Energy Systems, Summer Semester 2025

Lecture 4: Networks Introduction

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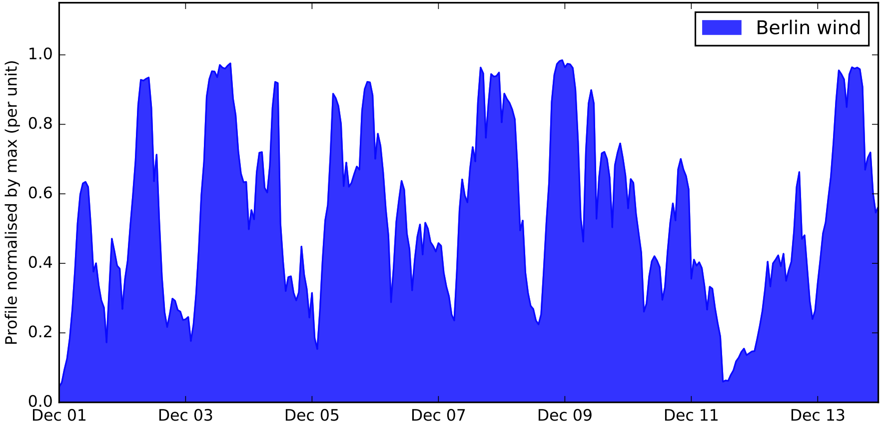
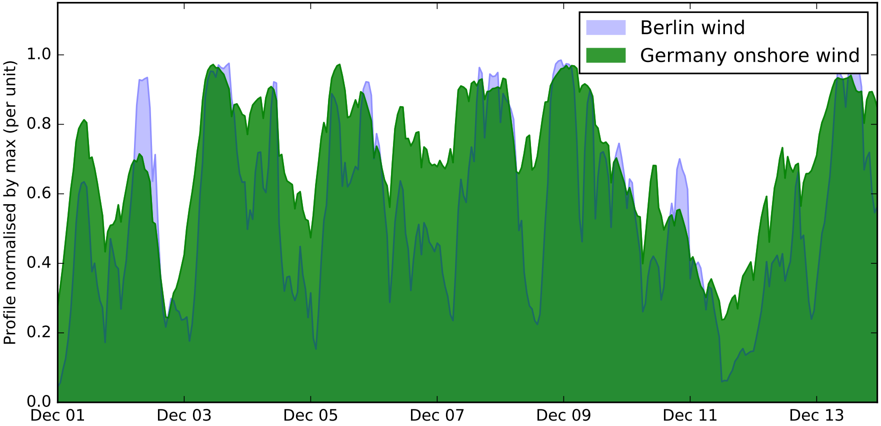
Single Location Versus Country Versus Continent

Variability: Single wind site in Berlin

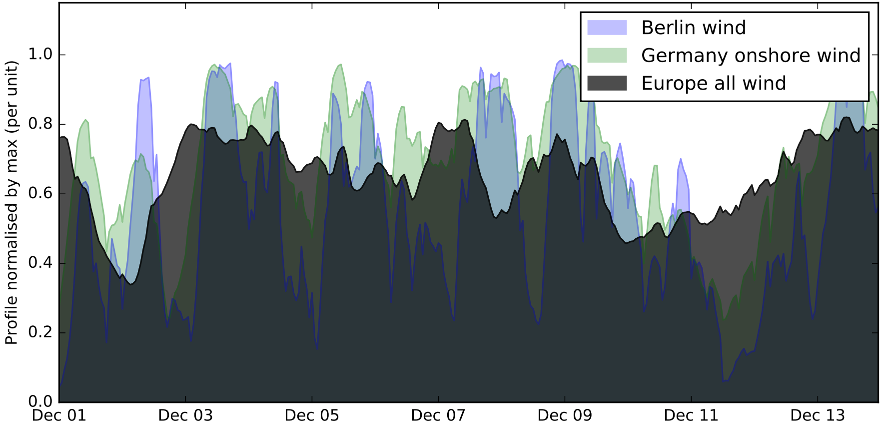
Looking at the wind output of a single wind plant over two weeks, it is highly variable, frequently dropping close to zero and fluctuating strongly.



