Energy Systems, Summer Semester 2025
Lecture 14: Research Topics

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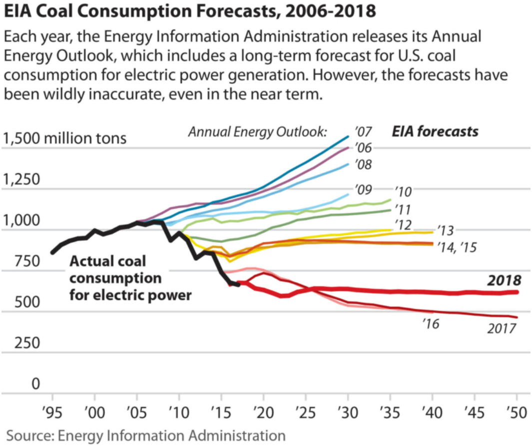
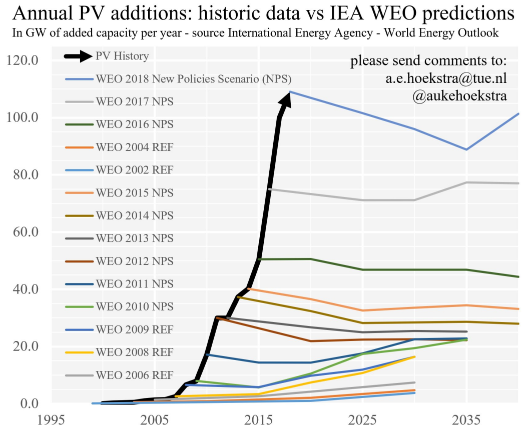
The World is Not a Perfect Optimization Model

We should be skeptical about models and modellers





We should be skeptical about models and modellers

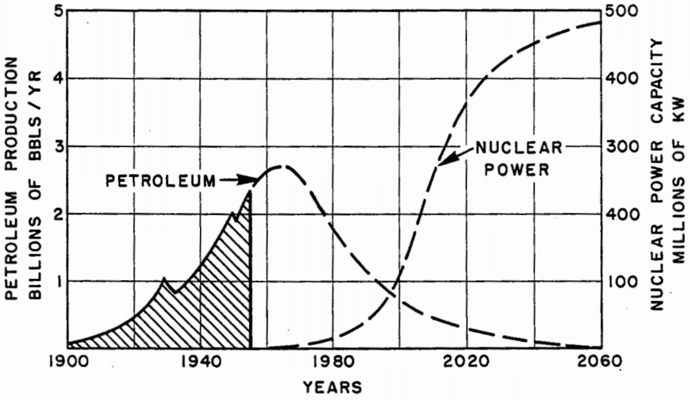


Figure 29 – Concurrent decline of petroleum production and rise of production of nuclear power in the United States. Growth rate of 10 percent per year for nuclear power is assumed; actual rate may be twice this amount.

- Possible scenario projected from 1956 by US geologist M. King Hubbert
- Oil production in the US did indeed peak in the 1970s, but returned to peak height in last decade thanks to shale oil extraction with fracking
- Nuclear expanded but plateaued
- **What might we be getting wrong in the 2020s?**

Source: Hubbert, 1956

We should be skeptical about models and modellers

Models can:

- **under- or overestimate rates of change** (e.g. under: PV uptake, over: onshore wind in UK/Germany/Netherlands)
- **underestimate social factors** (e.g. concern about nuclear / transmission / wind)
- **extrapolate based on uncertain data** (e.g. oil reserves, learning curves for PV)
- **focus on easy-to-solve rather than policy-relevant problems** (e.g. most research)
- **neglect uncertainty** (e.g. in short-term due to weather forecasts, or in long-term due to cost, political uncertainty and technological development)
- **neglect need for robustness** (e.g. securing energy system against contingencies, attack)
- **neglect complex interactions of markets and incentive structures** (e.g. abuse of market power, non-linearities not represented in models, lumpiness, etc.)
- **neglect non-linearities and non-convexities** (e.g. power flow, or also learning curves, behavioural effects, perverse local optima, many, many more)

Alternative modelling paradigms to optimisation

Not all models use optimisation. There are alternatives, such as:

- **Simulation models** Advantages: can run efficiently, tend to be more transparent, can include more complicated effects. Disadvantages: no mathematical proof of optimality.
- **Systems dynamics** Advantages: can capture long-run dynamics better, non-linear feedbacks. Disadvantages: potentially hard to parameterise, computation challenges.
- **Agent-based modelling** Advantages: can do detailed parameterisation of social behaviour, can capture emergent effects. Disadvantages: only as good as the parameterisation, computation challenges.

Robustness to Different Weather Years

Different Weather Years

Many of the simulations we looked at in this course, and many in the literature, used single weather years to determine optimal investments.

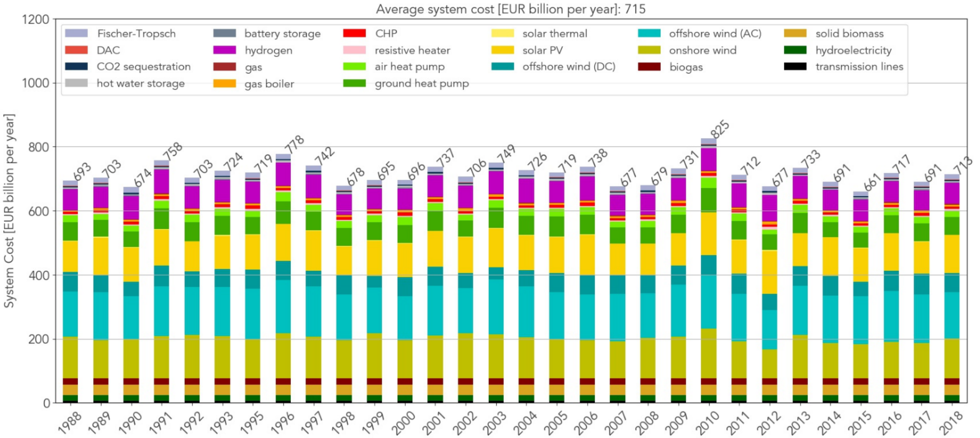
This is problematic since:

- Weather changes from year to year
- There are decadal variations of wind
- Demand changes (particularly space heating demand during cold years)

But computing investments against 30 years of data (262,800 hours) is not feasible.

Different Weather Years

If we use different weather years to optimize sector-coupled European model with net-zero CO_2 emissions (including industry) we see broadly stable technology choices but variations in total system costs of up to 20%. NB: In real world cannot reoptimize investment every year!



Source: Lin Yang MA thesis

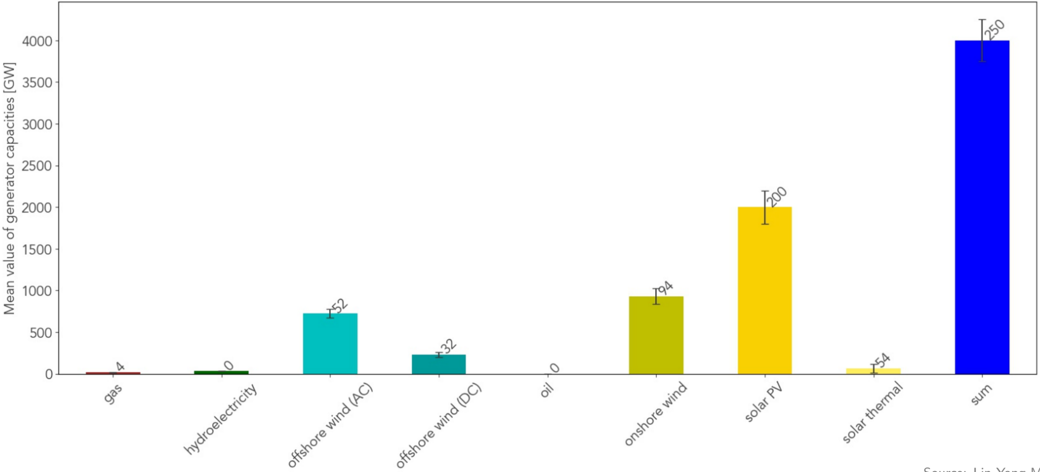
Different Weather Years

Biggest changes are driven by space heating demand. Cold years (like 2010) are more expensive.

