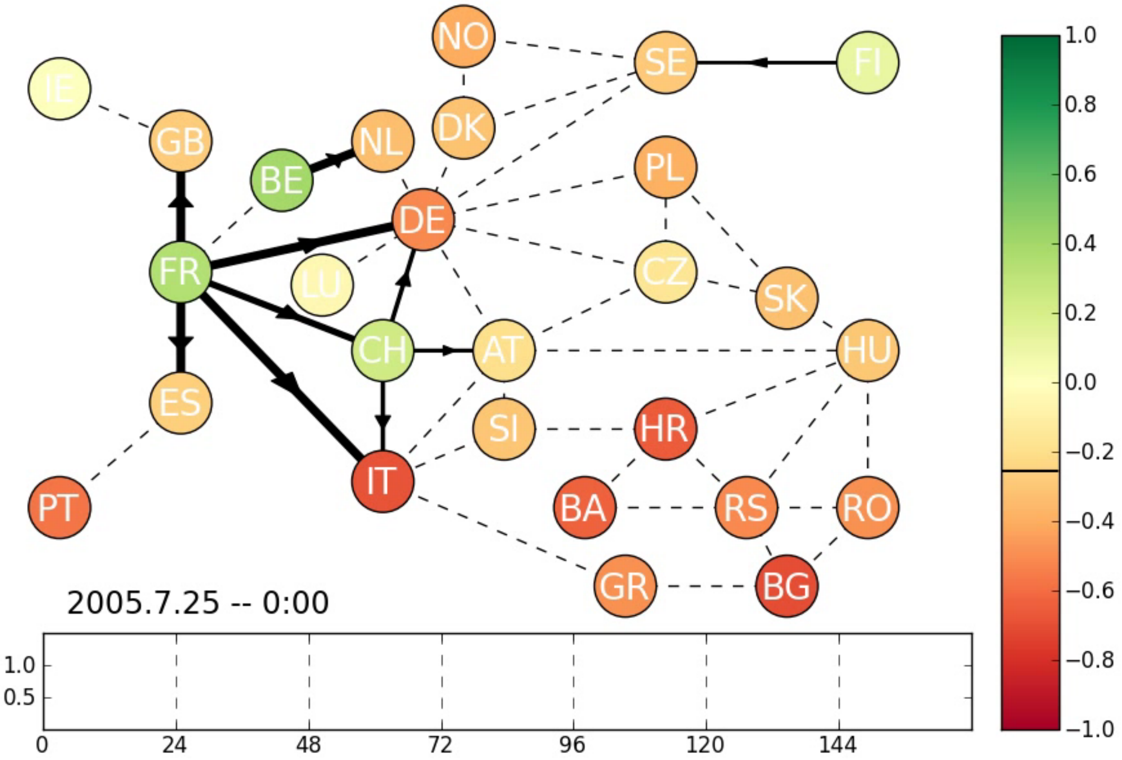
$$G_n^R(t) - L_n(t) = B_n(t) + P_n(t) + \cdots$$

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

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

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

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

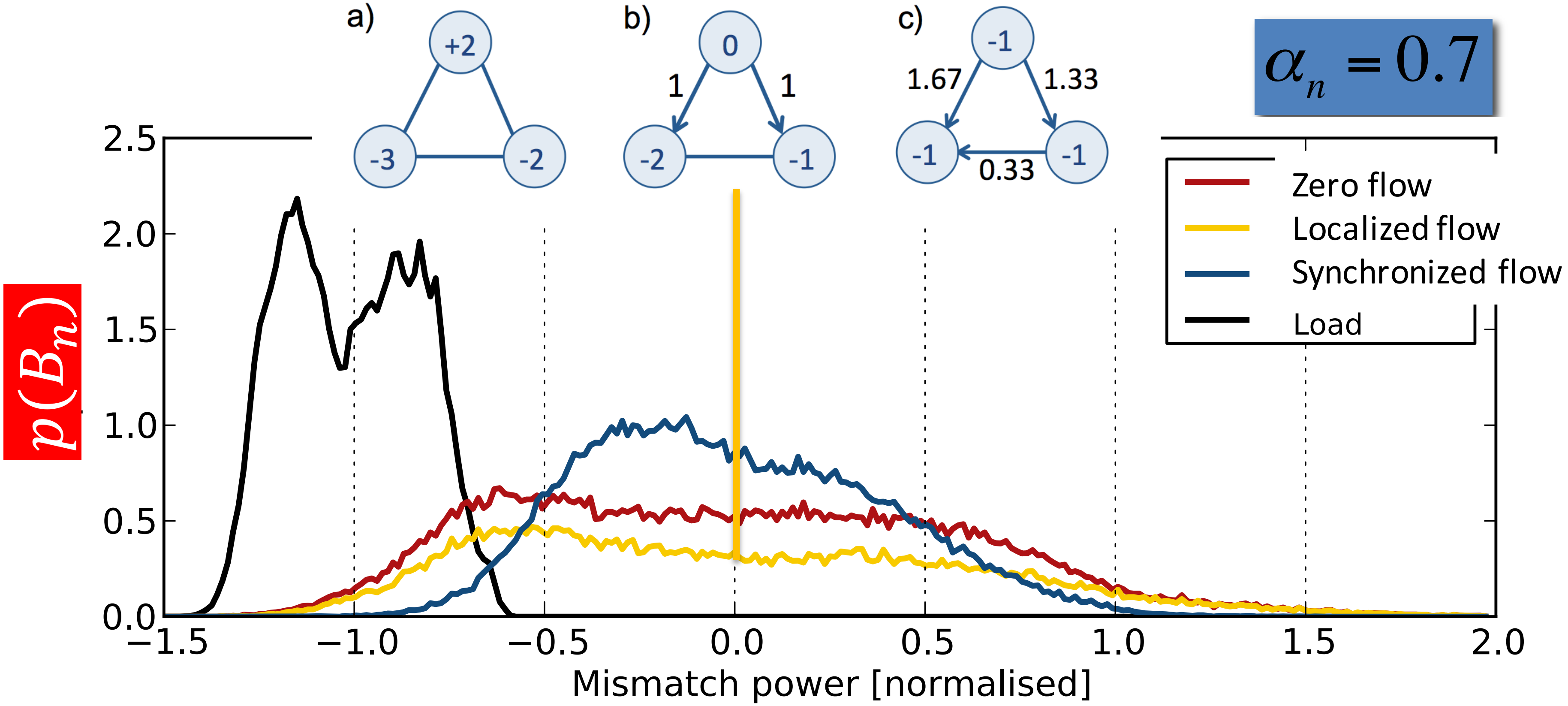


Balancing distribution (Germany)

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

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

$$\alpha_n = 0.7$$



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

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

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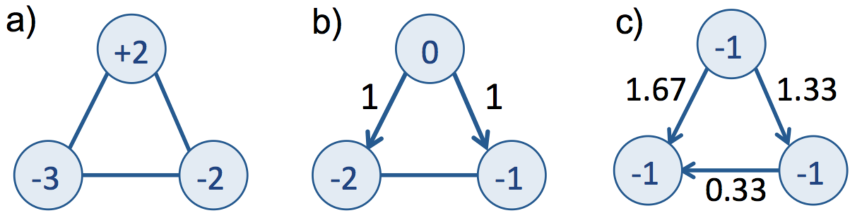
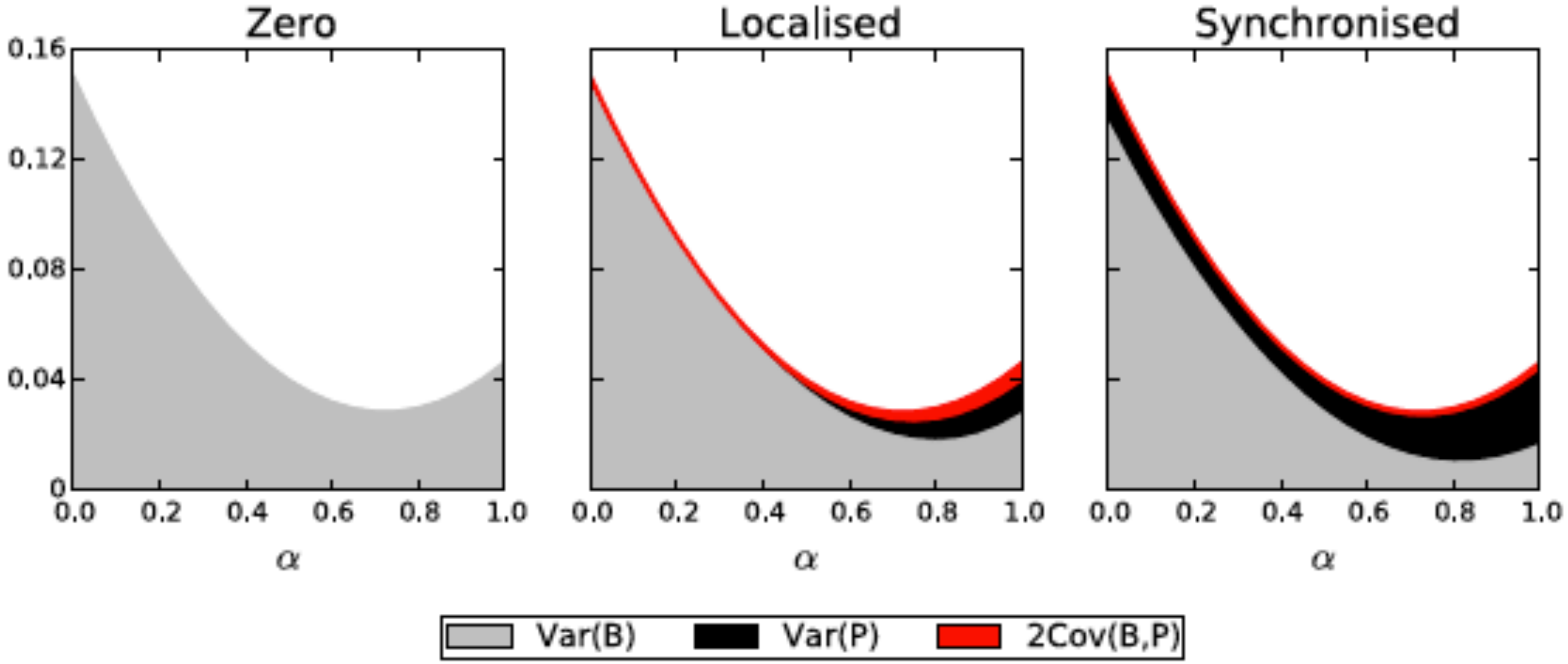
variance: balancing ↔ transmission

$$\begin{aligned}\Delta_n(t) &= \\ &= G_n^R(t) - L_n(t) \\ &= B_n(t) + P_n(t)\end{aligned}$$





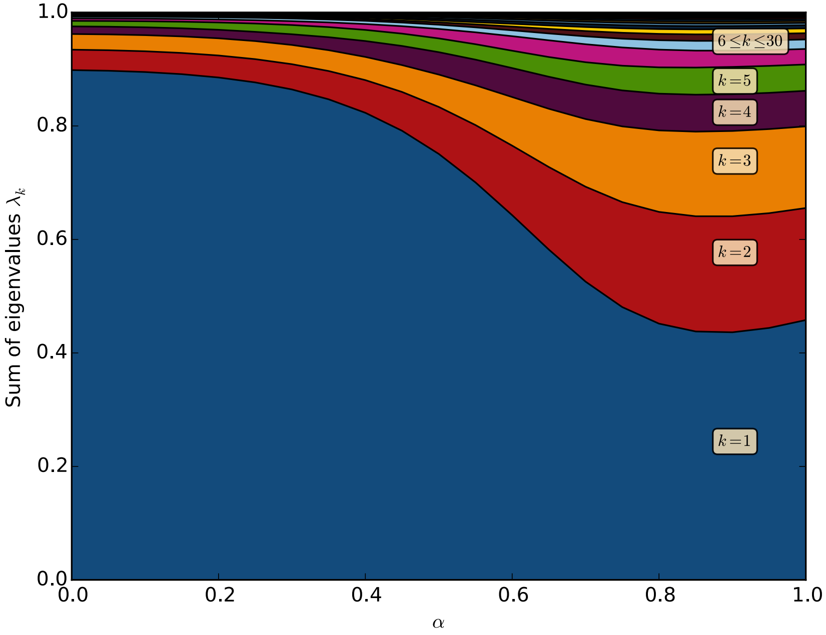
variance: balancing ⟺ transmission

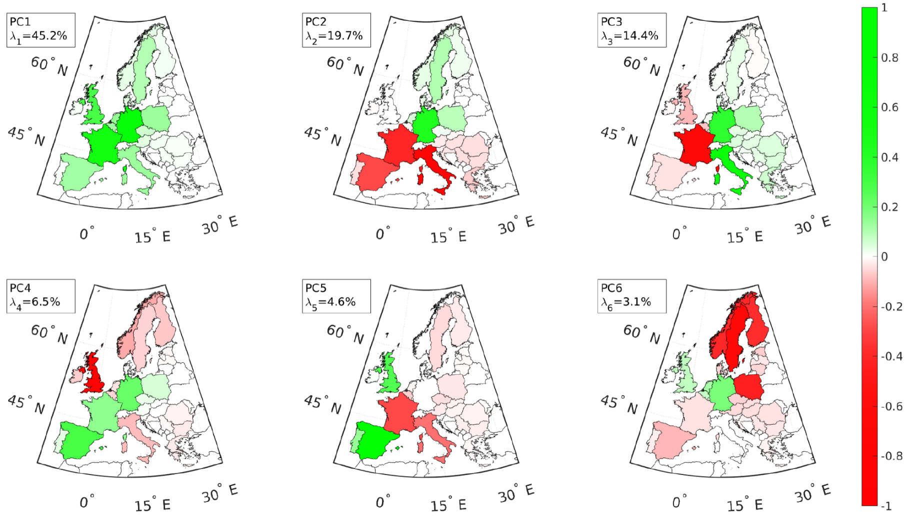
$$\vec{\Delta}(t) = \vec{G}^R(t) - \vec{L}(t) = \vec{B}(t) + \vec{P}(t)$$

$$= \sum_n \Delta_n(t)\,\vec{e}_n = \sum_k \frac{a_k(t)}{c}\,\vec{p}_k$$

principal component analysis

$$\langle \Delta_n \Delta_m \rangle$$





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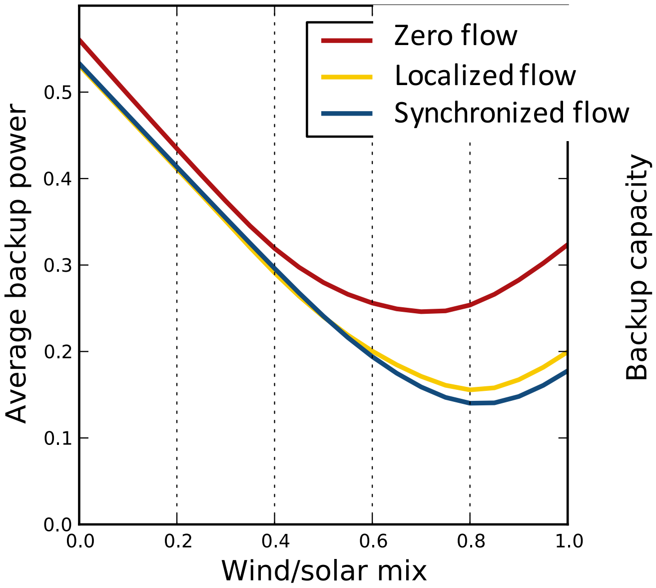
Infrastructure measures I

