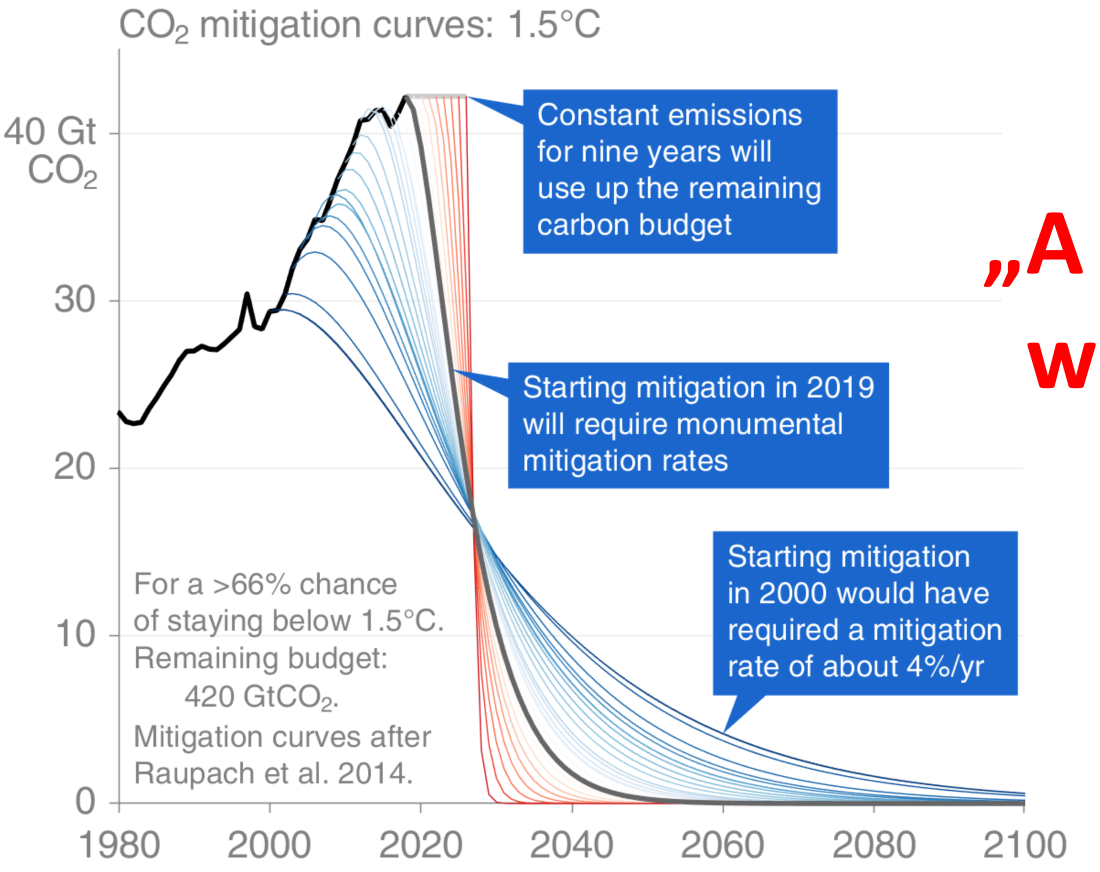
A complex-system modeller‘s view on the defossilisation of the European energy system



CO$_2$ mitigation curves: 1.5°C

Constant emissions for nine years will use up the remaining carbon budget

Starting mitigation in 2019 will require monumental mitigation rates

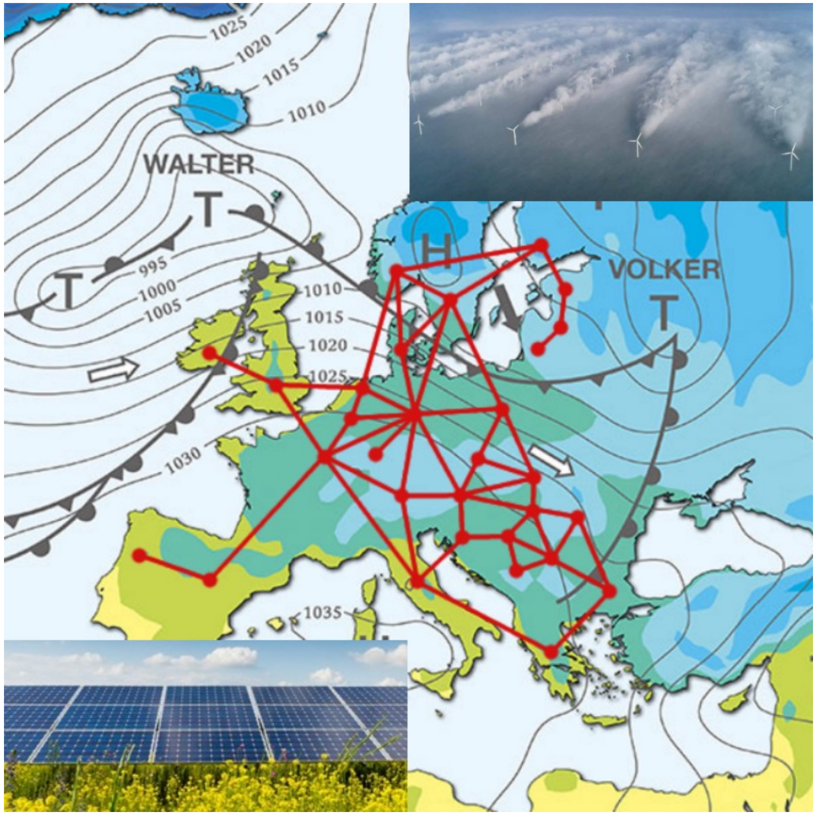
Starting mitigation in 2000 would have required a mitigation rate of about 4%/yr

For a >66% chance of staying below 1.5°C. Remaining budget: 420 GtCO$_2$. Mitigation curves after Raupach et al. 2014.

@robbie_andrew • Data: GCP • Emissions budget from IPCC SR1.5

„A goal is a dream with a deadline.“

A complex-system modeller‘s view on the defossilisation of the European energy system

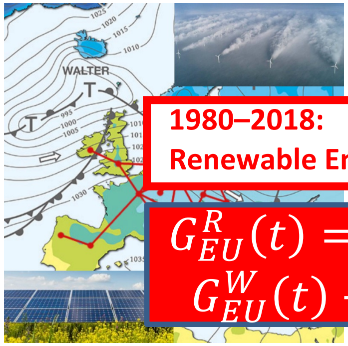


capture / extract
general system dynamics
+ meaningful insights
+ inspirational results

Let the weather decide!

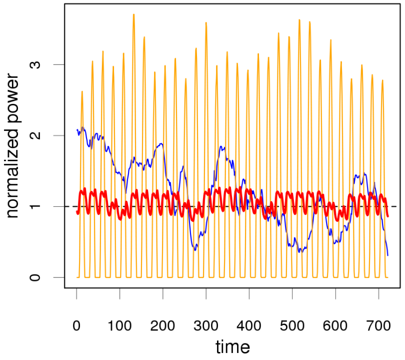
I. Back-on-the-envelope
II. Simplified network model
III. Techno-economic network model (PyPSA)

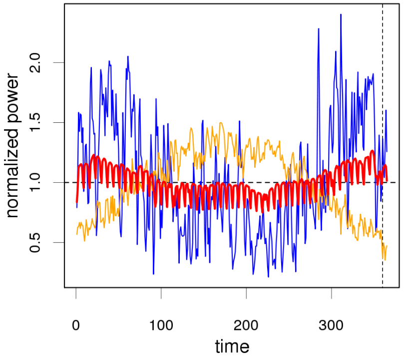
Fluctuating „weather forces“ + ideal storage in a copper-plate Europe



1980–2018: 1h, 30x30km²
Renewable Energy Atlas

$$G^R_{EU}(t) = G^W_{EU}(t) + G^S_{EU}(t)$$





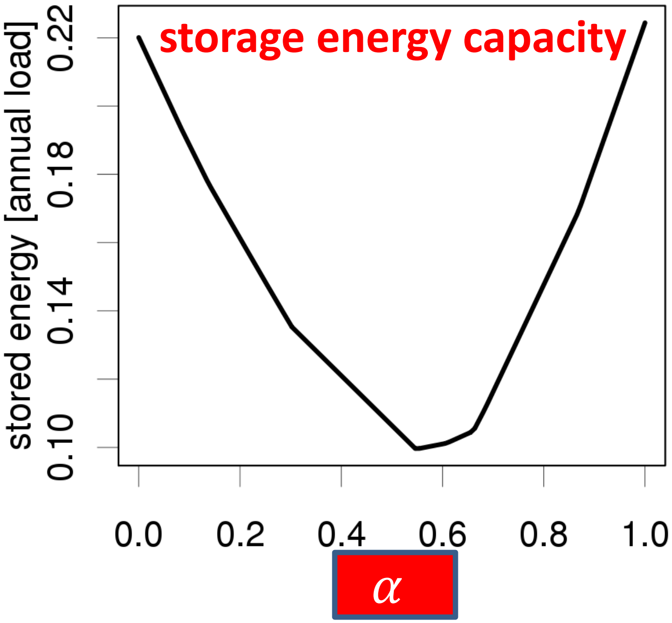
3 TIME SCALES:
- **diurnal (1h-1d)**
- **synoptic (2-10d)**
- **seasonal (1y)**

$$G^R_{EU}(t) - L_{EU}(t) = \Delta S_{EU}(t)$$

$$\langle G^R_{EU} \rangle = \langle L_{EU} \rangle \qquad \langle G^W_{EU} \rangle = \alpha \, \langle G^R_n \rangle \qquad \eta_{in/out} = 1$$

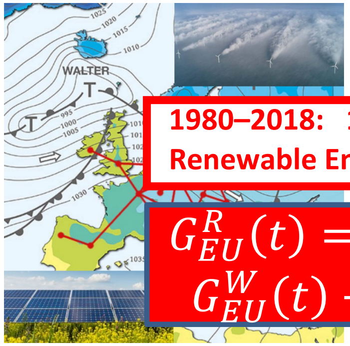
$$S(t) - S(t-1) = \\ = \begin{cases} \eta_{in} \, \Delta S_{EU}(t) & (\Delta S > 0) \\ \eta_{out}^{-1} \Delta S_{EU}(t) & (\Delta S < 0) \end{cases}$$

$$K^S_E = \max_t S(t) - \min_t S(t)$$



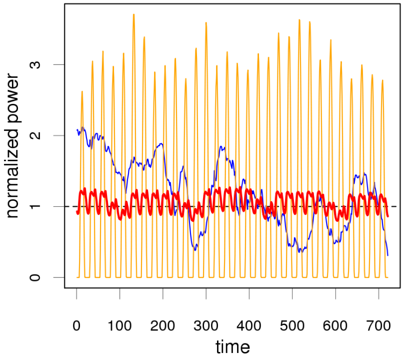
D Heide et.al.: Renewable Energy 35 (2010) 2483-89.

