Frontiers of European Energy System Modelling: Sector Coupling and Spatial Scale

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Forschungszentrum Jülich, IEK-3, 21st December 2016

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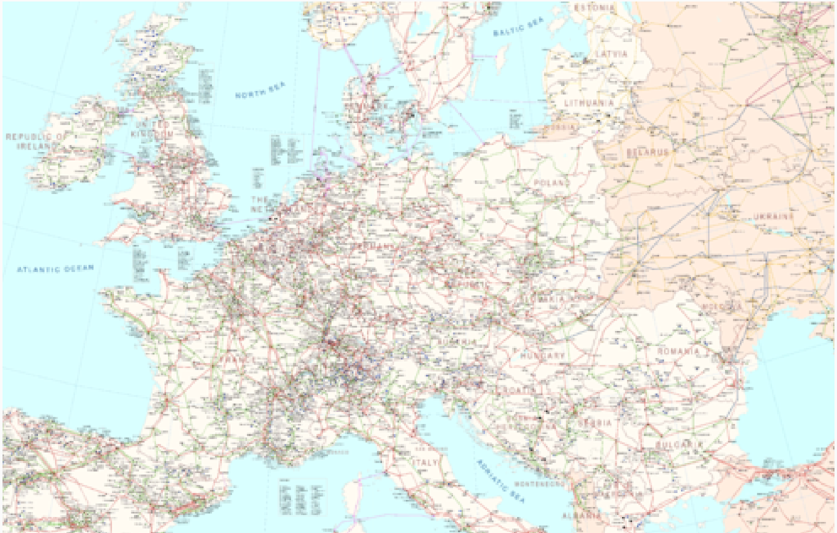
The Challenges of Optimising Highly Renewable Energy Systems

Research questions

1. What infrastructure (wind, solar, hydro generators, heating units, storage and networks) does a highly renewable energy system require and where should it go?
2. Given a desired CO_2 reduction (e.g. 95% compared to 1990), what is the cost-optimal combination of infrastructure (including all capital and marginal costs)?
3. What is the trade-off between international transmission, storage and sector-coupling?

Problem 1: Spatial and temporal resolution

Need high spatial resolution to represent VRE variations and transmission constraints.

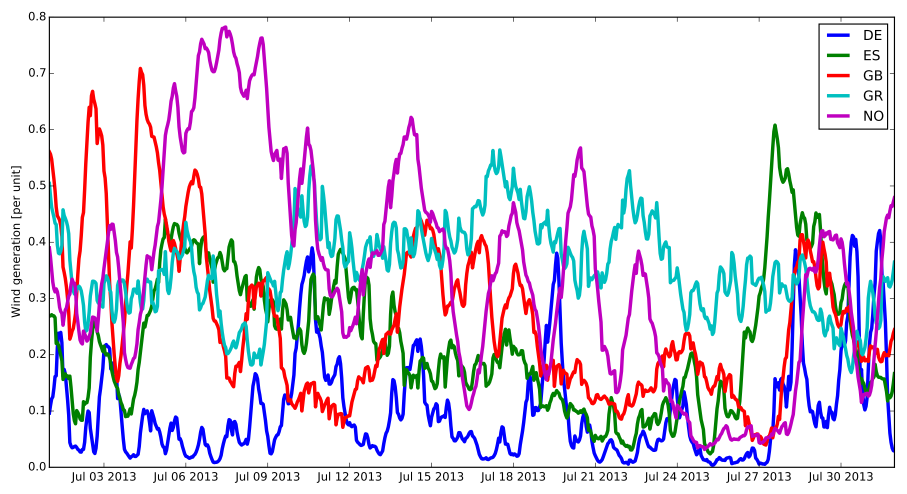


Source: ENTSO-E

Problem 1: Spatial and temporal resolution

Need high temporal resolution to represent load and VRE resource variability and correlations.

Wind generation in Europe in July 2013:



Problem 2: Spatial and temporal scope

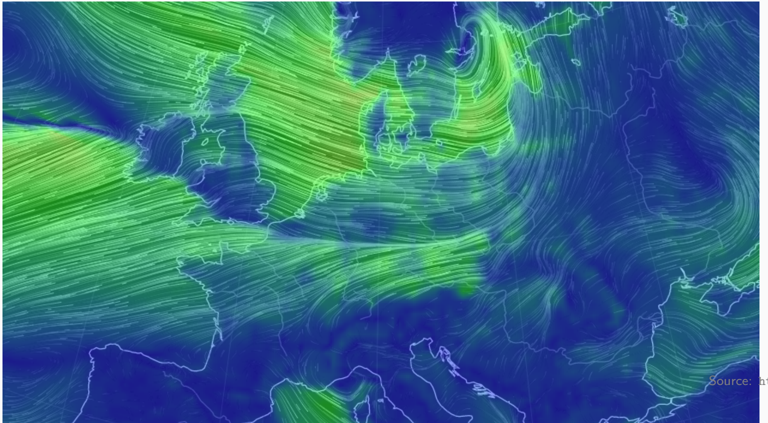
Wind and solar generation is variable in time and space. These variations occur on different scales and this requires different solutions.

Variation	Time scale	Space scale
Diurnal	1 day	Earth circumference
Synoptic	3-10 days	$\sim$600-1000 km
Seasonal	1 year	$\pm 23.4^\circ$ latitude

We can use hydro/chemical/thermal storage to balance temporal variations locally; for spatial balancing, large grids are required. These solutions are not all feasible or cost-effective...

Synoptic scales are key to cost-effectiveness in Europe

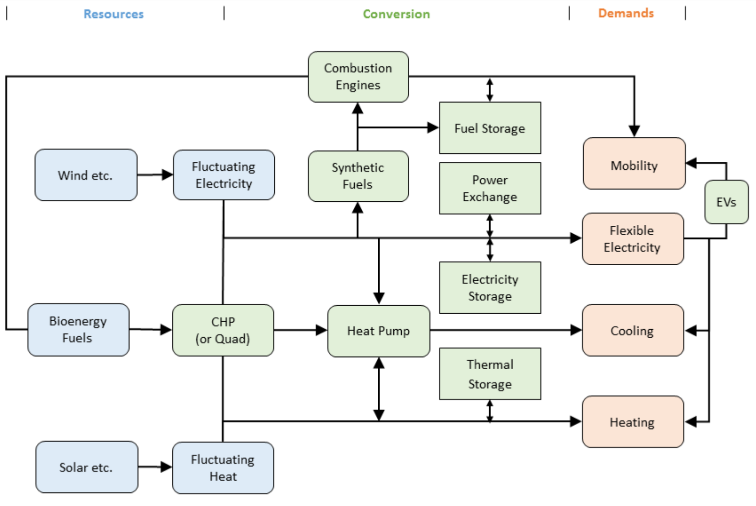
Given that wind is cheap and seasonally aligned with peak energy demand in Europe, cost-effective solutions tend to be dominated by wind. But wind has big synoptic-scale variations. These are caused by weather systems, which are bigger than countries and take days to pass, so you need either to integrate wind at the continental scale or use long-term storage.