For a whole country like Germany this results in valleys and peaks that are somewhat smoother, but the profile still frequently drops close to zero.

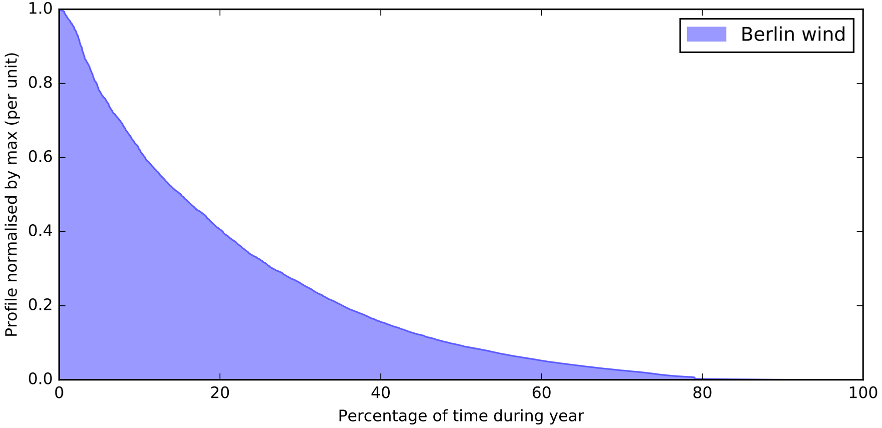


If we can integrate the feed-in of wind turbines across the European continent, the feed-in is considerably smoother: we've eliminated most valleys and peaks.



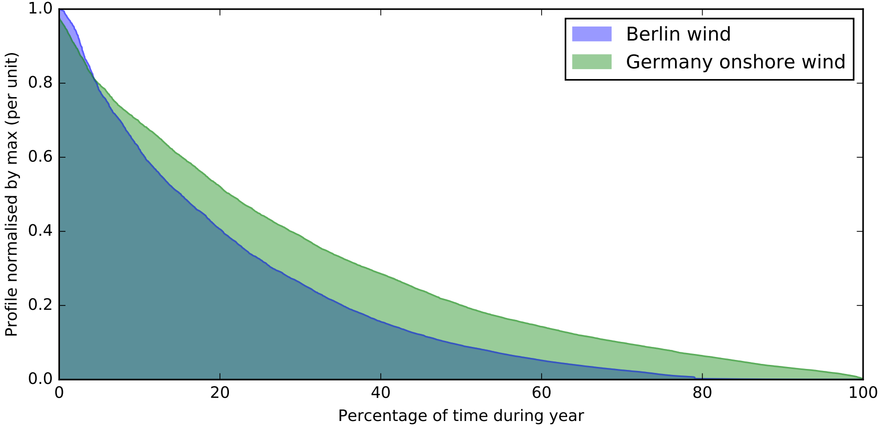
Duration curve: Berlin

A **duration curve** shows the feed-in for the whole year, re-ordered by from highest to lowest value. For a single location there are many hours with no feed-in.



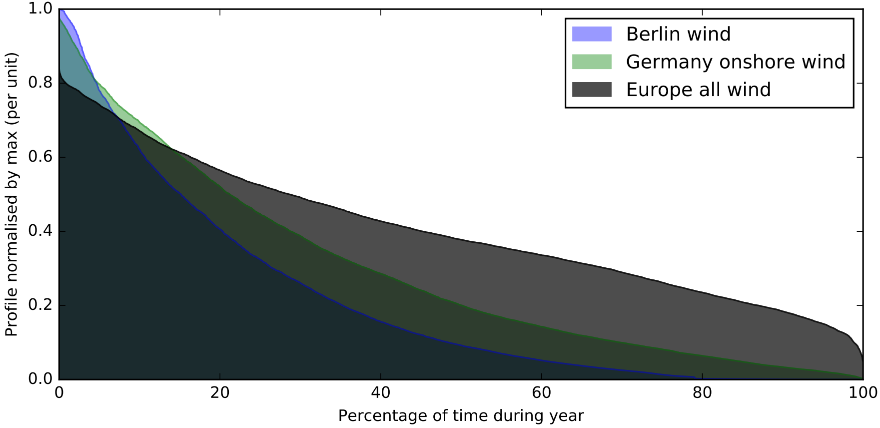
Duration curve: Germany

For a whole country there are fewer peaks and fewer hours with no feed-in.