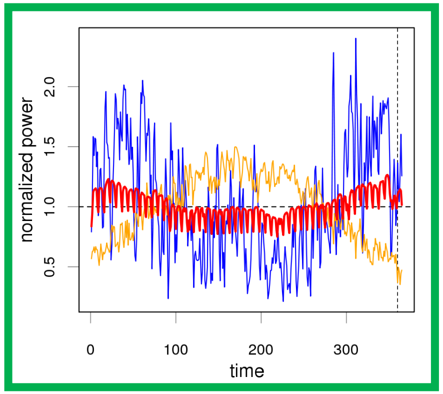
Fluctuating „weather forces“ + ideal storage in a copper-plate Europe



1980–2018: 1h, 30x30km²
Renewable Energy Atlas

$$G^R_{EU}(t) = G^W_{EU}(t) + G^S_{EU}(t)$$





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

$$G^R_{EU}(t) - L_{EU}(t) = \Delta S_{EU}(t)$$

$\langle G^R_{EU}\rangle = \langle L_{EU}\rangle$ $\langle G^W_{EU}\rangle = \alpha\,\langle G^R_n\rangle$ $\eta_{in/out} = 1$

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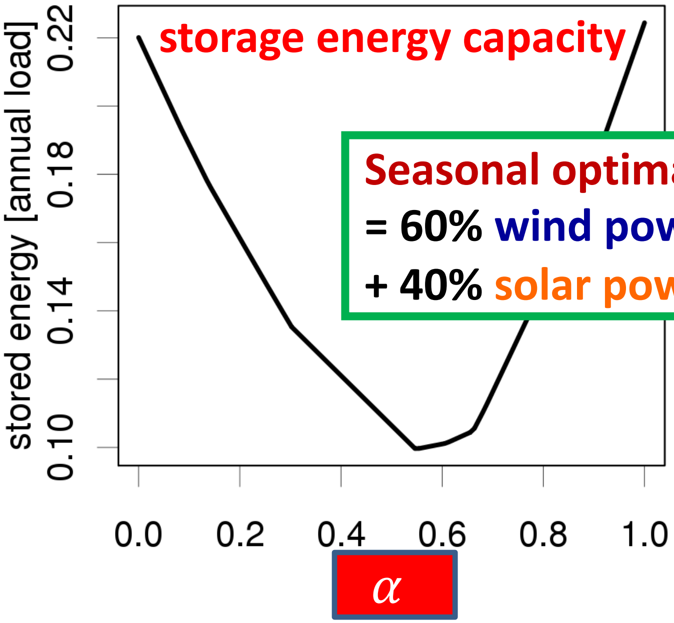
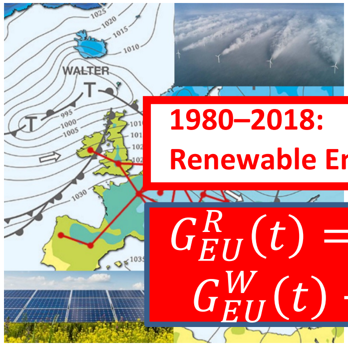
$$K^S_E = \max_t S(t) - \min_t S(t)$$



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

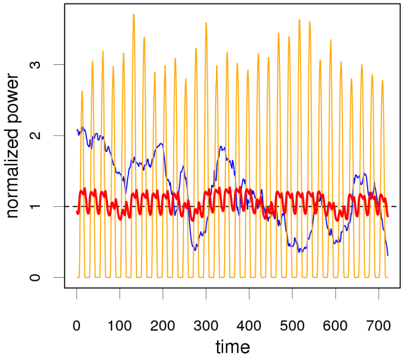
D Heide et.al.: Renewable Energy 35 (2010) 2483-89.

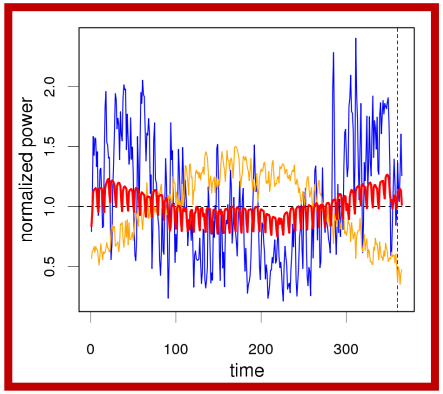
Fluctuating „weather forces“ + ideal storage in a copper-plate Europe



1980–2018: 1h, 30x30km²
Renewable Energy Atlas

$$G_{EU}^{R}(t) = G_{EU}^{W}(t) + G_{EU}^{S}(t)$$

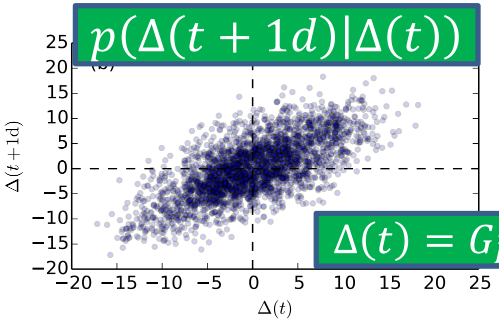




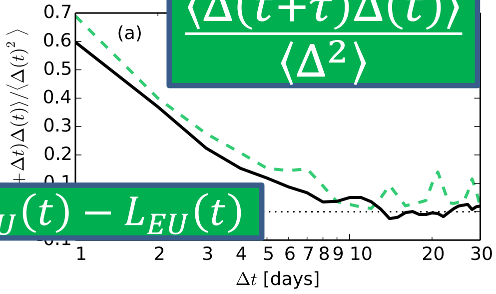
3 TIME SCALES:
diurnal (1h-1d)
synoptic (2-10d)
seasonal (1y)

temporal (synoptic) correlations

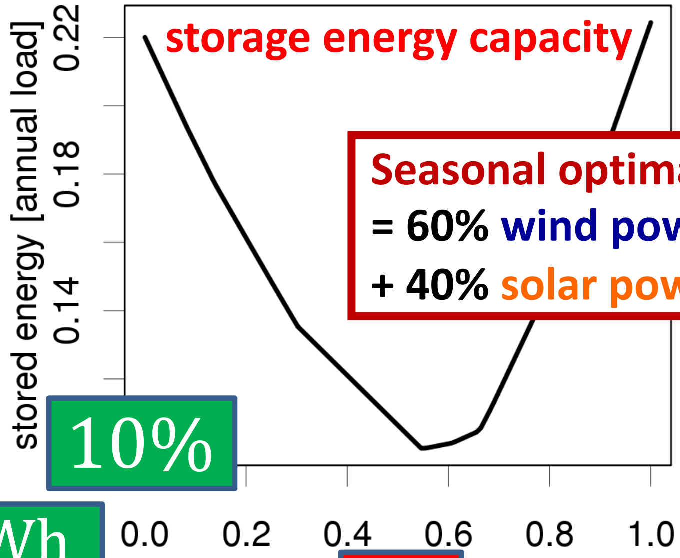
$$p(\Delta(t+1d)|\Delta(t))$$



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



$$\Delta(t) = G_{EU}^{R}(t) - L_{EU}(t)$$



storage energy capacity

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

10%

α

$$10\%\,\langle L_{EU}\rangle_{\text{annual}} \approx 340\text{ TWh}$$

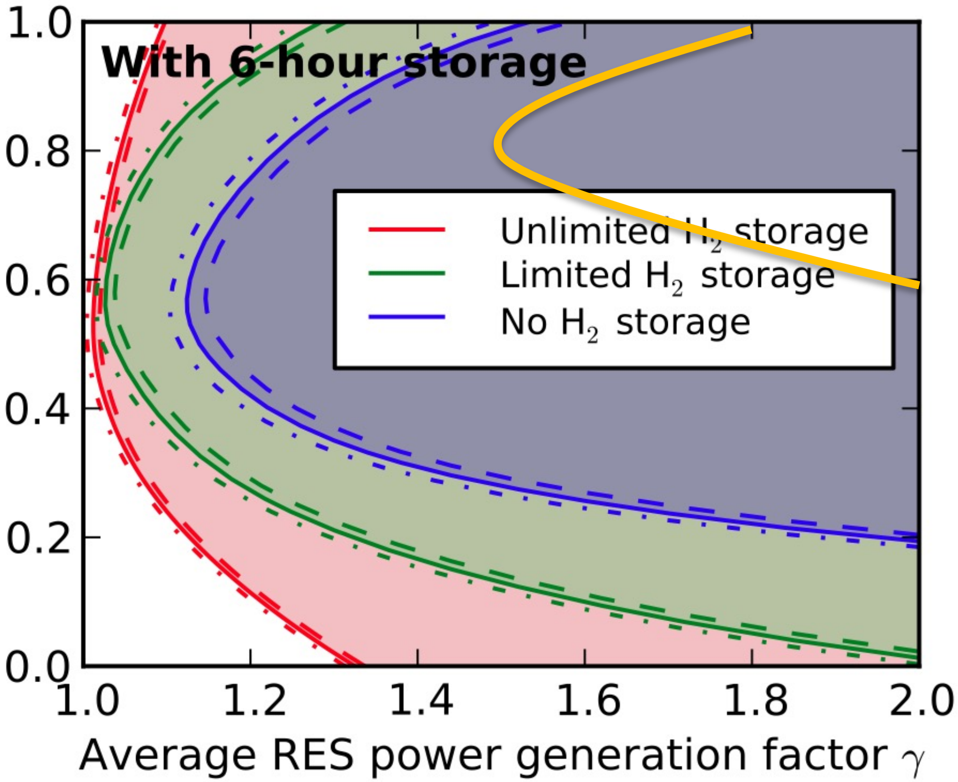
TV Jensen et.al.: EPJ ST 223 (2014) 2475-81.

