Energy System Modelling
Summer Semester 2019, Lecture 1

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Karlsruhe Institute of Technology (KIT), Institute for Automation and Applied Informatics (IAI)

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Karlsruhe Institute of Technology

Table of Contents

1. Administration
2. Course outline
3. The Greenhouse Gas Challenge
4. Introduction: Balancing Variable Renewable Energy in Europe
5. Electricity Consumption
6. Electricity Generation
7. Variable Renewable Energy (VRE)
8. Balancing a single country

Administration

Contact Details

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Group website (with **open MA theses**): `https://www.iai.kit.edu/english/ESM.php`

Personal website: `https://nworbmot.org/`

I am a physicist who has specialised in the optimisation of energy systems and the interactions of complex networks. I now work at the intersection of informatics, economics, engineering, mathematics, meteorology and physics.

Lectures and Exercise Classes

Dates: Thu 6.6, Fri 7.6, Thu 13.6, Fri 14.6, Thu 27.6

Each day will consist of 3 lectures and one exercise class:

09:00-10:30	Lecture 1
10:45-12:15	Lecture 2
13:00-14:30	Exercise Class
14:45-16:15	Lecture 3

Some of the exercises will require you to program in Python, so please bring a laptop. We will help you to install Python and the requisite libraries.

The course has 4 ECTS points.

Location: Campus Nord, Building 449, Room 126

Course Website

You can find the course website here:

`https://nworbmot.org/courses/esm-2019/`

by following the links from:

`https://nworbmot.org/`

Course notes, exercise sheets and other links can be found there.

Registration for Oral Exam

To get an evaluation at the end of the course, you need to register online for the oral examination.

The oral examinations will take place some time in July on a single date. The date will be decided during the final lecture, based on when we are all available.

MA Theses

We have some exciting opportunities in the Energy System Modelling group at IAI to do MA Theses, see the list here:

`https://www.iai.kit.edu/english/2552.php`

We are also open to new suggestions and themes if they fit with our research programme.

Literature

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

The following are concise:

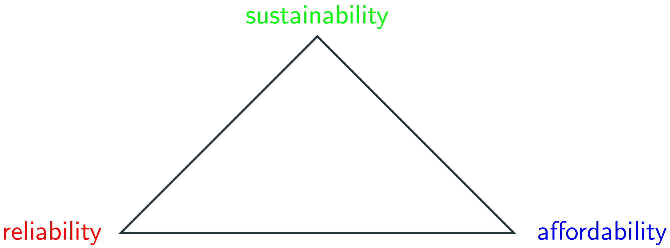
- Volker Quashning, “Regenerative Energiesysteme”, Carl Hanser Verlag München, 2015
- Leon Freris, David Infield, “Renewable Energy in Power Systems”, Wiley, 2006
- Göran Andersson Skript, “Elektrische Energiesysteme: Vorlesungsteil Energieübertragung,” online
- D.R. Biggar, M.R. Hesamzadeh, “The Economics of Electricity Markets,” Wiley, 2014

Course outline

What is Energy System Modelling?

Energy System Modelling is about the overall **design** and **operation** of the energy system.

How can we fulfil energy policy targets of **sustainability**, **reliability** and **affordability**?



What is Energy System Modelling?

- **Sustainability**: Can we supply energy while respecting environmental constraints (greenhouse gas emissions, preservation of wildlife), as well as social and political constraints (public acceptance of transmission lines, onshore wind, nuclear power, etc.)?
- **Reliability**: Can we ensure energy services are delivered whenever needed, even when the wind isn't blowing and the sun isn't shining, and even when components fail?
- **Affordability**: Can we deliver energy at a reasonable cost?

Some of these policy targets can come into **conflict** $\Longrightarrow$ **energy trilemma**.

