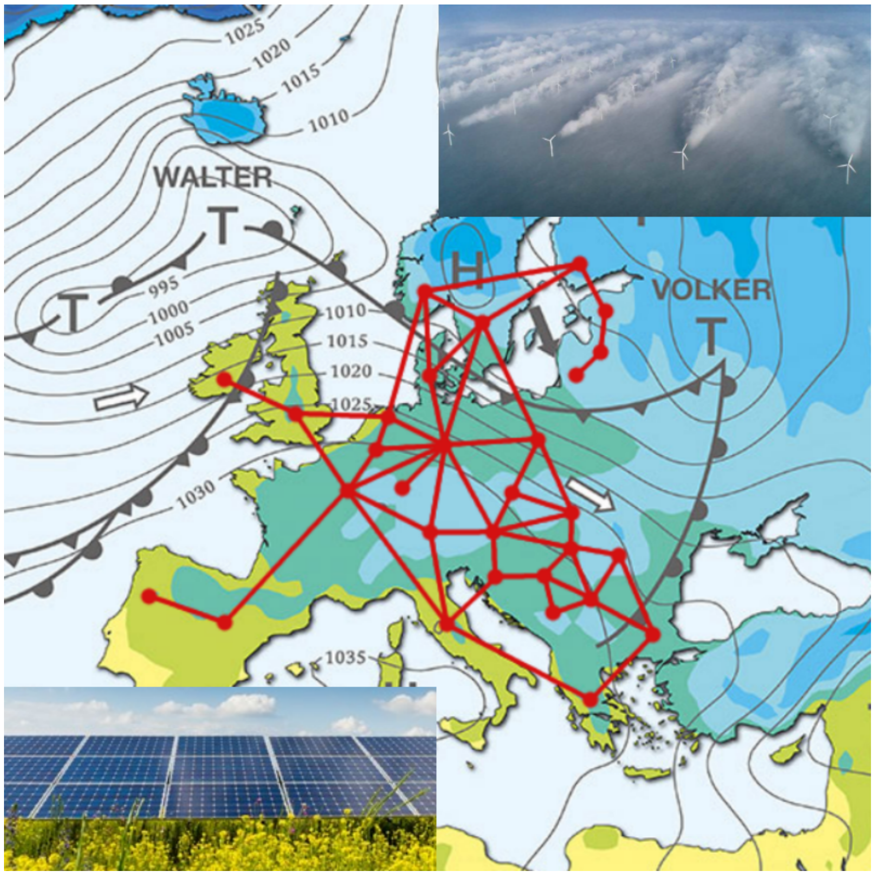
Flow-tracing and nodal cost allocation

in a heterogeneous highly renewable European electricity network



E Eriksen, L Schwenk-Nebbe, B Tranberg, T Brown, M Greiner:
Optimal heterogeneity of a simplified highly renewable pan-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 (2018) in press.

B Tranberg, A Thomsen, R Rodriguez, G Andresen, M Schäfer, M Greiner:
Power flow tracing in a simplified highly renewable European electricity network,
New J. Physics 17 (2015) 105002.

M Schäfer, B Tranberg, S Hempel, S Schramm, M Greiner:
Decompositions of injection patterns for nodal flow allocation in renewable electricity networks,
Eur. Phys. J. B 90 (2017) 144.

J Hörsch, M Schäfer, S Becker, S Schramm, M Greiner:
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.

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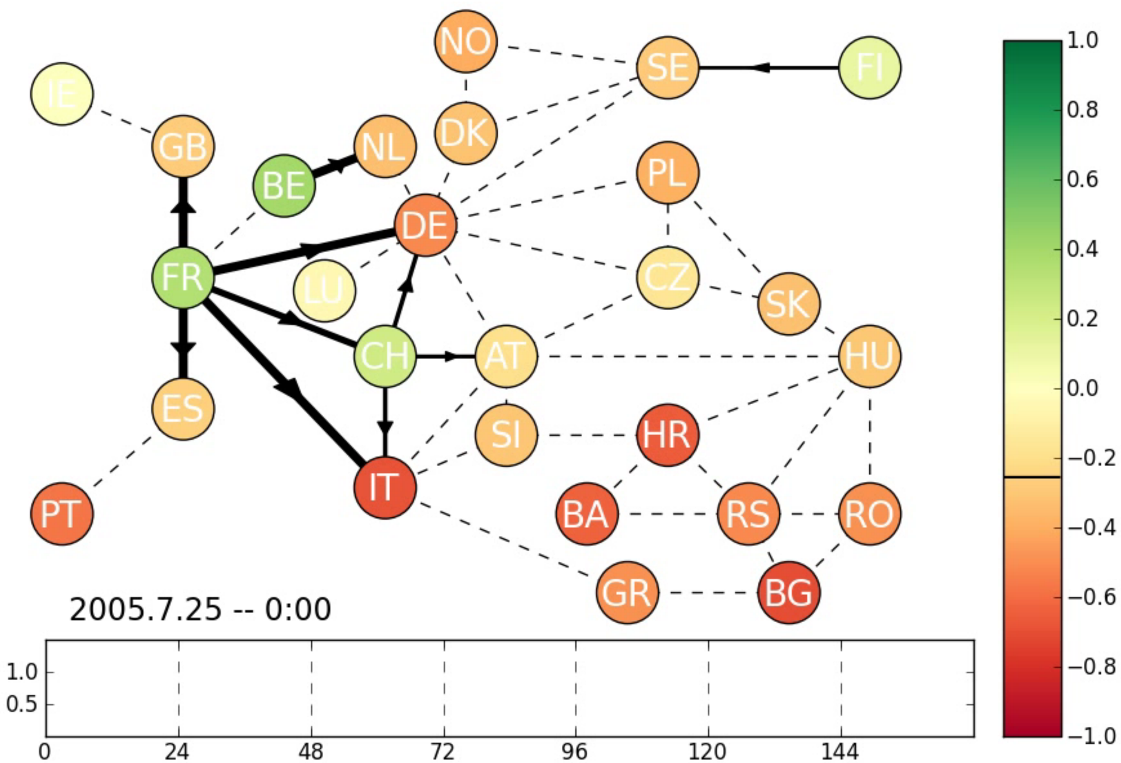
Renewable European electricity network + fluctuating „weather forces“

