The Role of Spatial Scale in Joint Optimisations of Generation and Transmission for Highly Renewable Scenarios

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The Challenges of Optimising Highly Renewable Energy Systems

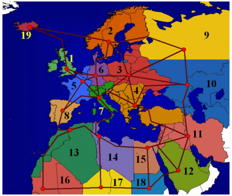
Three questions to answer

- How can we evaluate the two competing concepts for the ‘Energy Transition’: local, decentralised solar+storage versus large continental grids+wind?
- What are the consequences for the ‘Energy Transition’ if grid expansion is limited due to public acceptance problems?
- What is the consequence of modellers’ choice of spatial scale on optimisations of the energy system?

Examples from literature of energy system optimisation

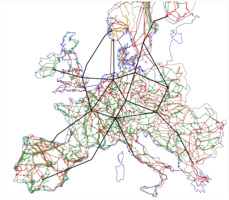
Study	Scope	Spatial resolution	Temporal resolution	What?	Flow physics
Czisch (2005)	MENA	low	high	electricity (gen and grid)	transport
Hagspiel et al. (2014)	EU	medium	low	electricity (gen and grid)	linear
Egerer et al. (2014)	EU	high	low	electricity (grid only)	linear
Fraunhofers ISE, IWES	DE	none	high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

Czisch



Hagspiel et al.

Egerer et al.



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.

Optimising Generation and Transmission Jointly

Linear optimisation problem

Objective is the minimisation of total annual system costs, composed of capital costs c_* (investment costs) and operating costs o_* (fuel ,etc.):

$$\min f(\bar{P}_\ell, \bar{g}_{n,s}, g_{n,s,t}) = \sum_\ell c_l \bar{P}_\ell + \sum_{n,s} c_{n,s} \bar{g}_{n,s} + \sum_{n,s,t} w_t o_{n,s} g_{n,s,t}$$

We optimise for n nodes, representative times t and transmission lines l:

- the transmission capacity $\bar{P}_\ell$ of all the lines ℓ
- the generation and storage capacities $\bar{g}_{n,s}$ of all technologies (wind/solar/gas etc.) s at each node n
- the dispatch $g_{n,s,t}$ of each generator and storage unit at each point in time t

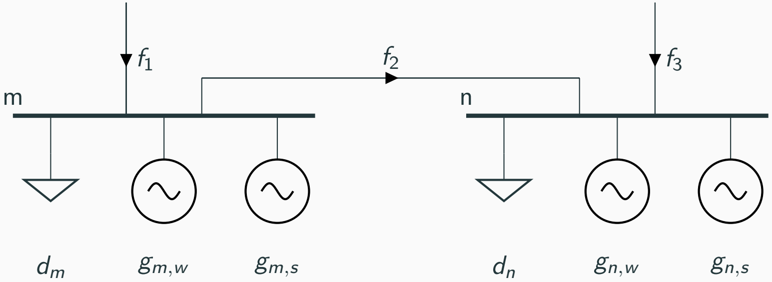
Representative time points are weighted w_t such that $\sum_t w_t = 365 * 24$ and the capital costs c_* are annualised, so that the objective function represents the annual system cost.

Constraints 1/5: Nodal energy balance

Demand $d_{n,t}$ at each node n and time t is always met by generation/storage units $g_{n,s,t}$ at the node or from transmission flows $f_{\ell,t}$ on lines attached at the node (Kirchhoff's Current Law):

$$d_{n,t} = \sum_s g_{n,s,t} + \sum_{\ell \in n} f_{\ell,t} \qquad \leftrightarrow \qquad \lambda_{n,t}$$

Nodes are shown as thick busbars connected by transmission lines (thin lines):