Course outline

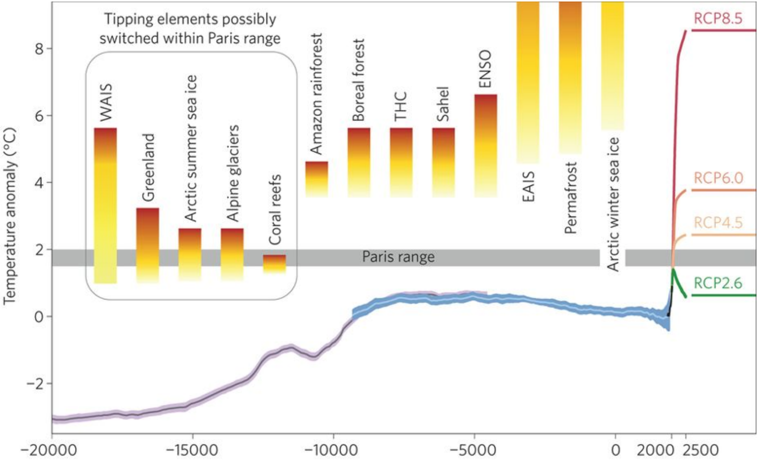
This course will cover the following topics:

- General properties of renewable power, time series analysis
- 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.)

The Greenhouse Gas Challenge

2015 Paris Agreement

The 2015 Paris Agreement pledged its signatories to 'pursue efforts to limit [global warming above pre-industrial levels] to 1.5°**C**' and hold 'the increase...to **well below** 2°**C**'. These targets were chosen to avoid potentially irreversible **tipping points** in the Earth's systems.



WAIS: West Antarctic Ice Sheet (5m sea level rise)

Greenland (7m)

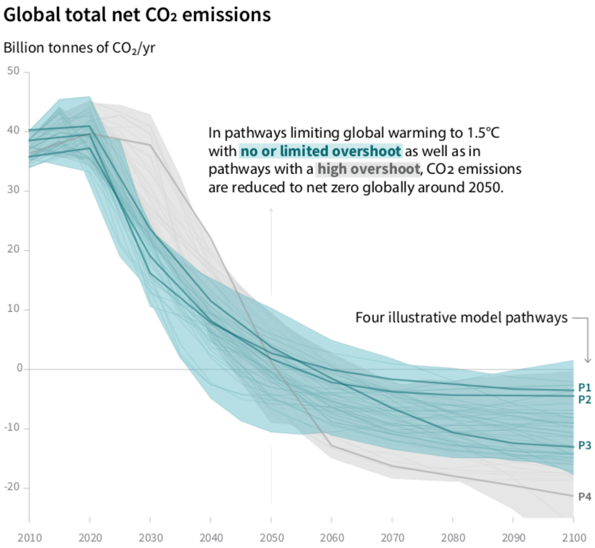
THC: thermohaline circulation (warms Europe)

ENSO: El Niño–Southern Oscillation (extreme weather)

EAIS: East Antarctic Ice Sheet (> 50 m)

Source: 'Why the right climate target was agreed in Paris', Nature Climate Change, 2016

