Complex Renewable Energy Networks
Summer Semester 2017, Lecture 14

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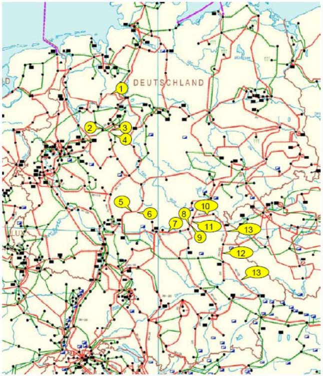
Cycles Flows and Grid Outages

Line Outages

Nr.	Zeit	kV	Leitung
1	22:10:13	380	Wehrendorf-Landesbergen
2	22:10:15	220	Bielefeld/Ost-Spexard
3	22:10:19	380	Bechterdissen-Elsen
4	22:10:22	220	Paderborn/Süd-Bechterdissen/Gütersloh
5	22:10:22	380	Dipperz-Großkrotzenburg 1
6	22:10:25	380	Großkrotzenburg-Dipperz 2
7	22:10:27	380	Oberhaid-Grafenrheinfeld
8	22:10:27	380	Redwitz-Raitersaich
9	22:10:27	380	Redwitz-Oberhaid
10	22:10:27	380	Redwitz-Etzenricht
11	22:10:27	220	Würgau-Redwitz
12	22:10:27	380	Etzenricht-Schwandorf
13	22:10:27	220	Mechlenreuth-Schwandorf
14	22:10:27	380	Schwandorf-Pleinting



When there are faults in the network, transmission lines can disconnect. This forces power flows onto the remaining network. If there is insufficient capacity, there can be a cascading line outage.

This happened in November 2006, where a cascading line outage caused the European network to split into three isolated parts, causing a major blackout.

Such outages may be exacerbated by high levels of variable renewable energy.

Recall angle formulation of linear power flow

Recall that for net power injections p_n at nodes n, flows f_ℓ on lines ℓ, network incidence matrix K and cycle basis C (kernel of K, $KC = 0$) we can express Kirchhoff's Circuit Laws as:

- Kirchhoff's Current Law (KCL): $\mathbf{p} = K\mathbf{f}$
- Kirchhoff's Voltage Law (KVL): $C^t X \mathbf{f} = 0$

Using voltage angle θ_n for each node and then using $f_l = \frac{\theta_i - \theta_j}{x_l}$:

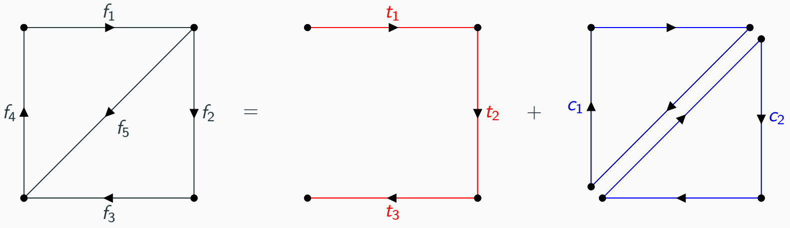
$$\mathbf{f} = X^{-1} K^t \theta \qquad (\sim E = -\nabla\phi)$$
$$\mathbf{p} = K X^{-1} K^t \theta \qquad (\sim \rho = \Delta\phi)$$

NB: $KX^{-1}K^t$ is a weighted Laplacian matrix for the graph, so the final equation has the form of a discrete Poisson equation sourced by $\mathbf{p}$.

Cycle formulation of linear power flow

We can use dual graph theory to decompose the flows in the network into two parts:

1. A flow on a spanning tree of the network, uniquely determined by nodal $\mathbf{p}$ (ensuring KCL)
2. Cycle flows, which don't affect KCL; their strength is fixed by enforcing KVL



$$f_\ell = t_\ell + \sum_k C_{\ell,k} c_k$$

Cycle formulation of linear power flow

The $N-1$ tree flows $\mathbf{t}$ are determined directly from the N nodal powers p_n and the network power balance constraint $\sum_n p_n = 0$.