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

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

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

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



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

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

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

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

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

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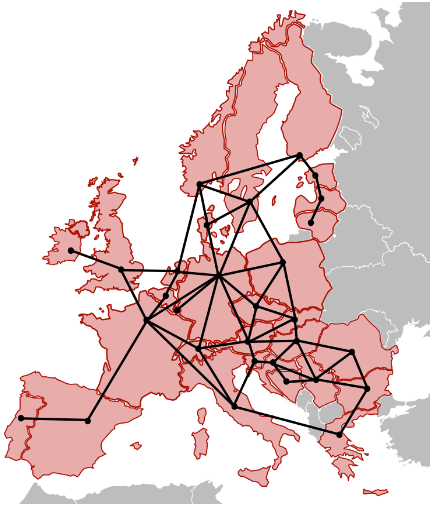
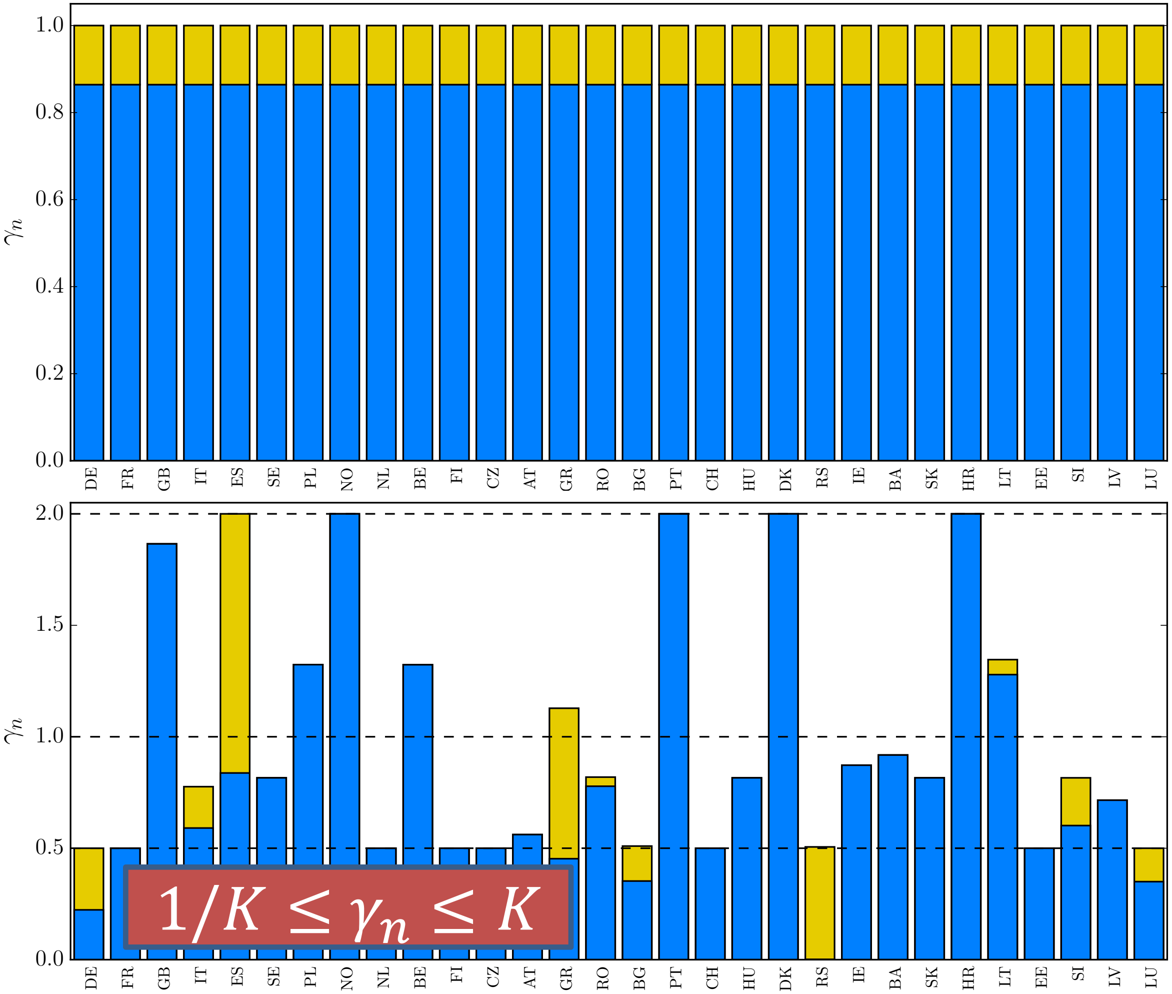
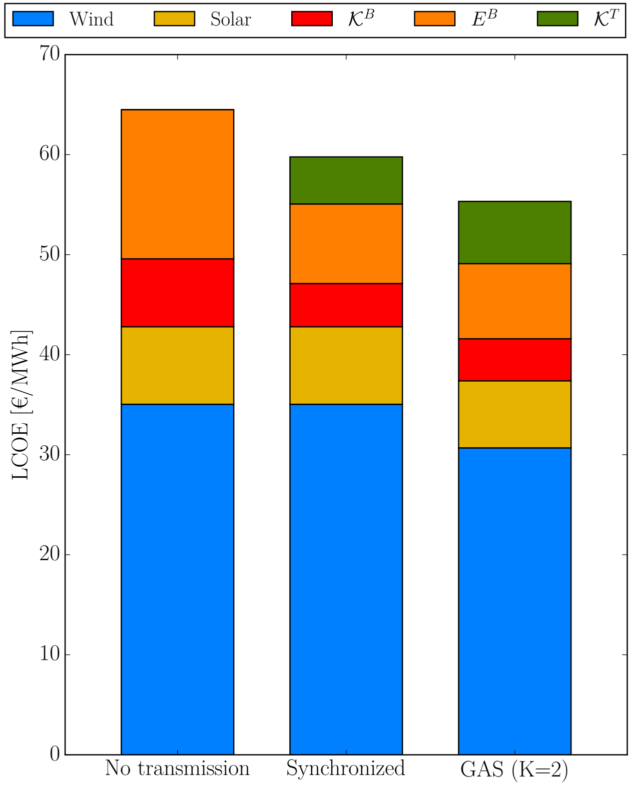
Breaking homogeneity: cost-optimal heterogeneity