The Global Carbon Dioxide Challenge: Net-Zero Emissions by 2050

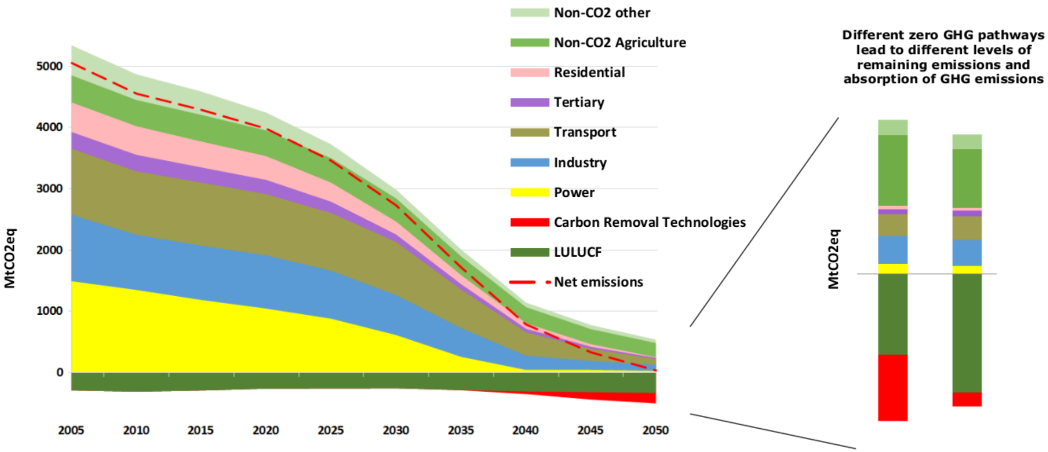


- Scenarios for global CO_2 emissions that limit warming to 1.5°C about industrial levels (**Paris agreement**)
- Today emissions **still rising**
- Level of use of negative emission technologies (NET) depends on rate of progress
- 2°C target without NET also needs rapid fall by 2050
- Common theme: **net-zero by 2050**

Source: IPCC SR15 on 1.5C, 2018

The Greenhouse Gas Challenge: Net-Zero Emissions by 2050

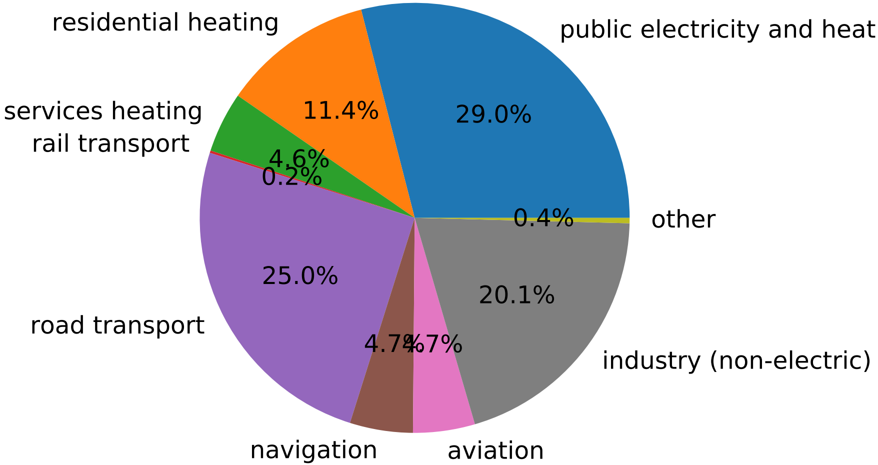
Paris-compliant 1.5° C scenarios from European Commission - **net-zero GHG in EU by 2050**



Source: European Commission ‘Clean Planet for All’, 2018

It's not just about electricity demand...

EU28 CO_2 emissions in 2016 (total 3.5 Gt CO_2, 9.7% of global):



Source: Brown, data from EEA

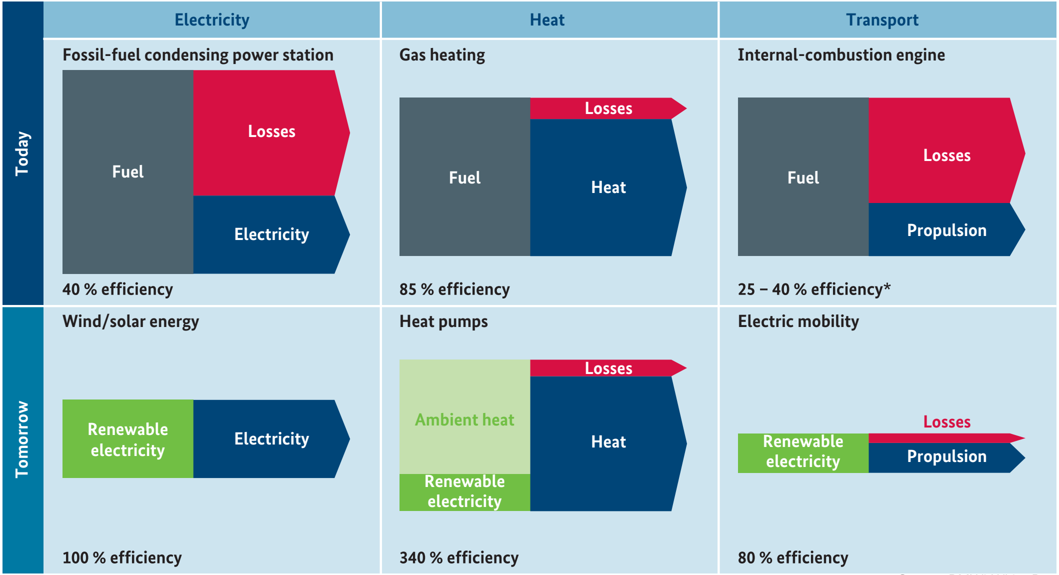
...but electrification of other sectors is critical for decarbonisation

