Decarbonization of the European energy system with strong sector couplings

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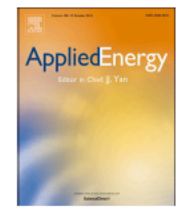

Impact of CO_2 prices on the design of a highly decarbonised coupled electricity and heating system in Europe

Check for updates

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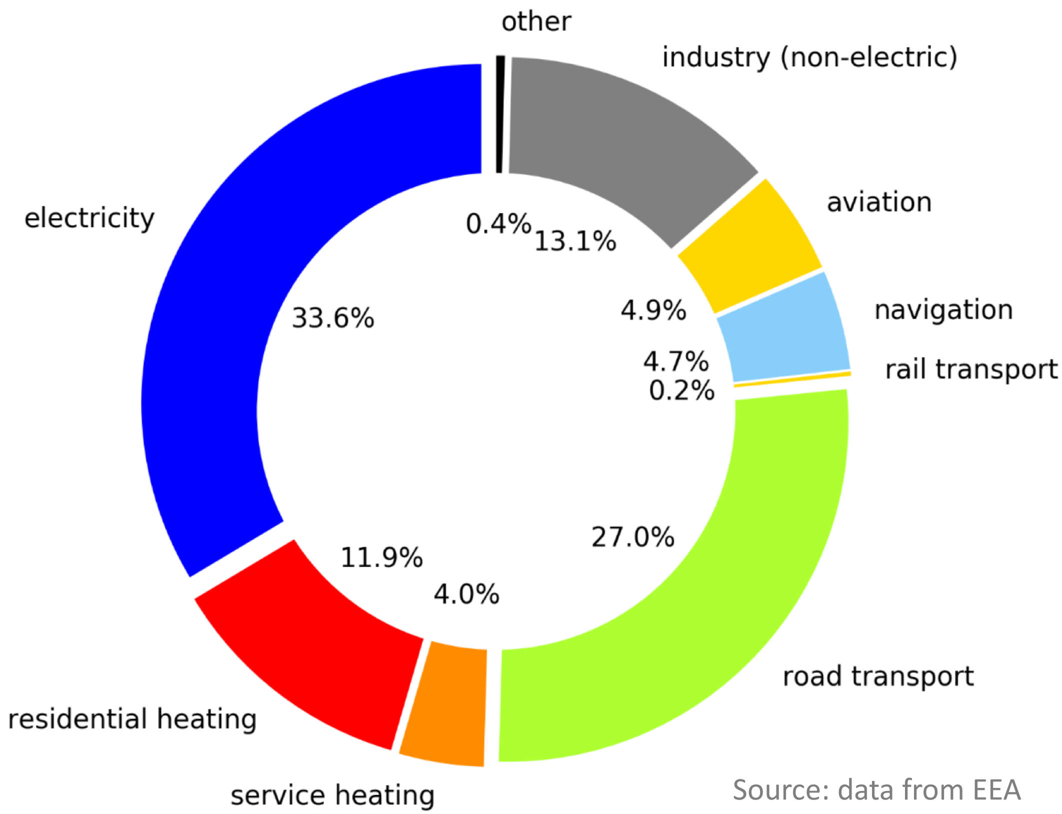
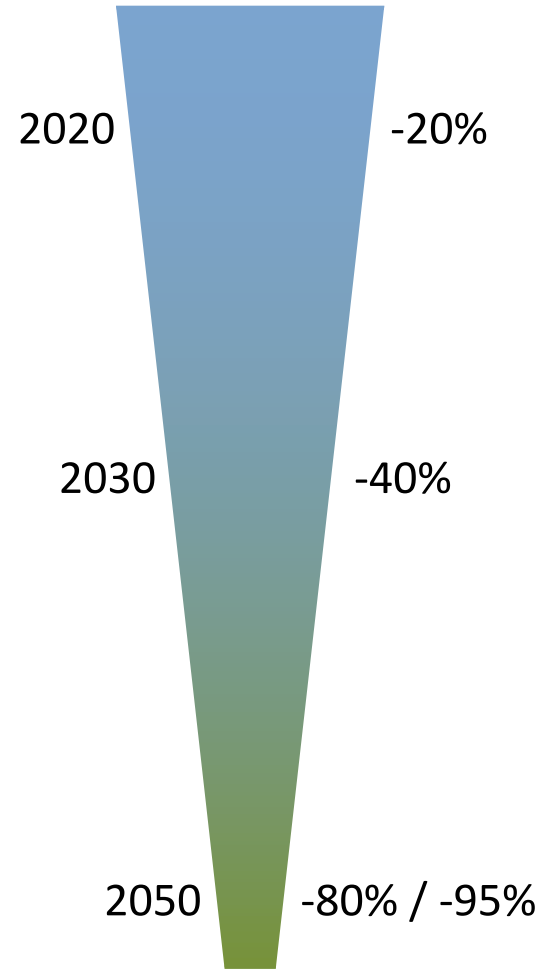
Motivation

CO_2 emissions European Union 2015



Source: data from EEA

EU CO_2 emissions

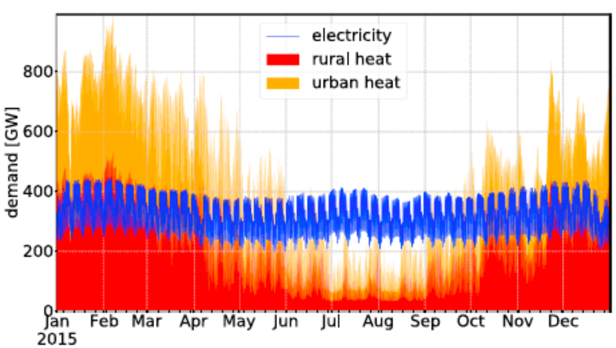


Question:

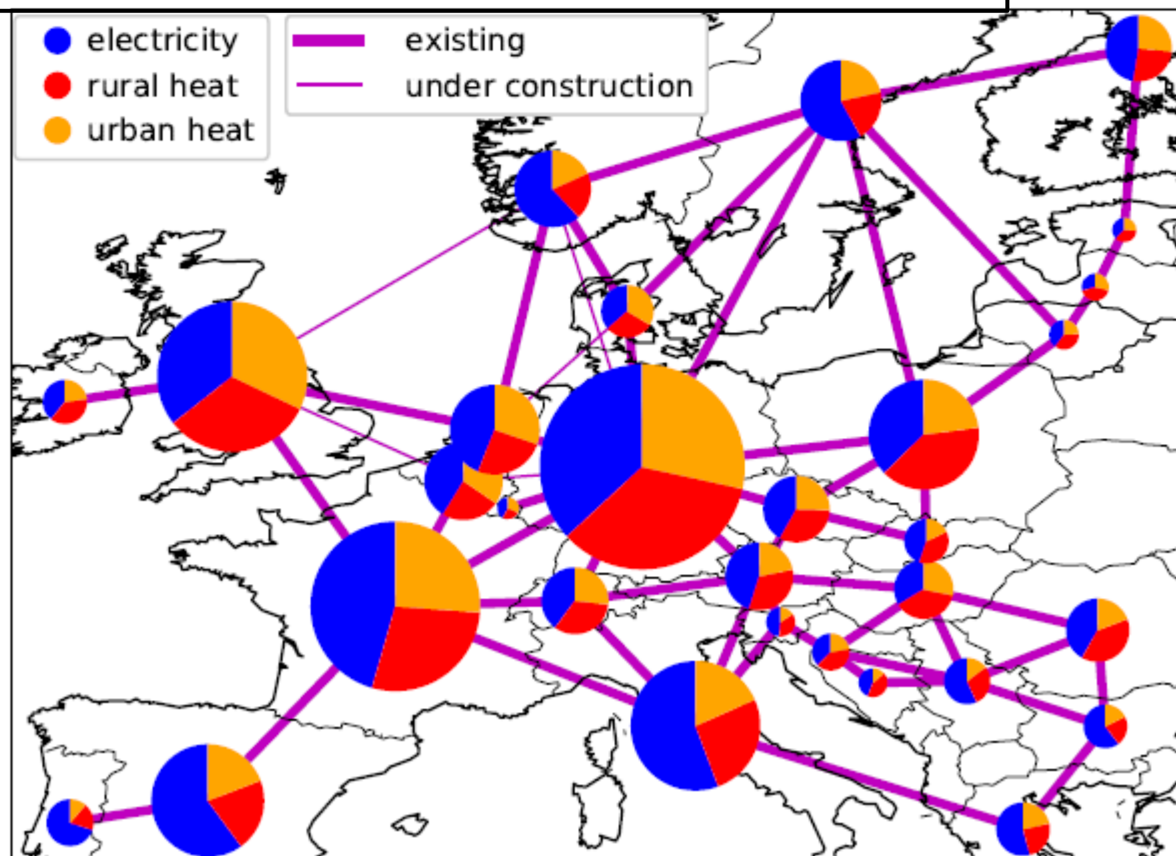
Is Installing Large Renewable Capacities Enough to Decarbonize the Coupled Electricity-and-Heating System in Europe?

simplified cross-sector network model

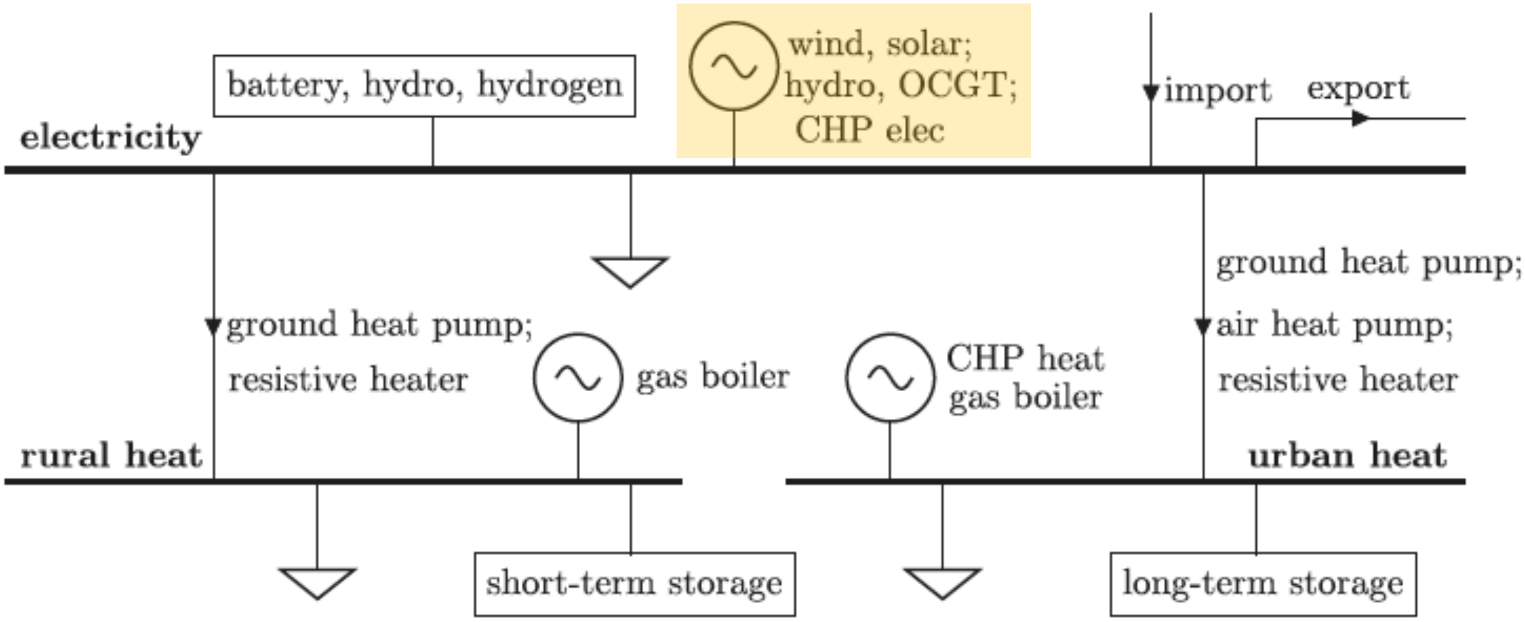
capture / extract
general system dynamics
+ meaningful insights
+ inspirational results