D Heide et.al.: Renewable Energy 35 (2010) 2483-89.

Fluctuating „weather forces“ + storage + balancing in a copper-plate Europe

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

$$\alpha_{EU} = \frac{\langle G^W_{EU}(t)\rangle}{\langle G^W_{EU}(t)+G^S_{EU}(t)\rangle}$$

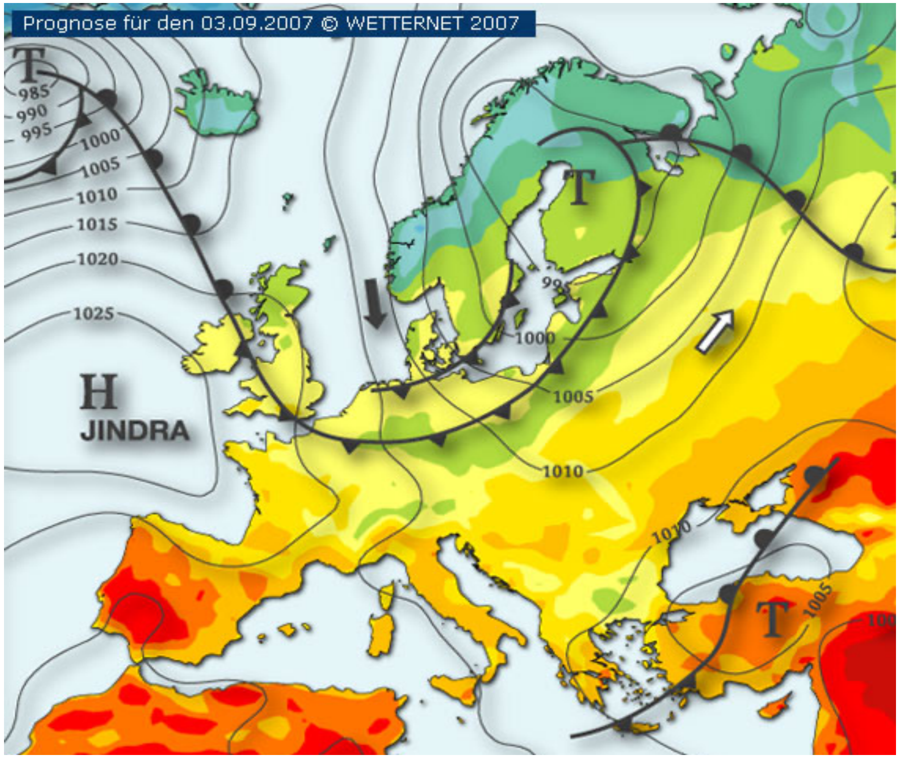


$$\gamma_{EU} = \frac{\langle G^W_{EU}(t)+G^S_{EU}(t)\rangle}{\langle L_{EU}\rangle}$$

$$\begin{aligned} G^R_{EU}(t) - L_{EU}(t) &= \\ = B^{H_2O}_{EU}(t) & \\ +\Delta S^{6h}_{EU}(t) & \\ +\Delta S^{H_2}_{EU}(t) & \end{aligned}$$

MG Rasmussen et.al.: Energy Policy 51 (2012) 642-51.

wind and solar power capacities



annual consumption (2009)
= 3360 TWh

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

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

Fluctuating „weather forces“ + Renewable European electricity network

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

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

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

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

$$\gamma_n = 1$$

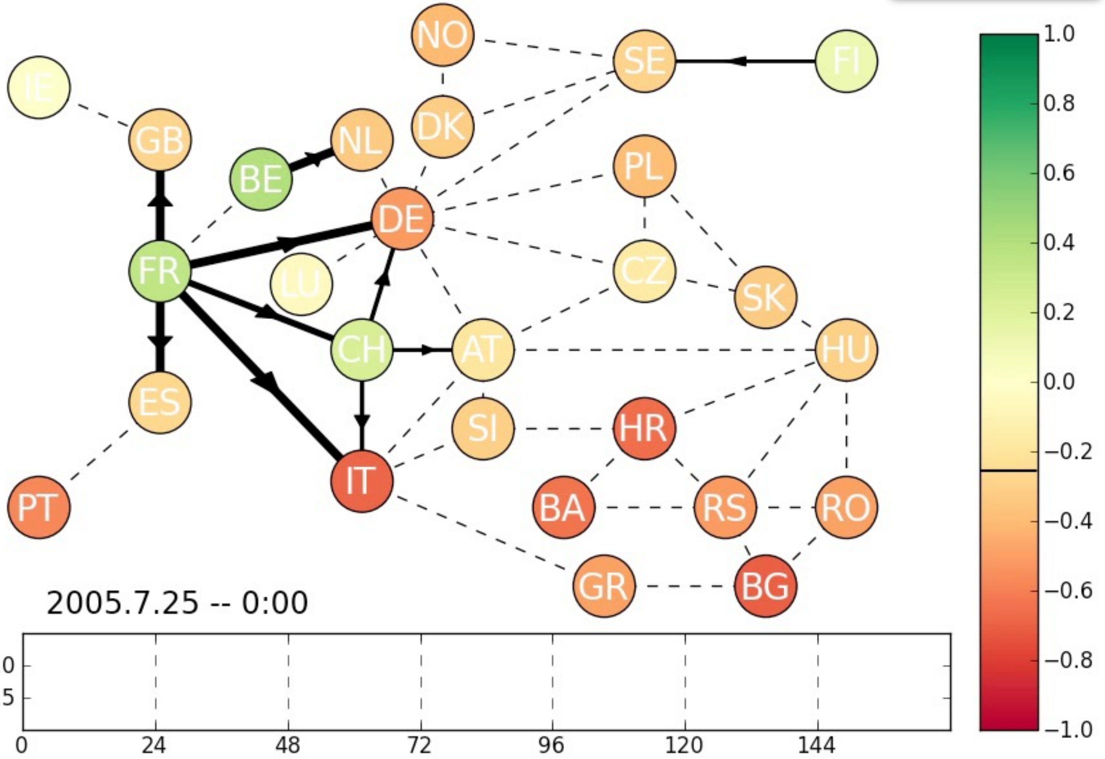
$$\alpha_n = 0.7$$

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

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

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

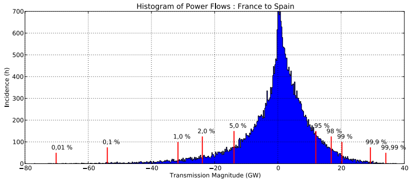
$$F_l(t) = \sum_n H_{ln} P_n(t)$$



RA Rodriguez et.al.: Energy, Sustainability & Society 5 (2015) 21.