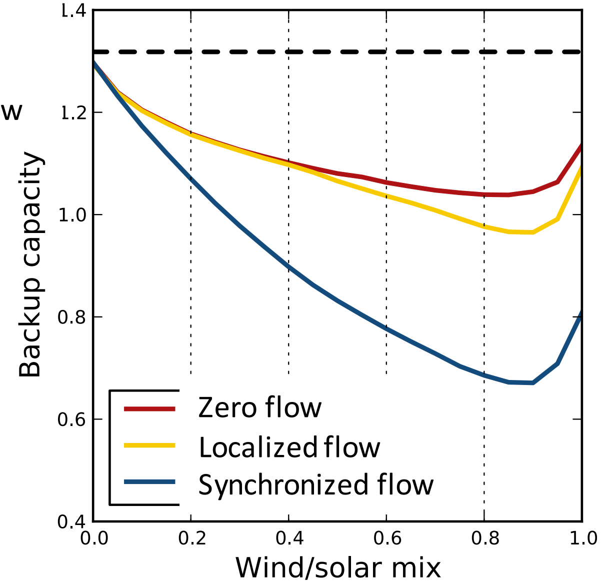
backup energy

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



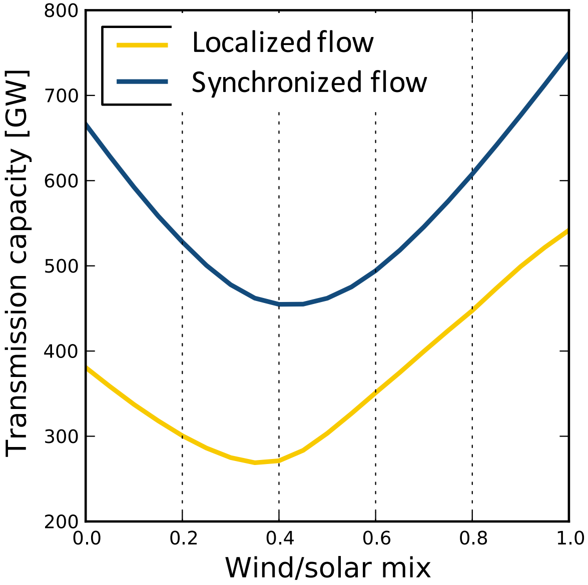
backup capacity

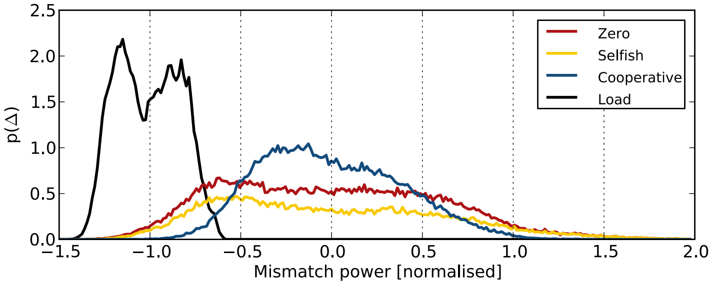
$$K_n^B = max_q(G_n^B)$$

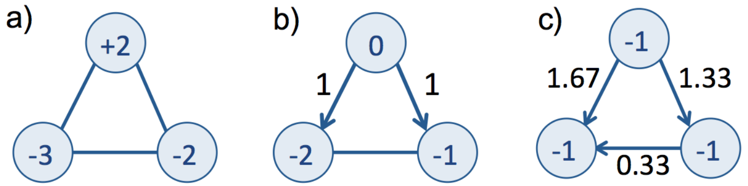


transmission capacity

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



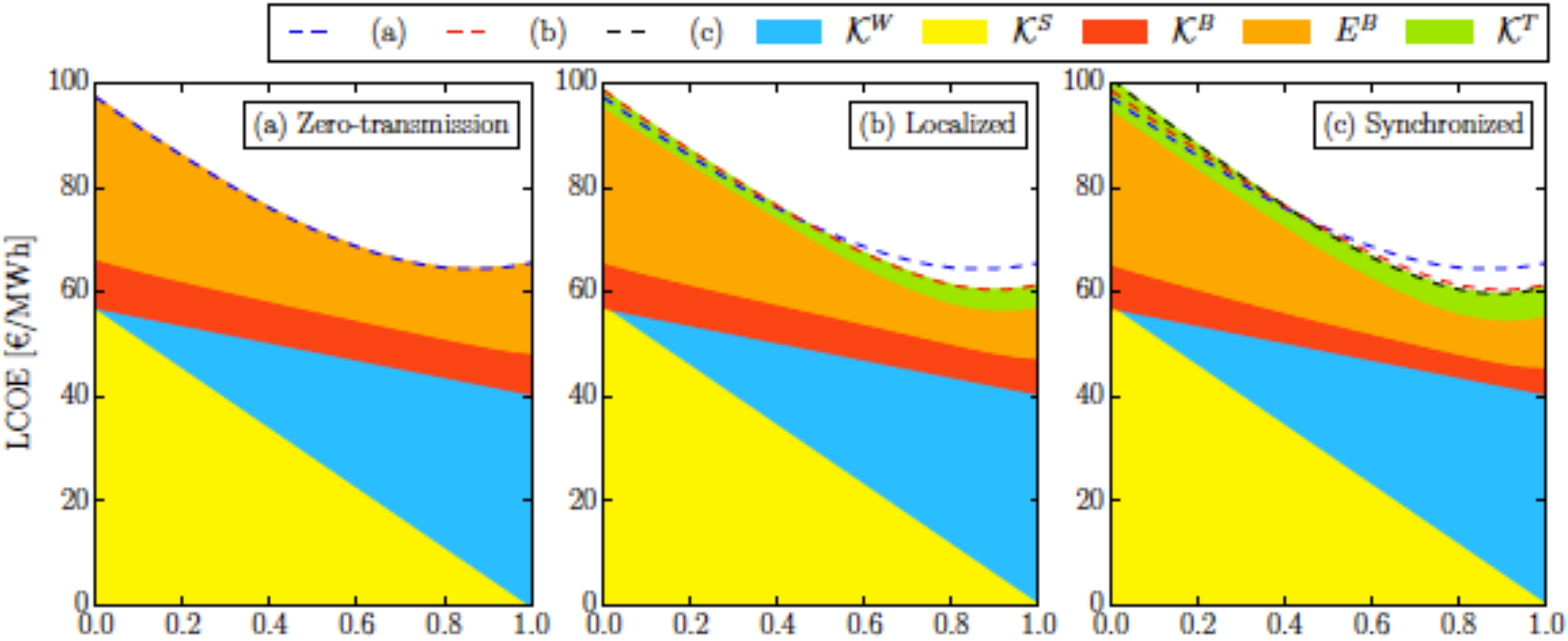




Infrastructure measures II

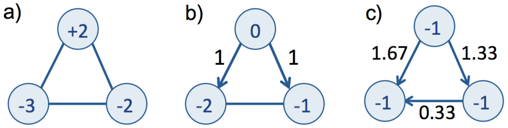
backup energy	$E_n^B = \langle G_n^B \rangle$
backup capacity	$K_n^B = max_q(G_n^B)$
transmission capacity	$K_l^T = max_q\lvert F_l \rvert \cdot d_l$
wind capacity	$K_n^W = \frac{\alpha_n \gamma_n \langle L_n \rangle}{CF_n^W}$
solar capacity	$K_n^S = \frac{(1-\alpha_n)\gamma_n \langle L_n \rangle}{CF_n^S}$

