Complex Renewable Energy Networks
Summer Semester 2017, Lecture 1

Dr. Tom Brown

19th April 2017

Frankfurt Institute of Advanced Studies (FIAS), Goethe-Universität Frankfurt
FIAS Renewable Energy System and Network Analysis (FRESNA)

brown@fias.uni-frankfurt.de

FIAS Frankfurt Institute for Advanced Studies

Table of Contents

Administration

Lectures and Exercise Classes

Lectures:

- Weekly, Wednesdays 14:00 - 16:00, Phys 01.114
- 19.04.2017 until 19.07.2017 (14 lectures)

Exercise Classes:

- Biweekly, Wednesdays 16:00 - 18:00, Phys 01.114
- 19.04.2017 until 12.07.2017 (7 classes)

Contact Details

Dr. Tom Brown

Postdoctoral Researcher

FIAS (Riedberg)

brown@fias.uni-frankfurt.de

I am a physicist who has specialised in the optimisation of energy systems and the interactions of complex networks.

Literature

There is no book which covers all aspects of this course. In particular there is no good source for the combination of complex network theory and renewables. But there are lots of online lecture notes. The world of renewables also changes fast...

The following are concise:

- Volker Quashning, “Regenerative Energiesysteme”, Carl Hanser Verlag München, 2015
- Leon Freris, David Infield, “Renewable Energy in Power Systems”, Wiley, 2006
- Göran Andersson Skript, “Elektrische Energiesysteme: Vorlesungsteil Energieübertragung,” online

Course Website

You can find the course website:

https://nworbmot.org/courses/complex_renewable_energy_networks/

by following the links from:

https://nworbmot.org/teaching.html

Course notes and other links can be found there.

Registration for Evaluation

To get an evaluation at the end of the course, you can only have missed 2 of the lectures.

A registration will be passed around in each lecture.

Please sign it.

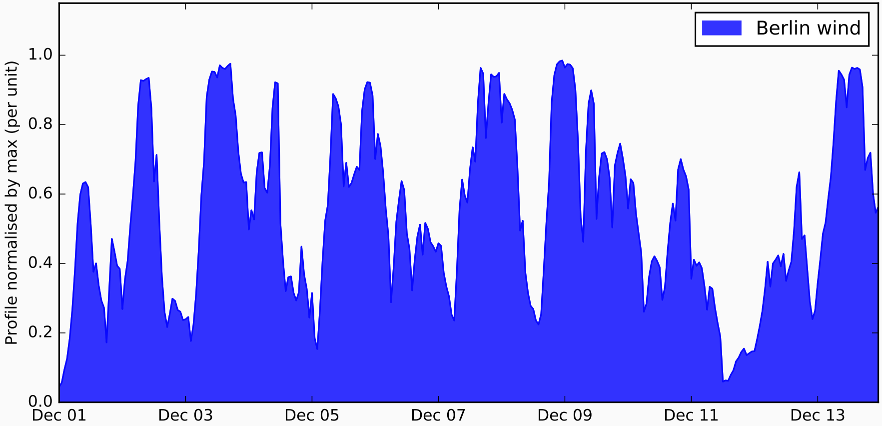
Introduction: Balancing Variable Renewable Energy

Research questions

1. What infrastructure (wind, solar, hydro generators, heating/cooling units, storage and networks) does a highly renewable energy system require and where should it go?
2. Given a desired CO_2 emissions reduction (e.g. 95% compared to 1990), what is the cost-optimal combination of infrastructure?
3. How do we deal with the variablility of wind and solar: balancing in space with networks or in time with storage?

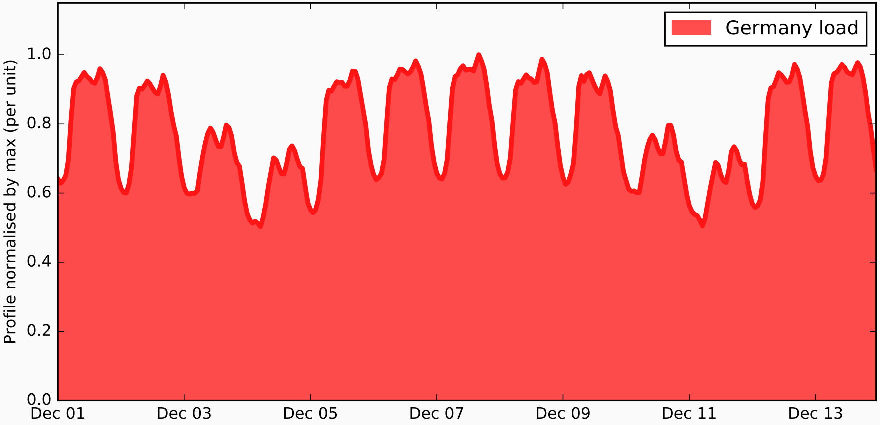
Variability: Single wind site in Berlin

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.



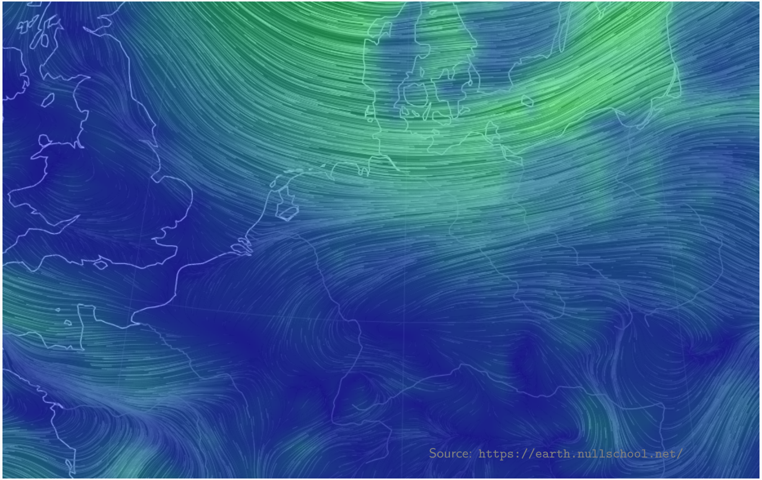
Electricity consumption is much more regular

Electrical demand is much more regular over time - dealing with the mismatch between locally-produced wind and the demand would require a lot of storage...



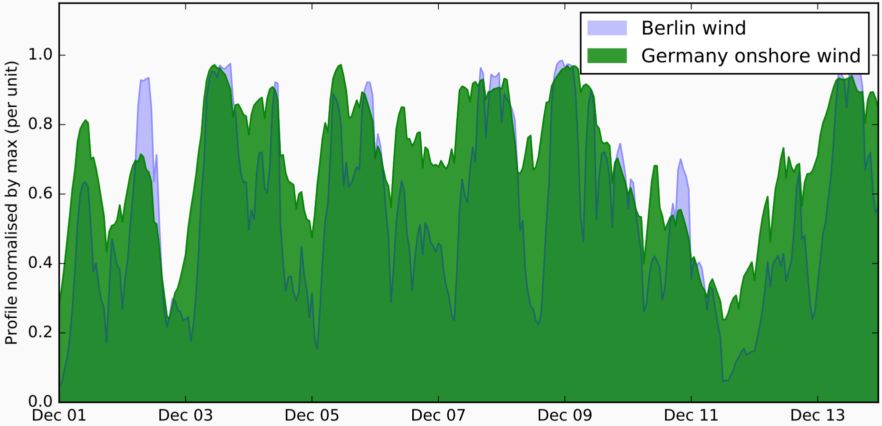
Variability: Different wind conditions over Germany

But the wind does not blow the same at every site at every time: at a given time there are a variety of wind conditions across Germany. These differences balance out over time and space.



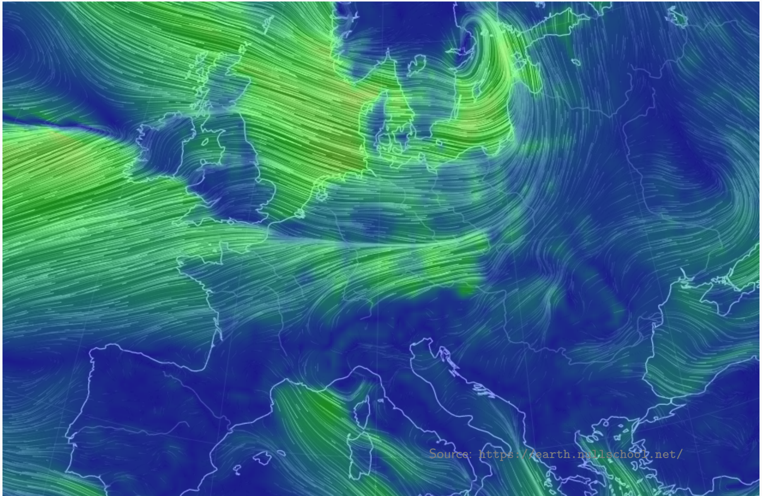
Variability: Single country: Germany

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.