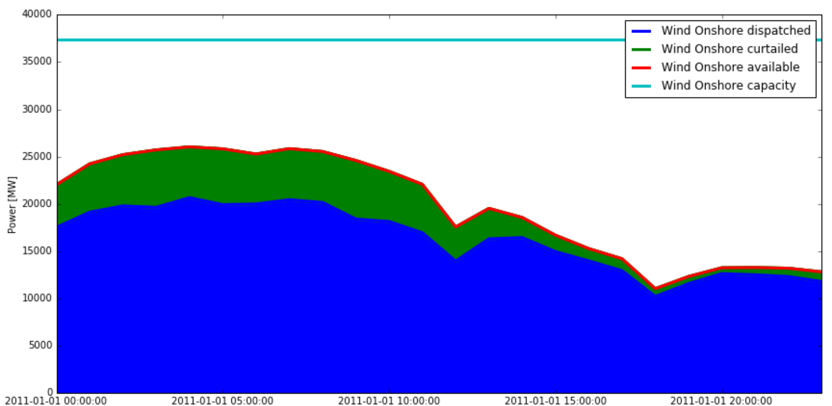


$d_m = g_{m,w} + g_{m,s} + f_1 - f_2$ $\qquad$ $d_n = g_{n,w} + g_{n,s} + f_2 + f_3$

Constraints 2/5: Generation availability

Generator/storage dispatch $g_{n,s,t}$ cannot exceed availability $\bar{g}_{n,s,t}$, which is bounded by capacity $\bar{g}_{n,s}$ and installable potential $\hat{g}_{n,s}$. Both the dispatch $g_{n,s,t}$ and the capacity $\bar{g}_{n,s}$ are subject to optimisation.

$$0 \leq g_{n,s,t} \leq \bar{g}_{n,s,t} \leq \bar{g}_{n,s} \leq \hat{g}_{n,s}$$



Constraints 3/5: Storage consistency

Storage units such as batteries or hydrogen storage can work in both storage and dispatch mode. They have a limited energy capacity (state of charge).

$$soc_{n,t} = \eta_0 soc_{n,t-1} + \eta_1 g_{n,t,\mathrm{store}} - \eta_2^{-1} g_{n,t,\mathrm{dispatch}}$$

There are efficiency losses η; hydroelectric dams can also have a river inflow.

Constraints 4/5: Transmission Flows

The linearised power flows f_ℓ for each line $\ell \in \{1, \dots L\}$ in an AC network are determined by the reactances x_ℓ of the transmission lines and the net power injection at each node p_n for $n \in \{1, \dots N\}$.

The flows are related to the angles at the nodes:

$$f_\ell = \frac{\theta_i - \theta_j}{x_\ell} \tag{1}$$

In addition, the angle differences around each cycle must add to zero (Kirchoff's Voltage Law).

Transmission flows cannot exceed the thermal capacities of the transmission lines (otherwise they sag and hit buildings/trees):

$$|f_{\ell,t}| \leq \bar{P}_\ell$$

Since the impedances x_ℓ change as capacity $\bar{P}_\ell$ is added, we do multiple runs and iteratively update the x_ℓ after each run, rather than risking a non-linear (or MILP) optimisation.

Constraints 5/5: Global constraints on CO_2 and transmission volumes

CO_2 limits are respected, given emissions $e_{n,s}$ for each fuel source s:

$$\sum_{n,s,t} g_{n,s,t} e_{n,s} \leq \mathrm{CAP}_{\mathrm{CO}_2} \qquad \leftrightarrow \qquad \mu_{\mathrm{CO}_2}$$

We enforce a reduction of CO_2 emissions by 95% compared to 1990 levels, in line with German and EU targets for 2050.

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

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

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

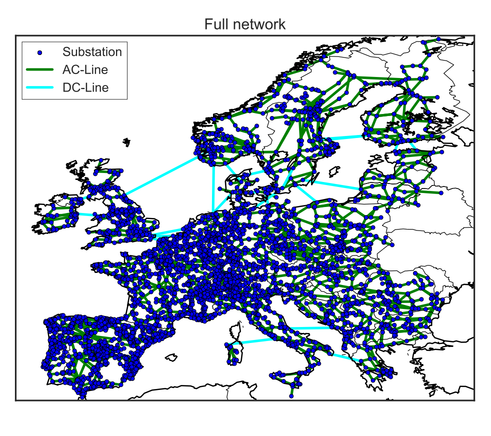
Spatial-Scale Dependence of Generation and Transmission Investment Optimisation

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

Our goal: maintain main transmission corridors of today to investigate highly renewable scenarios with no grid expansion. Since generation fleet is totally rebuilt, do not want to rely on current generation dispatch (like e.g. LMP algorithm).