Electrification is essential to decarbonise sectors such as transport, heating and industry, since we can use low-emission electricity from e.g. wind and solar to displace fossil-fuelled transport with electric vehicles, and fossil-fuelled heating with electric heat pumps.

Some scenarios show a **doubling or more of electricity demand**.

Source: Tesla; heat pump: Kristoferb at English Wikipedia

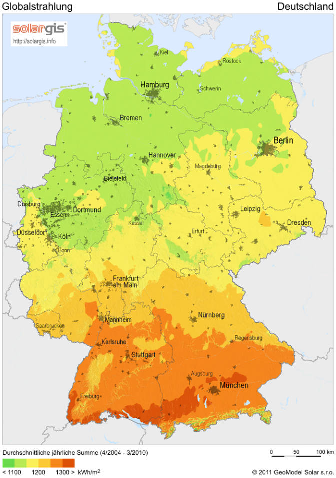
Efficiency of renewables and sector coupling

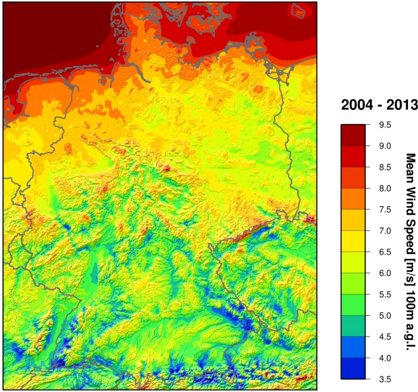


Source: BMWi White Paper 2015

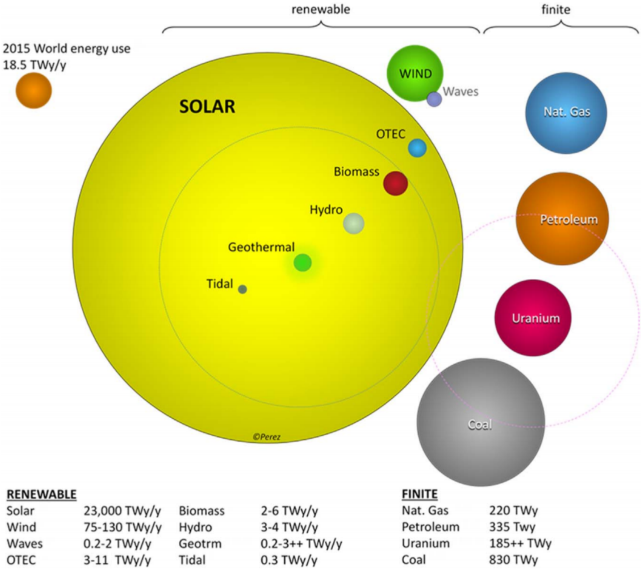
Why focus on wind and solar for electricity generation?