Levelized Cost of SYSTEM Energy



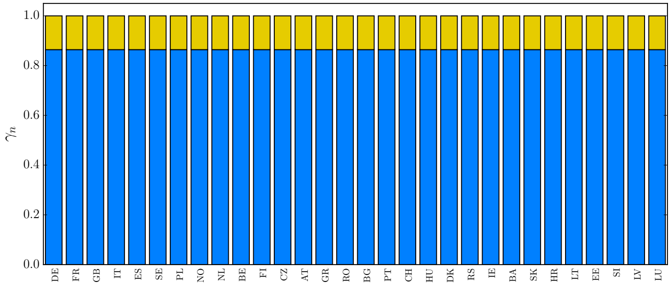
$\gamma_n = 1$

$\alpha_n = \alpha$

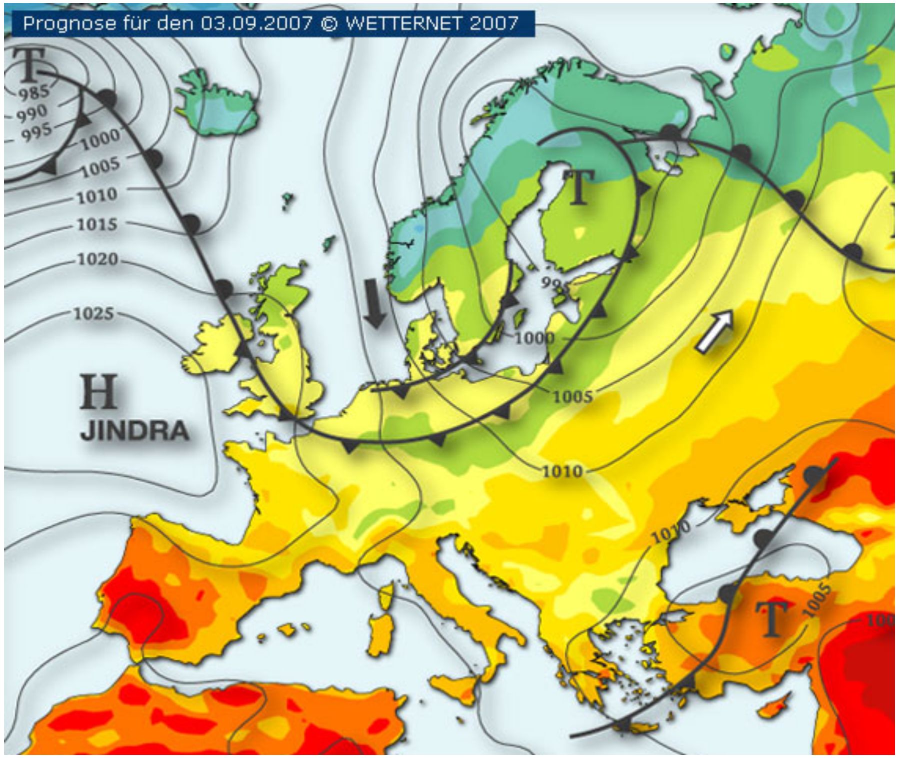


Coupling objectives: B ⟺ P

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



wind and solar power capacities

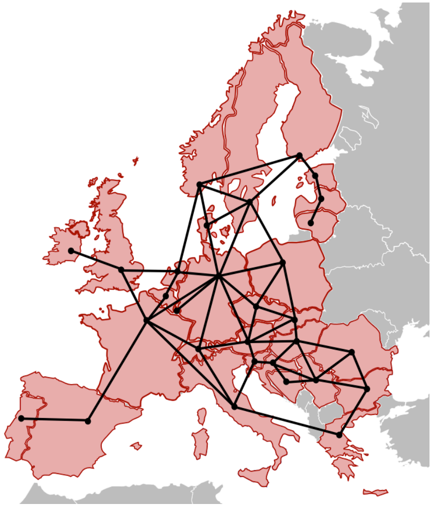


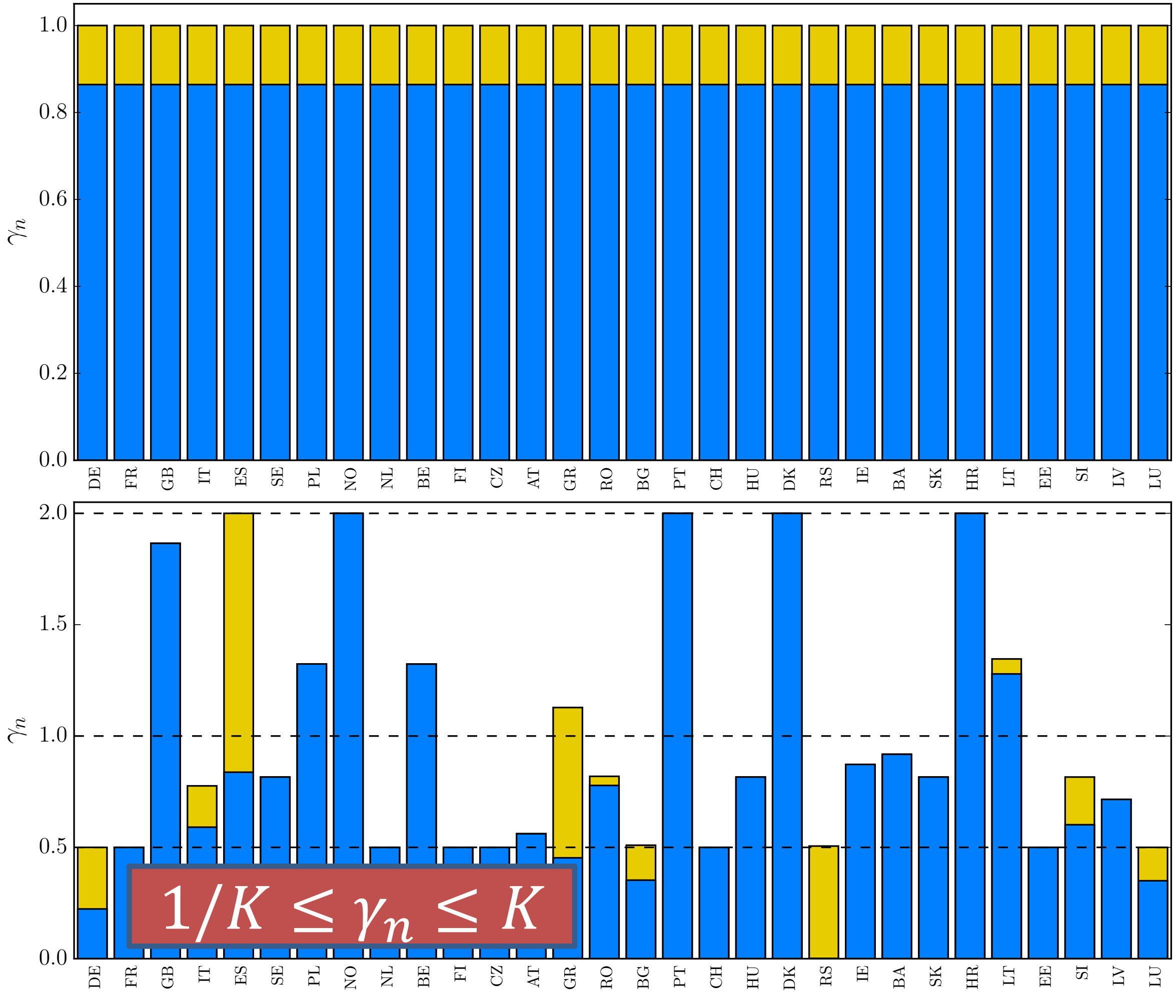
annual consumption (2009)
= 3400 TWh

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

Breaking homogeneity: cost-optimal heterogeneity

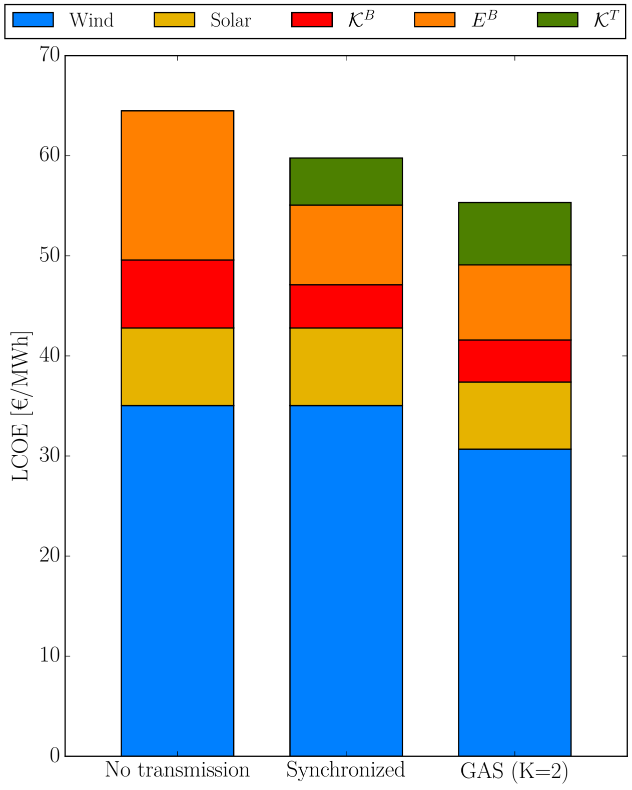




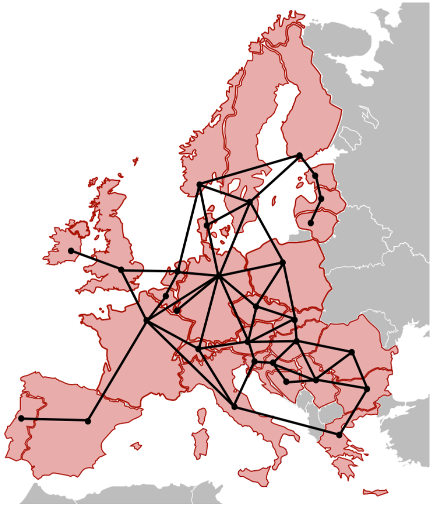
$1/K \leq \gamma_n \leq K$

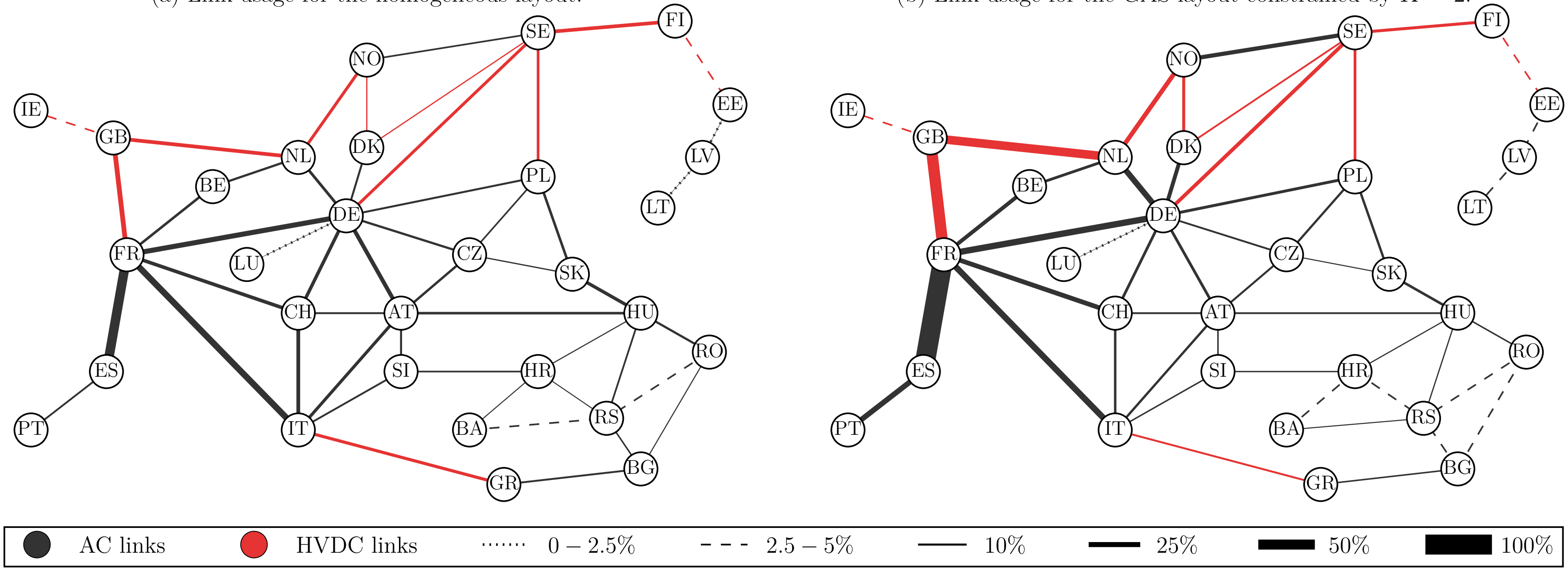
$\langle G_n^R \rangle = \gamma_n \langle L_n \rangle$

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



Breaking homogeneity: optimal heterogeneity




(a) Link usage for the homogeneous layout:

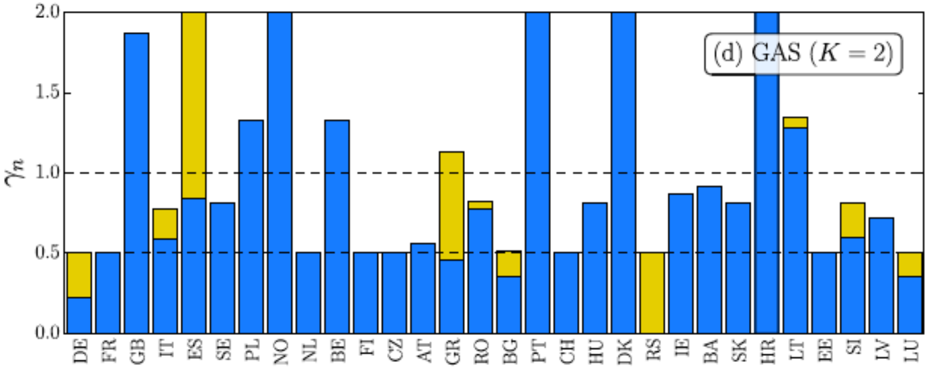
(b) Link usage for the GAS layout constrained by $K = 2$:

Back-on-the-envelop estimate

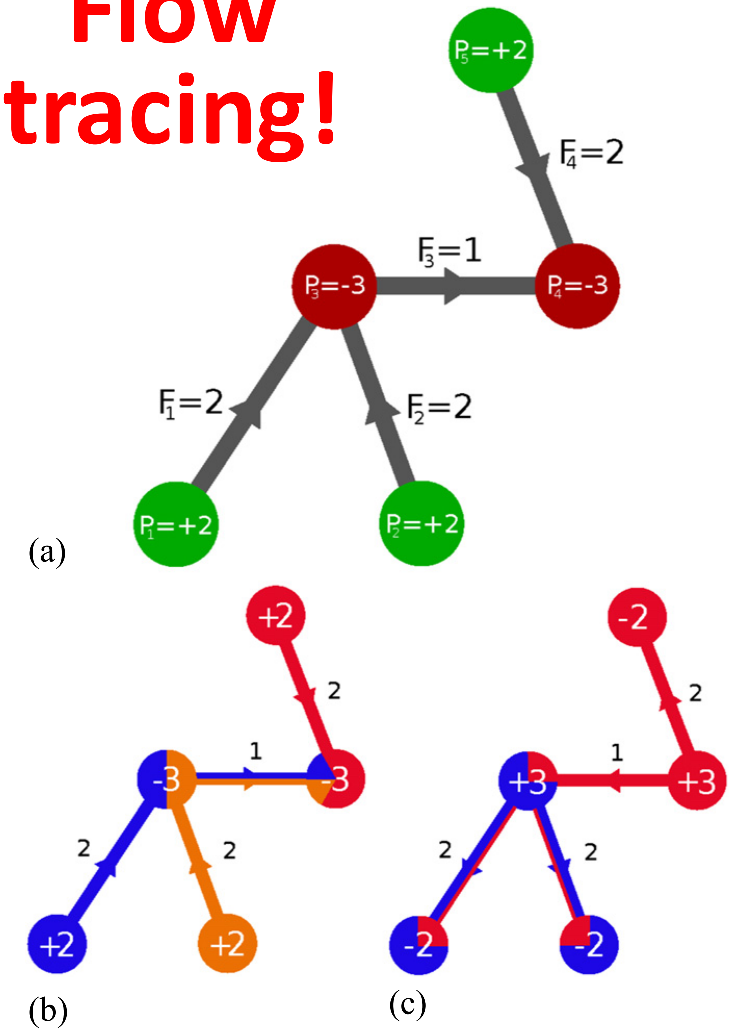
OPT-HOM-noT(K=1): 64.5 €/MWh
OPT-HOM(K=1): 56.6 €/MWh
OPT-HET(K=2): 53.8 €/MWh

EU cost reduction / y
= 3500 TWh/y x 10 €/MWh
= 35 x 10^9 €/y

Who pays for the heterogeneity?



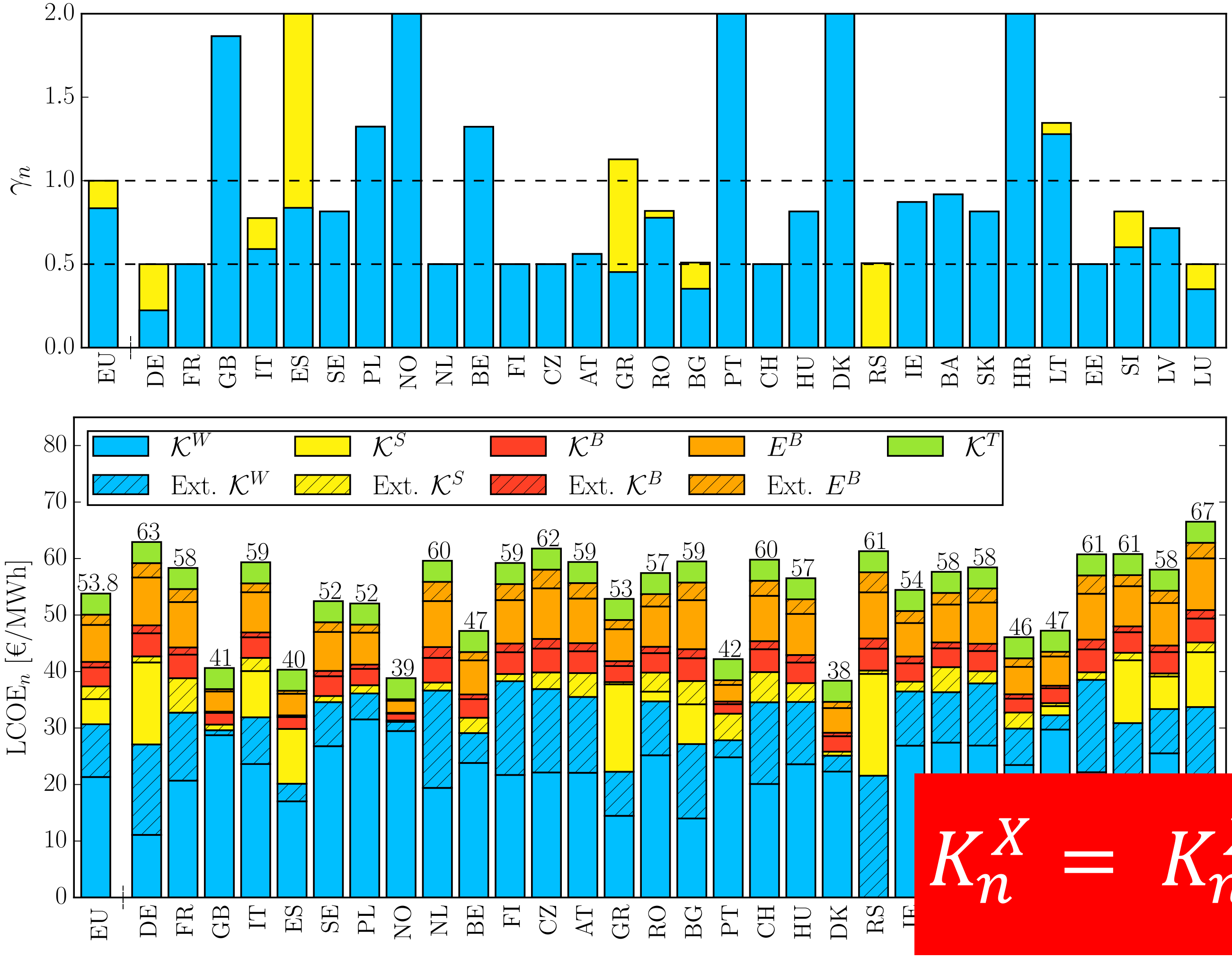
Flow tracing!



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

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

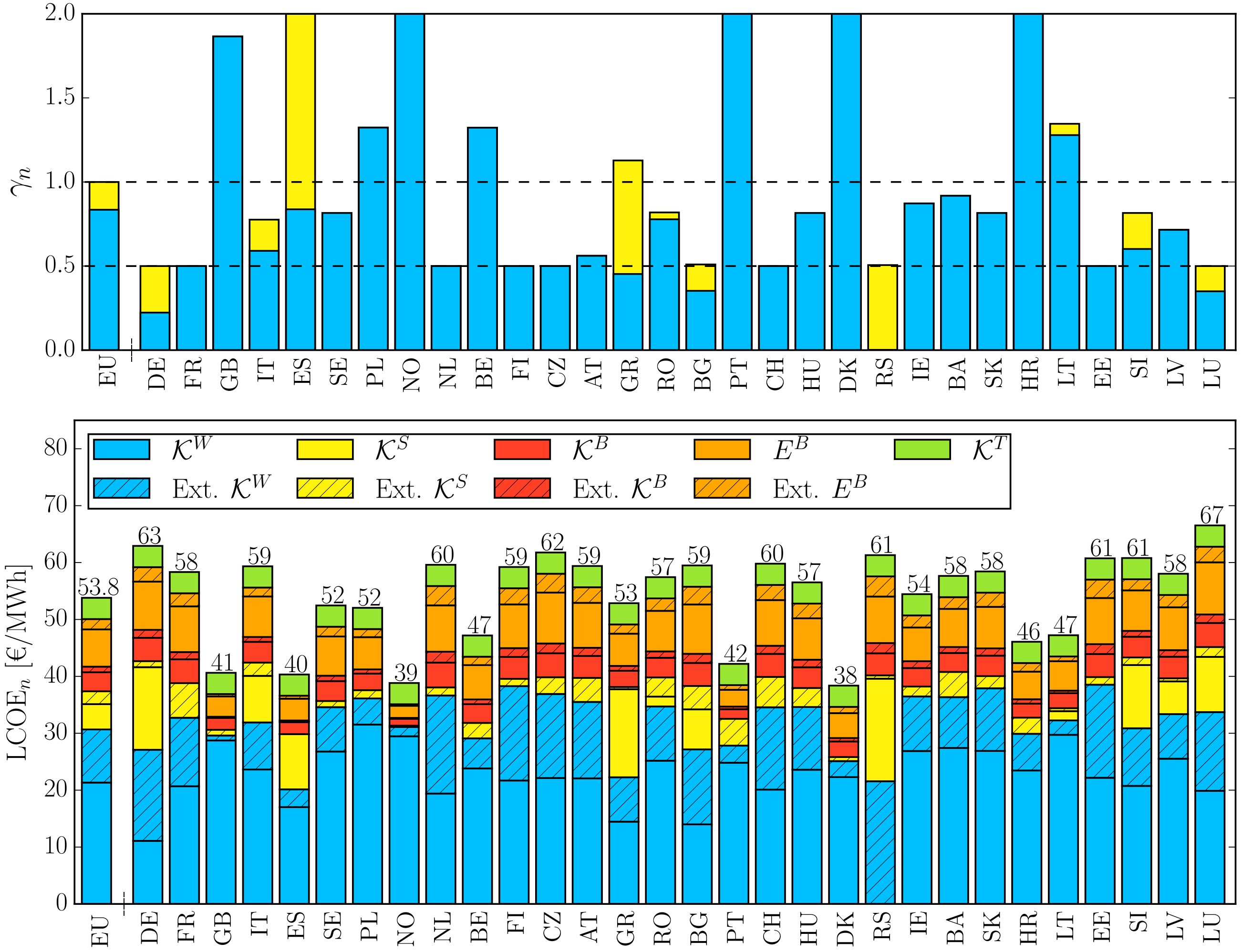
Who pays for the heterogeneity?