Today's grid was laid out to connect big generators and load centres.

Solution: Cluster nodes based on load and conventional generation capacity 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:

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

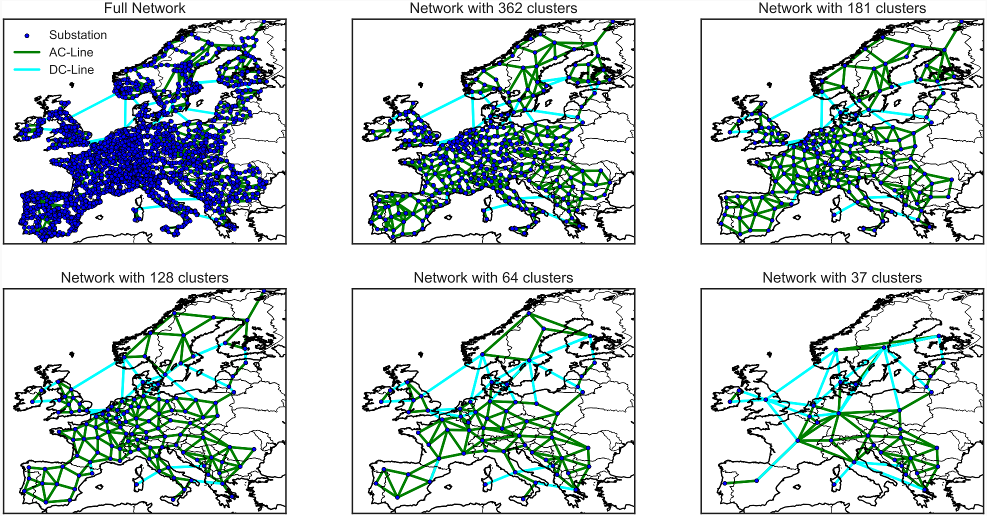
where each node is weighted w_n by the average load and the average conventional generation there.

Reconstitution of network

Once the partition of nodes is determined:

- A new node is created to represent each set of clustered nodes
- Hydro capacities and load is aggregated at the node; VRE (wind and solar) time series are aggregated, weighted by capacity factor; potentials for VRE aggregated
- Lines between clusters replaced by single line with length 1.25 $\times$ crow-flies-distance, capacity and impedance according to replaced lines
- $n - 1$ blanket safety margin factor grows from 0.3 with ≥ 200 nodes to 0.5 with 37 nodes (to account for aggregation)

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?

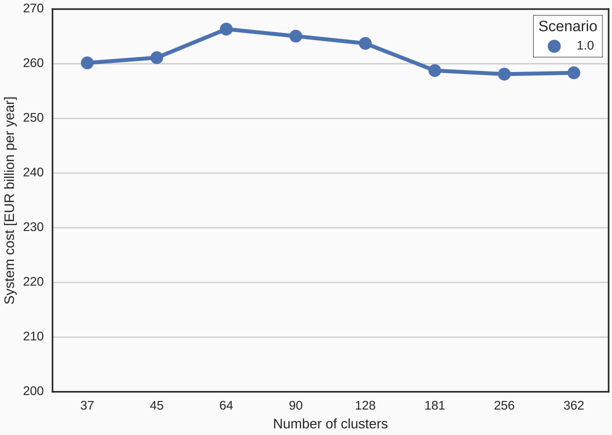
We expect

- 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?