- construction and operation have low greenhouse gas emissions
- good wind and sun are available in many parts of the world
- worldwide potential that exceeds demand by many factors
- rapidly falling costs





Worldwide potentials

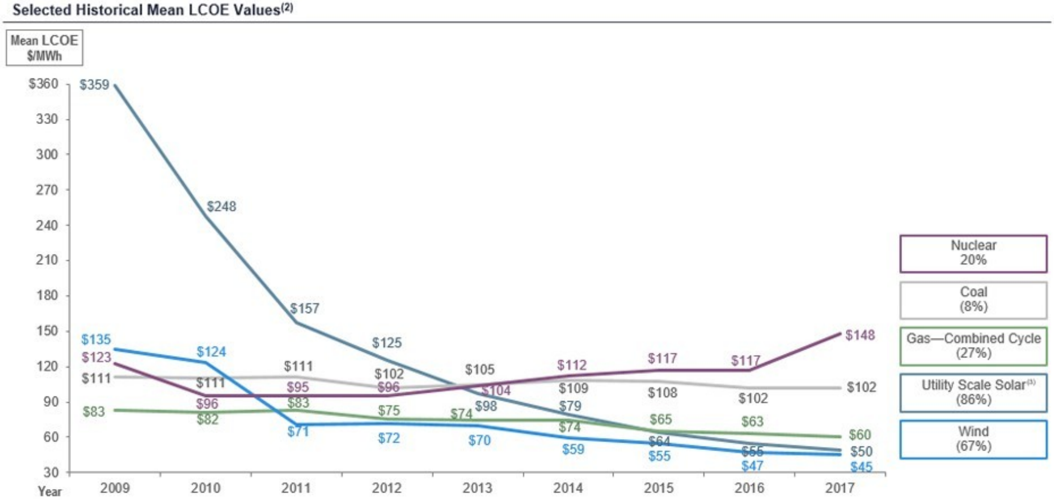


- Potentials for wind and solar exceed current demand by many factors (ignoring variability)
- Other renewable sources include wave, tidal, geothermal, biomass and hydroelectricity
- Uranium depends on the reactor: conventional thermal reactors can extract 50-70 times less than fast breeders

Source: Perez et al, Applied Policy, 2016

Low cost of wind & solar per MWh in 2017 (NB: ignores variability)

LCOE = **Levelised Cost of Energy** = Total Costs / Energy Output



Source: Lazard's LCOE Analysis V11

Must take account of variabilility & social & political constraints

Sustainability doesn't just mean taking account of environmental constraints.

There are also **social and political constraints**, particularly for transmission grid and onshore wind development.

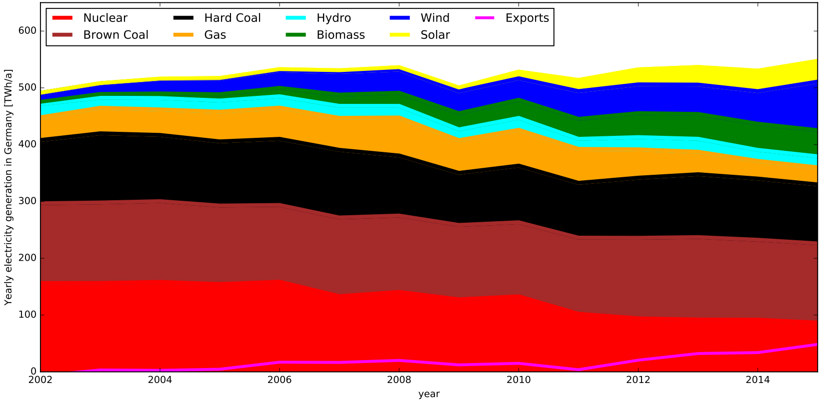
Energy Transition: Several changes happening simultaneously

Energiewende: The Energy Transition, consists of several parts:

- Transition to an energy system with low greenhouse gas emissions
- Renewables replace fossil-fuelled generation (and nuclear in some countries)
- Increasing integration of international electricity markets
- Better integration of transmission constraints in electricity markets
- Sector coupling: heating, transport and industry electrify
- More decentralised location and ownership in the power sector

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

What can informatics contribute?

In all these questions we are limited by **computational complexity**.

