Decarbonization of the European energy system with strong sector couplings

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Impact of CO_2 prices on the design of a highly decarbonised coupled electricity and heating system in Europe

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

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

energies

Article

Sectoral Interactions as Carbon Dioxide Emissions Approach Zero in a Highly-Renewable European Energy System

Tom Brown [1,*], Mirko Schäfer [2,3] and Martin Greiner [3]

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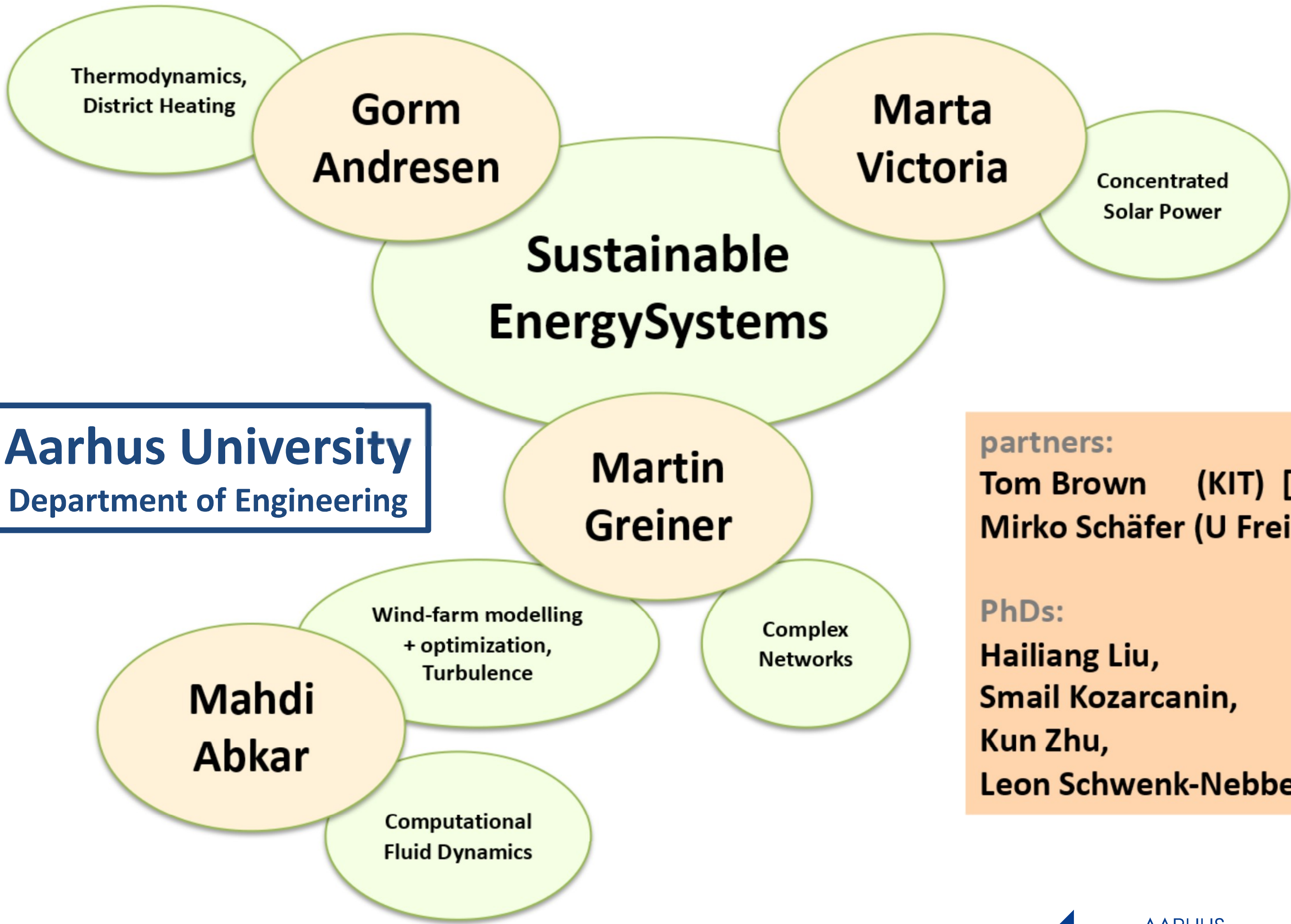

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Department of Engineering

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Mirko Schäfer (U Freiburg)

PhDs:
Hailiang Liu,
Smail Kozarcanin,
Kun Zhu,
Leon Schwenk-Nebbe

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simplified cross-sector network model

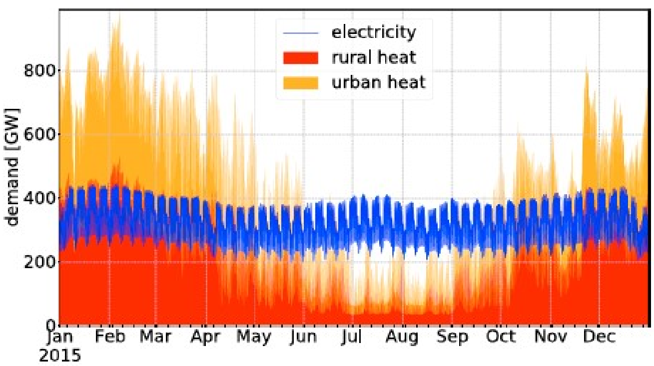
capture / extract general system dynamics + meaningful insights + inspirational results

PyPSA-Eur-Sec-30

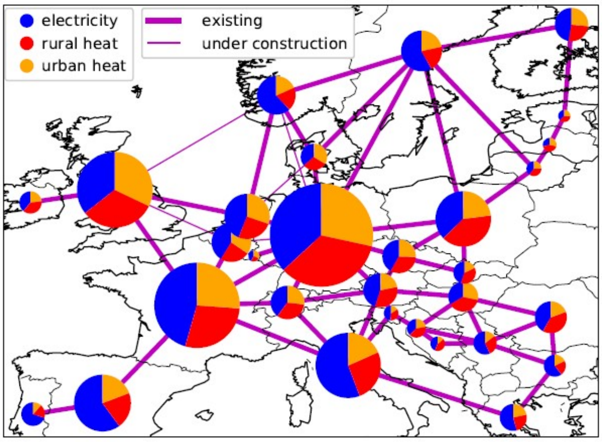
Joint capacity + dispatch optimization:

