

Energy Systems, Summer Semester 2022

Lecture 4: Electricity Time Series

Prof. Tom Brown, Philipp Glaum

[Department of Digital Transformation in Energy Systems](#), Institute of Energy Technology, TU Berlin

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1. Electricity Consumption
2. Electricity Generation
3. Variable Renewable Energy (VRE)
4. Balancing a Single Country

Electricity Consumption

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 coal, which can only be accessed by burning it.

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, $1 \text{ W} = 1 \text{ J/s}$.

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

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

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

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

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	~1-500 MW
CERN	200 MW
Germany total demand	35-80 GW

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

1 kWh = power consumption of 1 kW for one hour

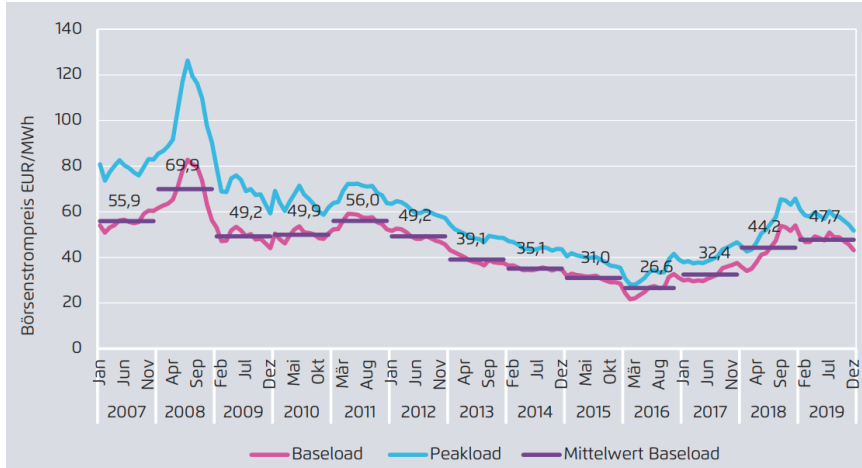
E.g. a 10 W lightbulb left on for two hours will consume

$$10 \text{ W} * 2 \text{ h} = 20 \text{ Wh}$$

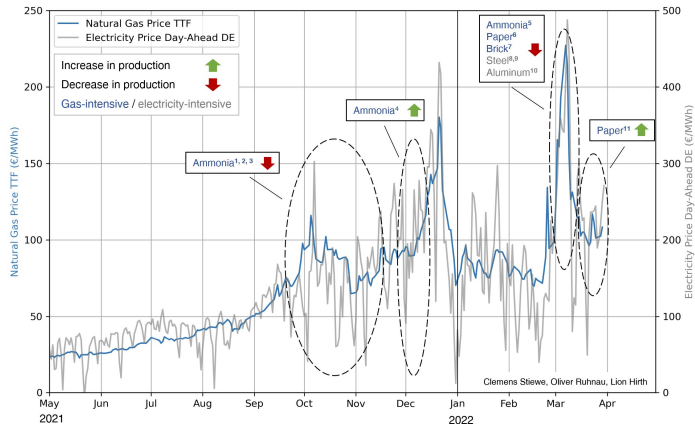
It is easy to convert this back to the SI unit for energy, Joules:

$$1 \text{ kWh} = (1000 \text{ W}) * (1 \text{ h}) = (1000 \text{ J/s}) * (3600 \text{ s}) = 3.6 \text{ MJ}$$

Energy is traded in MWh; before 2020, prices were 40-50 €/MWh. Sinking until 2016 thanks to renewables and the **merit order effect**, but rising since 2016 due to rising **CO₂ price**:



Industry responds to high natural gas and electricity prices in DE & EU



Sources: press releases of companies and associations, news articles. **1:** Yara reduces ammonia production in Europe by 40% due to high gas prices and imports ammonia instead, keeping the downstream fertilizer production running as usual; **2:** BASF reduces ammonia production in DE and BE due to high gas prices; **3:** SKW Priesteritz reduces ammonia production in DE by 30% due to high gas prices; **4:** Yara re-increases ammonia production in Europe; **5:** Yara reduces ammonia production in Europe; **6:** Norske Skog stops paper production due to high gas prices; **7:** Several members of the German brick industry association reduce their production due to high gas prices in DE; **8:** Stahlwerke Lech stops steel production due to high electricity prices on a daily basis in DE; **9:** Salzgitter reduces steel production due to high electricity prices on a shift-wise basis; **10:** Trimet reduces aluminum production by 50% in Essen (DE); **11:** Norske Skog re-increases paper production.



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

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 averaged 30 €/MWh, so what's going on??

Verbrauchsermittlung

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

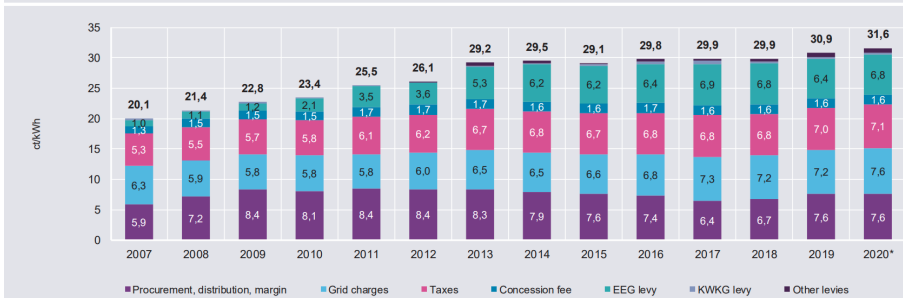
Betragsermittlung

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

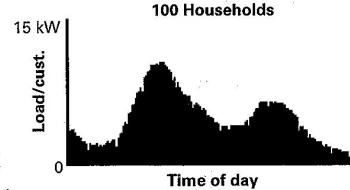
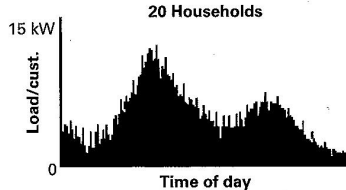
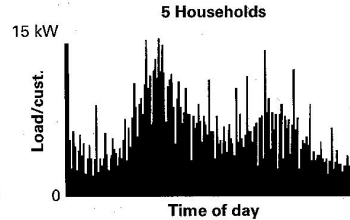
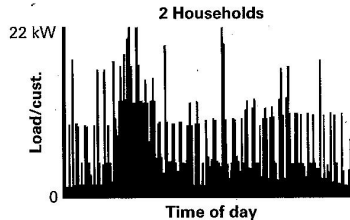
Although the wholesale price is going down, other taxes, grid charges and renewables subsidy (EEG surcharge) have kept the price high.

