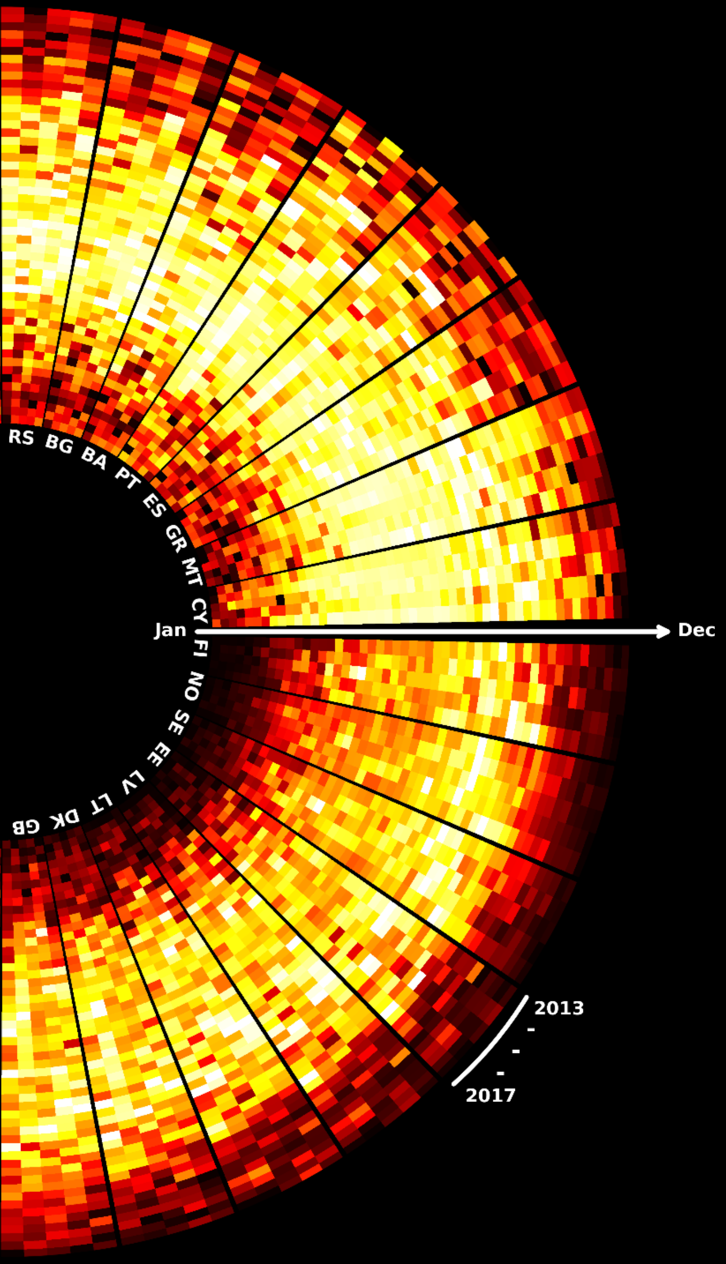
WIND ENERGY DENMARK   October 1, 2019



Decarbonization of the European energy system with strong sector couplings

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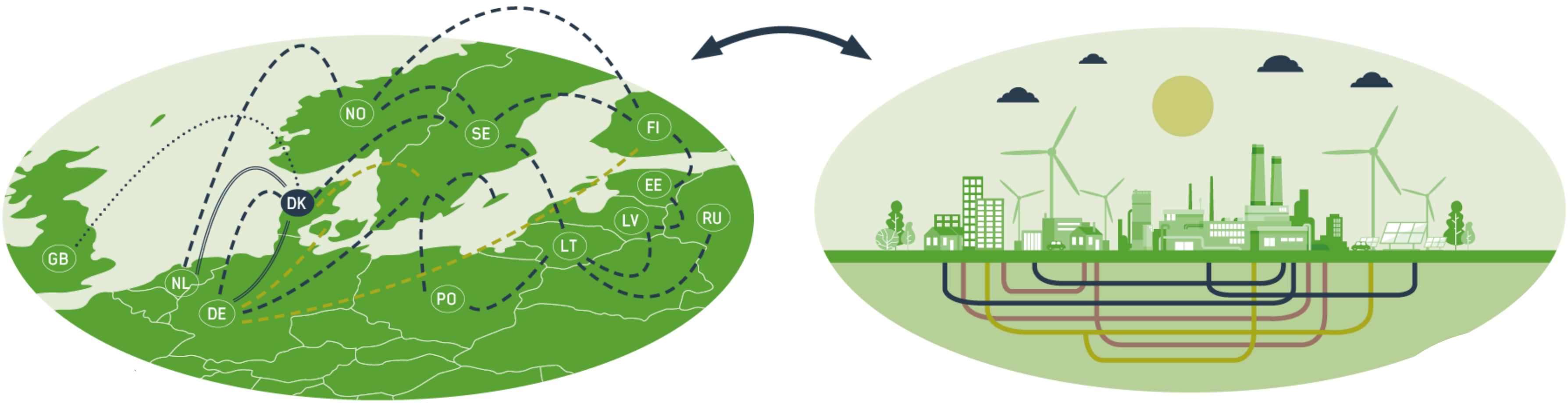
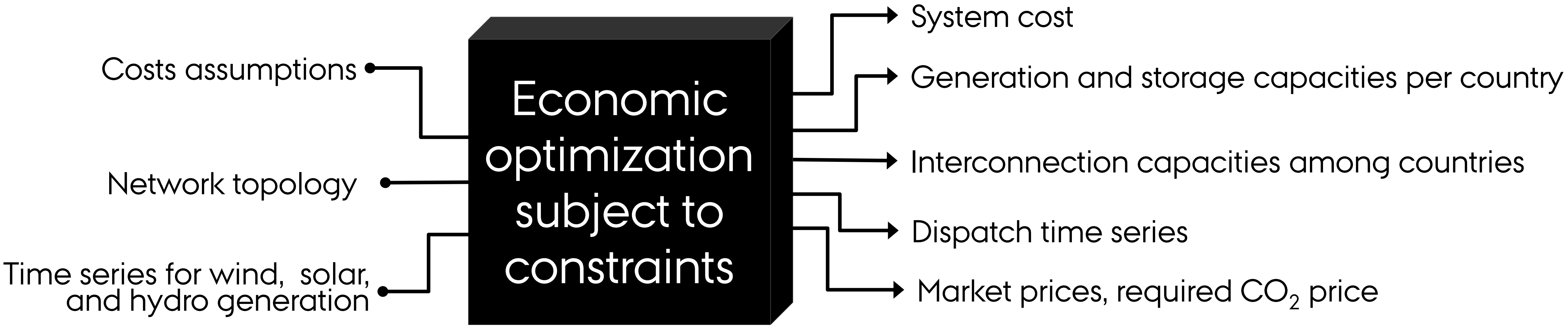
Motivation

Strategies to balance wind and solar generation:

- Storage
- Extend transmission capacities
- Sector coupling



Model overview



26 tech. x 30 countries x 8760 hours = $7{\cdot}10^6$ variables, solved in ~2 hours in simulation cluster

Research questions

What is the optimal wind to solar mix?

How are the results affected by costs assumptions?

How are the results affected by interconnection capacities expansion?