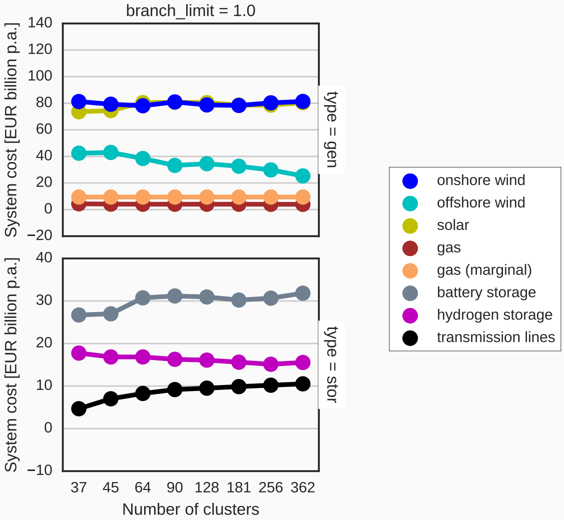
First we only optimize the gas, wind and solar generation capacities, the long-term and short-term storage capacities and their economic dispatch including the available hydro facilities without grid expansion.

Costs: System cost w/o grid expansion



- Steady total system cost at € 260 billion per year
- This translates to € 82/MWh (compared to today of € 50/MWh to € 60/MWh)

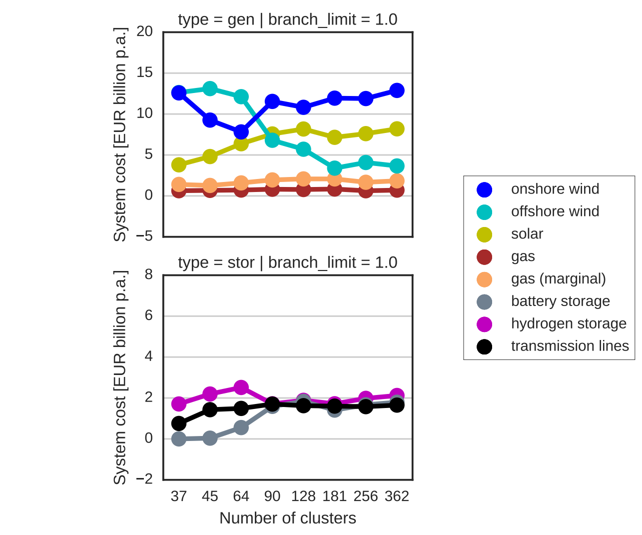
Costs: System cost and break-down into technologies (w/o grid expansion)



If we break this down into technologies:

- 37 clusters captures around half of total network volume
- Redistribution of capacities from offshore wind to solar
- Increasing solar share is accompanied by an increase of battery storage
- Single countries do not stay so stable

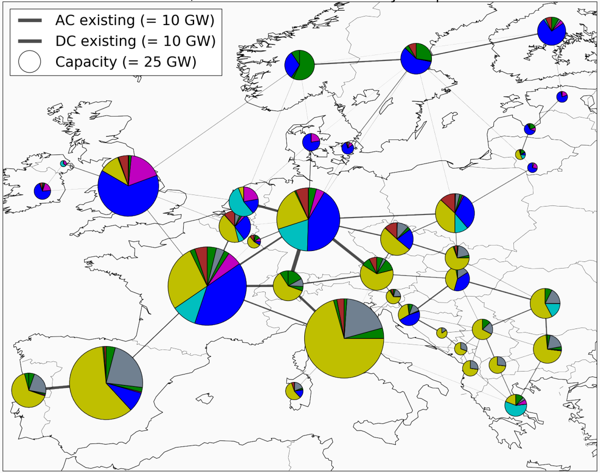
Costs: Focus on Germany (w/o grid expansion)



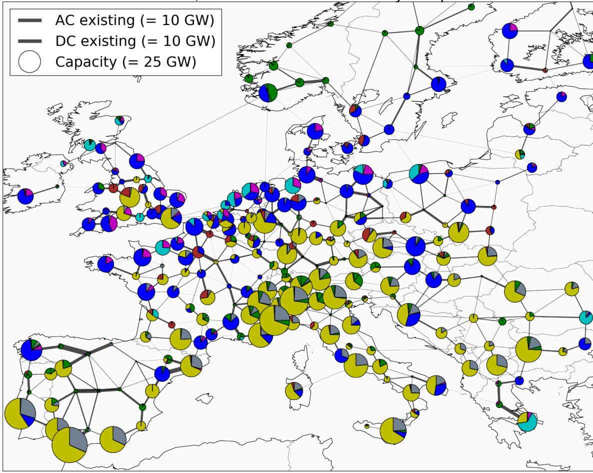
- Offshore wind replaced by onshore wind at better sites and solar (plus batteries), since the represented transmission bottlenecks make it impossible to transport the wind energy away from the coast
- the effective onshore wind capacity factors increase from 26% to up to 42%
- Investments stable at 181 clusters and above