Source: Lin Yang MA thesis

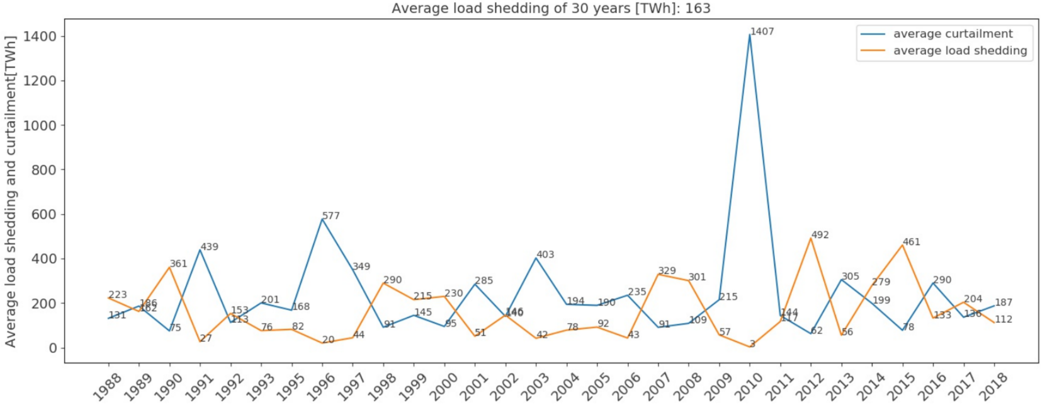
Different Weather Years

Optimal technology investments do not change dramatically from year to year. Here we show the mean capacities with standard deviation.



Source: Lin Yang MA thesis

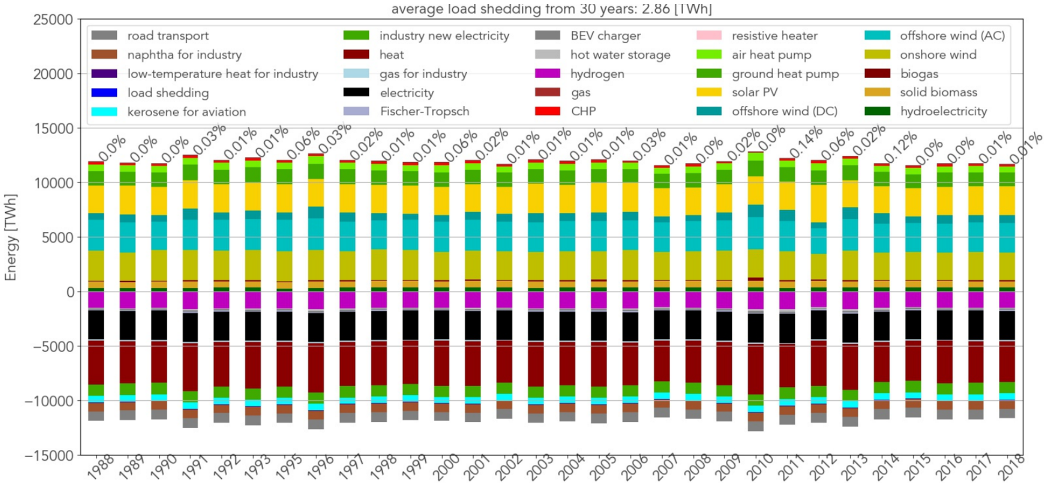
If we fix the optimal technology investments based on the weather of one year (x-axis), then run the dispatch over all 30 years (900 simulations in total), we can assess average curtailment and load-shedding. Using coldest year 2010 gives low load-shedding but high curtailment.



Source: Lin Yang MA thesis

Using 2010 investments

Using coldest year 2010 guarantees virtually no load-shedding in entire 30 years, but leads to excess energy in most years. Better to store excess energy from warmer years (e.g. chemically).



Source: Lin Yang MA thesis

Effects of Climate Change on Energy System

- What are the consequences of climate change for highly renewable energy systems?
- How will generation patterns for wind and solar change?
- What will be the effects on the dimensioning of wind, solar, storage, networks and backup generation?

Climate change scenarios: RCP 8.5

Take a simulated dataset of how the weather would look between today and the year 2100 with a scenario of high concentrations of greenhouse gases.

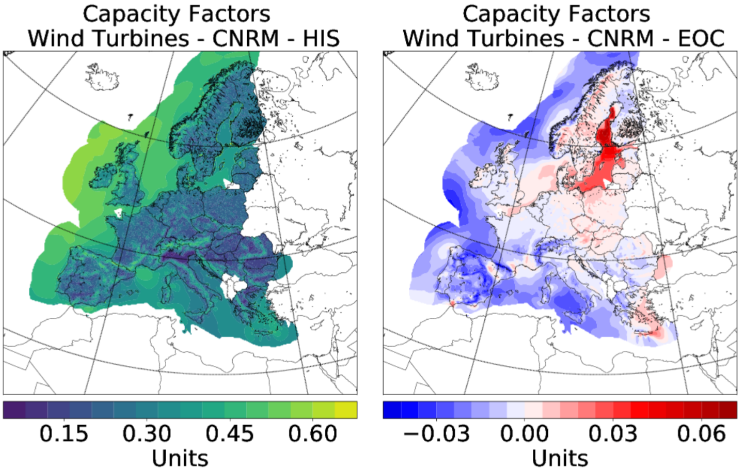
The scenario is called Representative Concentration Pathways 8.5 (RCP 8.5), since it estimates a radiative forcing of $\Delta P = 8.5\ \mathrm{W/m^2}$ (difference between insolation and energy radiated into space) at the end of the century. It is a **worst-case scenario** and extrapolates current greenhouse gas emissions without reduction efforts (improbable given current trajectories of coal, renewables and EVs). This corresponds to a CO_2-equivalent-concentration (including all forcing agents) of approximately 1250 ppm (today around 410 pmm for CO_2) and an average temperature increase of $\Delta T = 3.7 \pm 1.1$ C at the end of the century, dependent on the model used.

Compare historical values (HIS) to begin/middle/end of the century (B/M/EOC).