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

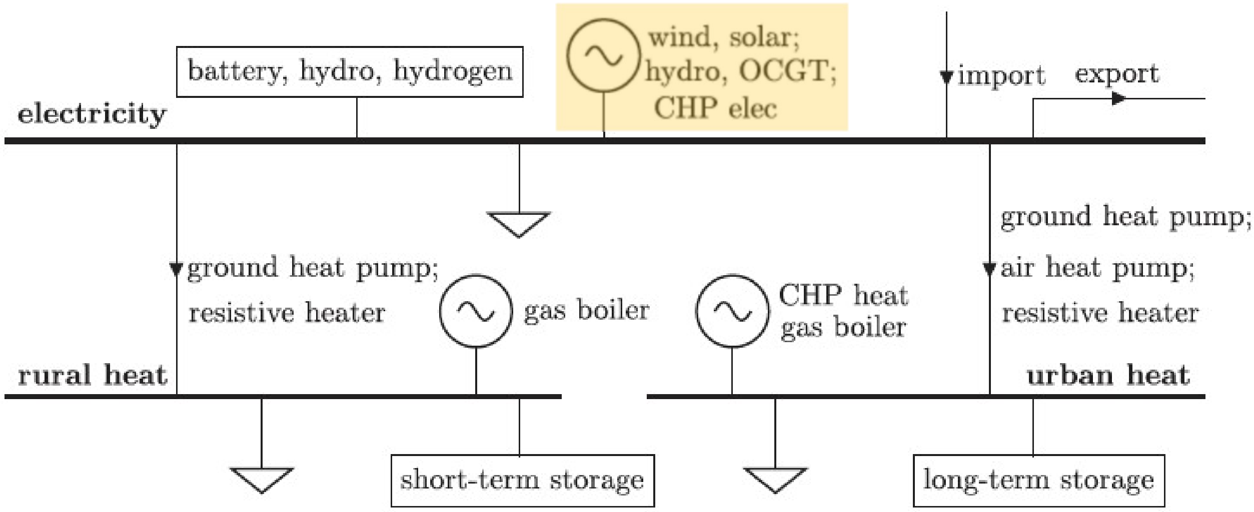
$$\min_{\substack{G_{n,s},E_{n,s},\\F_\ell,g_{n,s,t}}} \left[\sum_{n,s} c_{n,s} \cdot G_{n,s} + \sum_{n,s} \hat{c}_{n,s} \cdot E_{n,s} + \sum_{\ell} c_\ell \cdot F_\ell + \sum_{n,s,t} o_{n,s,t} \cdot g_{n,s,t} \right]$$



2015: 2854 TWh_{el}, 3562 TWh_{th}



"Smart energy" flow diagram of one country



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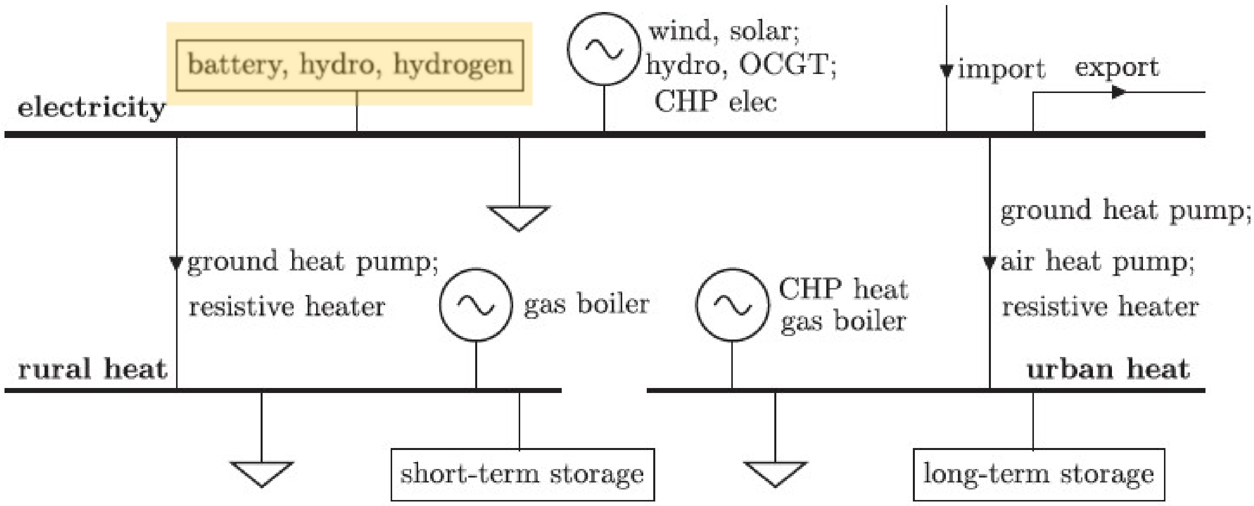
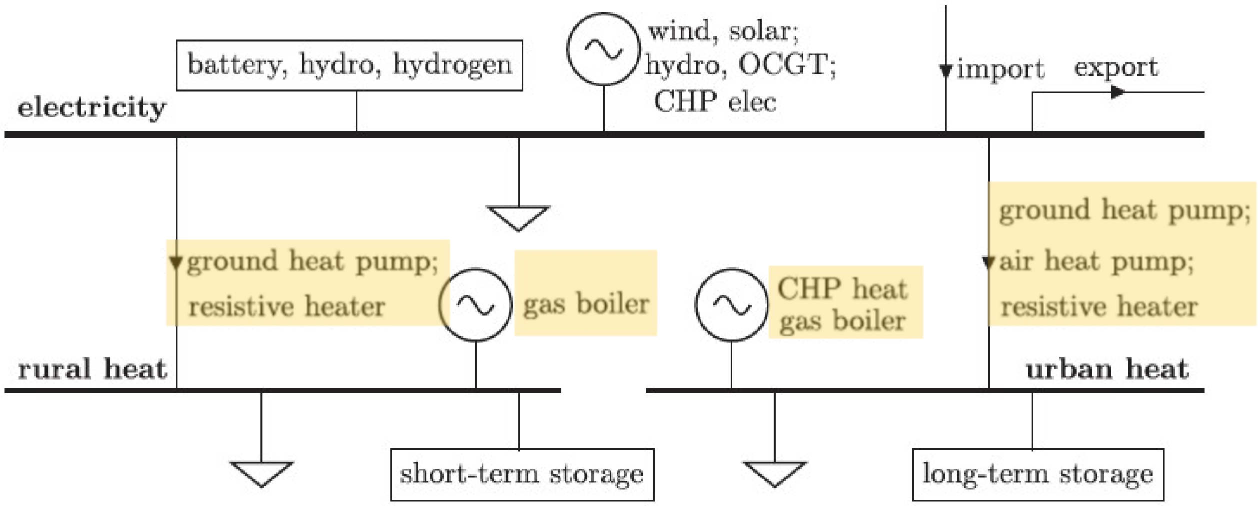
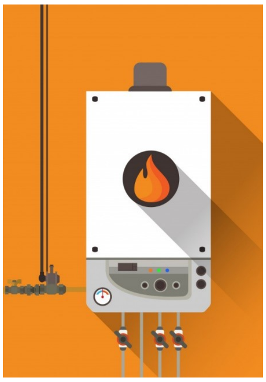
“Smart energy” flow diagram of one country