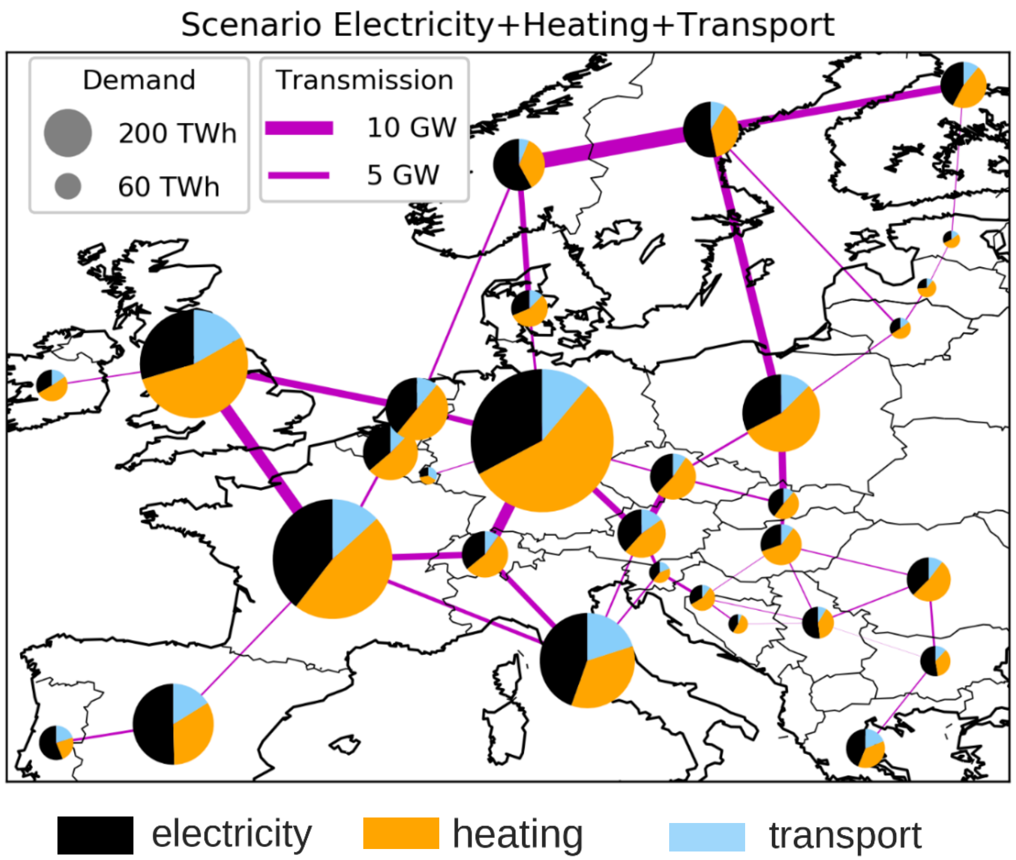
How are the results affected by the CO_2 emissions target?

Methods: Sector-coupled network model

Cost projections for 2030 for every technology

Technology	Overnight Cost[a][€]	Unit	FOM[b] [%/a]	Lifetime [years]	Efficiency	Source
Onshore wind	910	kW_{el}	3.3	30		[44]
Offshore wind	2506	kW_{el}	3	25		[44]
Solar PV utility-scale[c]	425	kW_{el}	3	25		[45]
Solar PV rooftop[c]	725	kW_{el}	2	25		[45]
OCGT[d]	560	kW_{el}	3.3	25	0.39	[44, 46]
Hydro reservoir[e]	2000	kW_{el}	1	80	0.9	[46]
Run-of-river[e]	3000	kW_{el}	2	80	0.9	[46]
Pumped hydro storage[e] (PHS)	2000	KW_{el}	1	80	$0.87 \cdot 0.87 = 0.76$	[46]
Batteries	144.6	KWh_{el}	0	15	$0.9 \cdot 0.9 = 0.81$[f]	[47]
Battery inverter	310	KW_{el}	3	20	0.9[f]	[47]
Hydrogen storage[g]	8.4	KWh_{el}	0	20	$0.8 \cdot 0.58 = 0.46$	[47]
Hydrogen electrolysis	350	KW_{el}	4	18	0.8	
Hydrogen fuel cell	339	KW_{el}	3	20	0.58	[47]
HVDC lines	400	MWkm	2	40	1	[48]
HVDC converter pair	150	kW	2	40	1	[48]

Methods: Sector-coupled network model



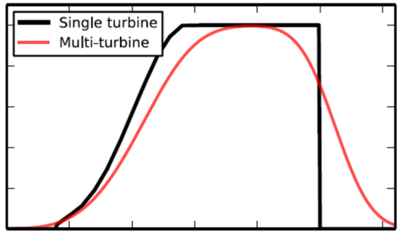
One-node-per-country network

Linear power flow

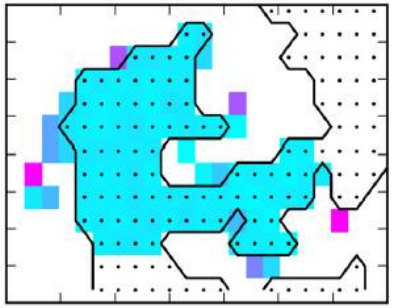
Hourly resolution

Methods: Modelling country-wise wind generation

Global weather data (1 hour, 40x40km^2)

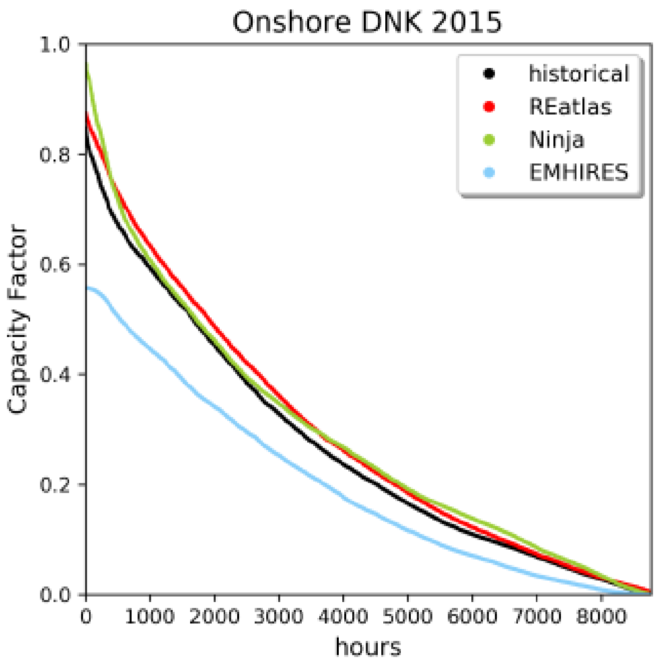


Converted to wind energy generation



Country-wise aggregation

Time series validated using historical data.