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



"Smart energy" flow diagram of one country



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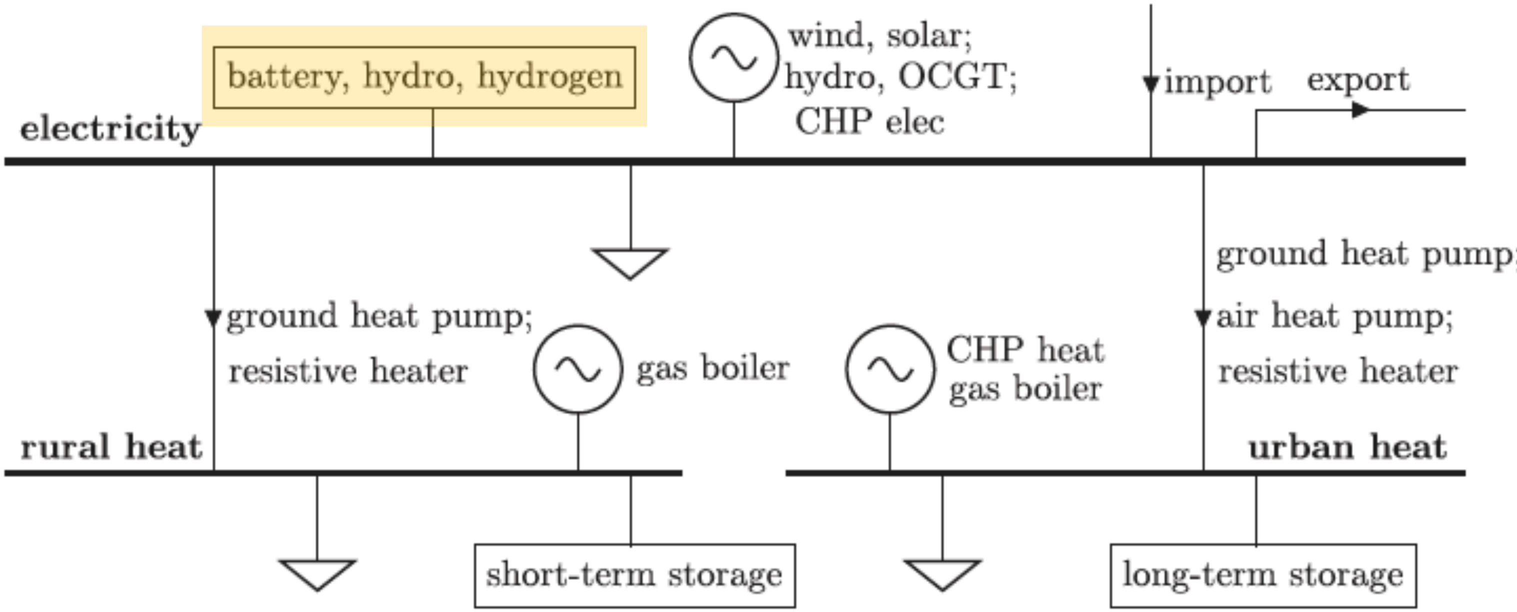
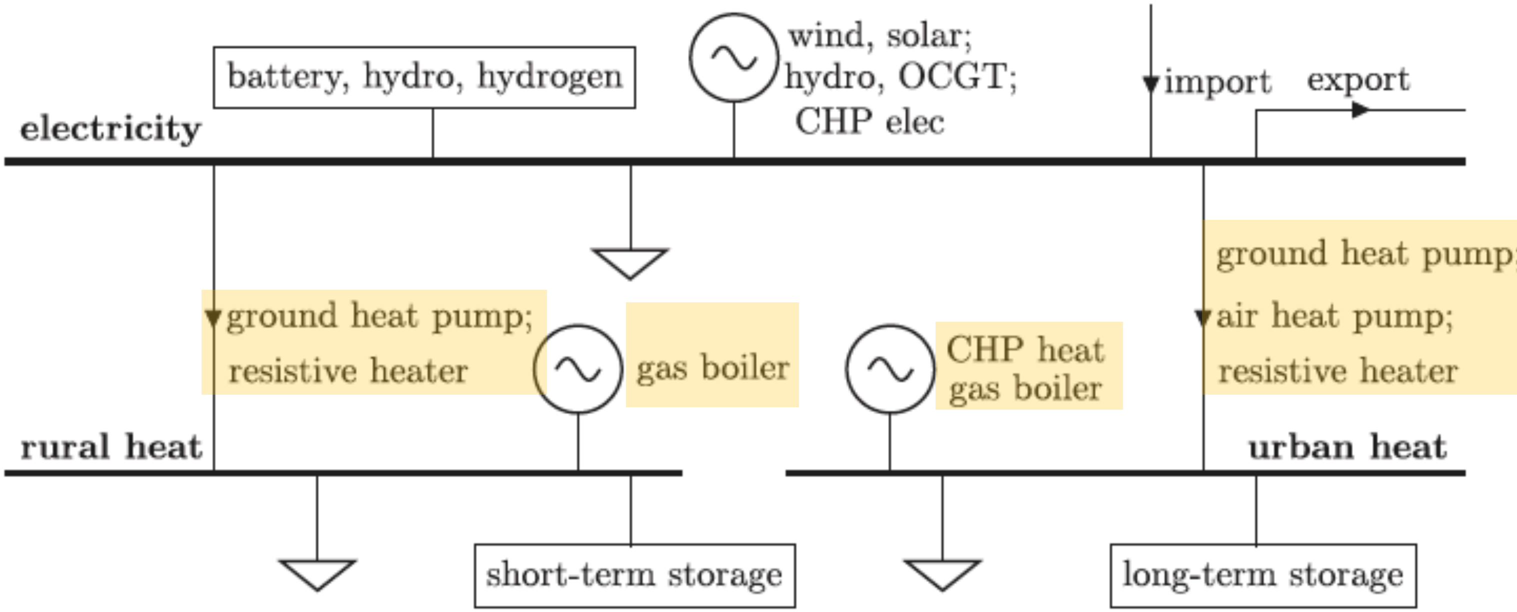
"Smart energy" flow diagram of one country



