Anpfiff zur zweiten Hälfte der Energiewende:

Grundlegende Gedanken aus den Natur- und Technikwissenschaften

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

(Albert Einstein)

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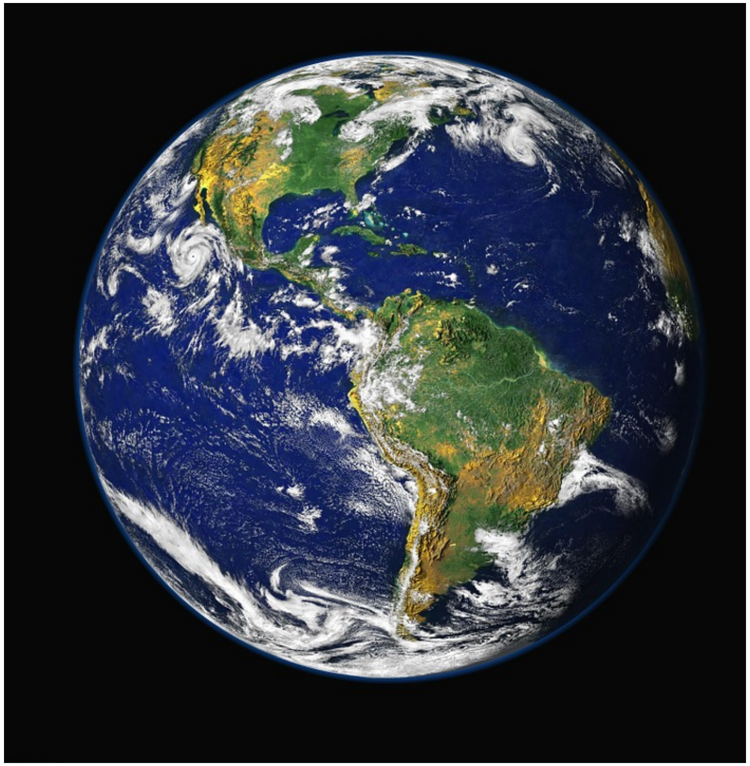

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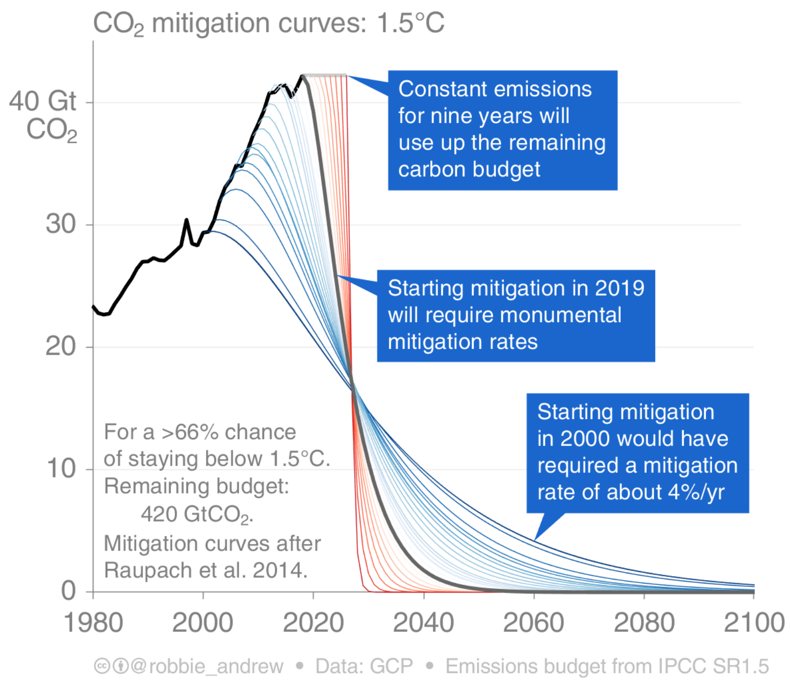
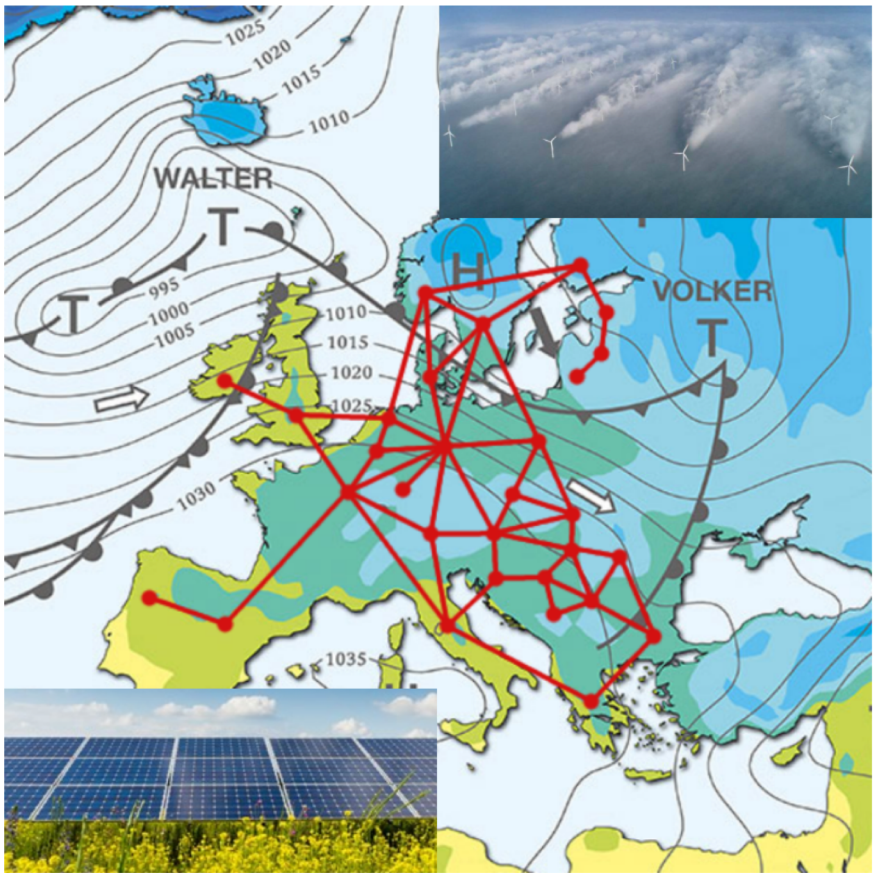
„A goal is a dream with a deadline“