Source: https://earth.nullschool.net/

Problem 3: Model complexity

Modelling all sectors of the energy system involves lots of interdependencies



Source: Aalborg

Problem 3: Model complexity

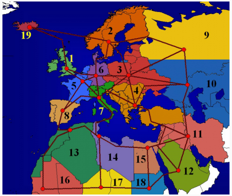
Modelling must respect physics

- How much detail in the input data do we need?
- Optimise transmission simultaneously with generation capacity?
- Optimise electricity, heating and transport together?
- How bad are linear approximations?
- Can we make the algorithms faster, to add detail in other areas?
- By looking at static situations, do we miss dynamic effects?

Examples from literature of energy system optimisation

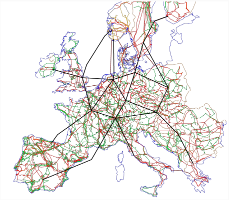
Study	Scope	Spatial resolution	Temporal resolution	What?	Flow physics
Czisch (2005)	MENA	low	high	electricity (gen and grid)	transport
Hagspiel et al. (2014)	EU	medium	low	electricity (gen and grid)	linear
Egerer et al. (2014)	EU	high	low	electricity (gen only)	linear
Fraunhofers ISE, IWES	DE	none	high	electricity, heating, transport	none

Czisch



Hagspiel et al.

Egerer et al.



Problem 4: Flatness of solution space near the optimum

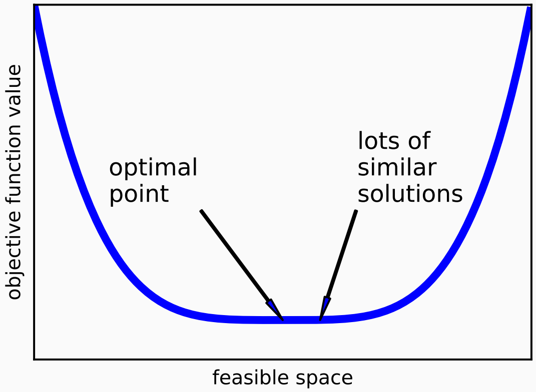
Once we've formulated our optimisation problem and solved it, we're not done.

How sensitive is our solution to small changes in the inputs?

In which directions do the costs explode?

Typical energy optimisation results are very flat around the optimum, i.e. there are many similar configurations with similar costs.

It is very important for policy-makers to know what freedom there is to adjust the solution, without exploding the costs.



Overarching goal

Find the "sweet spot" where:

- Computation time is finite (i.e. a week)
- Temporal resolution is "good enough"
- Spatial resolution is "good enough"
- Model detail is "good enough"

AND quantify the error we make by only being "good enough" (e.g. are important metrics $\pm 10\%$ or $\pm 50\%$ correct?)

AND be sure we're got a handle on all sectoral interdependencies that might affect the results.

Warm-Up: Electricity Sector in Europe with One-Node-Per-Country

Linear optimisation of annual system costs

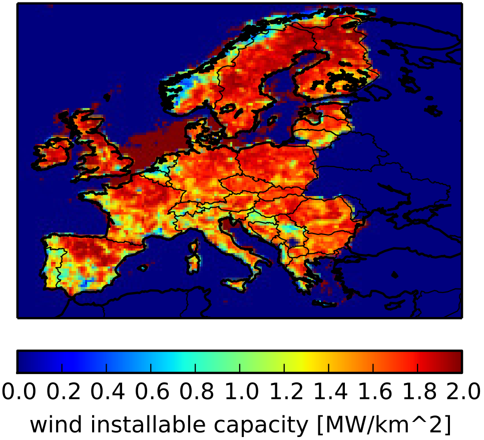
Given a desired CO_2 reduction, what is the most cost-effective energy system?

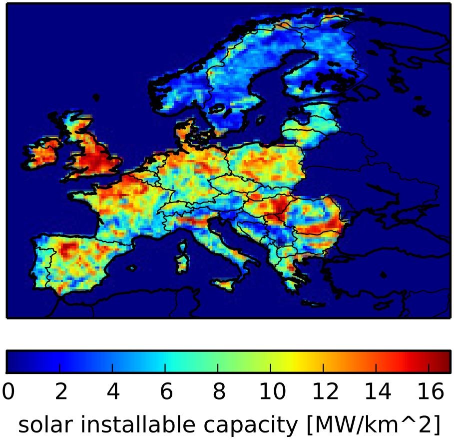
$$\text{Minimise}\begin{pmatrix}\text{Yearly system}\\\text{costs}\end{pmatrix} = \sum_n \begin{pmatrix}\text{Annualised}\\\text{capital costs}\end{pmatrix} + \sum_{n,t}(\text{Marginal costs})$$

subject to

- meeting energy demand at each node n (e.g. countries) and time t (e.g. hours of year)
- wind, solar, hydro (variable renewables) availability $\forall\, n, t$
- electricity transmission constraints between nodes
- (installed capacity) $\leq$ (geographical potential for renewables)
- CO_2 constraint (95% reduction compared to 1990)
- Flexibility from gas plants, battery storage, hydrogen storage, networks

Geographical potentials for wind and solar



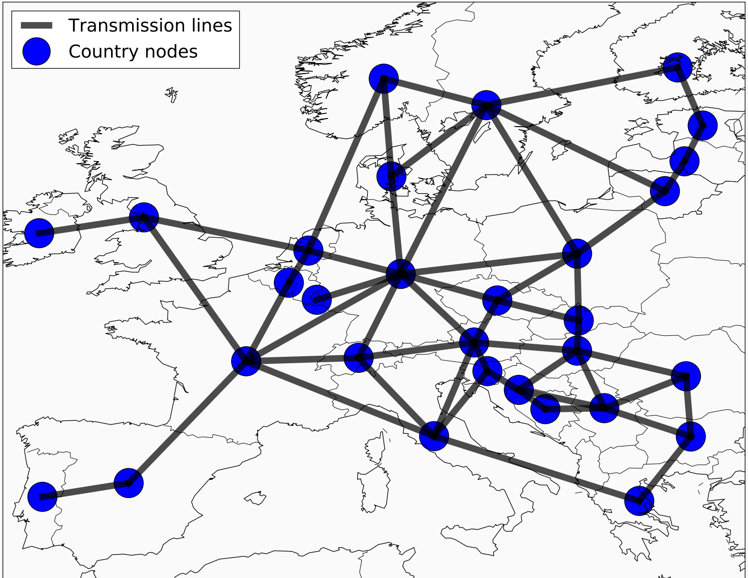


Cost and other assumptions

Quantity	Overnight Cost [€]	Unit	FOM [%/a]	Lifetime [a]
Wind onshore	1182	kW_{el}	3	20
Wind offshore	2506	kW_{el}	3	20
Solar PV	600	kW_{el}	4	20
Gas	400	kW_{el}	4	30
Battery storage	1275	kW_{el}	3	20
Hydrogen storage	2070	kW_{el}	1.7	20
Transmission line	400	MWkm	2	40

Interest rate of 7%, storage efficiency losses, only gas has CO_2 emissions, gas marginal costs.

Europe: One node per country



International versus national solutions: Global constraints on transmission volumes

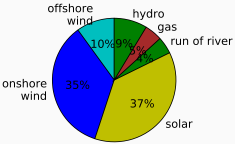
Transmission volume limits are respected, given length d_ℓ and capacity $\bar{P}_\ell$ of each line ℓ:

$$\sum_\ell d_\ell \bar{P}_\ell \quad \leq \quad \mathrm{CAP}_{\mathrm{trans}} \qquad\qquad \leftrightarrow \qquad \lambda_{\mathrm{trans}}$$

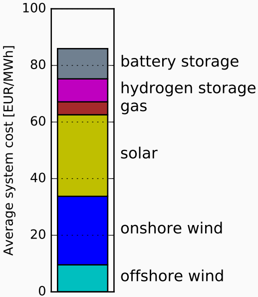
We successively change the transmission limit cap (measured in GWkm), to assess the costs of balancing power in time (i.e. storage) versus space (i.e. inter-connecting transmission networks).