Household electricity prices 2007 bis 2020

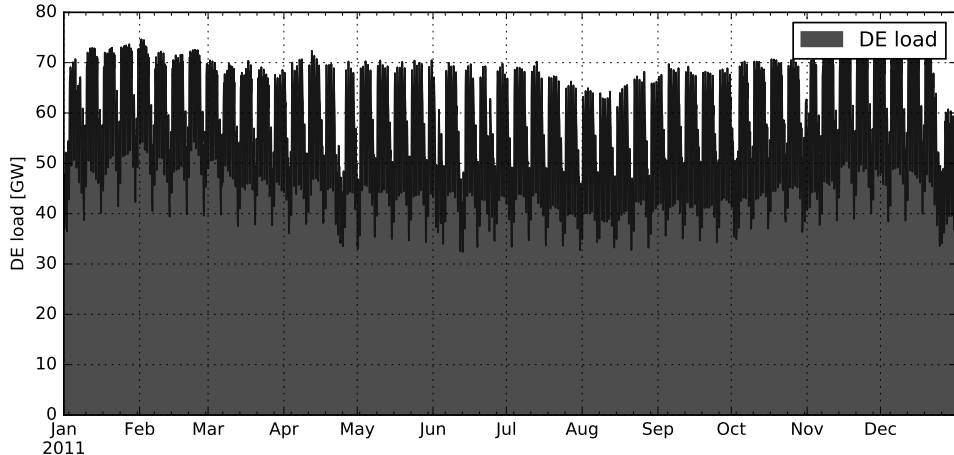


HOWEVER the EEG is only high because it is paying for solar panels bought at a time when they were still comparatively expensive; but through the German subsidy, production volumes were high and the learning curve has brought the costs down exponentially.

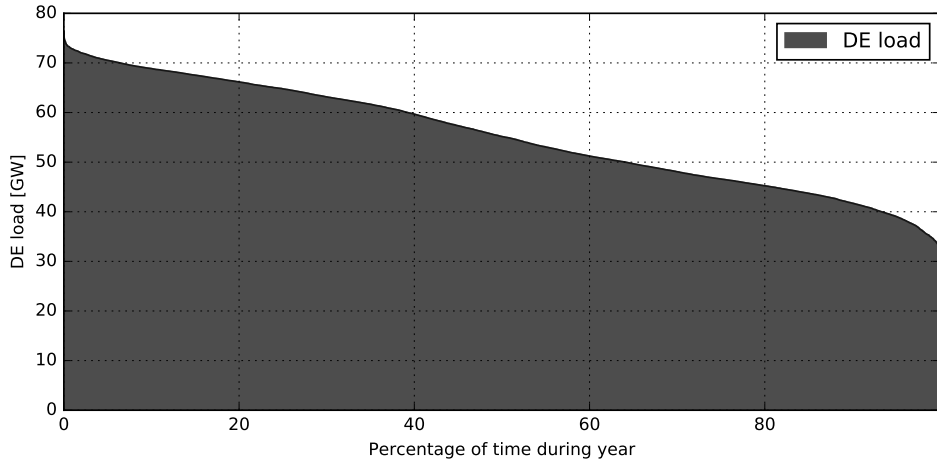
The discrete actions of individual consumers smooth out statistically if we aggregate over many consumers.



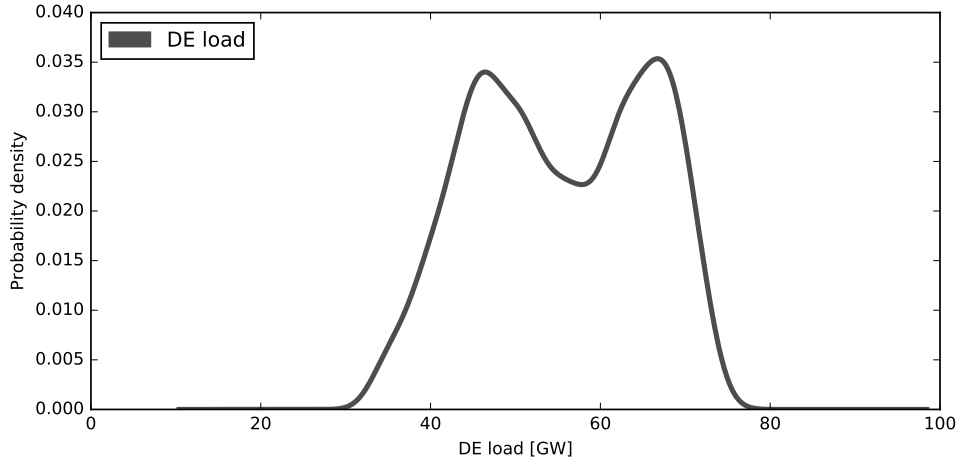
The Germany load curve (around 500 TWh/a) shows **daily**, **weekly** and **seasonal** patterns; religious festivals are also visible.

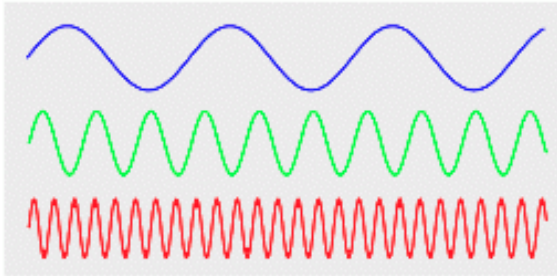
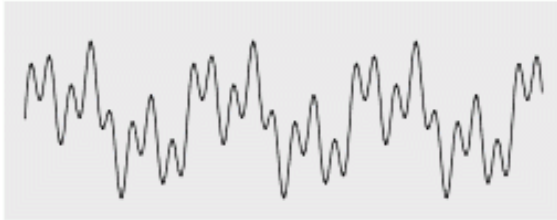


For some analysis it is useful to construct a **duration curve** by stacking the hourly values from highest to lowest.



Similarly we can also build the **probability density function** $pdf(x)$, $\int dx pdf(x) = 1$:

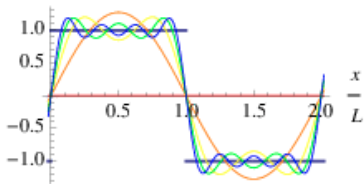




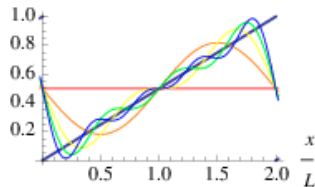
- Fourier analysis decomposes a **periodic** signal into simpler sine waves
- Every periodic signal can be broken down into a sum of sine waves with different **frequencies**

Common examples of Fourier approximations using more and more terms with high frequencies:

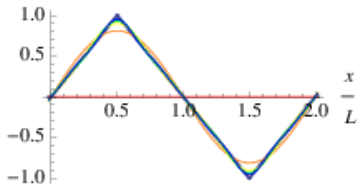
square wave



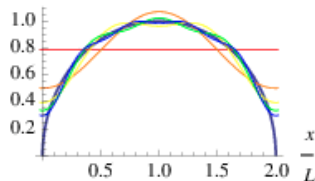
sawtooth wave



triangle wave



semicircle



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 $f : [0, T] \rightarrow \mathbb{C}$ 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 $f : [0, T] \rightarrow \mathbb{R}$, $a_{-n} = a_n^*$.

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).

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 .

