Energy System Modelling
Summer Semester 2020, Lecture 2

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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 (mostly methane), which can only be accessed by burning it.

Power: Flow of energy

Power is the rate of consumption of energy.

It is measured in **Watts**:

$$1 \text{ Watt } = 1 \text{ Joule per second}$$

The symbol for Watt is W, 1 W = 1 J/s.

$$1 \text{ kilo-Watt} = 1 \text{ kW} = 1{,}000 \text{ W}$$

$$1 \text{ mega-Watt} = 1 \text{ MW} = 1{,}000{,}000 \text{ W}$$

$$1 \text{ giga-Watt} = 1 \text{ GW} = 1{,}000{,}000{,}000 \text{ W}$$

$$1 \text{ tera-Watt} = 1 \text{ TW} = 1{,}000{,}000{,}000{,}000 \text{ W}$$

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

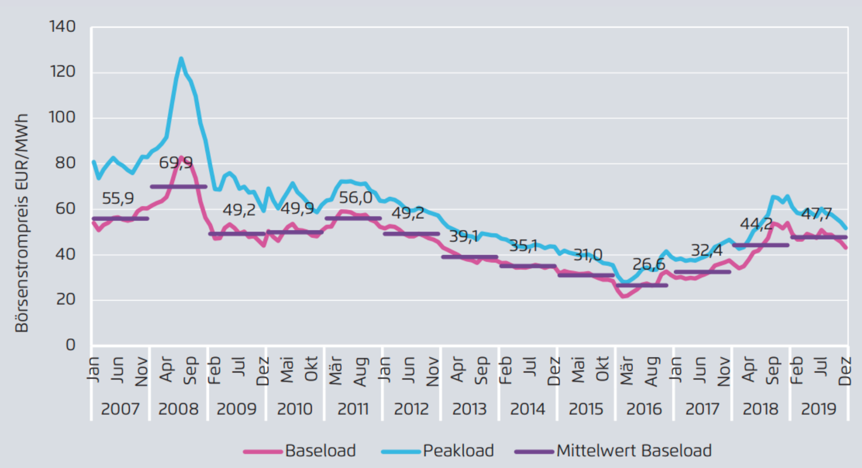
10 W * 2 h = 20 Wh

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

Electricity spot market: trading of energy

Energy is traded in MWh; current price around 40-50 €/MWh. Was sinking until 2016 thanks to renewables and the **merit order effect**, but rising since 2016 due to rising **CO_2 price**:



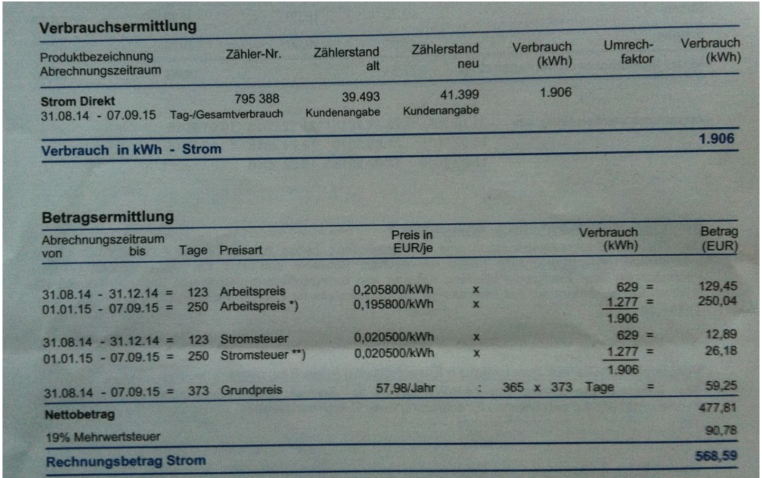
Source: Agora Energiewende Jahresauswertung 2019

Consumption metering

- Look for your electricity meter at home
- Mine here shows 42470.3 kWh
- Check what the value is a week later

Electricity bill

My bill for 2014-5: 1900 kWh for a year, at a cost of €570, which corresponds to 0.3 €/kWh or 300 €/MWh. But the spot market price is 30 €/MWh, so what's going on??



Verbrauchsermittlung

Produktbezeichnung Abrechnungszeitraum	Zähler-Nr.	Zählerstand alt	Zählerstand neu	Verbrauch (kWh)	Umrech-faktor	Verbrauch (kWh)
Strom Direkt 31.08.14 - 07.09.15	795 388 Tag-/Gesamtverbrauch	39.493 Kundenangabe	41.399 Kundenangabe	1.906		
Verbrauch in kWh - Strom						**1.906**

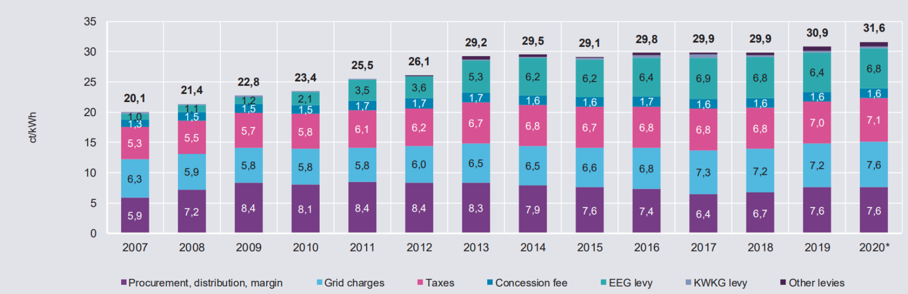
Betragsermittlung

Abrechnungszeitraum von - bis	Tage	Preisart	Preis in EUR/je			Verbrauch (kWh)	Betrag (EUR)
31.08.14 - 31.12.14 =	123	Arbeitspreis	0,205800/kWh	x		629 =	129,45
01.01.15 - 07.09.15 =	250	Arbeitspreis *)	0,195800/kWh	x		1.277 =	250,04
						1.906	
31.08.14 - 31.12.14 =	123	Stromsteuer	0,020500/kWh	x		629 =	12,89
01.01.15 - 07.09.15 =	250	Stromsteuer **)	0,020500/kWh	x		1.277 =	26,18
						1.906	
31.08.14 - 07.09.15 =	373	Grundpreis	57,98/Jahr	:	365 x 373	Tage =	59,25
Nettobetrag							477,81
19% Mehrwertsteuer							90,78
Rechnungsbetrag Strom							**568,59**

Household price breakdown

Although the wholesale price is going down, other taxes, grid charges and renewables subsidy (EEG surcharge) have kept the price high.

Household electricity prices 2007 bis 2020



HOWEVER the EEG is only high because it is paying for solar panels bought at a time when they were still comparatively expensive; but through the German subsidy, production volumes were high and the learning curve has brought the costs down exponentially.

Source: Agora Energiewende, 2019

Yearly energy to power

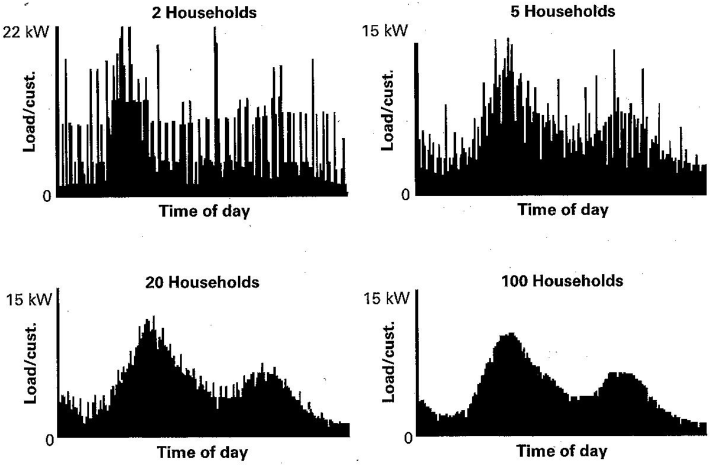
Germany consumes around 600 TWh per year, written 600 TWh/a.