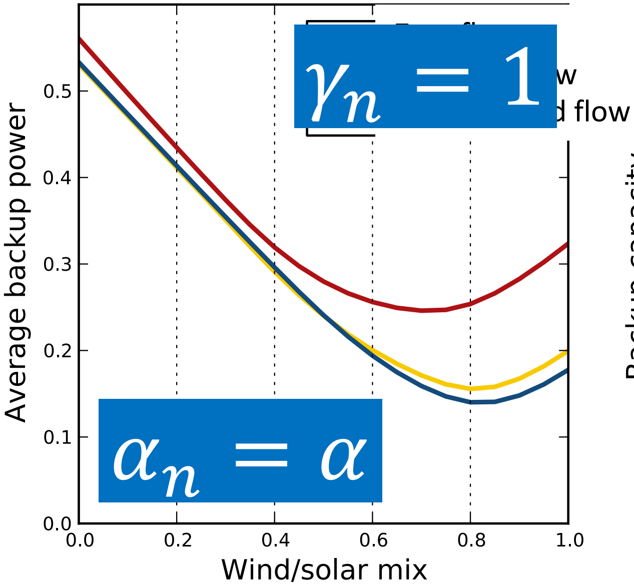
Infrastructure measures

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



backup energy

$$\langle G_n^B \rangle$$

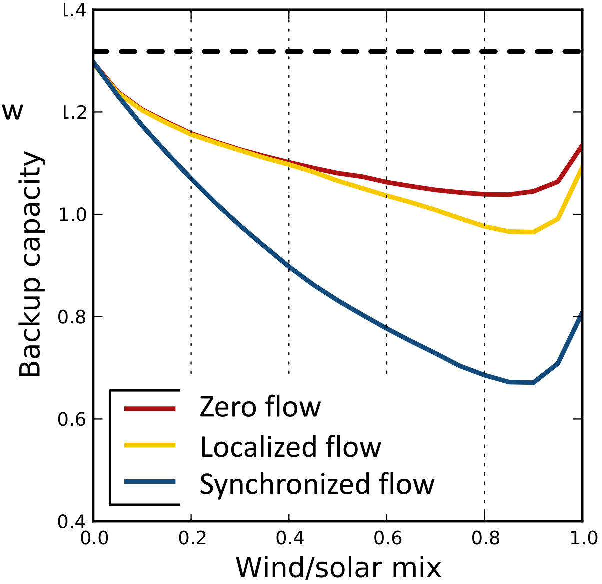


$\gamma_n = 1$

$\alpha_n = \alpha$

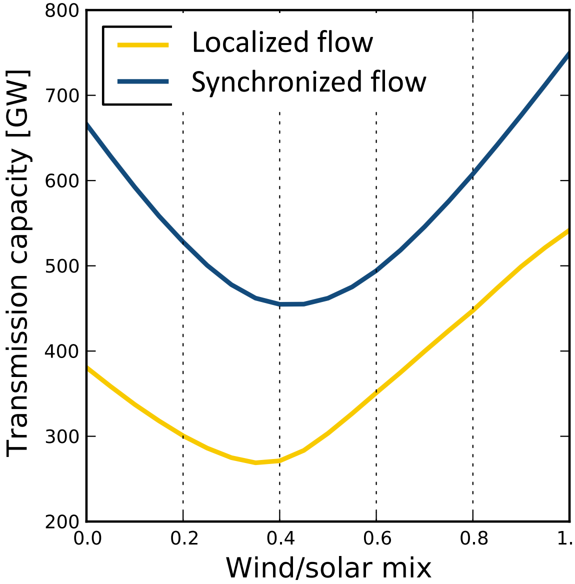
backup capacity

$$max_q(G_n^B)$$

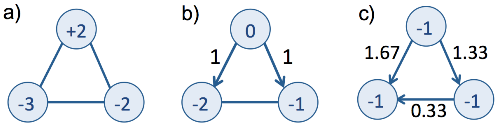


transmission capacity

$$\sum_l \max_q |F_l| \cdot d_l$$

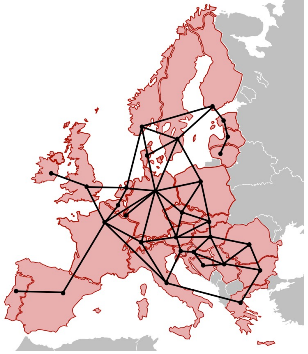


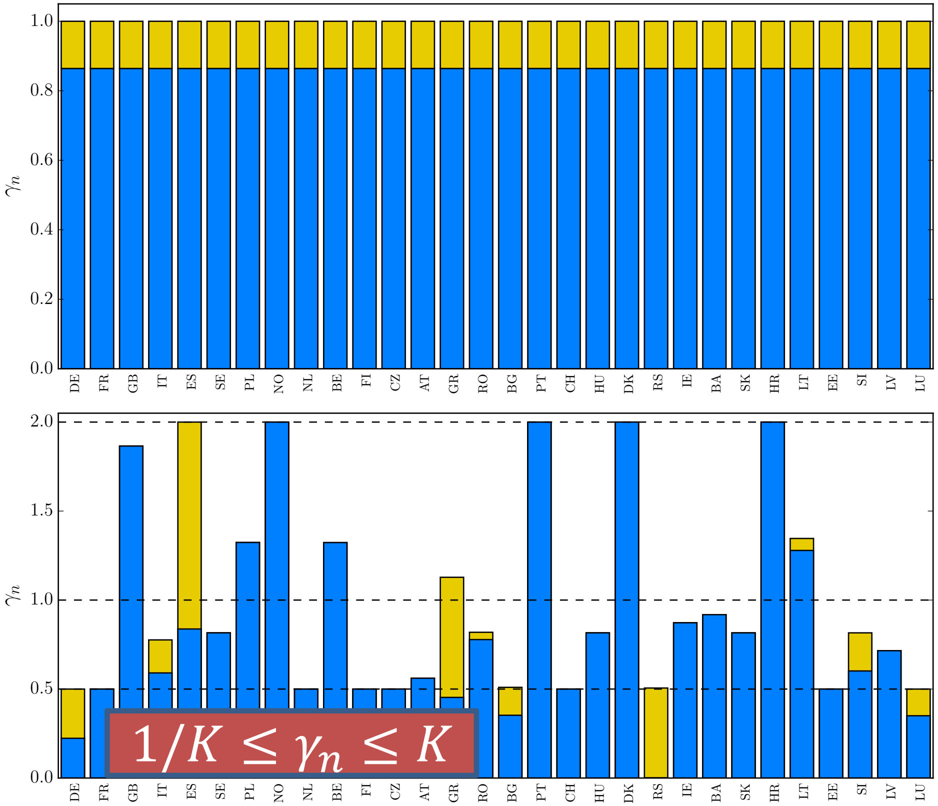
$K_n^W = \frac{\alpha_n \gamma_n \langle L_n \rangle}{CF_n^W}$ **wind / solar capacities** $K_n^S = \frac{(1-\alpha_n)\gamma_n \langle L_n \rangle}{CF_n^S}$



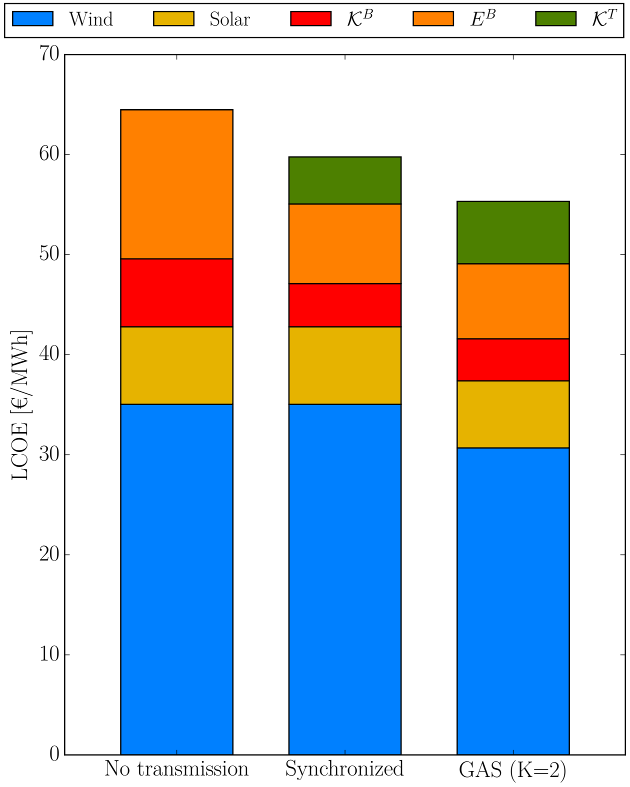
E Eriksen et.al.: Energy 133 (2017) 913-28.

System costs





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



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

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

EU cost reduction / y

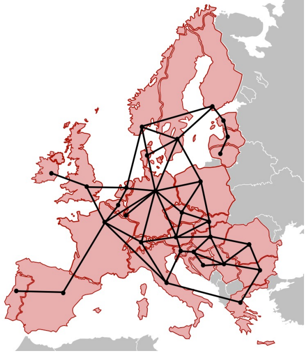
= 3500 TWh/y x 10 €/MWh

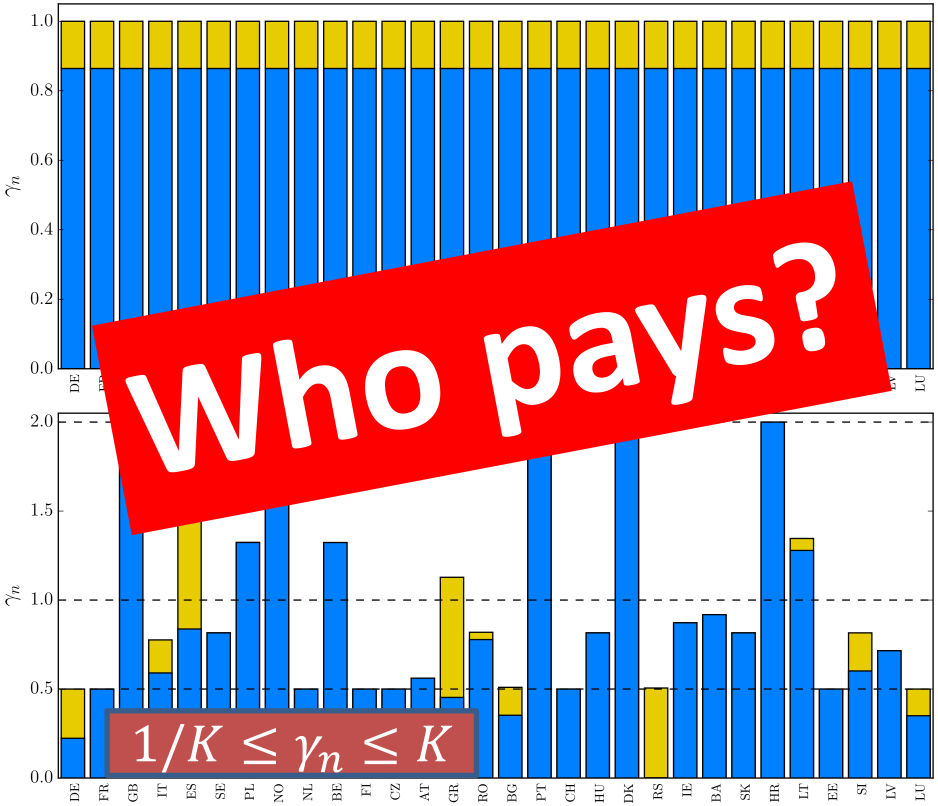
= 35 x 10^9 €/y

System costs

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

B Tranberg et.al.: Energy 150 (2018) 122-33.



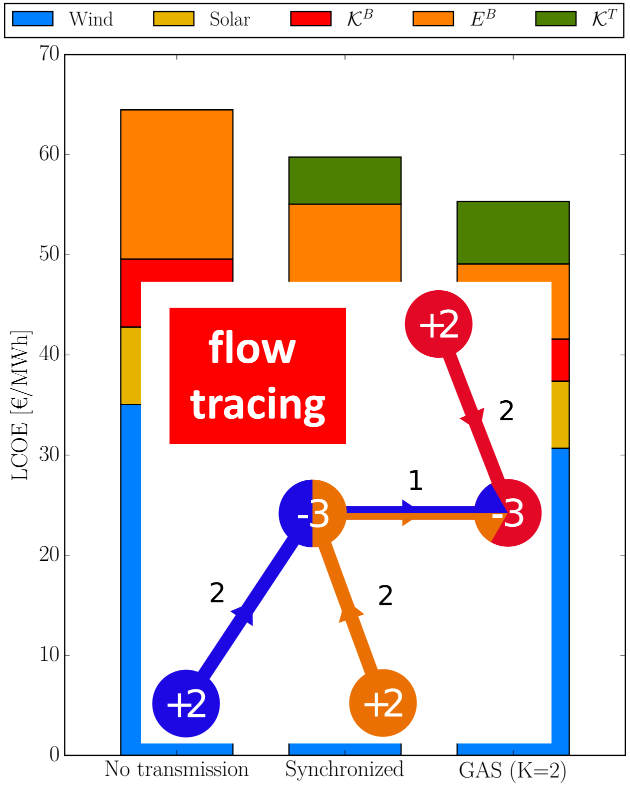


Who pays?