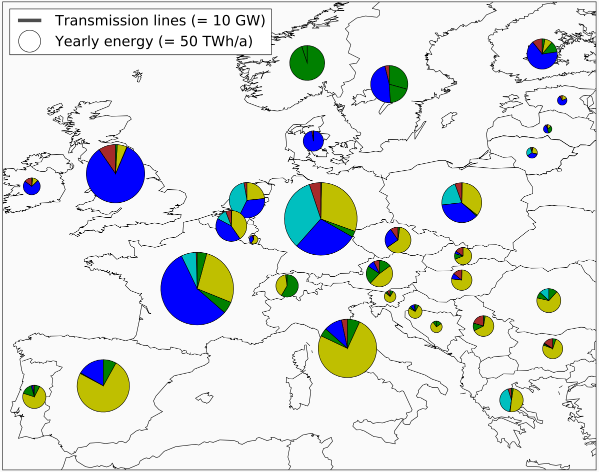
Costs: No interconnecting transmission allowed

Technology by energy:



Average cost €86/MWh:

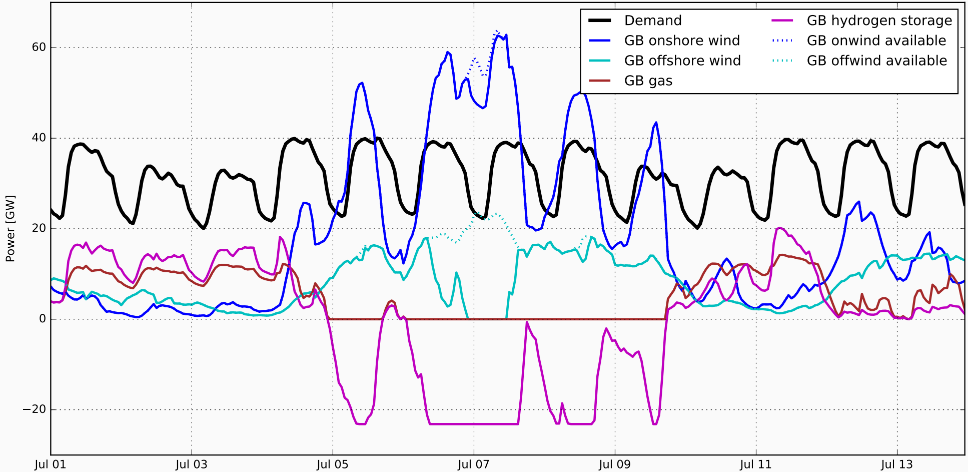




Countries must be self-sufficient at all times; lots of storage and some gas to deal with fluctuations of wind and solar.

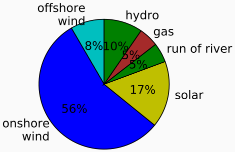
Dispatch with no interconnecting transmission

For Great Britain with no interconnecting transmission, excess wind is either stored as hydrogen or curtailed:

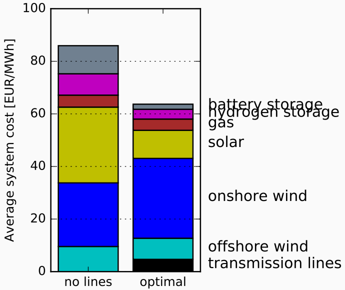


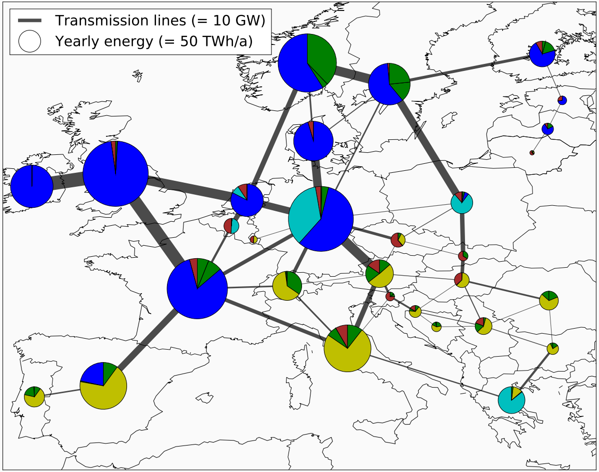
Costs: Cost-optimal expansion of interconnecting transmission

Technology by energy:



Average cost €64/MWh:

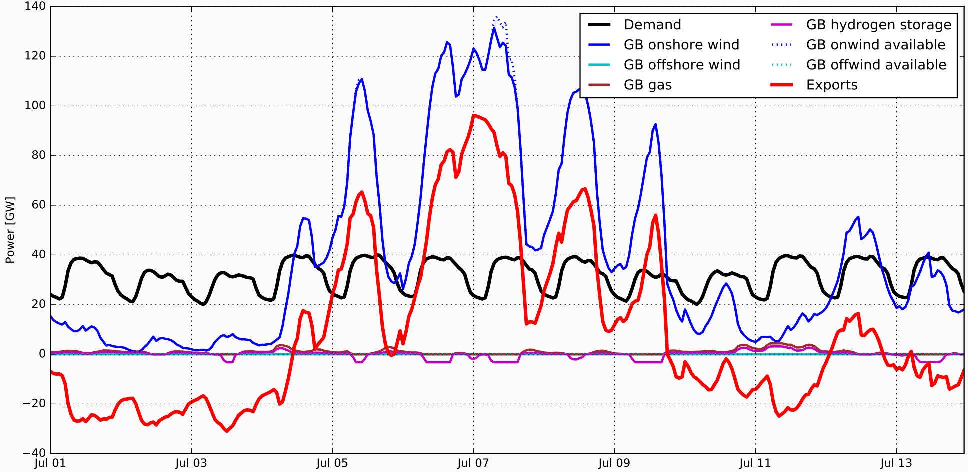




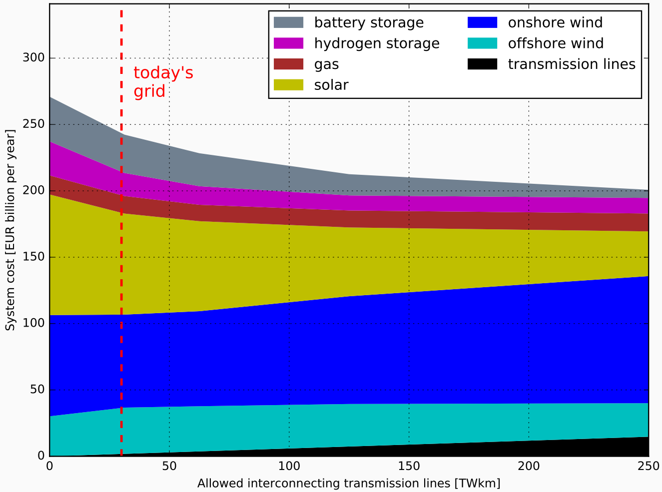
Large transmission expansion; onshore wind dominates. This optimal solution may run into public acceptance problems.

Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can be now be exported:

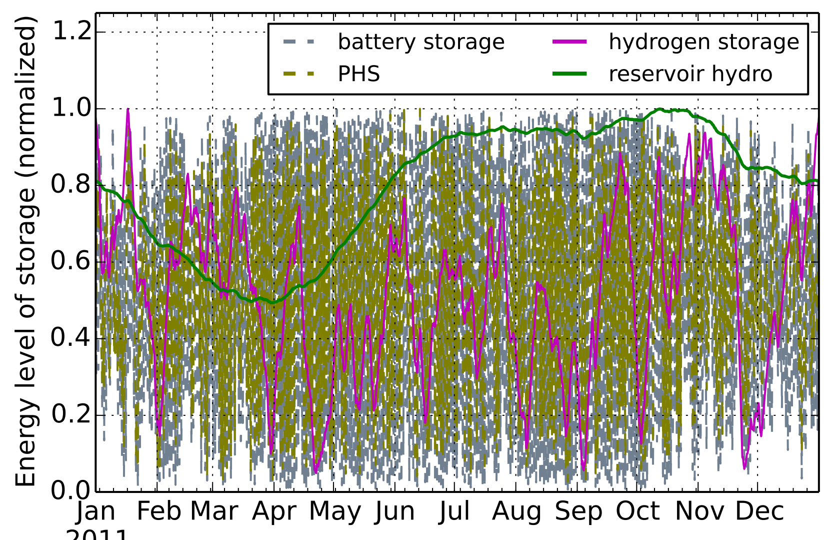


Electricity Only Costs Comparison



- Average total system costs can be as low as € 64/MWh
- Energy is dominated by wind (64% for the cost-optimal system), followed by hydro (15%) and solar (17%)
- Restricting transmission results in more storage to deal with variability, driving up the costs by up to 34%
- Many benefits already locked in at a few multiples of today's grid

Different flexibility options have difference temporal scales



- Hydro reservoirs are seasonal
- Hydrogen storage is synoptic
- Pumped hydro and battery storage are daily

Sector Coupling in a European Context

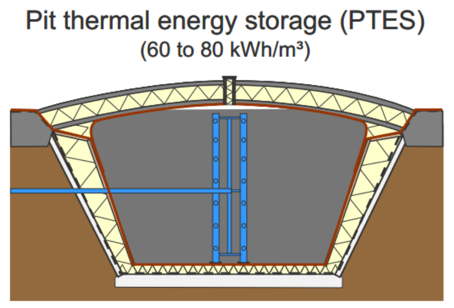
Sector Coupling

Idea: Couple the electricity sector to heating and mobility.

This enables decarbonisation of these sectors and offers more flexibility to the power system.

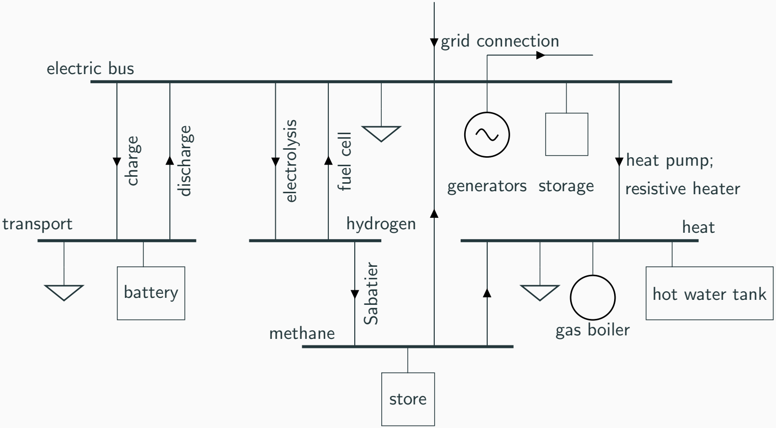
Battery electric vehicles can change their charging pattern to benefit the system and even feed back into the grid if necessary

Heat is much easier and cheaper to store than electricity, even over many months

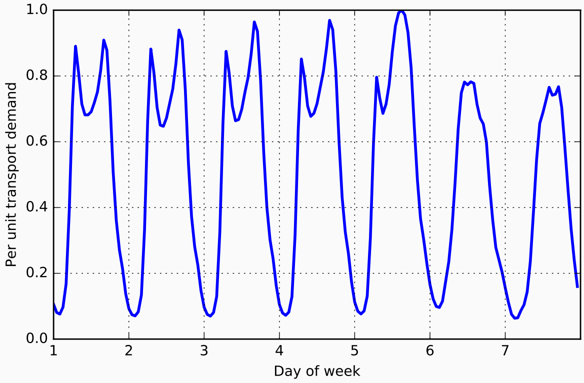


Sector coupling: A new source of flexibility

Couple the electricity sector (electric demand, generators, electricity storage, grid) to electrified transport and low-T heating demand (model covers 75% of final energy consumption in 2014).



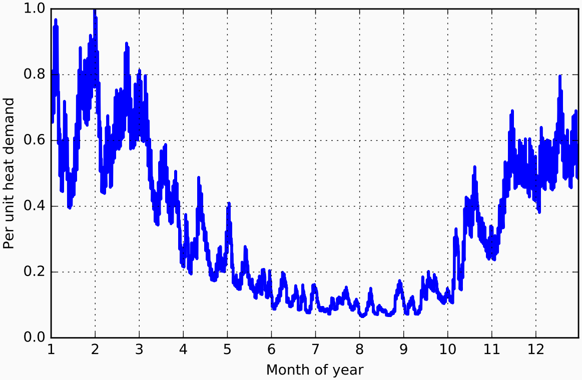
Transport sector: Battery Electric Vehicles



Weekly profile for the transport demand based on statistics gathered by the German Federal Highway Research Institute (BASt).

- All road and rail transport in each country is electrified; no changes in consumer behaviour assumed (e.g. car-sharing).
- Assumed that all passenger cars are Battery Electric Vehicles (BEVs), each with 50 kWh battery and 11 kW charging power, connected to grid 90% of time.
- BEVs are treated as exogenous (capital costs NOT included in calculation).
- Because of higher efficiency of electric motors, final energy consumption 3.5 times lower at 1014 TWh_{el}/a for the 30 countries.

Heating sector: Many Options with Thermal Energy Storage (TES)



Heat demand profile from 2011 in all 30 countries using population-weighted average daily T in each country, degree-day approx. and scaled to Eurostat total heating demand.

- All space and water heating in the residential and services sectors is considered, with no additional efficiency measures (conservative) - total heating demand is 3231 TWh_{th}/a.
- Heating demand can be met by resistive heaters, gas boilers, Combined-Heat-and-Power (CHP) units and heat pumps, which have an average Coefficient of Performance of 3. No waste heat or solar heating.
- Thermal Energy Storage (TES) is available to the system as hot water tanks.

Centralised District Heating versus Decentralised Heating

We model both fully decentralised heating and cases where up to 60% of heat demand is met with district heating in northern countries.