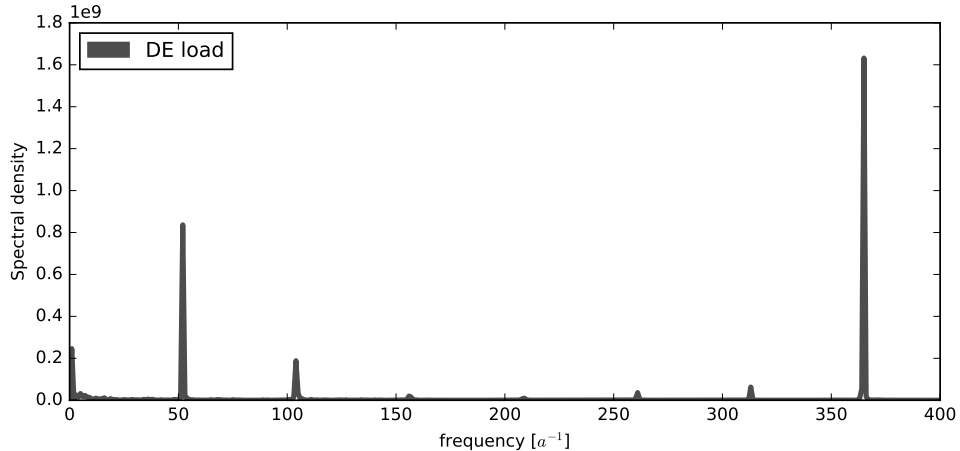
First hint: remember Euler's formula:

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

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

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

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



Electricity Generation

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:

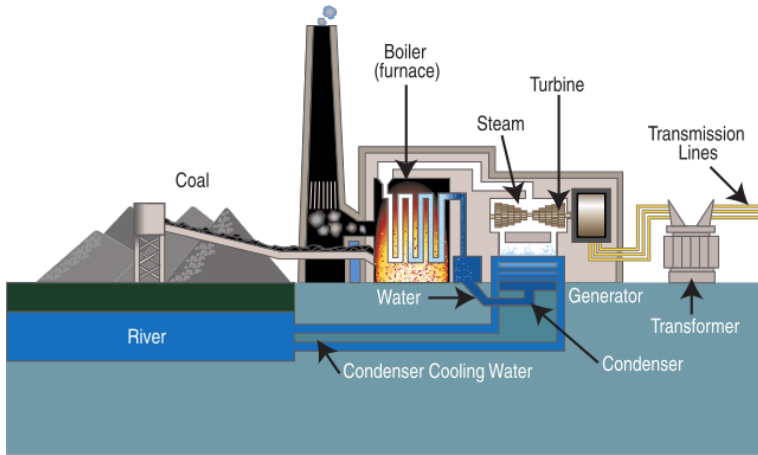
- Chemical energy, accessed by combustion (coal, gas, oil, biomass)
- Nuclear energy, accessed by fission reactions, perhaps one day by fusion too
- Hydroelectric energy, allowing water to flow downhill (gravitational potential energy)
- Wind energy (kinetic energy of air)
- Solar energy (accessed with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

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

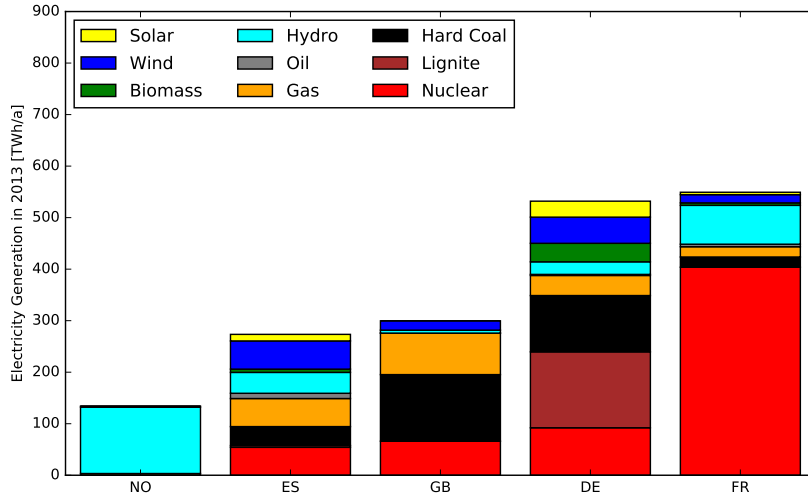
At full power, the following items generate:

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

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*.



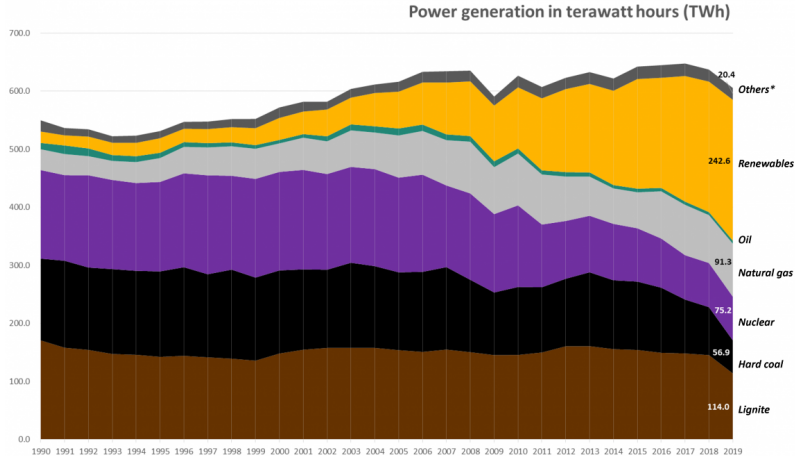
Example of electricity generation across major EU countries in 2013



Renewables reached 40% of electricity generation in Germany in 2019

Gross power production in Germany 1990 - 2019, by source.

Data: AG Energiebilanzen 2019, data preliminary.



* Without power generation from pumped storage.

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 MWh_{th} , to distinguish it from the electrical energy MWh_{el} .

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

Fuel	Calorific energy $\text{MWh}_{\text{th}}/\text{tonne}$	Per unit efficiency $\text{MWh}_{\text{el}}/\text{MWh}_{\text{th}}$	Electrical energy $\text{MWh}_{\text{el}}/\text{tonne}$
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

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 CO₂ 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

The CO₂ emissions of the fuel.

Fuel	t _{CO2} /t	t _{CO2} /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 CO₂ price in EU Emissions Trading Scheme (ETS) is around €50-100/t_{CO2}

You calculate: What CO₂ price to switch gas and lignite?

What CO₂ price, i.e. $x \text{ €/t}_{\text{CO}_2}$, is required so that the marginal cost of gas (CCGT) is lower than lignite?

NB: It helps to track units.

You calculate: What CO₂ price to switch gas and lignite?