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

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

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



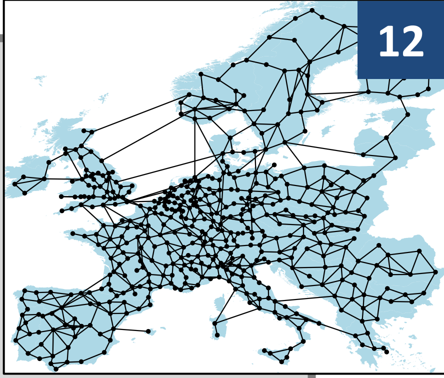
EU cost reduction / y

= 3500 TWh/y x 10 €/MWh

= 35 x 10^9 €/y

more (“phyneering”) topics:

principal spatio-temporal modes,
power-flow renormalization,
mesoscale turbulence + climate change



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.**

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.**

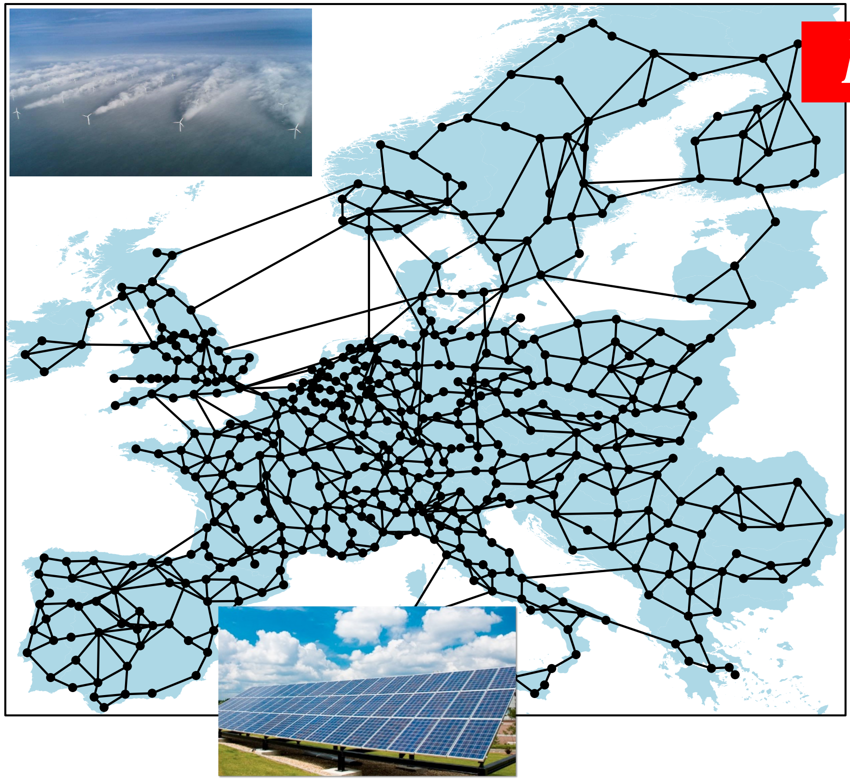
J Hörsch et.al.: *Flow tracing as a tool set for the analysis of networked large-scale renewable electricity systems,* **Int. J. Electrical Power and Energy Systems 96 (2018) 390-97.**

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 150 (2018) 122-33.**

F Hofmann et.al.: *Principal flow patterns across renewable electricity networks,* **Europhysics Letters 124 (2018) 18005.**

Development of a new power-flow forecasting tool



$N = 512$

$L = 956 \rightarrow K = 12$

$$\vec{F}(t) = \sum_{l=1}^{L} F_l(t)\,\vec{e}_l \approx \langle \vec{F} \rangle + \sqrt{Var(\vec{F})} \sum_{k=1}^{K} a_k^F(t)\,\vec{p}_k^F$$

$$G_n^W(t) \rightarrow P_n(t) \rightarrow F_l(t) = \sum_n H_{ln}\,P_n(t)$$

$$K^W \approx K^P \approx 85$$

F Hofmann et.al.: Europhys. Letters 124 (2018) 18005.

12 flow degrees of freedom:

- probabilisitic power flow + uncertainty analysis
- development of a low-dim. power-flow forecasting tool
- information processing in the brain

Techno-economic modeling: sector-coupled energy system

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

T Brown et.al.: *Synergies of sector coupling and transmission extension in a cost-optimised highly renewable European energy system*, **Energy 160 (2018) 720-39.**

D Schlachtberger et.al.: *Cost optimal scenarios of a future highly renewable European electricity system – exploring the influence of weather data, cost parameters and policy constraints*, **Energy 163 (2018) 100-14.**

M Schlott et.al.: *The impact of climate change on a cost-optimal highly renewable European electricity network*, **Applied Energy 230 (2018) 1645-59.**

K Zhu et.al.: *Impact of CO_2 prices on the design of a highly decarbonized coupled electricity and heating system in Europe*, **Applied Energy 236 (2019) 622-34.**

T Brown et.al.: *Sectoral interactions as carbon dioxide emissions approach zero in a highly-renewable European energy system*, **Energies 12 (2019) 1032.**

H Liu et.al.: *The role of hydro power, storage and transmission in the decarbonization of the Chinese power system*, **Applied Energy 239 (2019) 1308-21.**

H Liu et.al.: *A high-resolution hydro power time-series model for energy system analysis -- validated with Chinese hydro reservoirs*, **MethodsX 6 (2019) 1370-78.**

M Victoria et.al.: *The role of storage technologies throughout the decarbonization of the sector-coupled European energy system*, **Energy Conversion and Management 201 (2019) 111977.**

M Victoria et.al.: *The role of photovoltaics in a sustainable European energy system under variable CO2 emissions targets, transmission capacities, and costs assumptions*, **Progress in Photovoltaics: Research and Applications 3198 (2019) 1-10.**

K Zhu et.al.: *Impact of climatic, technical and economic uncertainties on the optimal design of a coupled fossil-free electricity, heating and cooling system in Europe*, **Applied Energy 262 (2020) 114500.**

M Victoria et.al.: *Early decarbonisation of the European energy system pays off*, **Nature Communications 11 (2020) 6223.**

L Schwenk-Nebbe et.al.: *CO_2 quota attribution effects on the European electricity system comprised of self-centred actors*, **Advances in Applied Energy 2 (2021) 100012.**

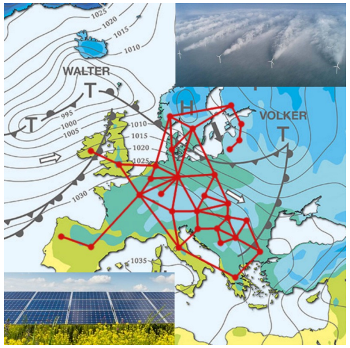
L Schwenk-Nebbe et.al.: *Principal spatiotemporal mismatch and electricity price patterns in a highly decarbonized networked European power system*, **iScience 25 (2022) 104380.**

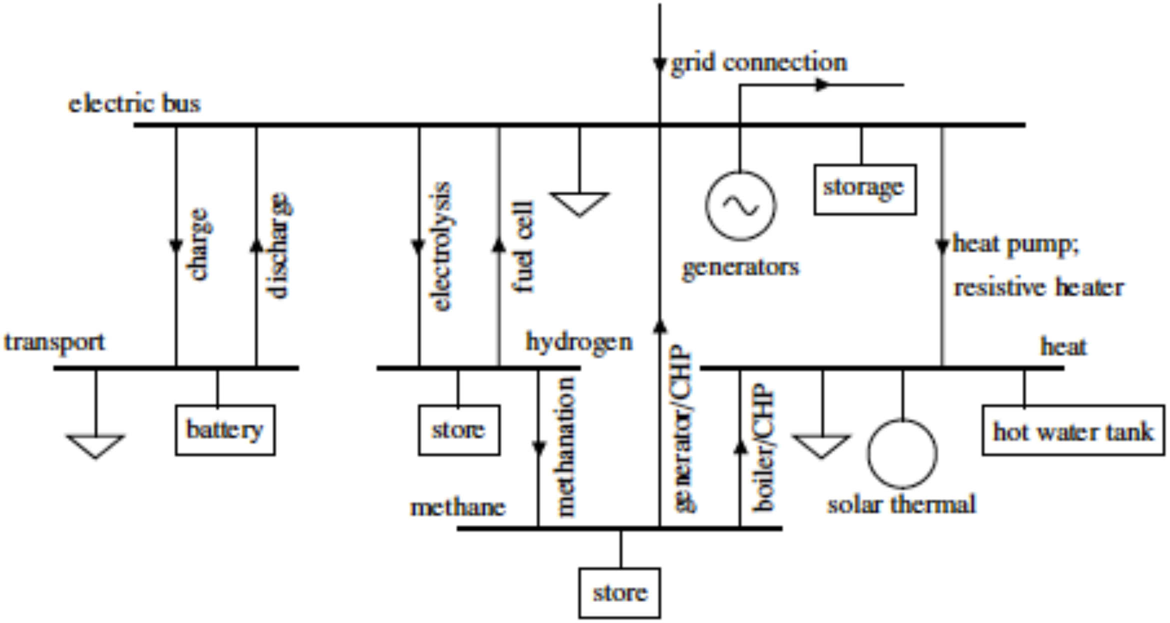
EK Gøtske et.al.: *Cost and Efficiency Requirements for Successful Electricity Storage in a Highly Renewable European Energy System*, **PRX Energy 2 (2023) 023006.**