Duration curve: Europe

For the whole of Europe there are no times with zero feed-in.



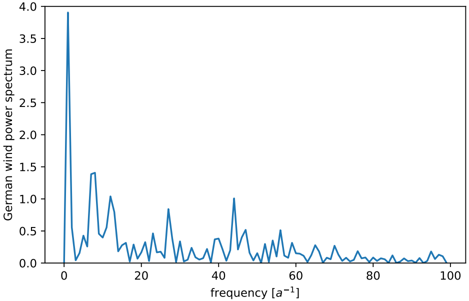
Statistical comparison

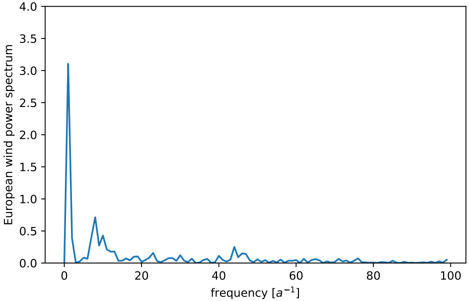
Area	Mean	Standard deviation
Berlin	0.21	0.26
Germany	0.26	0.24
Europe (including offshore)	0.36	0.19

Conclusion: Wind generation has much lower variability if you integrate it over a continent-sized area.

Fourier spectrum: weekly variations suppressed

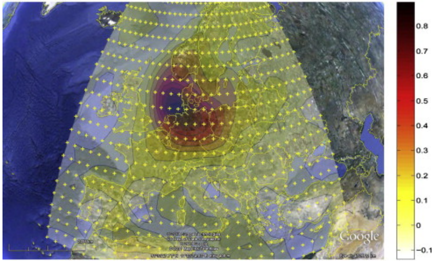
The **synoptic** (2-3 weeks) variations in the Fourier spectrum are also suppressed between Germany (left) and the Europe profile (right), however the seasonal variations remain.



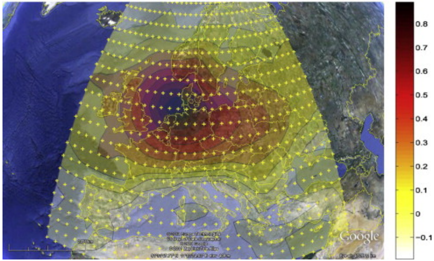


Why does this work? Consider the correlation length of wind

(a) Summer-day



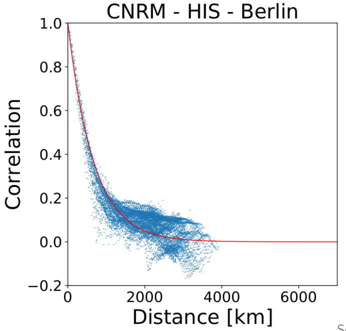
(b) Winter-day



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

Reminder: Pearson correlation coefficient

The **Pearson correlation coefficient** measures the linear correlation between two random variables X, Y. It is defined as the **covariance** of the two random variables normalised by their standard deviations, so that $\rho_{X,Y} \in [-1, 1]$.

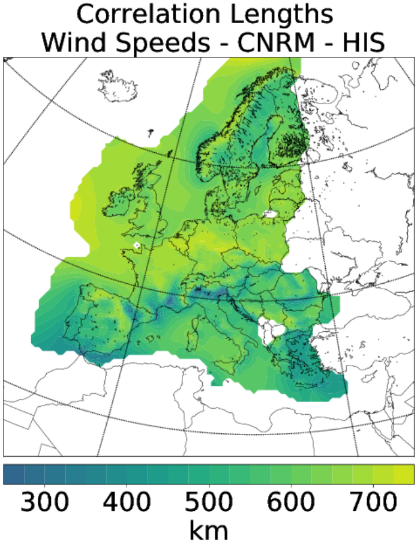
$$\rho_{X,Y} = \frac{\mathrm{cov}(X, Y)}{\sigma_X \cdot \sigma_Y} = \frac{\mathbb{E}\left[(X - \mu_X)(Y - \mu_Y)\right]}{\sigma_X \cdot \sigma_Y}$$

If the two random variables are perfectly proportional $Y = kX$ then we get

$$\rho_{X,Y} = \frac{\mathbb{E}\left[(X - \mu_X)k(X - \mu_X)\right]}{\sigma_X \cdot |k|\sigma_X} = \frac{k\mathrm{Var}(X)}{|k|\sigma_X^2} = \frac{k}{|k|} = \mathrm{sign}(k)$$

so that if $k > 0$ they are perfectly correlated with $\rho = 1$ and if $k < 0$ they are perfectly anti-correlated with $\rho = -1$.