What is the *average* power consumption?

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

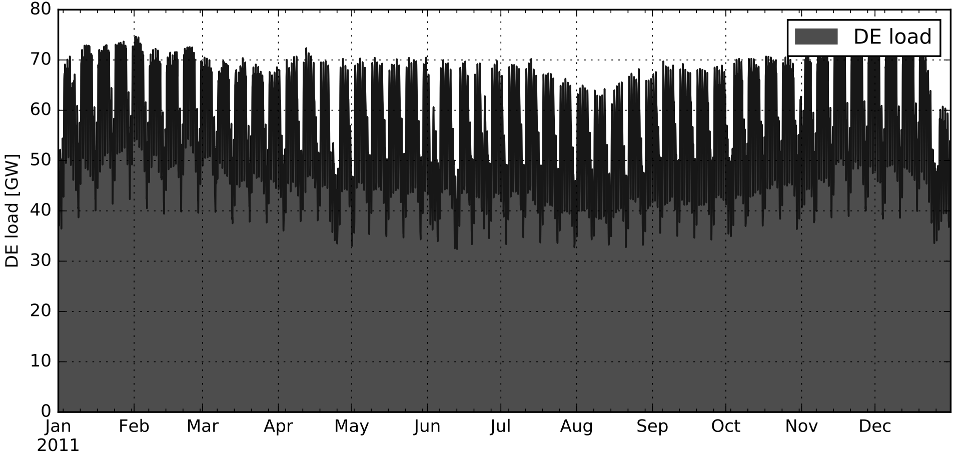
Discrete Consumers Aggregation

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



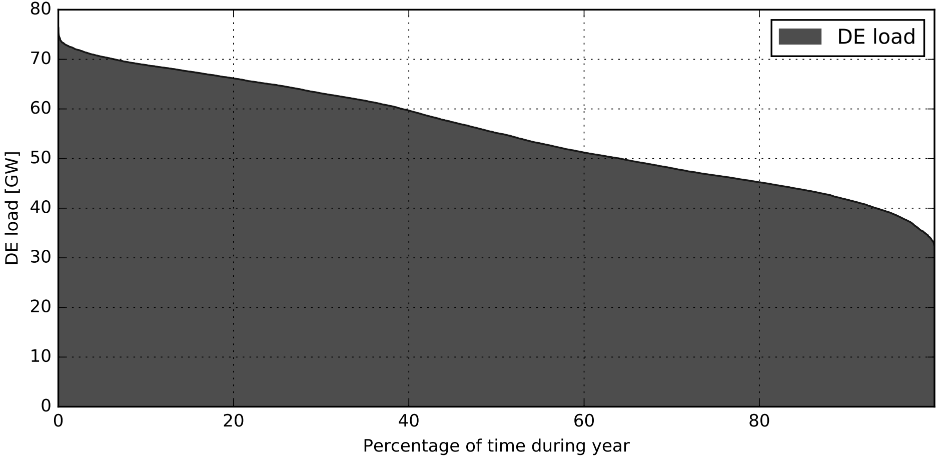
Load curve properties

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



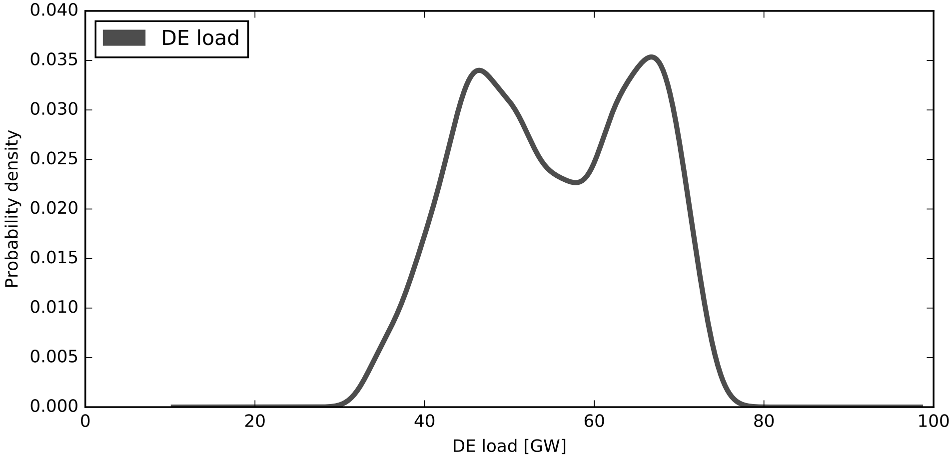
Load duration curve

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** $pdf(x)$, $\int dx\, pdf(x) = 1$:



Fourier transform to see spectrum

For a periodic, continuous, complex signal $f(t)$, we can decompose it in frequency space to see which frequencies dominate the signal. This is called a **Fourier transform/series**.

For period T (in our case a year) the function $f : [0, T] \to \mathbb{C}$ can be decomposed

$$f(t) = \sum_{n=-\infty}^{n=\infty} a_n e^{-\frac{i2\pi nt}{T}}$$

To recover the values of the **frequency amplitudes** a_n, integrate over T

$$a_n = \frac{1}{T} \int_0^T dt \left[f(t) e^{\frac{i2\pi nt}{T}} \right]$$

For a real-valued function $f : [0, T] \to \mathbb{R}$, $a_{-n} = a_n^*$.

For a periodic, **discrete** signal f_n, the **Fast Fourier Transform** (FFT) is a computationally advantageous algorithm and is implemented in many programming libraries (see tutorial).

Fourier transform: exercise

To remind yourself of how Fourier transforms work, check the formula for a_n by inserting the expansion of $f(t)$ into the formula for a_n.

First hint: remember Euler's formula:

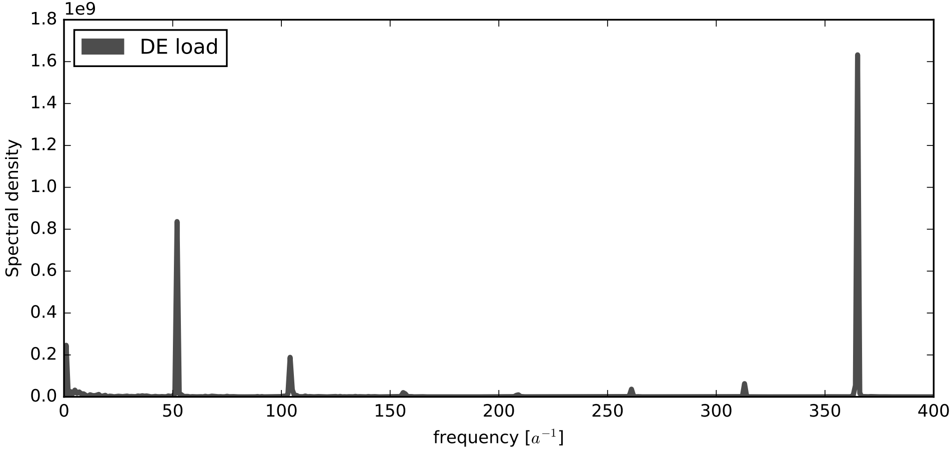
$$e^{i\theta} = \cos\theta + i\sin\theta$$

Second hint: think about integrating a periodic signal over its period:

$$\frac{1}{T}\int_0^T dt \cos\frac{2\pi nt}{T} = \begin{cases} 1, & \text{if } n = 0 \\ 0, & \text{otherwise} \end{cases}$$

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.