“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	-

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

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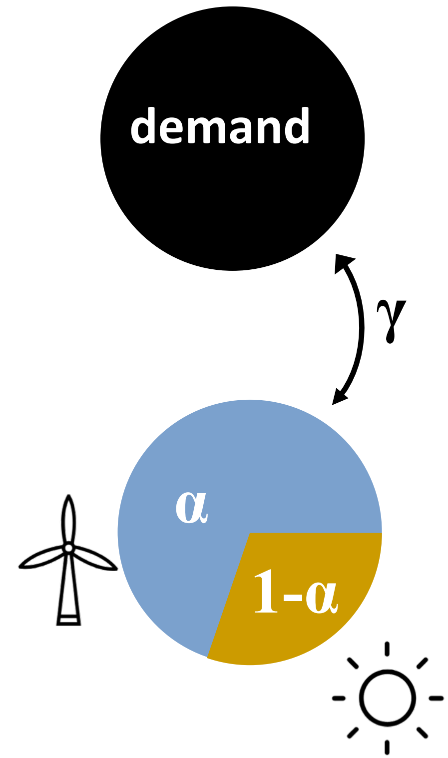
Joint capacity + dispatch optimization

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

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



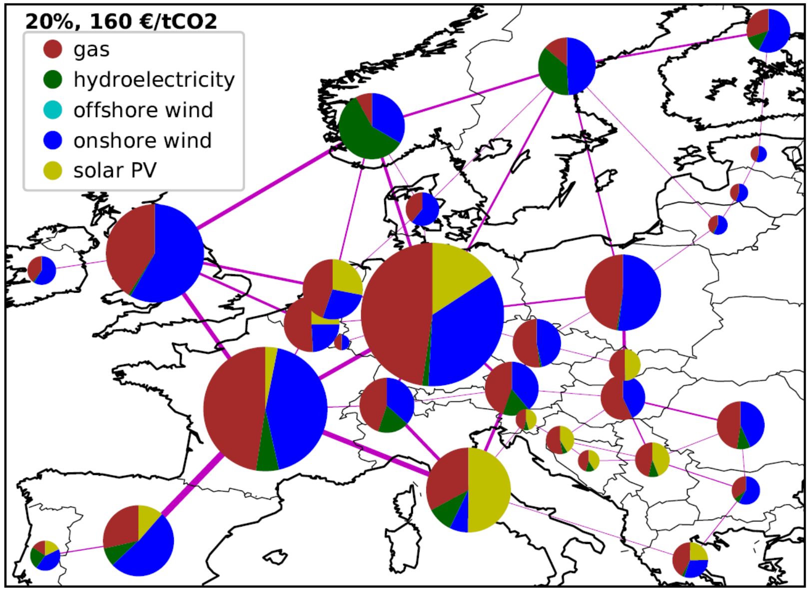
Joint capacity + dispatch optimization

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

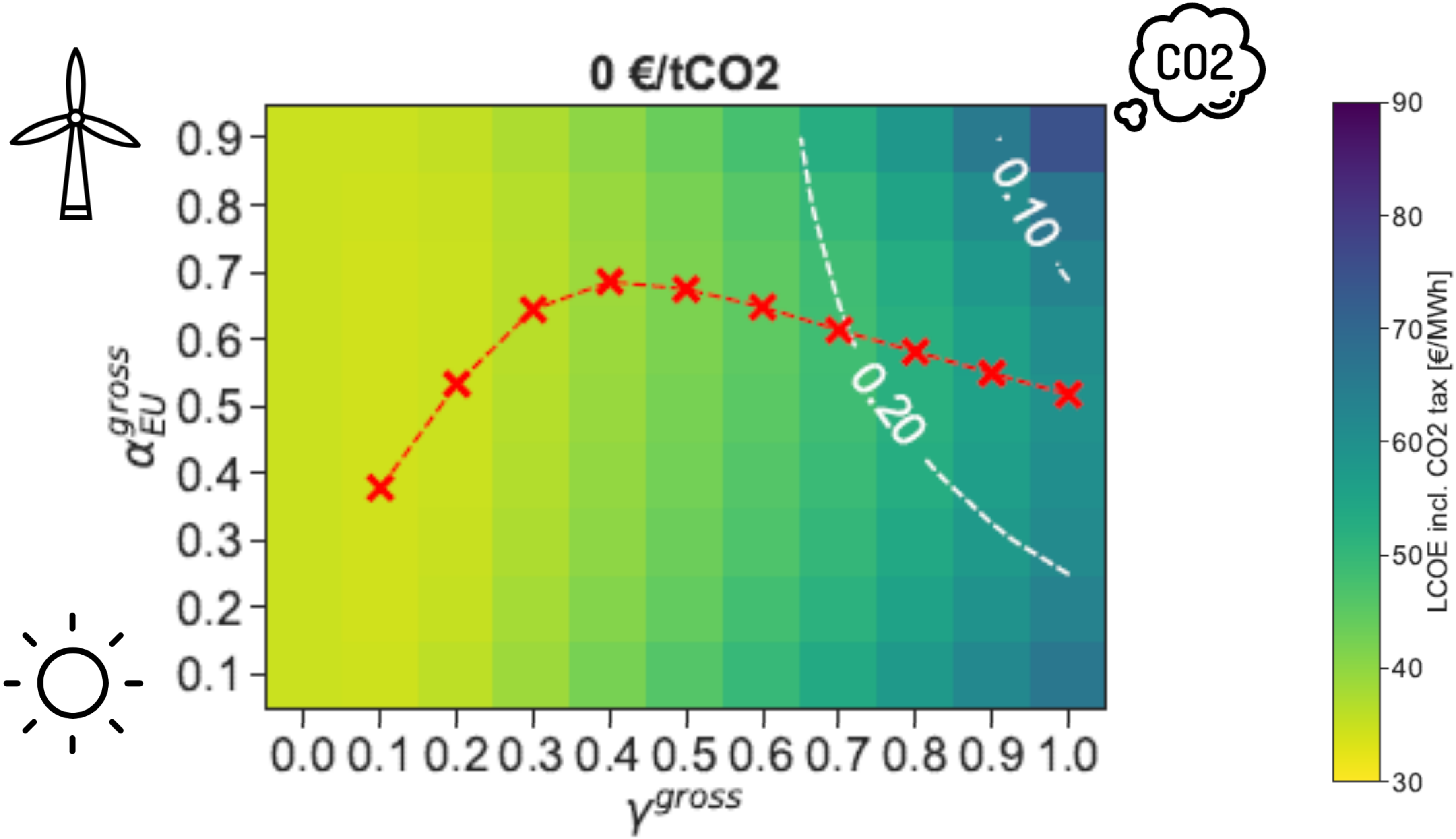
… and let the math decide the cost-optimal composition of energy generation, conversion, transmission and storage technologies