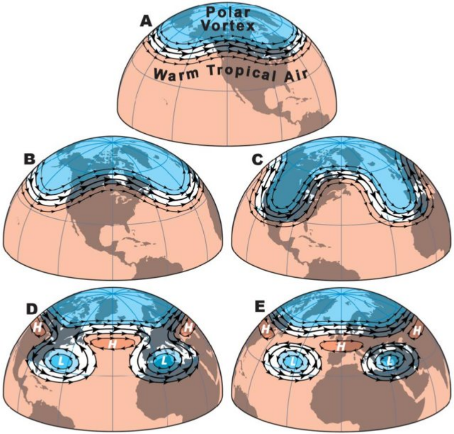
Wind speed correlation lengths



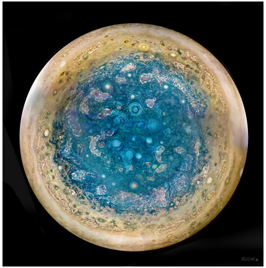
- Typically correlation lengths for wind are around 400 – 600 km.
- Smoothing requires aggregating uncorrelated sources, so need a bigger area, i.e. a continent (Europe is about 3500 km tall and 3100 km wide).
- Correlation lengths are longer in the North than the South because of big weather systems that roll in from the Atlantic to the North (in the South they get dissipated).

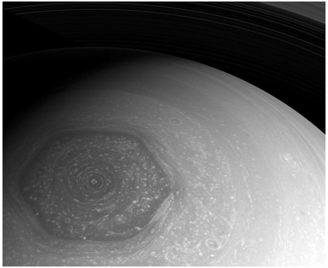
Source: Schlott et al, 2018

What sets these lengths?



- Reminder: atmospheric **Rossby waves** are giant meanders in high-altitude winds that have a major influence on weather.
- The wavelength of the Rossby waves sets the correlation length.





Source: Stuart et al, 2019

Mismatch between load and renewables

How does the mismatch change as we integrate over larger areas?

If we have for each time t a demand of d_t and a 'per unit' availability w_t for wind and s_t for solar, then if we have W MW of wind and S MW of solar, the effective **residual load** or **mismatch** is

$$m_t = d_t - Ww_t - Ss_t$$

We choose W and S such that on **average** we cover all the load

$$\langle m_t \rangle = 0$$

and so that the 70% of the energy comes from wind and 30% from solar ($W = 147$ GW and $S = 135$ GW for Germany).

This means

$$W \langle w_t \rangle = 0.7 \langle d_t \rangle \qquad S \langle s_t \rangle = 0.3 \langle d_t \rangle$$

Mismatch between load and renewables

Let p_t be the balance of power at each time. Because we cannot create or destroy energy, we need $p_t = 0$ at all times.

If the mismatch is positive $m_t > 0$, then we need **backup power** $b_t = m_t$ to cover the load in the absence of renewables, so that

$$p_t = b_t - m_t = b_t - d_t + Ww_t + Ss_t = 0$$

If the mismatch is negative $m_t < 0$ then we need **curtailment** $c_t = -m_t$ to reduce the excess feed-in from renewables, so that