What CO₂ price, i.e. $x \text{ €/tCO}_2$, 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 CO₂ price to the fuel cost. Left is lignite, right is gas:

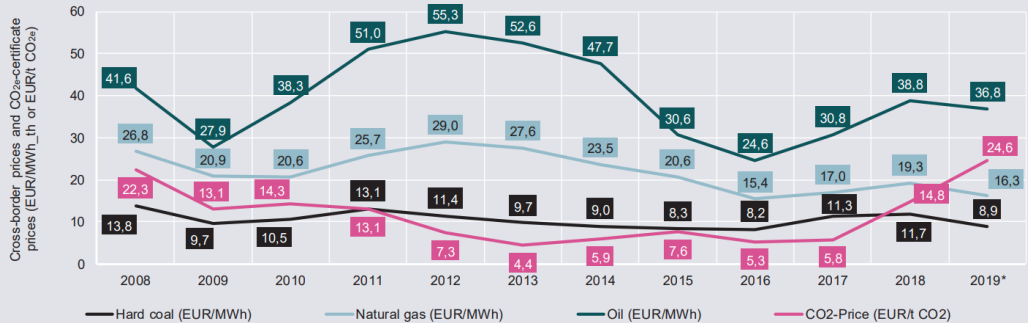
$$11 \text{ €/MWh}_{\text{el}} + (0.9 \text{ tCO}_2/\text{MWh}_{\text{el}}) \cdot (x \text{ €/tCO}_2) = 33 \text{ €/MWh}_{\text{el}} + (0.35 \text{ tCO}_2/\text{MWh}_{\text{el}}) \cdot (x \text{ €/tCO}_2)$$

Solve:

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

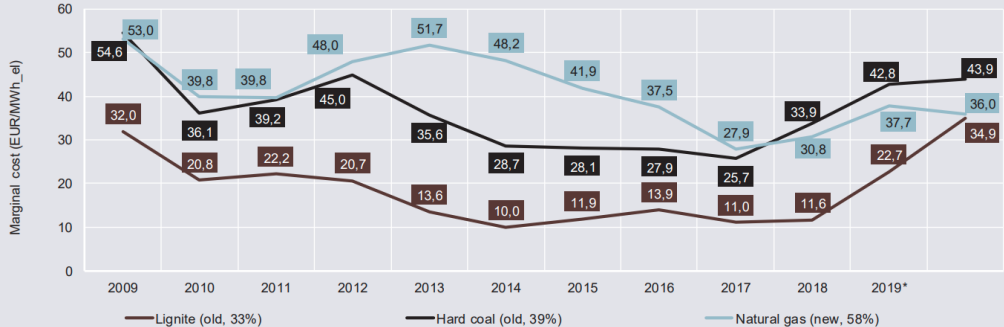
CO2 and import costs change over time...

Import prices for natural gas, hard coal, and oil, as well as CO₂ certificate prices

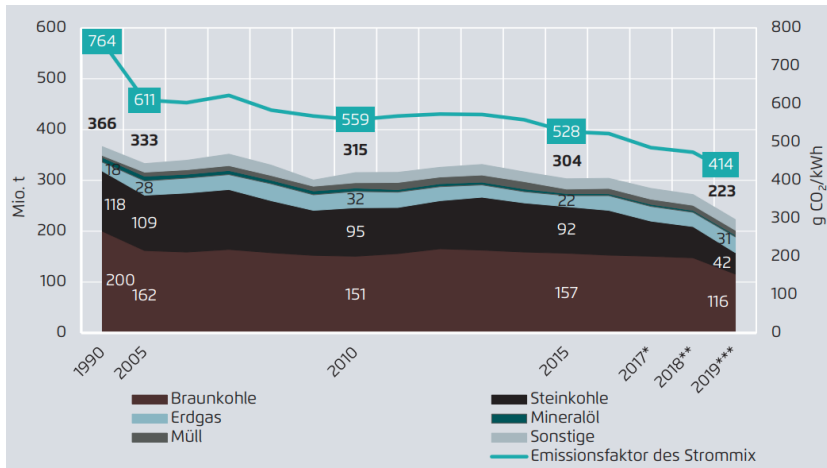


...which affects the marginal costs of generation

Marginal costs for new natural-gas power plants and old power plants fired with lignite and hard coal



CO₂ emissions in electricity generation stagnated for years because of coal, which is slowly being pushed out by the CO₂ price and in the longer term by the Kohleausstieg.



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:

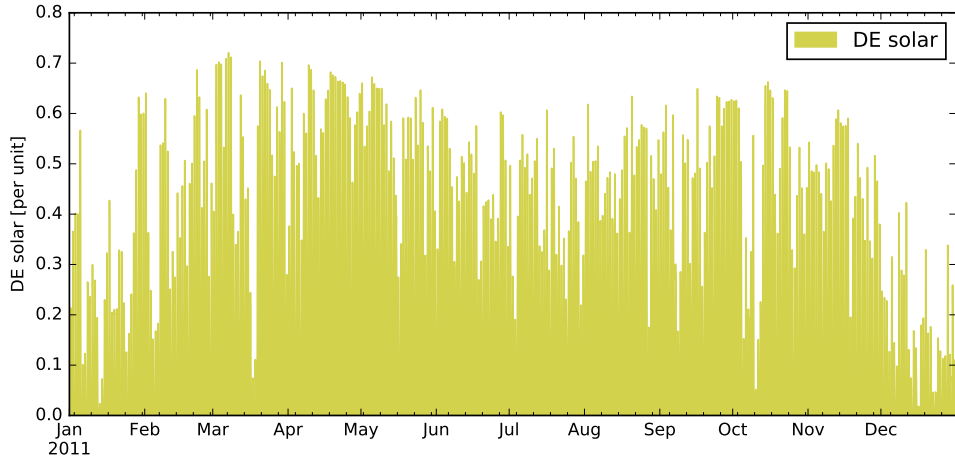
$$\text{full load hours} = \text{per unit capacity factor} \cdot 365 \cdot 24 = \text{per unit capacity factor} \cdot 8760$$

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

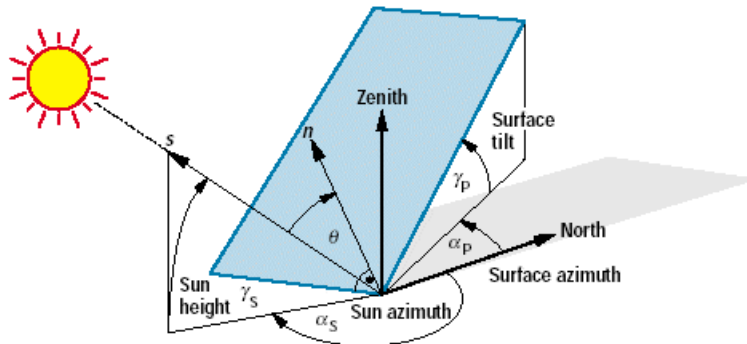
Variable Renewable Energy (VRE)

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).