Openly available time series for onshore and offshore in 30 European countries (1979-2017)
doi: 0.5281/zenodo.3245437

GLOBAL RENEWABLE ENERGY ATLAS

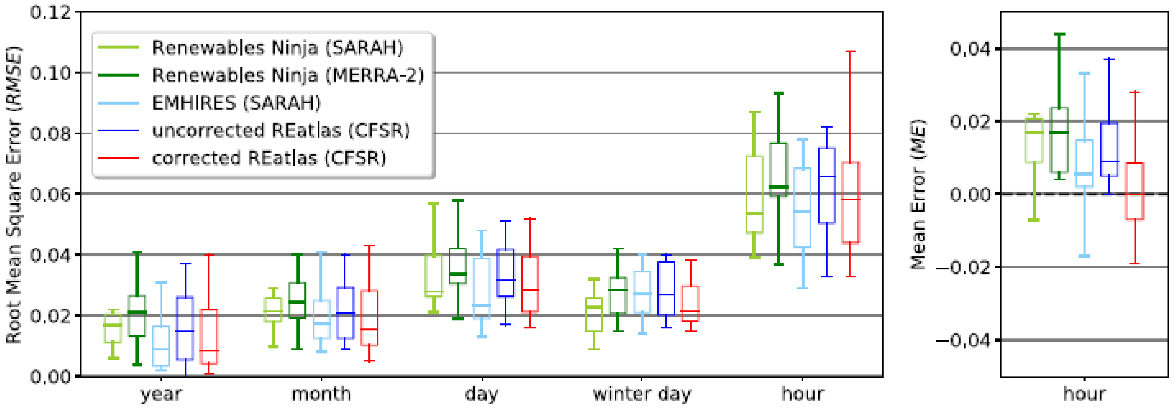
Andresen *et al.*, Energy 93, 2015

Methods: Modelling country-wise PV generation

Using validated reanalysis data to investigate the impact of the PV system configurations at high penetration levels in European countries

Marta Victoria[1,2] | Gorm B. Andresen[1,2]

Time series validated using historical data.



Openly available time series for 30 European countries (1979-2017) and different PV configurations: doi:10.5281/zenodo.1321809

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GLOBAL RENEWABLE ENERGY ATLAS

Victoria and Andresen, Progress In Photovoltaics 27 (7), 2019

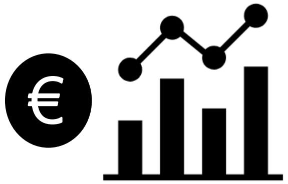
Methods: Sector-coupled network model

Economic optimization subject to constraints

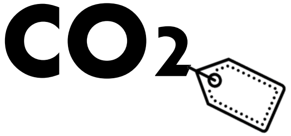
$$\min \left(\sum_{n} \mathit{generation\ costs} + \mathit{storage\ costs} + \mathit{transmission\ costs} + \sum_{n,t} \mathit{variable\ costs} \right)$$

Subject to constraints :

$$\mathit{generation} + \mathit{balance} = \mathit{demand} \quad \leftrightarrow \quad \lambda_{n,t} \qquad \forall n, t$$



$$\sum \mathit{emissions} \leq \mathit{CAP}_{CO2} \quad \leftrightarrow \quad \mu_{CO2}$$



Greenfield optimization, perfect competition and foresight, long-term market equilibrium
Implemented in PyPSA (Python for Power System Analysis)

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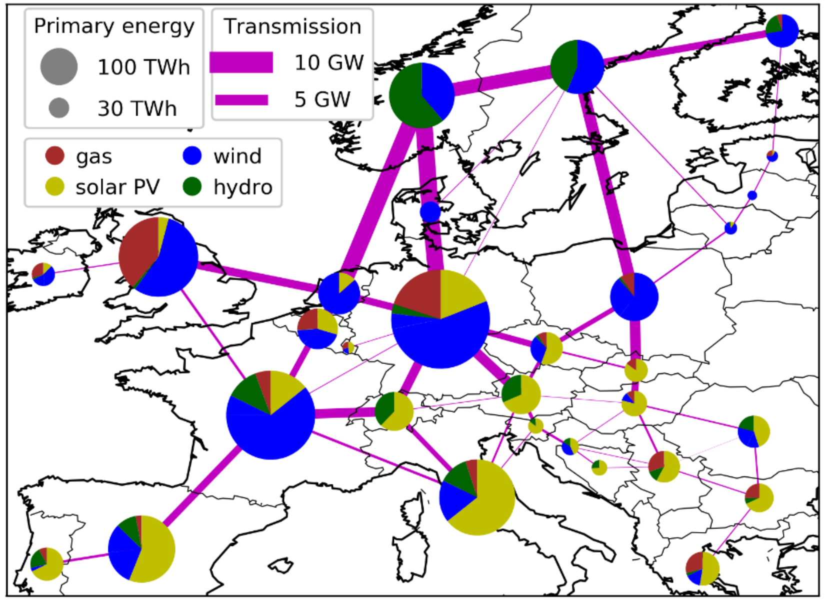
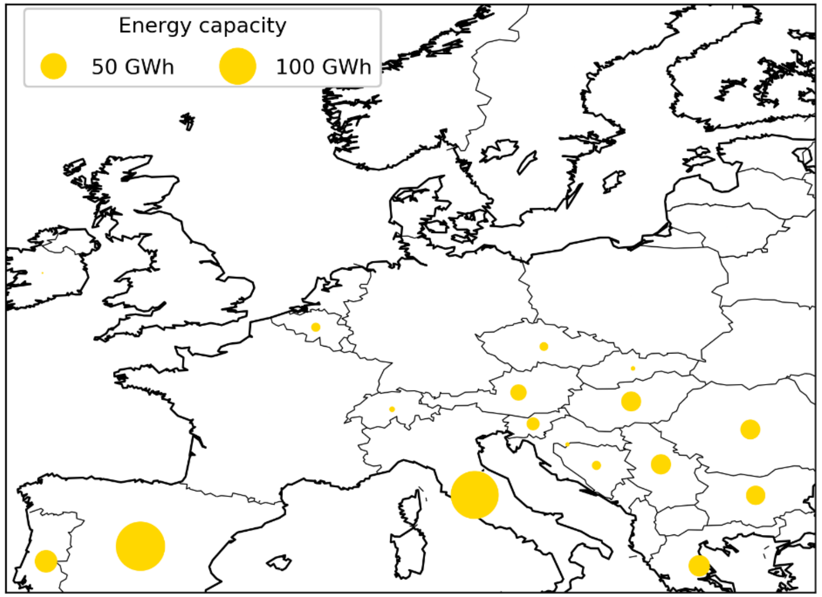
Results: Optimal power system for 95% CO_2 emissions reduction

Primary energy



Wind generation represents in average 55% of the electricity demand (570 GW onshore wind capacity, 60 GW offshore wind capacity)