$$p_t = -m_t - c_t = -c_t - d_t + Ww_t + Ss_t = 0$$

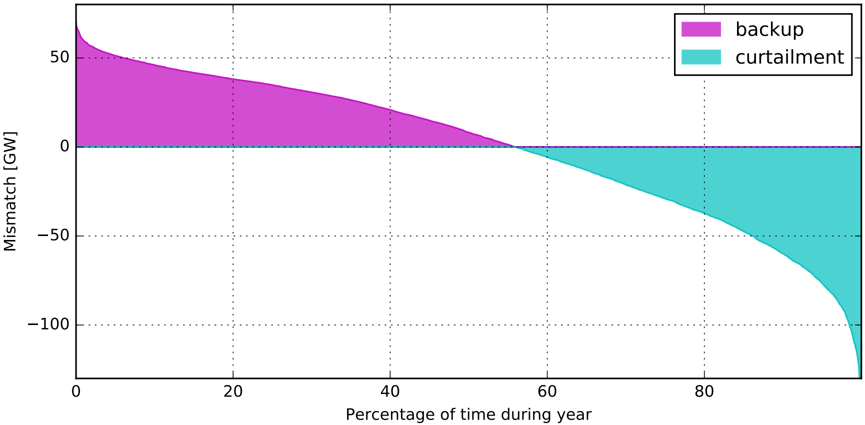
At any one time we have either backup or curtailment

$$p_t = b_t - m_t - c_t = Ww_t + Ss_t + b_t - d_t - c_t = 0$$

Mismatch for Germany

Backup generation needed for 31% of the total load.

Peak mismatch is 91% of peak load (around 80 GW).

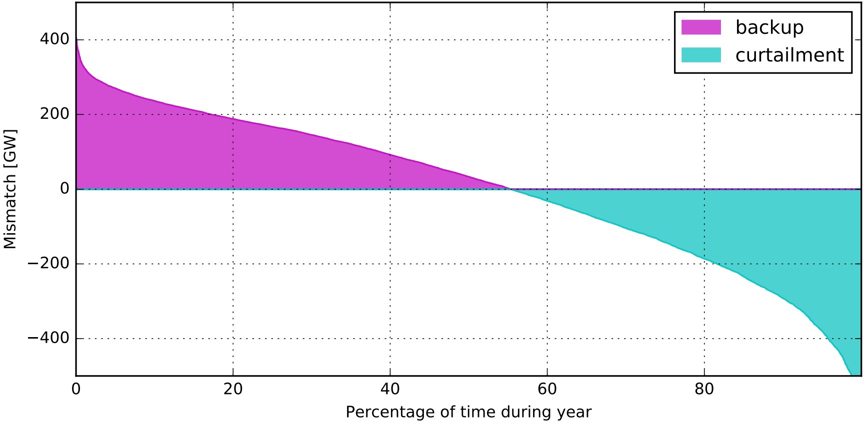


Mismatch for Europe

Requires 750 GW each of onshore wind and solar.

Backup generation needed for only 24% of the total load.

Peak mismatch is 79% of peak load (around 500 GW).



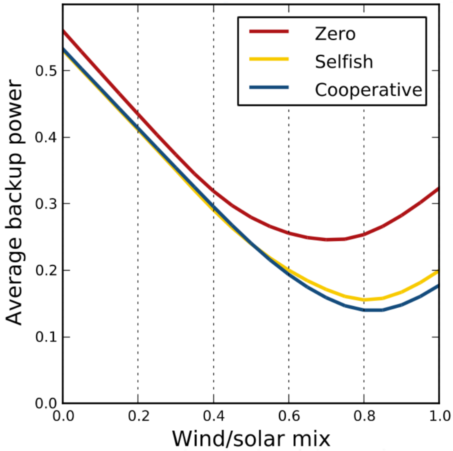
Conclusions

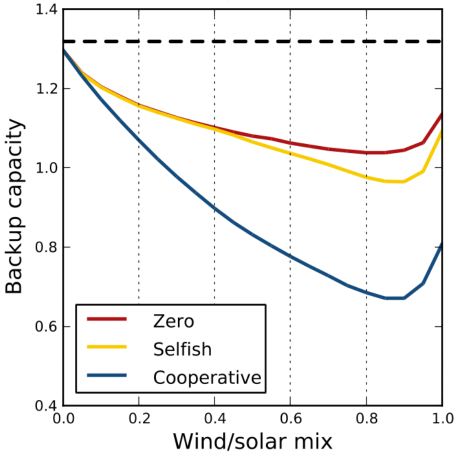
- Integration over a larger area smooths out the fluctuations of renewables, particularly wind.
- Wind backs up wind.
- This means we need **less backup energy**.
- And **less backup capacity**.