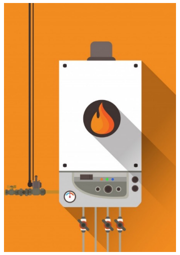
Defossilisation of a simplified networked electricity + heating system

PyPSA-Eur-Sec-30

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



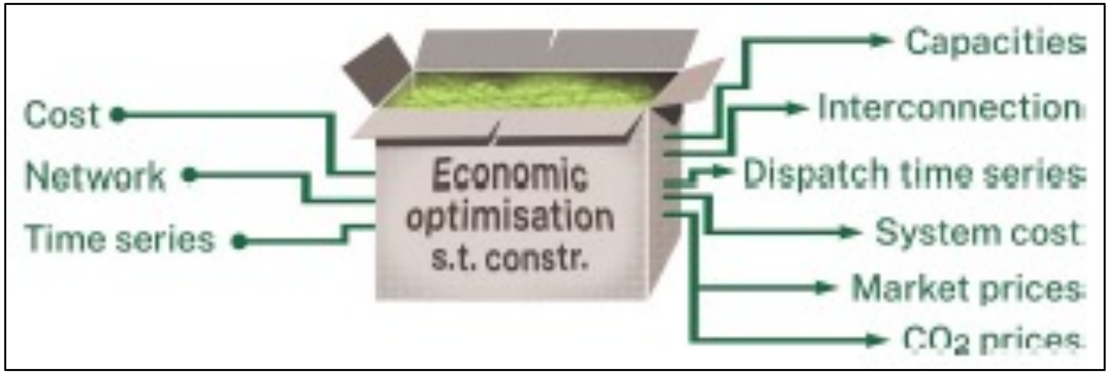




simplified cross-sector network model

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

PyPSA-Eur-Sec-30



$$\min_{\substack{G_{n,s},E_{n,s},\\ F_\ell,g_{n,s,t}}} \left[\overbrace{\sum_{n,s} c_{n,s} \cdot G_{n,s}}^{\text{generation costs}} + \overbrace{\sum_{n,s} \hat{c}_{n,s} \cdot E_{n,s}}^{\text{storage costs}} + \overbrace{\sum_{\ell} c_\ell \cdot F_\ell}^{\text{transmission costs}} + \overbrace{\sum_{n,s,t} o_{n,s,t} \cdot g_{n,s,t}}^{\text{variable costs}} \right]$$

Subject to constraints :

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

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

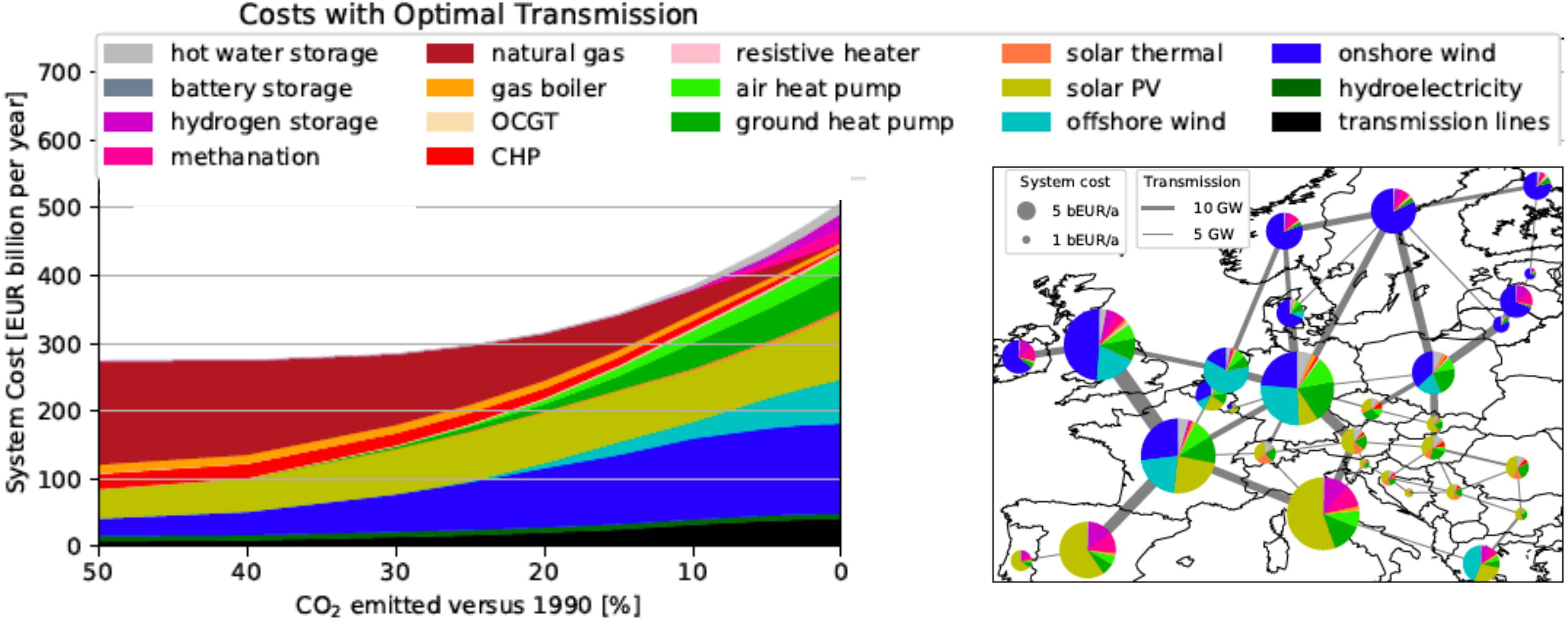
$$\boxed{\sum_{n,s,t} \varepsilon_s \frac{g_{n,s,t}}{\eta_{n,s}} + \sum_{n,s} \varepsilon_s \left(e_{n,s,t=0} - e_{n,s,t=T}\right) \leq \mathrm{CAP}_{CO_2} \quad \leftrightarrow \quad \mu_{CO_2}}$$

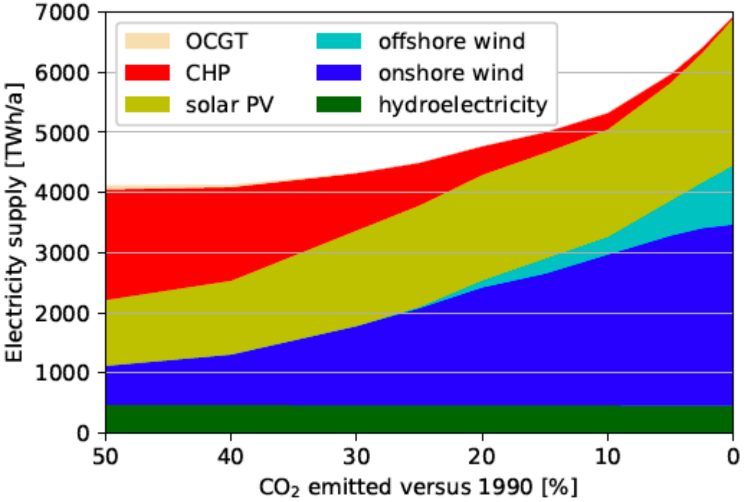
CO_2 emission constraint

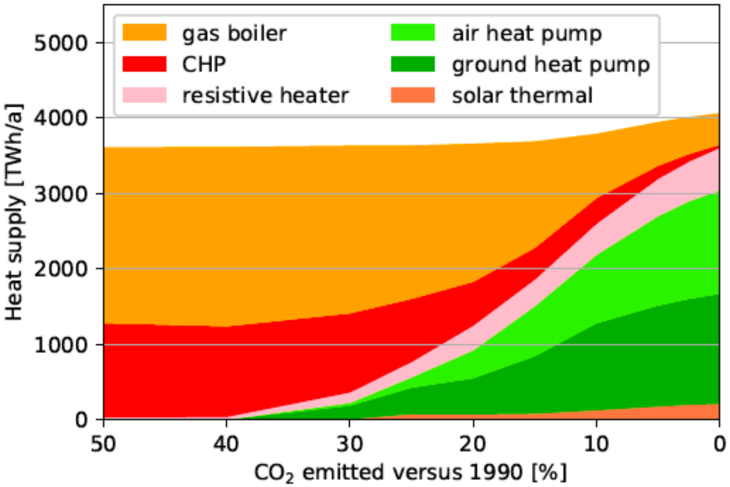
$$\boxed{\min\left(Costs \; - \; \lambda \cdot Constraint\right)}$$