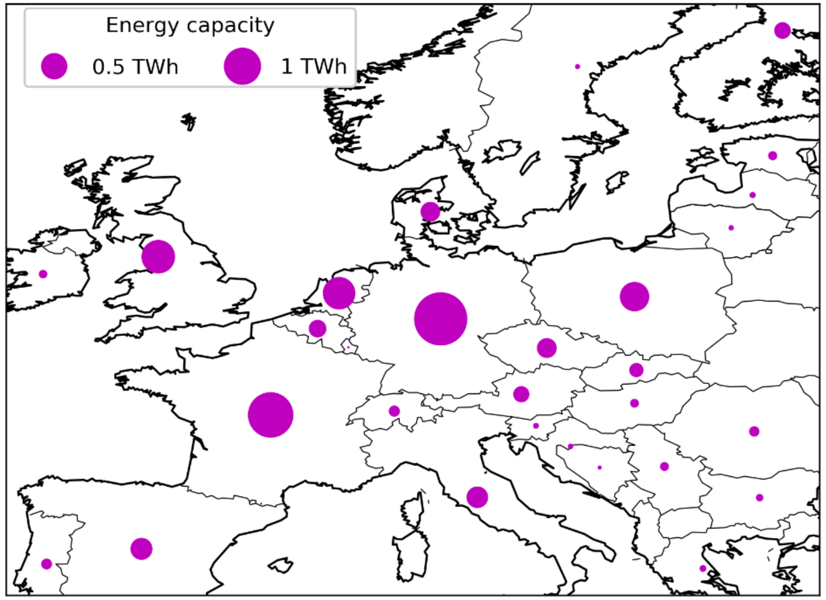
Electric Batteries



Southern countries: PV + batteries

$$\frac{energy\ capacity}{power\ capacity} \sim 6\ hours$$

Hydrogen storage

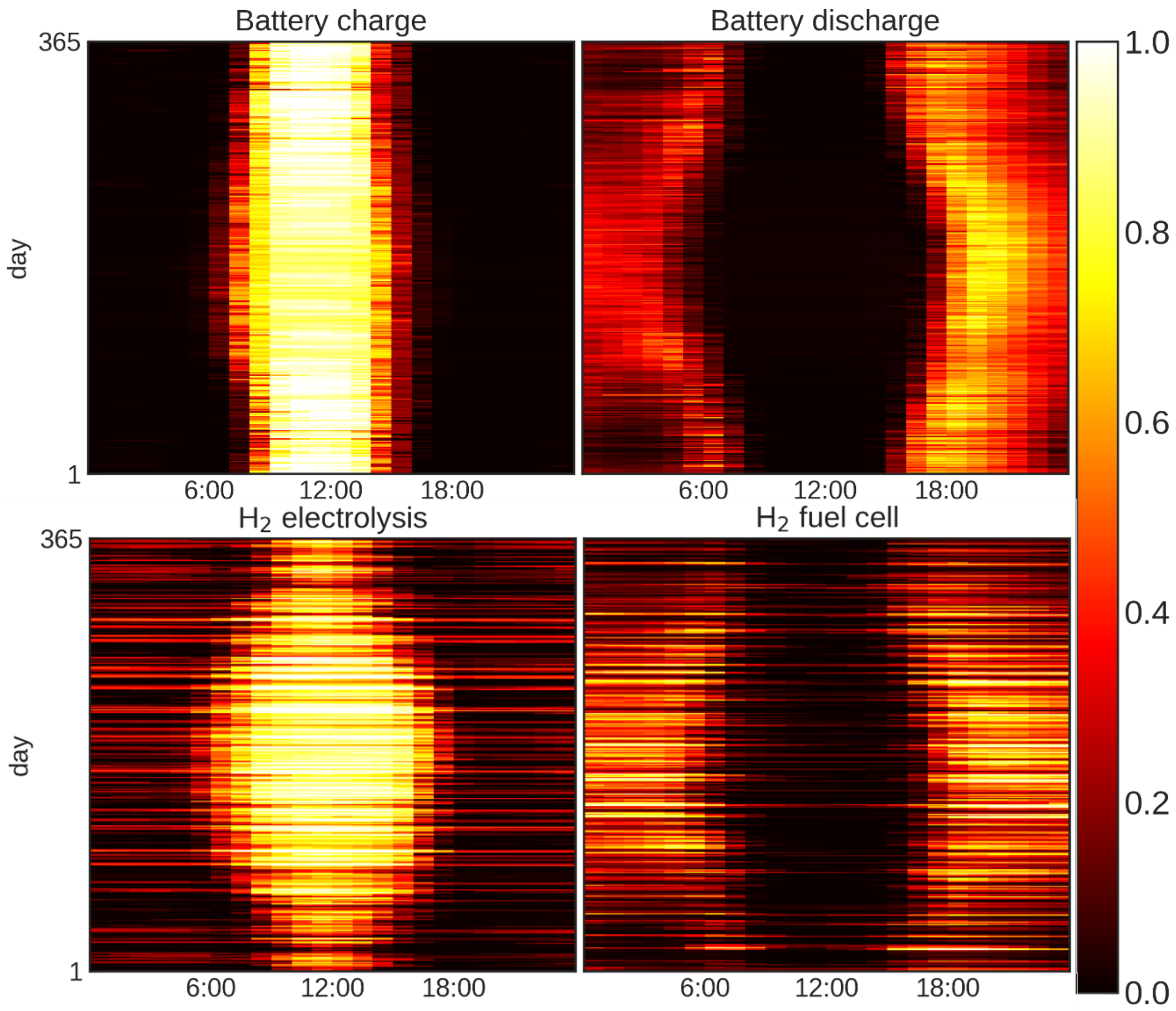


Northern countries: wind + hydrogen storage + interconnections

$$\frac{energy\ capacity}{power\ capacity} \sim 2\ days$$

Victoria *et al.*, Energy Conversion and Management (2019)