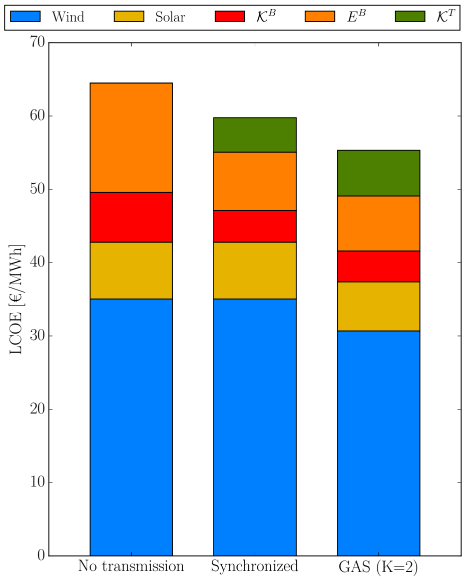


$$K_n^X = K_{nn}^X + \sum\nolimits_{m\neq n} K_{nm}^X$$

$$\widetilde{K}_n^X = K_{nn}^X + \sum\nolimits_{m\neq n} K_{mn}^X$$

Benefit of cooperation





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

some “physics” challenges

emerging renewable energy networks:
    socio-economic market + investment games

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

flexibility classes

storage phase transition

climate change + mesoscale turbulence

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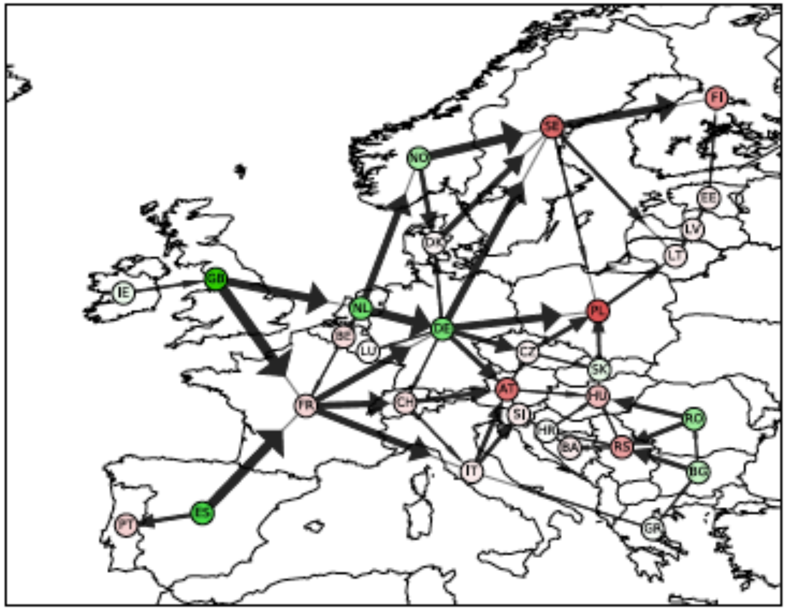
Decompositions of injection patterns for nodal flow allocation in renewable electricity networks

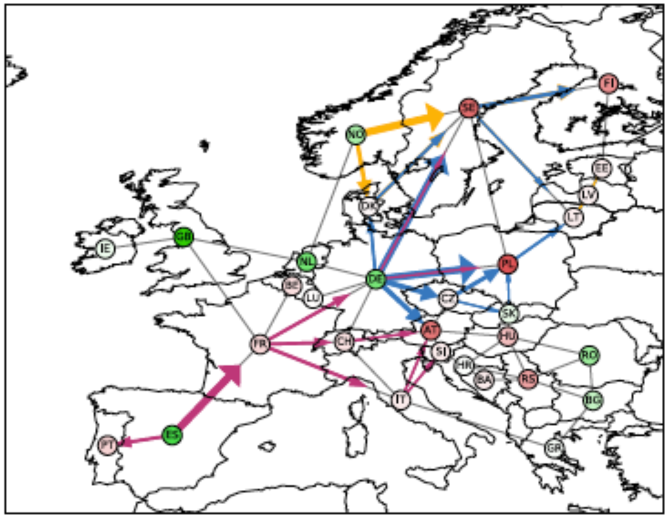
Mirko Schäfer[1,a], Bo Tranberg[1,2], Sabrina Hempel[3,b], Stefan Schramm[3], and Martin Greiner[1]

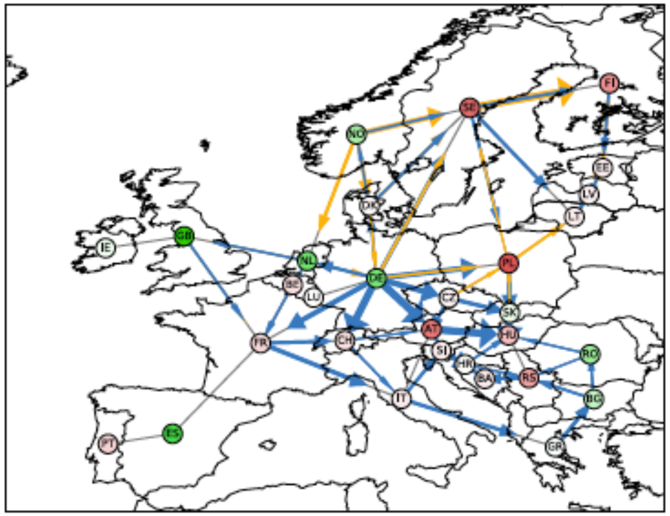
THE EUROPEAN PHYSICAL JOURNAL B

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



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





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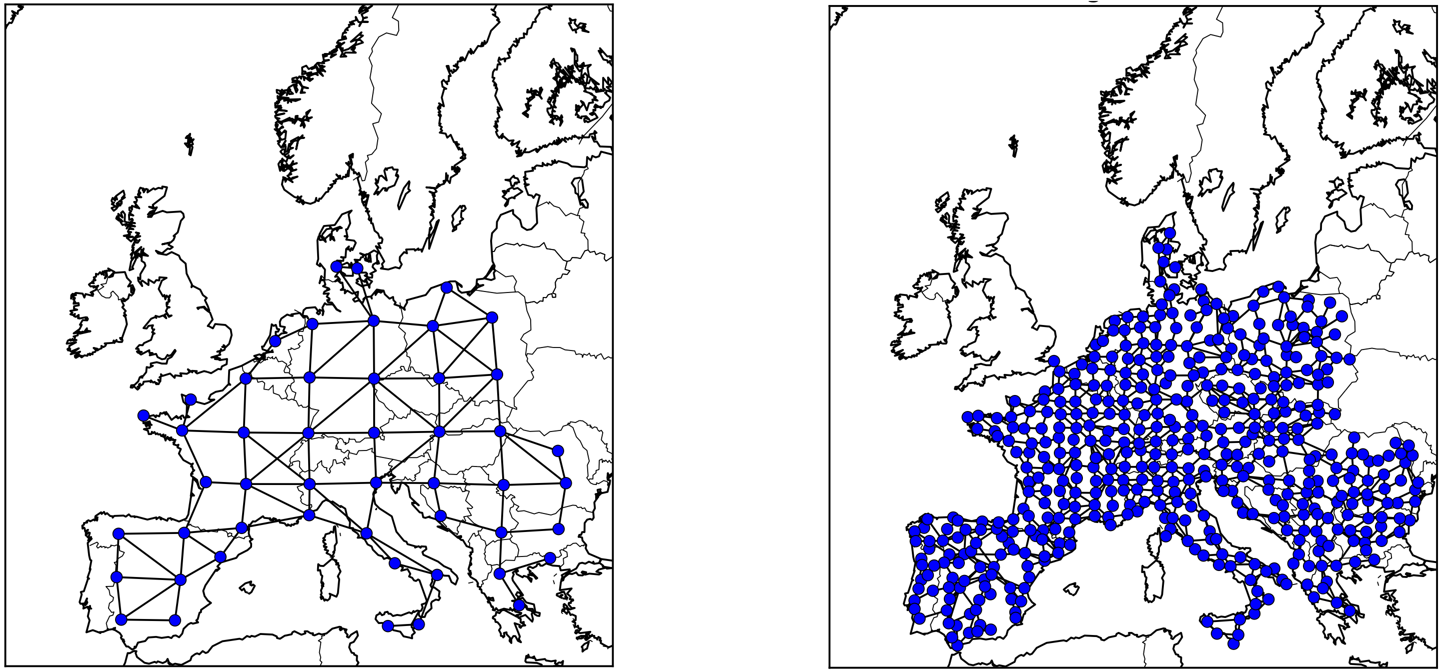
Scaling of transmission capacities in coarse-grained renewable electricity networks

M. Schäfer[1], S. Bugge Siggaard[2], Kun Zhu[1], C. Risager Poulsen[2] and M. Greiner[1]

A Letters Journal Exploring the Frontiers of Physics

EPL, **119** (2017) 38004
doi: 10.1209/0295-5075/119/38004



$$\sum_{l=1}^{\textbf{small } L} K_l^T d_l \approx \sum_{l=1}^{\textbf{large } L} K_l^T d_l$$

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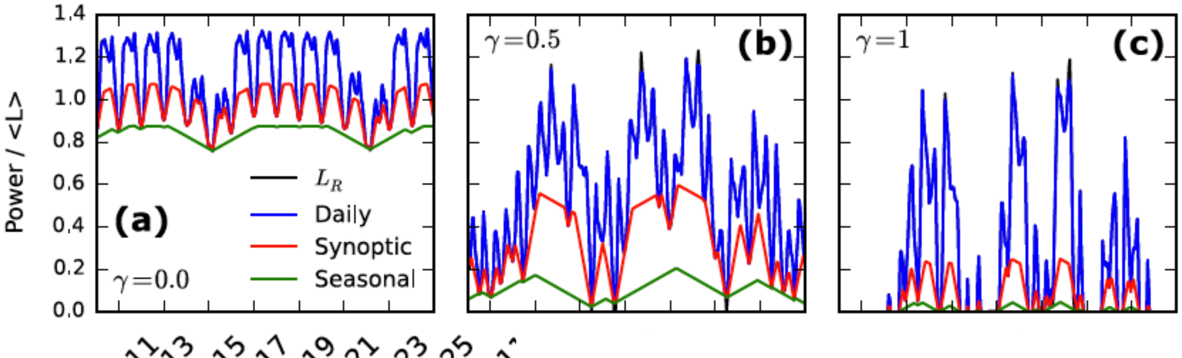
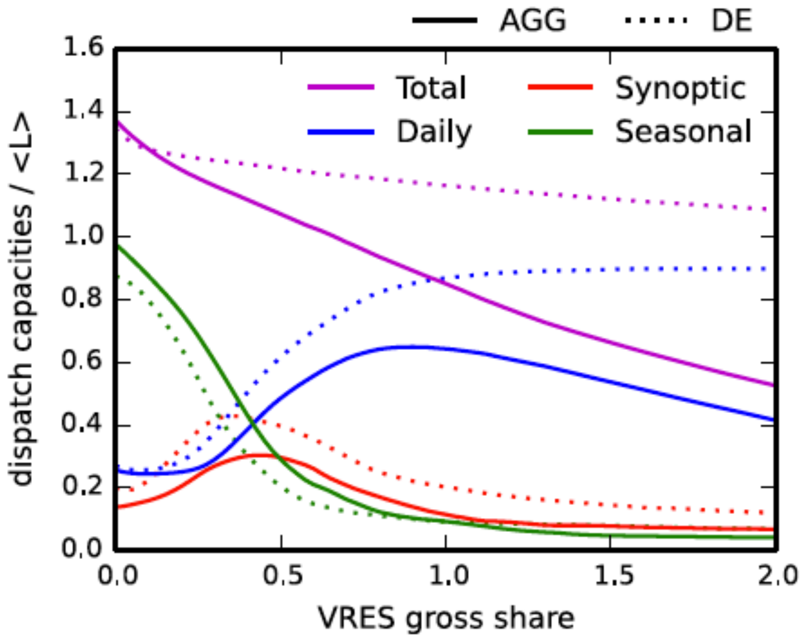
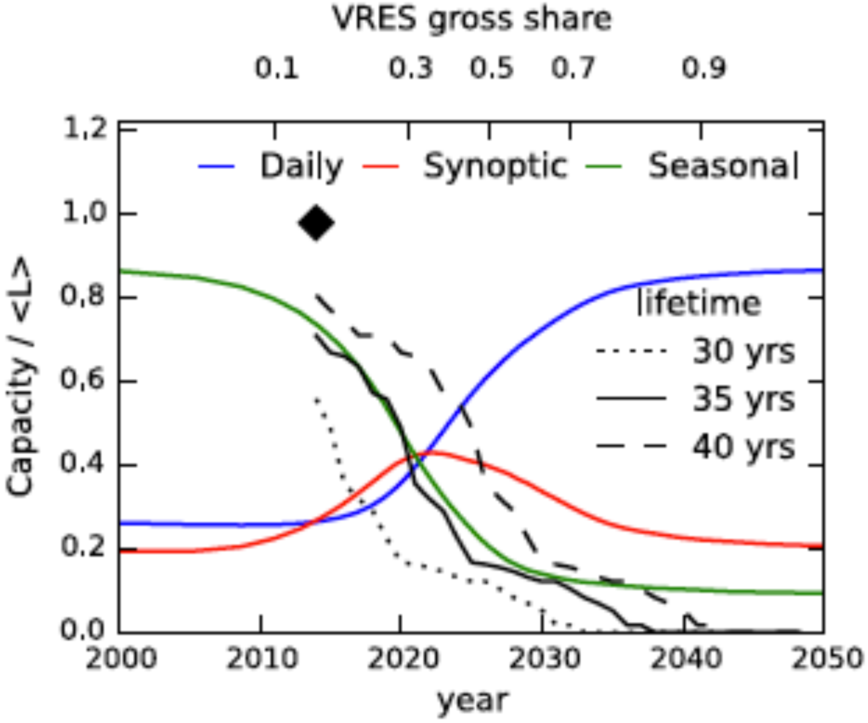
Emerging renewable electricity system: German flexibility classes