Green-field optimization of electricity + heating system

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







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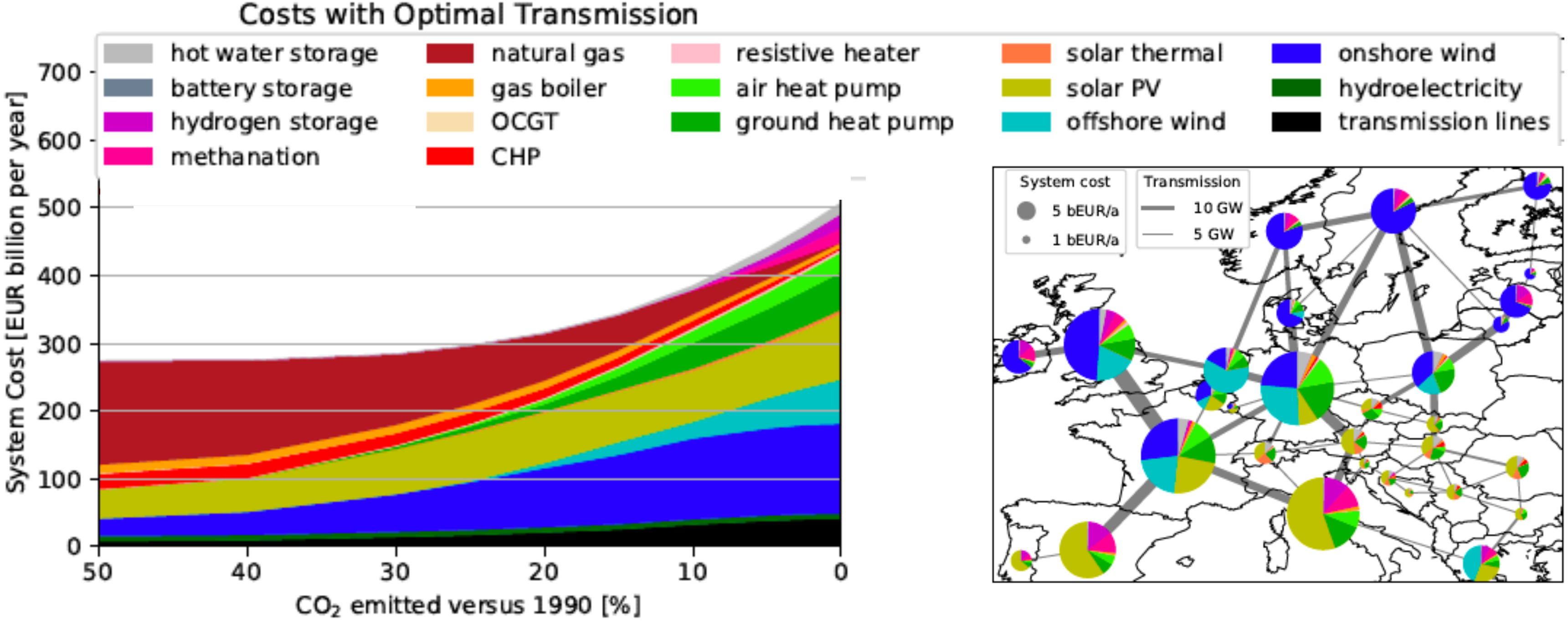
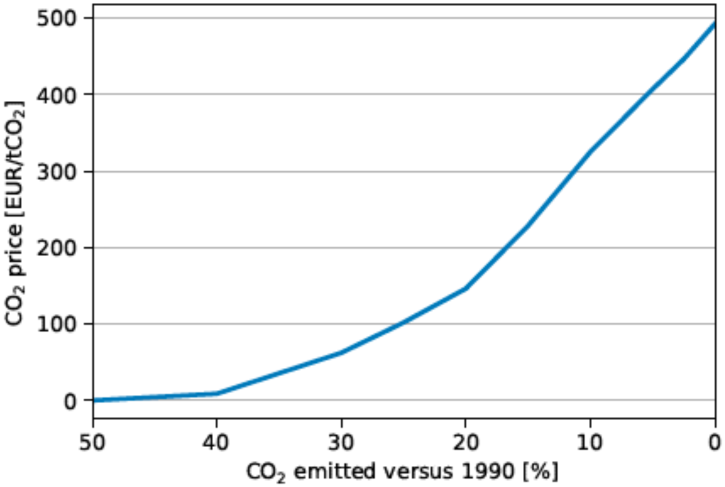




$$\min\left(Costs - \lambda \cdot Constraint\right)$$

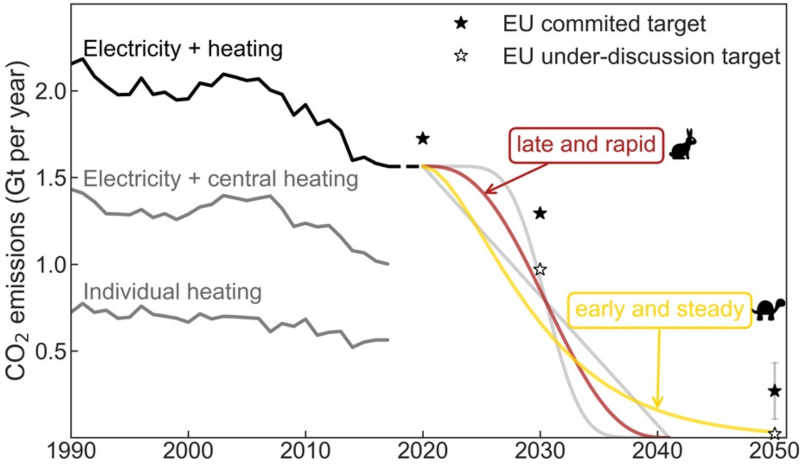
CO$_2$ tax is required to

- **incentivize an efficient + highly decarbonized all-sector energy system**
- **avoid renewable curtailment, combustion of fossil fuel, and inefficient technologies**
- **incentivize efficient technologies such as heat pumps + power-to-gas**

Defossilisation of the European energy system

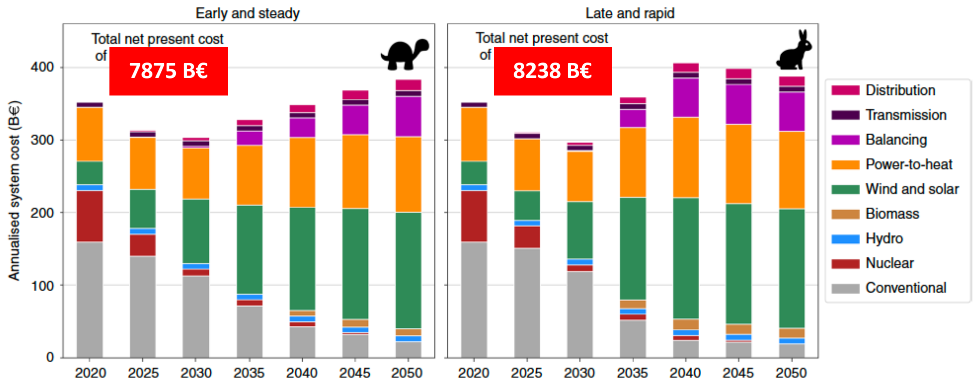
myopic (brown-field) optimization

M Victoria et.al.: Nature Communications 11 (2020) 6223.



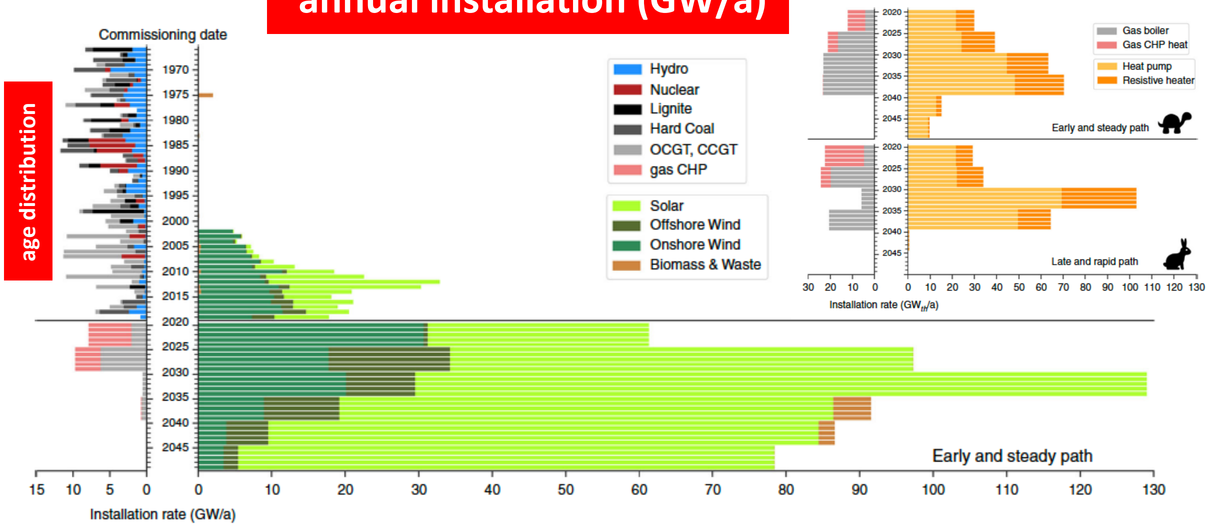
21 Gt CO$_2$ (≤ 1.75°C)

annualised system costs



annual installation (GW/a)

age distribution



tech+econ+pol brownfield optimisation of the EU 2035 electricity system

15% of 1990 CO_2 emissions

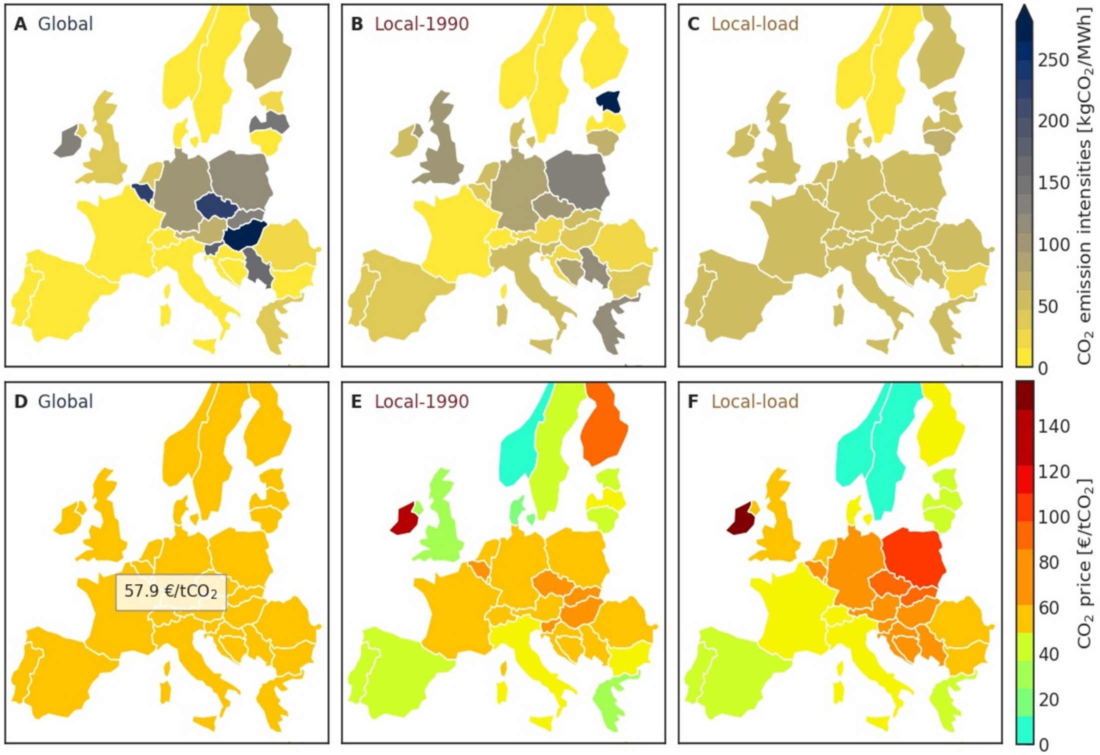
L Schwenk-Nebbe et.al.: Advances in Applied Energy 2 (2021) 100012.