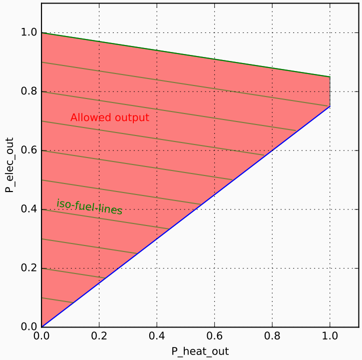
Decentral heating can be supplied by:

- Gas boilers
- Resistive heaters
- Small CHPs
- Water tanks with short time constant $\tau = 3$ days
- Heat pumps

Central heating can be supplied via district heating networks by:

- Gas boilers
- Resistive heaters
- Large CHPs
- Water tanks with long time constant $\tau = 180$ days

CHP feasible dispatch:



Cost and other assumptions

Quantity	Overnight Cost [€]	Unit	FOM [%/a]	Lifetime [a]
Sabatier	1100	kW_{gas}	2	20
Heat pump	1050	kW_{th}	1.5	20
Resistive heater	100	kW_{th}	2	20
Gas boiler	300	kW_{th}	1	20
Decentral CHP	1400	kW_{el}	3	25
Central CHP	650	kW_{el}	3	25
Central water tanks	20	m^3	1	40
District heating	400	kW_{th}	1	50

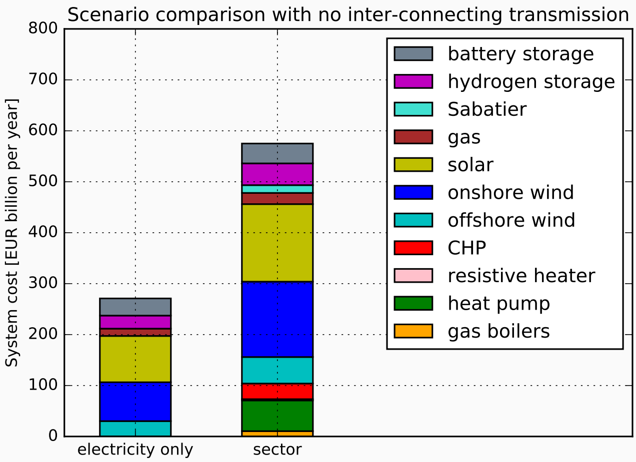
Costs oriented towards Henning & Palzer (2014, Fraunhofer ISE)

Scenarios: Add flexibility one feature at a time

We now consider 8 scenarios where flexibility is added in stages:

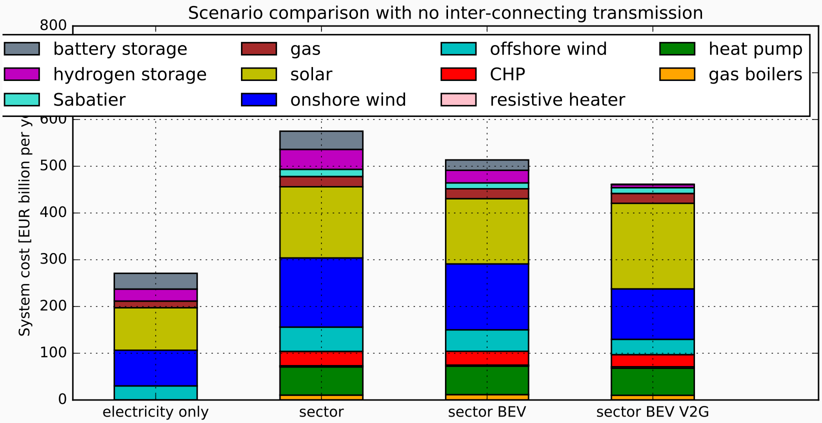
1. **electricity only**: no sector coupling
2. **sector**: sector coupling to heating and transport with no use of sector flexibility
3. **sector BEV**: sector coupling; Battery Electric Vehicles (BEV) can shift their charging time
4. **sector BEV V2G**: sector coupling; BEV can in addition feed back into the grid (Vehicle-2-Grid)
5. **sector T3**: sector coupling with short-term Thermal Energy Storage (TES) $\tau = 3$ days
6. **sector T180**: sector coupling with long-term TES $\tau = 180$ days
7. **sector central**: sector coupling with 60% district heating in North
8. **sector all flex**: sector coupling with all flexibility options

From electricity to sector coupling



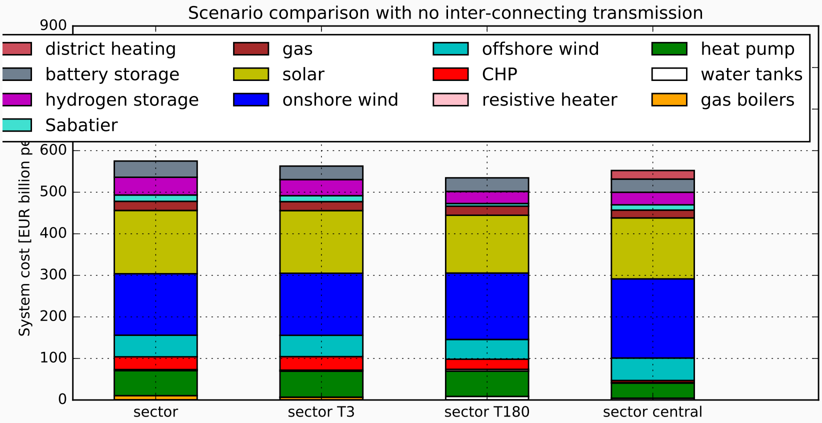
- With sector coupling costs are over twice as much because of higher energy demand, heating units and strong seasonality of heating demand.
- Decentralised heating demand peak (1262 GW_{th}) met by heat pumps (41%), gas boilers (26%), resistive heaters (17%) and CHP (15%).
- No additional flexibility activated.
- Around 10% of demand for gas is met by Power-To-Gas.

Using Electric Vehicle flexibility



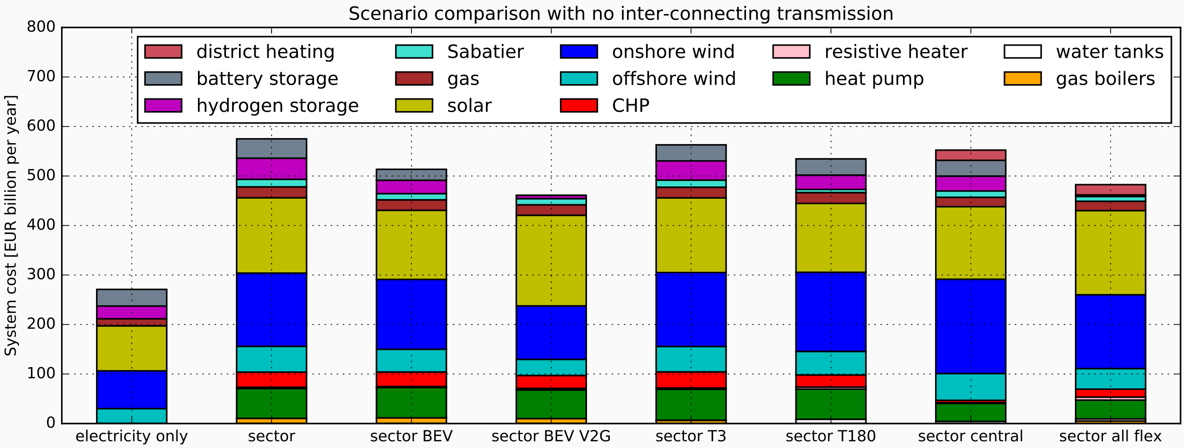
- Shifting the charging time to benefit the system reduces system costs by 11%.
- This Demand-Side Management reduced the need for stationary storage by half.
- Allowing BEVs to feed back into the grid (V2G) reduces costs by a further 9%.
- This eliminates the need for batteries and allows more solar to be integrated.