Then, we calculate CO_2 emissions

primary energy

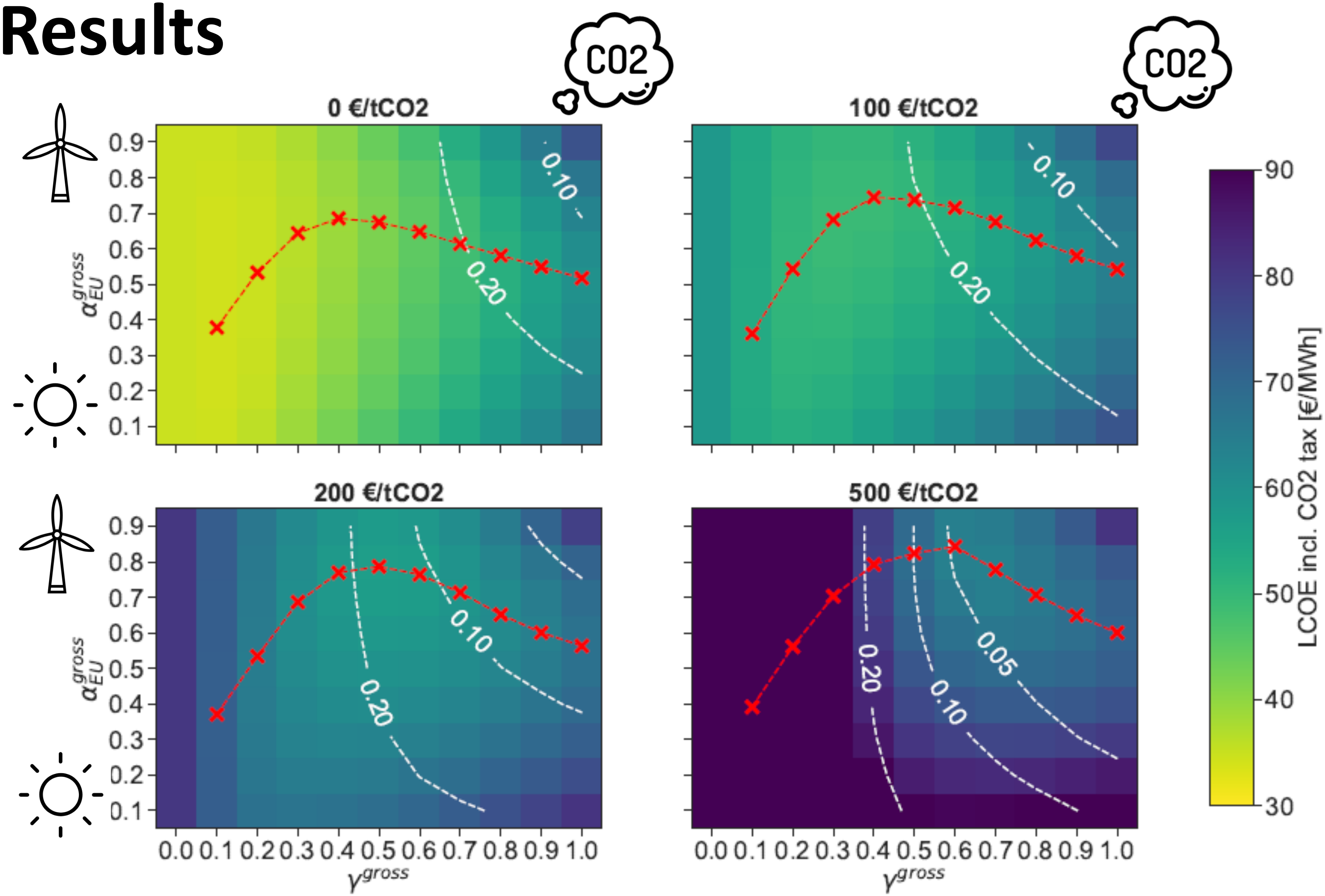


Results



CO2
0 €/tCO2
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
α_{EU}^{gross}
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
γ^{gross}
0.10
0.20
90
80
70
60
50
40
30
LCOE incl. CO2 tax [€/MWh]