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



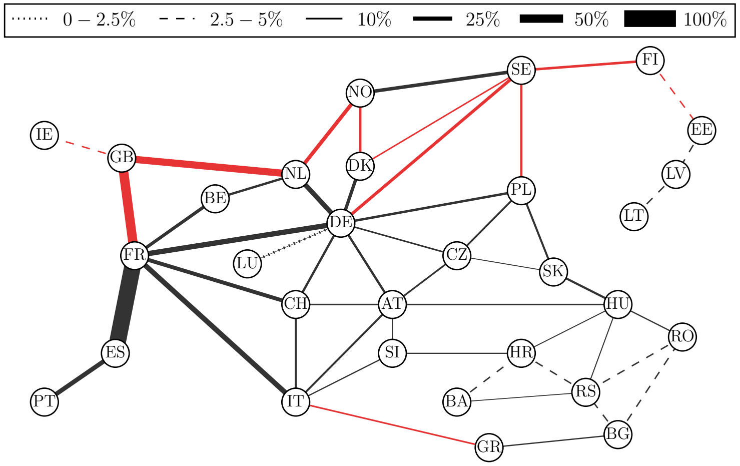
$$\langle G_n^R \rangle = \gamma_n \langle L_n \rangle$$

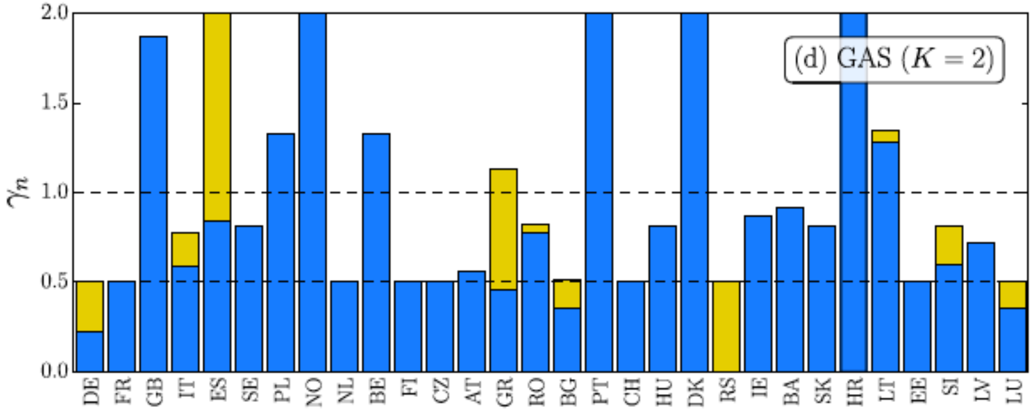
$$\langle G_n^W \rangle = \alpha_n \langle G_n^R \rangle$$