Results: 95% CO_2 emissions reduction

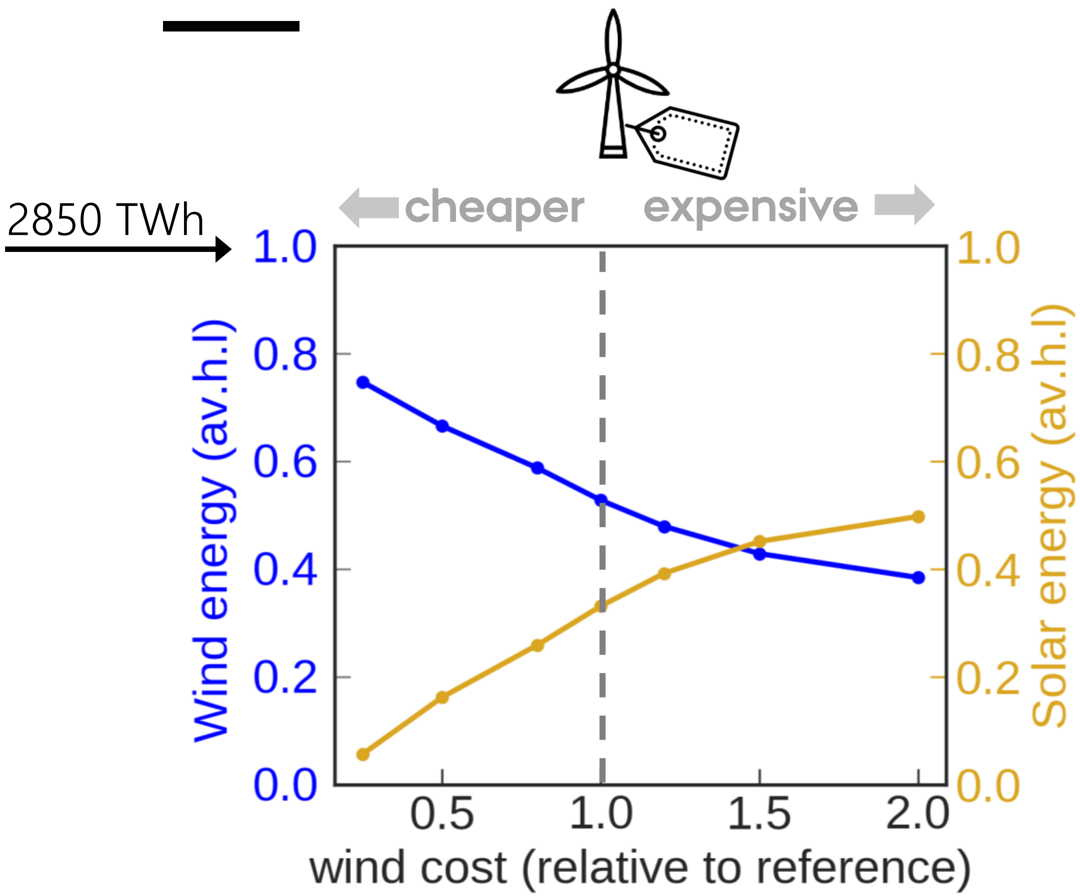


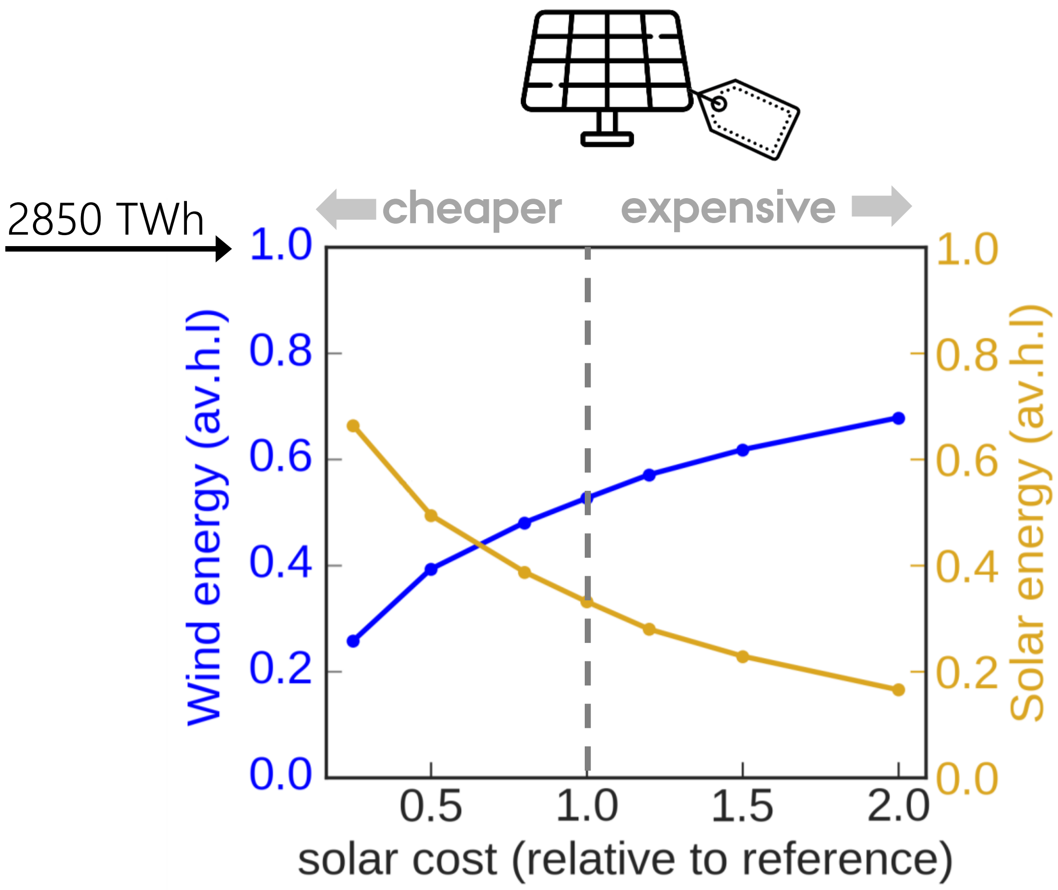
As expected, batteries charge during the day and discharge during the night.

Hydrogen storage operation is impacted by wind generation fluctuations with weekly frequency.

Victoria *et al.*, Energy Conversion and Management (2019)