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

37 clusters, branch limit of 1 of today's capacities



256 clusters, branch limit of 1 of today's capacities



Interaction between network expansion and spatial scale

6 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:

$$\bar{P}_l \geq \bar{P}_l^{\mathrm{today}} \tag{3}$$

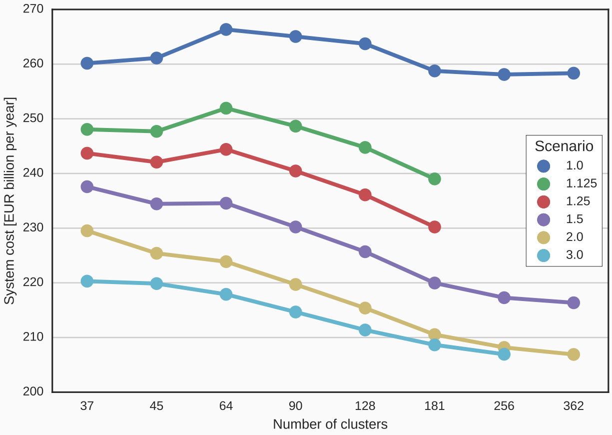
$$\sum_l d_l \bar{P}_l \leq \mathrm{CAP}_{\mathrm{trans}} \tag{4}$$

where

$$\mathrm{CAP}_{\mathrm{trans}} = x\, \mathrm{CAP}_{\mathrm{trans}}^{\mathrm{today}} \tag{5}$$

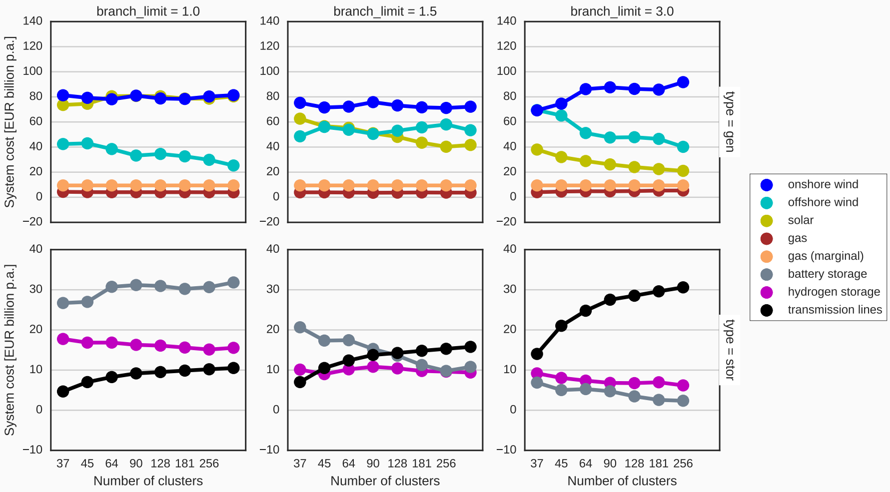
for $x = 1$ (today's grid) $x = 1.125, 1.25, 1.5, 2,$ $x = 3$ (optimal for overhead line at high number of cluster).