Changes to wind capacity factors

Left: historic (HIS) wind capacity factors 1970-2005

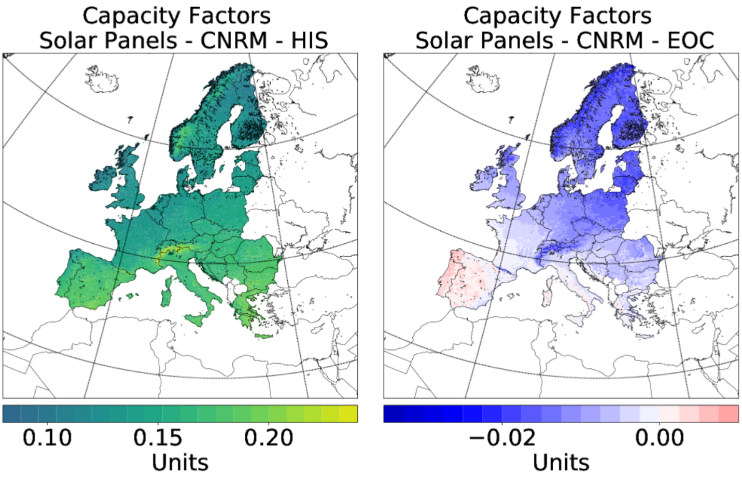
Right: change at end of century (EOC) 2070-2100



- Small ($\sim 5\%$) average increase in Northern Europe
- Small ($\sim 5\%$) average decrease in Southern Europe

Source: Schlott et al, 2018

Changes to solar capacity factors

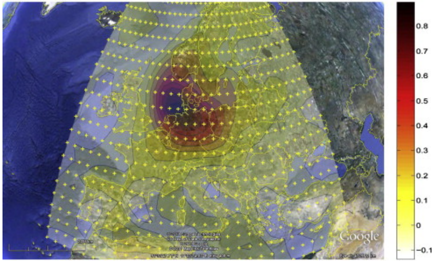


- Small ($\sim 5\%$) increase in in Southern Europe around Mediterranean
- Smallish ($\sim 10\%$) decrease in Northern Europe (due to increased cloud cover)
- Solar results known to be a little unreliable because of cloud modelling etc.

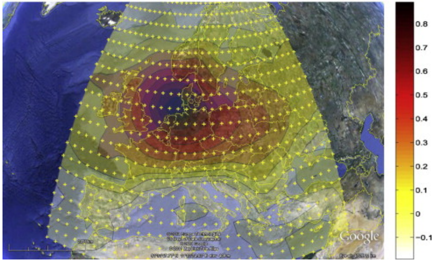
Source: **Schlott et al, 2018**

Correlation Length

(a) Summer-day



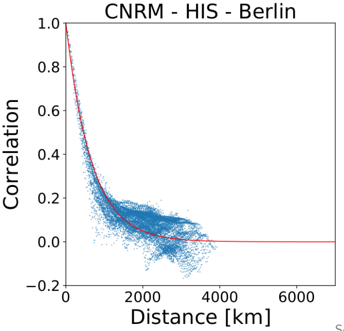
(b) Winter-day



The Pearson correlation coefficient of wind time series with a point in northern Germany decays exponentially with distance. Determine the **correlation length** L by fitting the function:

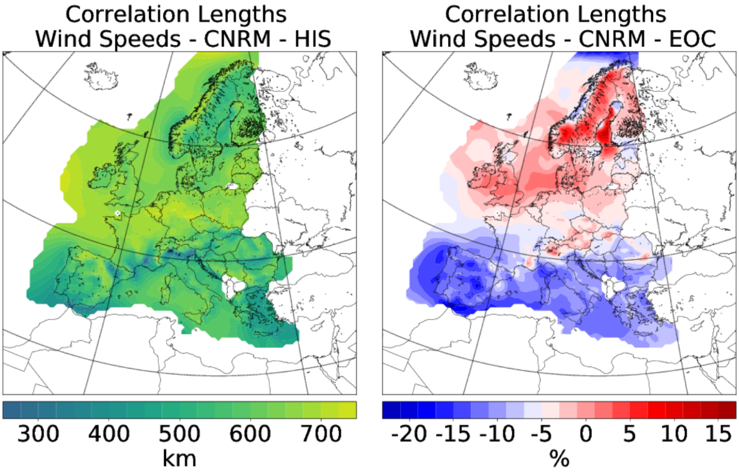
$$\rho \sim e^{-\frac{x}{L}}$$

to the radial decay with distance x.



Source: Hagspiel et al, 2012

Changes to wind speed correlation lengths



- Correlation lengths are longer in the North than the South because of big weather systems that roll in from the Atlantic to the North (in the South they get dissipated).
- With global warming, correlation lengths grow longer in the North and shorter in the South.
- This is because weather systems have more energy and are bigger in the North.

Source: Schlott et al, 2018

Effects of climate change on power system

Conclusions from study of effects on the power system:

- Most effects are small ($\sim 5-10\%$); total system costs increase by only 5%.
- Longer correlation lengths see greater benefit from continental transmission.
- Impact of climate change is of a similar magnitude to the uncertainty between the different weather models.
- Not considered: Space heating and cooling demand changes may have bigger effect on overall energy system.
- Not considered: Impact of extreme weather events (storms, fires, droughts).

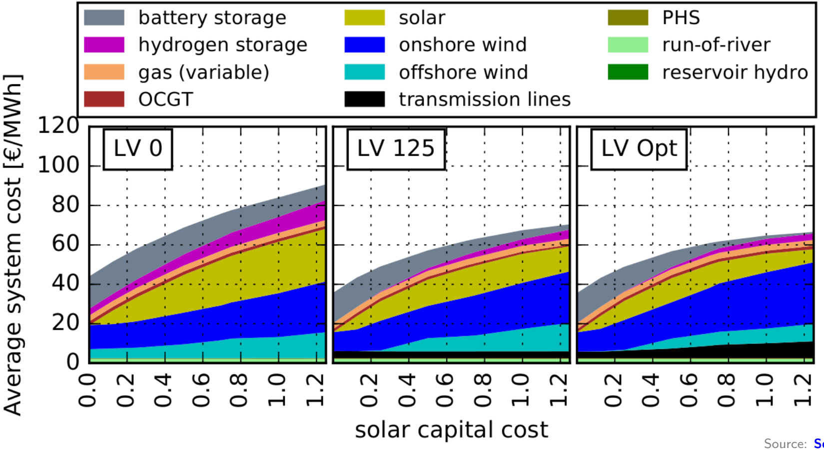
For more results, see 'The Impact of Climate Change on a Cost-Optimal Highly Renewable European Electricity Network,' **https://arxiv.org/abs/1805.11673**

Cost and Political Uncertainty

Power System Model: Sensitivity to Changing Solar Cost

In 30-node European electricity system with 95% CO_2 reduction, change solar capital cost relative to default. NB: Even at zero solar cost, there is still wind. Why? Seasonality.

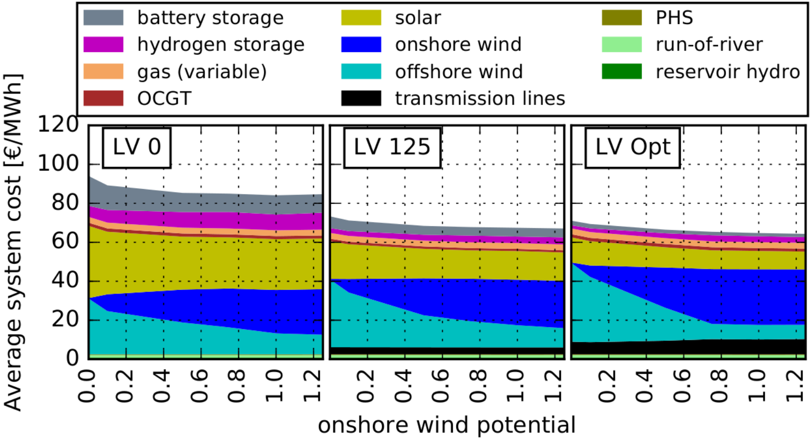
LV 0: No cross-border grid, LV 125: compromise grid, LV Opt: optimal grid.



Source: Schlachtberger et al, 2018

In electricity system with 95% CO_2 reduction, reduce installable potential for onshore wind.

Onshore substituted with offshore at only small extra system cost. BUT assumes sufficient grid capacity within each country to get offshore from coast to load.