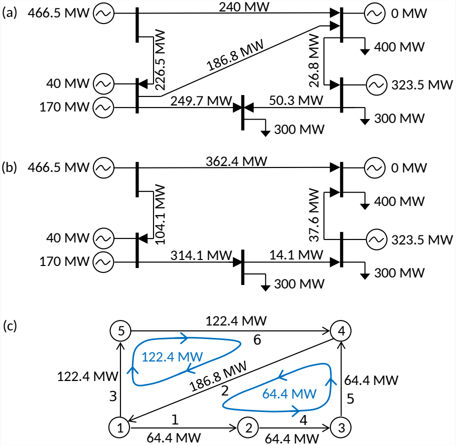
We solve for the $L-N+1$ cycle flows c_k by enforcing the $L-N+1$ KVL equations:

$$C^t X \mathbf{f} = C^t X(\mathbf{t} + C\mathbf{c}) = 0$$

The matrix C is the incidence matrix of the weak dual graph, $C^t XC$ is the weighted Laplacian of the dual graph and the above equation becomes a discrete Poisson equation:

$$C^t XC\mathbf{c} = -C^t X\mathbf{t}$$

Line outages from cycles

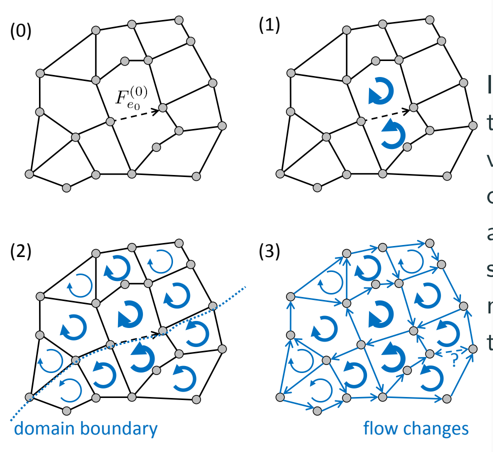


The outage of a line only affects the cycle flows.

(a) shows the flows before the outage;
(b) shows the flows after the outage of the diagonal line;
(c) shows the change in flows, decomposed into cycle flows.

Therefore the effect of the line outage on the other flows in the network can be entirely understood in terms of the cycle flows, corresponding to the nodes of the weak dual graph.

Line outages from cycles

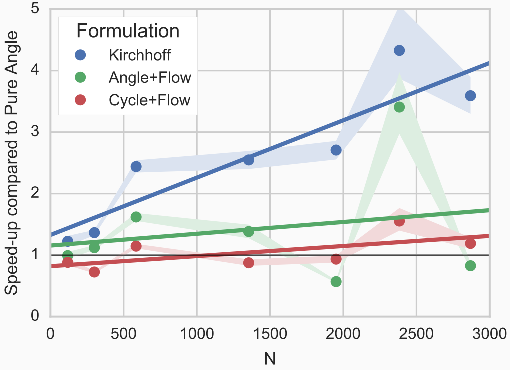


If we consider the outage of a line, the change in flows can be expressed very compactly in terms of the change in the cycles flows, $\Delta \mathbf{c}$, which are determined by a Poisson equation sourced by a term $\mathbf{q}$ that only has non-zero entries for cycles bordering the failed line

$$C^t X C \Delta \mathbf{c} = \mathbf{q}$$

For a plane network where the line fails away from the boundary, $\mathbf{q}$ is a dipole source for the two cycles that border the failed line.