Decarbonisation of the networked European Energy System



I. simple modeling: **Renewable European electricty network**

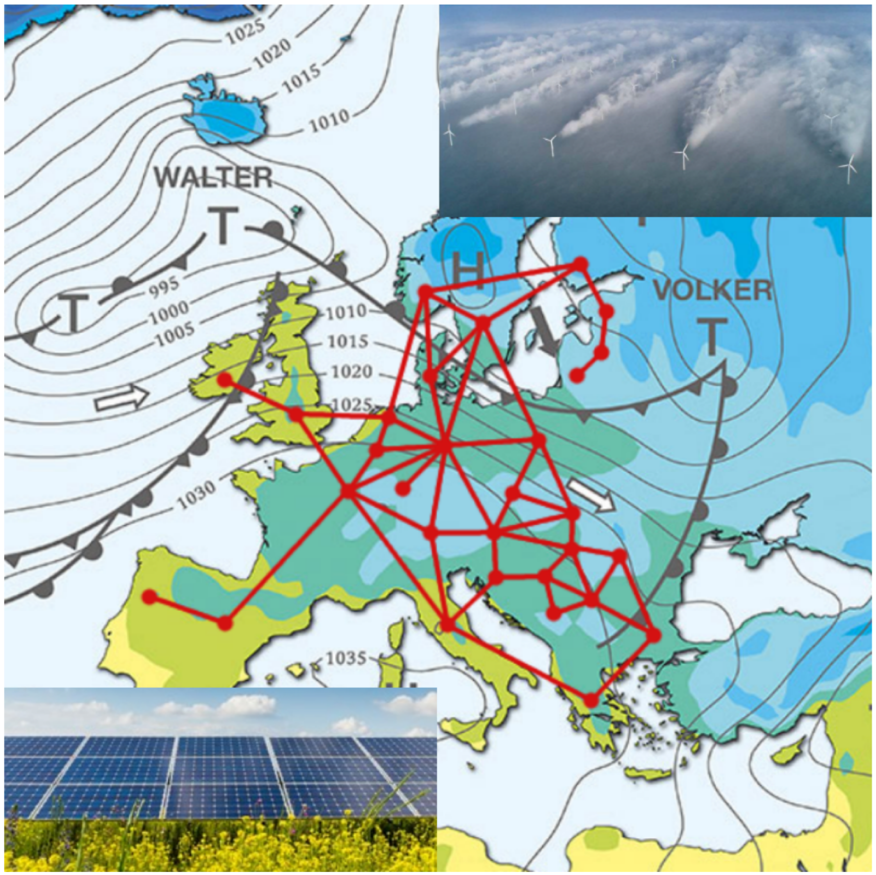
- weather-driven optimal design
- value of cooperation

II. advanced modeling: **electricity → energy network**

- constraints
  + (unavoidable) consequences

capture / extract
general system dynamics
+ meaningful insights
+ inspirational results

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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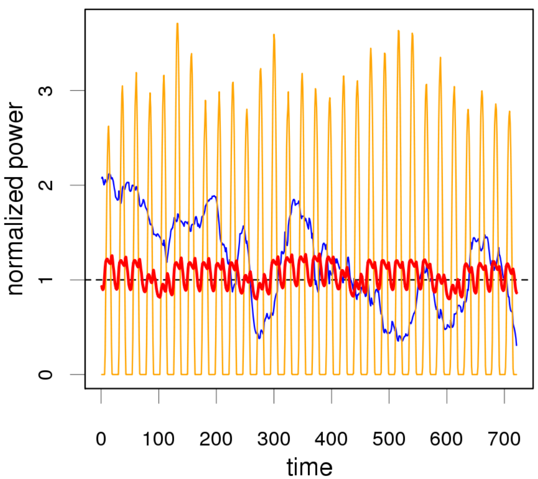
Renewable European electricity network + fluctuating „weather forces“

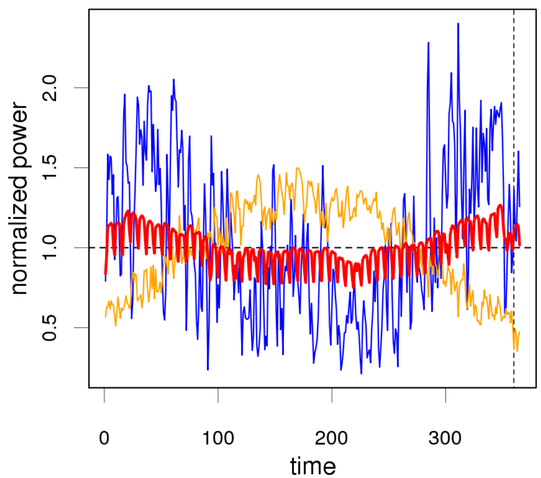
$$G_n^R(t) = G_n^W(t) + G_n^S(t)$$

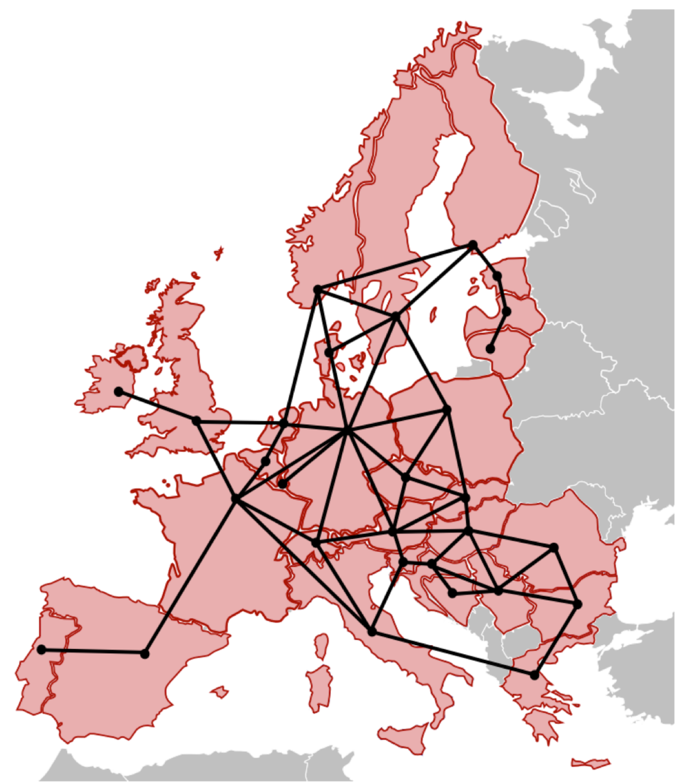
$$\langle G_n^R \rangle = \gamma_n \langle L_n \rangle$$