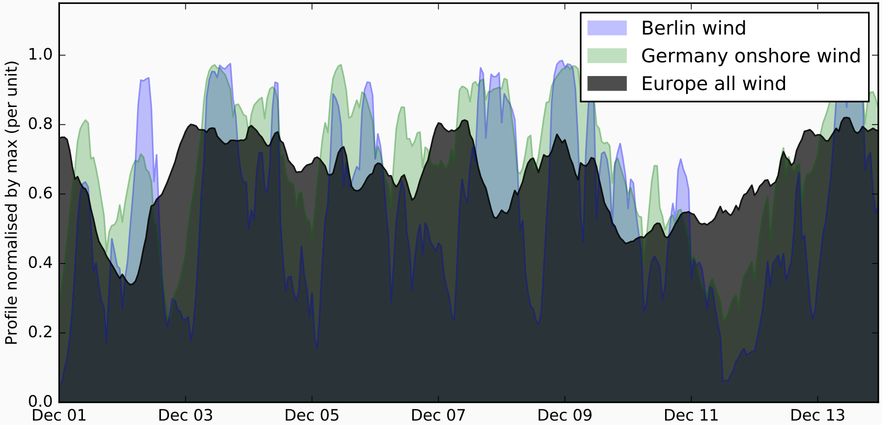
Variability: Different wind conditions over Europe

The scale of the weather systems are bigger than countries, so to leverage the full smoothing effects, you need to integrate wind at the continental scale.



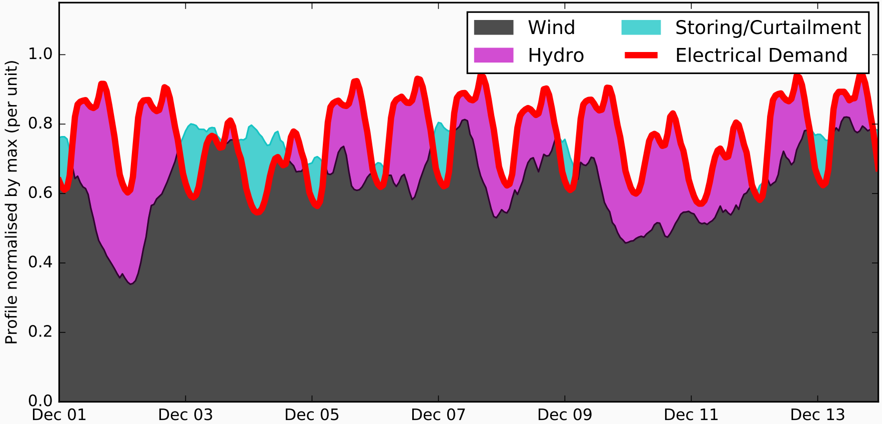
Variability: A continent: Europe

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.



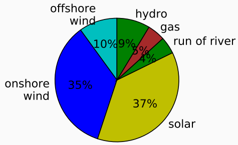
Variability: A continent: Wind plus Hydro

Flexible, renewable hydroelectricity from storage dams in Scandinavia and the Alps can fill many of the valleys; excess energy can either be curtailed (spilled) or stored.

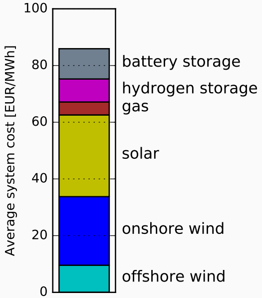


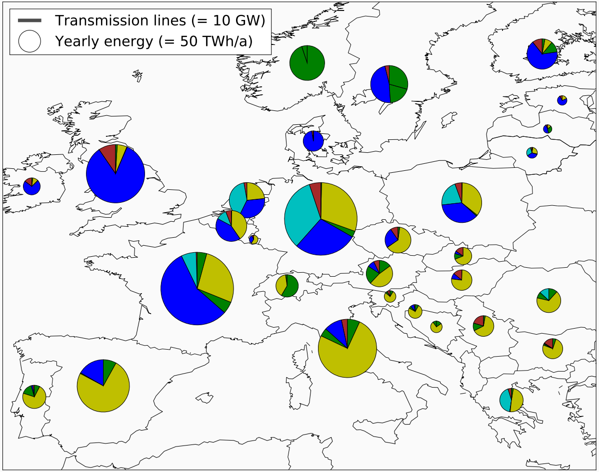
Costs: No interconnecting transmission allowed

Technology by energy:



Average cost €86/MWh:

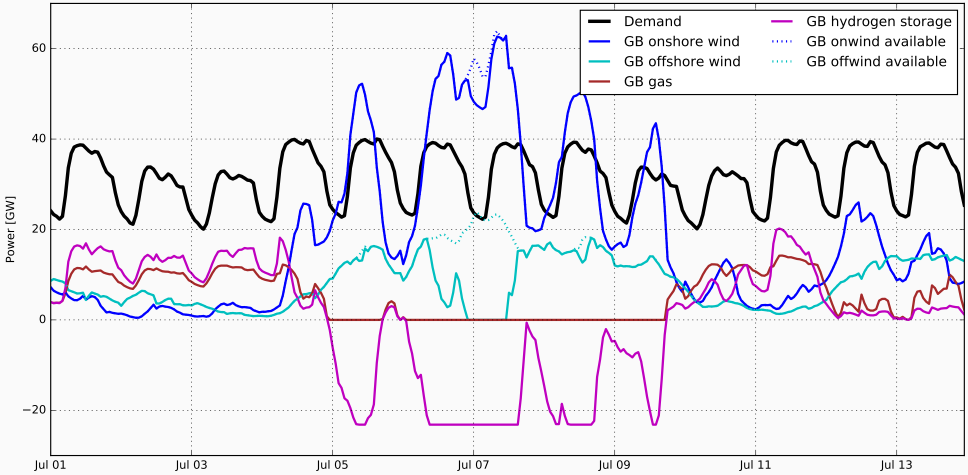




Countries must be self-sufficient at all times; lots of storage and some gas to deal with fluctuations of wind and solar.

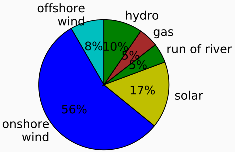
Dispatch with no interconnecting transmission

For Great Britain with no interconnecting transmission, excess wind is either stored as hydrogen or curtailed:

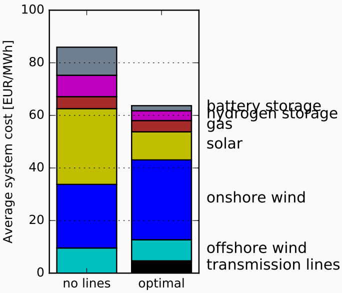


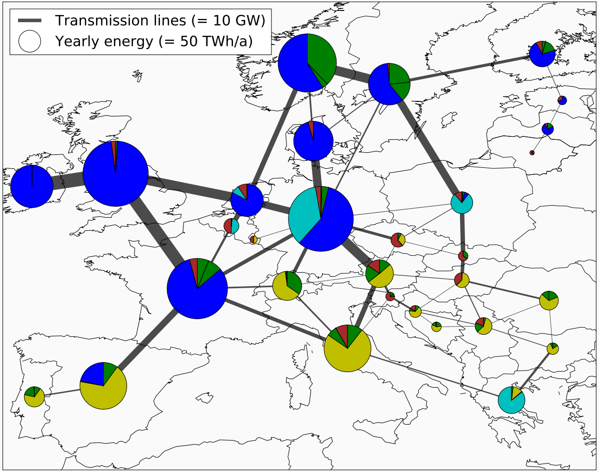
Costs: Cost-optimal expansion of interconnecting transmission

Technology by energy:



Average cost €64/MWh:

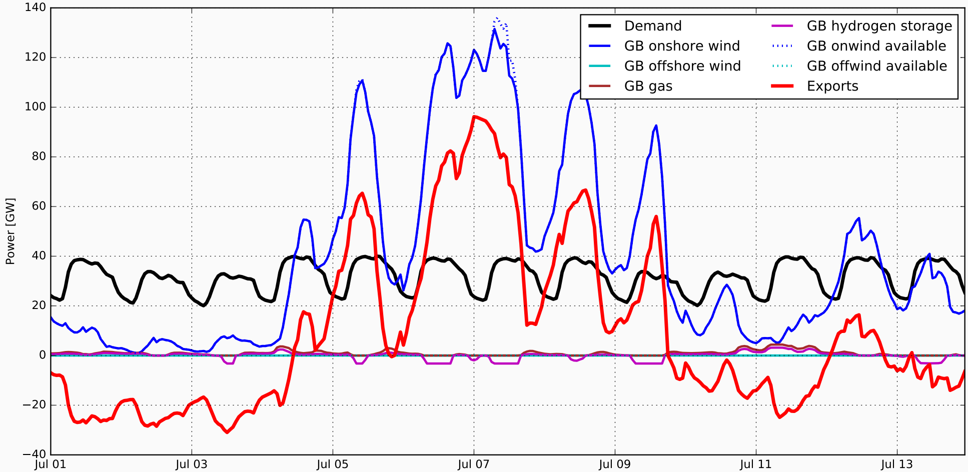




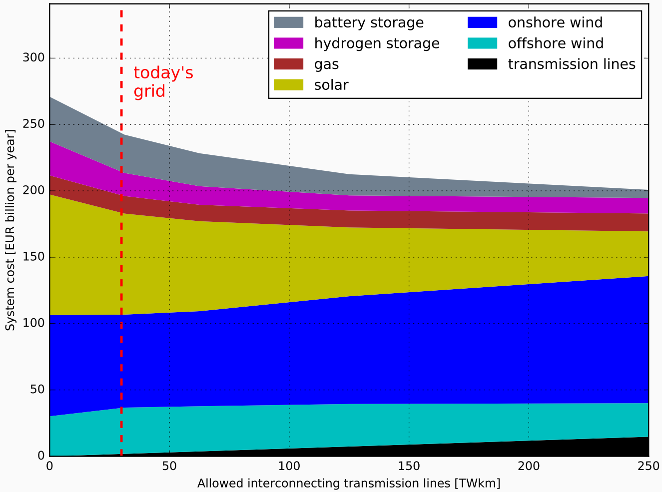
Large transmission expansion; onshore wind dominates. This optimal solution may run into public acceptance problems.

Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can be now be exported:



Electricity Only Costs Comparison



- Average total system costs can be as low as € 64/MWh
- Energy is dominated by wind (64% for the cost-optimal system), followed by hydro (15%) and solar (17%)
- Restricting transmission results in more storage to deal with variability, driving up the costs by up to 34%
- Many benefits already locked in at a few multiples of today's grid

Course outline

Course outline

This course will cover the following topics:

- General properties of renewable power
- Backup generation, curtailment
- Network modelling in power systems
- Storage modelling
- Optimization theory
- Energy system economics
- Dynamics of renewable energy networks (synchronization, etc.)
- Complex network techniques for renewable energy networks (flow tracing, etc.)

Electricity Consumption

Why is electricity useful?

Electricity is a versatile form of energy carried by electrical charge which can be consumed in a wide variety of ways (with selected examples):

- Lighting (lightbulbs, halogen lamps, televisions)
- Mechanical work (hoovers, washing machines, electric vehicles)
- Heating (cooking, resistive room heating, heat pumps)
- Cooling (refrigerators, air conditioning)
- Electronics (computation, data storage, control systems)
- Industry (electrochemical processes)

Compare the convenience and versatility of electricity with another energy carrier: the chemical energy stored in natural gas (methane), which can only be accessed by burning it.

Power: Examples of consumption

At full power, the following items consume:

Item	Power
New efficient lightbulb	10 W
Old-fashioned lightbulb	70 W
Single room air-conditioning	1.5 kW
Kettle	2 kW
Factory	$\sim$1-500 MW
CERN	200 MW
Germany total demand	35-80 GW

Energy

In the electricity sector, energy is usually measured in 'Watt-hours', Wh.

1 kWh = power consumption of 1 kW for one hour

E.g. a 10 W lightbulb left on for two hours will consume

10 W * 2 h = 20 Wh

It is easy to convert this back to the SI unit for energy, Joules:

1 kWh = (1000 W) * (1 h) = (1000 J/s)*(3600 s) = 3.6 MJ

Yearly energy to power

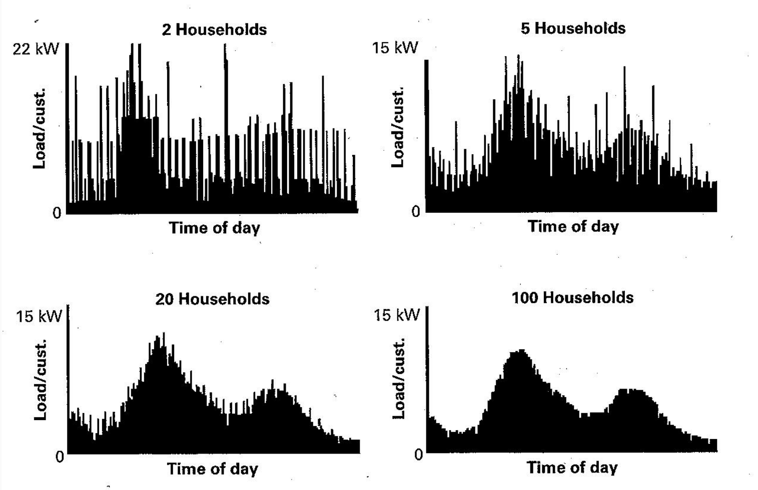
Germany consumes around 600 TWh per year, written 600 TWh/a.

What is the *average* power consumption?

$$
\begin{aligned}
600 \text{ TWh/a} &= \frac{(600 \text{ TW}) * (1 \text{ h})}{(365 * 24 \text{ h})} \\
&= \frac{600}{8760} \text{ TW} \\
&= 68.5 \text{ GW}
\end{aligned}
$$

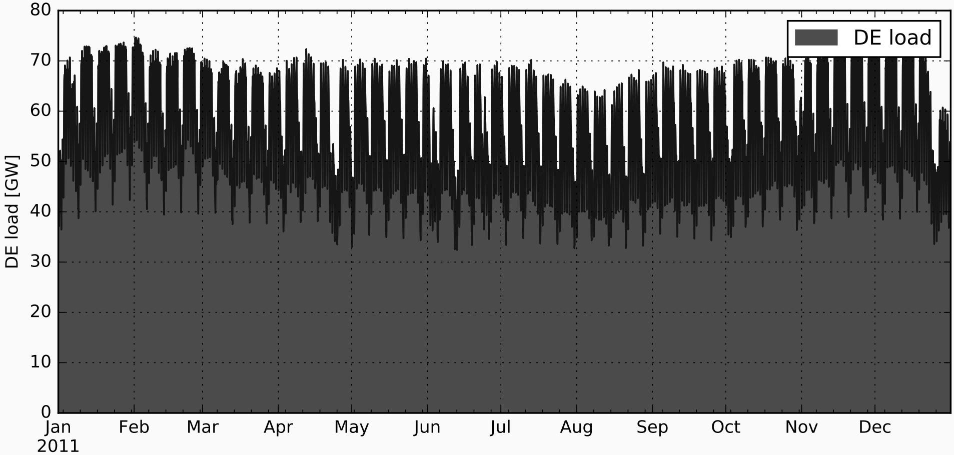
Discrete Consumers Aggregation

The discrete actions of individual consumers smooth out statistically if we aggregate over many consumers.