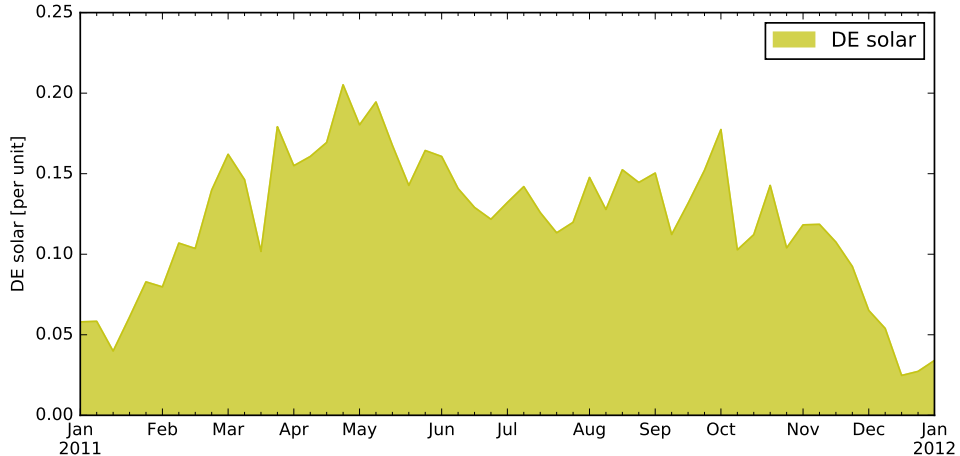


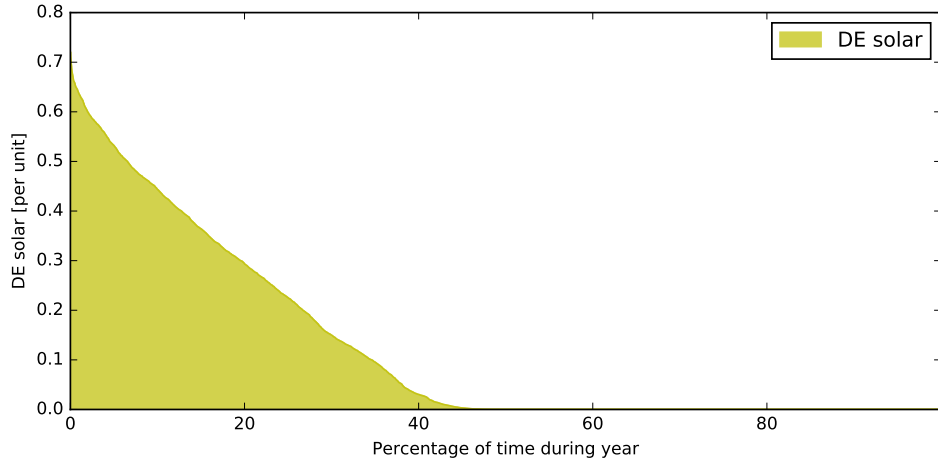
How do we derive solar time series?

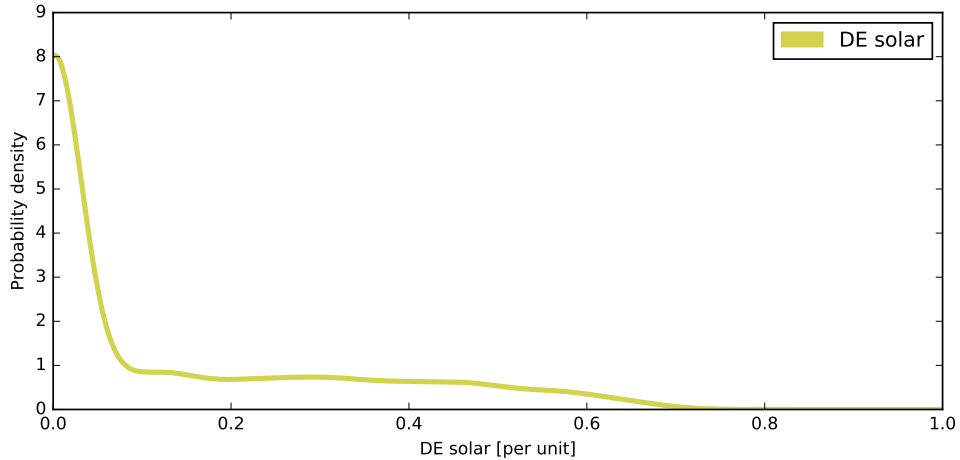
We take times series weather data for the solar radiation (also called irradiation or insolation) at each location in W/m^2 . This is often provided for a horizontal surface, so we need to convert for the angles of the solar panel to the horizontal, and account for factors that affect the energy conversion (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.



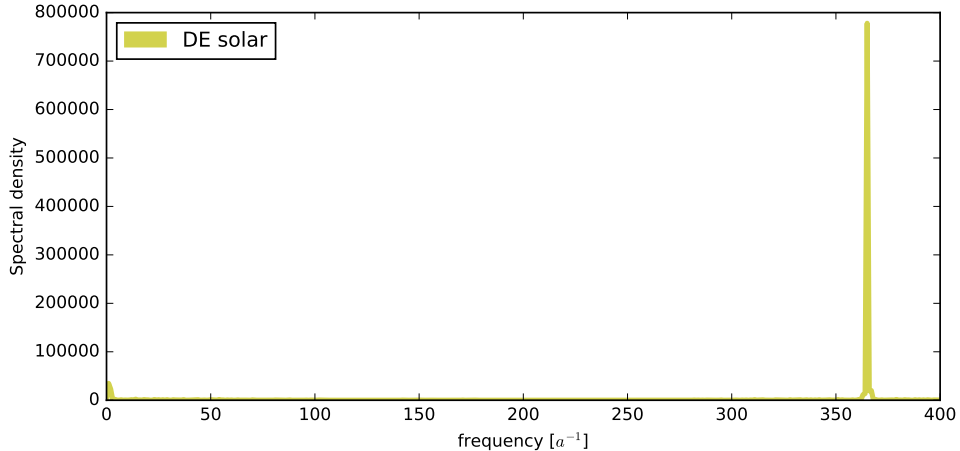
If we take a weekly average we see higher solar in the summer.



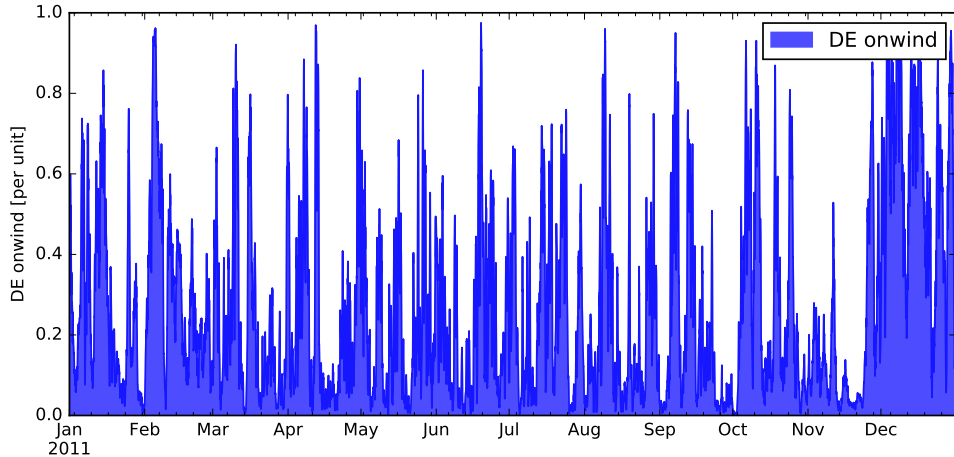




If we Fourier transform, the **seasonal** and **daily** patterns become visible.

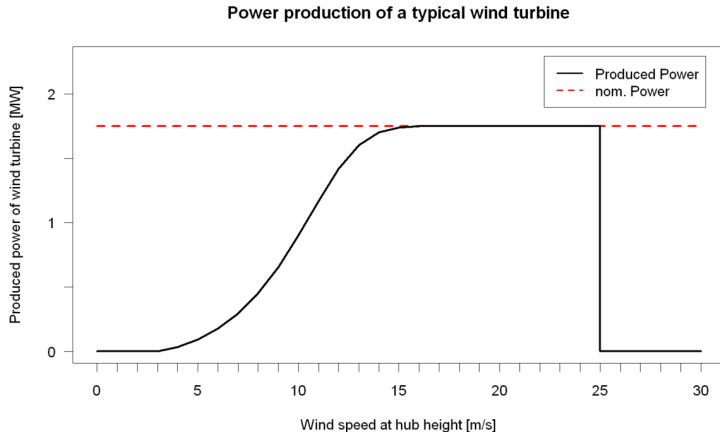


Wind is variable, like solar, but the variations are on different time scales. It drops close to zero and rarely reaches full output (when aggregated over all of Germany).