“Smart energy” flow diagram of one country





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Joint capacity + dispatch optimization

Technology	Overnight Cost[€]	Unit	FOM[a] [%/a]	Lifetime [a]	CF[b]/ Efficiency	LCOE[b] [€/MWh]
Onshore wind[c]	910	kW_{el}	3.3	30	0.23[0.07-0.33]	52[35-224]
Offshore wind[c]	2506	kW_{el}	3	25	0.31[0.09-0.51]	91[66-182]
Solar PV[c]	575	kW_{el}	2.5	25	0.13[0.06-0.19]	55[39-114]
OCGT[d]	560	kW_{el}	3.3	25	0.39	63
CHP [d]	600	kW_{th}	3.0	25	0.47	54
Gas boiler[d,e]	63/175	kW_{th}	1.5	20	0.9	25/26
Resistive heater	100	kW_{th}	2	20	0.9	-
Heat pump[e]	1400/933	kW_{th}	3.5	20	[3.03-3.79]/[2.73-3.04]	-
Battery storage[f]	144.6	kWh	0	15	1.0	-
Hydrogen storage[f]	8.4	kWh	0	20	1	-
Hot water tank[e,f]	860/30	m^3	1	20/40	$\tau = 3/180$ days	-
HVDC lines	400	MWkm	2	40	1	-

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Joint capacity + dispatch optimization

Economic optimization:

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

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

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

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

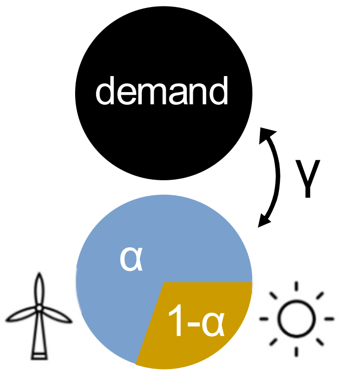
Maximum power flowing through the links

Renewable generation proportional to demand in every country

$$g_{i,VRES}^{gross} = \gamma_i^{gross} \sum_{t,n \in i} d_{n,t}$$

Wind solar mix optimized for every country

$$g_{i,W}^{gross} = \alpha_i^{gross} \, g_{i,VRES}^{gross}$$



Joint capacity + dispatch optimization

Economic optimization:

generation costs · storage costs · transmission costs · variable costs (including CO_2 tax)

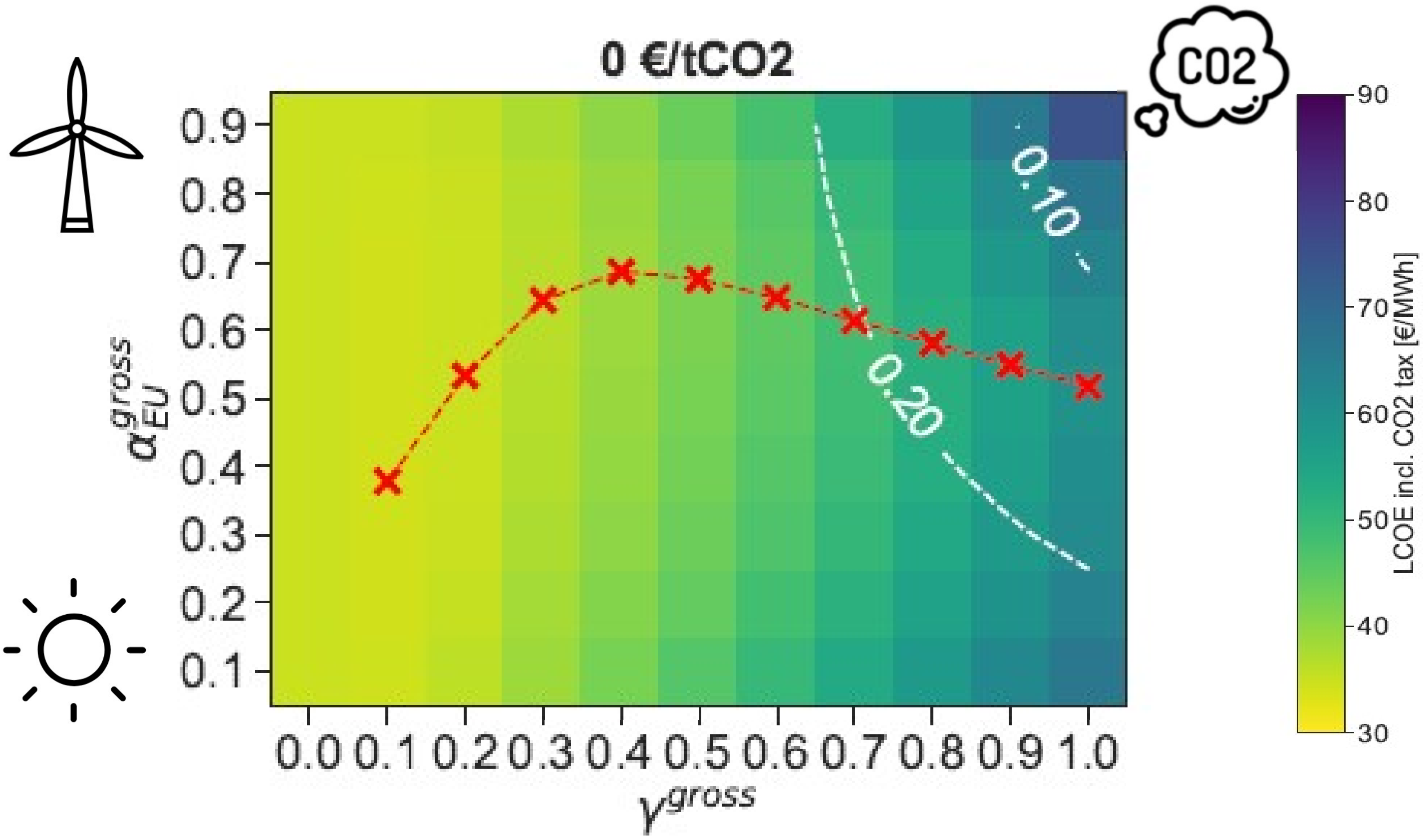
$$\min_{\substack{G_{n,s},E_{n,s},\\ F_\ell, g_{n,s,t}}} \left[\sum_{n,s} c_{n,s} \cdot G_{n,s} + \sum_{n,s} \hat{c}_{n,s} \cdot E_{n,s} + \sum_{\ell} c_\ell \cdot F_\ell + \sum_{n,s,t} o_{n,s,t} \cdot g_{n,s,t} \right]$$