Results



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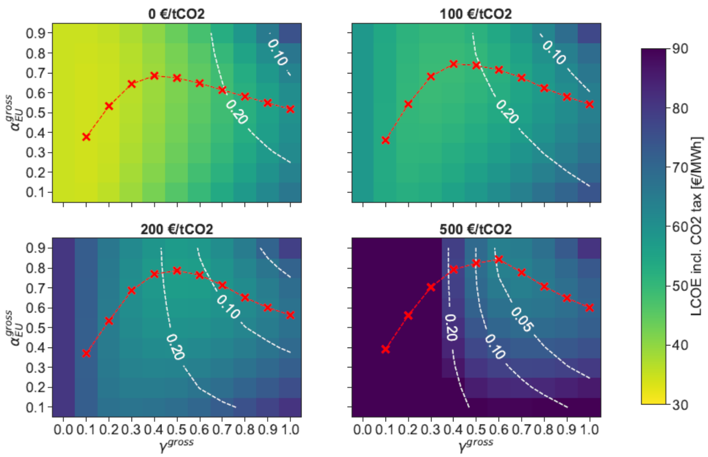
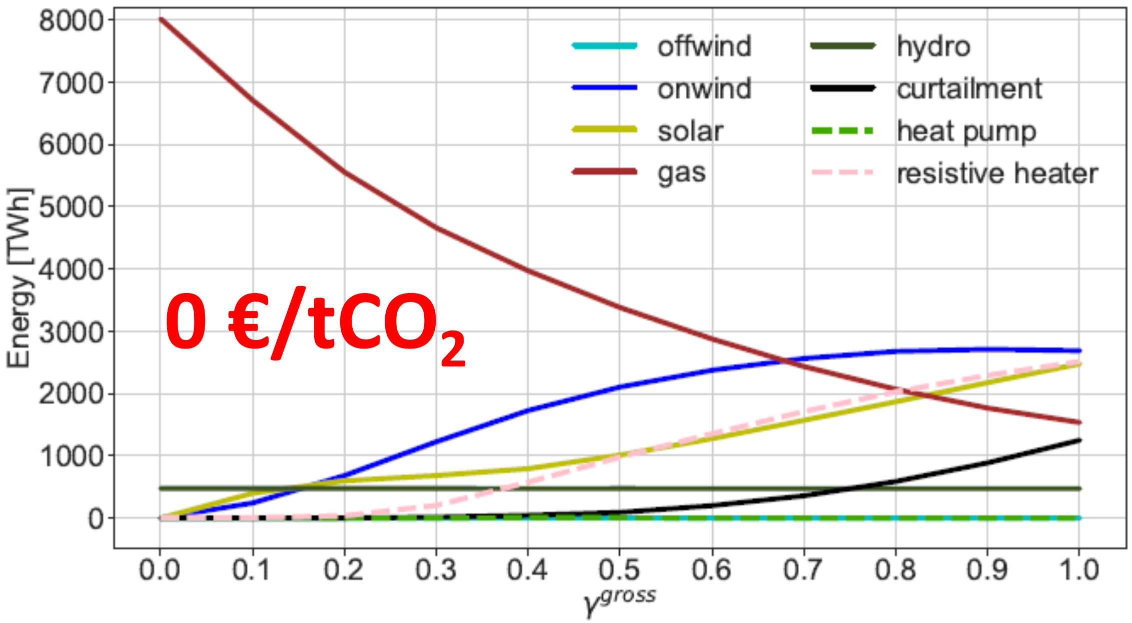
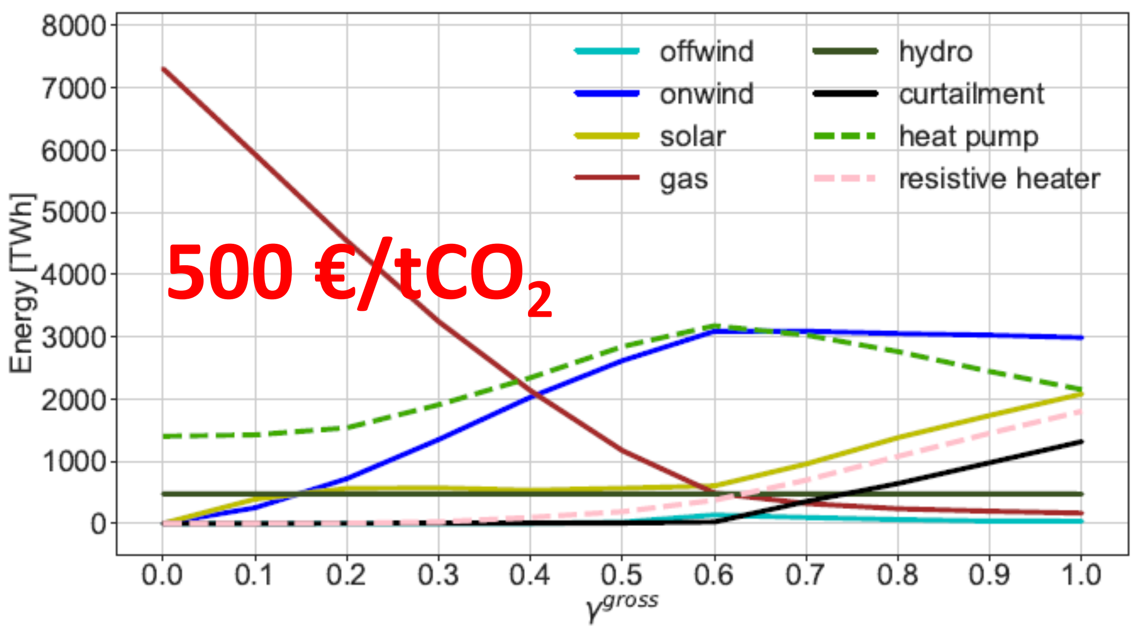
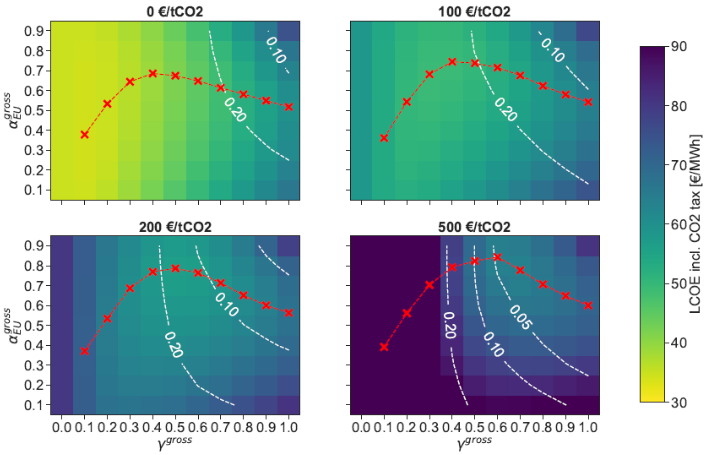
Results

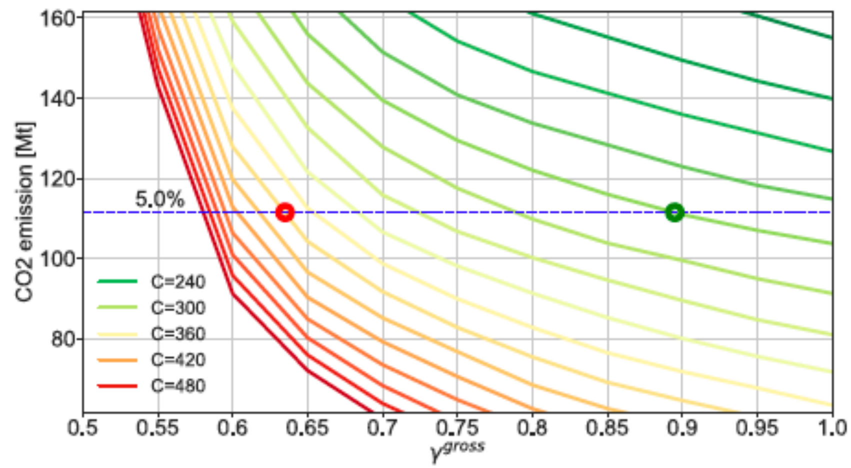

0 €/tCO2
100 €/tCO2
200 €/tCO2
500 €/tCO2
α_{EU}^{gross}
γ^{gross}
LCOE incl. CO2 tax [€/MWh]