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

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“

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

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

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

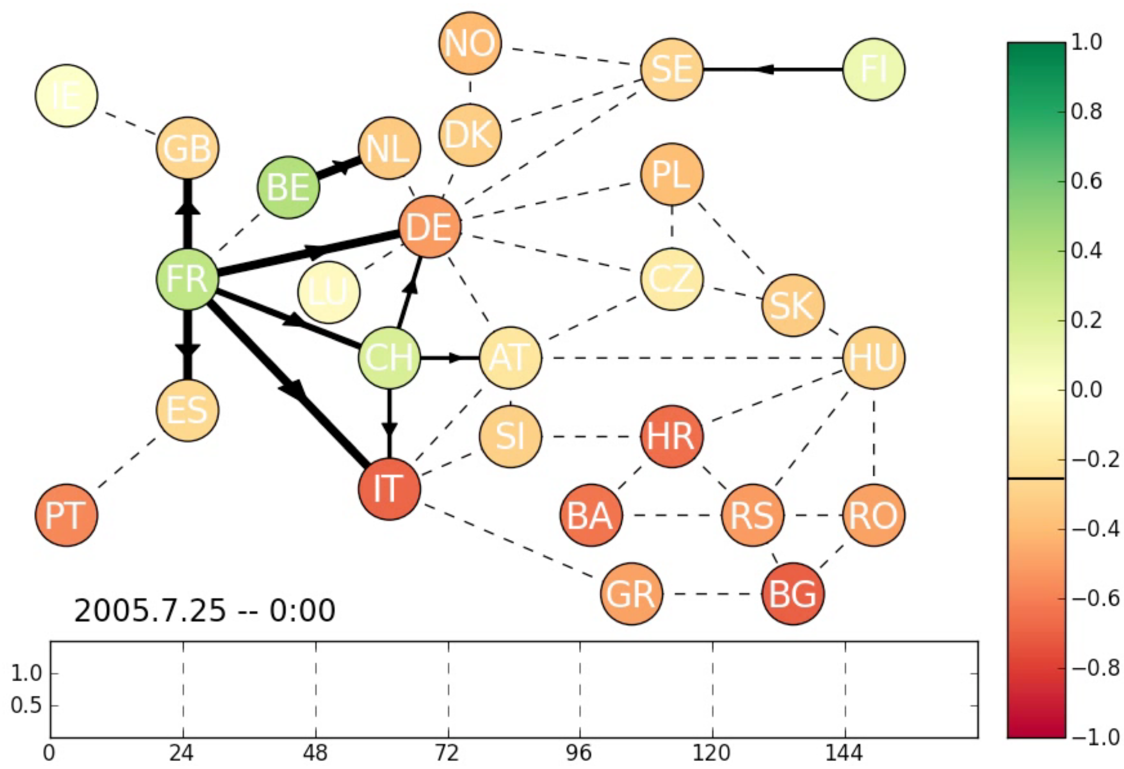
$$G_n^R(t) - L_n(t) = B_n(t) + P_n(t) + \cdots$$