Informatics can contribute on the **data side**:

- Processing and analysing enormous weather datasets
- Geographical potential analysis with GIS tools
- Visualisation of results

and on the **algorithmic side**:

- Data reduction: clustering and PCA examples to follow later
- New optimisation routines for speed and accuracy
- Information theory to trace interdependencies

Build on informatics' **interdisciplinary** links to engineering, economics, meteorology, mathematics and physics.

Introduction: Balancing Variable Renewable Energy in Europe

Goals for Energy System Modelling

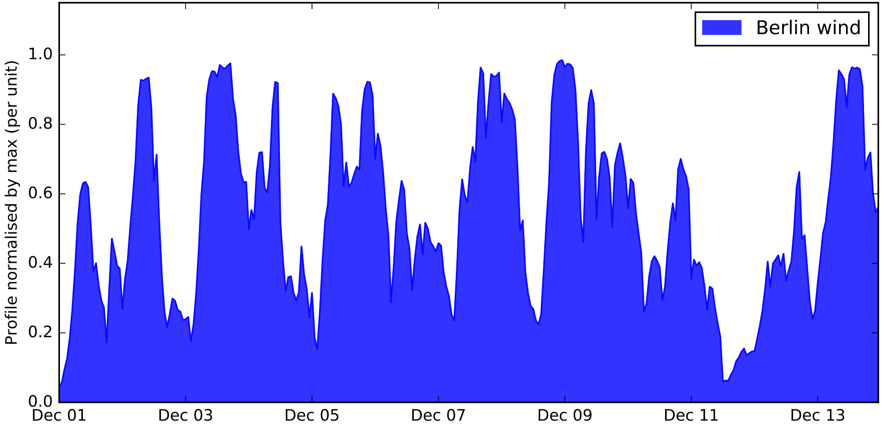
1. What **infrastructure** (wind, solar, hydro generators, heating/cooling units, storage and networks) does a highly renewable energy system require and **where** should it go?

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?

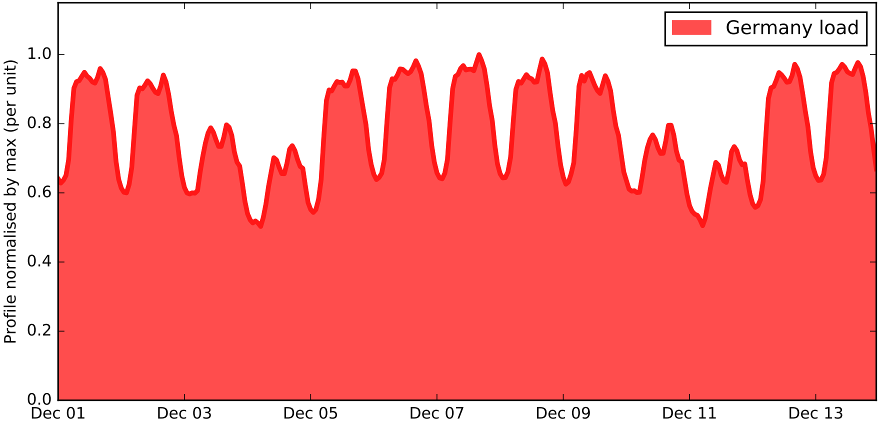
Variability: Single wind site in Berlin

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.



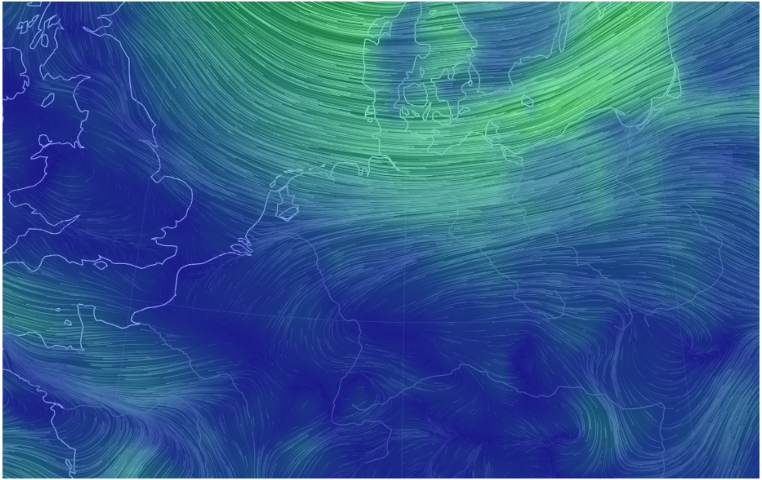
Electricity consumption is much more regular