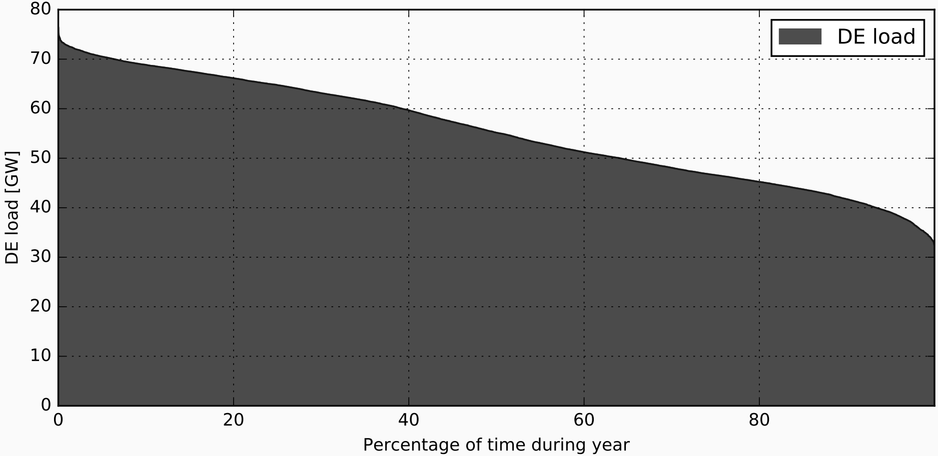
Load curve properties

The Germany load curve (around 500 TWh/a) shows daily, weekly and seasonal patterns; religious festivals are also visible.



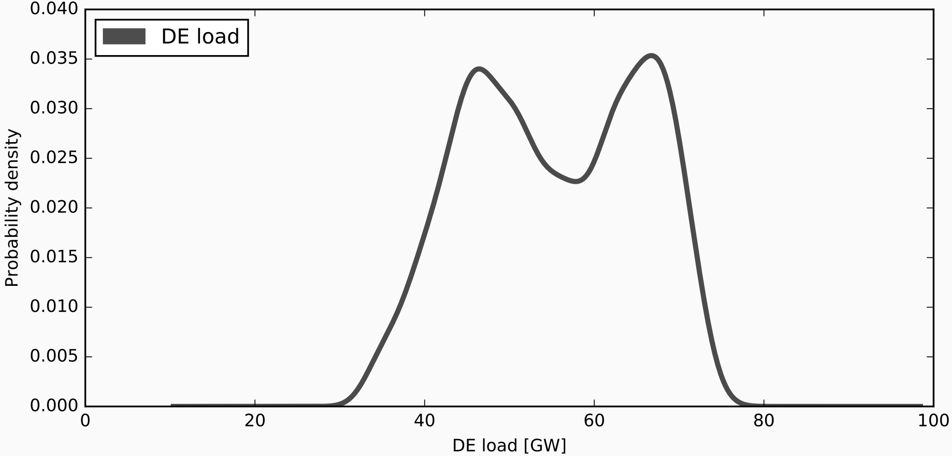
Load duration curve

For some analysis it is useful to construct a duration curve by stacking the hourly values from highest to lowest.



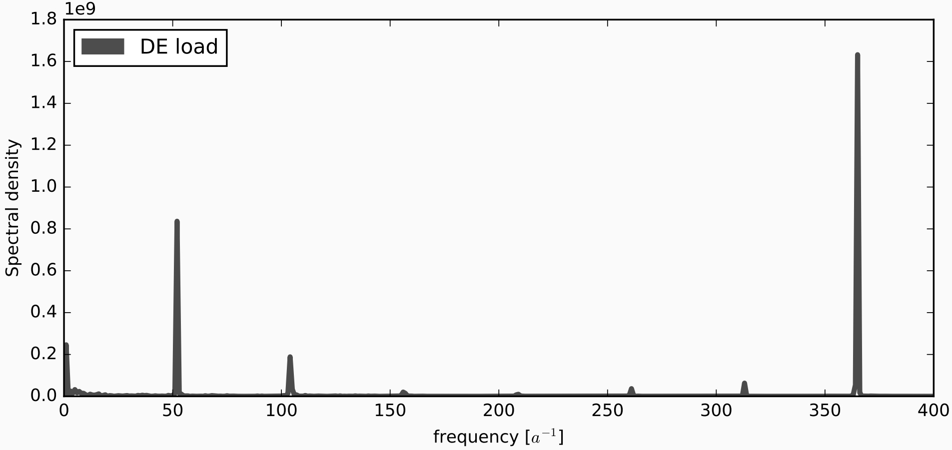
Load density function

Similarly we can also build the probability density function:



Load spectrum

If we Fourier transform, the seasonal, weekly and daily frequencies are clearly visible.



Electricity Generation

How is electricity generated?

Conservation of Energy: Energy cannot be created or destroyed: it can only be converted from one form to another.

There are several 'primary' sources of energy which are converted into electrical energy in modern power systems:

- Chemical energy, accessed by combustion (coal, gas, oil, biomass)
- Nuclear energy, accessed by fission reactions, perhaps one day by fusion too
- Hydroelectric energy, allowing water to flow downhill (gravitational potential energy)
- Wind energy (kinetic energy of air)
- Solar energy (accessed with photovoltaic (PV) panels or concentrating solar thermal power (CSP))
- Geothermal energy

NB: The definition of 'primary' is somewhat arbitrary.

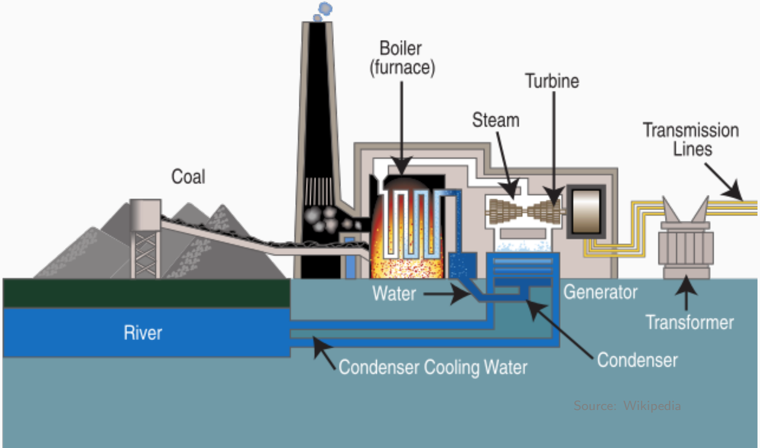
Power: Examples of generation

At full power, the following items generate:

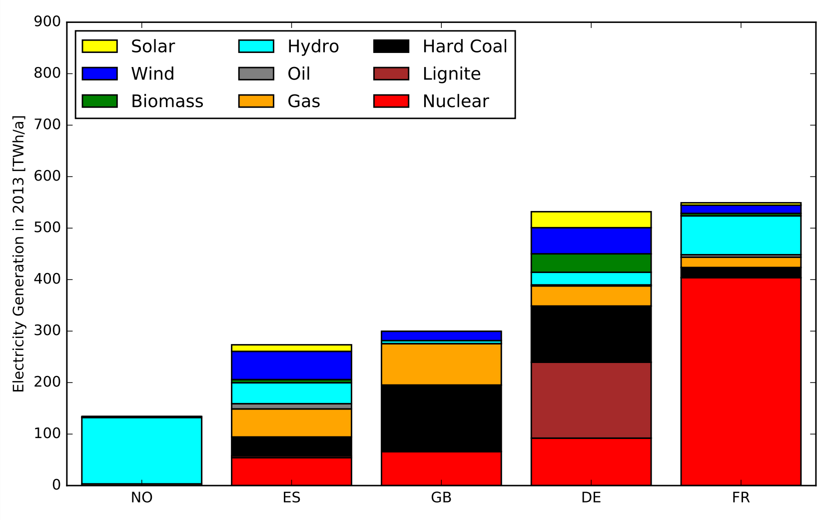
Item	Power
Solar panel on house roof	15 kW
Wind turbine	3 MW
Coal power station	1 GW

Generators

With the exception of solar photovoltaic panels (and electrochemical energy and a few other minor exceptions), all generators convert to electrical energy via rotational kinetic energy and electromagnetic induction in an *alternating current generator*.

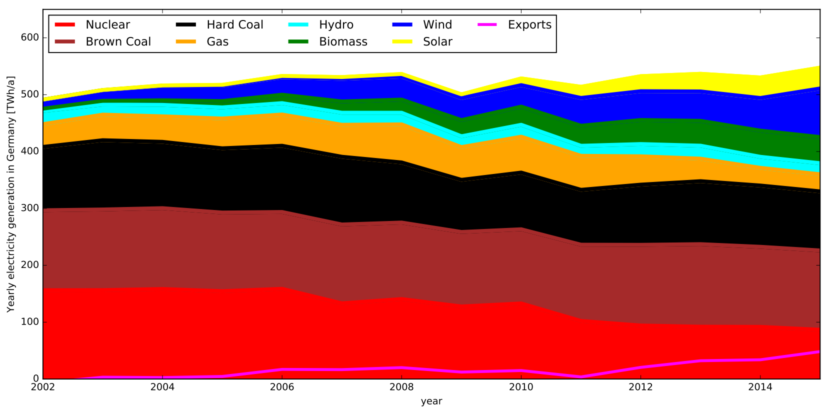


Example of electricity generation across major EU countries in 2013



Electricity generation in Germany per year

In 15 years Germany has gone from a system dominated by nuclear and fossil fuels, to one with 33% renewables in electricity consumption.