$$\min \langle (L(t) - G^R(t) - \textstyle\sum_i B_i(t))^2 \rangle$$







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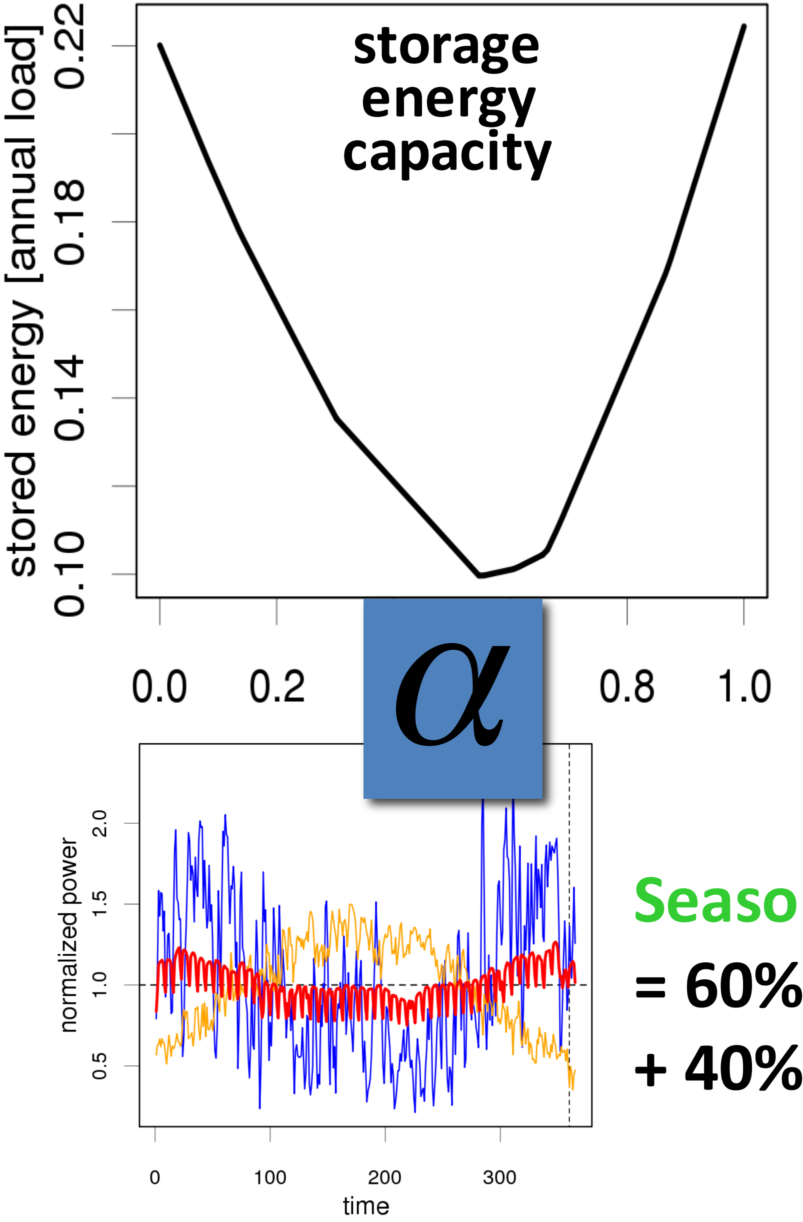
How much storage? @ 100% penetration in EU



$$S(t) - S(t-1) =$$

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

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

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

Seasonal optimal mix

= 60% wind power

+ 40% solar power

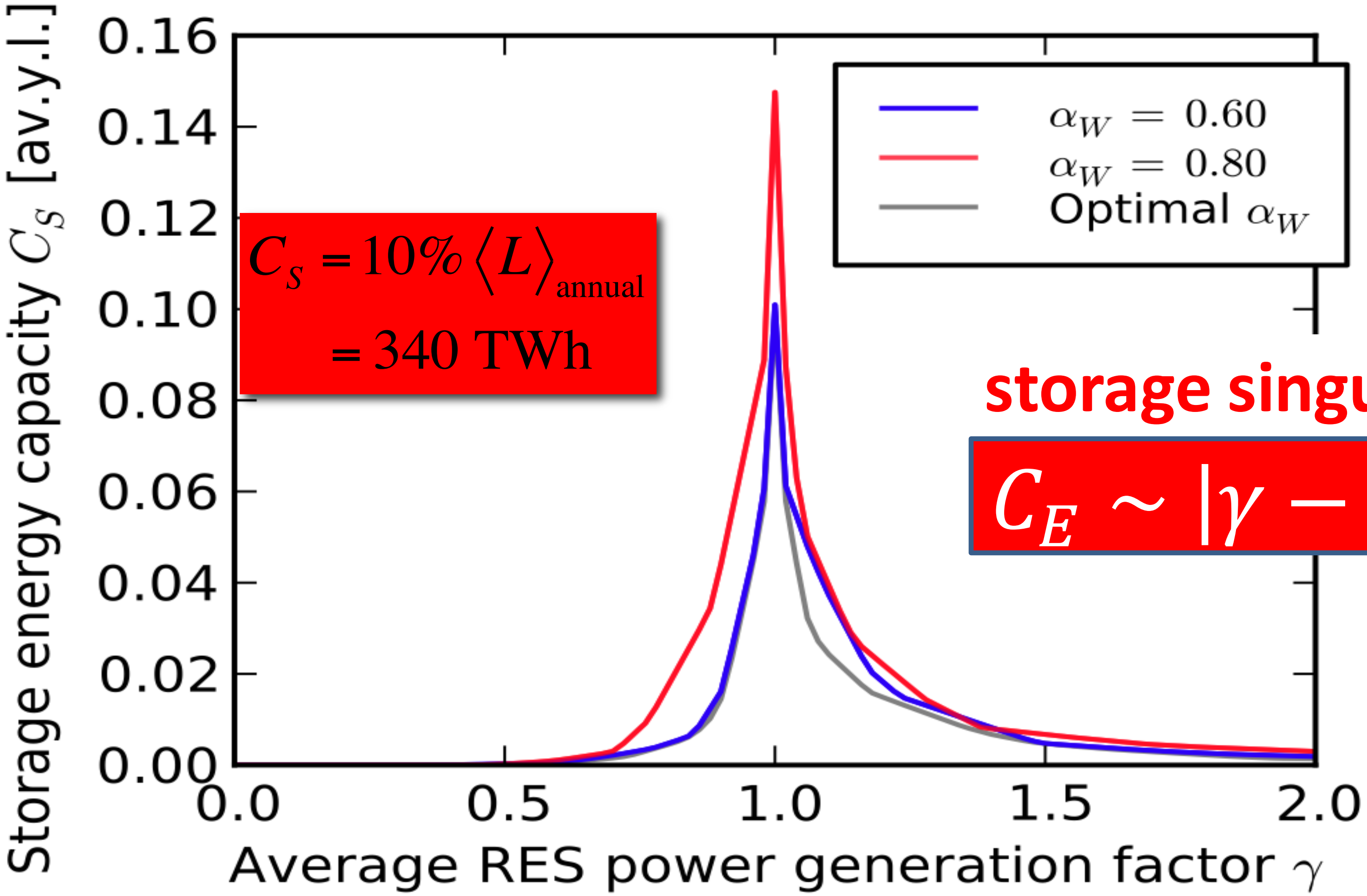
$$C_S = 10\% \left\langle L \right\rangle_{\mathrm{annual}}$$

$$= 340 \text{ TWh}$$

Emergence of a phase transition for the required amount of storage in highly renewable electricity systems

Tue Vissing Jensen[1,2,a] and Martin Greiner[3,b]

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS
223, 2475–2481 (2014)

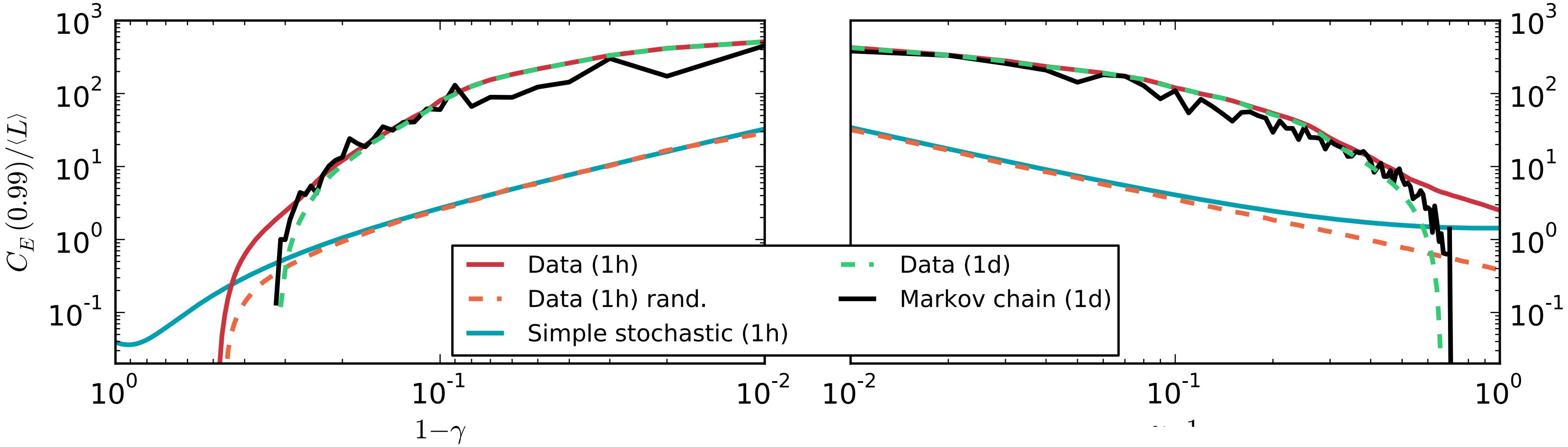


$$C_S = 10\% \langle L \rangle_{\text{annual}}$$
$$= 340 \text{ TWh}$$

storage singularity

$$C_E \sim |\gamma - 1|^{-\delta}$$

Enhanced Storage Singularity



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

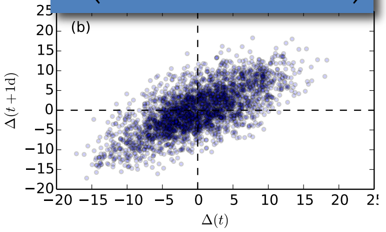
$$C_E(\text{random}) \propto \frac{1}{|\gamma-1|^{\delta}}$$

$$\delta = 1$$

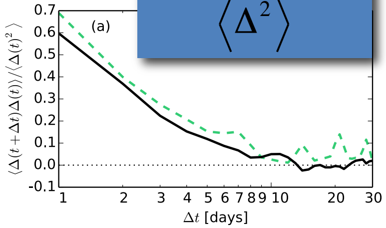
$$C_E(1\text{h}) \approx C_E(1\text{d})$$

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

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Mesoscale Wind Turbulence

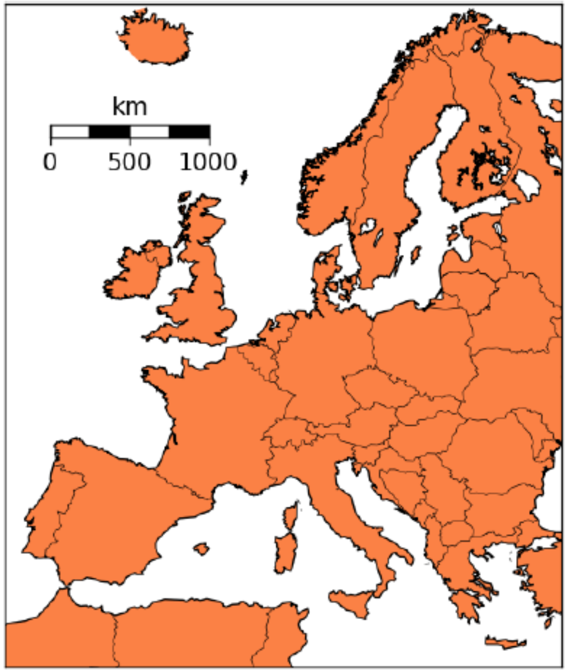
$$\mathrm{E}(k) \sim k^{-5/3}$$

$$\Delta v_l \sim l^{1/3}$$

$$\eta = 5km \;\le l\; \le L = 600km$$

$$\mu \approx 0.36$$

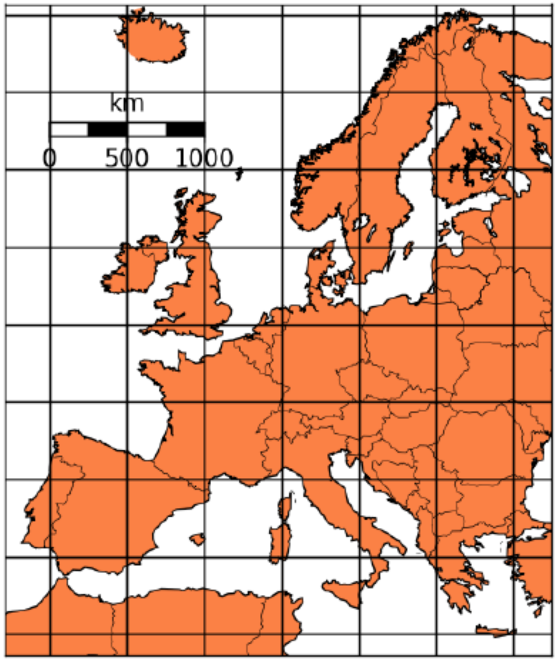
$$\left\langle \Delta v_\eta^2(x+d)\, \Delta v_\eta^2(x) \right\rangle \sim d^{-\mu}$$



R Baïle + J Muzy: *Spatial Intermittency of surface layer wind fluctuations at mesoscale range*, **Phys.Rev.Lett. 105 (2010) 254501**. **P Milan, M Wächter + J Peinke:** *Turbulent character of wind energy*, **Phys.Rev.Lett. 110 (2013) 138701**. **R Calif, F Schmitt + Y Huang:** *Multifractal description of wind power fluctuations using arbitrary order Hilbert spectral analysis*, **Physica A 392 (2013) 4106-20.** **J Apt:** *The spectrum of power from wind turbines,* **J. Power Sources 169 (2007) 369-74.**

2dim multifractal fBm

$$\mathrm{v}(\mathbf{x}) = \mathrm{v}_{typ} + \frac{\sqrt{m(\mathbf{x})}}{\langle\sqrt{m}\rangle}\mathrm{v}_{fBm}(\mathbf{x})$$



$L\,,\ \sigma_0\,,\ \mathrm{H}\,,\ \mu$

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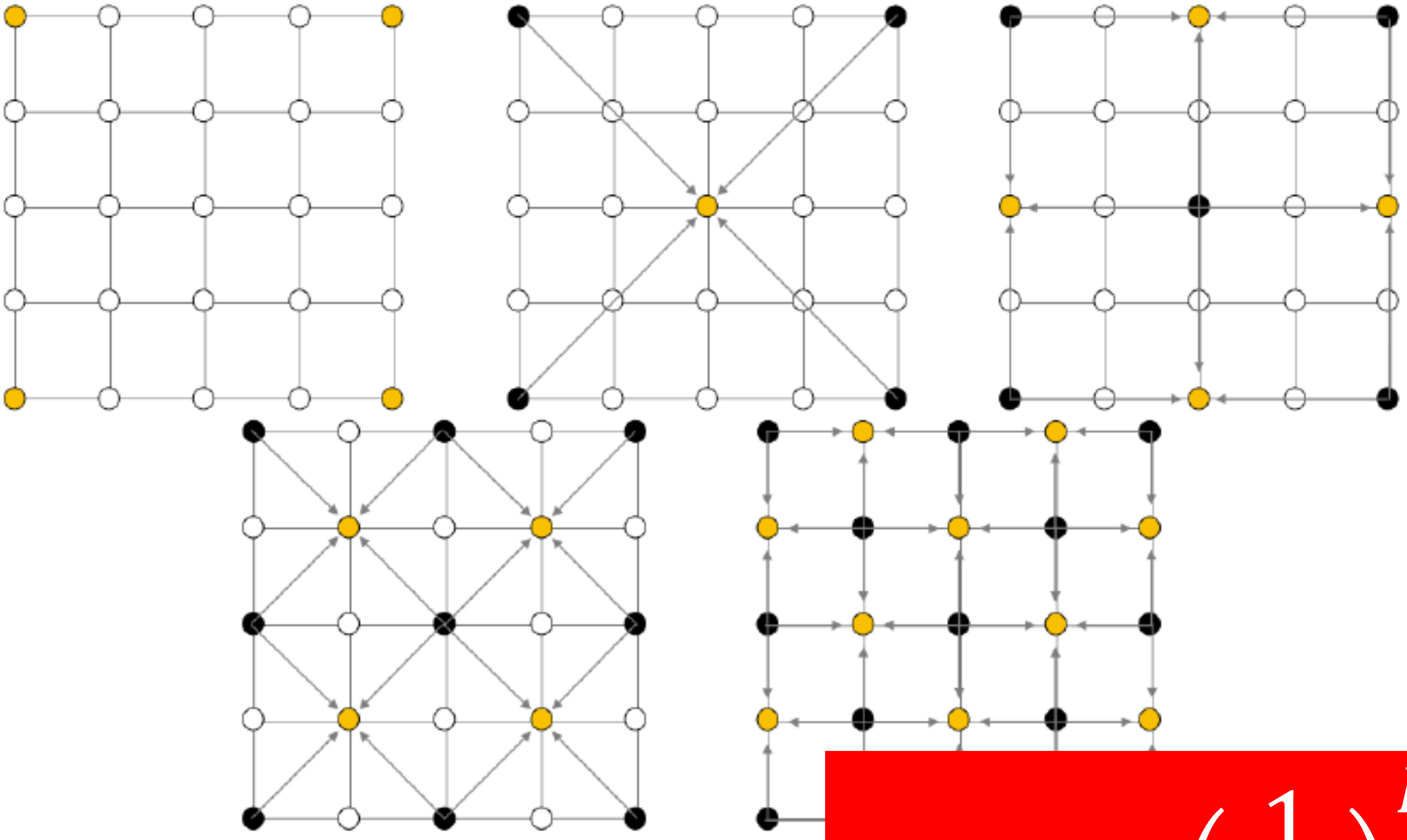
2dim fBm: midpoint displacement method