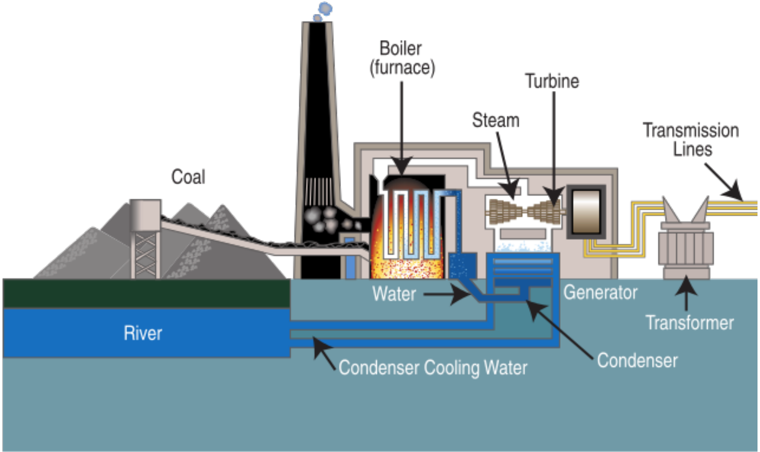
Power: Examples of generation

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

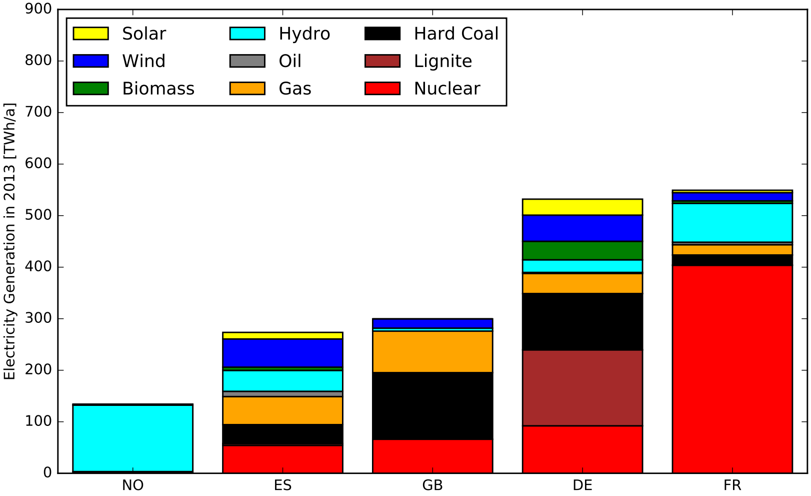
Generators

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*.

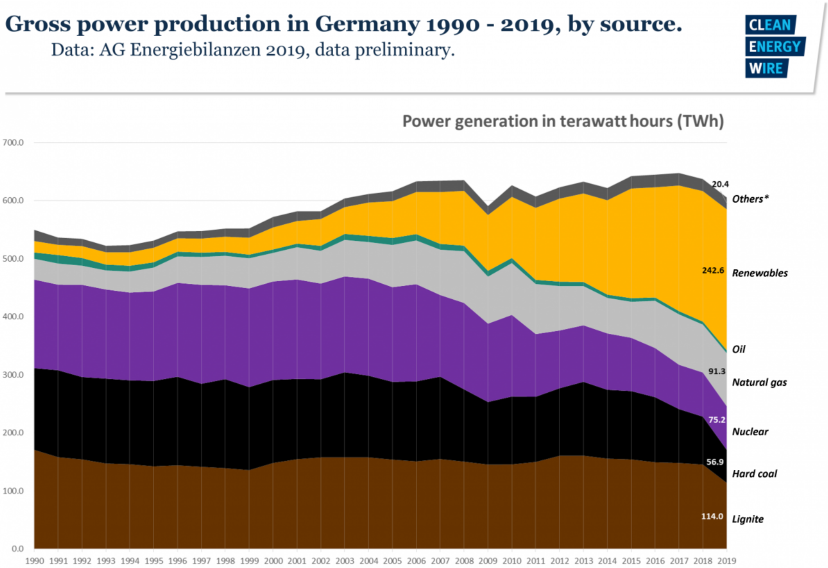


Source: Wikipedia

Example of electricity generation across major EU countries in 2013



Renewables reached 40% of gross electricity generation in Germany in 2019



* Without power generation from pumped storage.

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 $\mathrm{MWh}_{\mathrm{th}}$, to distinguish it from the electrical energy $\mathrm{MWh}_{\mathrm{el}}$.

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

Fuel	Calorific energy $\mathrm{MWh}_{\mathrm{th}}$/tonne	Per unit efficiency $\mathrm{MWh}_{\mathrm{el}}/\mathrm{MWh}_{\mathrm{th}}$	Electrical energy $\mathrm{MWh}_{\mathrm{el}}$/tonne
Lignite	2.5	0.4	1.0
Hard Coal	6.7	0.45	2.7
Gas (CCGT)	15.4	0.58	8.9
Uranium (unenriched)	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}.

For the full marginal cost, we have to also add the CO_2 price and the variable operation and maintenance (VOM) costs.

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	11	24
Gas (CCGT)	0.58	19	33
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 (CCGT)	3.1	0.2	0.35
Uranium	0	0	0

Current CO_2 price in EU Emissions Trading Scheme (ETS) is around €$25/t_{CO2}$

You calculate: What CO_2 price to switch gas and lignite?

What CO_2 price, i.e. x €/t_{CO2}, is required so that the marginal cost of gas (CCGT) is lower than lignite?

NB: It helps to track units.

You calculate: What CO_2 price to switch gas and lignite?

What CO_2 price, i.e. x €/t_{CO2}, is required so that the marginal cost of gas (CCGT) is lower than lignite?

NB: It helps to track units.