We fix the renewable penetration and the level of CO_2 tax …

…and let the math decide the cost-optimal composition of energy generation, conversion, transmission and storage technologies.

Then, we calculate CO_2 emissions.

Results



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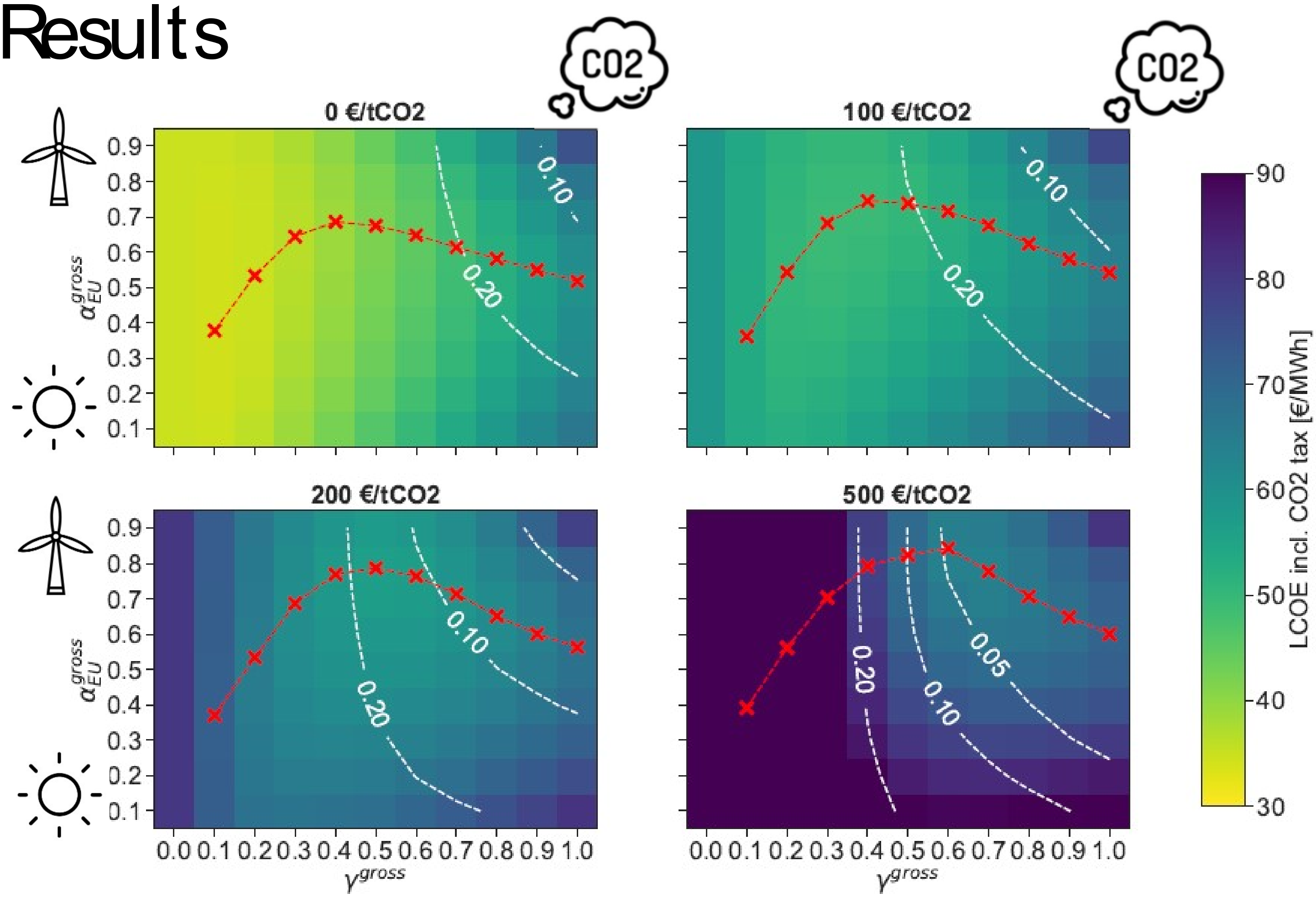
Results