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

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

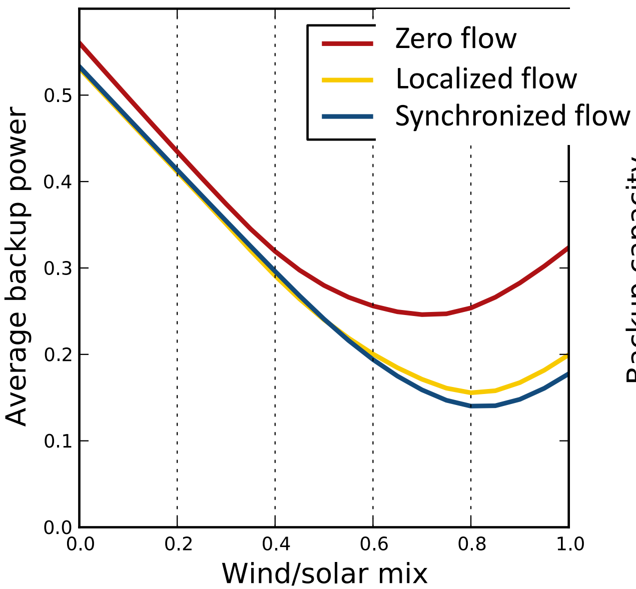
$$\sum_n P_n(t) = 0$$

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



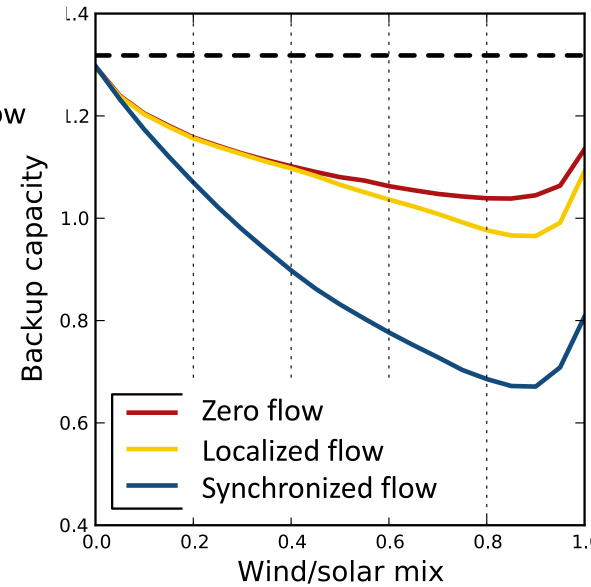
backup energy

$\langle G_n^B \rangle$



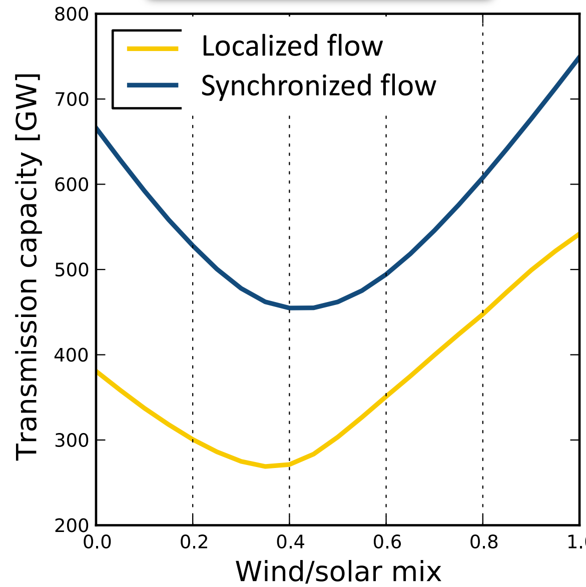
backup capacity

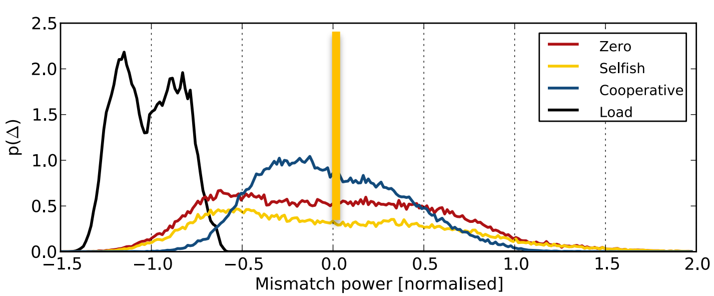
$max_q(G_n^B)$

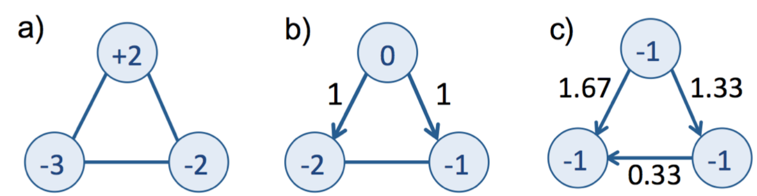


transmission capacity

$\sum_l \max_q |F_l|$



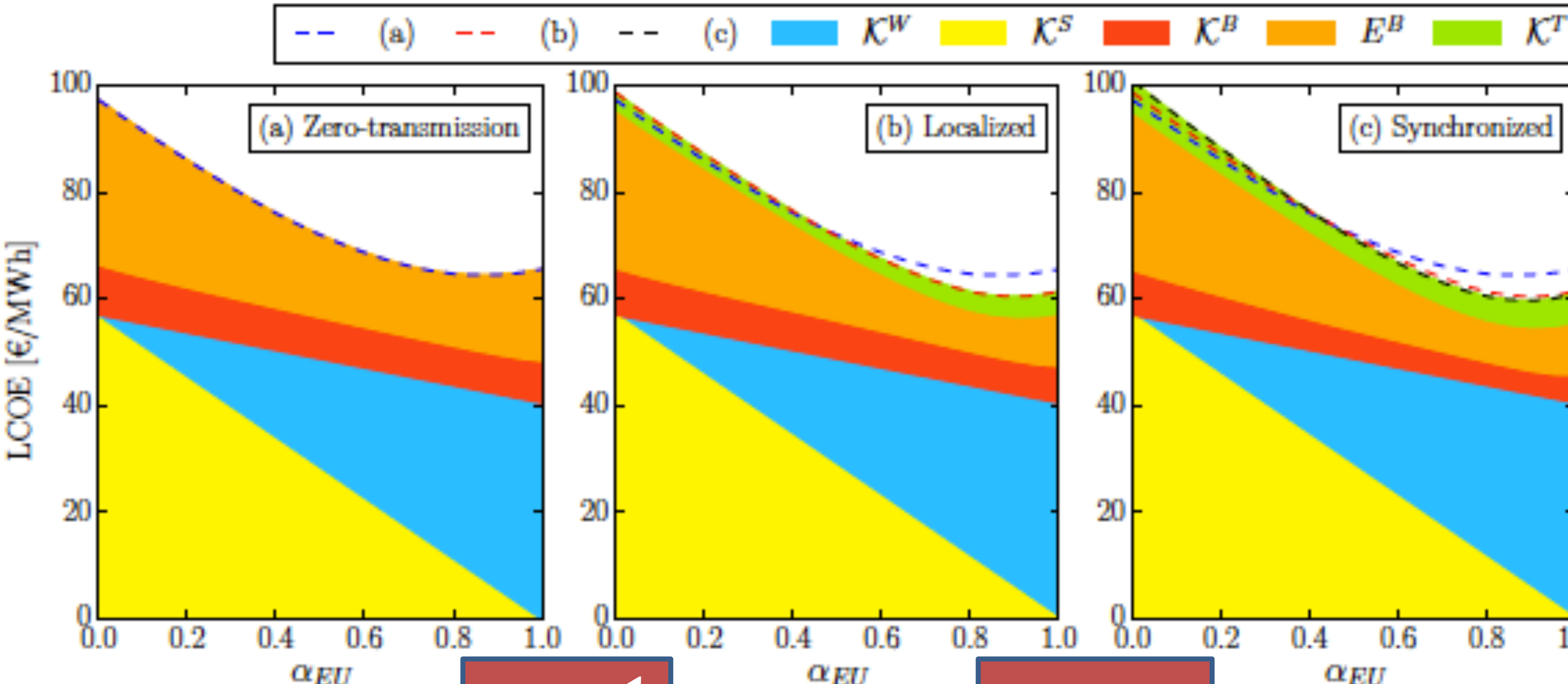




Infrastructure measures

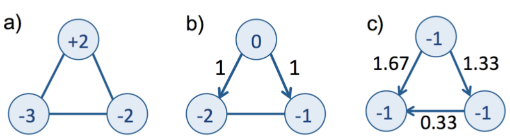
backup energy	$E_n^B = \langle G_n^B \rangle$
backup capacity	$K_n^B = max_q(G_n^B)$
transmission capacity	$K_l^T = max_q \lvert F_l \rvert \cdot d_l$
wind capacity	$K_n^W = \frac{\alpha_n \gamma_n \langle L_n \rangle}{CF_n^W}$
solar capacity	$K_n^S = \frac{(1-\alpha_n)\gamma_n \langle L_n \rangle}{CF_n^S}$