Who pays for …

… the transmission grid?

… the heterogeneity?





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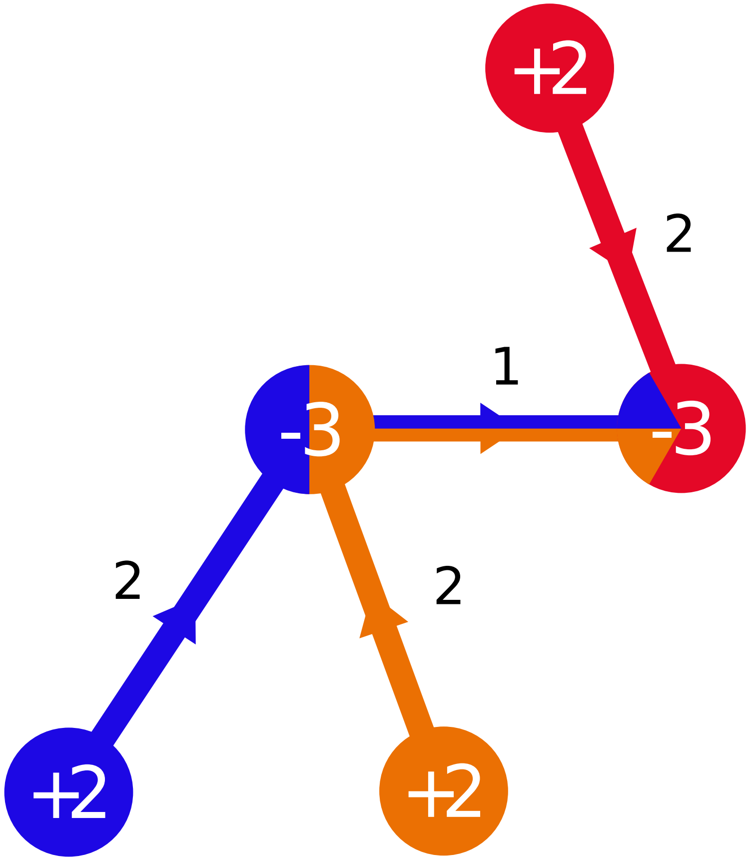
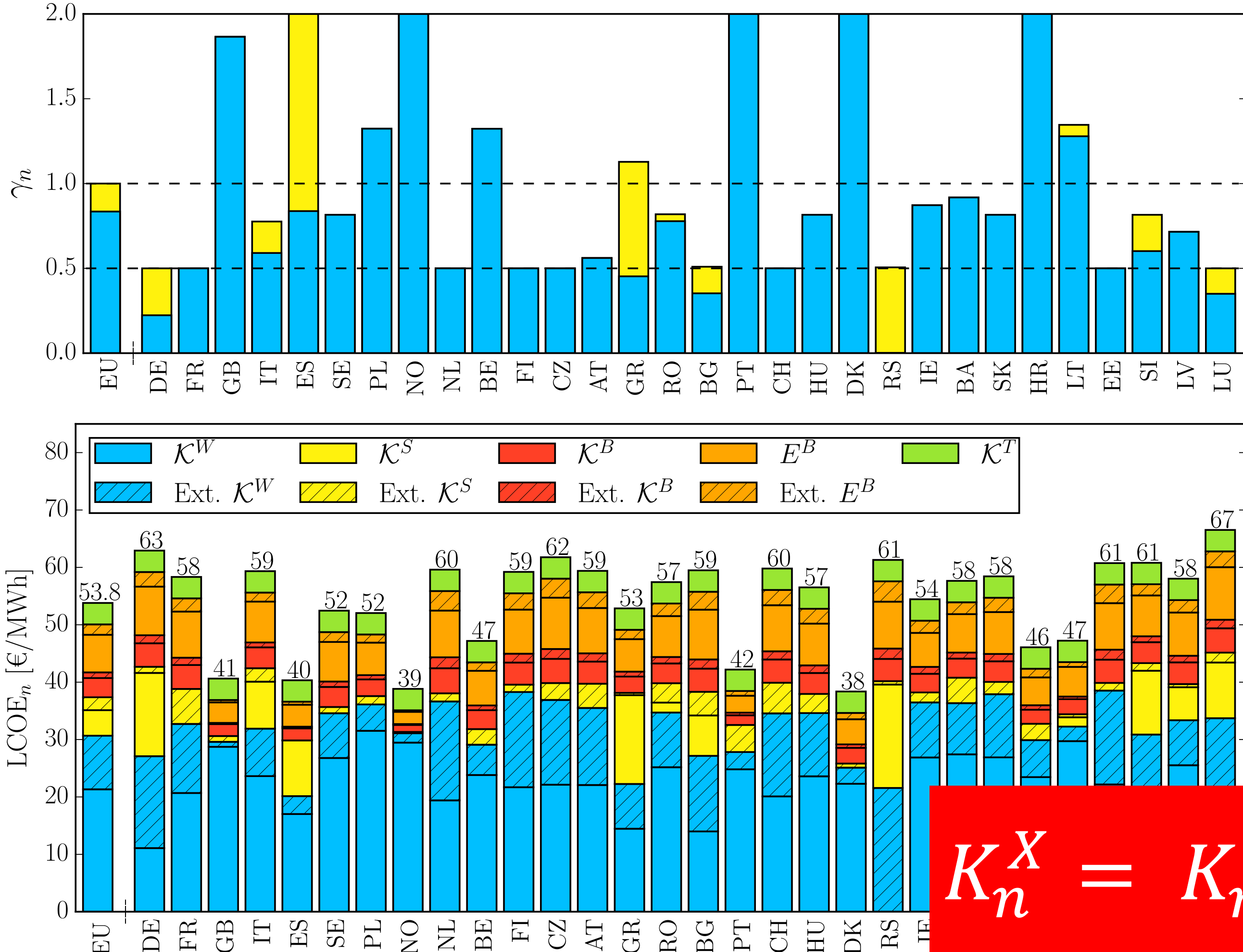
Flow tracing