Results: sensitivity to wind and PV cost

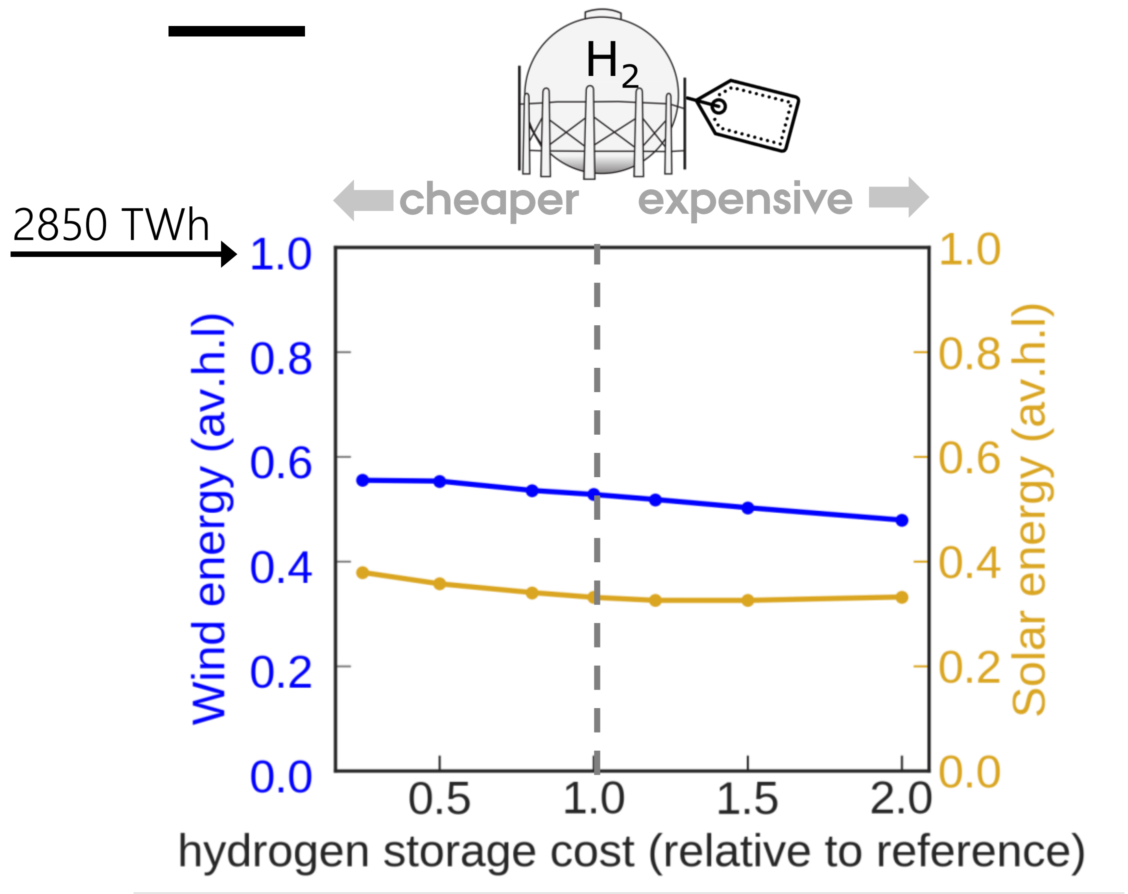


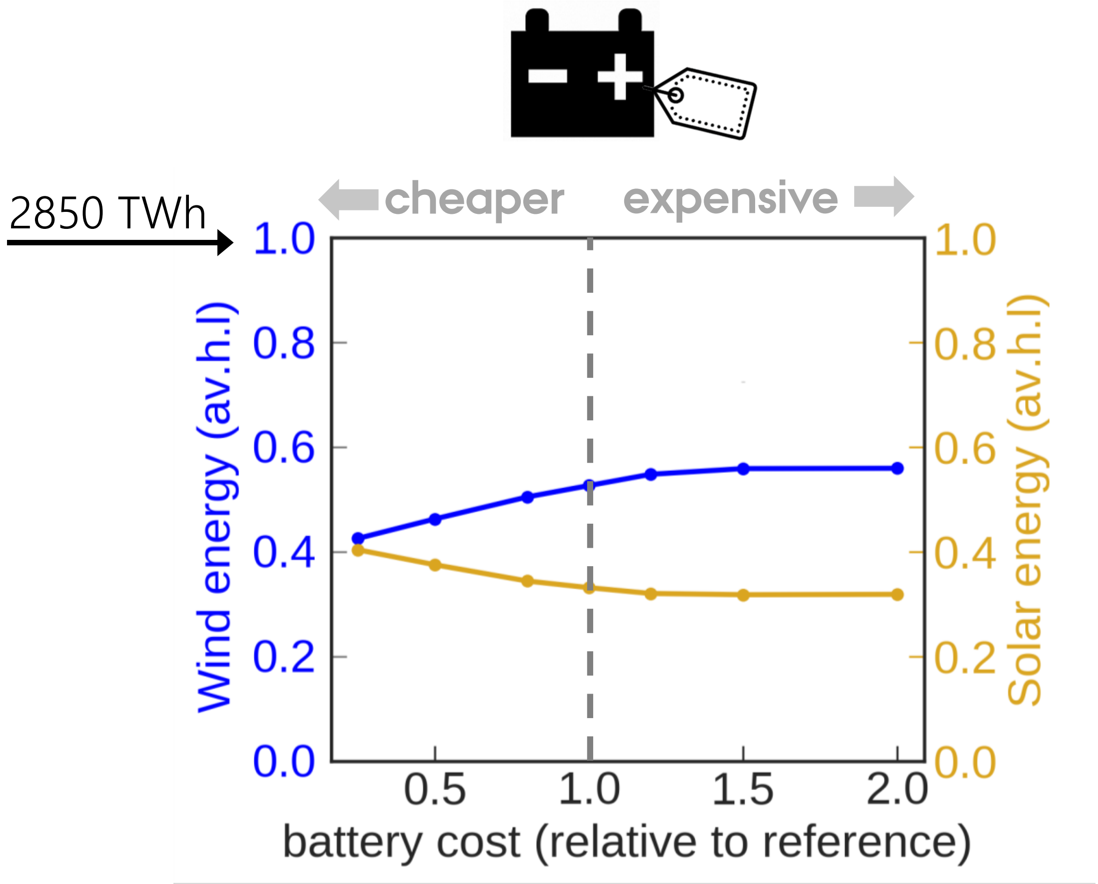


Even for very cheap PV, no 100% solar system is optimum as it would requires large (expensive) battery capacity.

Victoria *et al.*, Progress in Photovoltaics EUPVSEC Special Issue (2019)

Results: sensitivity to hydrogen storage and battery cost

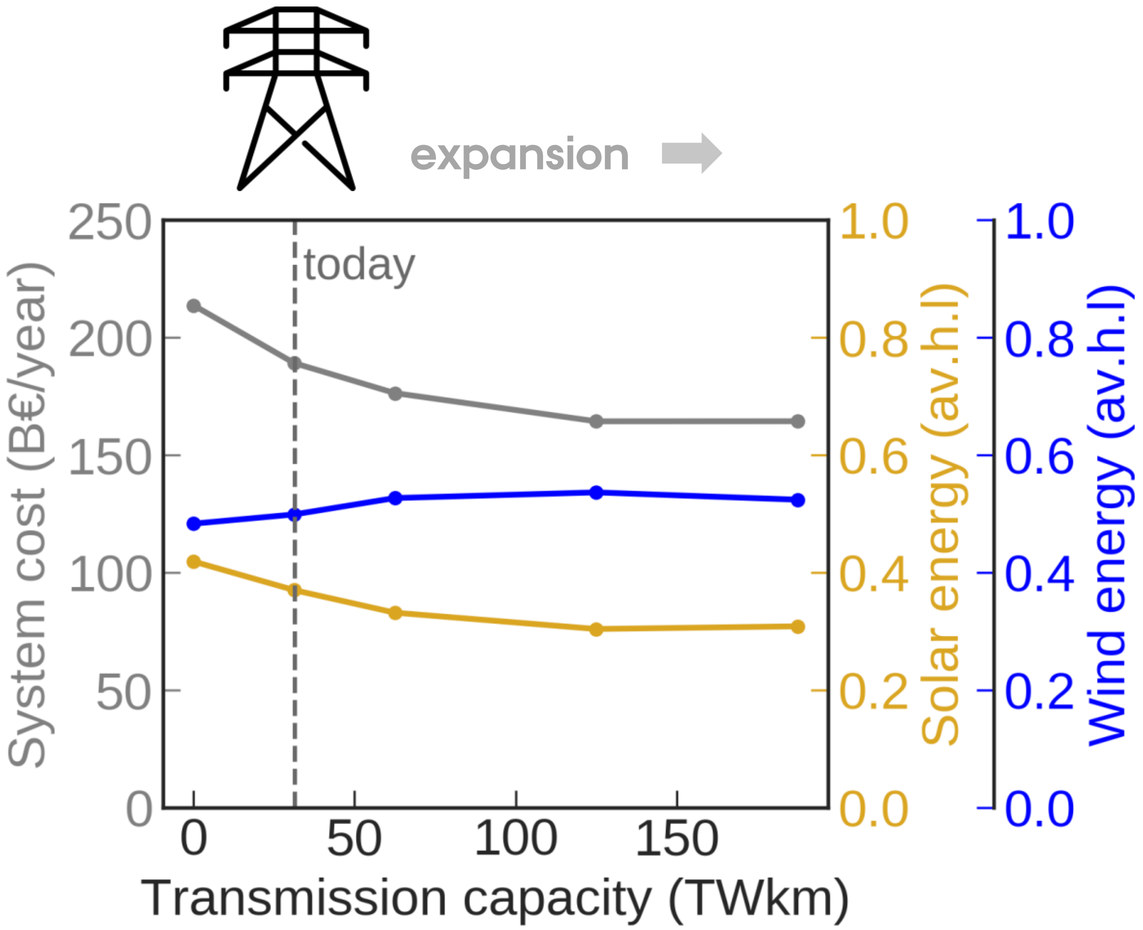




Cheap batteries increase optimal PV penetration.