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

1x transmission

K = 1

global vs. local CO_2 emission constraints



... and required emission prices

global (efficiency):

Emission Trading System

local (fairness):

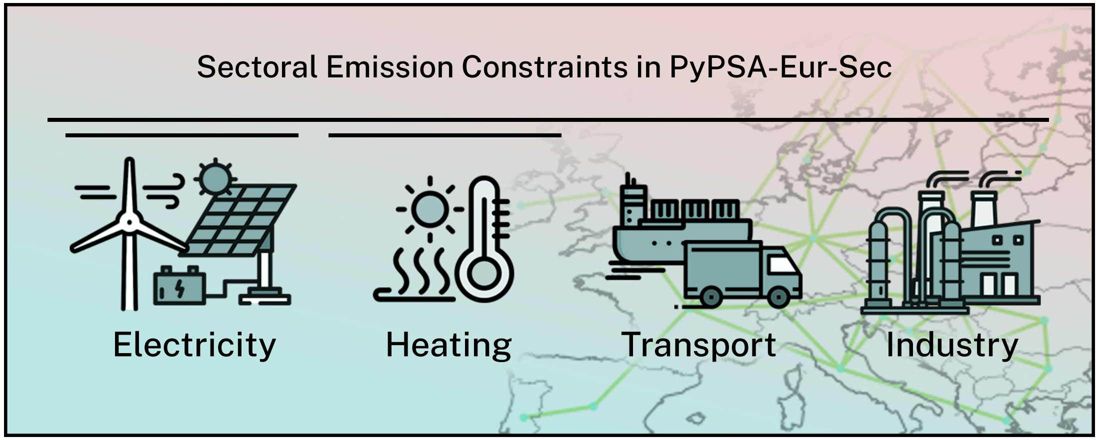
Effort Sharing Regulation

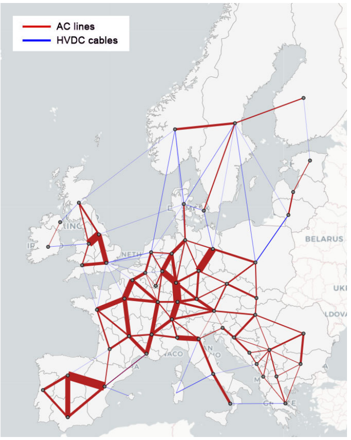
Deep collaboration between countries lowers total system costs, and more equal CO_2 emissions + prices.

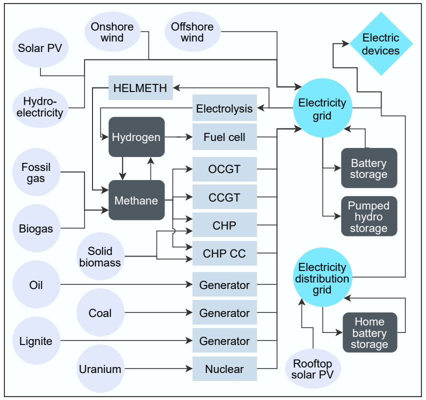
PyPSA-Eur-Sec

Tom Brown (TU Berlin)
Marta Victoria (Aarhus U)

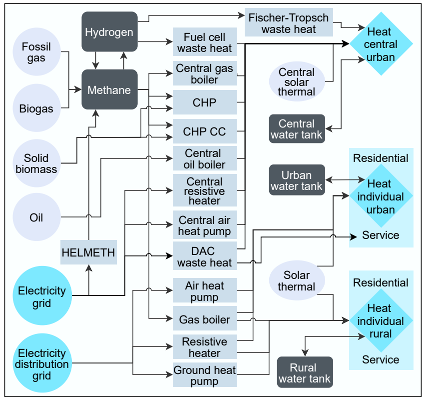
Outlook:
Design of the future EU energy system



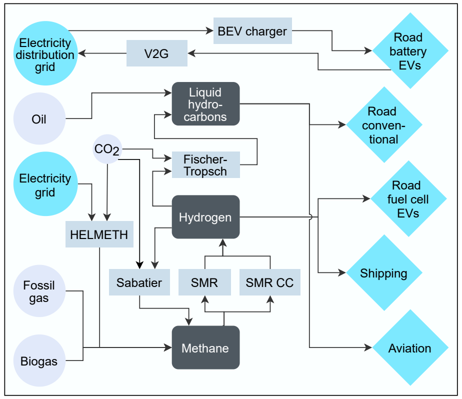




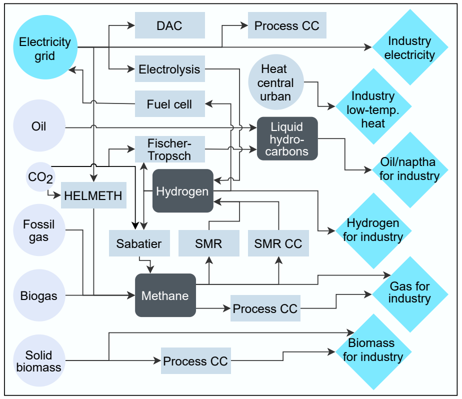
electricity



heating



transport



industry

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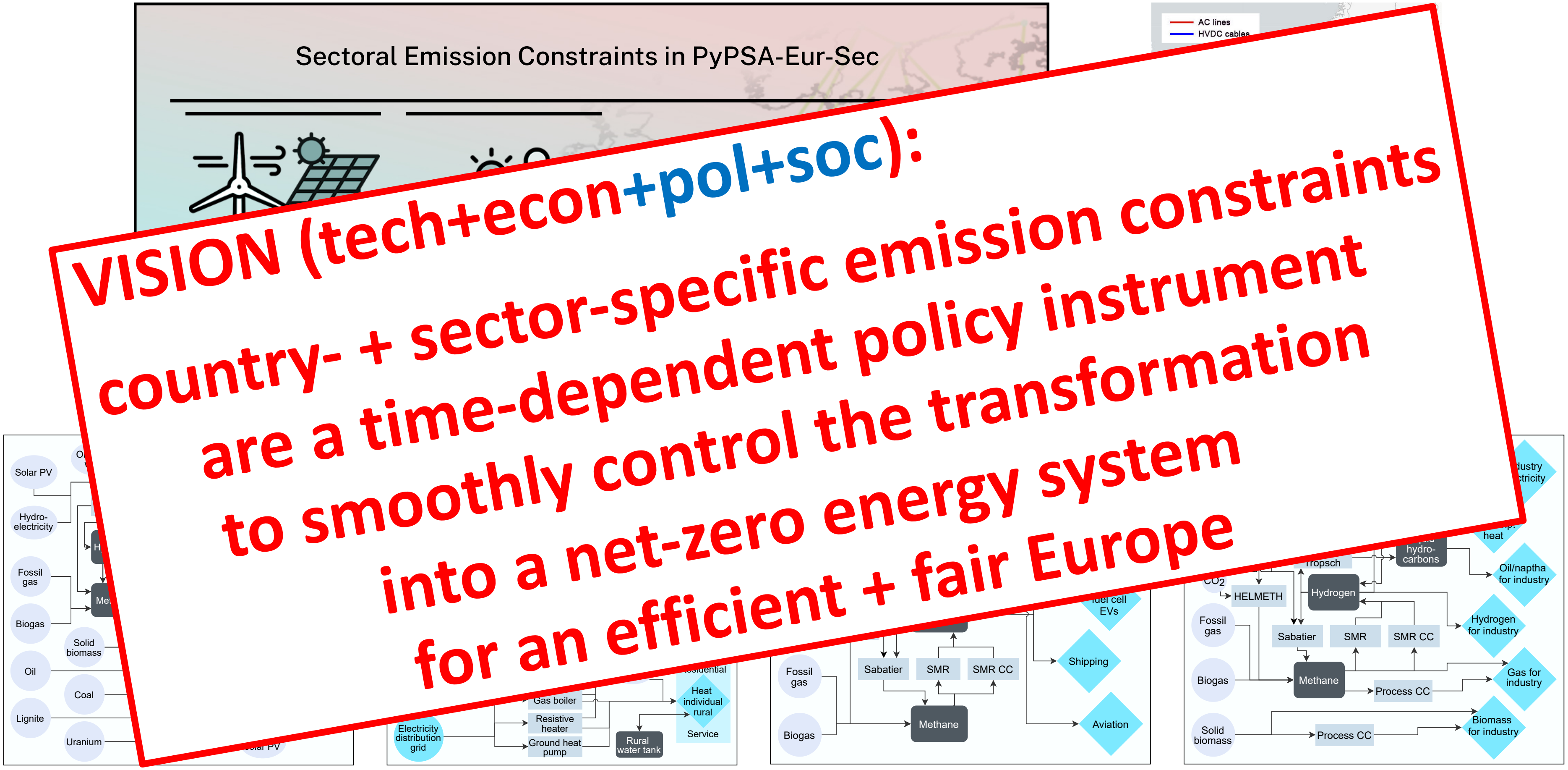
Outlook:
Design of the future EU energy system



VISION (tech+econon+pol+soc):

country- + sector-specific emission constraints are a time-dependent policy instrument to smoothly control the transformation into a net-zero energy system for an efficient + fair Europe

electricity **heating** **transport** **industry**

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Aarhus University
Department of Mechanical
and Production Engineering

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