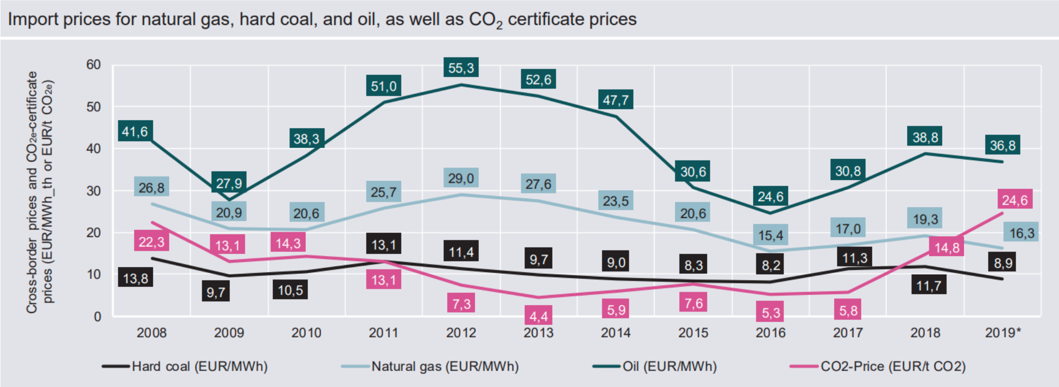
We need to solve for the switch point by adding the CO_2 price to the fuel cost. Left is lignite, right is gas:

$$11\ \text{€}/\mathrm{MWh_{el}} + (0.9\ \mathrm{tCO_2}/\mathrm{MWh_{el}}) \cdot (x\ \text{€}/\mathrm{tCO_2}) = 33\ \text{€}/\mathrm{MWh_{el}} + (0.35\ \mathrm{tCO_2}/\mathrm{MWh_{el}}) \cdot (x\ \text{€}/\mathrm{tCO_2})$$

Solve:

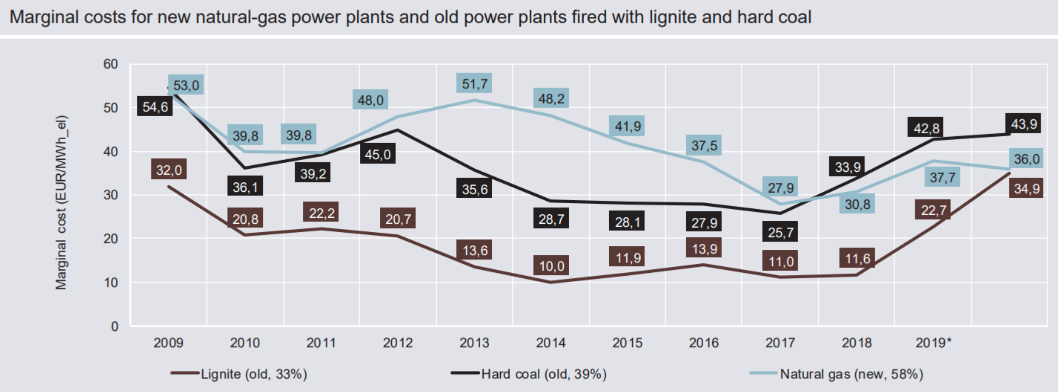
$$x = \frac{33 - 11}{0.9 - 0.35} = 40$$

CO2 and import costs change over time...



Source: Agora Energiewende, 2019

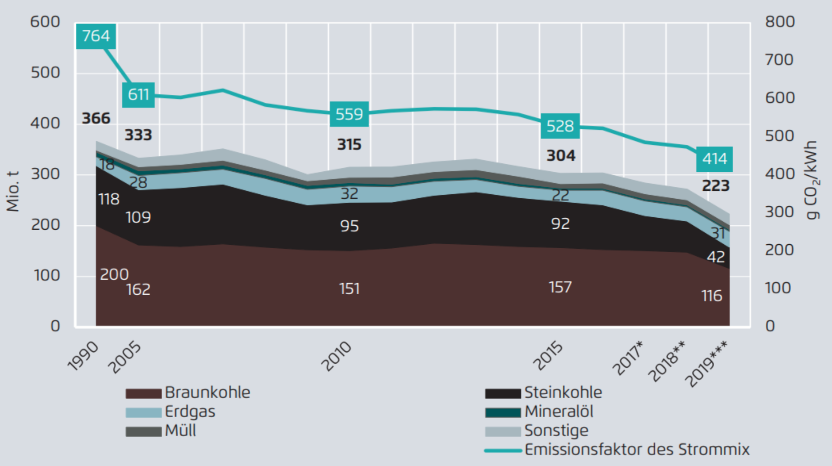
...which affects the marginal costs of generation



Source: Agora Energiewende, 2019

CO2 emissions from electricity sector

CO_2 emissions in electricity generation stagnated for years because of coal, which is slowly being pushed out by the CO_2 price and in the longer term by the Kohleausstieg.



Source: Agora Energiewende Jahresauswertung 2019

Capacity Factors and Full Load Hours

A generator's **capacity factor** is the average power generation divided by the power capacity.

For variable renewable generators it depends on weather, generator model and curtailment; for dispatchable generators it depends on market conditions and maintenance schedules.

A generator's **full load hours** are the equivalent number of hours at full capacity the generator required to produce its yearly energy yield. The two quantities are related:

$$\text{full load hours} = \text{per unit capacity factor} \cdot 365 \cdot 24 = \text{per unit capacity factor} \cdot 8760$$

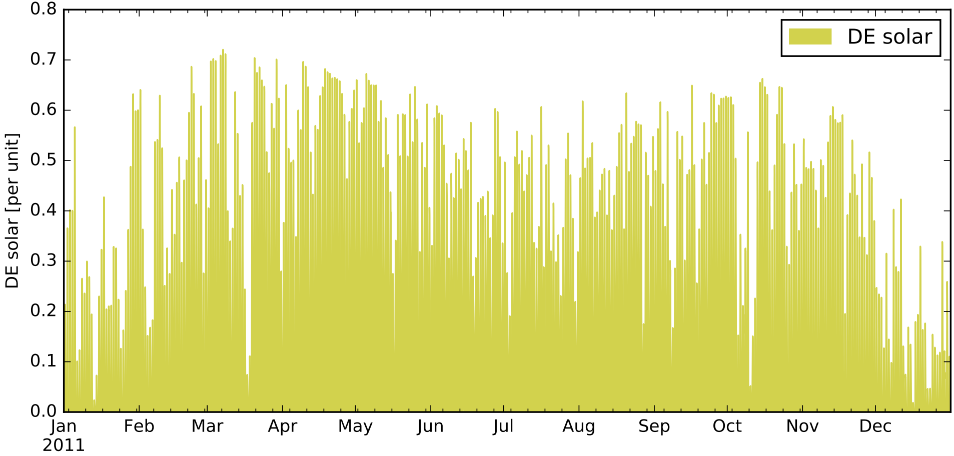
Typical values for Germany:

Fuel	capacity factor [%]	full load hours
wind	20-35	1600-3000
solar	10-12	800-1000
nuclear	70-90	6000-8000
open-cycle gas	20	1500

Variable Renewable Energy (VRE)

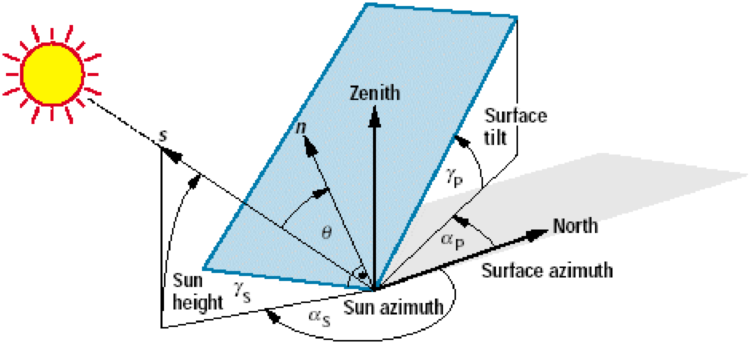
Solar time series

Unlike the load, the solar feed-in is much more variable, dropping to zero and not reaching full output (when aggregated over all of Germany).



How do we derive solar time series?