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

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

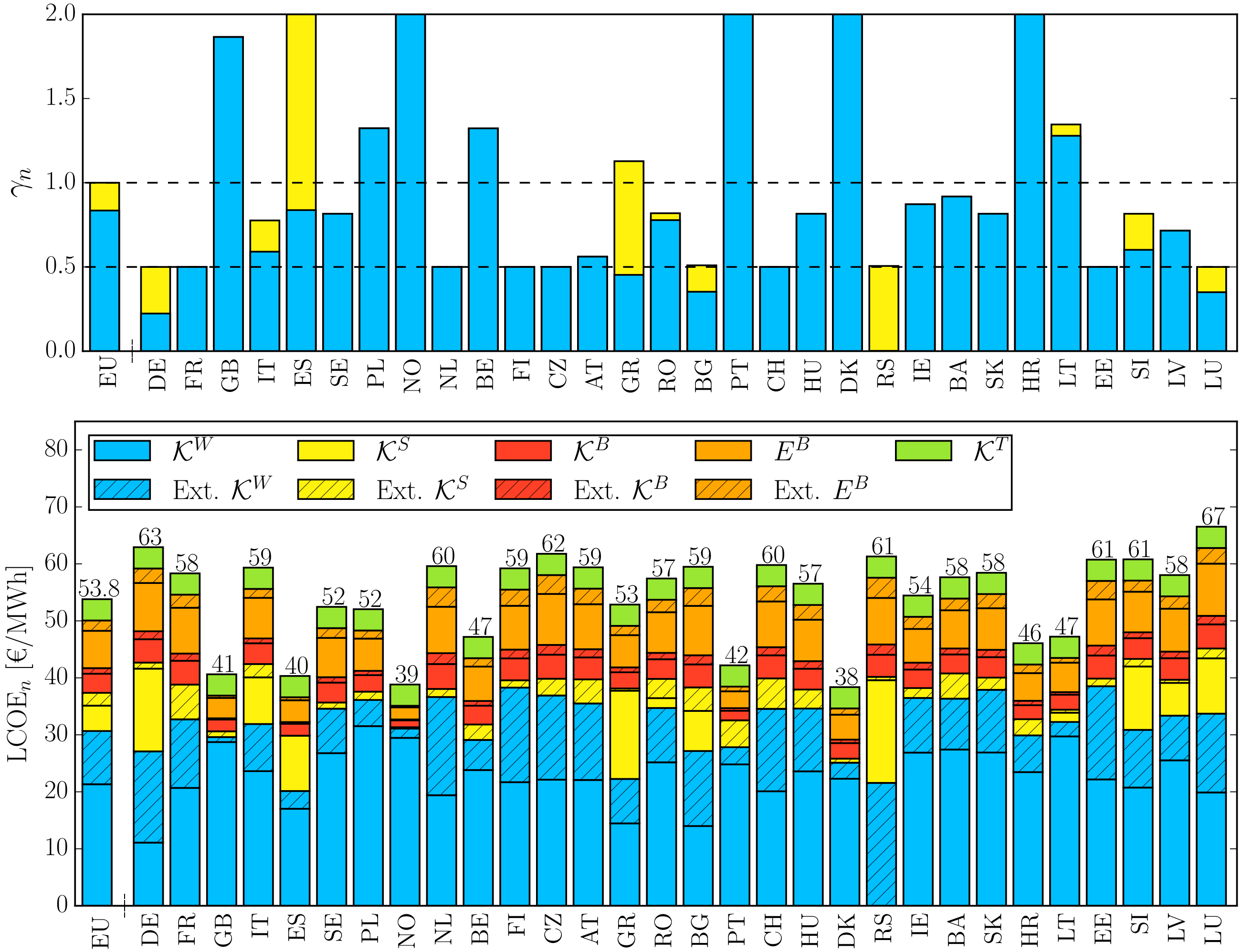
Who pays for the heterogeneity?