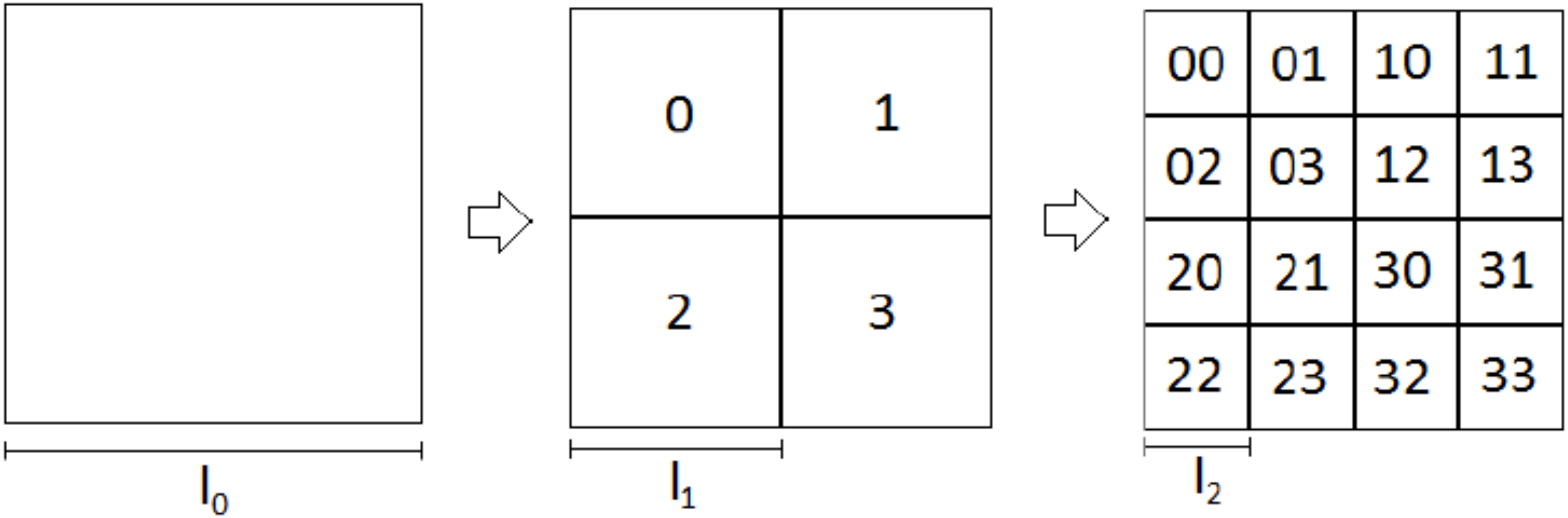
L , σ_0 , H



$$\sigma_{i+1} = \left(\frac{1}{\sqrt{2}}\right)^{H} \sigma_i$$

2dim multifractality: random multiplicative cascade

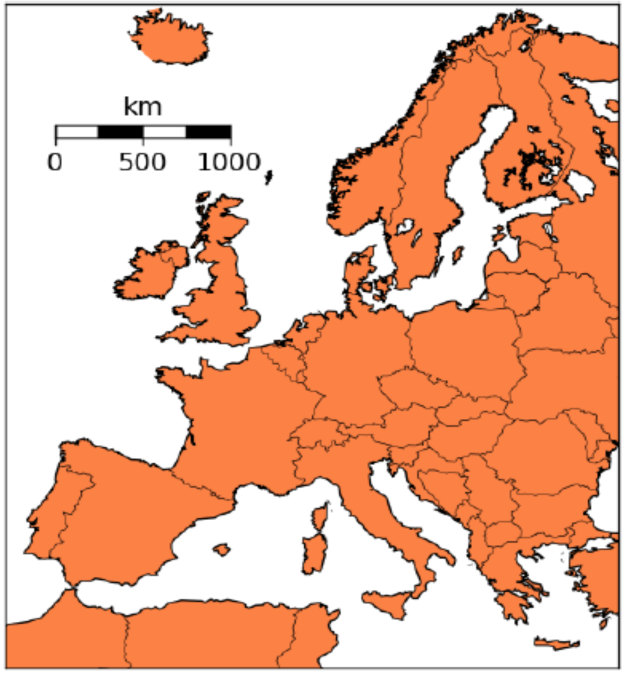
$L\,,\mu$



$$m_{i+1}(\mathbf{x}) = q_{i+1}(\mathbf{x})\, m_i(\mathbf{x})$$

Mesoscale wind power generation

$$\mathrm{v}(\mathbf{x}) = \mathrm{v}_{typ} + \frac{\sqrt{m(\mathbf{x})}}{\langle\sqrt{m}\rangle}\mathrm{v}_{fBm}(\mathbf{x})$$



$$\mathrm{v}(\mathbf{x}) \rightarrow G_n^W(t)$$

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

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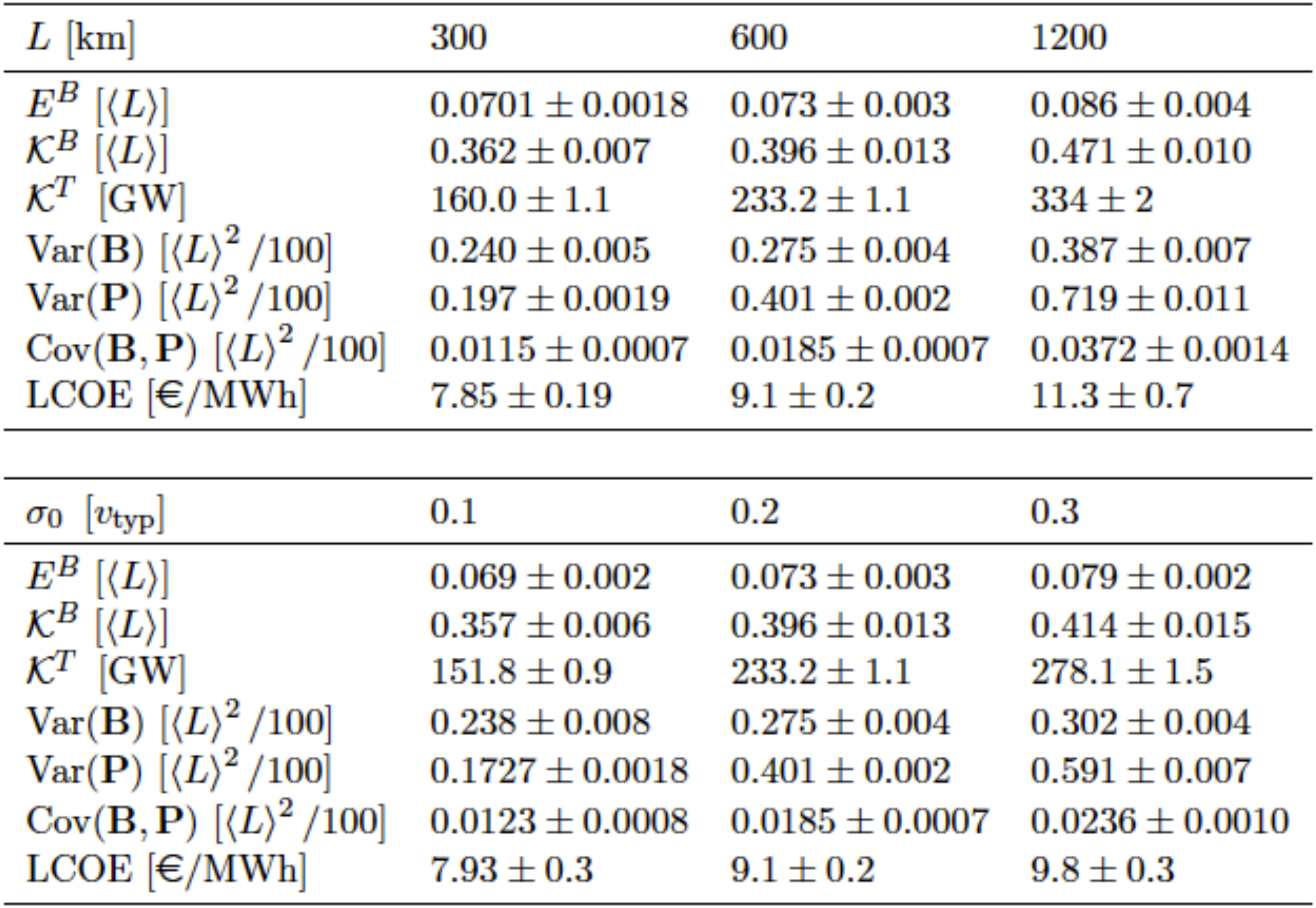
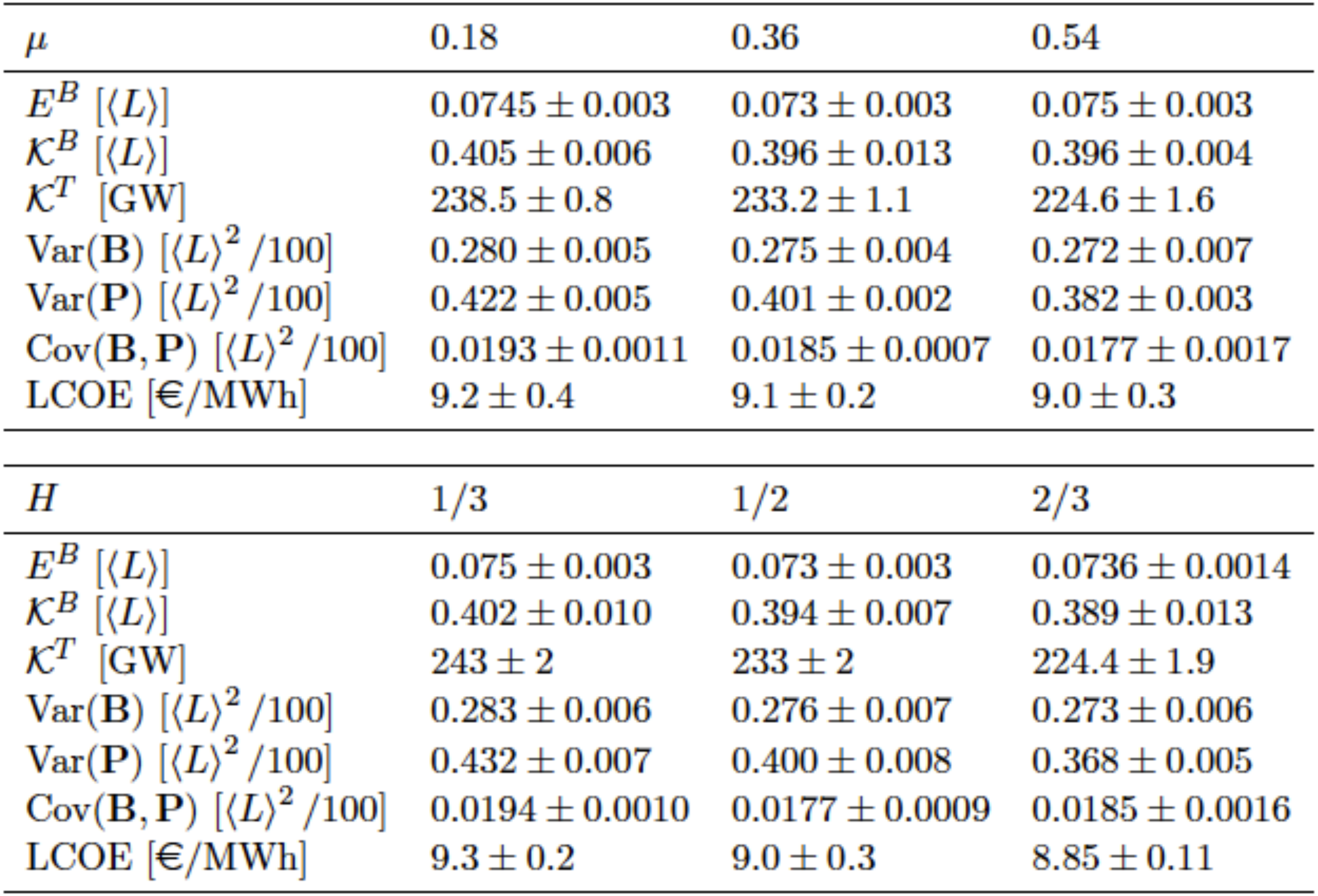
Impact of synthetic climate change



L [km]	300	600	1200
E^B $[\langle L \rangle]$	0.0701 ± 0.0018	0.073 ± 0.003	0.086 ± 0.004
$\mathcal{K}^B$ $[\langle L \rangle]$	0.362 ± 0.007	0.396 ± 0.013	0.471 ± 0.010
$\mathcal{K}^T$ [GW]	160.0 ± 1.1	233.2 ± 1.1	334 ± 2
$\mathrm{Var}(\mathbf{B})$ $[\langle L \rangle^2/100]$	0.240 ± 0.005	0.275 ± 0.004	0.387 ± 0.007
$\mathrm{Var}(\mathbf{P})$ $[\langle L \rangle^2/100]$	0.197 ± 0.0019	0.401 ± 0.002	0.719 ± 0.011
$\mathrm{Cov}(\mathbf{B},\mathbf{P})$ $[\langle L \rangle^2/100]$	0.0115 ± 0.0007	0.0185 ± 0.0007	0.0372 ± 0.0014
LCOE [€/MWh]	7.85 ± 0.19	9.1 ± 0.2	11.3 ± 0.7

σ_0 $[v_{\mathrm{typ}}]$	0.1	0.2	0.3
E^B $[\langle L \rangle]$	0.069 ± 0.002	0.073 ± 0.003	0.079 ± 0.002
$\mathcal{K}^B$ $[\langle L \rangle]$	0.357 ± 0.006	0.396 ± 0.013	0.414 ± 0.015
$\mathcal{K}^T$ [GW]	151.8 ± 0.9	233.2 ± 1.1	278.1 ± 1.5
$\mathrm{Var}(\mathbf{B})$ $[\langle L \rangle^2/100]$	0.238 ± 0.008	0.275 ± 0.004	0.302 ± 0.004
$\mathrm{Var}(\mathbf{P})$ $[\langle L \rangle^2/100]$	0.1727 ± 0.0018	0.401 ± 0.002	0.591 ± 0.007
$\mathrm{Cov}(\mathbf{B},\mathbf{P})$ $[\langle L \rangle^2/100]$	0.0123 ± 0.0008	0.0185 ± 0.0007	0.0236 ± 0.0010
LCOE [€/MWh]	7.93 ± 0.3	9.1 ± 0.2	9.8 ± 0.3