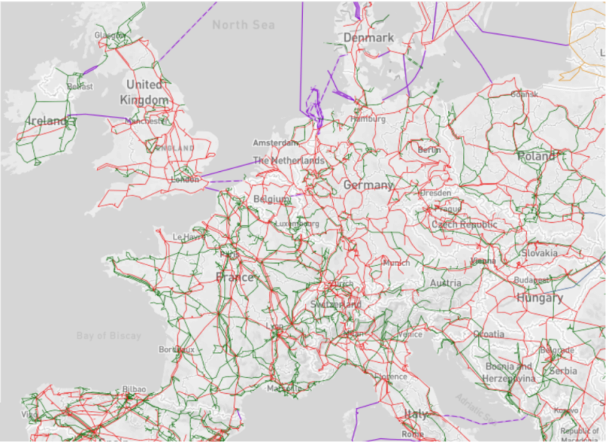
Source: Schlachtberger et al, 2018

See Schlachtberger et al, 'Cost optimal scenarios of a future highly renewable European electricity system: Exploring the influence of weather data, cost parameters and policy constraints,' 2018, https://arxiv.org/abs/1803.09711

Effect of Spatial Scale on Results of Energy System Optimisations

Motivation: Transmission bottlenecks

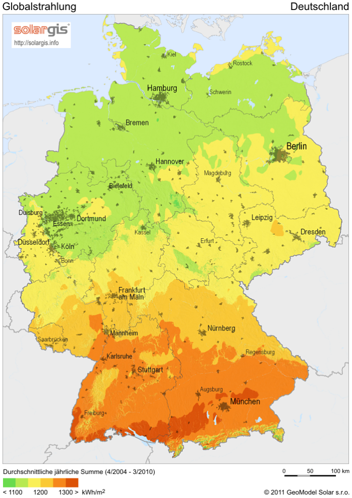
Many of the results we've examined so far have aggregated countries to a single node. However, there are also transmission network bottlenecks **within** countries (e.g. North to South Germany).

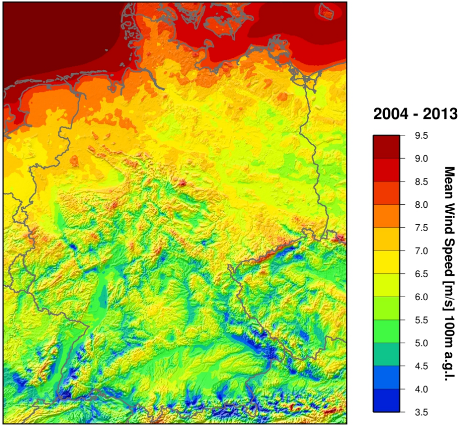


Source: ENTSO-E

Motivation: Wind and solar resource variation

There is also considerable variation in wind and solar resources...





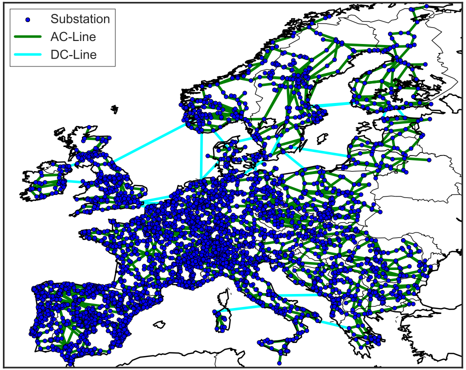
Spatial resolution

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.

Full network



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 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).

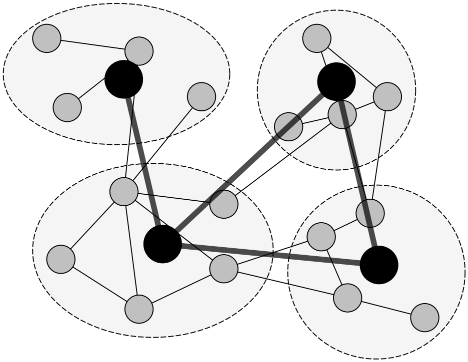
Not always tested on real network data.

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 spatial distribution using k-means, with a weighting to sites with higher average load and conventional generation capacity.



k-means clustering on load & conventional generation

Suppose the N nodes i have spatial coordinates (x_i, y_i). The k-means algorithm works by partitioning them into $k \leq N$ sets N_c for $c = 1, \ldots k$ such that the sum of squared distance to the centroid (x_c, y_c) (mean point inside each set) is minimised:

$$\min_{\{(x_c, y_c)\}} \sum_{c=1}^{k} \sum_{i \in N_c} w_i \left\| \begin{pmatrix} x_c \\ y_c \end{pmatrix} - \begin{pmatrix} x_i \\ y_i \end{pmatrix} \right\|^2$$

Each node i is weighted w_i by the average load and the average conventional generation there.

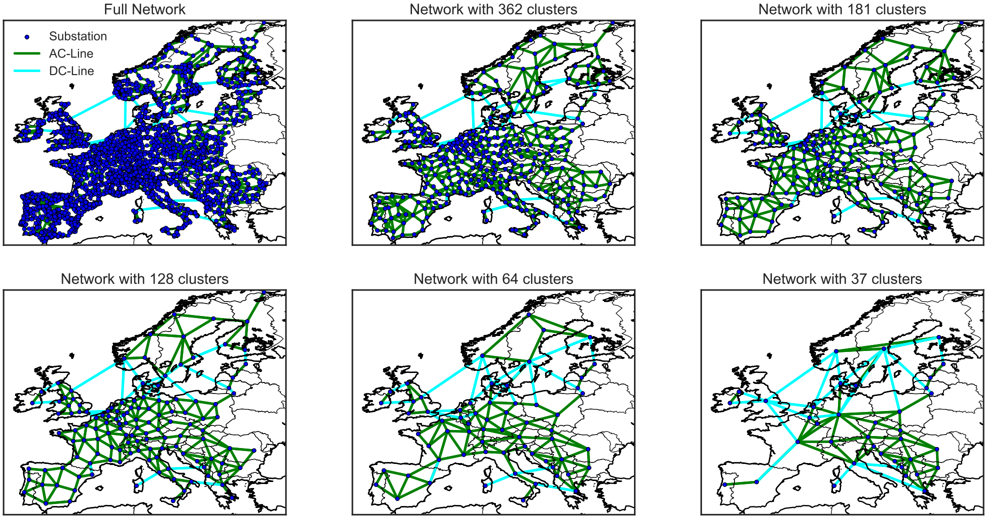
Use the centroid as the location of the new clustered node.

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 $\geq$ 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**.

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

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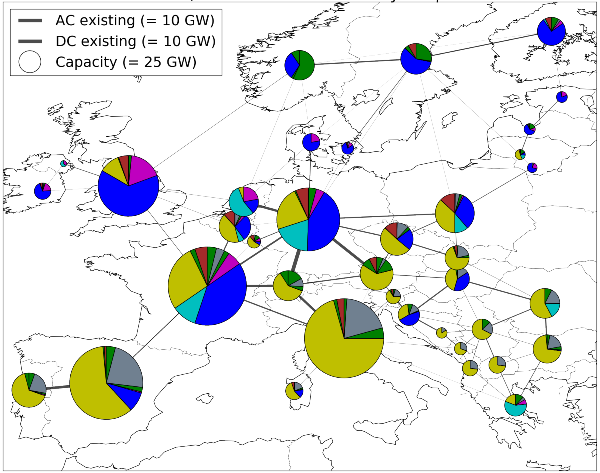
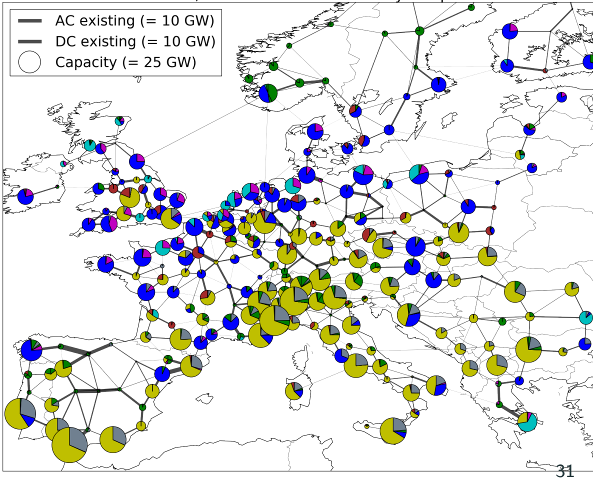
offshore wind · onshore wind · solar · gas · hydro · hydrogen storage · battery storage