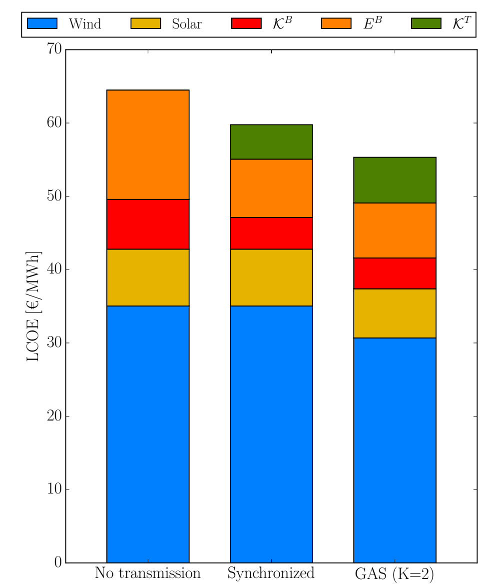


$$K_n^X = K_{nn}^X + \sum_{m \neq n} K_{nm}^X$$

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

Benefit of cooperation





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

next "physics" challenges

big networks:

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

epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS
EPL, **119** (2017) 38004
doi: 10.1209/0295-5075/119/38004

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

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

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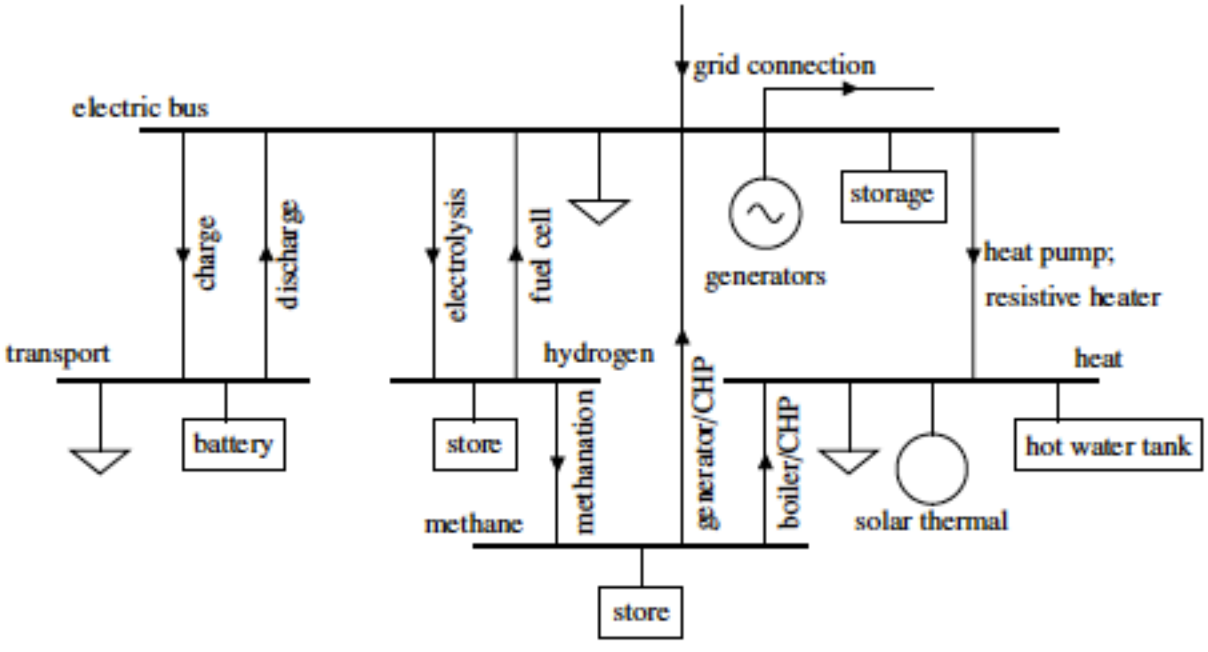
"engineering" challenge:
electricity → "smart" energy system

cross-sector coupling



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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]