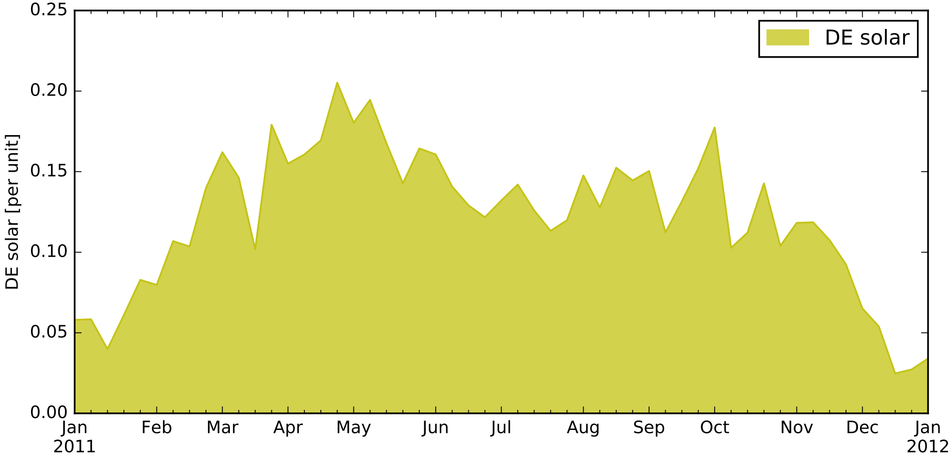
We take times series weather data for the solar radiation (also called irradiation or insolation) at each location in W/m^2. This is often provided for a horizontal surface, so we need to convert for the angles of the solar panel to the horizontal, and account for factors that affect the energy conversion (losses, outside temperature). We have a software library **atlite** that takes care of this. See `https://model.energy` or `https://renewables.ninja` for live examples.



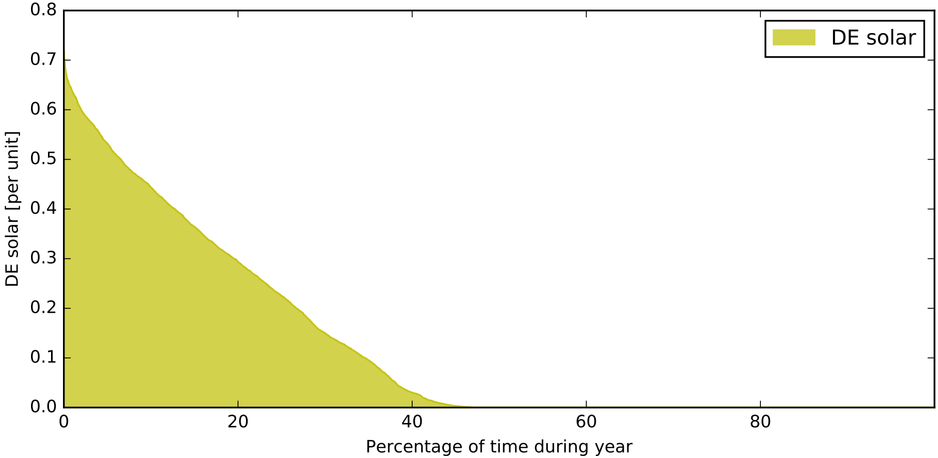
Source: Volker Quaschning

Solar time series: weekly

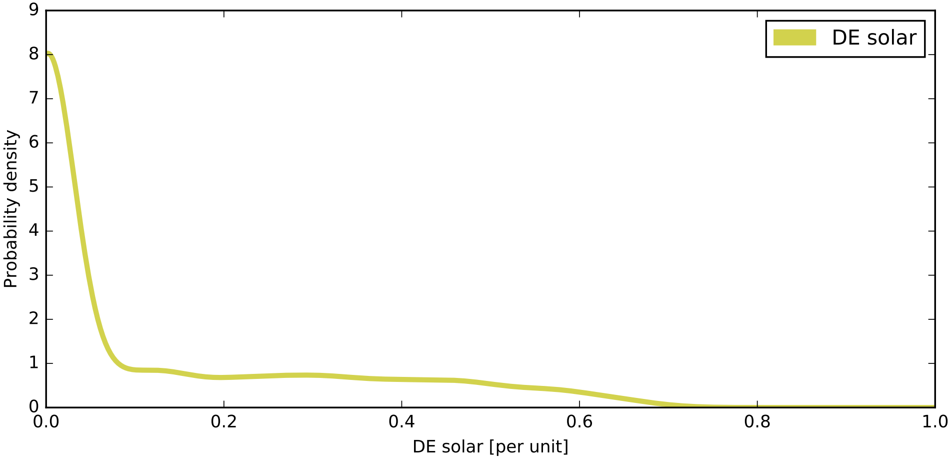
If we take a weekly average we see higher solar in the summer.