‘Cost-optimal design of a simplified, highly renewable pan-European electricity system’

by Rolando A. Rodriguez, Sarah Becker, Martin Greiner, Energy 83 (2015) 658-668

‘average backup power’ indicates backup energy; zero has no transmission between countries versus cooperative



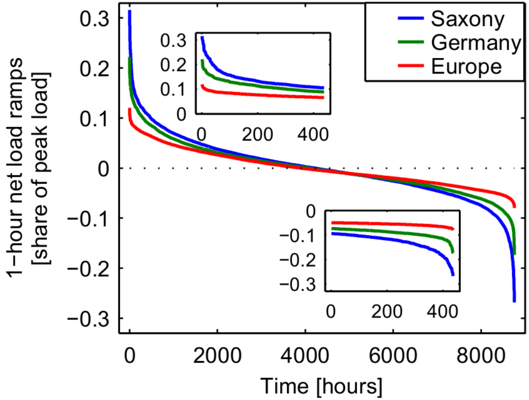


Flexibility Requirements

'Integration of wind and solar power in Europe: Assessment of flexibility requirements'

by Huber, Dimkova, Hamacher, Energy 69 (2014) 236e246

1-hour net load ramp duration curves at the regional, country and European spatial scales at 50% share of renewables and 20% PV in the wind/PV mix for the meteorological year 2009.



Big Caveat

There is a big caveat to this analysis.

We've assumed that we can move power around Europe without penalty.

However, in reality, we can only transport within restrictions of the power network.

In general we will have different power imbalances $p_{i,t}$ at each location/node i and instead of $p_t = 0$ we will have

$$\sum_i p_{i,t} = 0$$

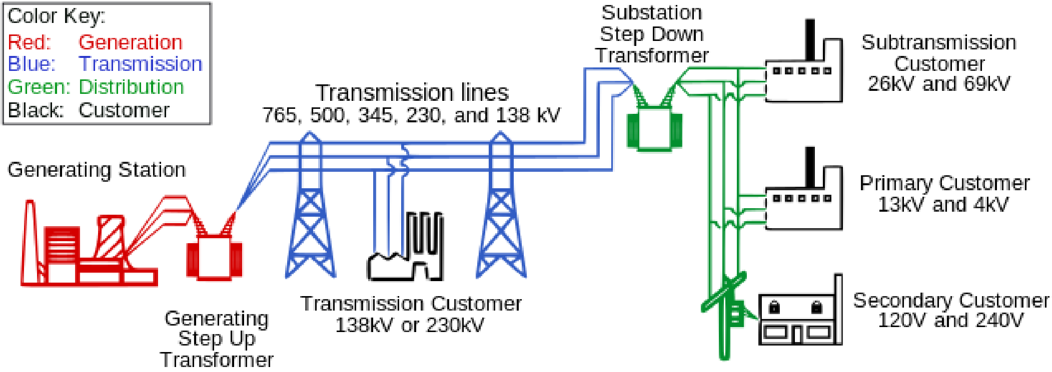
(neglecting power losses in the network).

Moving excess power to locations of consumption is the role of the network.

Electricity Networks

Electricity Transport from Generators to Consumers

Electricity can be transported over long distances with low losses using the high voltage transmission grid (losses go like I^2R, power transmission like VI, so reduce I by raising V):



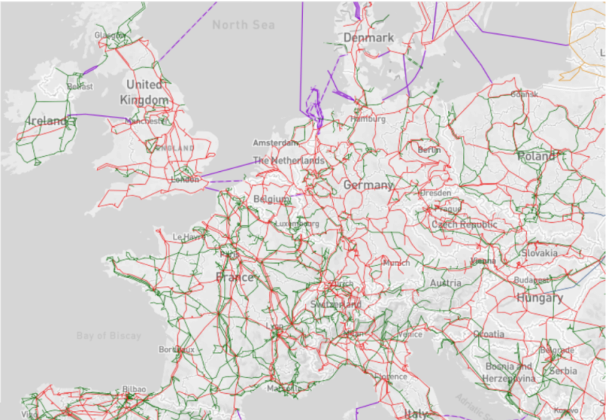
Usually in houses the voltage is 230 V, but in the transmission grid it is transformed up to hundreds of thousands of Volts.