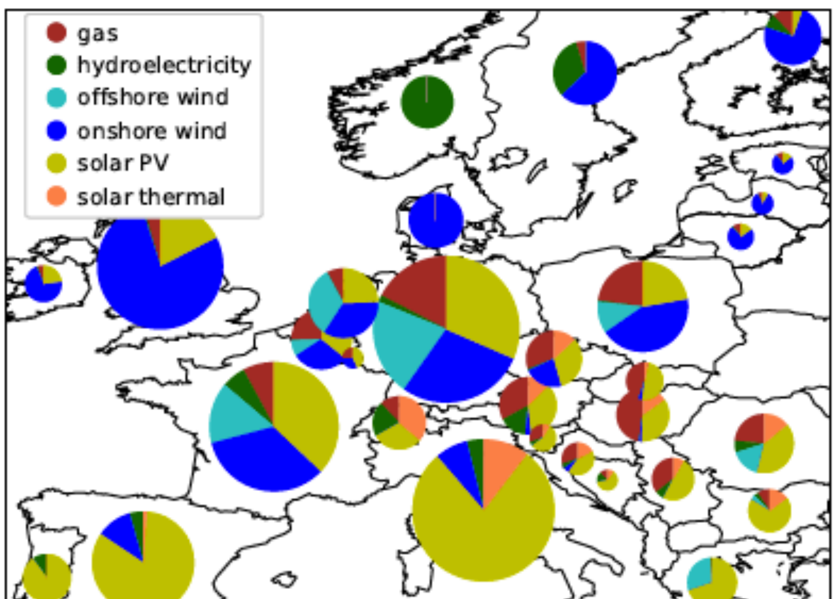
$$\min_{\substack{G_{n,s},E_{n,s},F_\ell,\\ g_{n,s,t},f_{\ell,t}}} \left[\sum_{n,s} c_{n,s}\cdot G_{n,s} + \sum_{n,s}\hat{c}_{n,s}\cdot E_{n,s} + \sum_{\ell} c_\ell\cdot F_\ell + \sum_{n,s,t} o_{n,s,t}\cdot g_{n,s,t}\right] \qquad (1)$$

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

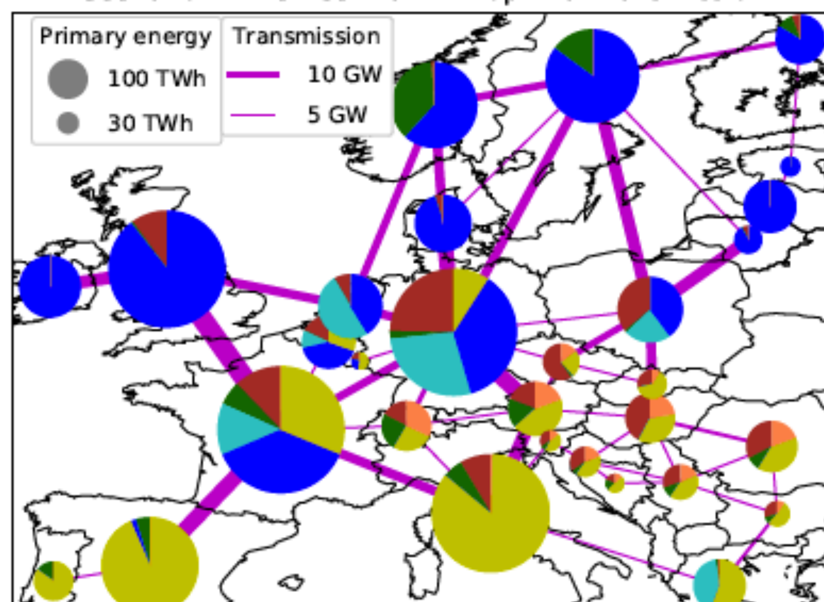
$$\sum_{\ell\in \mathrm{HVDC}} l_\ell \cdot F_\ell \le \mathrm{CAP}_{LV}$$