Costs: Total system cost

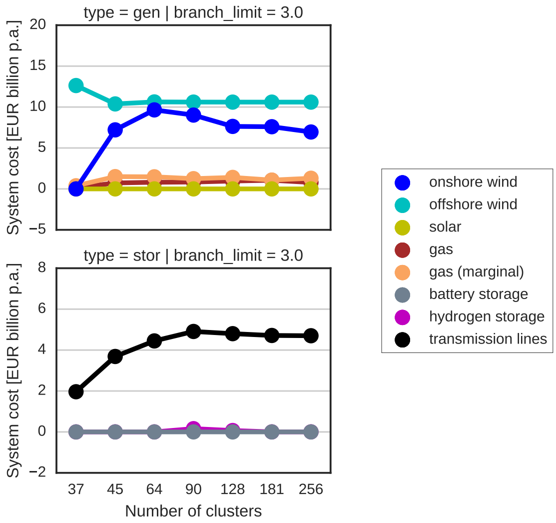


- Steady cost for No Expansion (1)
- For expansion scenarios, as clusters increase, the better expoitation of good sites decreases costs faster than transmission bottlenecks increase them
- Decrease in cost is v. non-linear as grid expanded (25% grid expansion gives 50% of optimal cost reduction)
- Only a moderate 20 – 25% increase in costs from the Optimal Expansion scenario (3) to the No Expansion scenario (1).

Costs: Break-down into technologies

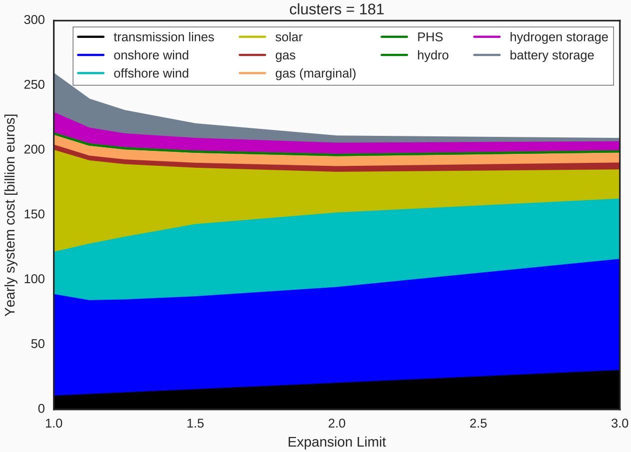


Costs: Focus on Germany (CAP = 3)



- Investment reasonably stable at 128 clusters and above
- System consistently dominated by wind
- No solar or battery for any number of clusters

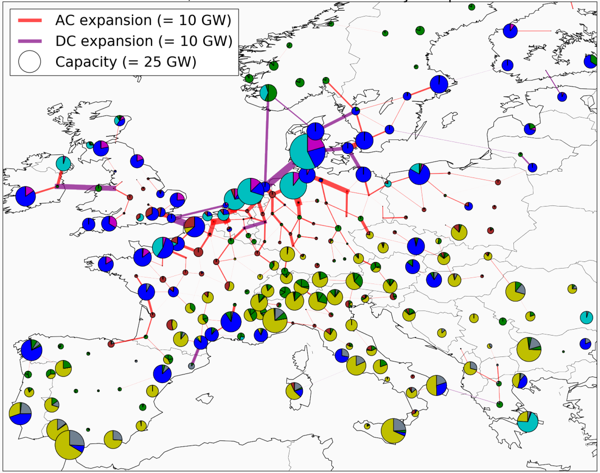
Behaviour as CAP is changed



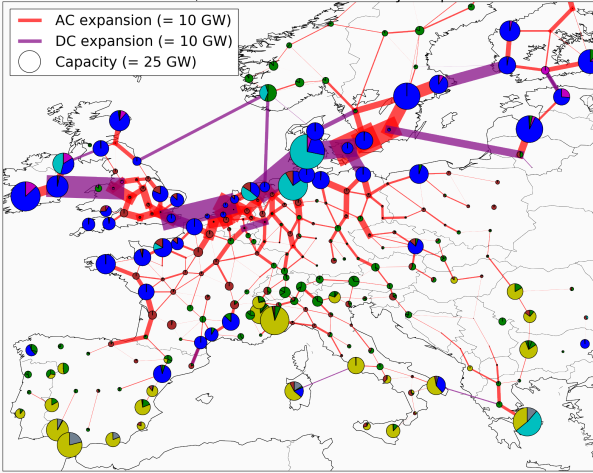
- Same non-linear development with high number of nodes that we saw with one node per country
- Most of cost reduction happens with small expansion; cost rather flat once capacity has doubled, reaching minimum (for overhead lines) at 3 times today's capacities
- Solar and batteries decrease significantly as grid expanded
- Reduction in storage losses too

