Energy System Modelling
Summer Semester 2019, Lecture 12

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Karlsruhe Institute of Technology

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Oral examination sample questions

Oral exam

The following question are *not* identical to the oral exam, but give an indication of the difficulty level of the questions.

General Questions

- Describe variations of wind and solar in space and time (lecture 1)
- Describe what you would expect from the Fourier transform of wind and solar time series (lecture 1)
- What are the options for balancing variable renewables?
- What happens to feed-in when integrated over larger areas? (lecture 2)
- What is the correlation length of the wind? (lecture 2)
- When balancing with only storage, how does storage volume depend on frequency of variations for a sinusoidal generation pattern? (lecture 4, sheet 2)
- When balancing only with networks, how does network distance depend on wavelength of variations?

Network physics

- What is the incidence matrix? Write down the incidence matrix of a given network. (lecture 2)
- What is the Laplacian? (lecture 2)
- How are power, voltage angles and the Laplacian related for a linear power flow calculation? (lecture 3)
- How is the PTDF derived? (lecture 3)

Optimisation

- Write down the typical form of an optimisation problem. (lecture 6)
- What are the KKT conditions? (lecture 6)
- Describe each KKT condition. (lecture 6)
- How does the maximisation of economic welfare relate to optimisation and KKT?
- Write down KKT for a given two-node problem. (lecture 8)
- Screening curves, demand duration curve: derive generation fleet for given parameters (lecture 8, sheet 4)
- Explain the merit order effect (lecture 10, 11)
- What is the 'no profit rule' (lecture 10)
- Are extreme prices in markets a problem? How can we incentivise capacity? (lecture 10)

Other topics

- Write down the relation between storage dispatch/storing and energy. (lecture 4)
- How is Demand Side Management different from Storage? (lecture 5)
- Describe the opportunities of coupling to other energy sectors (lecture 9)
- What techniques can we use to reduce the complexity of energy system modelling calculations? (spatial clustering in lecture 11, PCA)
- What algorithms can we use to trace power flow from sources to sinks? (flow tracing)
- How is the frequency affected by power imbalances? (lecture 12)

Grid Dynamics and Synchronization

From Static to Dynamic

So far we have considered the power system only in its static **steady state** (or hourly snapshots of the steady state), i.e. where the time derivatives of all system quantities are zero.

However, the power system is changing all the time, both in slow, predictable ways (the load changing in a statistically-smoothed way) and in sudden, unpredictable ways, e.g. if a generator fails and 500 MW is lost, or if a power line or transformer fails while heavily loaded (e.g. due to lightning, trees falling, diggers or human operator error). The continental European is designed to survive the sudden loss of 3 GW of generation.

In the next few slides we will look at the **dynamics** of the power system.

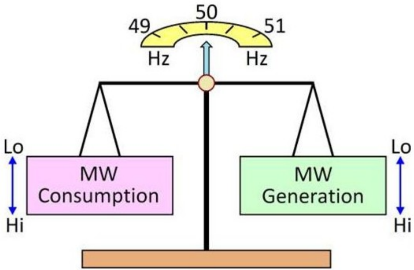
Time scales

Dynamic phenomena in power systems can be classified by the time scales on which they occur, for example:

1. Electro-magnetic transients (e.g. switching, lightning strikes) (100 Hz – MHz)
2. Electro-mechanical swings (e.g. rotor swings in synchronous machines) (0.1 – 3 Hz)
3. Non-electric dynamics (e.g. mechanical phenomena and thermodynamics) (up to tens of Hz)

We will focus on number 2, i.e. frequency dynamics due to interactions between changing loads and rotating machines (generators and motors).

Balancing Power via Steady Frequency



Generation and demand have to be kept in balance at all times (since we cannot create or destroy energy).