Victoria *et al.*, Progress in Photovoltaics EUPVSEC Special Issue (2019)

Results: transmission capacity

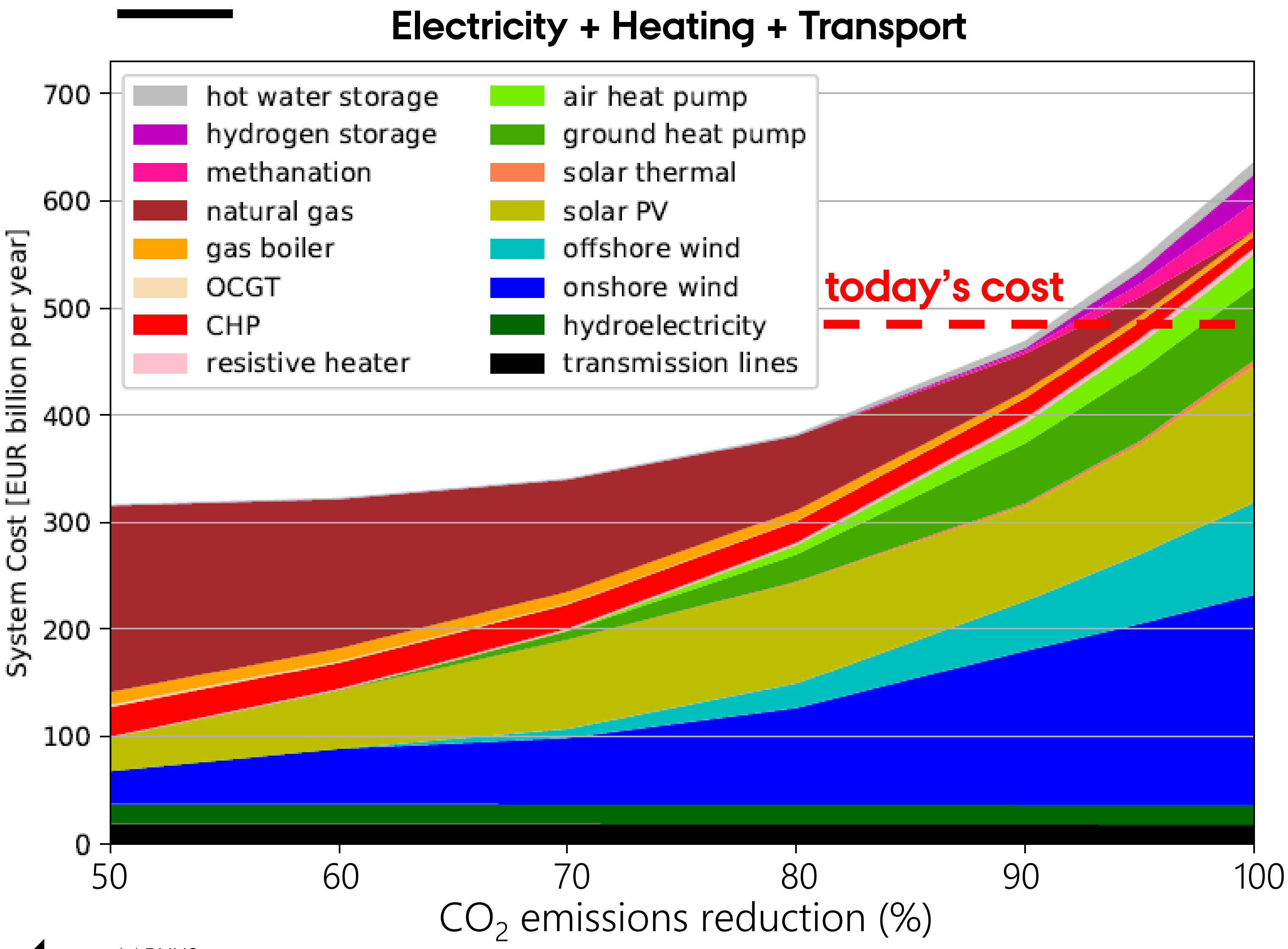


Increasing transmission capacity reduces PV optimal penetration.

Increasing transmission capacity reduces system costs but most of the benefits are captured by the initial 25% grid expansion.

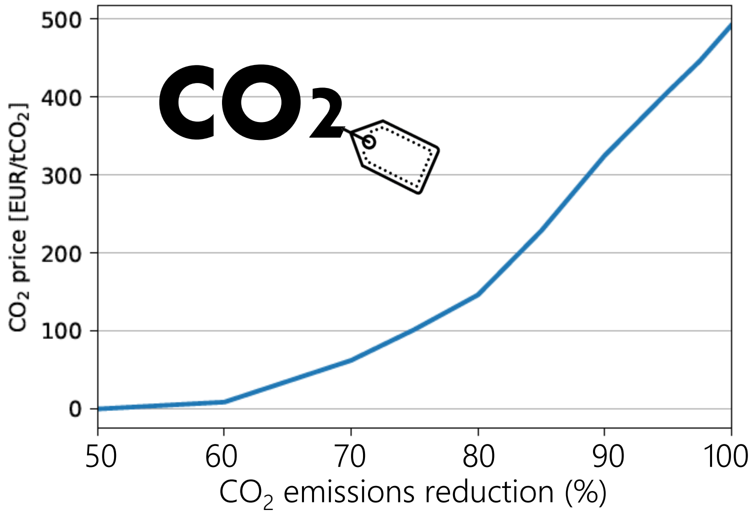
Victoria *et al.*, Progress in Photovoltaics EUPVSEC Special Issue (2019)

Results: variable CO_2 reduction



As CO_2 emissions are restricted the system becomes more expensive …

… but not linearly, the last 20% is the hardest!



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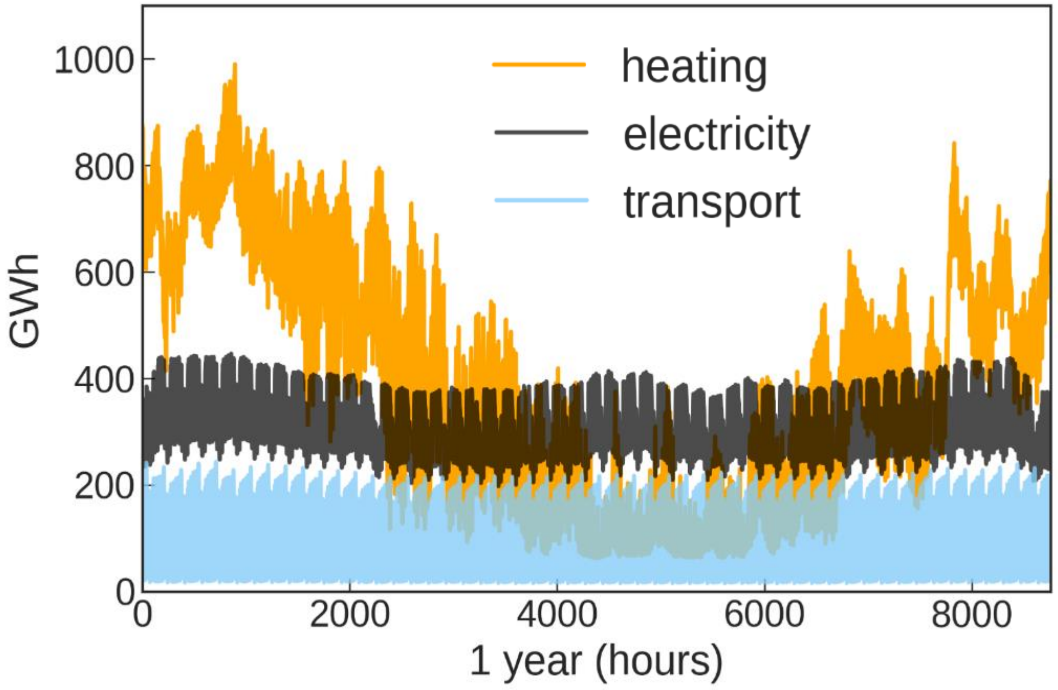
Brown *et al.*, Energies (2019)

Results: sector-coupling

Sector coupling brings opportunities and challenges.