Using heating sector flexibility

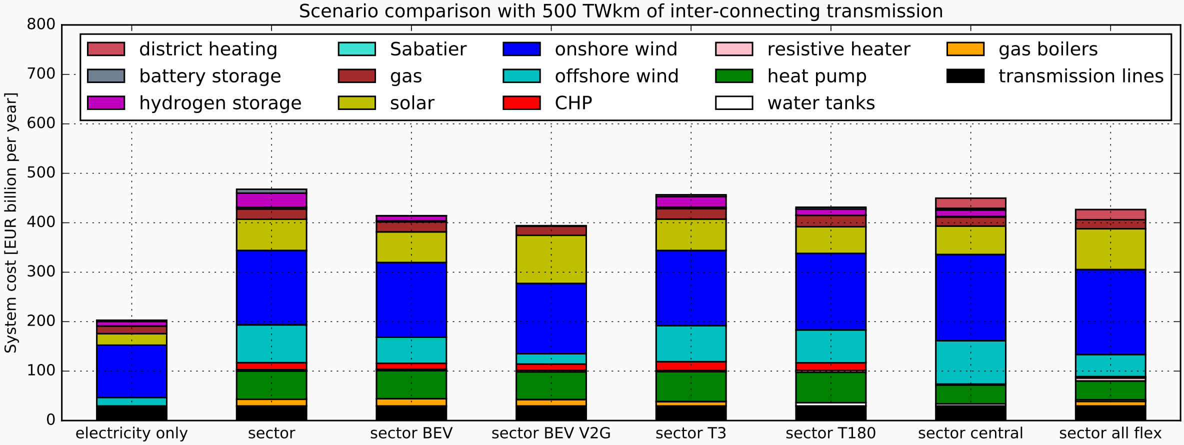


- Allowing short-term Thermal Energy Storage (TES) ($\tau = 3$ days) has only a 2% effect on the costs.
- Allowing long-term TES ($\tau = 180$ days) has a 7% effect on the costs, but cannot be done with decentralised heating.
- Using 60% centralised heating increases total costs due to district heating costs and not being able to use heat pumps.

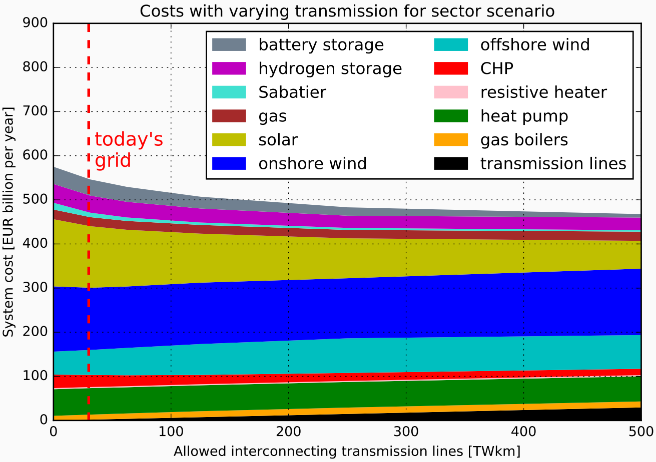
Scenario comparison with no inter-connecting transmission



Scenario comparison with optimal inter-connecting transmission

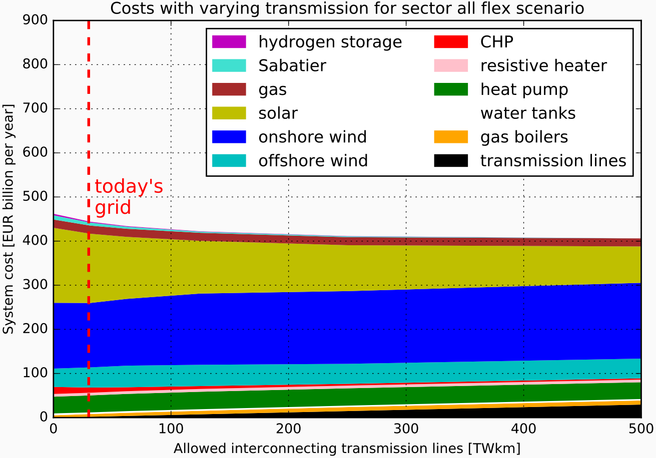


Sector Coupling with No Extra Flexibility



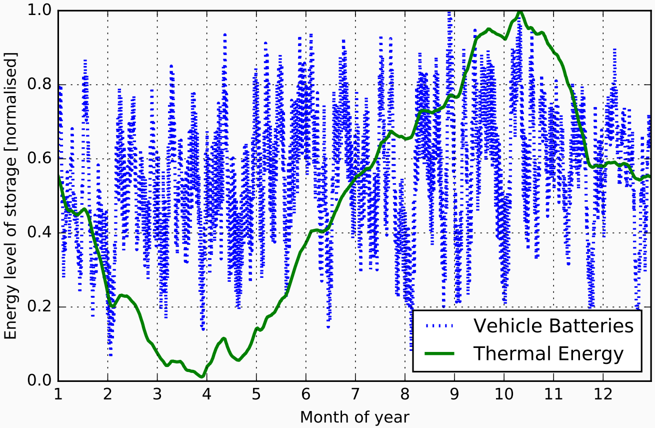
- Solution with no inter-connecting transmission costs 33% more than optimal transmission (comparable to electricity-only scenario)
- Gas boilers replace CHPs as transmission inceases, since transmission reduces need for gas for balancing in electricity sector
- Need stationary batteries and hydrogen storage to balance RES variability
- Transmission allows cheaper wind to substitute for solar power

Sector Coupling with All Extra Flexibilty (BEV, central and TES with $\tau = 180$ days



- The benefits of inter-connecting transmission are now much weaker: it reduces costs by only 12%
- Even with no transmission, the system is cheaper than all levels of transmission for sector-coupling with no sector flexibility
- System costs are comparable to today's (with same cost assumptions, today's system comes out around € 377 billion per year, excluding 'externalities')

Storage energy levels: different time scales



The different scales on which storage flexibility work can be seen clearly when examining the state of charge.

- Thermal Energy Storage (TES) has a dominant seasonal pattern, charging in summer and discharging in winter. Additional synoptic-scale fluctuations are super-imposed.
- Battery Electric Vehicles (BEV) with Vehicle-To-Grid (V2G) show large fluctuations on daily and synoptic scales.

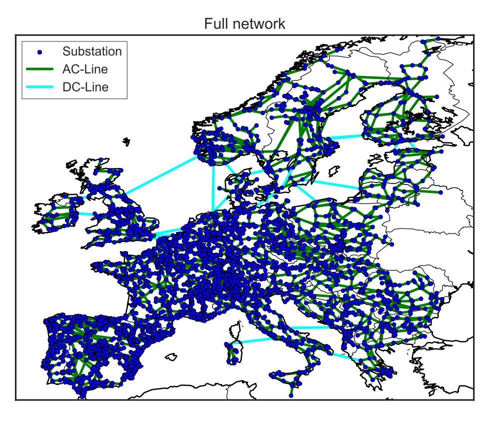
Spatial-Scale Dependence of Generation and Transmission Investment Optimisation

Spatial resolution

We need spatial resolution to:

- capture the geographical variation of renewables resources and the load
- capture spatio-temporal effects (e.g. size of wind correlations across the continent)
- represent important transmission constraints

BUT we do not want to have to model all 5,000 network nodes of the European system.