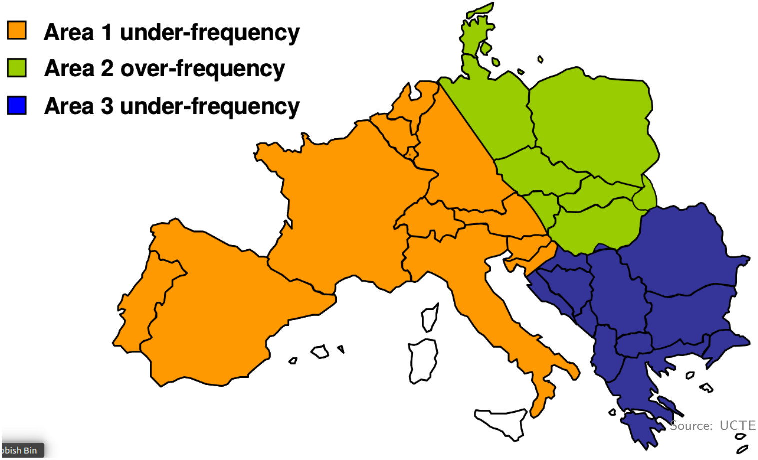
This is reflected in the alternating current grid frequency (50 Hz in Europe and most of Africa/Asia; 60 Hz in much of Americas).

If there is more generation than load, the extra energy is converted to rotational energy of the synchronous rotating machines and the frequency goes up.

If there is more load than generation, the deficit energy is substituted by rotational energy of the synchronous rotating machines and the frequency goes down.

Example: Grid split and partial blackout 4.11.2006

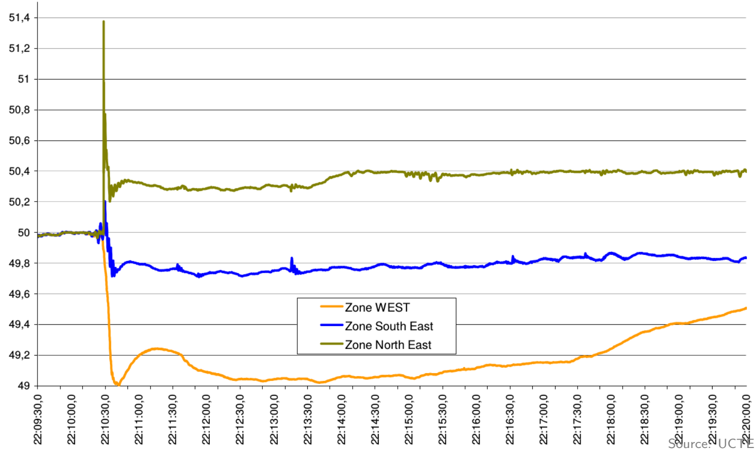
On 4th November 2006 a cascading line outage caused the continental European network to split into three parts. The individual parts were not perfectly balanced: excess generation in North-East, too little in West.



Source: UCTE 2006 Report

Example: Grid split and partial blackout 4.11.2006

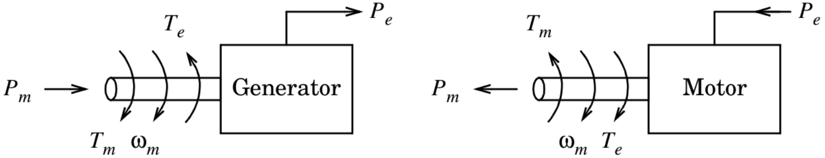
The frequency was only stabilised by load shedding (blackouts) once the frequency hit 49 Hz in the West.



Source: UCTE 2006 Report

Synchronous machines

For a single synchronous machine (left in generation mode; right in motor mode) we will now examine the relation between the **mechanical power** P_m, the **electrical power** P_e, the **frequency** ω, the **angle** θ and the **mechanical and electrical torques** T_m, T_e.