Solar duration curve

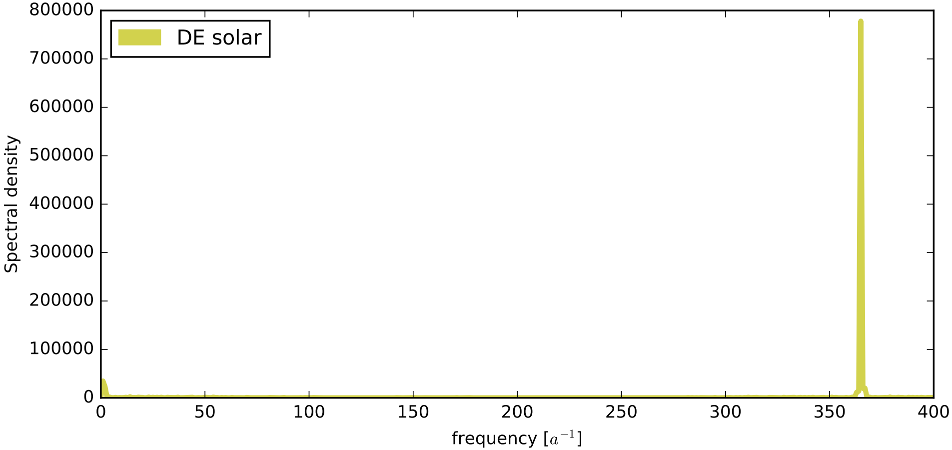


Solar density function



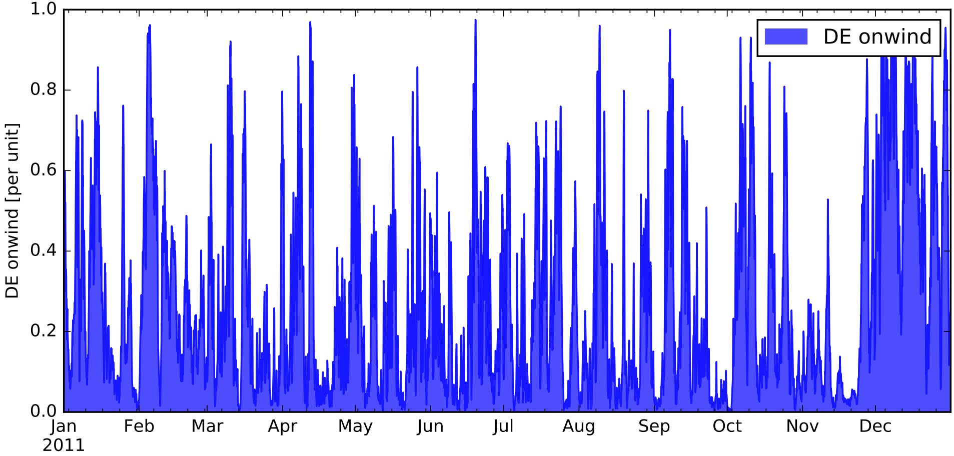
Solar spectrum

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



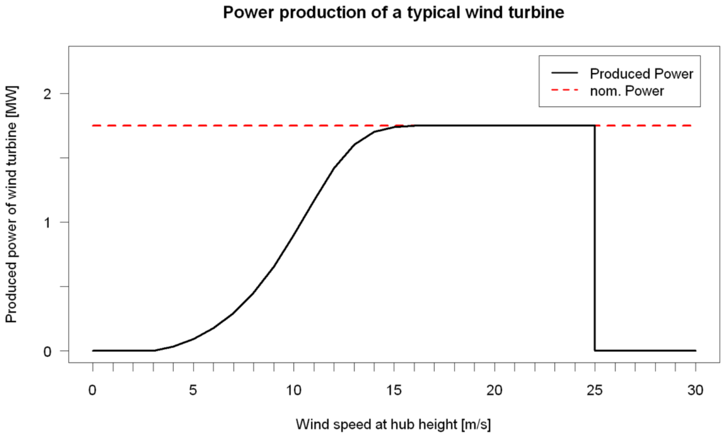
Wind time series

Wind is variable, like solar, but the variations are on different time scales. It drops close to zero and rarely reaches full output (when aggregated over all of Germany).



How do we derive wind time series?

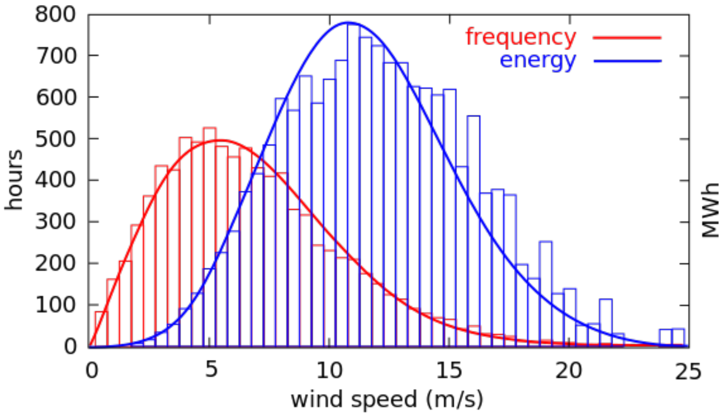
We take times series weather data for the wind speeds at hub height (e.g. 60-100m) at each location in ms^{-1}. In theory the power in the wind goes like v^3, but in practice high wind speeds are rare and it is not economic to build the generator so large.



Source: Wikipedia

How do we derive wind time series?

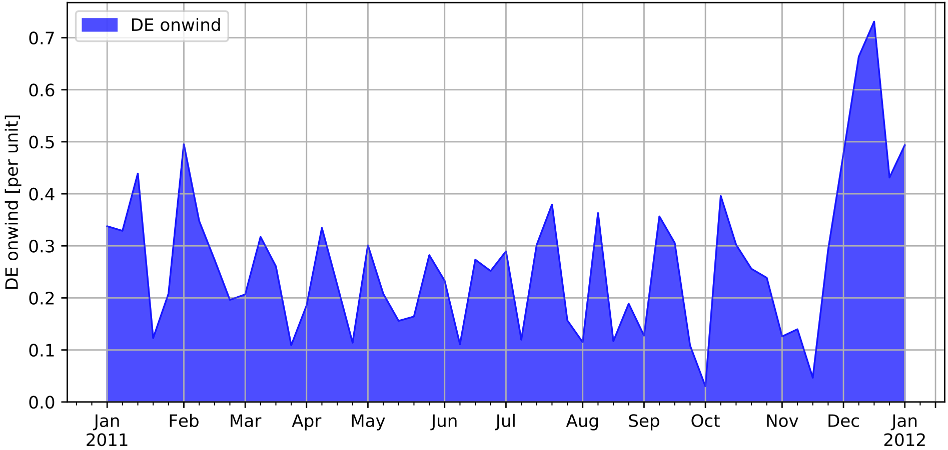
Wind speeds are typically distributed according to a Weibull probability distribution. Although the wind speeds are clustered at the lower end, most of the energy is generated between 5 and 15 ms^{-1}.



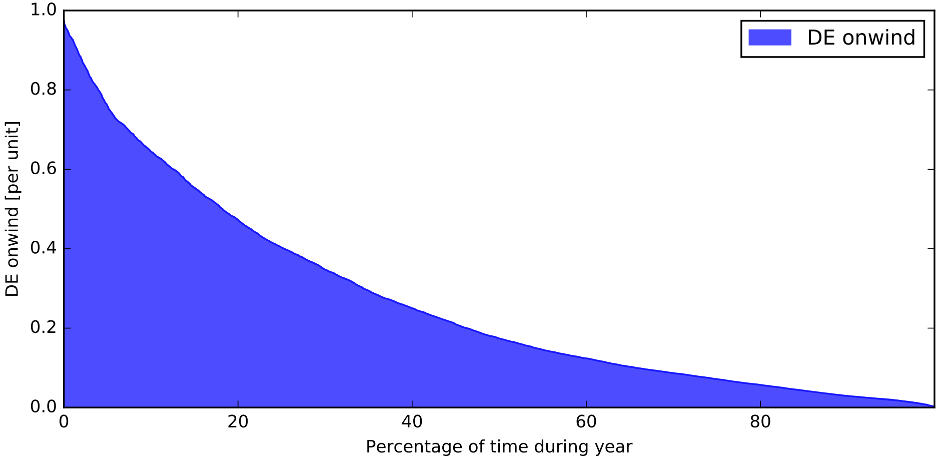
Source: Wikipedia

Wind time series: weekly

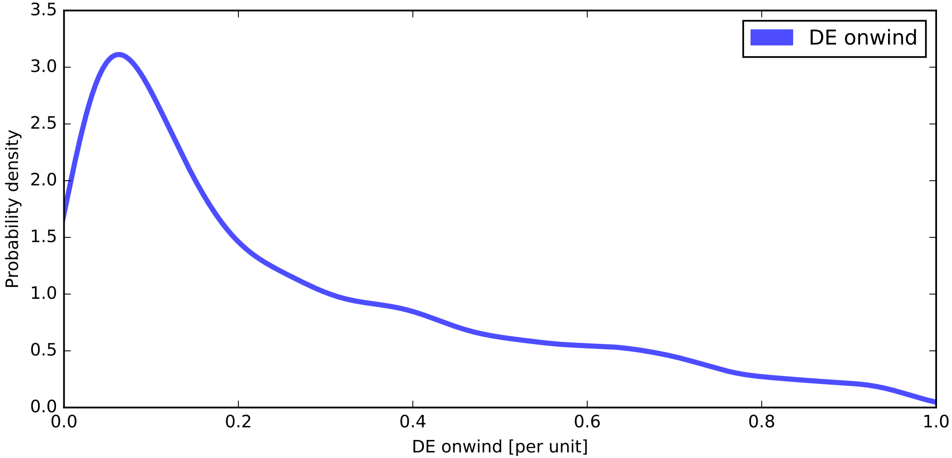
If we take a weekly average we see higher wind in the winter and some periodic patterns over 2-3 weeks (**synoptic scale**).