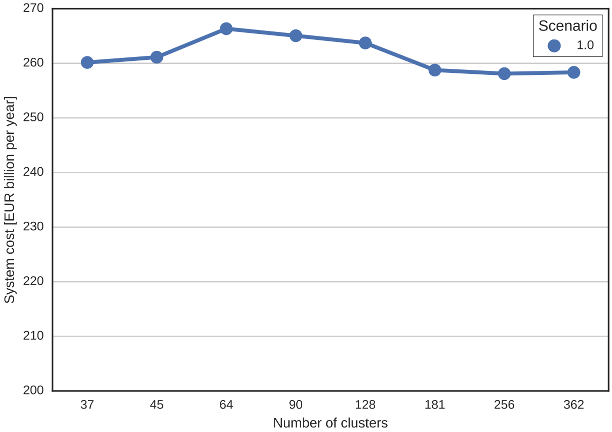
37 clusters, branch limit of 1 of today's capacities



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

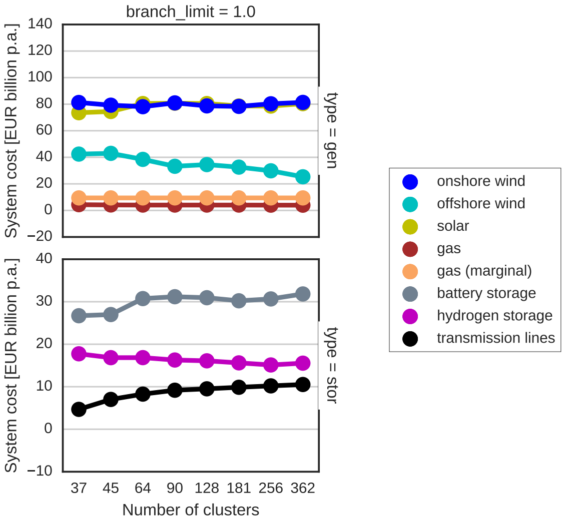


Costs: System cost w/o grid expansion



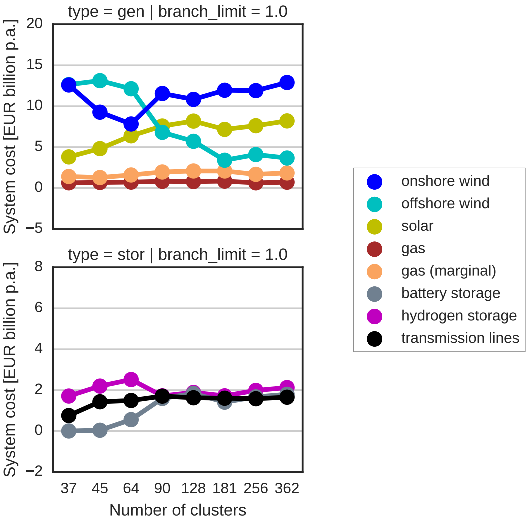
- Steady total system cost at € 260 billion per year
- This translates to € 82/MWh (compared to today of € 50/MWh to € 60/MWh)

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



- 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

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 F_ℓ of each line ℓ:

$$F_\ell \geq F_\ell^{\mathrm{today}} \tag{1}$$

$$\sum_\ell d_\ell F_\ell \leq \mathrm{CAP}_{\mathrm{trans}} \tag{2}$$

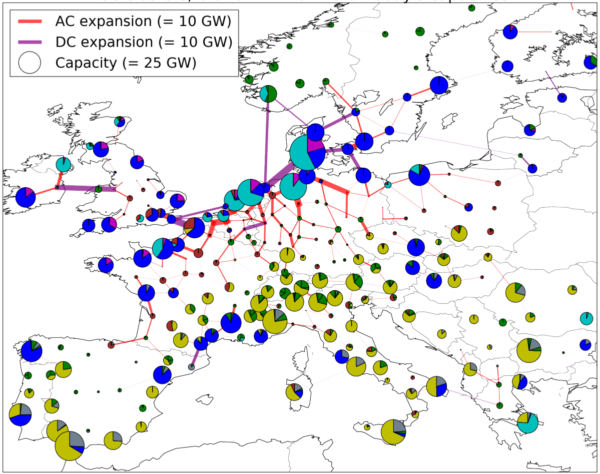
where

$$\mathrm{CAP}_{\mathrm{trans}} = x\,\mathrm{CAP}_{\mathrm{trans}}^{\mathrm{today}} \tag{3}$$

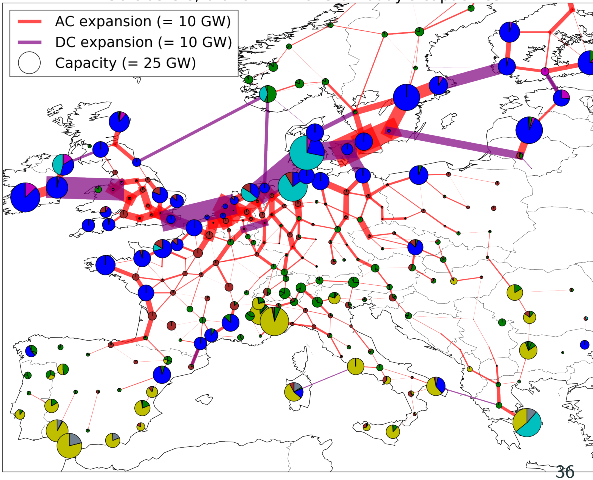
for $x = 1$ (today's grid) $x = 1.125, 1.25, 1.5, 2,$ $x = 3$ (optimal for overhead line at high number of cluster).

With expansion

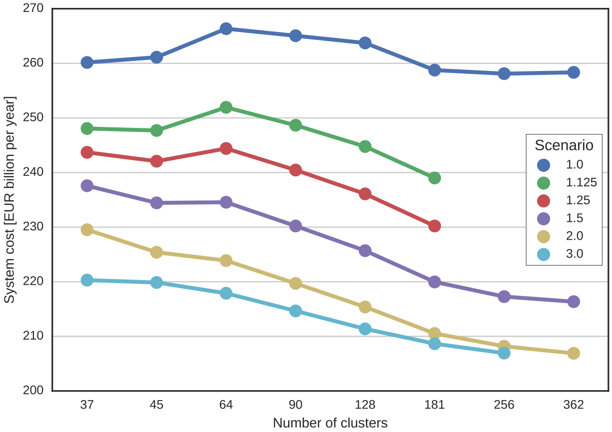
256 clusters, branch limit of 1.5 of today's capacities