For the rotor dynamics we have for the moment of inertia J

$$J\frac{d^2\theta}{dt^2} = T_m - T_e$$

Source: Göran Andersson lecture notes

Swing equation

Multiplying by the frequency $\omega = \dot{\theta}$ we get the **swing equation**

$$\omega J \frac{d^2\theta}{dt^2} = P_m - P_e$$

The total inertia is given by $H = \frac{1}{2}\omega^2 J$ so we get

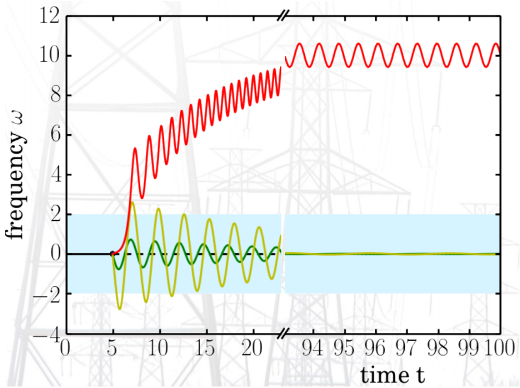
$$\frac{2H}{\omega}\frac{d^2\theta}{dt^2} = P_m - P_e$$

It is now clear what will happen if $P_m \neq P_e$.

Networks of synchronous machines

Networks of oscillators, i.e. an oscillator with angle θ_i at every node, can be studied. We get using a simplification of the load flow equations for P_e

$$\frac{2H_i}{\omega_i}\frac{d^2\theta_i}{dt^2} = P_m - \sum_j \frac{1}{x_{ij}} \sin(\theta_i - \theta_j)$$



The solutions have several interesting properties: basins of stability, limit cycles, etc. We can study them in a

simpler physics model called the **Kuramoto model**.

Source: Paul Schultz

Kuramoto model

This very similar model for synchronization was introduced in 1975 by Kuramoto:

$$\frac{d\theta_i}{dt} = \omega_i + \frac{K}{N}\sum_{j=1}^{N}\sin(\theta_j - \theta_i)$$

where θ_i is a phase, K is the coupling strength, multiplied by the sine of the phase differences, and ω_i is the natural frequency of the oscillator.

Suppose the natural frequencies are distributed with pdf $g(\omega)$.

To understand synchronisation in this model, Kuramoto introduced **order parameters** R and ψ defined by

$$Re^{i\psi(t)} = \frac{1}{N}\sum_{j=1}^{N} e^{i\theta_j(t)}$$

Kuramoto model

This allows us to re-write the equations as

$$\frac{d\theta_i}{dt} = \omega_i + \frac{KR}{N}\sin(\psi - \theta_i)$$

Now the interaction with the other θ_i is concealed inside the ψ.

The coupling between the θ_i grows with R; if $R = 0$ there is no synchrony and the phases are smeared around the circle. If $R \sim 1$ then the phases are synchronized.

We will show that the oscillators with $|\omega_i| \leq KR$ are locked at $\theta_i = \arcsin(\frac{\omega_i}{KR})$, whereas those with $|\omega_i| > KR$ are drifting.

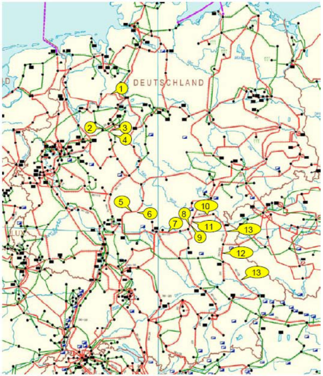
See also: `https://en.wikipedia.org/wiki/Kuramoto_model`, `http://www.stevenstrogatz.com/articles/from-kuramoto-to-crawford-exploring-the-onset-of-synchronizatio`
`https://arxiv.org/abs/1511.07139`,
`http://scala.uc3m.es/publications_MANS/PDF/finalKura.pdf`

Videos: `https://www.youtube.com/watch?v=sROKYelaWbo`,
`https://www.youtube.com/watch?v=eAXVa__XWZ8`,

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 $f_l = \frac{\theta_i - \theta_j}{x_l}$:

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

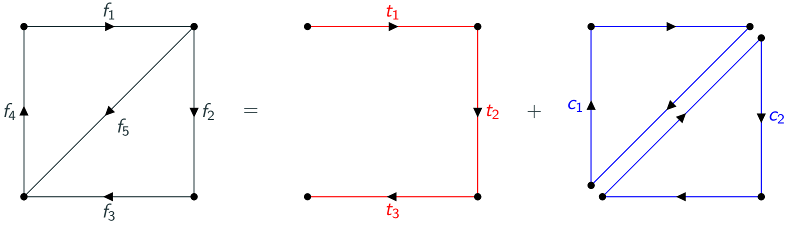
$$\mathbf{p} = KX^{-1}K^t\theta \qquad (\sim \rho = \Delta\phi)$$

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 $\sum_n p_n = 0$.

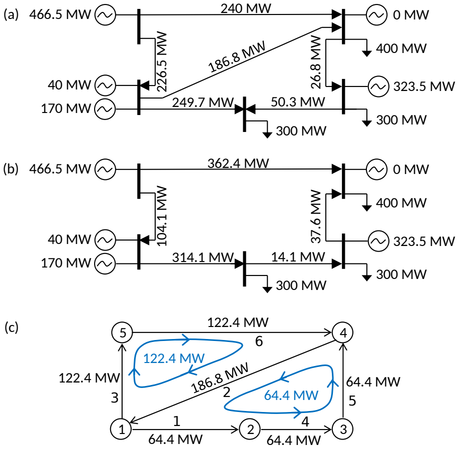
We solve for the $L-N+1$ cycle flows c_k by enforcing the $L-N+1$ KVL equations:

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

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**.

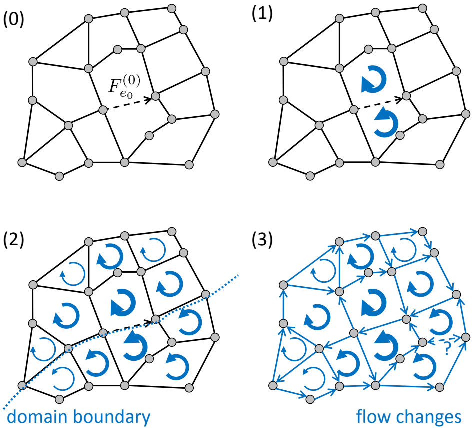
(a) shows the flows before the outage;

(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

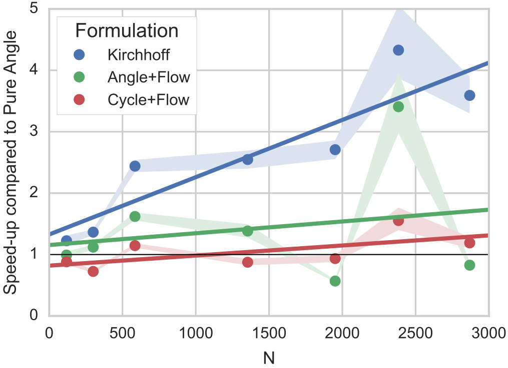


If we consider the outage of a line, the change in flows can be expressed very compactly in terms of the change in the cycles flows, $\Delta\mathbf{c}$, which are determined by a Poisson equation sourced by a term $\mathbf{q}$ that only has non-zero entries for cycles bordering the failed line

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

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**

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.

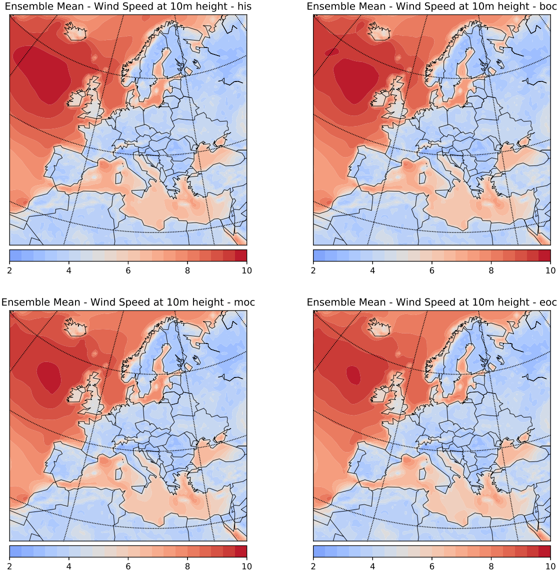
Climate change scenarios: RCP 8.5

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).