Line outages from cycles

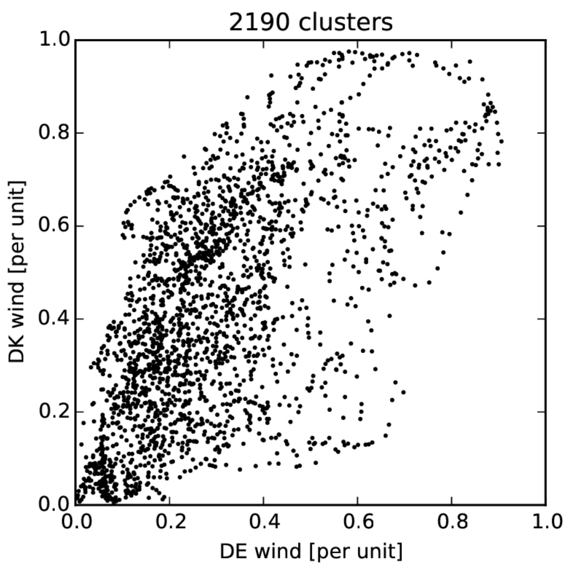


If we reformulate the linear optimal power flow using cycle flows instead of voltage angles we find:

- A speed-up of up to 20 times
- Average speed-up of factor 3
- Speed-up is highest for large networks with lots of decentralised generators

Principal Component Analysis

Idea behind Principal Component Analysis



- Suppose we have many samples of N variables over time, e.g. a dataset $x_1(t), x_2(t), \ldots x_N(t)$.
- For typical datasets, some of these variables will be correlated, e.g. Danish (DK) and German (DE) wind time series (an $N = 2$ example).
- In Principal Component Analysis (PCA) we rotate to a basis where correlations are visible and hopefully the rest is 'noise'.

Principal Component Analysis

For Principal Component Analysis (PCA) we have N variables $x_1(t), x_2(t), \dots x_N(t)$ and compute the covariance matrix:

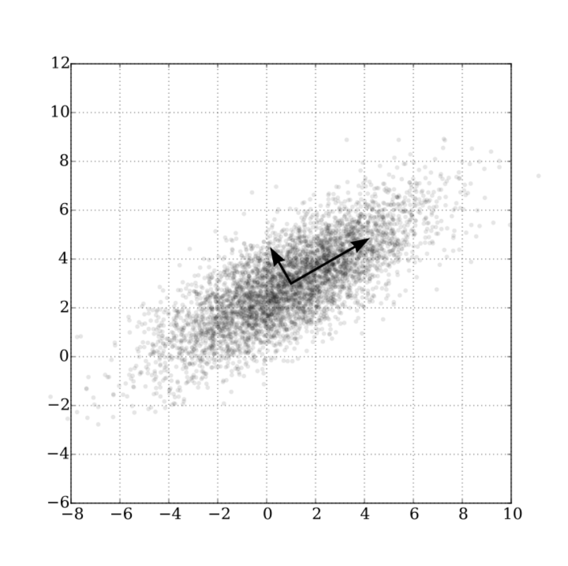
$$\Sigma_{ij} = \mathbb{E}\left[(X_i - \mathbb{E}[X_i])\,(X_j - \mathbb{E}[X_j])\right]$$

This is a real symmetric matrix. We take the N orthogonal eigenvectors and order them according to the size of the N eigenvectors (the size of the variance along each eigenvector).

We're 'fitting an ellipse' to the point cloud.

Projected onto our new othogonal eigenvector basis, our time series are now no longer correlated (since the correlation matrix has been diagonalised).

Idea behind Principal Component Analysis



- In this example we've fitted the components to the direction of maximum variance, and the sideways orthogonal orthogonal component with much less variance.