Wind duration curve

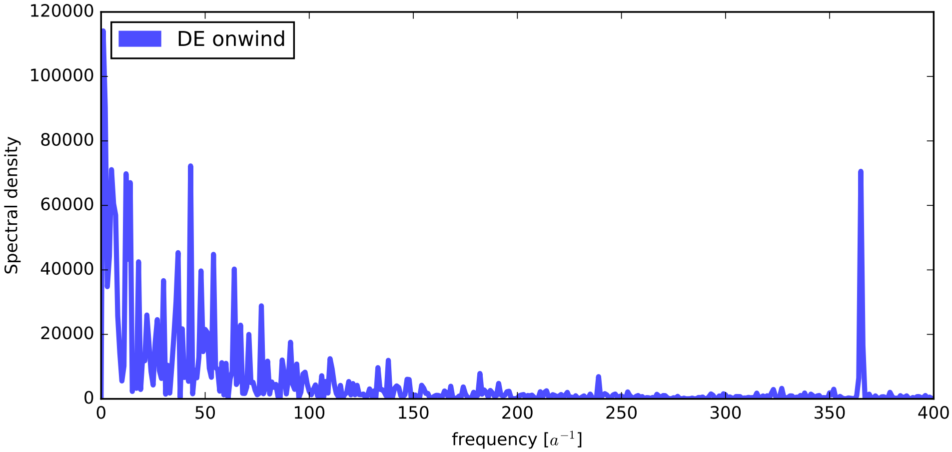


Wind density function



Wind spectrum

If we Fourier transform, the **seasonal**, **synoptic** (2-3 weeks) 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 and solar do we need? We have three time series:

- $\{d_t\}, d_t \in \mathbb{R}$ 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

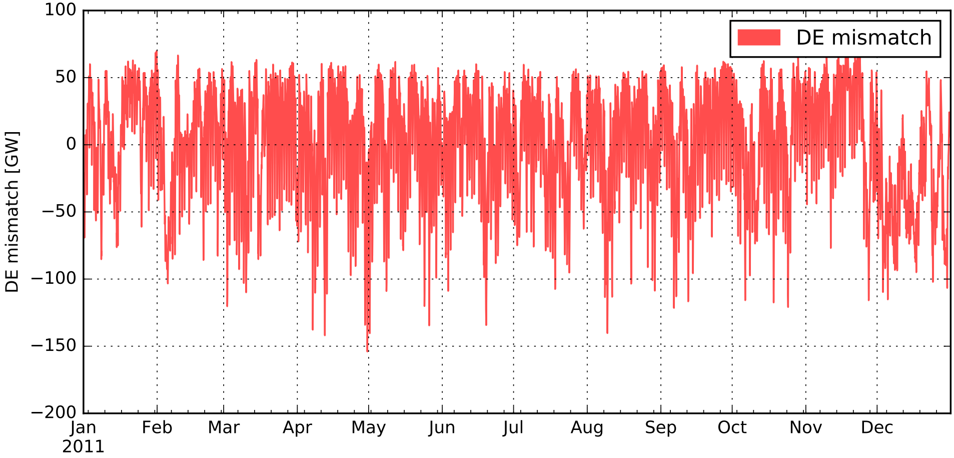
$$m_t = d_t - Ww_t - Ss_t$$

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

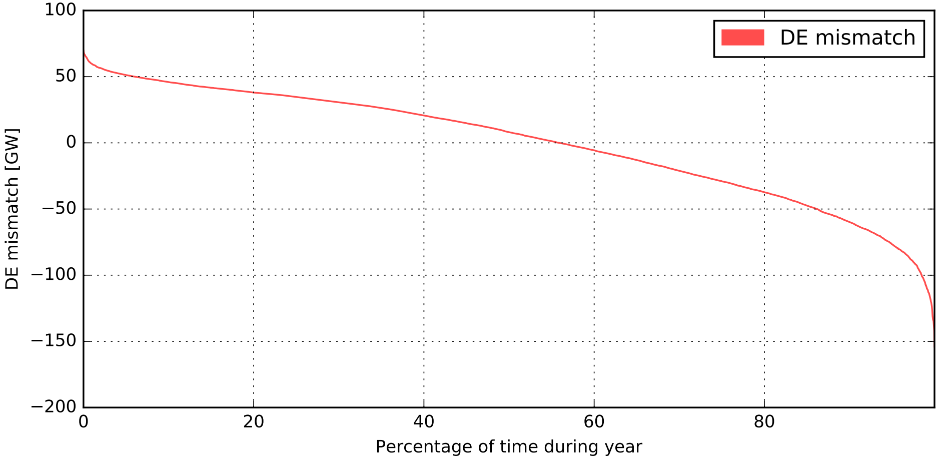
$$\langle m_t \rangle = 0$$

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

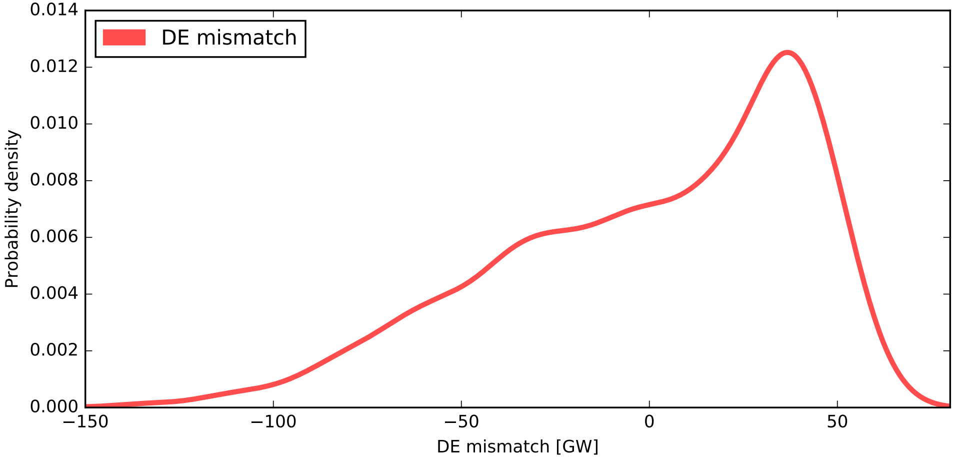
Mismatch time series



Mismatch duration curve

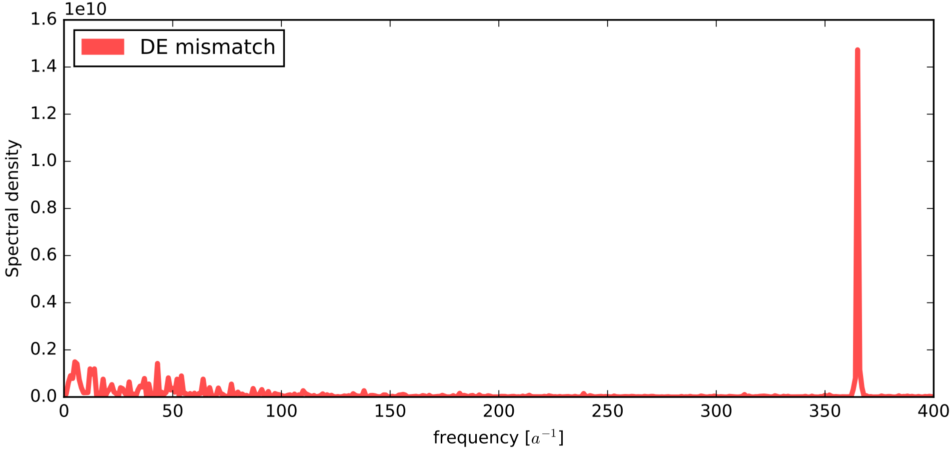


Mismatch density function



Mismatch spectrum

If we Fourier transform, the synoptic (from wind) and daily patterns (from demand and solar) become visible. Seasonal variations appear to cancel out.