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

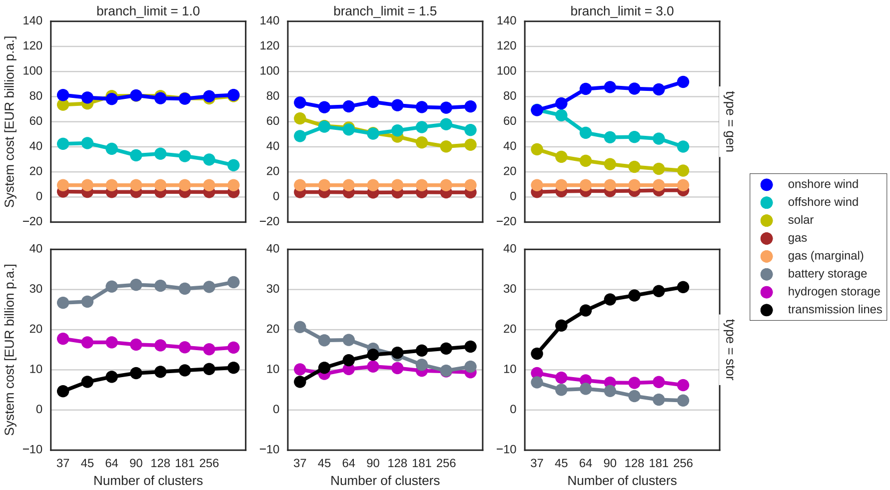


Costs: Total system cost

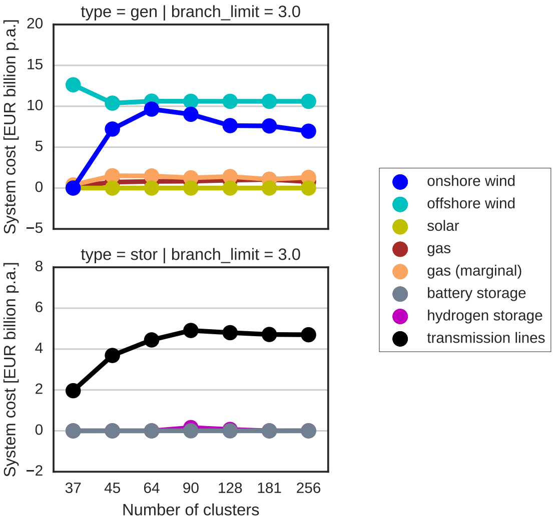


- Steady cost for No Expansion (1)
- For expansion scenarios, as clusters increase, the better expoitation of good sites decreases costs faster than transmission bottlenecks increase them
- Decrease in cost is v. non-linear as grid expanded (25% grid expansion gives 50% of optimal cost reduction)
- Only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

Costs: Break-down into technologies

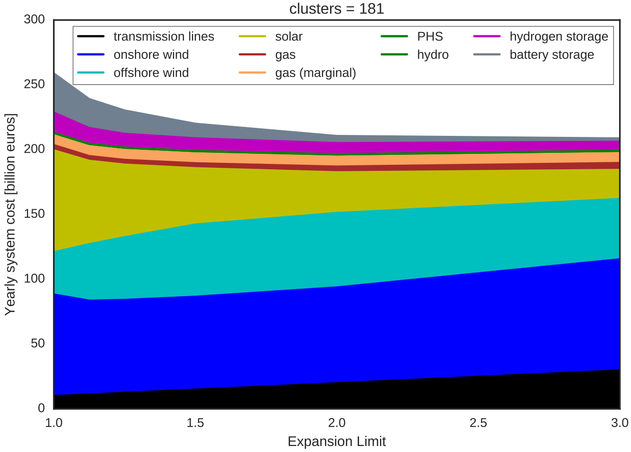


Costs: Focus on Germany (CAP = 3)



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

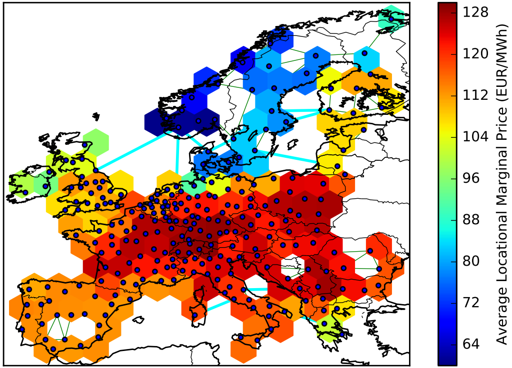
Behaviour as CAP is changed



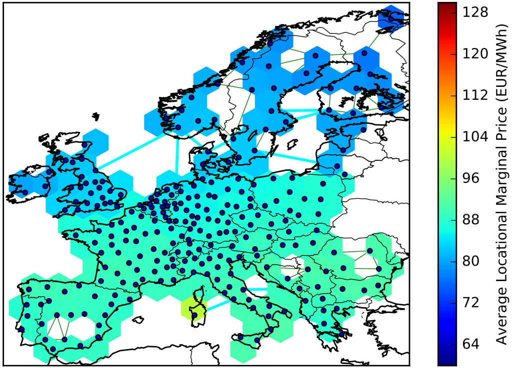
- Same non-linear development with high number of nodes that we saw with one node per country
- Most of cost reduction happens with small expansion; cost rather flat once capacity has doubled, reaching minimum (for overhead lines) at 3 times today's capacities
- Solar and batteries decrease significantly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

Locational Marginal Prices CAP=1 versus CAP=3

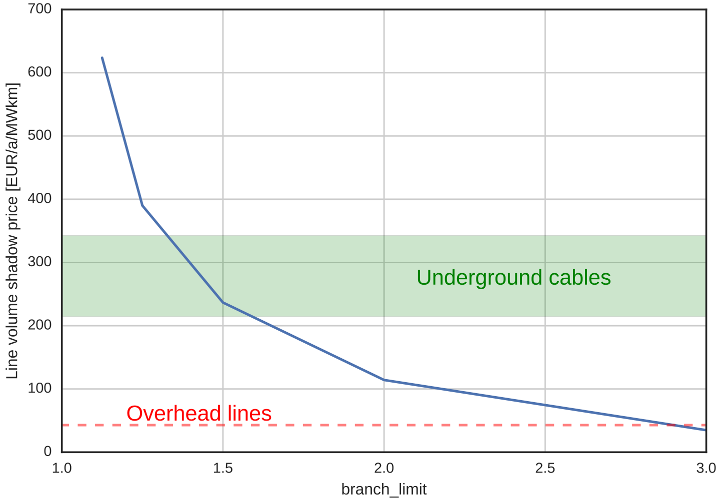
With today's capacities:



With three times today's grid:

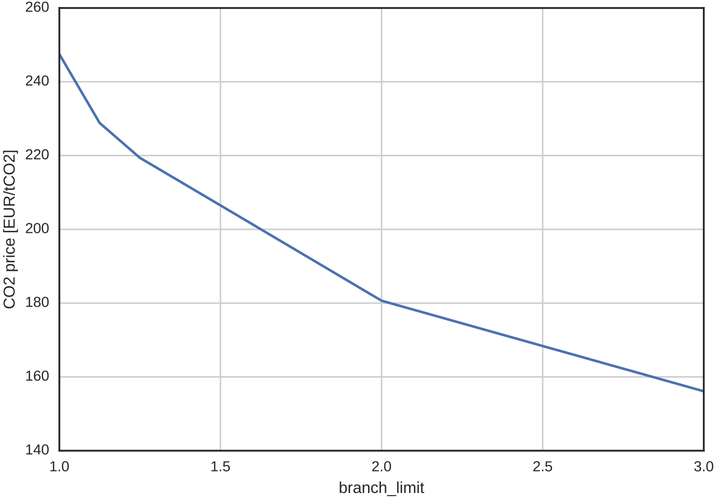


Grid expansion CAP shadow price for 181 nodes as CAP relaxed



- 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 €/tCO2 required to reach these solutions, depending on line volume cap

More Details in Paper

For more details, see the following paper:

- J. Hörsch, T. Brown, "The role of spatial scale in joint optimisations of generation and transmission for European highly renewable scenarios," EEM 2017, **link**.