Source: Author's own representation based on `https://www.energy-charts.de/energy_en.htm`

Efficiency

When fuel is consumed, much/most of the energy of the fuel is lost as waste heat rather than being converted to electricity.

The thermal energy, or calorific value, of the fuel is given in terms of $\mathrm{MWh_{th}}$, to distinguish it from the electrical energy $\mathrm{MWh_{el}}$.

The ratio of input thermal energy to output electrical energy is the efficiency.

Fuel	Calorific energy $\mathrm{MWh_{th}}$/tonne	Per unit efficiency $\mathrm{MWh_{el}}/\mathrm{MWh_{th}}$	Electrical energy $\mathrm{MWh_{el}}$/tonne
Lignite	2.5	0.4	1.0
Hard Coal	6.7	0.45	2.7
Gas	15.4	0.4	6.16
Uranium	150000	0.33	50000

Fuel costs to marginal costs

The cost of a fuel is often given in €/kg or €/MWh$_{th}$.

Using the efficiency, we can convert this to €/MWh$_{el}$.

Fuel	Per unit efficiency MWh$_{el}$/MWh$_{th}$	Cost per thermal €/MWh$_{th}$	Cost per elec. €/MWh$_{el}$
Lignite	0.4	4.5	11
Hard Coal	0.45	10	22
Gas	0.4	23	58
Uranium	0.33	3.3	10

CO2 emissions per MWh

The CO_2 emissions of the fuel.

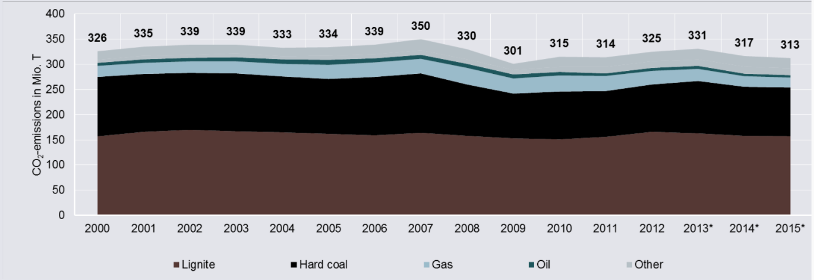
Fuel	t_{CO2}/t	t_{C02}/MWh_{th}	t_{CO2}/MWh_{el}
Lignite	0.9	0.36	0.9
Hard Coal	2.4	0.36	0.8
Gas	3.1	0.2	0.5
Uranium	0	0	0

Current CO_2 price in EU Emissions Trading Scheme (ETS) €5.27/t_{CO2}

CO2 emissions from electricity sector

Despite the increase in renewables in the electricity sector, CO_2 emission have not been reduced substantially in Germany. This is partly because German exports have also increased.

CO_2 emissions in the power sector 2000-2015 by energy source

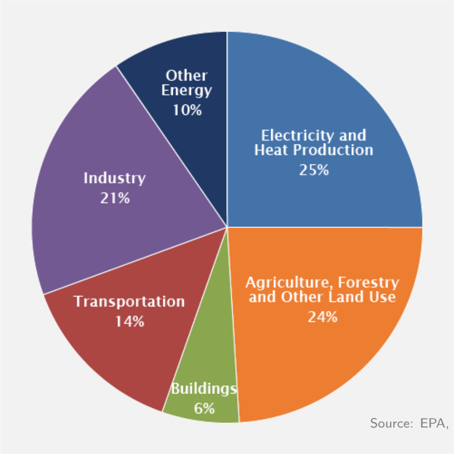


UBA 2015a; * own calculations

Source: Agora Energiewende

Other sectors

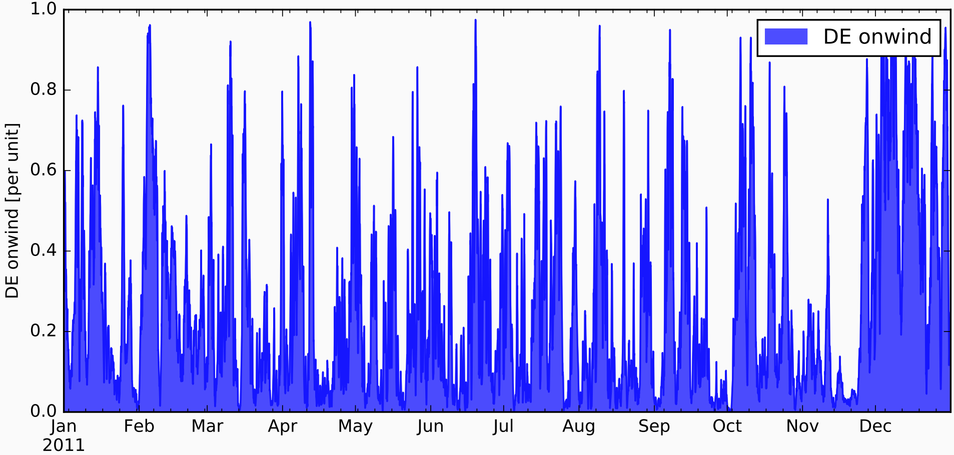
The CO_2 emissions from electricity generation contribute only a fraction to total global greenhouse gas emissions. However electricity generation is one of the easiest places to reduce emissions, aside from directly reducing energy consumption.



Source: EPA, IPCC (2014)

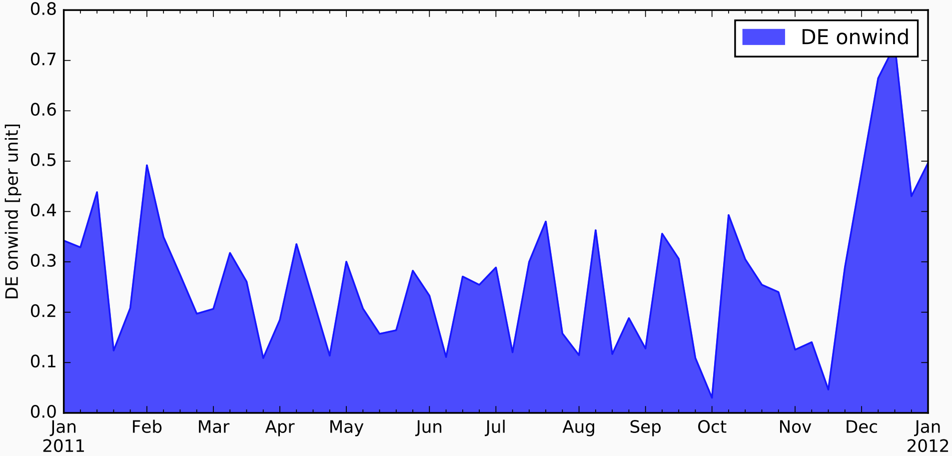
Wind time series

Unlike the load, the wind is much more variable, regularly dropping close to zero and rarely reaching full output (when aggregated over all of Germany).