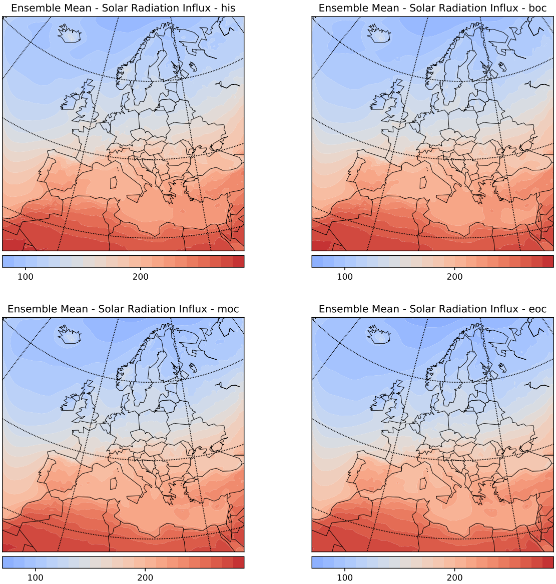
Changes to wind speeds



- 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

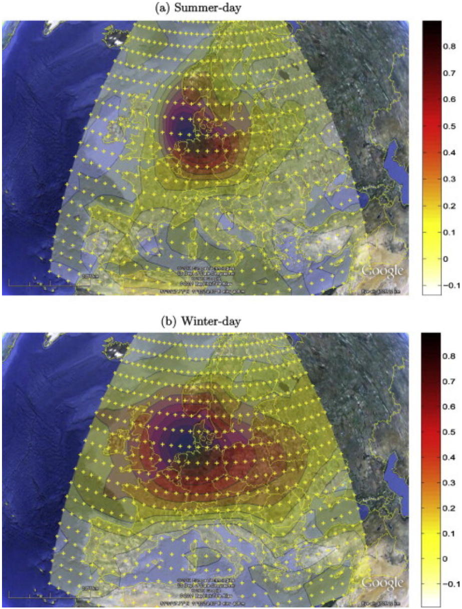
Changes to mean short-wave radiation



- 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



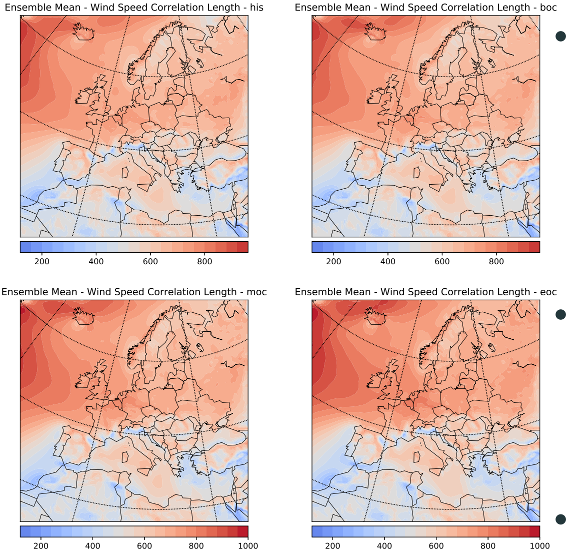
- The correlation of wind time series with a point in northern Germany decays with distance.
- Determine the **correlation length** L by fitting the function:

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

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 systems have more energy and are bigger in the North.

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?

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

Sensitivity of Optimisation to Cost and Weather Data

Sensitivity of Optimisation to Cost and Weather Data

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