Levelized Cost of SYSTEM Energy



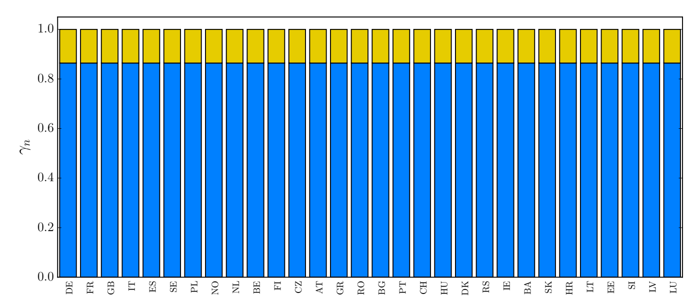
$\gamma_n = 1$

$\alpha_n = \alpha$

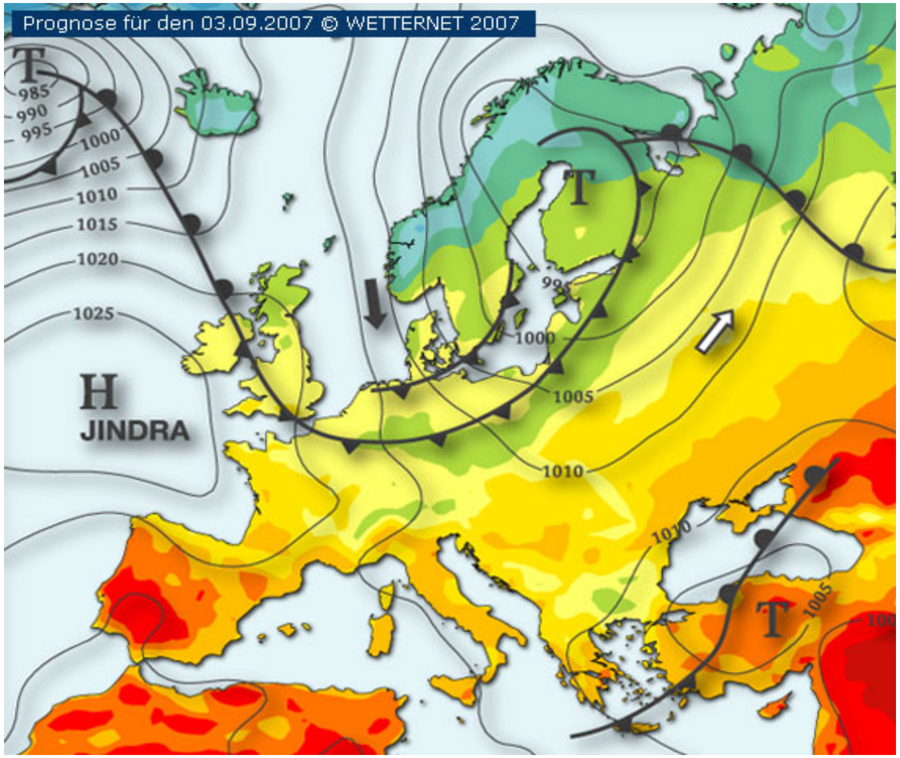


Coupling objectives: B ⟺ P

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



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

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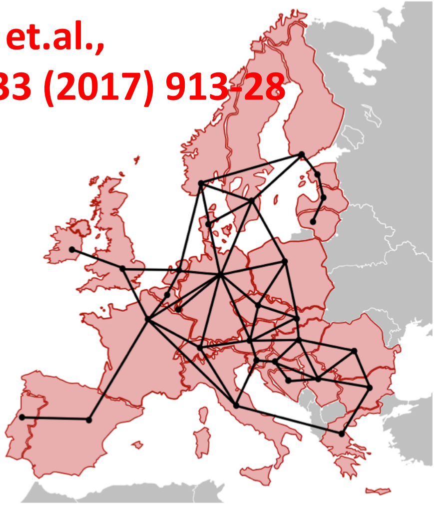
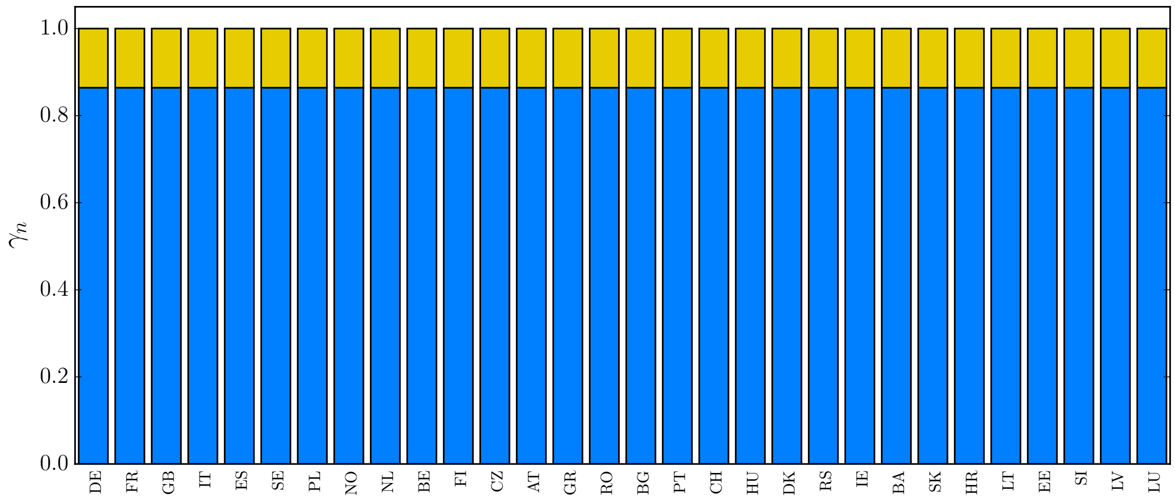
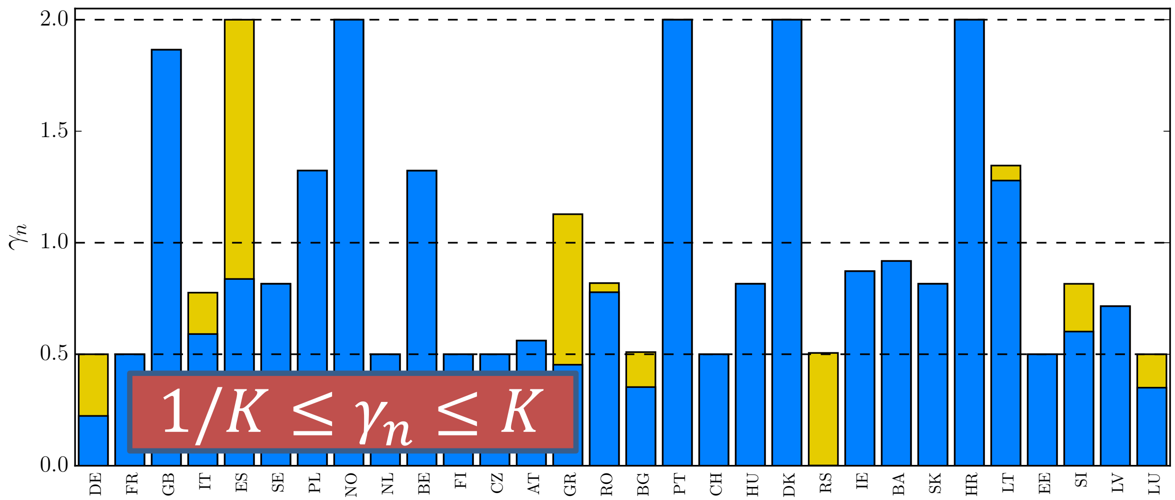
Breaking homogeneity: cost-optimal heterogeneity