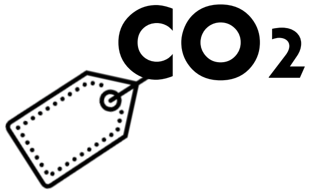
Electric Vehicles whose batteries can charge and discharge into the grid, will bring significant short-term storage benefiting solar PV optimal penetration.

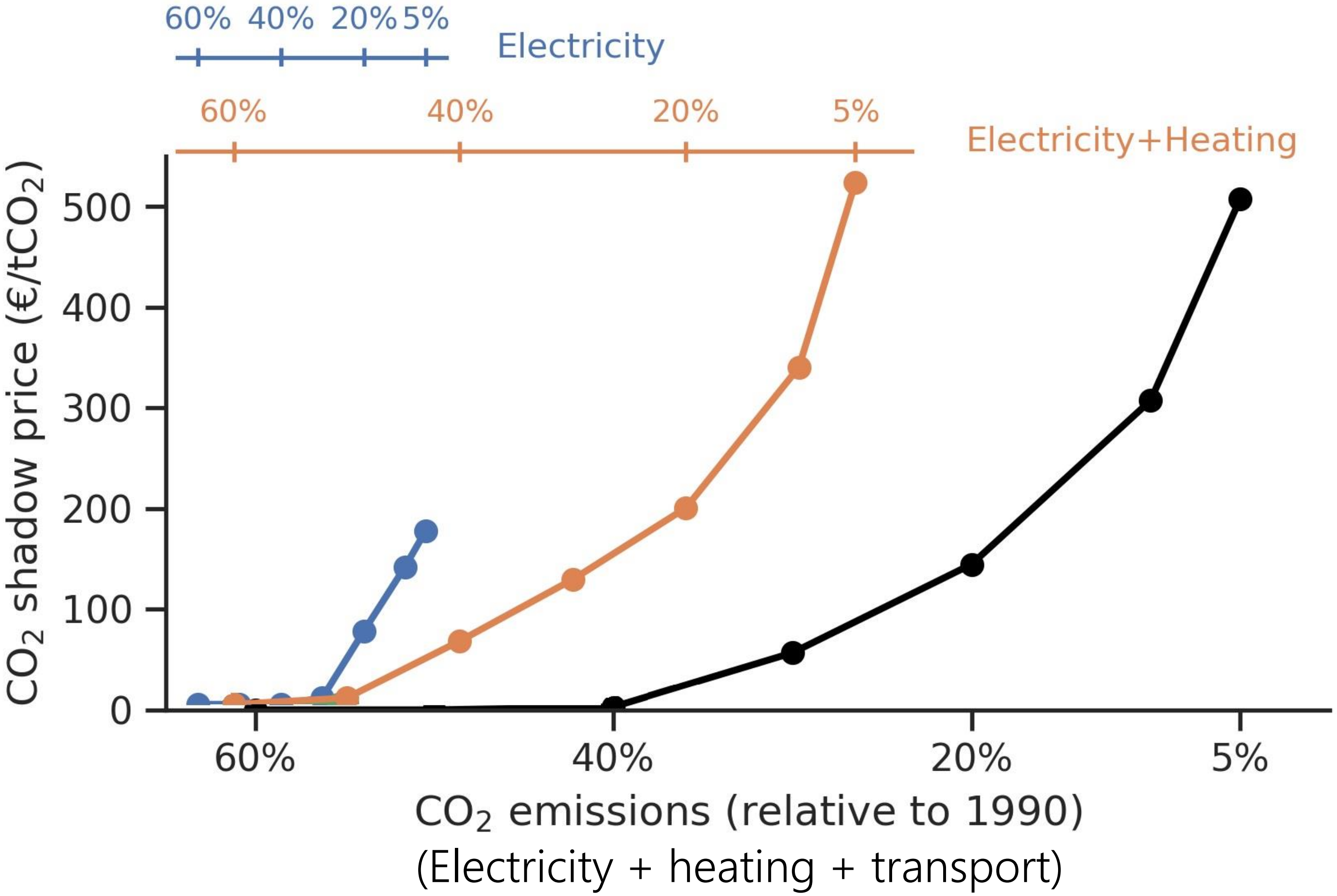
By increasing demand and bringing extra flexibility to the system, sector-coupling delays the need for large storage capacities.



Results: sector-coupling

Higher CO_2 prices needed to decarbonize the heating sector





Victoria *et al.*, Energy Conversion and Management (2019)

Summary

What is the optimal wind to solar mix?

For 95% CO_2 emissions reduction wind generation represents in average 55% of the electricity demand.

Strong links: Solar PV + batteries, Wind + H_2 storage + interconnection

How are the results affected by costs assumptions?

100% solar system won't be optimal. Cheap batteries benefit solar penetration.

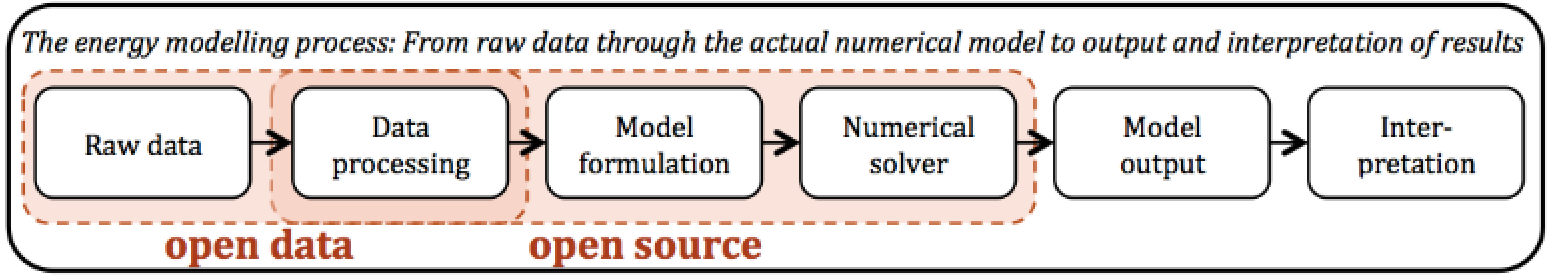
How are the results affected by interconnection capacities expansion?

Expanding interconnection benefits wind and decreases system cost but most of the reduction is obtained for the initial grid expansion.

How are the results affected by the CO_2 emissions limit?

As CO_2 emissions are restricted the system becomes more expensive but not linearly, the last 20% is the hardest.

The whole chain from raw data to modelling results should be open:



Open data + free software ⇒ Transparency + Reproducibility

open energy
modelling initiative
openmod

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