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

Scenario All-Flex-Central with no transmission



Scenario All-Flex-Central with optimal transmission

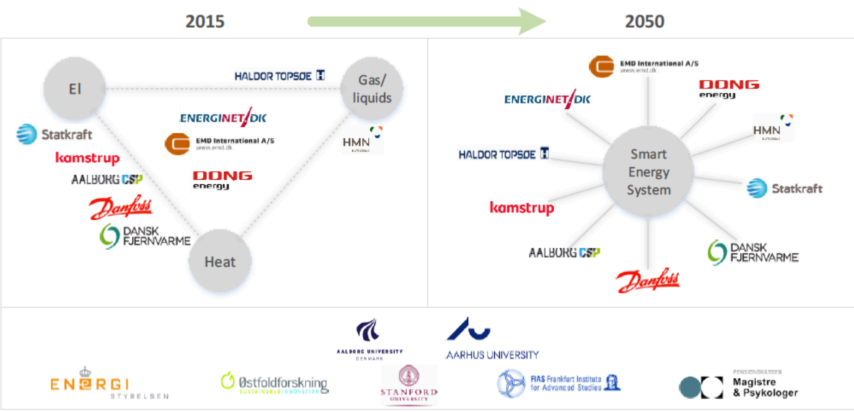


„Energiewende“: kickoff to the second half

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

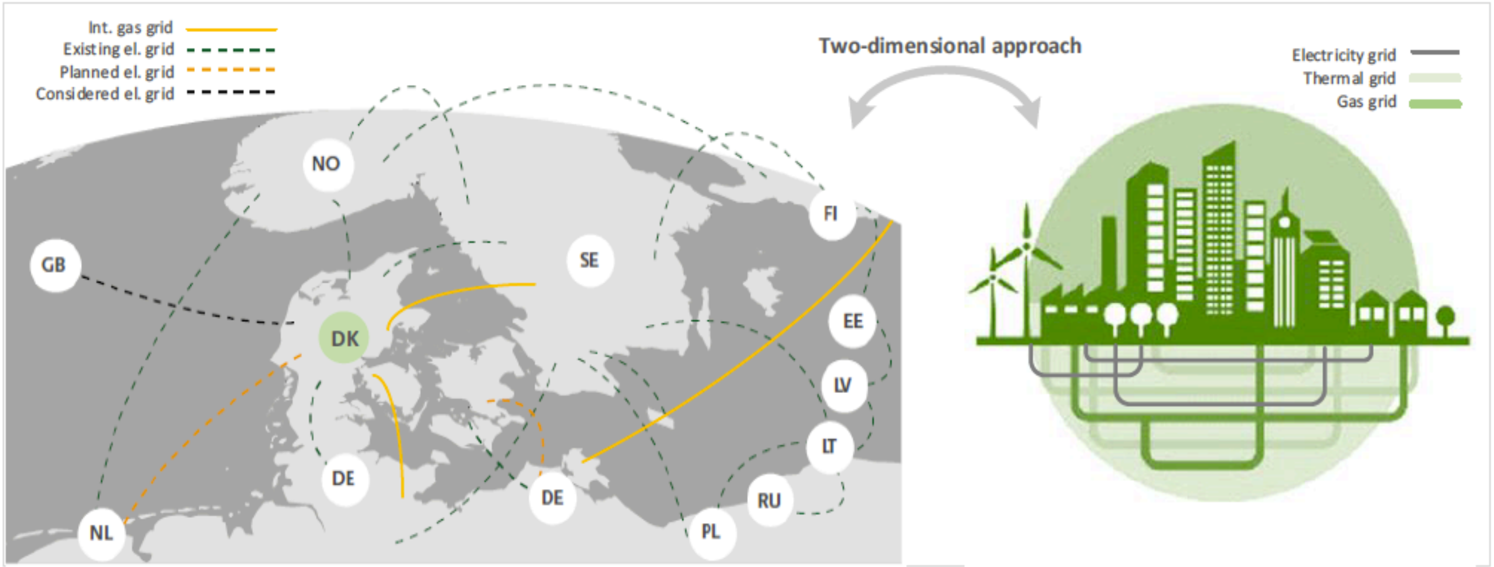


Figure 1. RE-Invest will combine the Smart Energy Systems cross-sectoral approach (right side) at Aalborg University with the cross-border approach (left side) and tools developed by Aarhus University at the European scale. This will lead to a ***novel two-dimensional interconnectivity approach*** *for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

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FunRes

Fundamental Research on Renewable Energy Systems

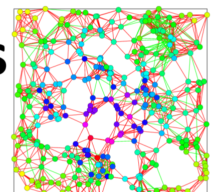
at the interface between engineering + physics + mathematics + economics

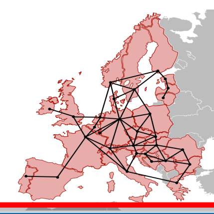
Gorm Andresen + Mahdi Abkar + Martin Greiner (greiner@eng.au.dk)

M Schäfer	(Carlsberg PostDoc)
M Victoria	(PostDoc)
M Dahl	(Master15 + PhD18)
B Tranberg	(Master15 + PhD19)
H Liu	(Master16 + PhD19)
S Kozarcanin	(Master15 + PhD19)
K Zhu	(PhD20)
J Kruse	(Master18)
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

J Trane	(Master18)
A Khamas	(Master18)
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 147 (2018) 534-46.**
B Tranberg et.al.: *Flow-based nodal cost allocation in a heterogeneous highly renewable European electricity system*, **Energy (2018) in press.**
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 + Turbulence (10 ECTS),
Wind Energy (5 ECTS),
Thermodynamics + Heat Transfer (10 ECTS),
Turbomachinery + Compressible Fluids (5 ECTS).

Occasional: Statistical Turbulence (5 ECTS),
Complex Networks (5 ECTS),
Renewable Energy Networks (5 ECTS).

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