E Eriksen et.al., Energy 133 (2017) 913-28



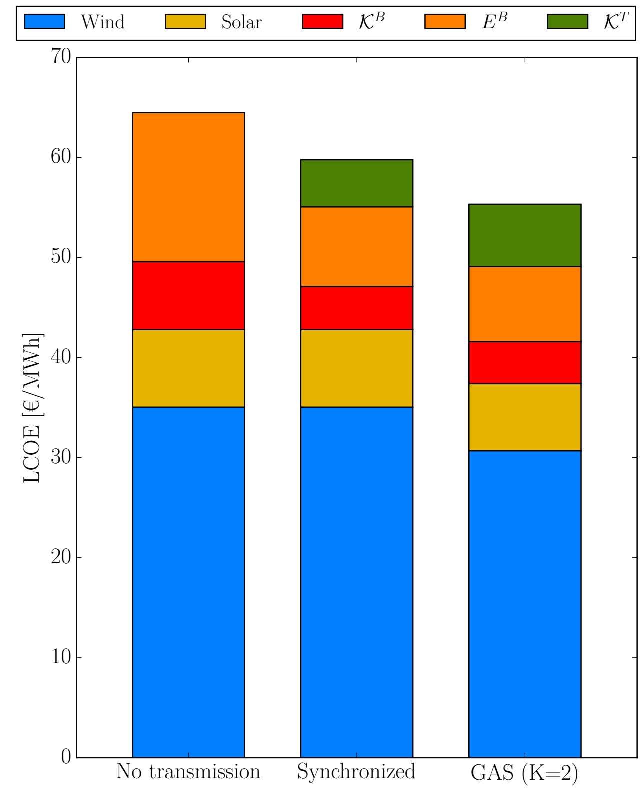




$$1/K \leq \gamma_n \leq K$$

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

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



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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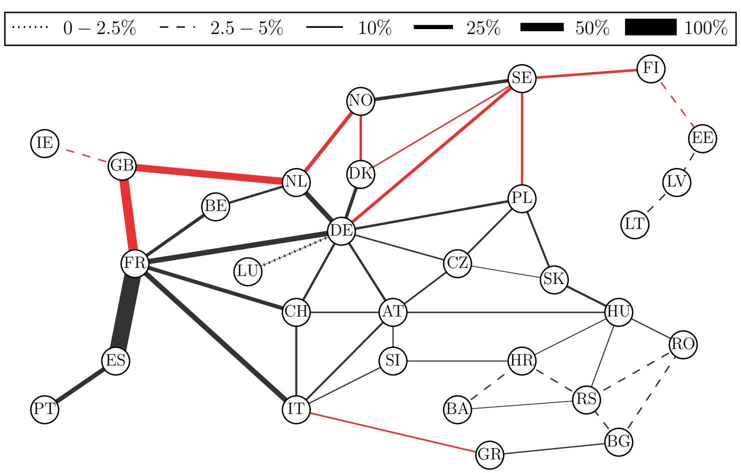
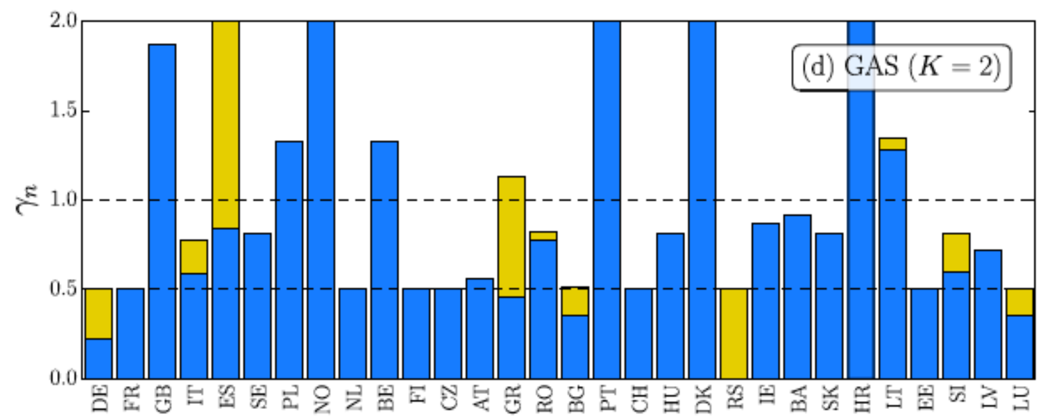
30 European friends you have to be!

but …… who pays for …

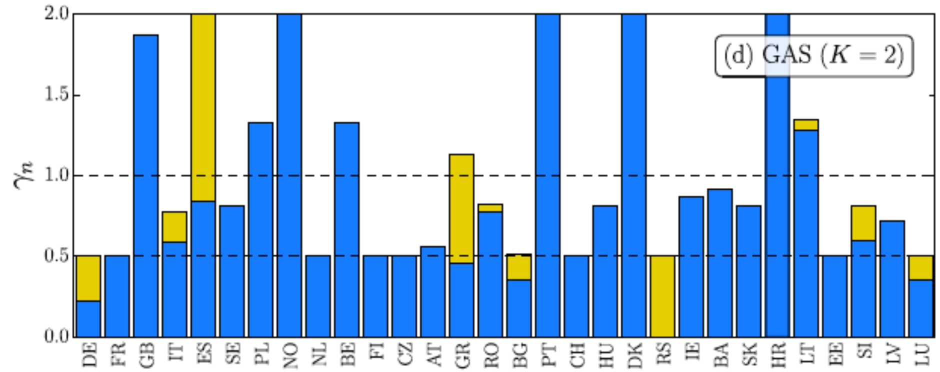
…… the heterogeneity?

…… the transmission grid?

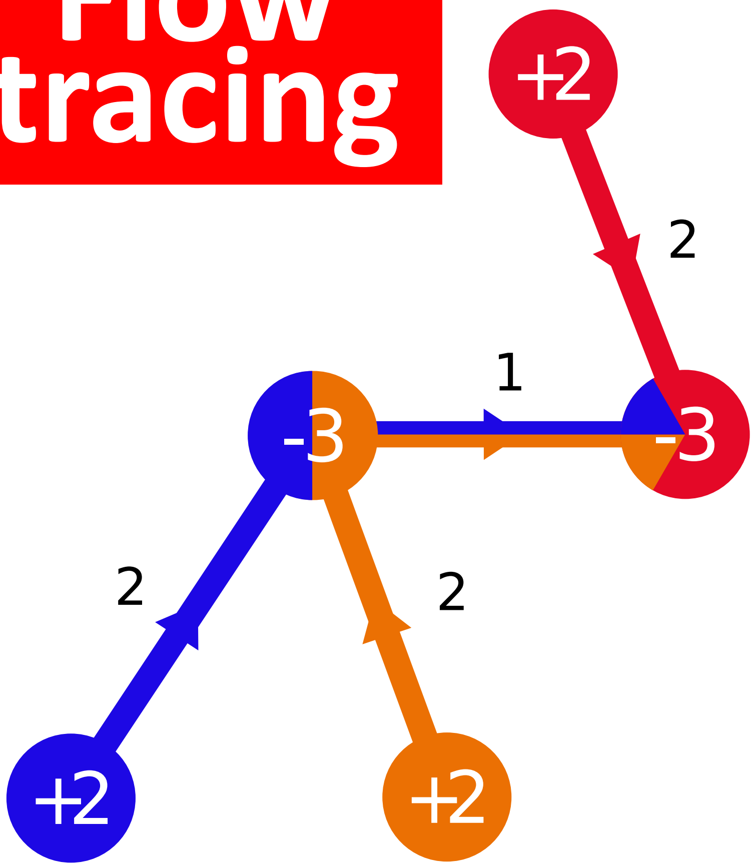




Who pays for the heterogeneity?