Source: Wikipedia

European transmission network

Flows in the European transmission network must respect both Kirchoff's laws for physical flow and the thermal and/or other limits of the power lines.

Taking account of network flows and constraints in the electricity market is a major and exciting topic at the moment.

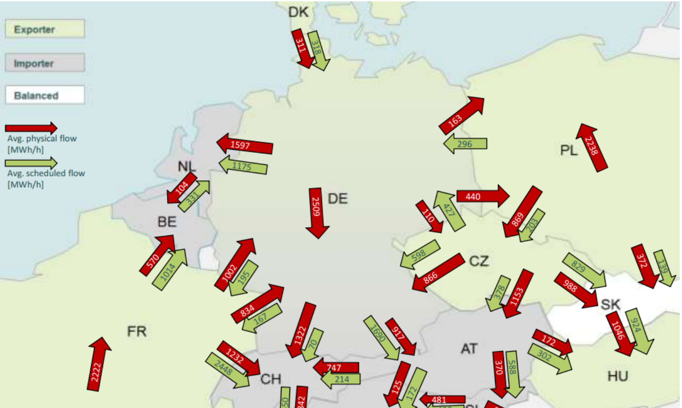


Source: ENTSO-E

Network Bottlenecks and Loop Flows

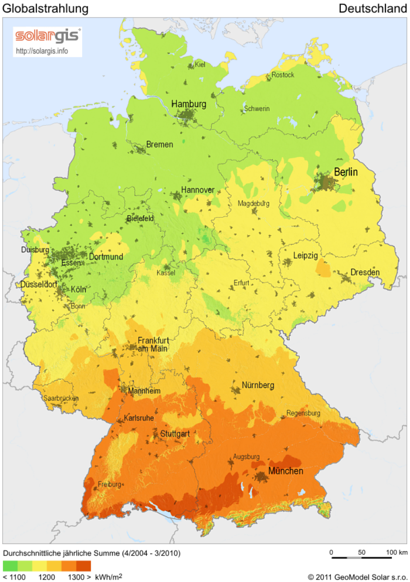
Electricity is traded in large market zones. Power trades between zones ("scheduled flows") do not always correspond to what flows according to the network physics ("physical flows"). This leads to political tension as wind from Northern Germany flows to Southern Germany via Poland and the Czech Republic.

Figure 7: Average physical and scheduled flows [MWh/h], 01.01.2011 – 31.12.2012



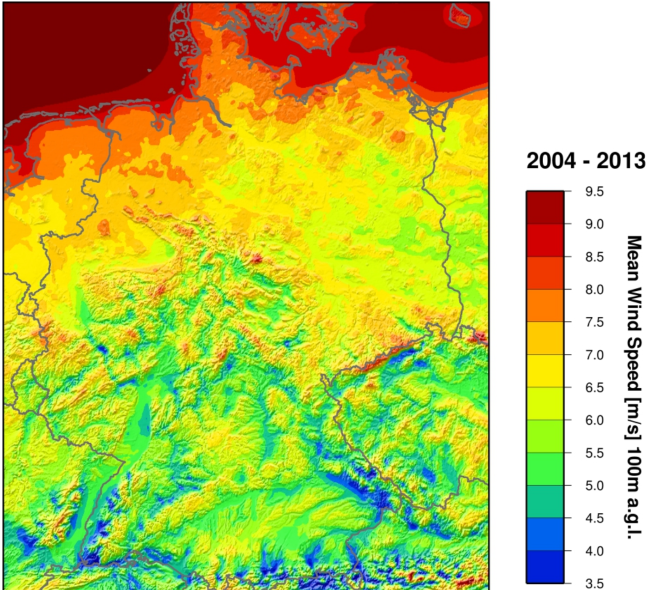
Source: THEMA Consulting Group

Solar resource distribution in Germany



- Solar insolation at top of atmosphere is on average 1361 W/m^2 (orbit is elliptical).
- In Germany average insolation on a horizonal surface is around 1200 kWh/m^2.
- A 1 kW solar panel (around 7 m^2) will generate around 1000 kWh/a.