Impact of synthetic climate change

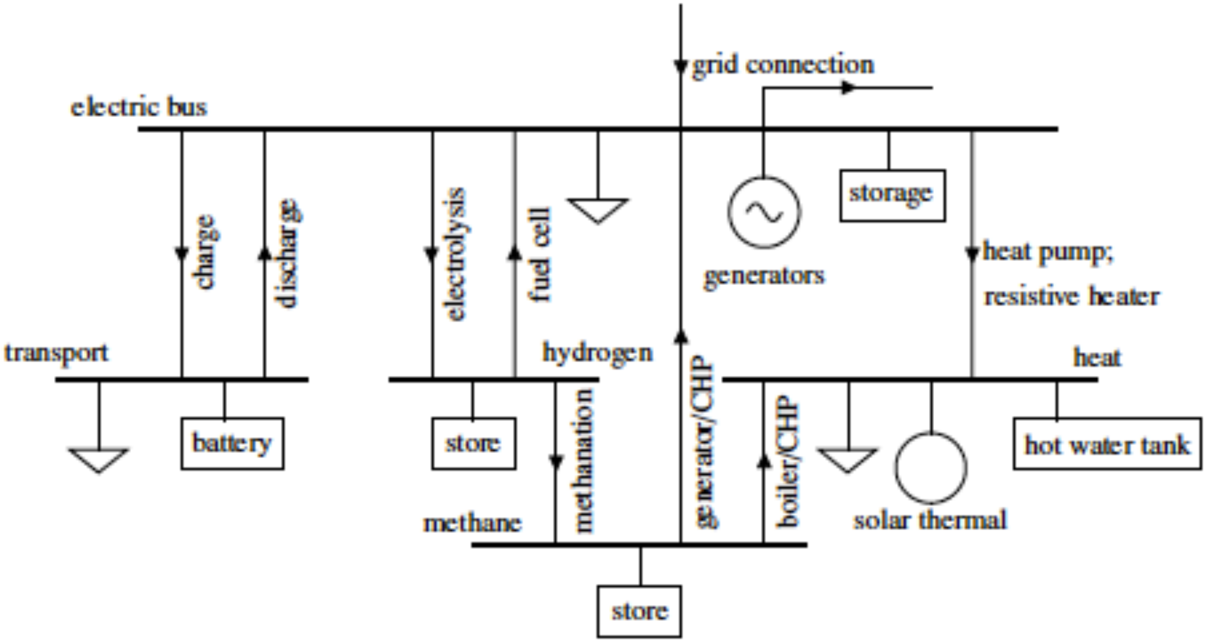


μ	0.18	0.36	0.54
E^B $[\langle L\rangle]$	0.0745 ± 0.003	0.073 ± 0.003	0.075 ± 0.003
$\mathcal{K}^B$ $[\langle L\rangle]$	0.405 ± 0.006	0.396 ± 0.013	0.396 ± 0.004
$\mathcal{K}^T$ [GW]	238.5 ± 0.8	233.2 ± 1.1	224.6 ± 1.6
$\mathrm{Var}(\mathbf{B})$ $[\langle L\rangle^2/100]$	0.280 ± 0.005	0.275 ± 0.004	0.272 ± 0.007
$\mathrm{Var}(\mathbf{P})$ $[\langle L\rangle^2/100]$	0.422 ± 0.005	0.401 ± 0.002	0.382 ± 0.003
$\mathrm{Cov}(\mathbf{B},\mathbf{P})$ $[\langle L\rangle^2/100]$	0.0193 ± 0.0011	0.0185 ± 0.0007	0.0177 ± 0.0017
LCOE [€/MWh]	9.2 ± 0.4	9.1 ± 0.2	9.0 ± 0.3

H	1/3	1/2	2/3
E^B $[\langle L\rangle]$	0.075 ± 0.003	0.073 ± 0.003	0.0736 ± 0.0014
$\mathcal{K}^B$ $[\langle L\rangle]$	0.402 ± 0.010	0.394 ± 0.007	0.389 ± 0.013
$\mathcal{K}^T$ [GW]	243 ± 2	233 ± 2	224.4 ± 1.9
$\mathrm{Var}(\mathbf{B})$ $[\langle L\rangle^2/100]$	0.283 ± 0.006	0.276 ± 0.007	0.273 ± 0.006
$\mathrm{Var}(\mathbf{P})$ $[\langle L\rangle^2/100]$	0.432 ± 0.007	0.400 ± 0.008	0.368 ± 0.005
$\mathrm{Cov}(\mathbf{B},\mathbf{P})$ $[\langle L\rangle^2/100]$	0.0194 ± 0.0010	0.0177 ± 0.0009	0.0185 ± 0.0016
LCOE [€/MWh]	9.3 ± 0.2	9.0 ± 0.3	8.85 ± 0.11

“engineering” challenge:
electricity → “smart” energy system

cross-sector coupling



Synergies of sector coupling and transmission extension in a cost-optimised, highly renewable European energy system

submitted to Energy

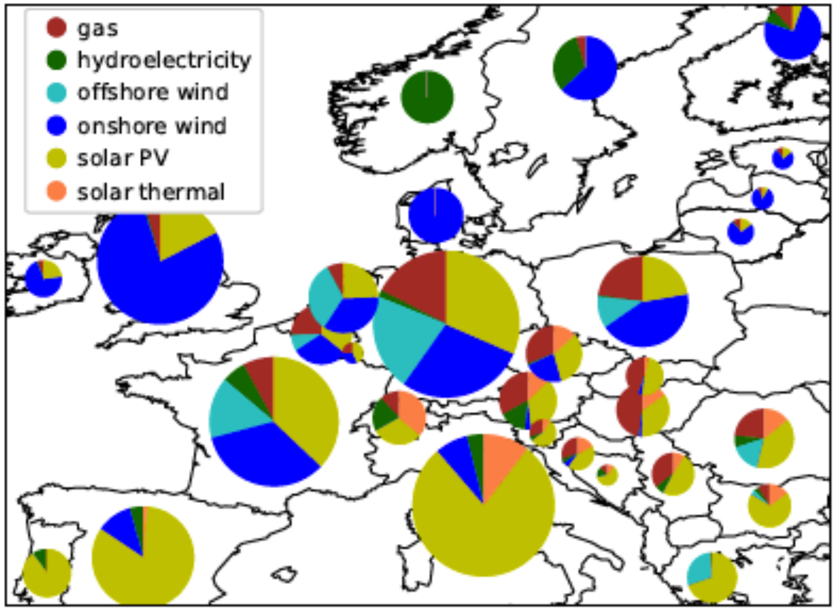
T. Brown[a,*], D. Schlachtberger[a], A. Kies[a], S. Schramm[a], M. Greiner[b]

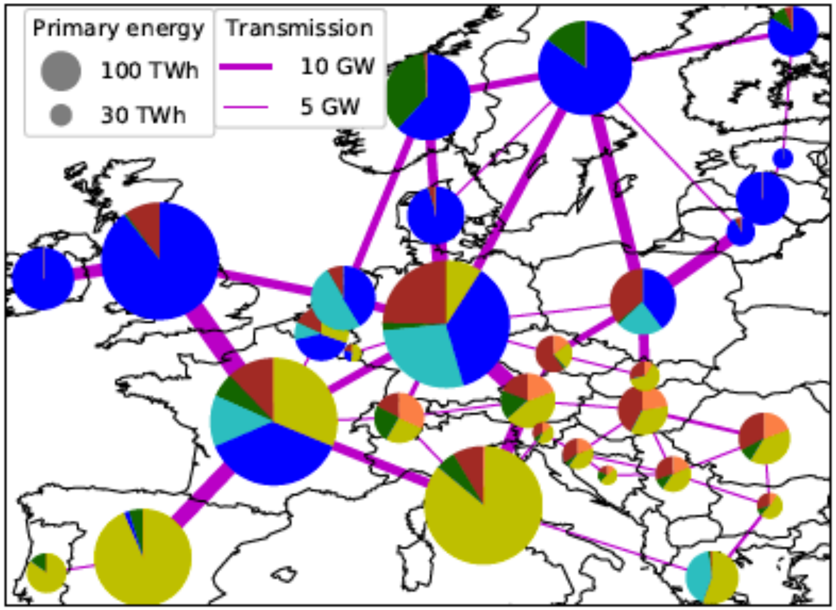
$$\min_{\substack{G_{n,s},E_{n,s},F_\ell,\\ g_{n,s,t},f_{\ell,t}}} \left[\sum_{n,s} c_{n,s}\cdot G_{n,s} + \sum_{n,s}\hat{c}_{n,s}\cdot E_{n,s} + \sum_{\ell} c_\ell \cdot F_\ell + \sum_{n,s,t} o_{n,s,t}\cdot g_{n,s,t}\right] \qquad (1)$$

$$\sum_s g_{n,s,t} + \sum_\ell \alpha_{\ell,n,t}\cdot f_{\ell,t} = d_{n,t} \qquad \leftrightarrow \qquad \lambda_{n,t} \quad \forall\, n,t$$

$$\sum_{\ell\in \mathrm{HVDC}} l_\ell \cdot F_\ell \le \mathrm{CAP}_{LV}$$

$$\sum_{n,s,t} \varepsilon_s \frac{g_{n,s,t}}{\eta_{n,s}} + \sum_{n,s}\varepsilon_s\left(e_{n,s,t=0}-e_{n,s,t=T}\right) \le \mathrm{CAP}_{CO2} \qquad \leftrightarrow \qquad \mu_{CO2}$$


Scenario All-Flex-Central with no transmission


Scenario All-Flex-Central with optimal transmission

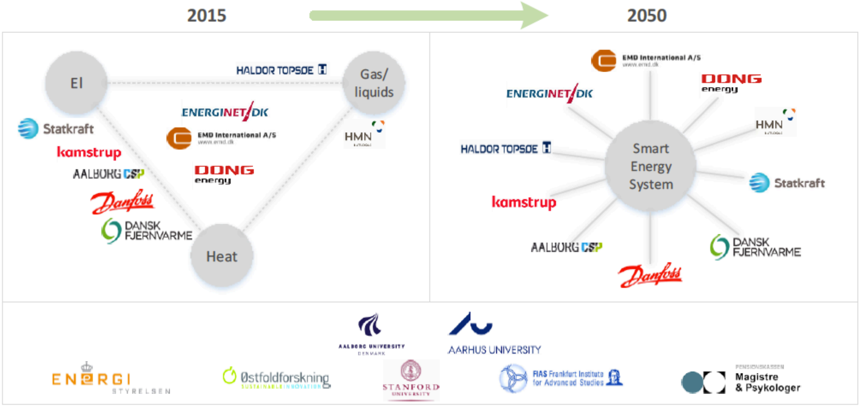
„Energiewende“: kickoff to the second half

Danmarks Innovationsfond Grand Solutions (04.2017-03.2021, 2.3 M€)

RE-Invest

Renewable Energy Investment Strategies

– a 2dim interconnectivity approach



Aalborg U

+

Aarhus U

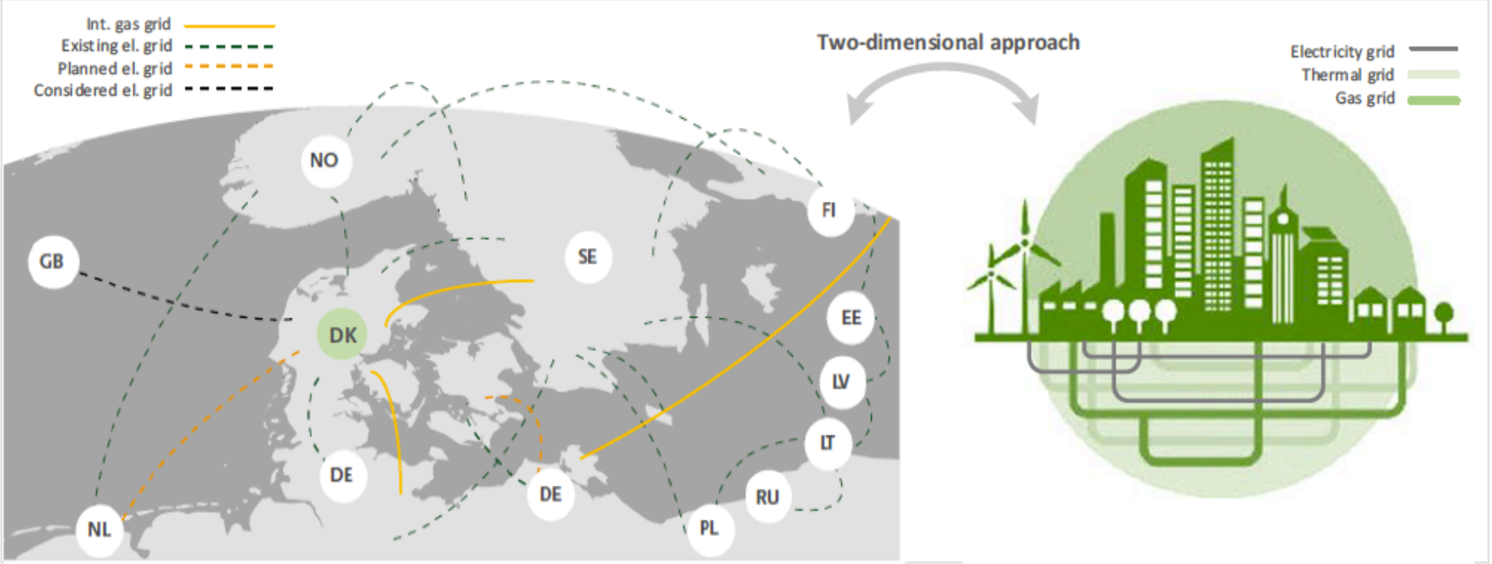


Figure 1. RE-Invest will combine the Smart Energy Systems cross-sectoral approach (right side) at Aalborg University with the cross-border approach (left side) and tools developed by Aarhus University at the European scale. This will lead to a ***novel two-dimensional interconnectivity approach*** *for the design of robust and cost-effective investment strategies towards a sustainable energy system.*

FunRes

Fundamental Research on Renewable Energy Systems

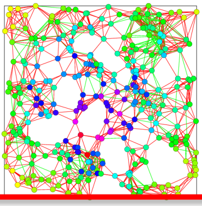
at the interface between engineering + physics + mathematics + economics

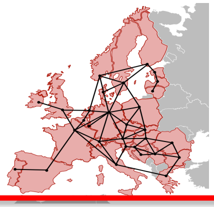
Gorm Andresen + Mahdi Abkar +
Martin Greiner (greiner@eng.au.dk)

M Schäfer	(Carlsberg PostDoc)
D Schlachtberger	(PostDoc)
M Victoria	(PostDoc)
M Dahl	(Master15 + PhD18)
B Tranberg	(Master15 + PhD19)
H Liu	(Master16 + PhD19)
S Kozarcanin	(Master15 + PhD19)
K Zhu	(PhD20)
S Siggaard	(Master17)
M Kofoed	(Master16)
L Schwenk_Nebbe	(Master16)
M Janum	(Master16)
M Raunbak	(Master16)
C Poulsen	(Master16)
N Skou-Nielsen	(Master15)
M Hansen	(Master15)
K Holm	(Master15)
E Eriksen	(Master15)
A Thomsen	(Master14)
B Sairanen	(Master14)
T Jensen	(Master13)
T Zeyer	(Master13)
A Søndergaard	(Master13)
R Rodriguez	(PhD14)
M Rasmussen	(PostDoc11)

(1) Highly Renewable Energy Networks

(2) Complex Networks





(3) Wind-farm Modeling + Optimization

(4) Turbulence

B Carlsen	(Master16)
A Huche	(Master16)
E Thorgersen	(Master16)
M Therkildsen	(Master15)
P Nybroe	(Master15)
J Otten	(Master15)
J Bjerre	(Master15)
J Herp	(Master13)
U Poulsen	(Assist Prof)

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D Heide et.al.: *Seasonable optimal mix of wind and solar power in a future, highly renewable Europe*, **Renewable Energy 35 (2010) 2483-89**.