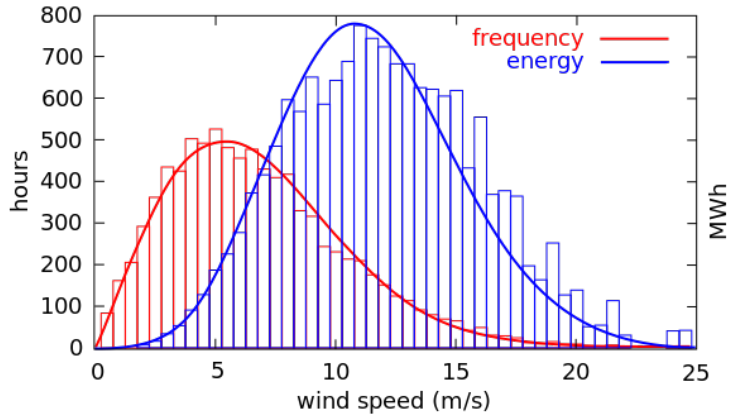
How do we derive wind time series?

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.

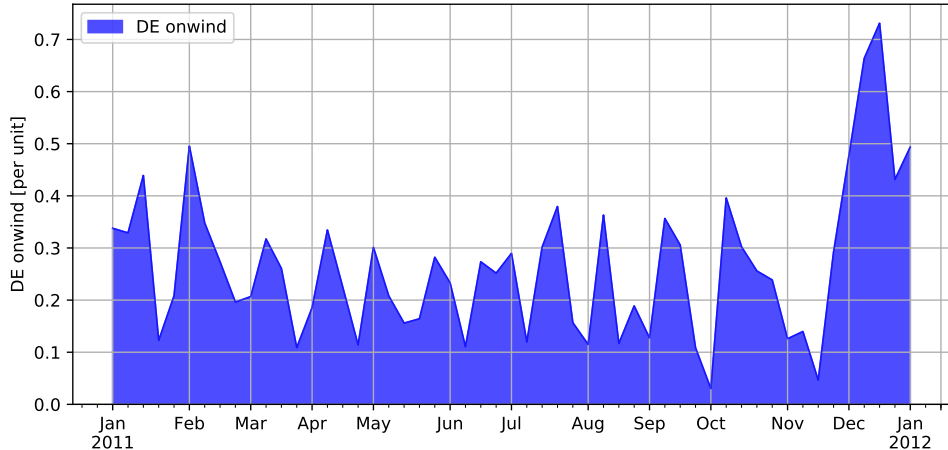


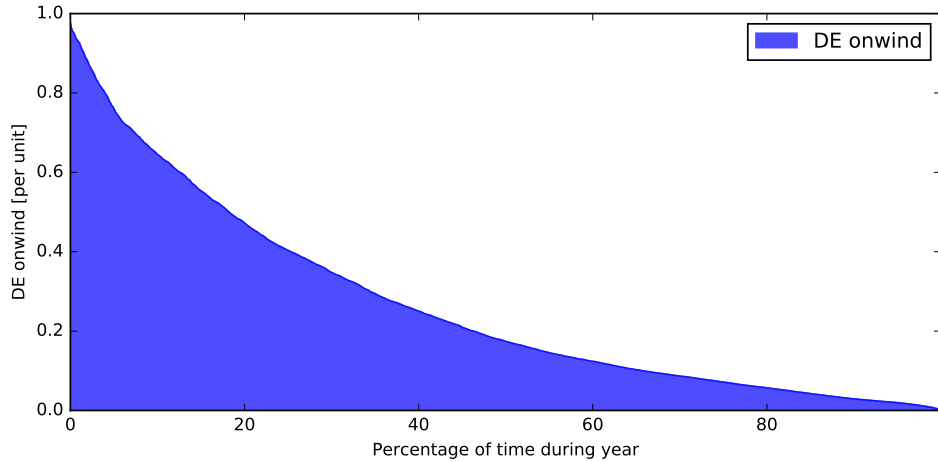
How do we derive wind time series?

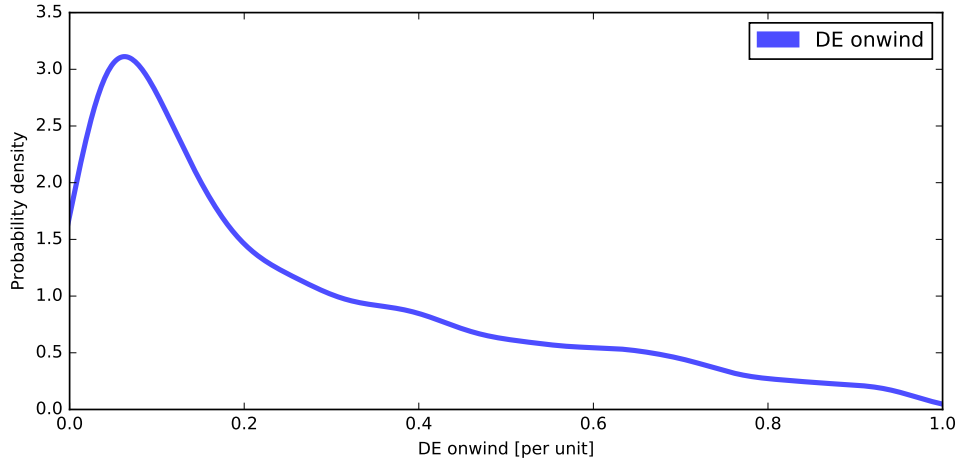
Wind speeds are typically distributed according to a Weibull probability distribution. Although the wind speeds are clustered at the lower end, most of the energy is generated between 5 and 15 ms^{-1} .



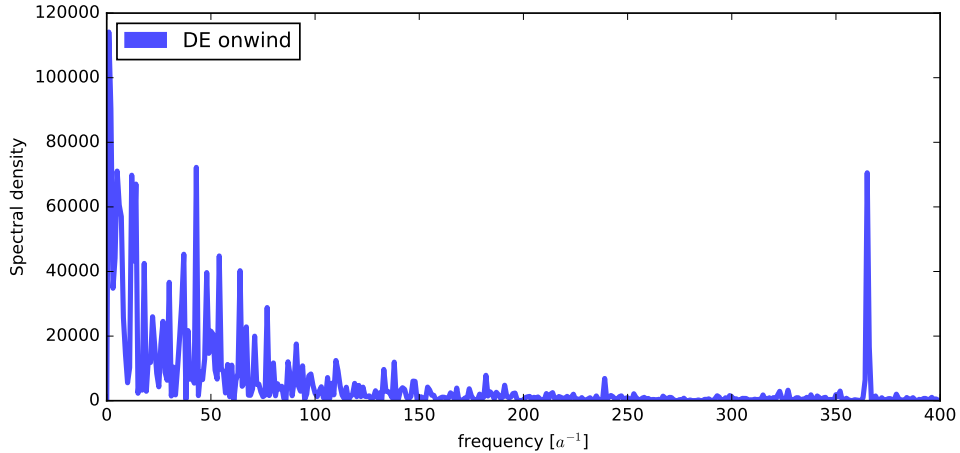
If we take a weekly average we see higher wind in the winter and some periodic patterns over 2-3 weeks (**weekly or synoptic scale**).