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

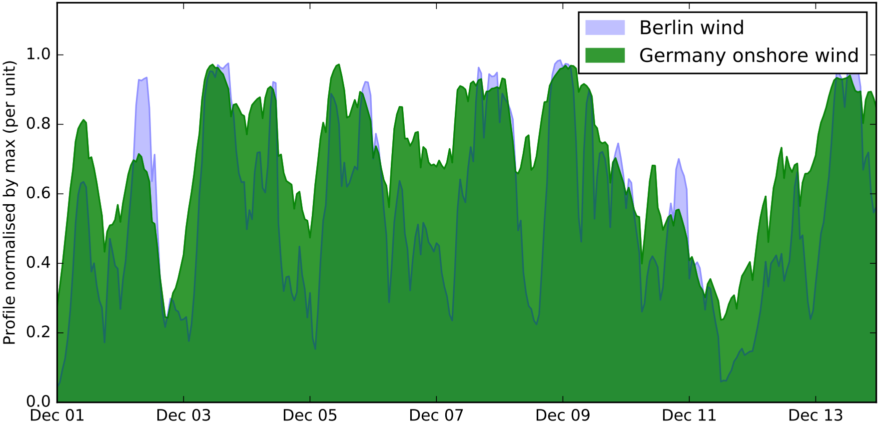
The wind does not blow the same at every site at every time: at a given time there are a variety of wind conditions across Germany. These differences **balance out over time and space**.



Source: `https://earth.nullschool.net/`

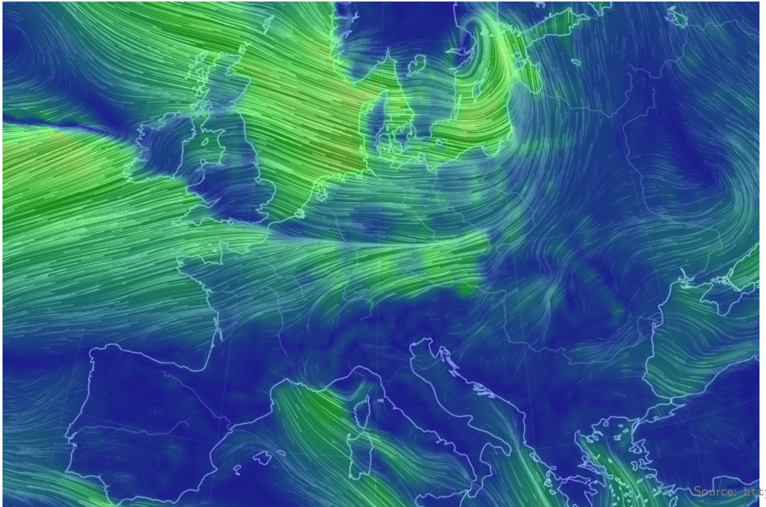
Variability: Single country: Germany

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

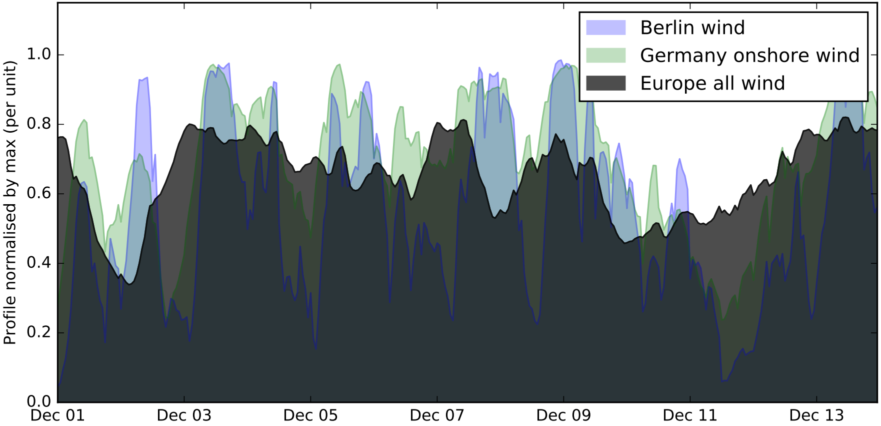
The scale of the weather systems are bigger than countries, so to leverage the full smoothing effects, you need to integrate wind at the **continental scale**.