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) 2515-23**.

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

RA Rodriguez et.al.: *Transmission needs across a fully renewable European power system*, **Renewable Energy 63 (2014) 467-76**.

S Becker et.al.: *Transmission grid extensions during the build-up of a fully renewable pan-European electricity supply*, **Energy 64 (2014) 404-18**.

TV Jensen et.al.: *Emergence of a phase transition for the required amount of storage in highly renewable electricity systems*, **EPJ ST 223 (2014) 2475-81**.

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) 443-58**.

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.: *Renwable build-up pathways for the US: Generation costs are not system costs*, **Energy 81 (2015) 437-45.**

RA Rodriguez et.al.: *Cost-optimal design of a simplified, highly renewable pan-European electricity system*, **Energy 83 (2015) 658-68**.

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

GB Andresen et.al.: *Validation of Danish wind time series from a new global renewable energy atlas for energy system analysis*, **Energy 93 (2015) 1074-88**.

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

D Schlachtberger et.al.: *Backup flexibility classes in renewable electricity systems*, **Energy Conversion and Management 125 (2016) 336-46.**

E Eriksen et.al.: *Optimal heterogeneity of a simplified highly renewable pan-European electricity system*, **Energy 133 (2017) 913-28.**

D Schlachtberger et.al.: *The benefits of cooperation in a highy renewable European electricity network*, **Energy 134 (2017) 469-81.**

M Schäfer et.al.: *Decompositions of injection patterns for nodal flow allocation in renewable electricity networks*, **Eur. Phys. J. B 90 (2017) 144.**

M Schäfer et.al.: *Scaling of transmission capacities in coarse-grained renewable electricity networks*, **Europhysics Letters 119 (2017) 38004.**

M Raunbak et.al.: *Principal mismatch patterns across a simplified highly renewable European electricity network*, **Energies 10 (2017)1934.**

J Hörsch et.al.: *Flow tracing as a tool set for the analysis of networked large-scale renewable electricity systems*, **Int. J. Electrical Power and Energy Systems 96 (2018) 390-97.**

H Liu et.al.: *Cost-optimal design of a simplified highly renewable Chinese electricty network*, **Energy (2018) accepted.**

B Tranberg et.al.: *Flow-based nodal cost allocation in a heterogeneous highly renewable European electricity system*, **Energy (2017) submitted.**

T Brown et.al.: *Synergies of sector coupling and transmission extension in a cost-optimised highly renewable European energy system*, **Energy (2018) submitted.**

Research-driven Teaching (ENG + PHY)

Regular: Fluid Dynamics (5 ECTS),
Wind Energy (5 ECTS).

Occasional: Advanced Fluid Dynamics (5 ECTS),
Turbulence (5 ECTS),
Complex Networks (5 ECTS),
Complex Renewable Energy Networks (5 ECTS).

FunRes

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at the interface between engineering + physics + mathematics + economics

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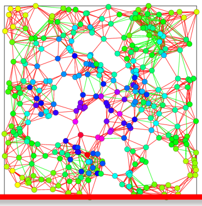
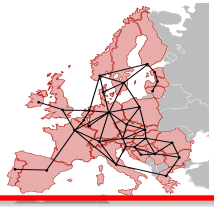
(2) Complex Networks





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J Herp	(Master13)
U Poulsen	(Assist Prof)

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Miscellaneous Material

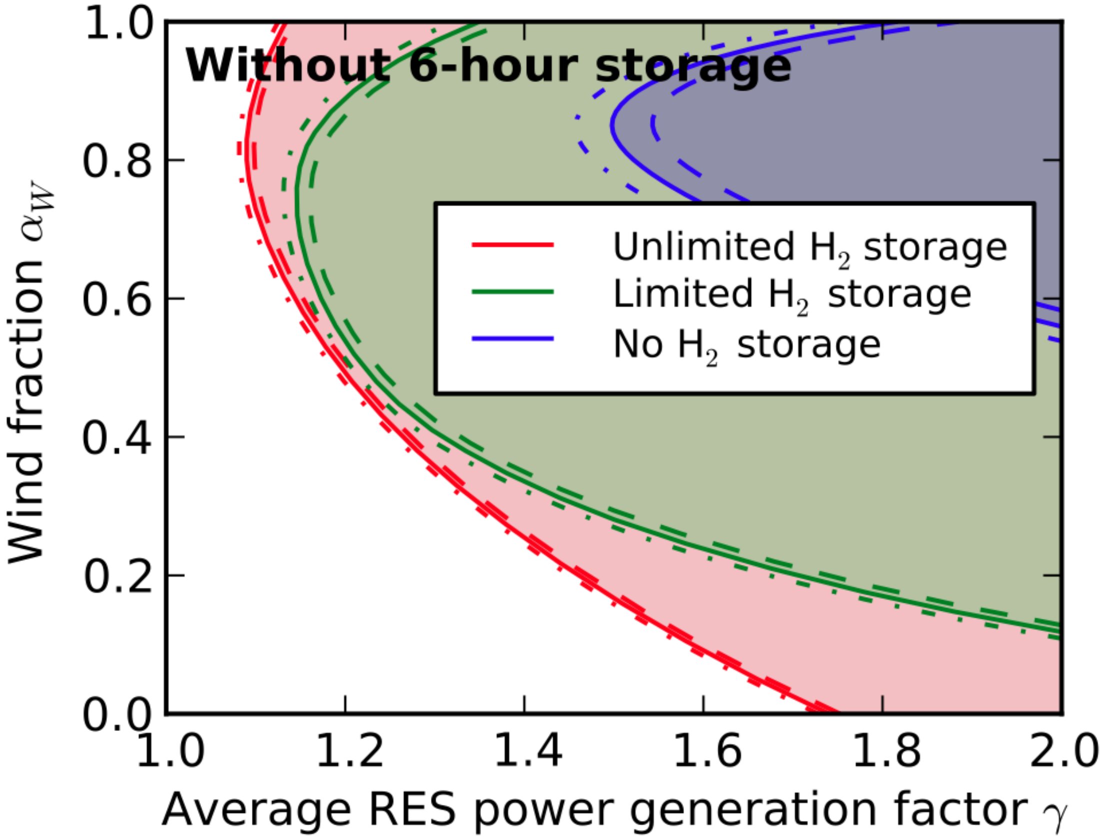
What about synergies: balancing + storage?

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

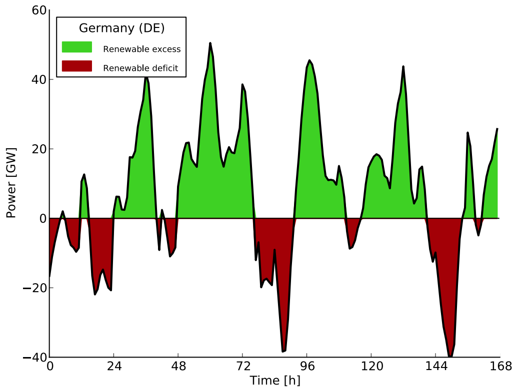
$$G_n^B(t) = \left(B_n(t)\right)_-$$

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

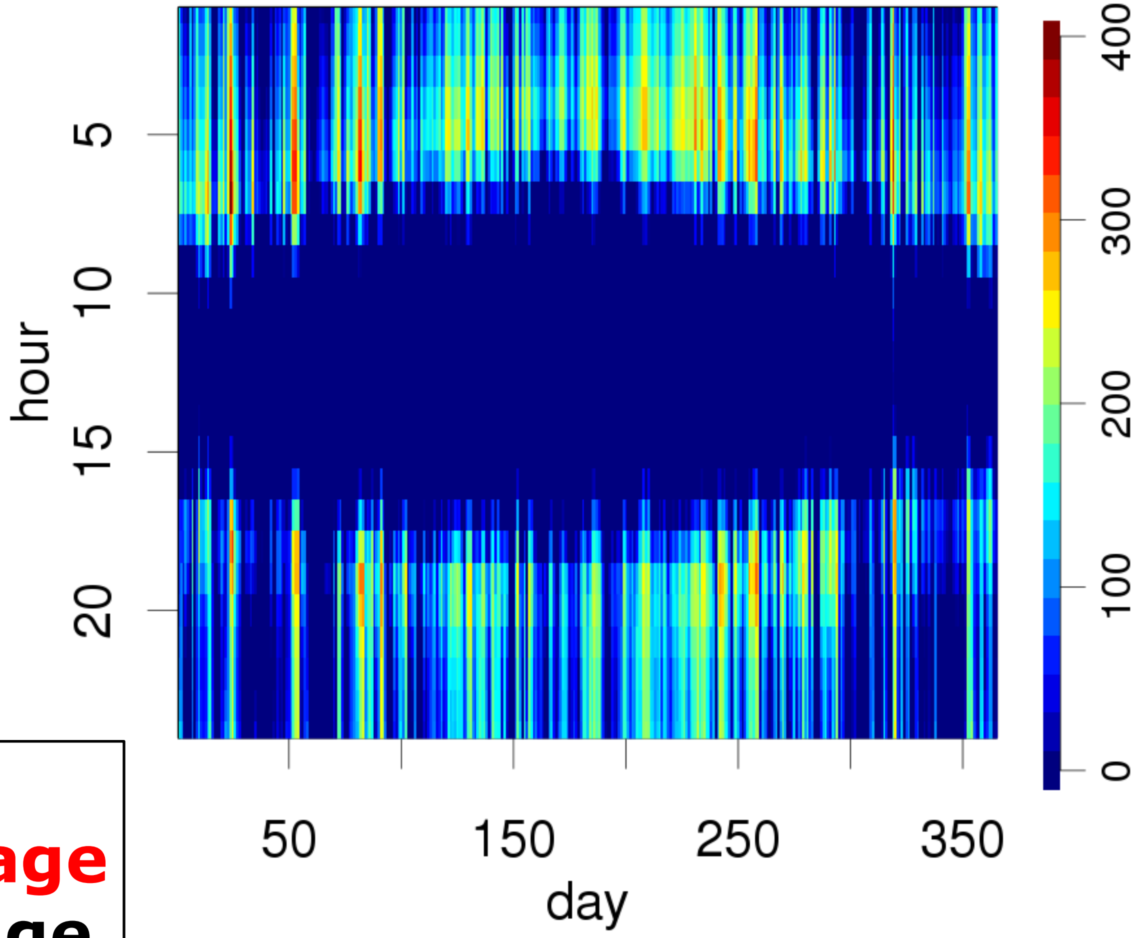
6h "battery" storage (2.2 TWh, $\eta=1.0$)
+ seasonal H2 storage (25 TWh, $\eta=0.6$)
+ "hydro/bio" balancing (150 TWh)



More balancing/storage synergies: When is $G^B(t)=0$?

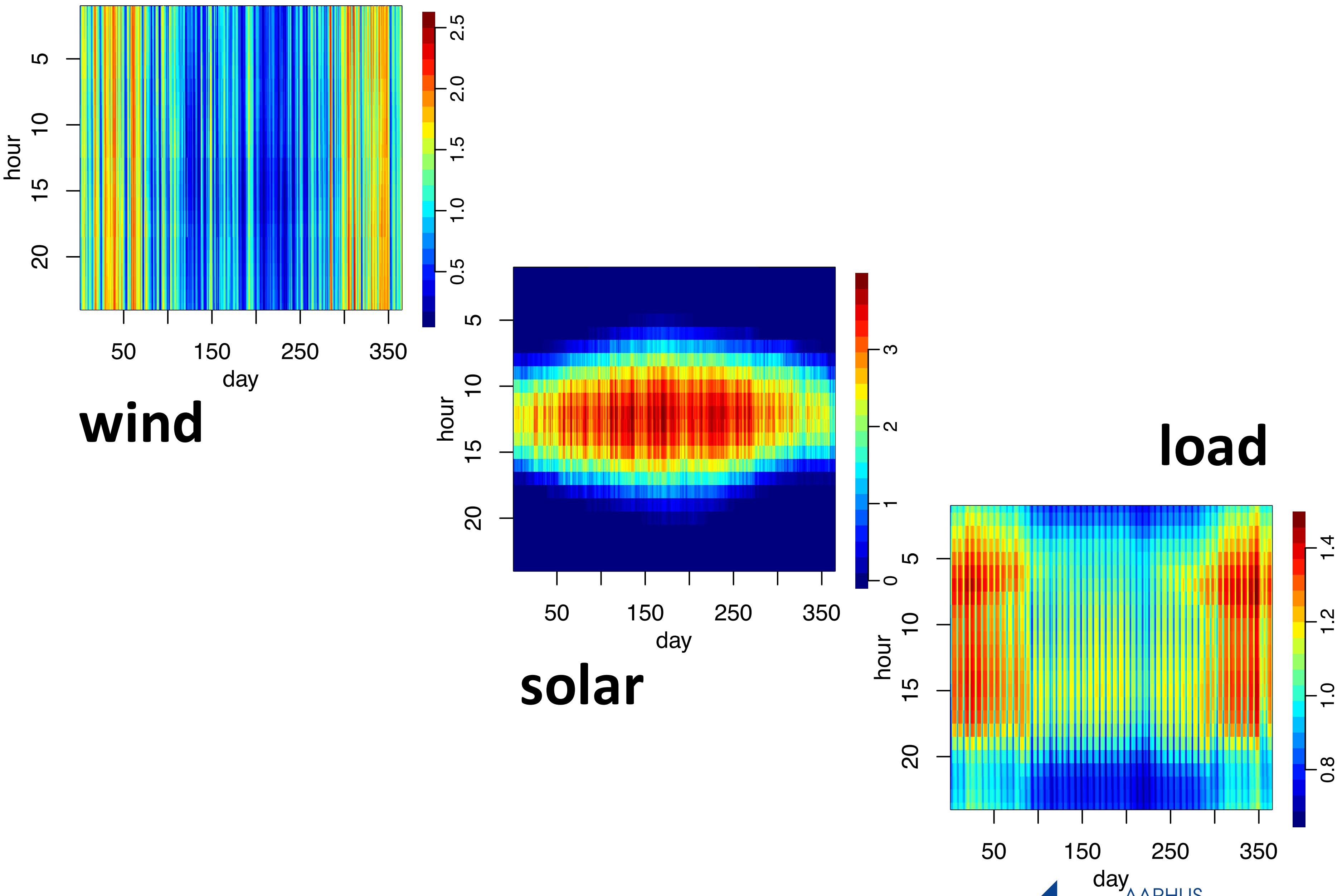


$$G^B(t) = -\min\left(\Delta(t),0\right)$$



balancing power, 60% / 40%

balancing
+ intra-day storage
+ seasonal storage

hour
5
10
15
20
50
150
250
350
day
0.5
1.0
1.5
2.0
2.5
wind
hour
5
10
15
20
50
150
250
350
day
0
1
2
3
solar
load
hour
5
10
15
20
50
150
250
350
day
0.8
1.0
1.2
1.4

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