Flow tracing

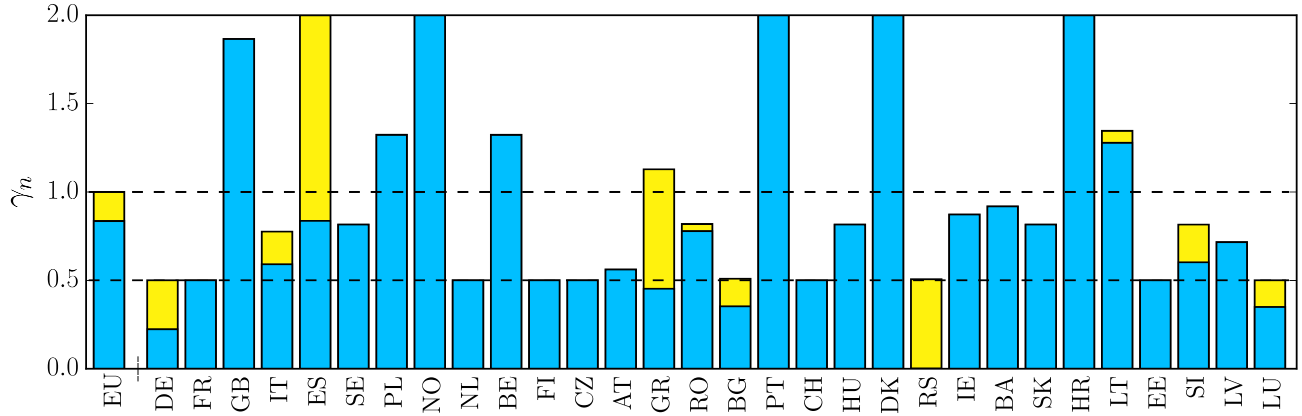


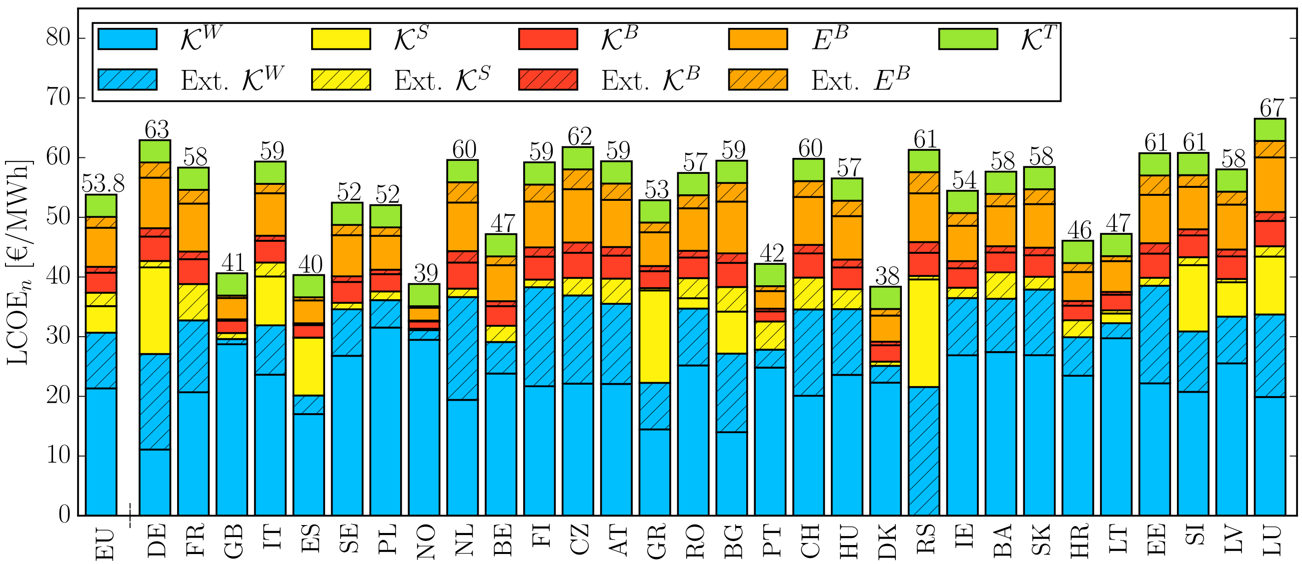
$$K_n^{\mu} = K_{nn}^{\mu} + \sum_{m \neq n} K_{nm}^{\mu}$$

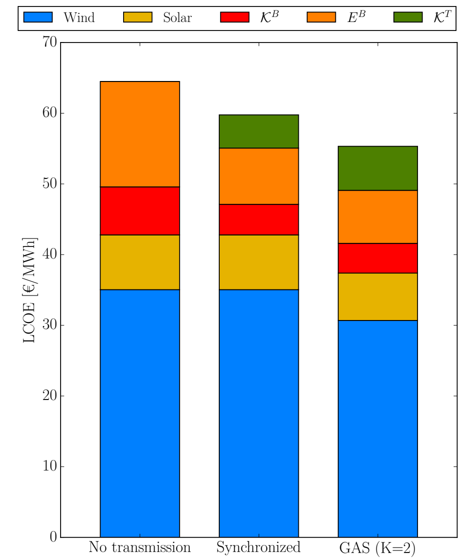
$$\widetilde{K}_n^{\mu} = K_{nn}^{\mu} + \sum_{m \neq n} K_{mn}^{\mu}$$

B Tranberg et.al., NJP 17 (2015) 105002
M Schäfer et.al., Eur.Phys.J.B 90 (2017) 144
B Tranberg et.al., Energy 150 (2018) 122-33

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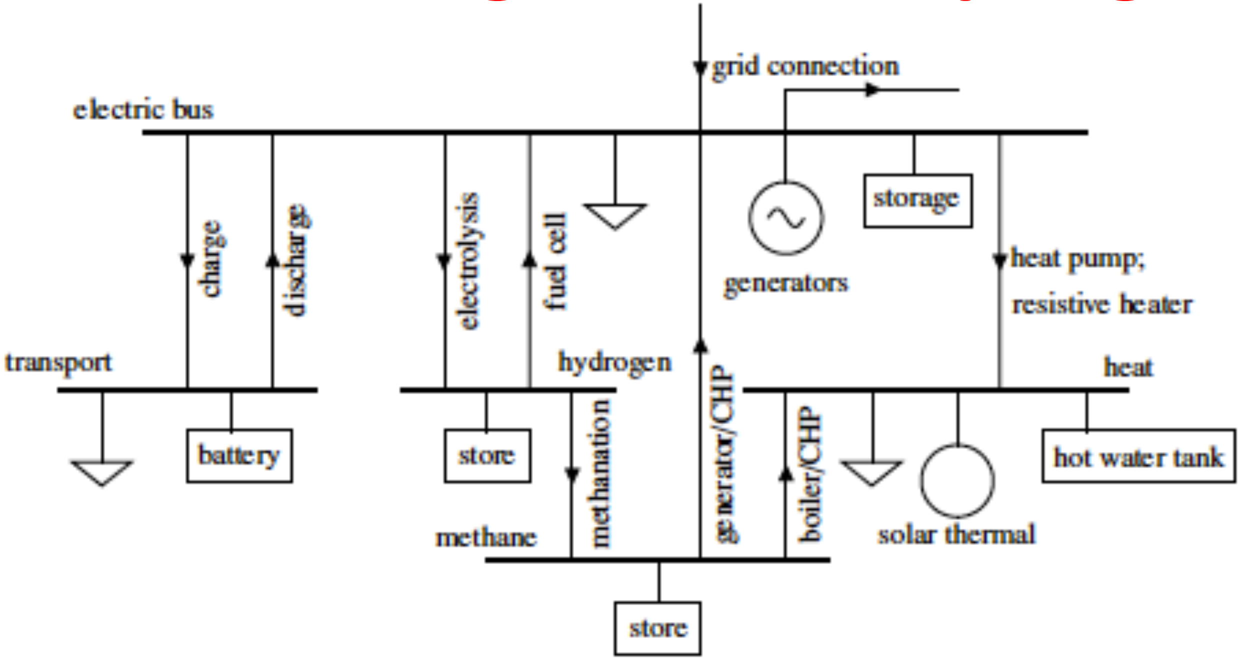
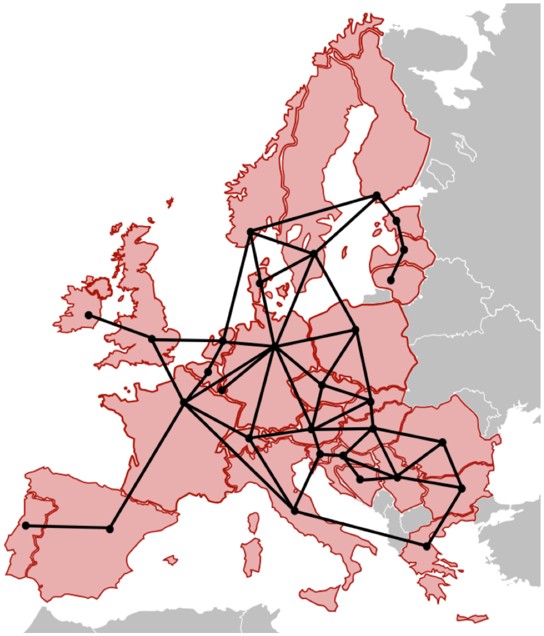
II. Advanced Modeling:
electricity → "smart" energy network