Source: Wikipedia

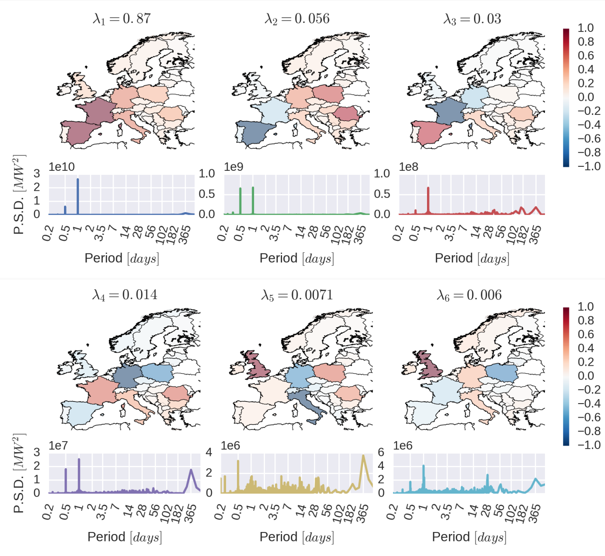
Application of PCA to renewable time series

In his MA thesis, Fabian Hofmann did a PCA analysis on the wind, solar and load time series for the different nodes in our European electricity system model. This built on work from Martin Greiner's group at Aarhus University.

By looking at where feed-in is correlated, you can learn a lot about the spatio-temporal patterns which drive investment in infrastructure (renewable generators, backup, storage and networks).

Fabian then looked at the Fourier analysis of the time series of the projected components.

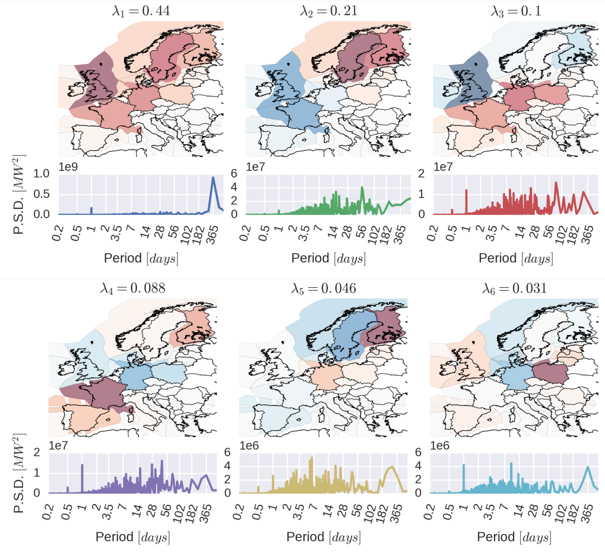
PCA on solar time series



- For solar, 'breathing mode' dominates, with daily variations.
- The next mode is an East-West dipole for the rising/setting Sun.
- The third mode is an North-South dipole with a strong seasonal variation.

Source: Fabian Hofmann

PCA on wind time series

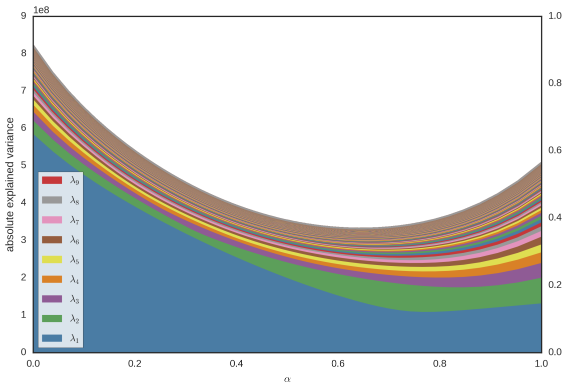


- Wind is less concentrated in a few components.
- First breathing component is predominantly seasonal.
- Synoptic variations in dipoles.
- Multipoles contain a variety of temporal scales.