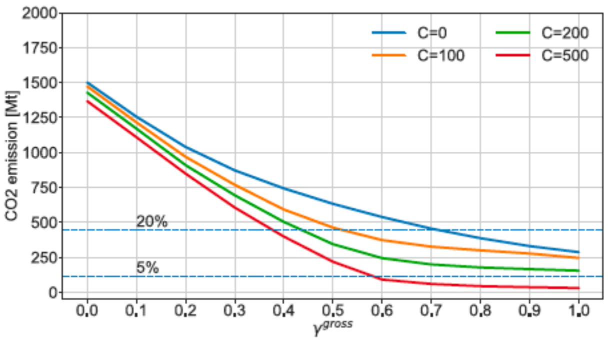

offwind
onwind
solar
gas
hydro
curtailment
heat pump
resistive heater
Energy [TWh]
γ^{gross}
0 €/tCO$_2$

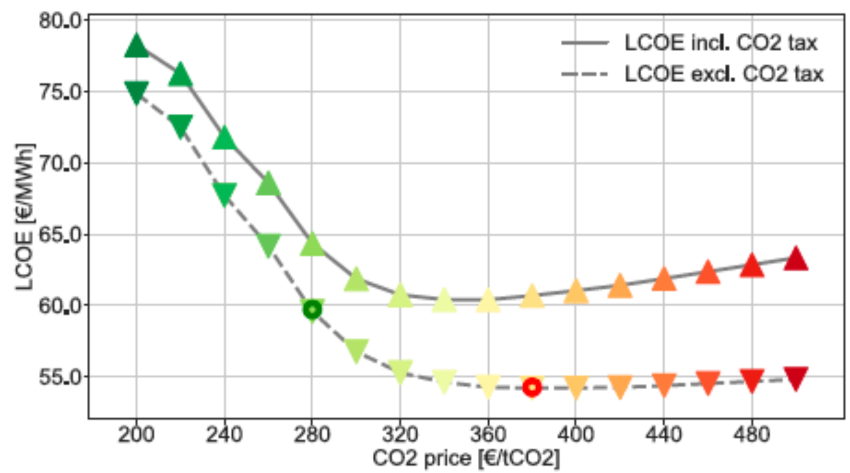

offwind
onwind
solar
gas
hydro
curtailment
heat pump
resistive heater
Energy [TWh]
γ^{gross}
500 €/tCO$_2$

Results



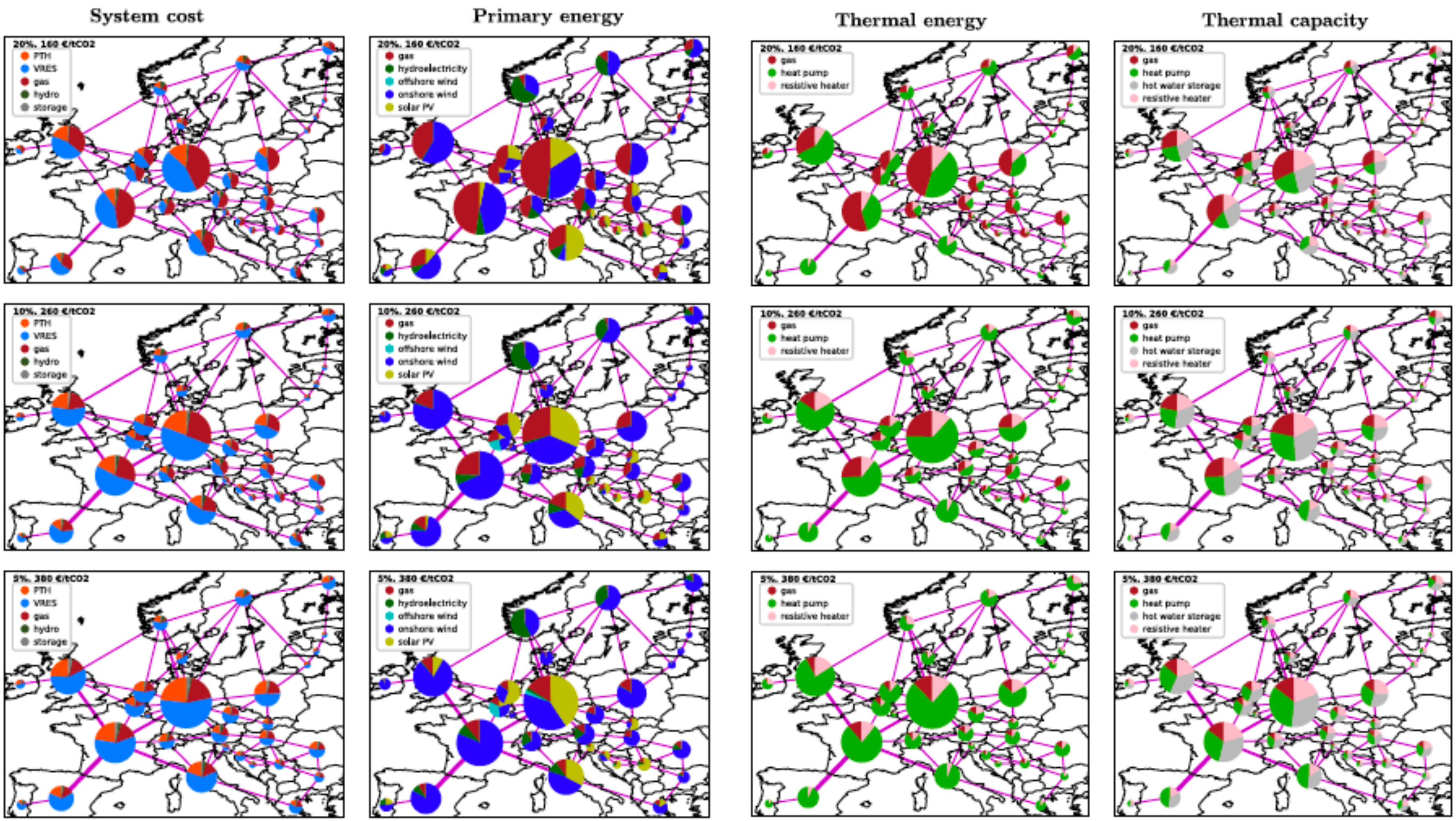






380 €/tCO_2

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

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**

Next steps

- biomass + heat savings
- more sectors: transportation, industry, …
- large → small scale modelling
- transition pathways 2020 → 2050
- impact of climate change
- quantitative tech+econ+soc+pol consulting