How to deal with the mismatch?

The problem is that

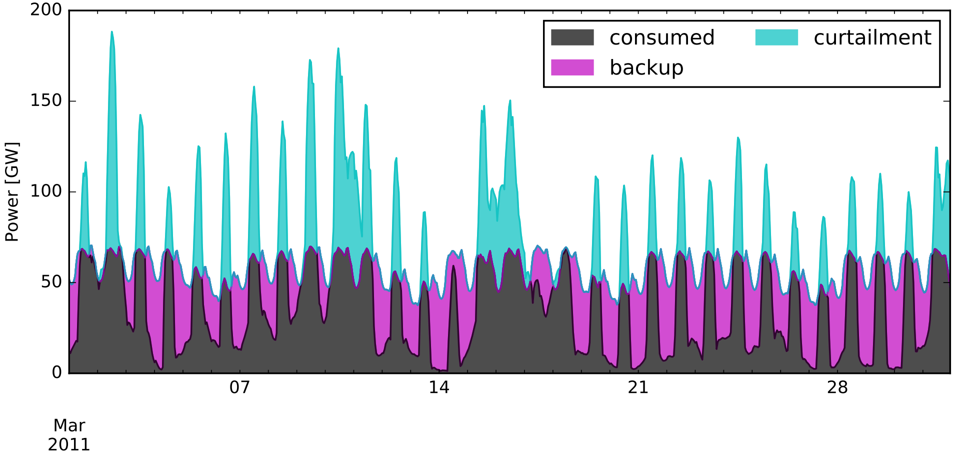
$$\langle m_t \rangle = 0$$

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

This means:

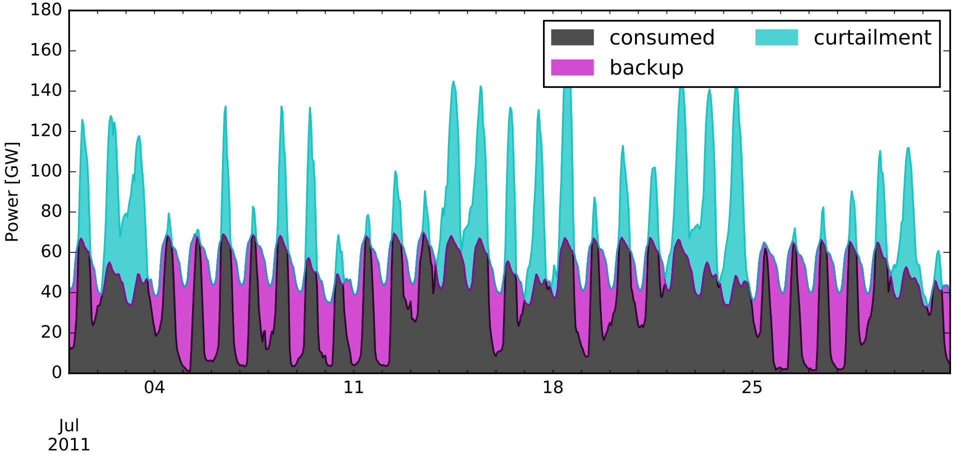
- If $m_t > 0$, i.e. we have unmet demand, then we need backup generation from **dispatchable** sources e.g. hydroelectricity reservoirs, fossil/biomass fuels.
- If $m_t < 0$, i.e. we have over-supply, then we have to shed / spill / **curtail** the renewable energy.

Mismatch



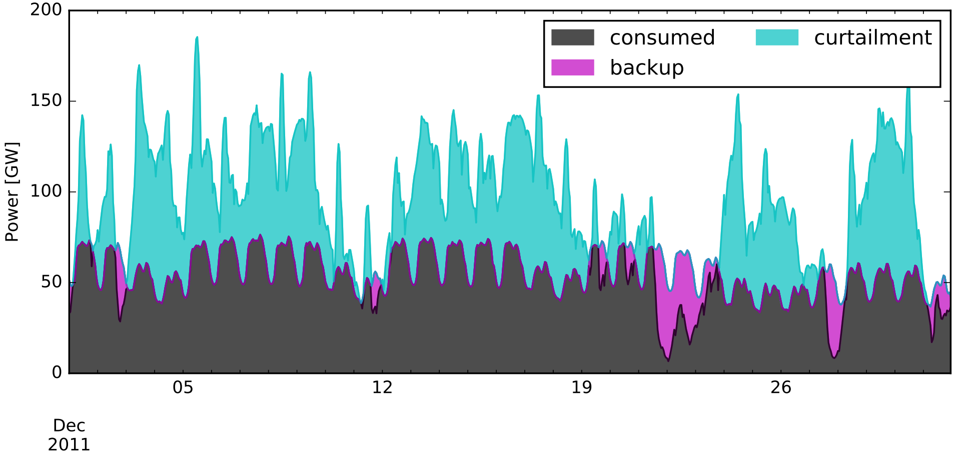
200
150
100
50
0
Power [GW]
07
14
21
28
Mar
2011
consumed
curtailment
backup

Mismatch



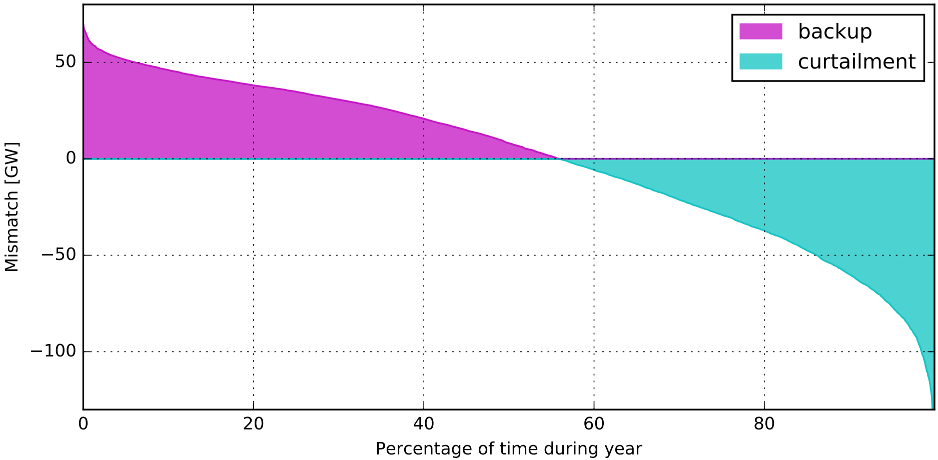
consumed
curtailment
backup
Power [GW]
180
160
140
120
100
80
60
40
20
0
04
11
18
25
Jul
2011

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 **four other solutions**:

1. **Smoothing** stochastic variations of renewable feed-in **over continental areas**, e.g. the whole of Europe.
2. Using **electricity storage** to shift energy from times of surplus to times of deficit.
3. Shifting demand to different times, when renewables are abundant, i.e. **demand-side management** (DSM).
4. Consuming the electricity in **other sectors**, e.g. transport or heating, where there are further possibilities for DSM (battery electric vehicles, heat pumps) and cheap storage possibilities (e.g. thermal storage or power-to-gas as hydrogen or methane).