In an upcoming paper with Martha Frysztacki and the same authors, we disentangle the effects of the network resolution from the renewable resource resolution.

Conclusions

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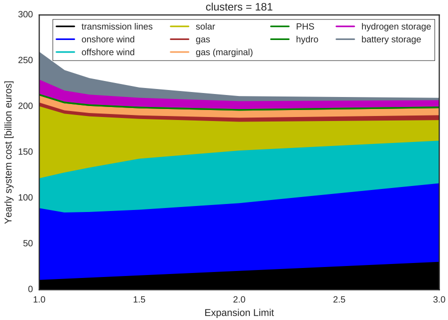
- Generation costs always dominate grid costs, but the grid can cause higher generation costs if expansion is restricted
- Systems with no grid extension beyond today are up to 25% more expensive, but small grid extensions (e.g. 25% more capacity than today) can lock in big savings
- Need at least around 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
- This is **no single solution** for highly renewable systems, but a **family of solutions** with different costs and compromises
- 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

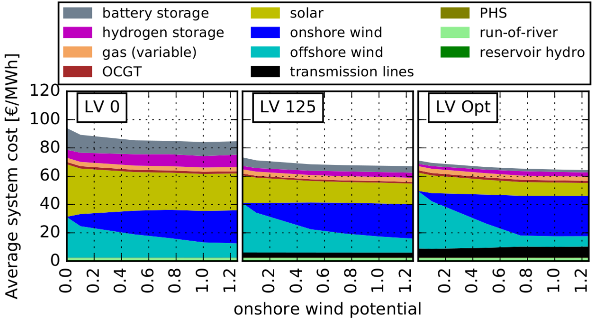
Near-Optimal Energy Systems

Flat directions near optimum

Both for changing transmission expansion AND onshore wind installable potentials, we've seen that total system costs are **flat around the optimum**.

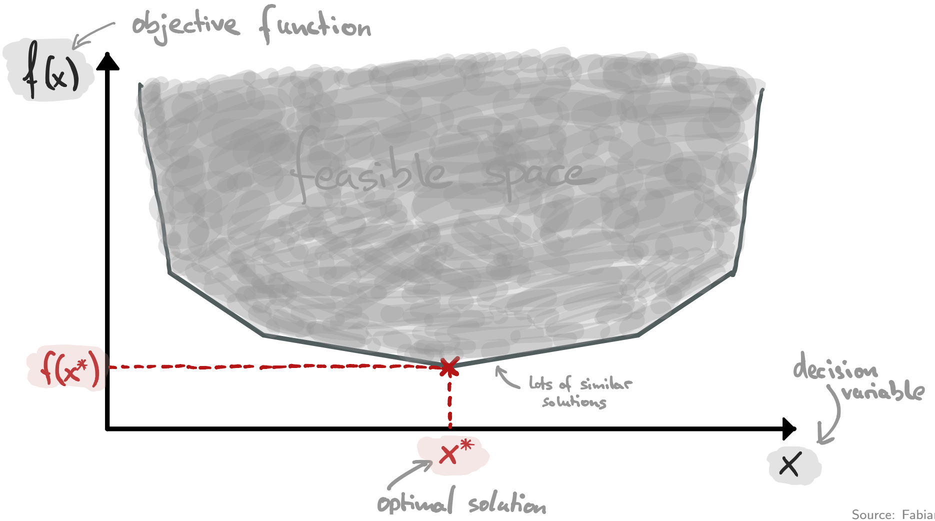
Can we explore this **near-optimal space** more systematically?





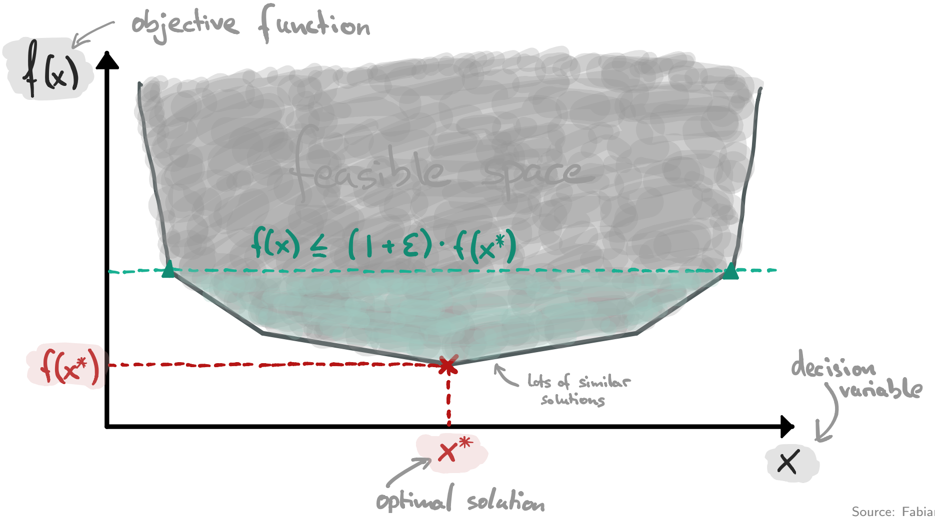
Large Space of Near-Optimal Energy Systems

There is a **large degeneracy** of different possible energy systems close to the optimum.



Source: Fabian Neumann

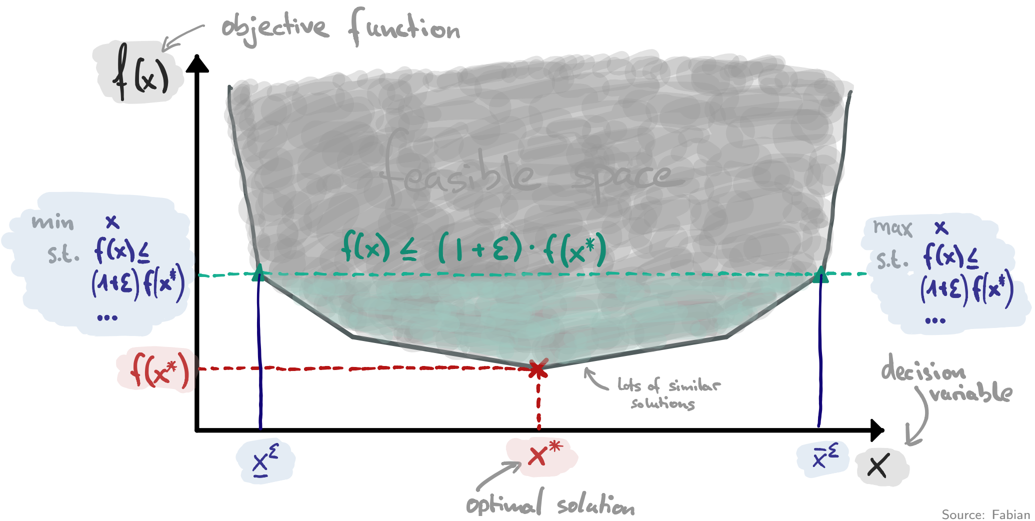
Consider the part of the feasible space within ε of the optimum $f(x^*)$.



Source: Fabian Neumann

Large Space of Near-Optimal Energy Systems

Now within ε of the optimum $f(x^*)$, try minimising or maximising x, to probe space.