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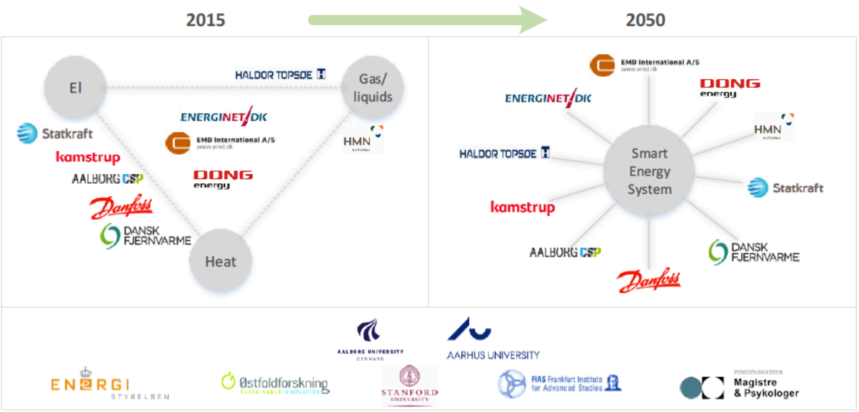
„Energiewende“: kickoff to the second half

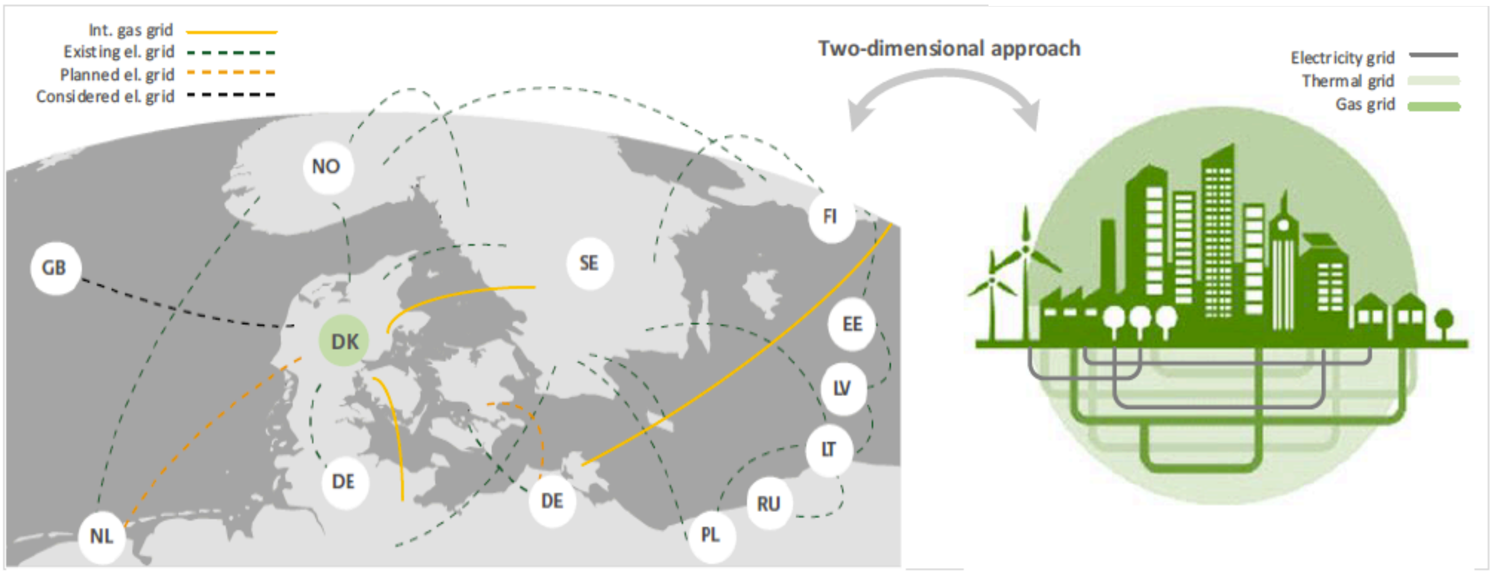
Danmarks Innovationsfond Grand Solutions (04.2017-03.2022, 2.3 M€)



RE-Invest

Renewable Energy Investment Strategies

– a 2dim interconnectivity approach



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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More papers

T Brown, D Schlachtberger, A Kies, S Schramm, M Greiner:
Synergies of sector coupling and transmission extension in a cost-optimized highly renewable European energy system,
Energy 160 (2018) 720-39.

T Brown, M Schäfer, M Greiner:
System properties of a sector-coupled, highly-renewable model of the European energy system as carbon dioxide emissions are restricted,
Energies (2019) in press.

D Schlachtberger, T Brown, S Schramm, M Greiner:
The benefits of cooperation in a highly renewable European electricity network,
Energy 134 (2017) 469-81.

D Schlachtberger, T Brown, M Schäfer, S Schramm, M Greiner:
Cost optimal scenarios of a future highly renewable European electricity system: exploring the influence of weather data, cost parameters and policy constraints,
Energy 163 (2017) 100-14.

M Schlott, A Kies, T Brown, S Schramm, M Greiner:
The impact of climate change on a cost-optimal highly renewable European electricity network,
Applied Energy 230 (2018) 1645-59.

openmod open energy modelling initiative

We are hosting the next Open Energy Modelling Workshop !!!

Aarhus University

22-24th May 2019

https://en.wikipedia.org/wiki/Open_Energy_Modelling_Initiative#Workshops

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