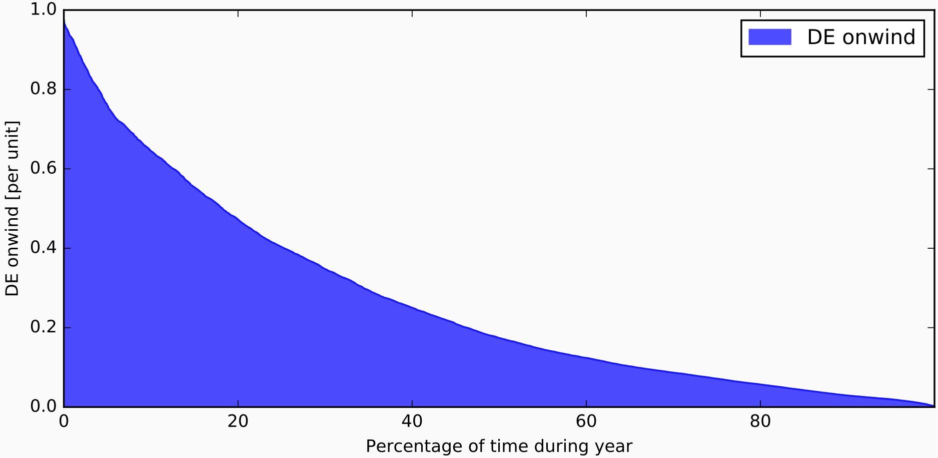


Wind time series: weekly

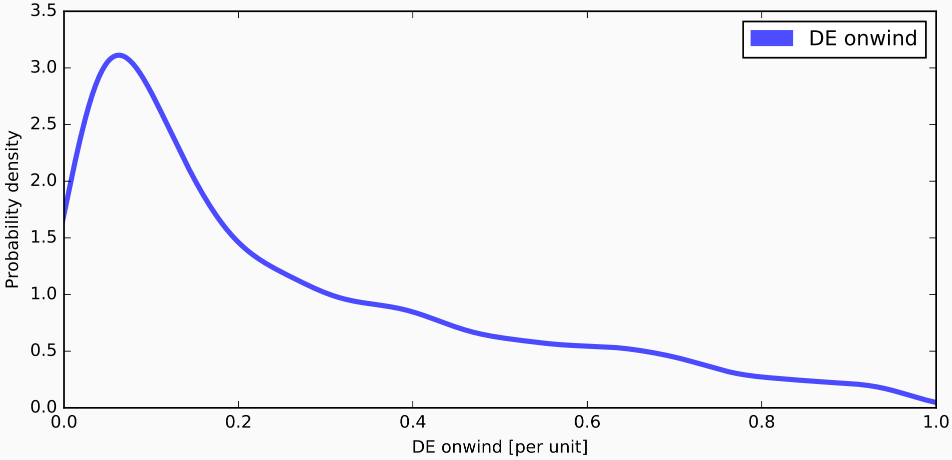
If we take a weekly average we see higher wind in the winter and some periodic patterns over 2-3 weeks (synoptic scale).



Wind duration curve

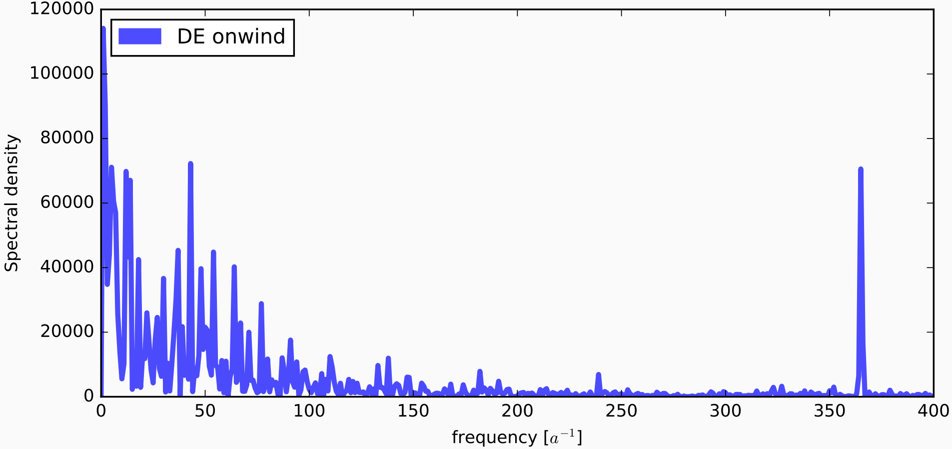


Wind density function



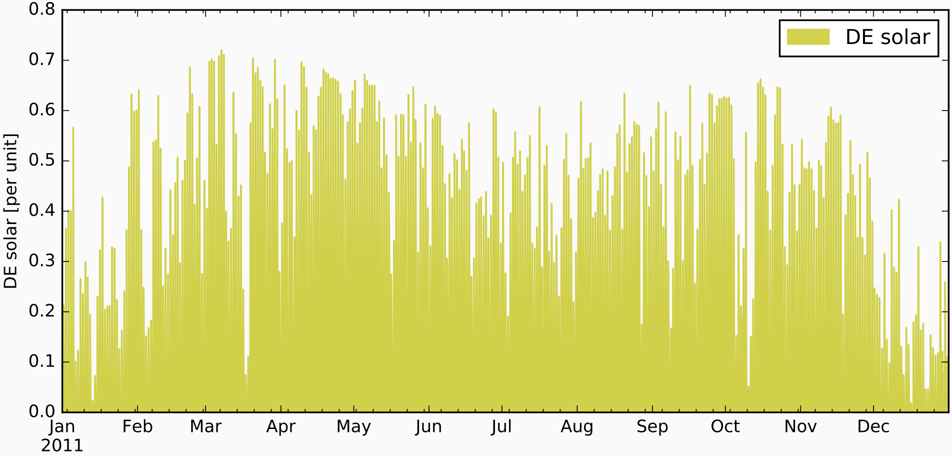
Wind spectrum

If we Fourier transform, the seasonal, synoptic and daily patterns become visible.



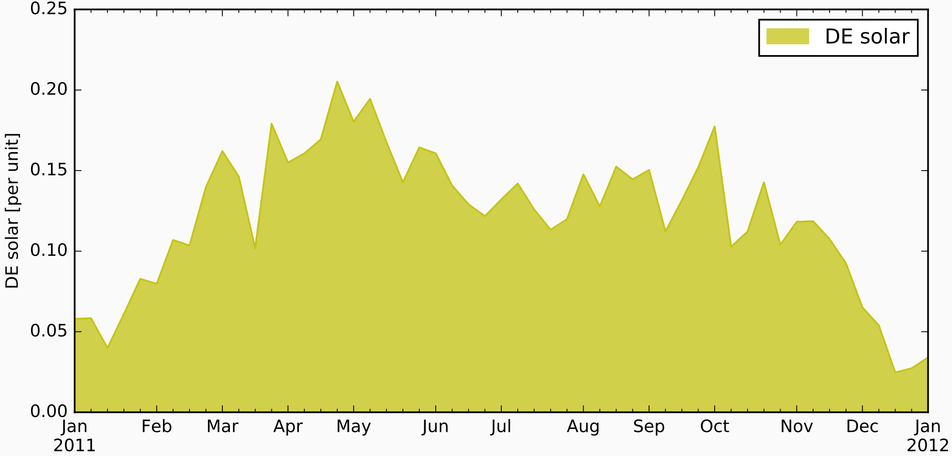
Solar time series

Solar is variable, but more predictable than wind.

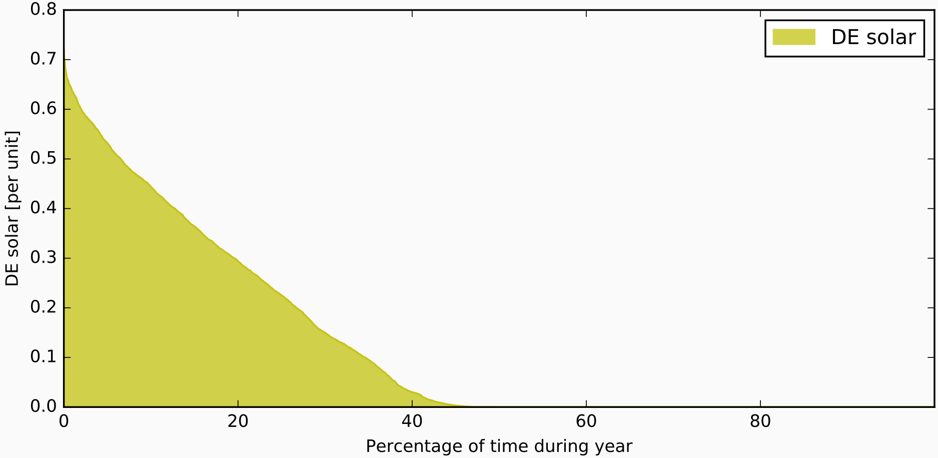


Solar time series: weekly

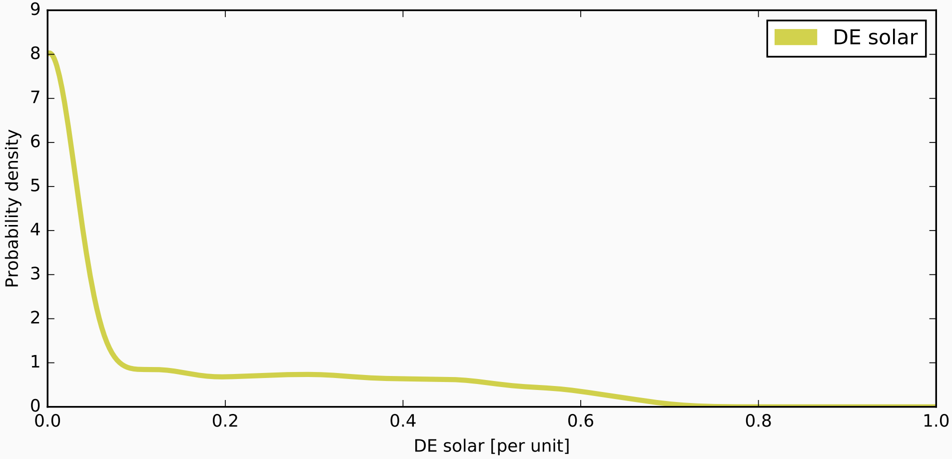
If we take a weekly average we see higher solar in the summer.