With expansion

256 clusters, branch limit of 1.5 of today's capacities

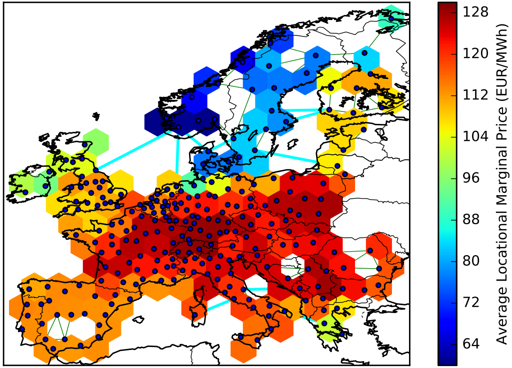


256 clusters, branch limit of 3 of today's capacities

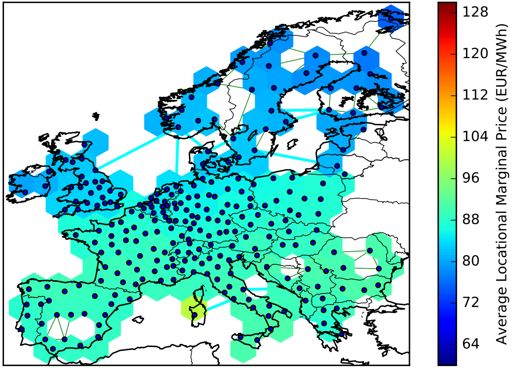


Locational Marginal Prices CAP=1 versus CAP=3

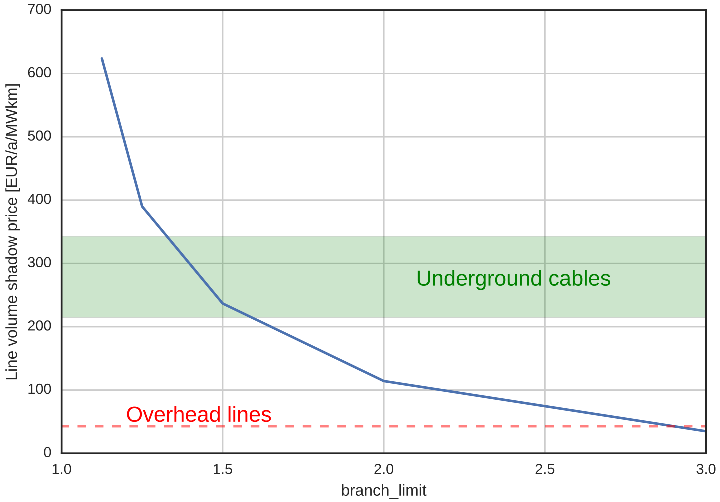
With today's capacities:



With three times today's grid:

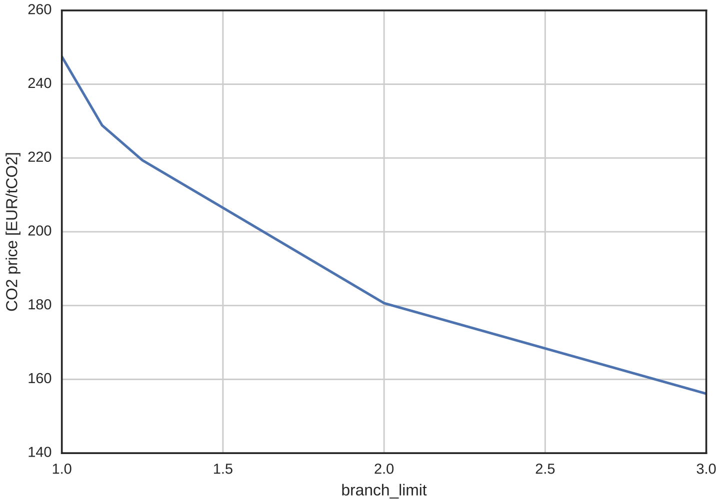


Grid expansion CAP shadow price for 181 nodes as CAP relaxed



- With overhead lines the optimal system has around 3 times today's transmission volume
- With underground cables (5-8 times more expensive) the optimal system has around 1.3 to 1.6 times today's transmission volume