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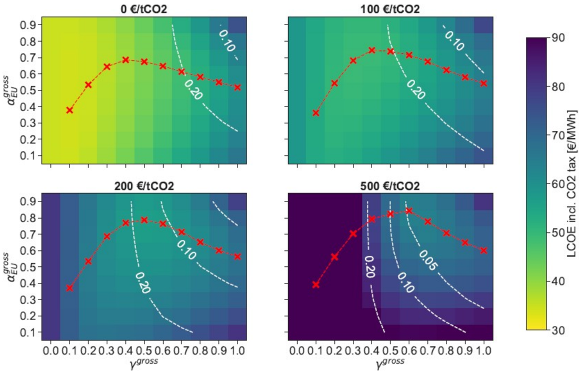
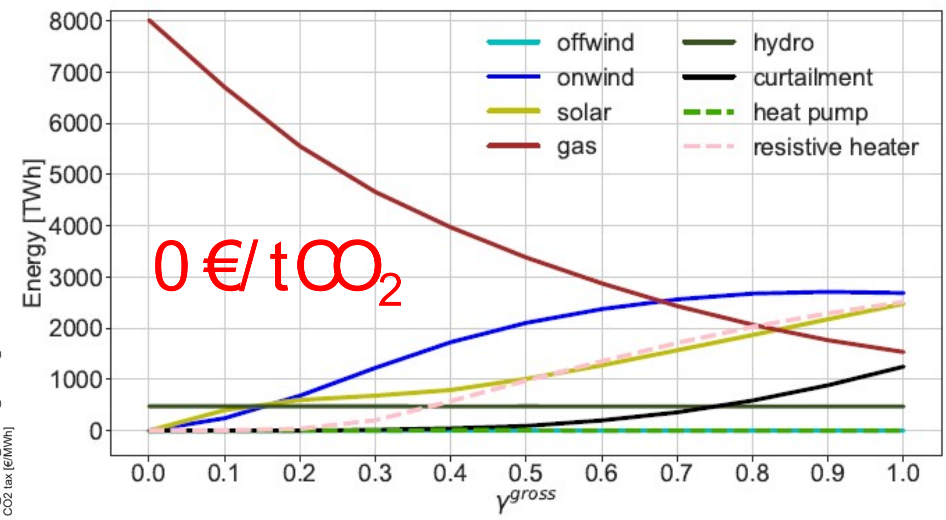
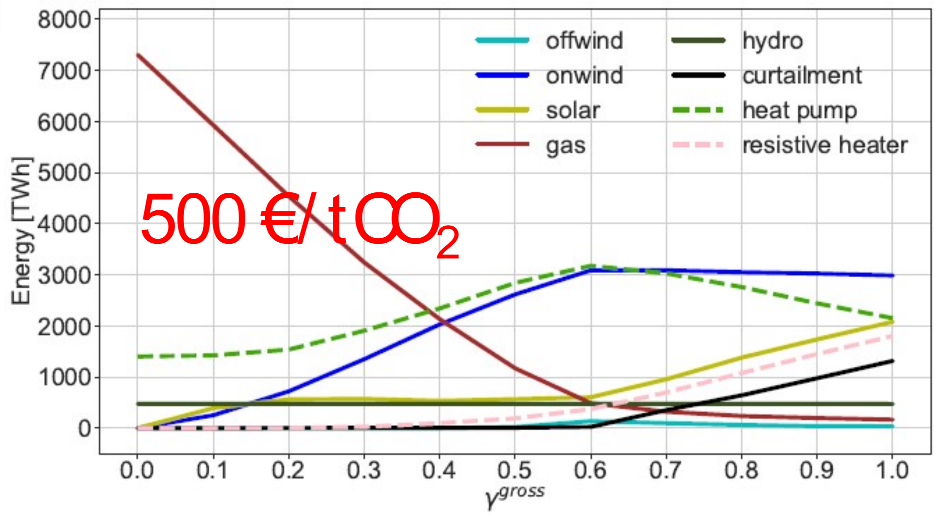
Results


0 €/tCO2
100 €/tCO2
200 €/tCO2
500 €/tCO2
LCOE incl. CO2 tax [€/MWh]
γ^{gross}
α_{EU}^{gross}


0 €/ tCO2
offwind
onwind
solar
gas
hydro
curtailment
heat pump
resistive heater
Energy [TWh]
γ^{gross}


500 €/ tCO2
offwind
onwind
solar
gas
hydro
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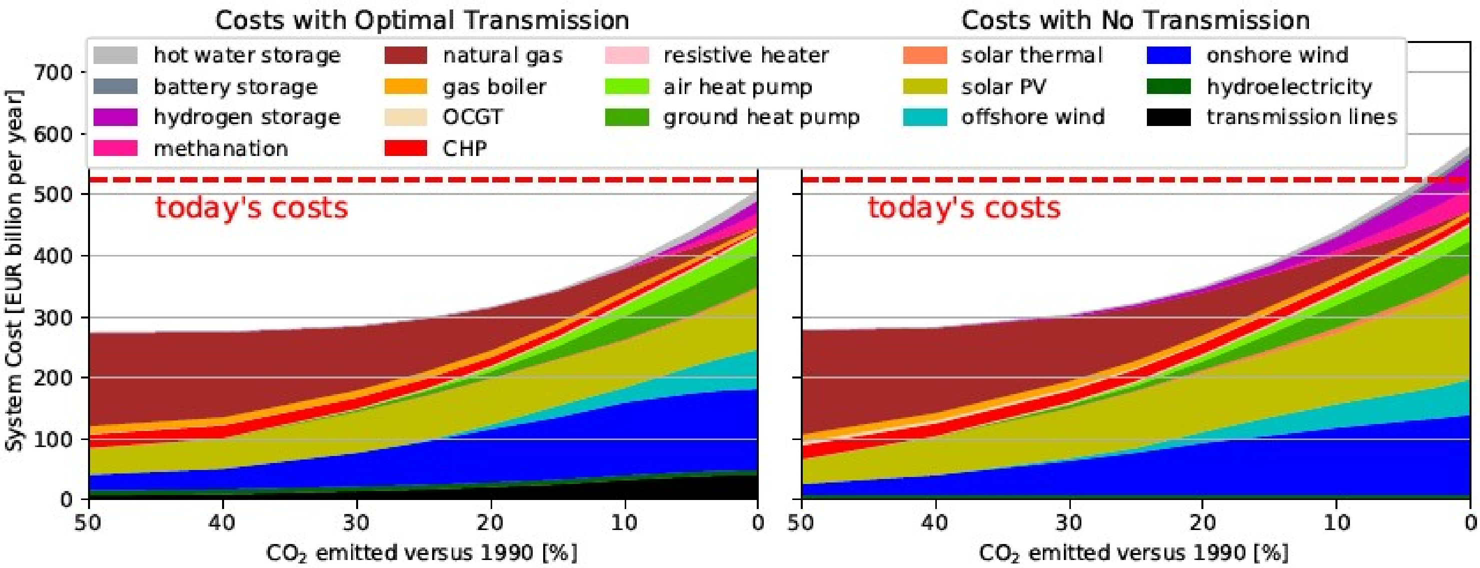
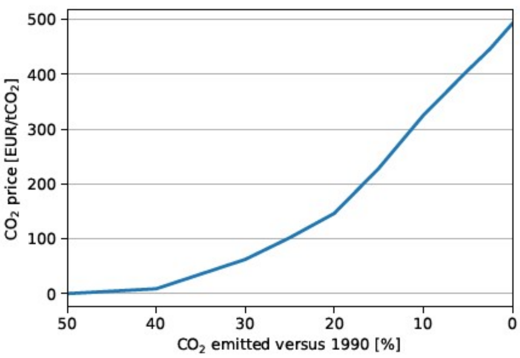
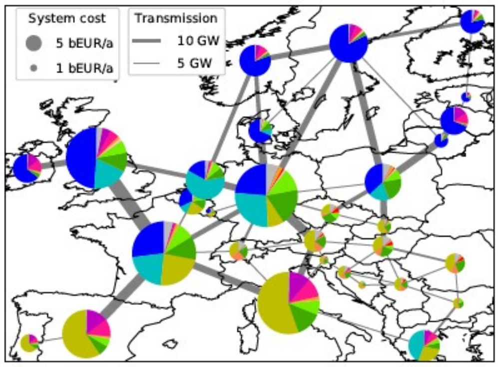
heat pump
resistive heater
Energy [TWh]
γ^{gross}