Solar duration curve

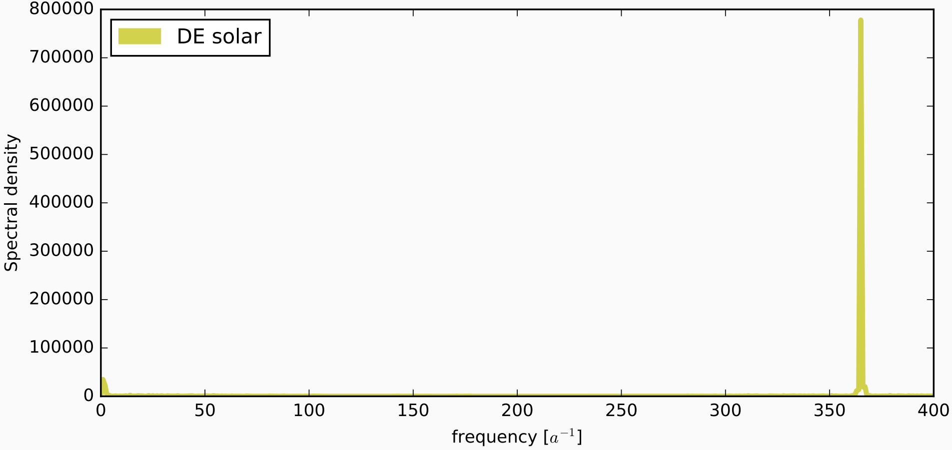


Solar density function



Solar spectrum

If we Fourier transform, the seasonal and daily patterns become visible.



Balancing a single country

Power mismatch

Suppose we now try and cover the electrical demand with the generation from wind and solar.

How much wind do we need? We have three time series:

- $\{\ell_t\}, \ell_t \in \mathbb{R}$ the load (varying between 35 GW and 80 GW)
- $\{w_t\}, w_t \in [0,1]$ the wind availability (how much a 1 MW wind turbine produces)
- $\{s_t\}, s_t \in [0,1]$ the solar availability (how much a 1 MW solar turbine produces)

We try W MW of wind and S MW of solar. Now the effective residual load or mismatch is

$$m_t = \ell_t - W w_t - S s_t$$

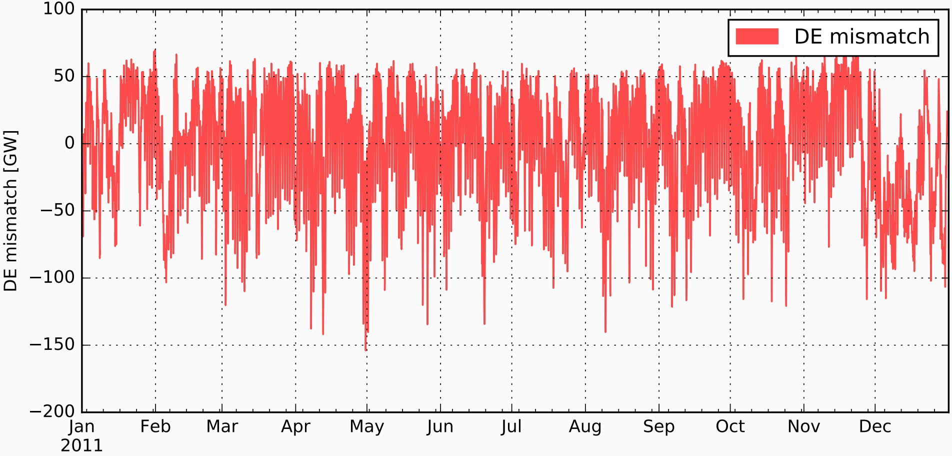
We choose W and S such that on average we cover all the load

$$\langle m_t \rangle = 0$$

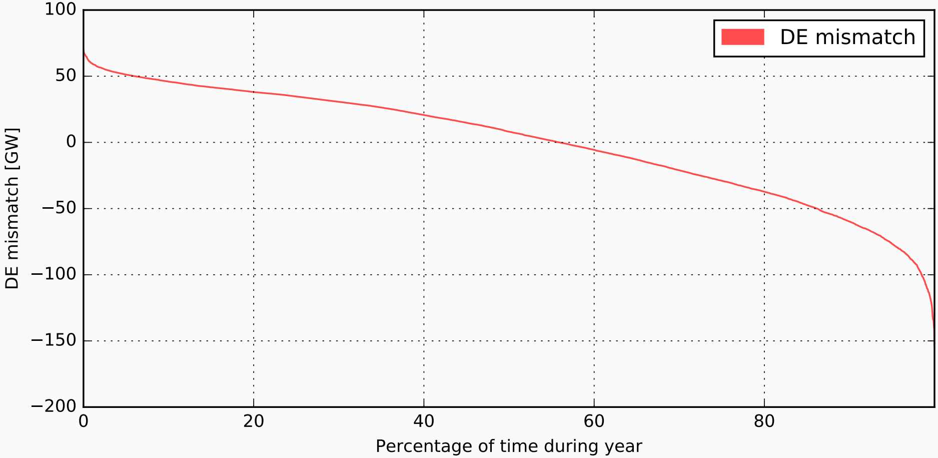
and so that the 70% of the energy comes from wind and 30% from solar ($W = 147$ GW and $S = 135$ GW).

Mismatch time series

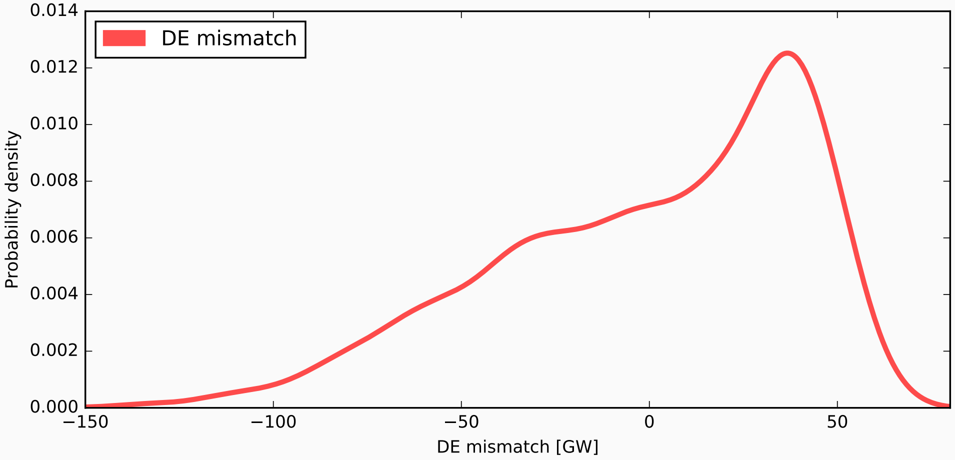
Mismatch is variable, but more predictable than wind.