Source: Own representation of Bart Wiegman's GridKit extract of the online ENTSO-E map, https://doi.org/10.5281/zenodo.55853

Clustering: Many algorithms in the literature

There are lots of algorithms for clustering/aggregating networks, particularly in the engineering literature:

- k-means clustering on (electrical) distance
- k-means on load distribution
- Community clustering (e.g. Louvain)
- Spectral analysis of Laplacian matrix
- Clustering of Locational Marginal Prices with nodal pricing (sees congestion and RE generation)
- PTDF clustering
- Cluster nodes with correlated RE time series

The algorithms all serve different purposes (e.g. reducing part of the network on the boundary, to focus on another part).

k-means clustering on load & conventional generation

Cluster nodes based on load and conventional generation using k-means.

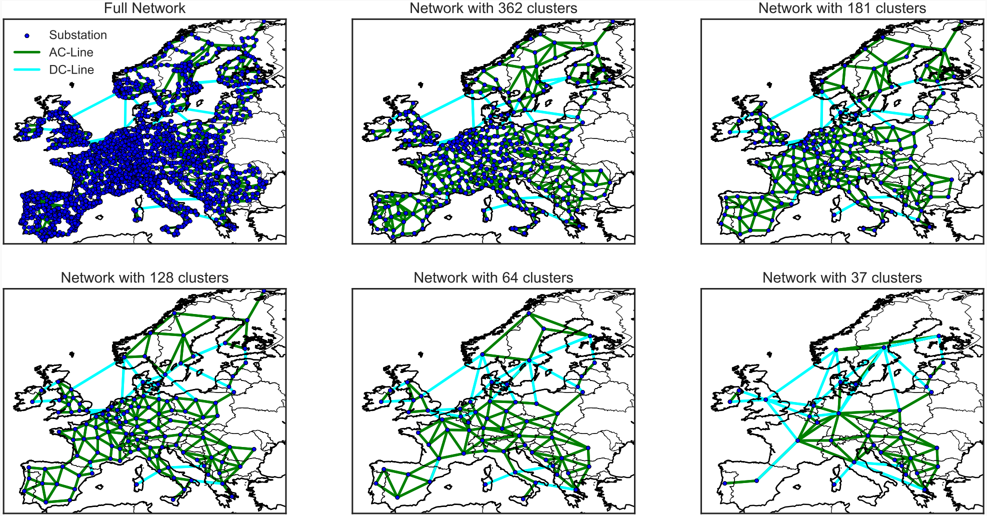
I.e. find k centroids and the corresponding k-partition of the original nodes that minimises the sum of squared distances from each centroid to its nodal members:

$$\min_{\{x_c\}} \sum_{c=1}^{k} \sum_{n \in N_c} w_n ||x_c - x_n||^2 \tag{1}$$

where each node is weighted w_n by the average load and the average conventional generation there.

NB: Totally ignores grid topology. It works because network was principally laid out between generation and load centers.

k-means clustering: Networks



Question of spatial resolution

How is the overall minimum of the cost objective (building and running the electricity system) affected by an increase of spatial resolution in each country?

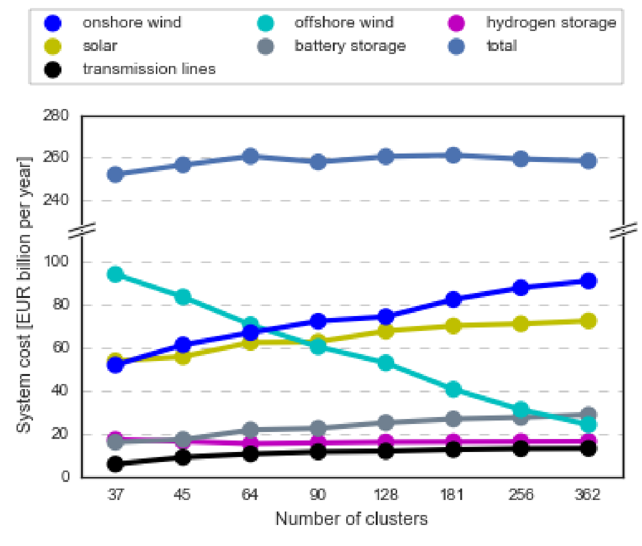
We expect

- A better representation of existing internal bottlenecks will prevent the transport of e.g. offshore wind to the South of Germany.
- Localised areas of e.g. good wind can be better exploited by the optimisation.

Which effect will win?

First we only optimize the gas, wind and solar generation capacities, the long-term and short-term storage capacities and their economic dispatch including the available hydro facilities; without grid expansion.

Costs: System cost and break-down into technologies (w/o grid expansion)

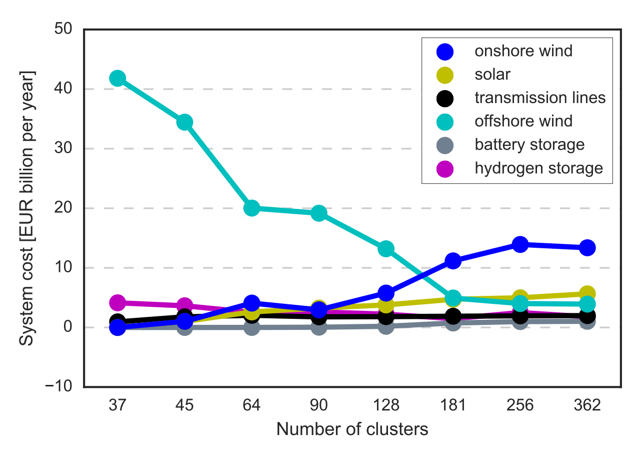


- Steady total system cost at 260 billion EUR (82 EUR/MWh)

BUT

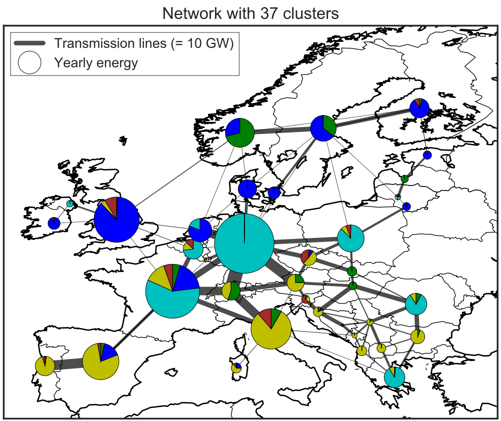
- Redistribution of capacities from offshore wind to onshore wind and solar
- Increasing solar share is accompanied by an increase of battery storage

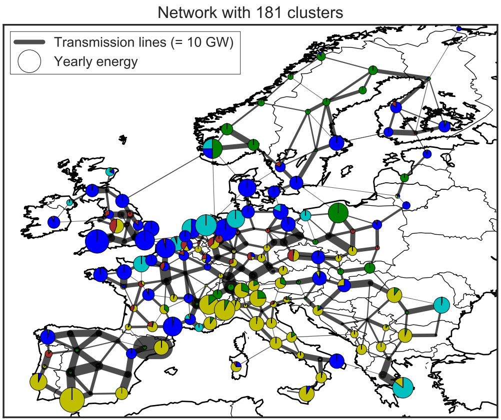
Costs: Germany (w/o grid expansion)



- Offshore wind dominated system is replaced by
- onshore wind and a moderate amount of solar, since
- the represented transmission bottlenecks make it impossible to transport the wind energy away from the coast, while
- the effective onshore wind capacity factors increase from 26% to up to 42%.