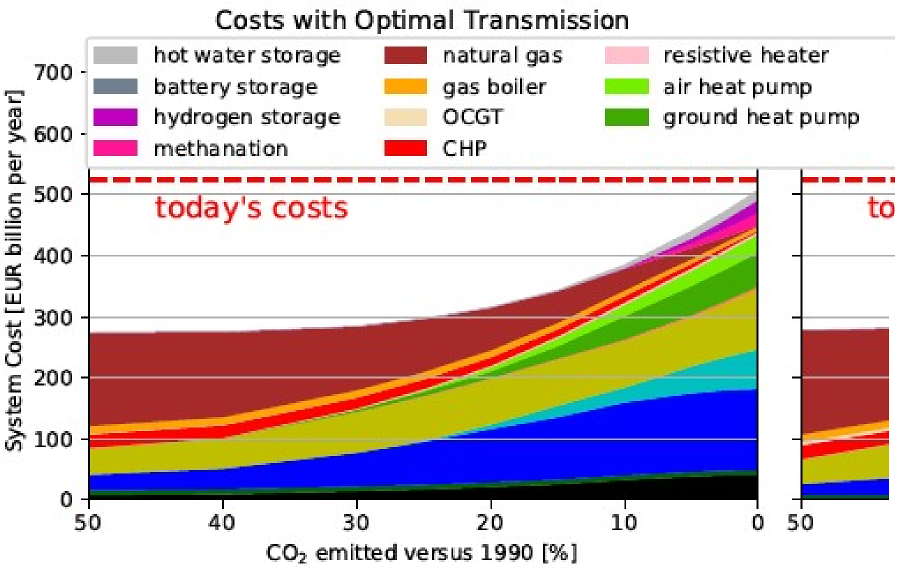
More results: electricity + heating + transportation

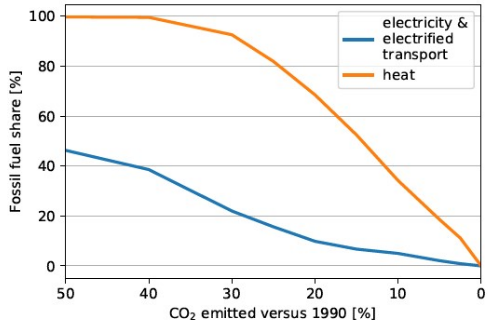


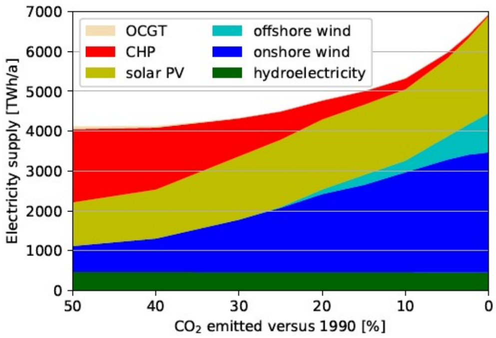


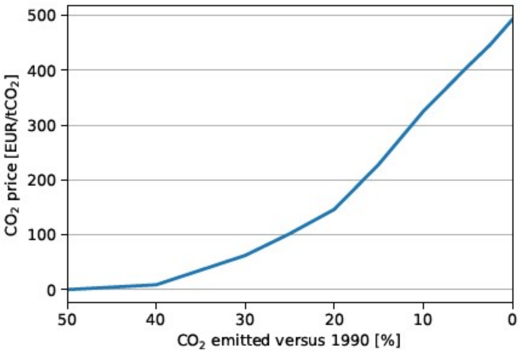


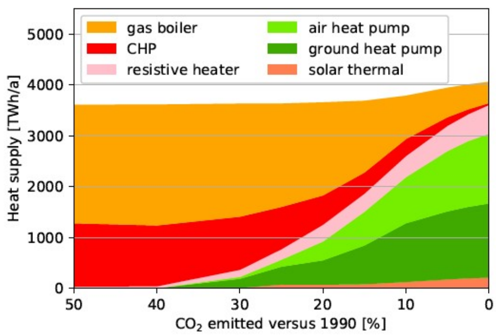
More results: electricity + heating + transportation