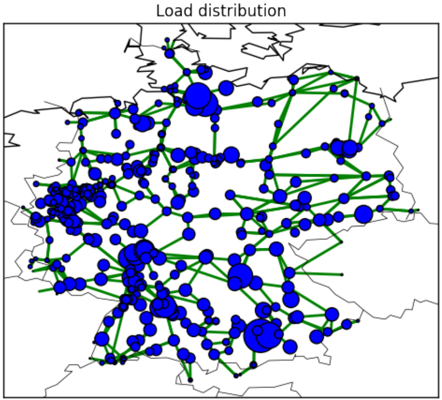
Wind resource distribution in Germany

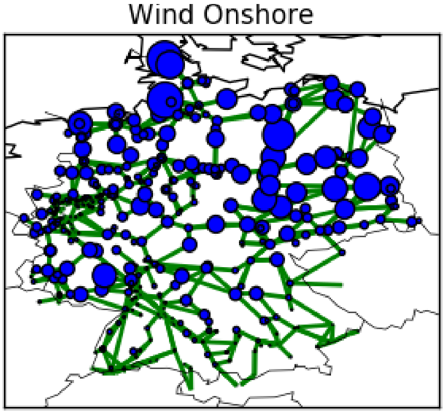


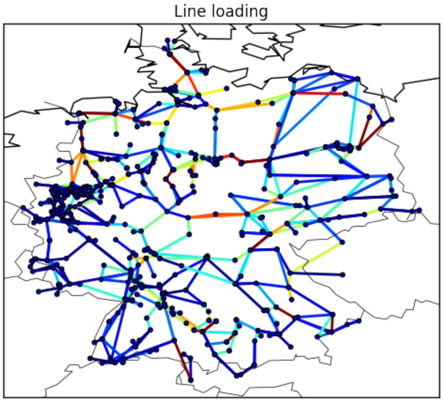
- Best wind speeds in Germany in North and on hills.
- In theory power output goes like cube $\propto v^3$ of wind speed v.
- In practice power-speed relationship is only partially cubic.

The Problem

Renewables are not always located near demand centres, as in this example from Germany.





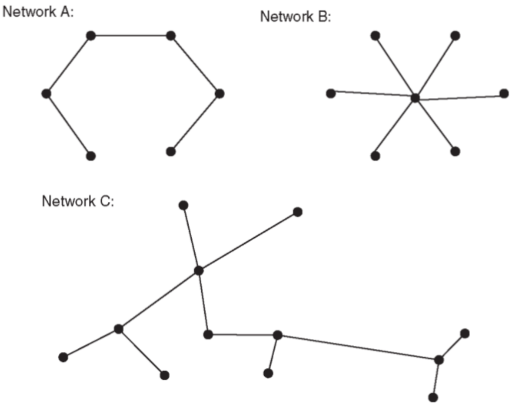


- This leads to **overloaded lines** in the middle of Germany, which cannot transport all the wind energy from North Germany to the load in South Germany
- It also overloads lines in neighbouring countries due to **loop flows** (unplanned physical flows 'according to least resistance' which do not correspond to traded flows)
- It also **blocks imports and exports** with neighbouring countries, e.g. Denmark

Different types of networks: radial networks

In a **radial** or **tree-like** network there is only one path between any two nodes on the network.

The power flow is thus completely determined by the nodal power imbalances.

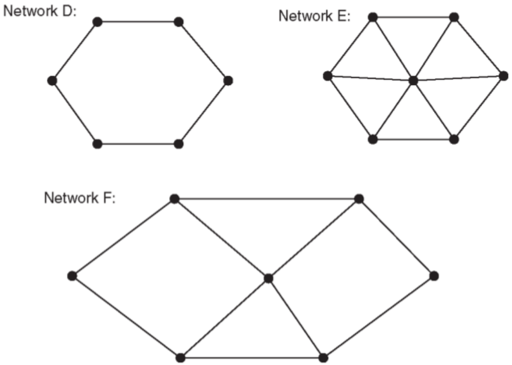


Source: Biggar & Hesamzadeh

Different types of networks: meshed networks

In a **meshed** network there are at least two nodes with multiple paths between them.

The power flow is now not completely determined. We need new information: the impedances in the network.



Source: Biggar & Hesamzadeh