Decarbonization of the European energy system with strong sector couplings





T Brown et.al.,
Energy 160 (2018) 720-39

K Zhu, M Victoria et.al.,
Applied Energy 236 (2019) 622-34

T Brown et.al.,
Energies 12 (2019) 1032

simplified cross-sector network model

capture / extract general system dynamics + meaningful insights + inspirational results

PyPSA-Eur-Sec-30

Joint capacity + dispatch optimization:

generation costs | storage costs | transmission costs | variable costs (excluding CO_2 tax)

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

Subject to constraints :

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

Supply hourly inelastic demand

$$\underline{f}_{\ell,t} \cdot F_\ell \leq f_{\ell,t} \leq \bar{f}_{\ell,t} \cdot F_\ell \qquad \forall \ell, t$$

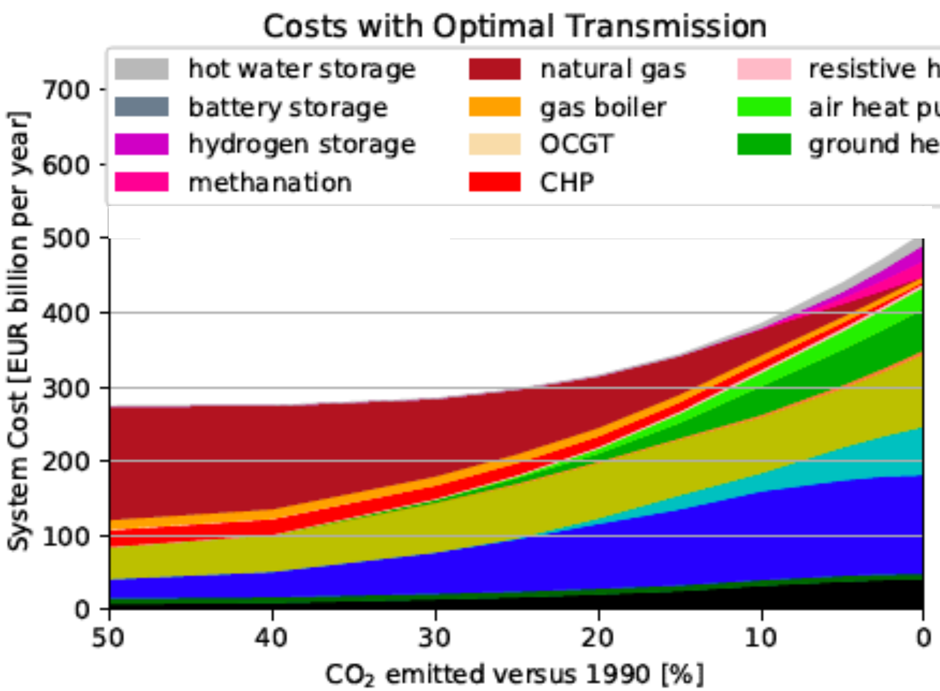
Maximum power flowing through the links

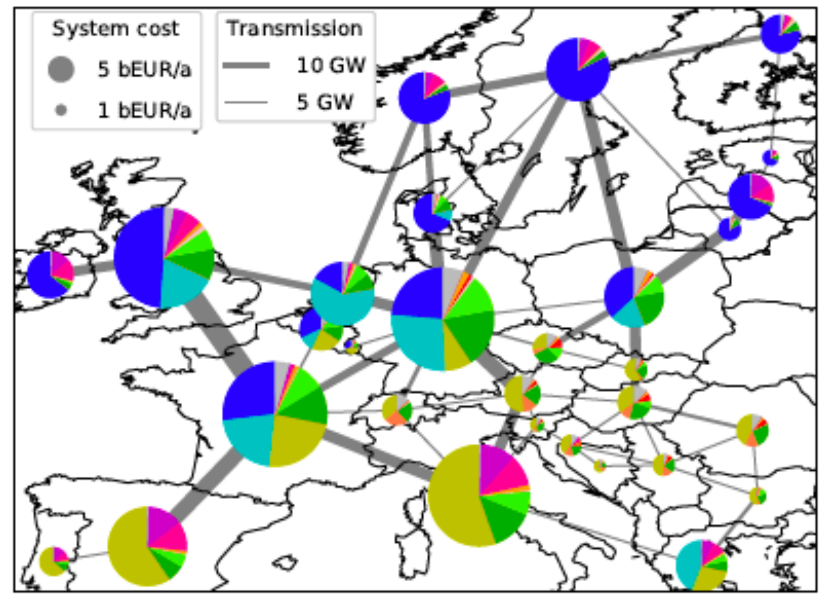
$$\sum_{n,s,t} \varepsilon_s \frac{g_{n,s,t}}{\eta_{n,s}} + \sum_{n,s} \varepsilon_s \left(e_{n,s,t=0} - e_{n,s,t=T} \right) \leq \mathrm{CAP}_{CO_2} \quad \leftrightarrow \quad \mu_{CO_2}$$

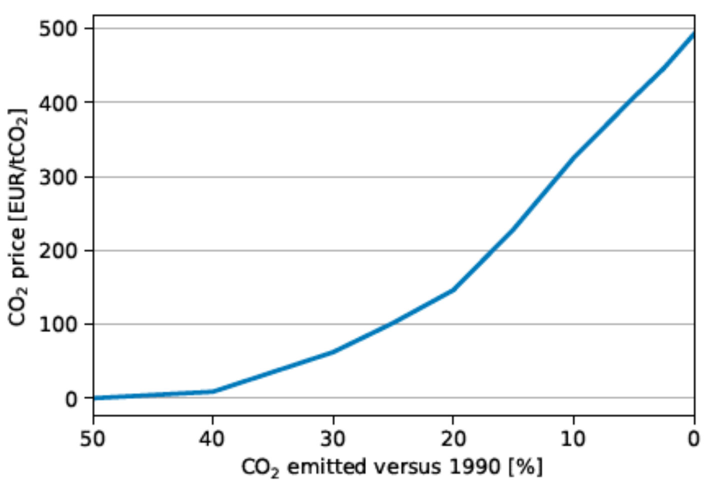
CO_2 emission constraint

$$\min\left(Costs - \lambda \cdot Constraint\right)$$

electricity + heating + transportation







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Aalborg U
+ Aarhus U

"engineering" challenges:

reINVEST

- tech+econon transition pathways 2020 → 2050
- impact of climate change
- large → small scale modelling
- tech+econ+soc+pol modeling/control/consulting

iClimate
(AU ENV + ENG)

(Applied Theoretical) Physics of complex Socio-Economic Systems:
„modelling challenges to boldly go where no one has gone before"

Thermodynamics,
District Heating

Gorm Andresen

Marta Victoria

Solar
Photovoltaics

Sustainable Energy Systems

Aarhus University
Department of Engineering

Martin Greiner

Wind-farm modelling
+ optimization,
Turbulence

Complex
Networks

Mahdi Abkar

Computational
Fluid Dynamics

partners:
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PhDs:
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Smail Kozarcanin,
Kun Zhu,
Leon Schwenk-Nebbe

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