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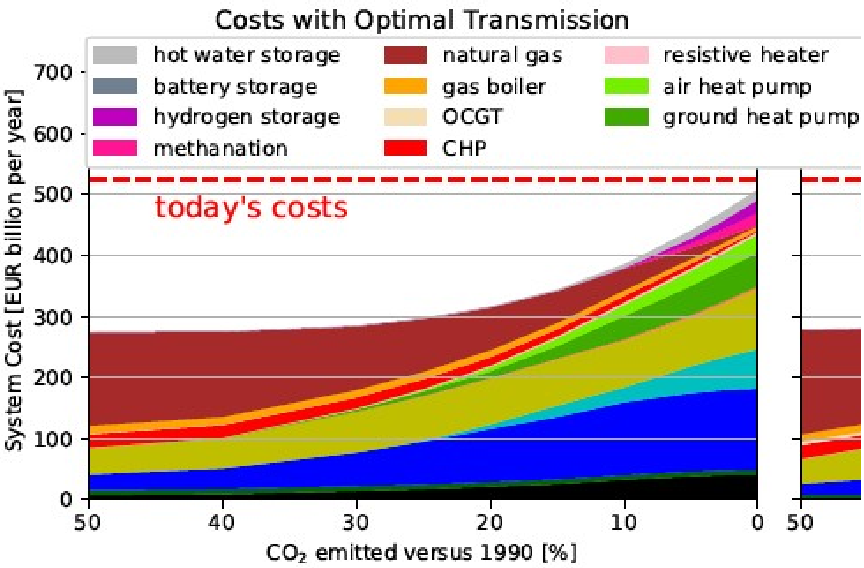
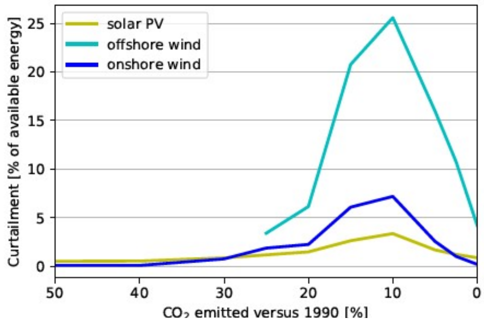
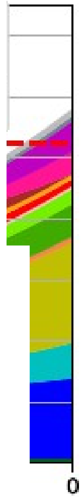
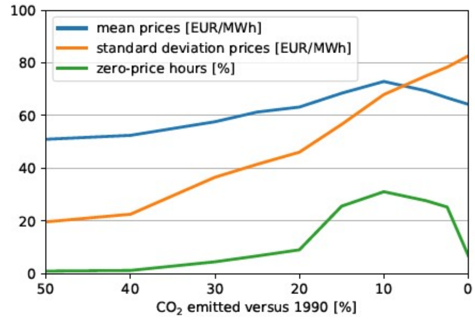
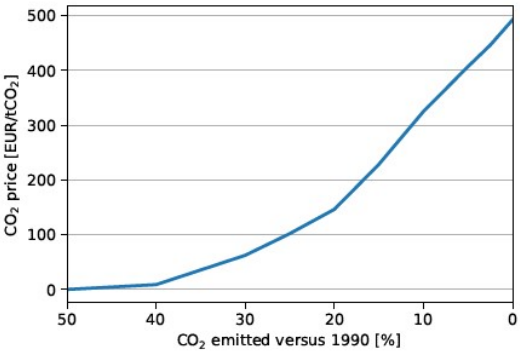
More results: electricity + heating + transportation

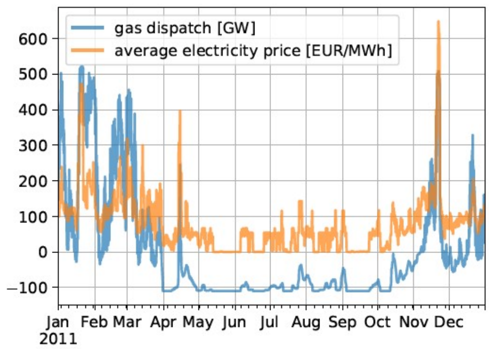












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Summary

Is Installing Large Renewable Capacities Enough to Decarbonize the Coupled Electricity-and-Heating System in Europe?

No! ... CO_2 tax is required to

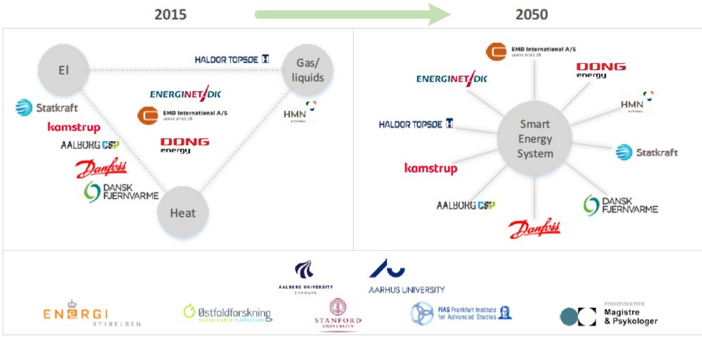
- incentivize an efficient + highly decarbonized electricity-heating system
- avoid renewable curtailment, combustion of fossil fuel, and inefficient technologies
- incentivize efficient technologies such as heat pumps

„Energiewende“: kickoff to the second half

Danmarks Innovationsfond Grand Solutions
(04.2017-03.2022, 2.3 M€)

RE-Invest

Renewable Energy Investment Strategies
– a 2dim interconnectivity approach



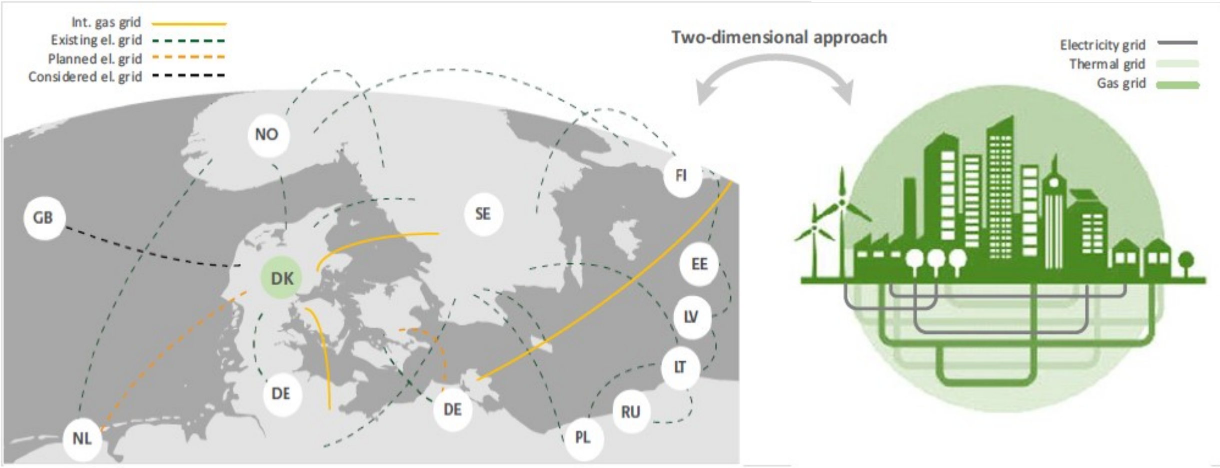


Figure 1. RE-Invest will combine the Smart Energy Systems cross-sectoral approach (right side) at Aalborg University with the cross-border approach (left side) and tools developed by Aarhus University at the European scale. This will lead to a **novel two-dimensional interconnectivity approach** for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