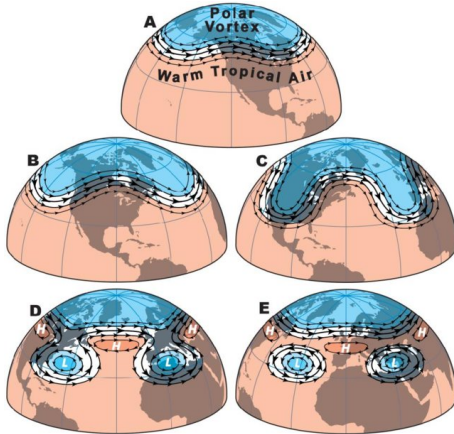




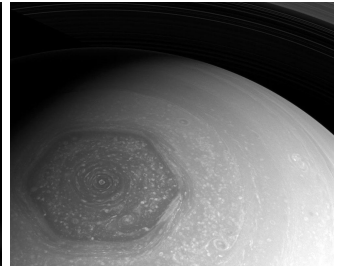
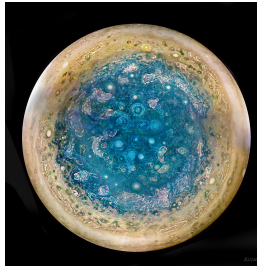
If we Fourier transform, the **seasonal**, **synoptic** (2-3 weeks) and **daily** patterns become visible.



What causes weekly variations?



- Large weather systems follow atmospheric **Rossby waves**. Rossby waves are giant meanders in high-altitude winds that have a major influence on weather.
- Also found on other planets like Jupiter and Saturn (general feature of rotating fluids).



Balancing a Single Country

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)

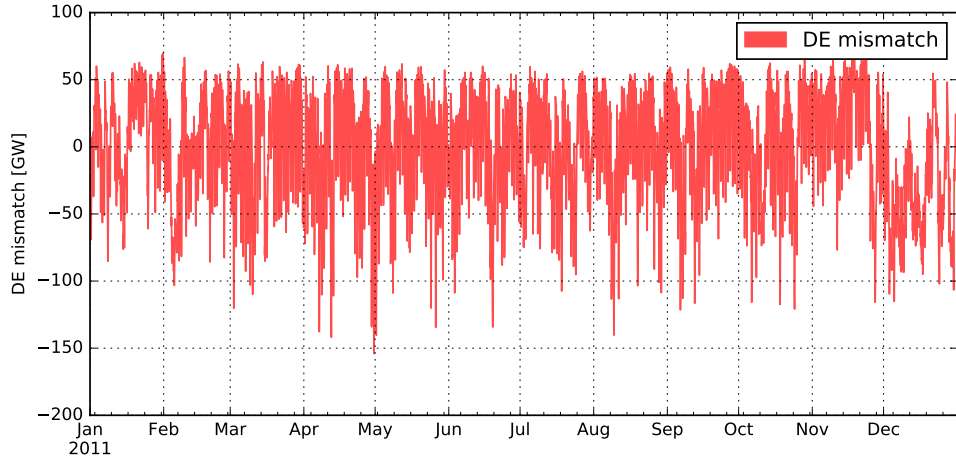
We try W MW of wind and S MW of solar. Now the effective **residual load** or **mismatch** is

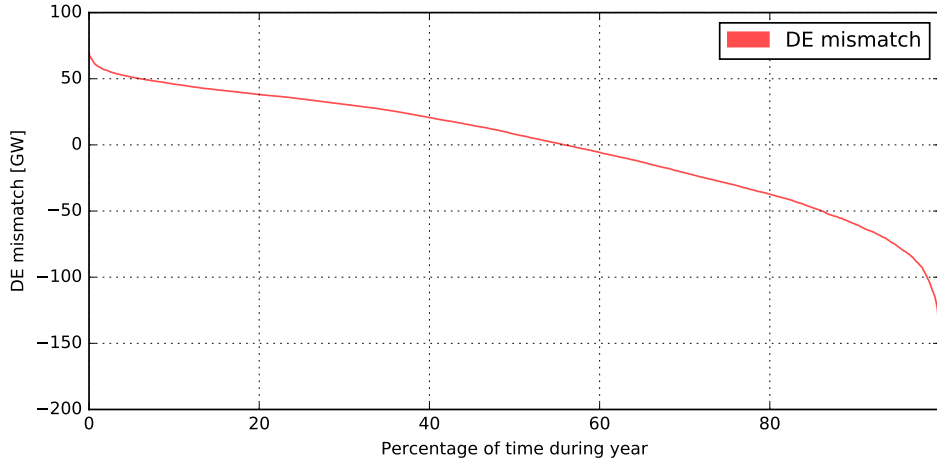
$$m_t = d_t - Ww_t - Ss_t$$

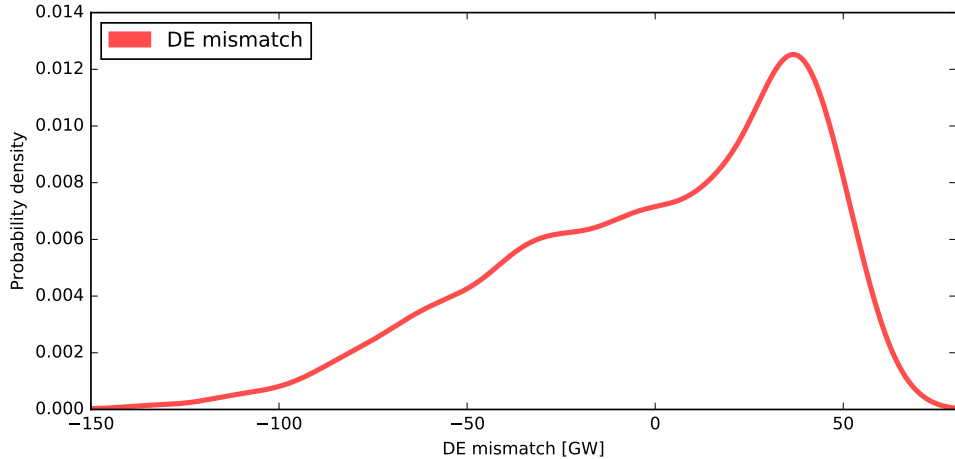
We choose W and S such that on **average** we cover all the load