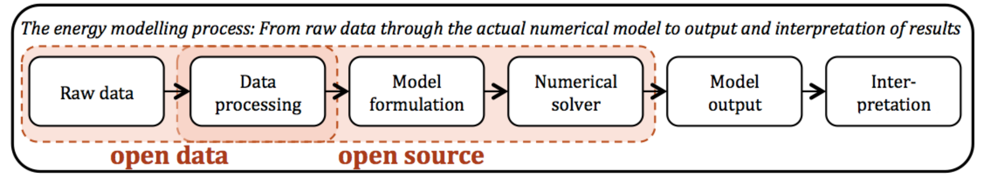
CO2 prices versus line cap for 181 clusters



- CO_2 price of between 150 and 250 €/tCO_2 required to reach these solutions, depending on line volume cap

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! Next workshop in Frankfurt, 19-21 April 2017.

openmod open energy modelling initiative

openmod-initiative.org

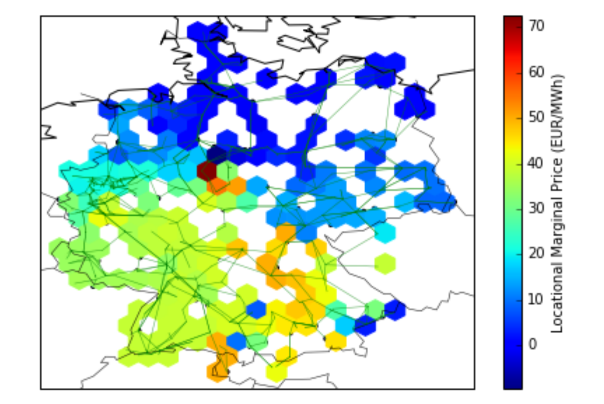
Source: openmod initiative

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

- This is no single solution for highly renewable systems, but a family of solutions with different costs and compromises
- Generation costs always dominate grid costs, but the grid can cause higher generation costs if expansion is restricted
- Systems with no grid extension beyond today are up to 25% more expensive, but small grid extensions (e.g. 25% more capacity than today) can lock in big savings
- Need at least around 200 clusters for Europe to see grid bottlenecks if no expansion
- Can get away with $\sim$ 120 clusters for Europe if grid expansion is allowed
- Much of the stationary storage needs can be eliminated by sector-coupling: DSM with electric vehicles, thermal storage; this makes grid expansion less beneficial
- Understanding the need for flexibility at different temporal and spatial scales is key to mastering the complex interactions in the energy system

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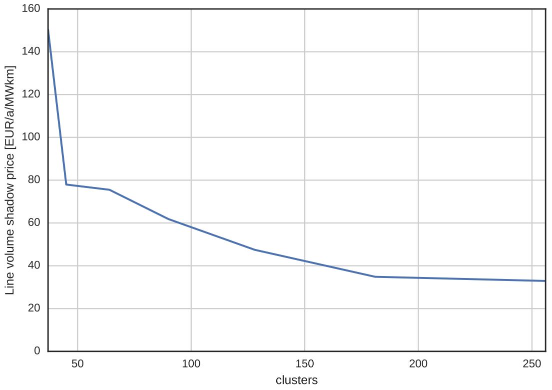
Cost and other assumptions

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.

Shadow costs of line extension CAP for 3 times today's volume



- For 200+ nodes the shadow price converges on the annual cost of a MWkm of overhead line (around € 30/a/MWkm)
- Value of lines is much higher with smaller number of clusters. Why?
- Possible reasons: inter-connectors in general weaker than country-internal connectors; more nodes means more flexibility to avoid network expansion