Source: Fabian Hofmann

Changing variance and PCA with wind-solar mix

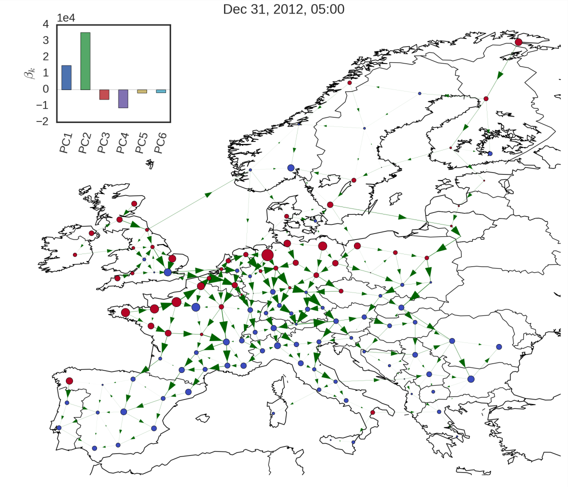
In this graph we look at the total variance of the mismatch between wind, solar and load, decomposed into the different principle components. This is plotted as a function of the wind-solar energy mix ($\alpha = 0$ is all solar, $\alpha = 1$ is all wind).



- Much of reduction in variance comes from reducing solar breathing-mode peak for low α.
- At high α the strong seasonality of wind becomes a problem.

Source: Fabian Hofmann

PCA and Flow patterns



- The 'breathing' monopole doesn't result in strong flows because of its spatial homogeneity.
- Here we plot the flow pattern from the North-South dipole.
- The principal components dominant the flow patterns and can be used to dimension the grid infrastructure.

Source: Fabian Hofmann

PCA Conclusions

- With Principal Component Analysis (PCA) we can analyse the spatio-temporal patterns of wind and solar feed-in.
- Only a few prinicipal components (PCs) dominant the time series, consisting of breathing modes and dipoles; the rest is mostly ‘noise’.
- We can use PCA to understand how to dimension backup reserves.
- The first few PCs also dominate transmission flows, simplifying transmission investment analysis.
- Fabian also investigated how the PCs change with spatial resolution: for Europe, the PCs are stable above 128 nodes (similar to spatial scale analysis from Lecture 11).

Effect of Climate Change on Renewable Energy Systems

Climate change

Ongoing MA thesis by Markus Schlott:

- 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?

If we can answer these questions, we know our energy system will be robust against expected changes to the climate.

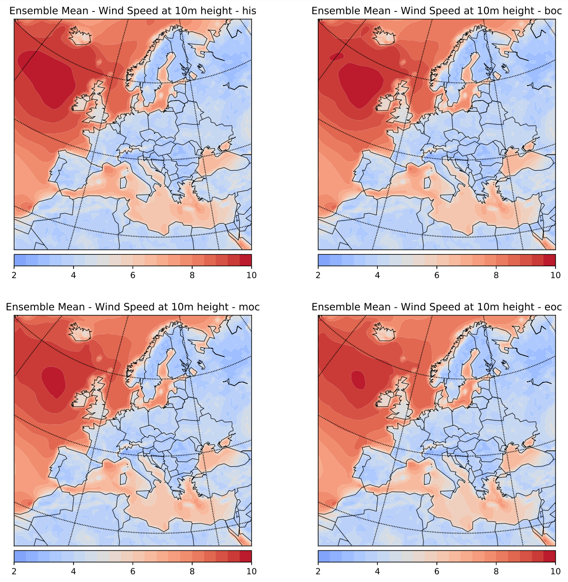
Climate change scenarios: RCP 8.5

Markus took a simulated dataset of how the weather would look between today and the year 2100 with a scenario of high concentrations of greenhouse house 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 'business as usual' scenario and extrapolates the current greenhouse gas emission without reduction efforts. 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).