Nodal energy shares per technology (w/o grid expansion)





Interaction between network expansion and spatial scale

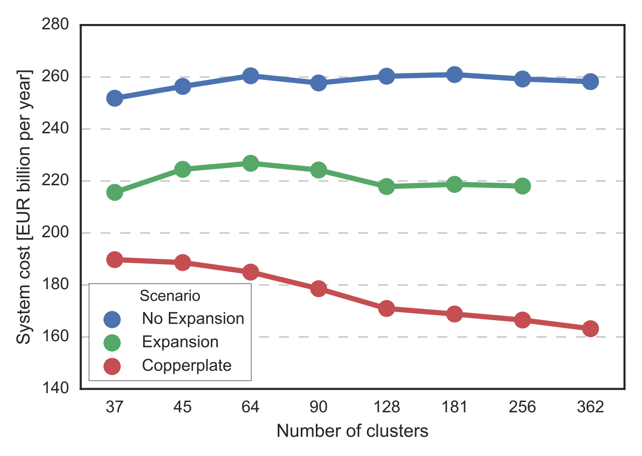
Three different scenarios of network expansion by constraining the overall transmission line volume in relation to today's line volume $\mathrm{CAP}_{\mathrm{trans}}^{\mathrm{today}}$, given length d_l and capacity $\bar{P}_l$ of each line l:

$$\sum_l d_l \bar{P}_l \leq \mathrm{CAP}_{\mathrm{trans}} \tag{2}$$

where

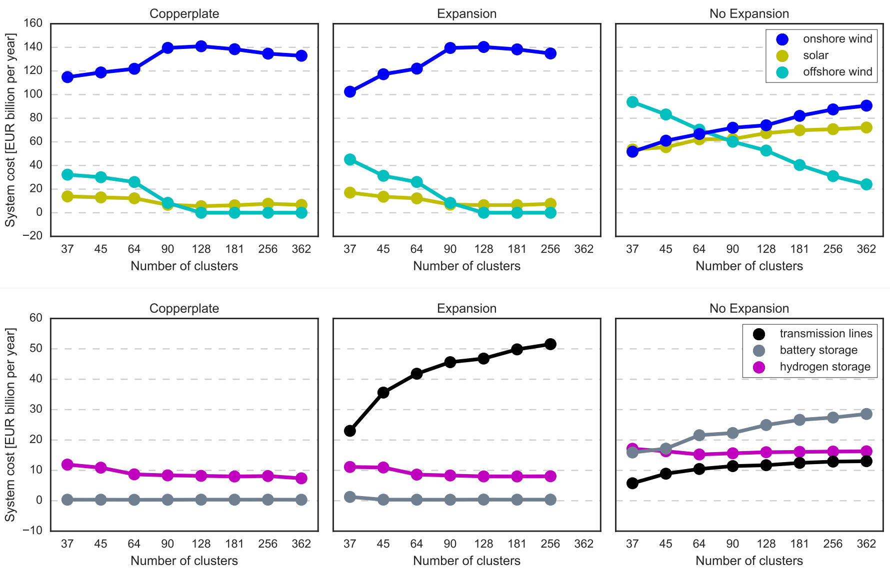
- $\mathrm{CAP}_{\mathrm{trans}} = \infty$ (Copperplate Scenario),
- $\mathrm{CAP}_{\mathrm{trans}} = 4\,\mathrm{CAP}_{\mathrm{trans}}^{\mathrm{today}}$ (Expansion Scenario) or
- $\mathrm{CAP}_{\mathrm{trans}} = \mathrm{CAP}_{\mathrm{trans}}^{\mathrm{today}}$ (No Expansion Scenario)

Costs: Total system cost



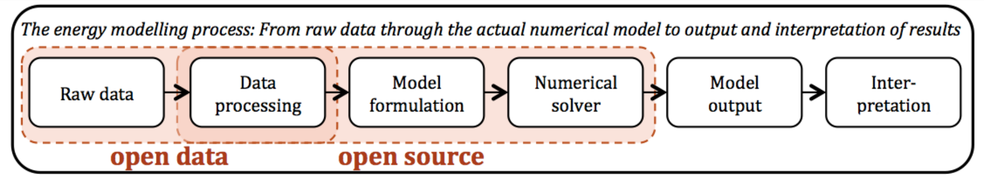
- Copperplate scenario isolates effects of better exploitation of good resource sites without interference of effect of higher network costs.
- More-or-less steady for the No Expansion and the Expansion scenario: The better RE availability balances the additional line costs.
- Only a moderate 20% increase in costs from the Expansion scenario to the No Expansion scenario.

Costs: Break-down into technologies



Idea of Open Energy Modelling

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



Open data + free software ⇒ Transparency + Reproducibility

There's an initiative for that, with a wiki, a lively mailing list and regular workshops:

openmod open energy modelling initiative

openmod-initiative.org

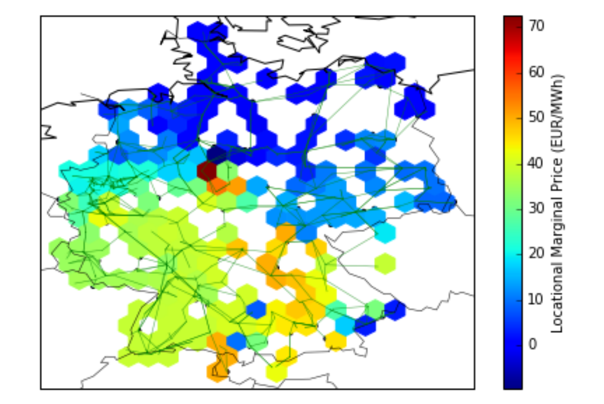
Source: openmod initiative

Python for Power System Analysis (PyPSA)

The FIAS software PyPSA is online at `http://pypsa.org/` and on github. It can do:

- Static power flow
- Linear optimal power flow
- Security-constrained linear optimal power flow
- Total electricity system investment optimisation

It has models for storage, meshed AC grids, meshed DC grids, hydro plants, variable renewables and sector coupling.



Conclusions

Conclusions

- The questions are no longer *whether a renewable system is possible* or *whether it can be affordable*; rather it is what compromises will we make and how much will they cost?
- System costs can be comparable to today's (excluding vehicle capital costs), if we allow lots of onshore wind, international grid expansion and sector-coupling flexibility.
- However, solutions with no or little transmission but more solar and storage are only between 14% and 33% more expensive, which gives policy-makers scope.
- Flexible sector coupling using grid-friendly Battery Electric Vehicles can reduce costs by 20% by eliminating the need for almost all stationary electricity storage.
- Increasing the spatial resolution to see local grid bottlenecks may not have a big effect on total costs (since it is offset by better resource exploitation) but it does cause a shift in technologies from offshore wind to onshore wind and solar.
- Understanding the need for flexibility at different temporal and spatial scales is key to mastering the complex interactions in the energy system

Copyright

The source LaTeX, self-made graphics and Python code used to generate the self-made graphics are available here:

`http://nworbmot.org/talks.html`