Aalborg U
+
Aarhus U

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Next steps

reINVEST

- include: biomass, heat savings, industry sector, …
- transition pathways 2020 à 2050

- impact of climate change
- large à small scale modelling
- quantitative tech+econ+soc+pol consulting

iClimate (AU ENV + ENG)

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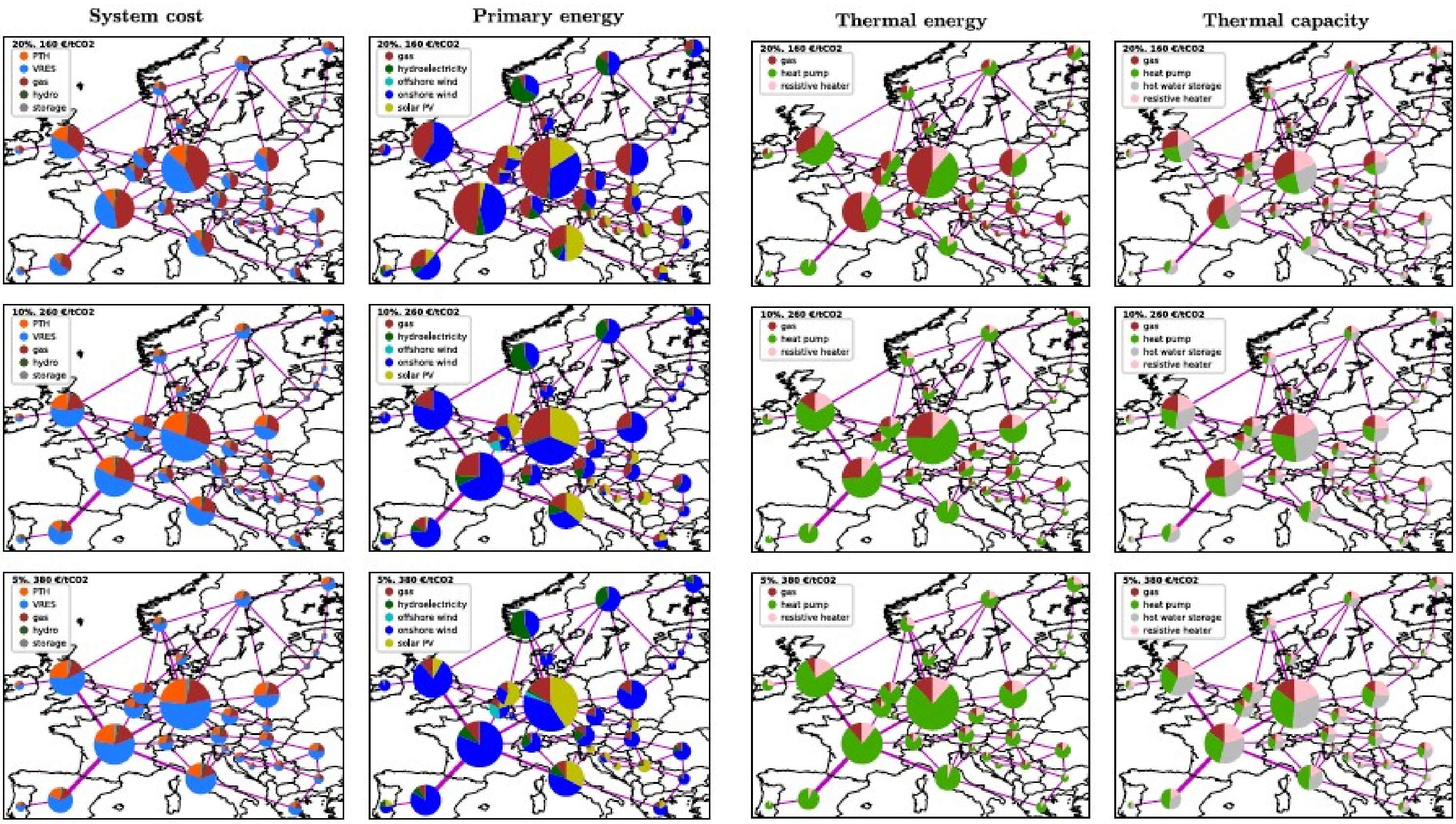
Results



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Results

Transmission volume[b]	Optimal volume			Todays volume		
Emission level	20%	10%	5%	20%	10%	5%
CO_2 price	160	260	380	200	320	580
Gross penetration	0.46	0.57	0.64	0.5	0.64	0.7
Gross wind/solar	0.77	0.8	0.8	0.73	0.74	0.79
System cost incl. CO_2 tax	348	378	397	380	417	456
System cost excl. CO_2 tax	277	320	355	291	346	391
LCOE incl. CO_2 tax	54.3	58.9	61.9	59.2	64.9	71.1
LCOE excl. CO_2 tax	43.2	49.8	55.4	45.4	53.9	60.9
Onshore wind	1,090	1,406	1,567	1,126	1,428	1,591
Offshore wind	0	10	21	5	33	88
Solar PV	542	616	719	703	902	812
Resistive heater	307	389	464	434	581	673
Heat pump	69	113	148	67	103	143
Gas boiler	567	469	332	512	399	300
OCGT	0	0	0	17	1	0
CHP	363	243	165	464	336	268
Battery storage	9	10	0	145	180	143
Hydrogen storage	0	0	0	0	0	0
Hot water tank	7,768	27,823	91,796	17,232	57,818	156,753
Transmission volume	141	176	196	32	32	32