Mismatch duration curve

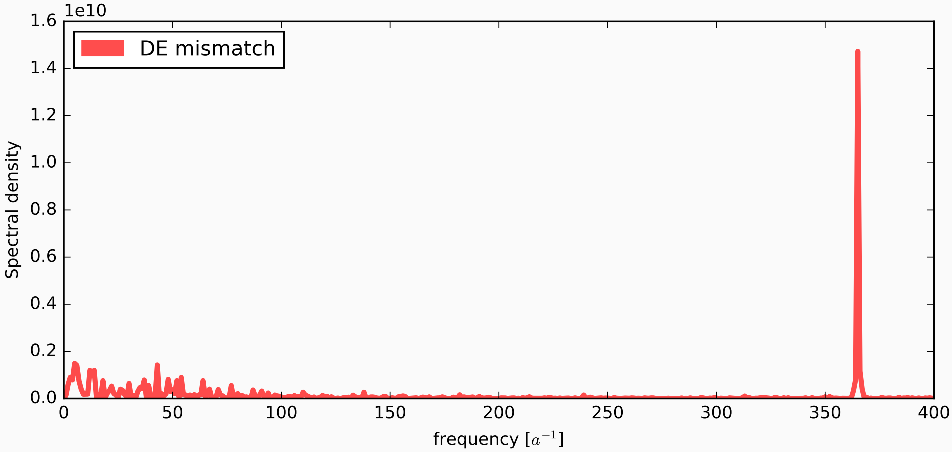


Mismatch density function



Mismatch spectrum

If we Fourier transform, the seasonal and daily patterns become visible.



How to deal with the mismatch?

The problem is that

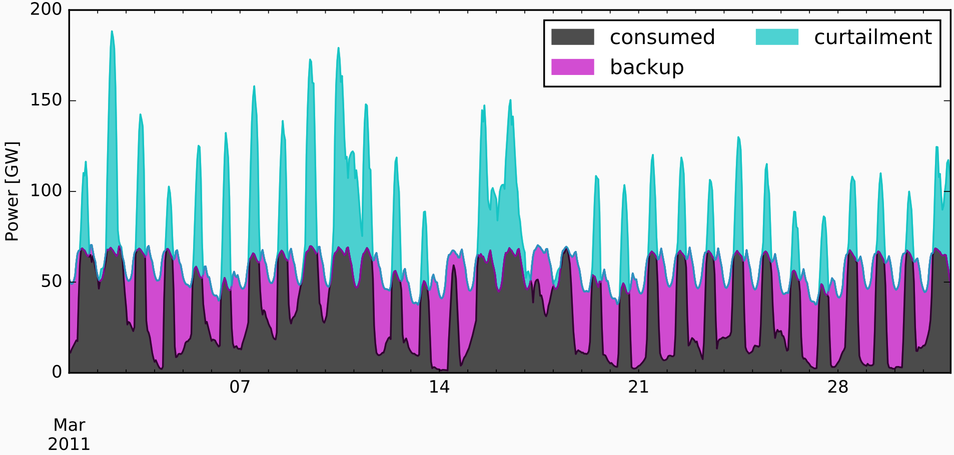
$$\langle m_t \rangle = 0$$

is not good enough! We need to meet the demand in every single hour.

This means:

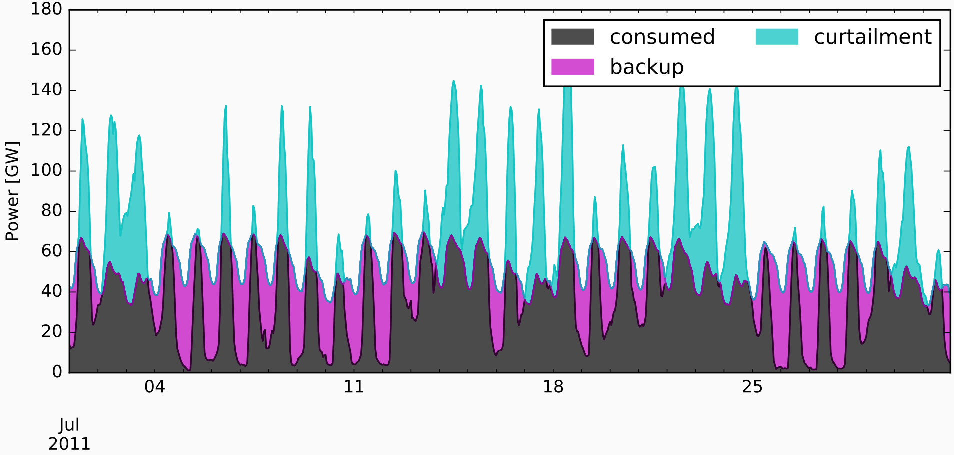
- If $m_t > 0$, i.e. we have unmet demand, then we need backup generation from dispatchable sources e.g. hydroelectricity reservoirs, fossil/biomass fuels.
- If $m_t < 0$, i.e. we have over-supply, then we have to shed / spill / curtail the renewable energy.

Mismatch



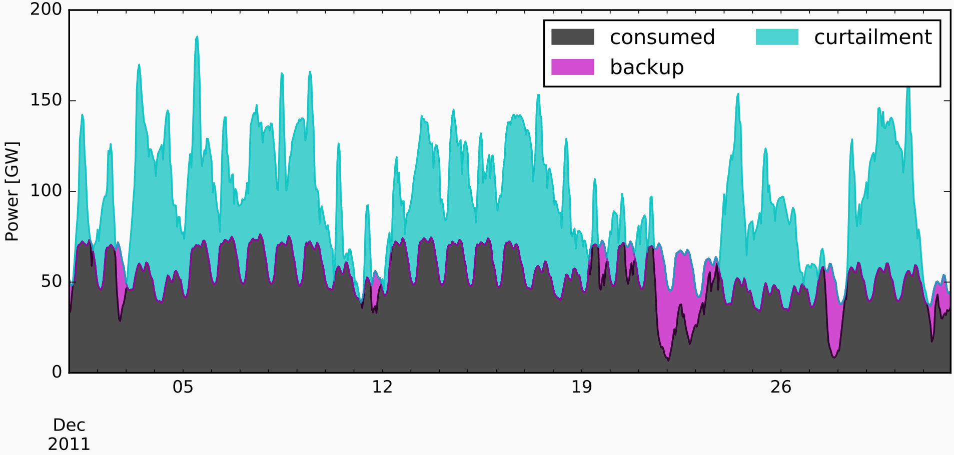
200
150
100
50
0
Power [GW]
07
14
21
28
Mar
2011
consumed
curtailment
backup

Mismatch



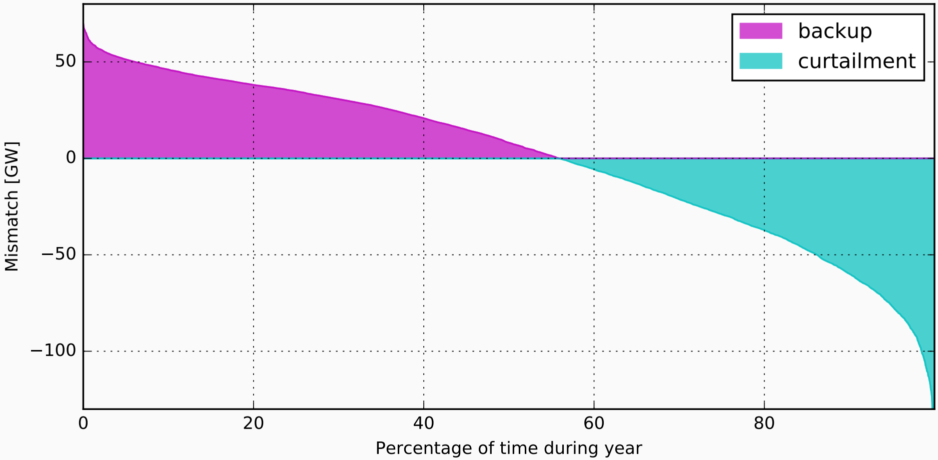
180
160
140
120
100
80
60
40
20
0
Power [GW]
04
11
18
25
Jul
2011
consumed
curtailment
backup

Mismatch



200
150
100
50
0
Power [GW]
05
12
19
26
Dec
2011
consumed
curtailment
backup

Mismatch duration curve



What to do?

Backup energy costs money and may also cause CO_2 emissions.

Curtailing renewable energy is also a waste.

We'll look in the next lectures at 4 solutions:

1. Smoothing stochastic variations of renewable feed-in over larger areas, e.g. the whole of European.
2. Using storage to shift energy from times of surplus to deficit.
3. Shifting demand to different times, when renewables are abundant.
4. Consuming the electricity in other sectors, e.g. transport or heating.