$$\langle m_t \rangle = 0$$

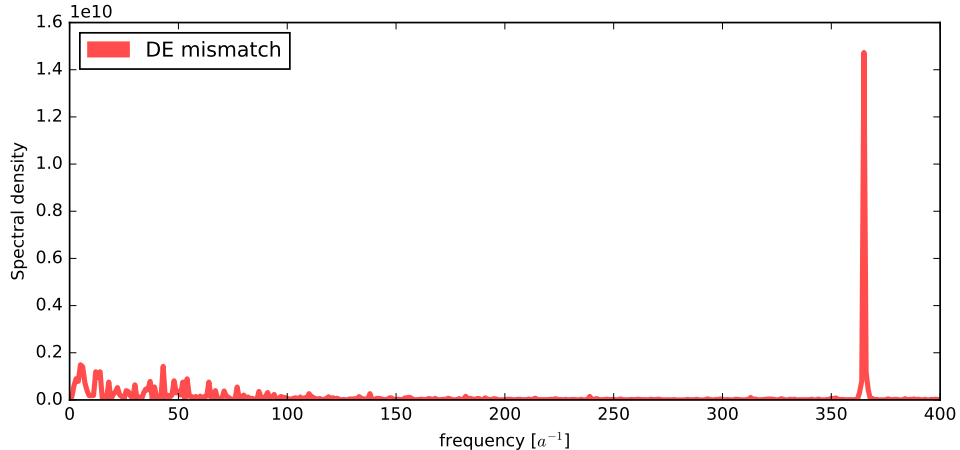
and so that the 70% of the energy comes from wind and 30% from solar ($W = 147$ GW and $S = 135$ GW).







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



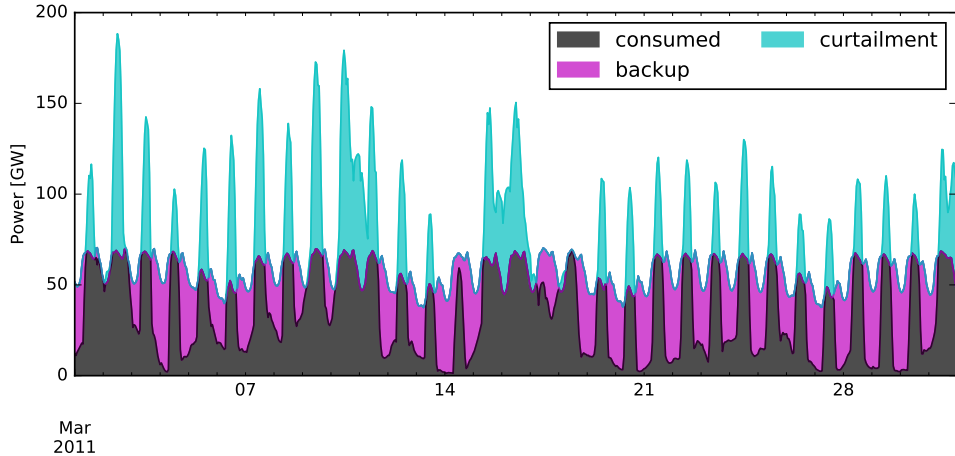
The problem is that

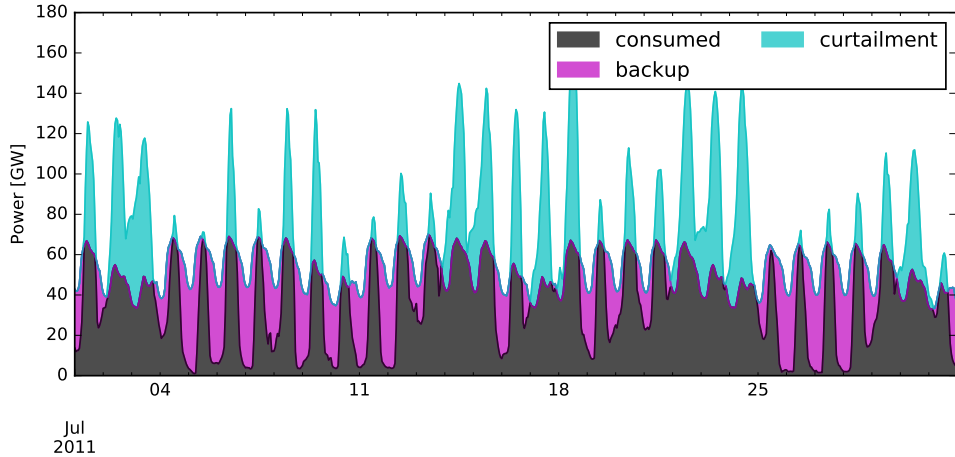
$$\langle m_t \rangle = 0$$

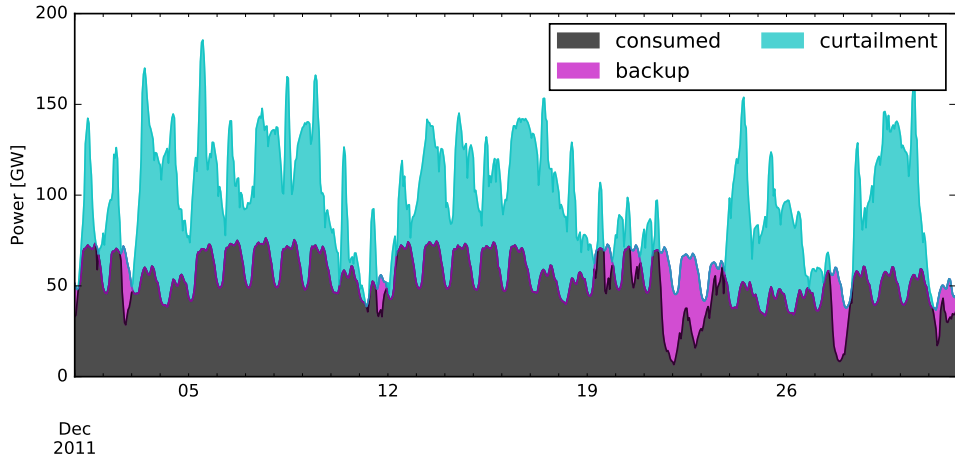
is not good enough! We need to meet the demand in every single hour.

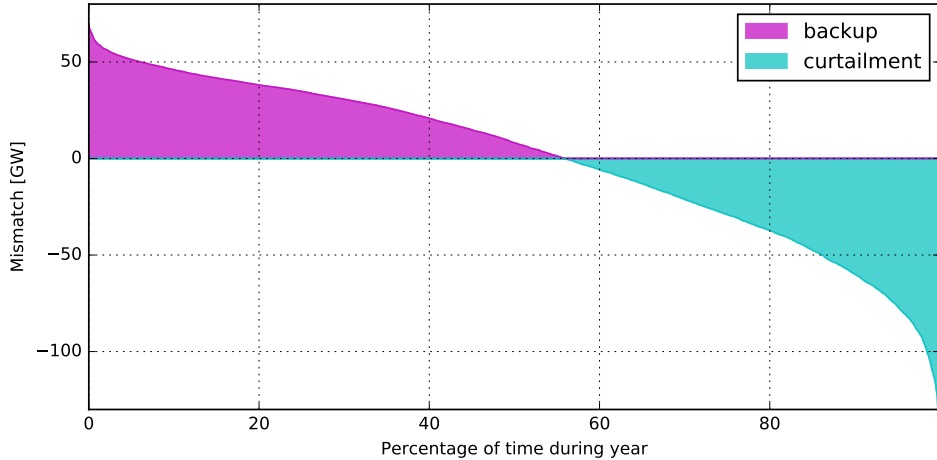
This means:

- 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.









Backup energy costs money and may also cause CO₂ emissions.

Curtailling 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).