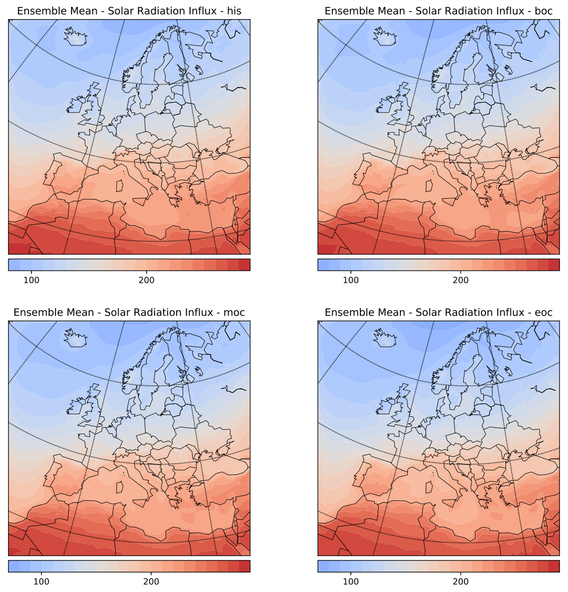
Changes to wind speeds



- Very small changes to mean wind speeds (also very local)
- Small ($\sim 5\%$) average increase in Northern Europe
- Small ($\sim 5\%$) average decrease in Southern Europe

Source: Markus Schlott

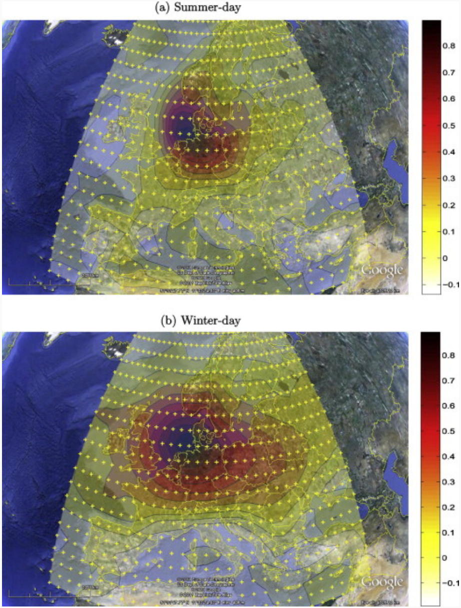
Changes to mean short-wave radiation



- Small ($\sim 5\%$) increase in downward short-wave radiation 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: Markus Schlott

Correlation Length



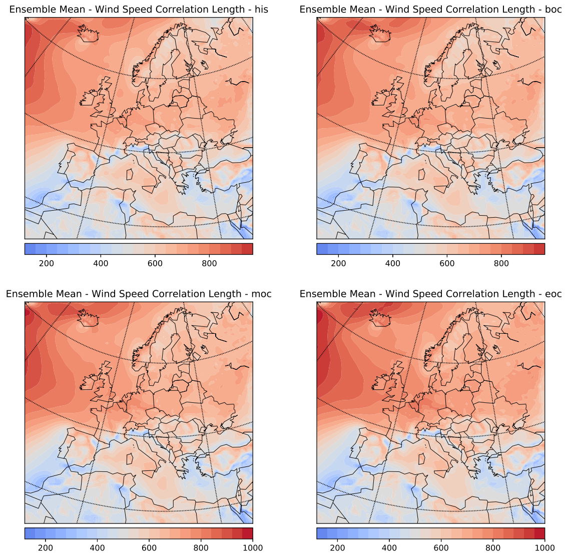
- The correlation of wind time series with a point in northern Germany decays with distance.
- Determine the correlation length L by fitting the function:

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

to the radial decay with distance x.

Source: Hagspiel et al, 2012

Changes to wind speed correlation lengths



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

Source: Markus Schlott

Effects of climate change on power system

What kind of changes do we expect to the optimal power system?

- Most effects are small ($\sim 5 - 10\%$) so we don't expect massive changes.
- More wind capacity built in the North to take advantage of improving wind speeds?
- Somewhat counteracted by higher correlation lengths in North - need bigger networks or more long-term storage?

Hard to say, but Markus' calculations will be done soon...

Admin

Masters in the Renewable Energy Group

If you are interested in writing your BA or MA thesis on the topic of Complex Renewable Energy Networks, just write to me or Prof. Stefan Schramm (`schramm@fias.uni-frankfurt.de`).

Oral Exam

The oral exam will take place on 25/26/27 July 2017 at FIAS, Uni Campus Riedberg.