Source: Fabian Neumann

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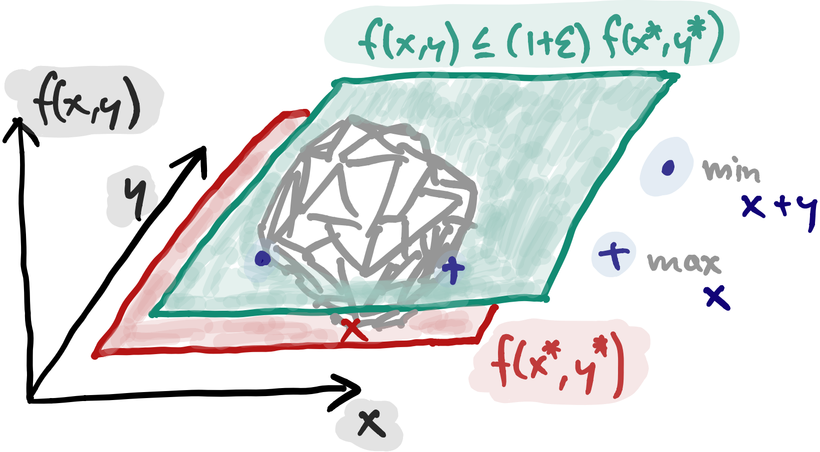
NB: Decision space of variables is multi-dimensional, so can probe only one direction at a time.



Source: Fabian Neumann

Application: Highly-Renewable European Electricity System

Apply this technique to a 100-node model of the European electricity with 100% renewable energy.

1. Find the **least-cost power system**.
2. For $\varepsilon \in \{0.5, 1, \ldots, 10\}\%$ **minimise/maximise** investment in
   - generation capacity (onshore and/or offshore wind, solar),
   - storage capacity (hydrogen, batteries, total storage) and
   - transmission volume (HVAC lines and HVDC links)

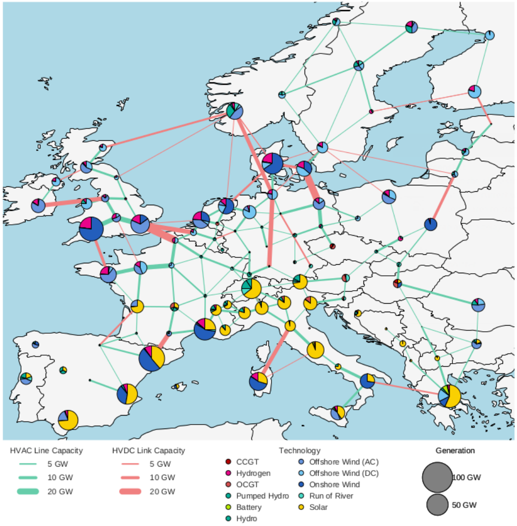
   such that **total annual system costs increase by less than ε**.

Methodology adapted from Method to Generate Alternatives (MGA) but 'alternatives' are forced in politically-interesting directions.

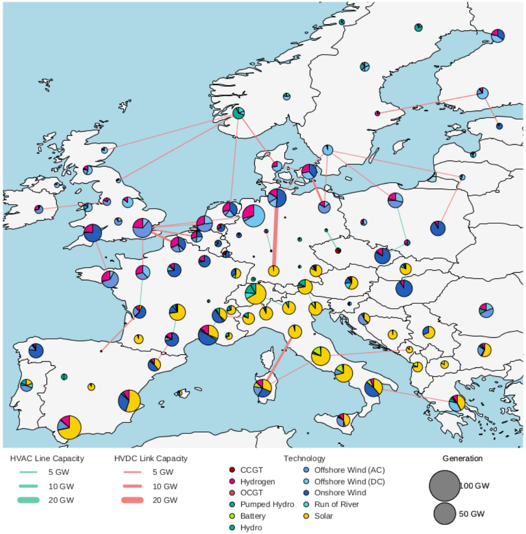
Source: Fabian Neumann

Example: 100% renewable electricity system for Europe

Capacity expansion in optimum:



$\varepsilon = 10\%$ above optimum, minimise new grid:



Source: Neumann & Brown, 2020

Example: 100% renewable electricity system for Europe

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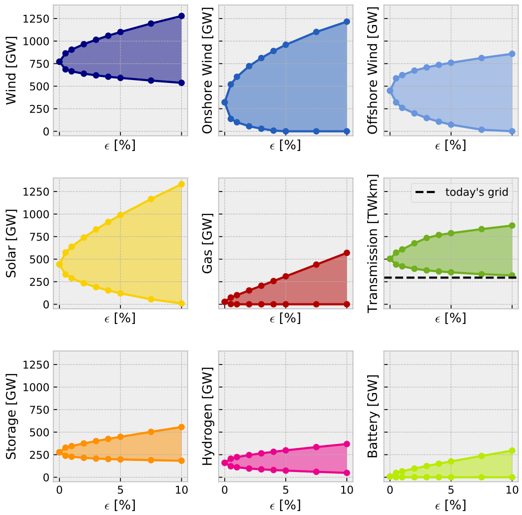


Within 10% of the optimum we can:

- Eliminate most grid expansion
- Exclude onshore or offshore wind or PV
- Exclude battery or most hydrogen storage

Robust conclusions: wind, some transmission, some storage, preferably hydrogen storage, required for a cost-effective solution.

This gives space to choose solutions with **higher public acceptance**.

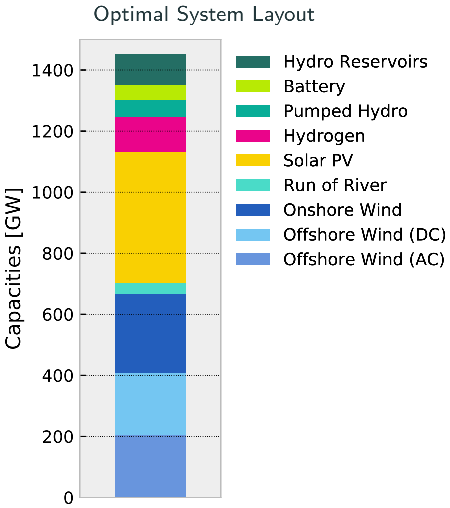
Source: Neumann & Brown, 2020

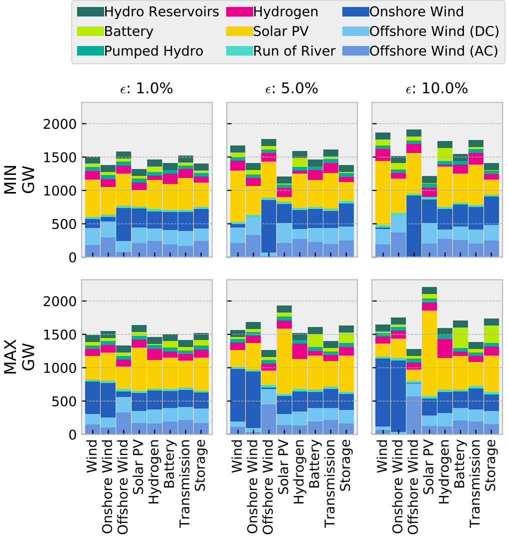
Flat directions allow society to choose based on other criteria

This flatness may allow us to choose solutions with **higher public acceptance** at only **small extra cost**.

These trade-offs will occupy us for the next 30 years!

Dependencies: Extremes cannot be achieved simultaneously





Near-Optimal Systems: Conclusions

- Optimizing a single model gives a **false sense of exactness**.
- There are many uncertainties about cost assumptions and political targets.
- There are also **structural model uncertainties** since the feasible space can be very **flat** near the optimum, such that the solution chosen is random within flat area.
- We can use these techniques to probe the **near-optimal space**.
- This gives us fuzzier but **more robust** conclusions (e.g. need wind, some transmission and some long-term storage for a cost-effective solution).
- It also allows us to find cost-effective solutions with **higher public acceptance**.

More details: Fabian Neumann, Tom Brown, "The Near-Optimal Feasible Space of a Renewable Power System Model," 2020, EPSR, https://arxiv.org/abs/1910.01891.