Source: https://earth.nullschool.net/

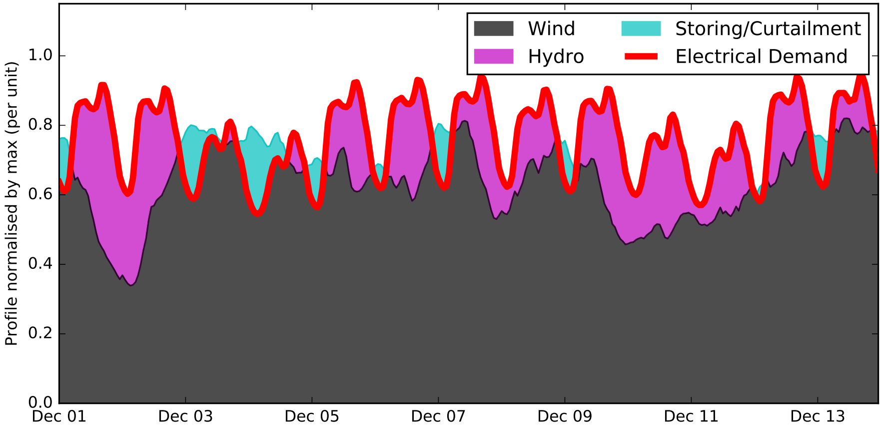
Variability: A continent: Europe

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.

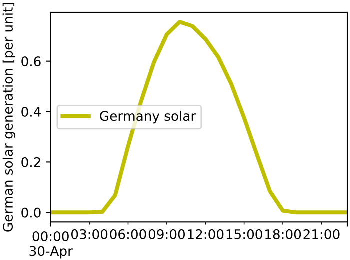


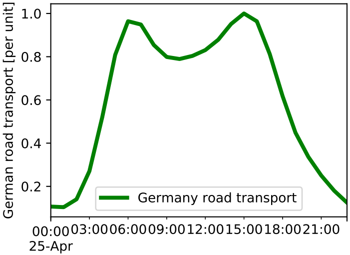
Variability: A continent: Wind plus Hydro

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.



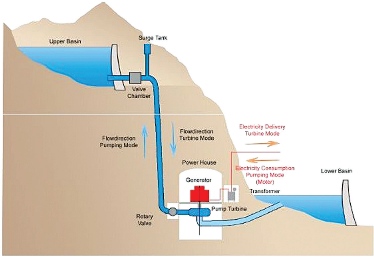
Daily variations: challenges and solutions



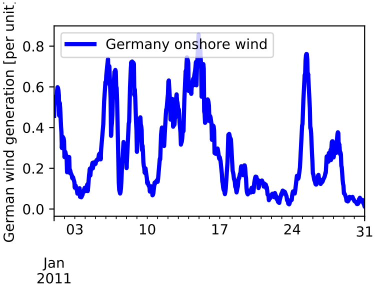


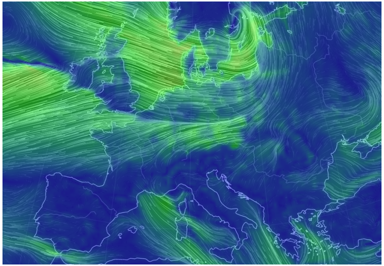
Daily variations in supply and demand can be balanced by

- **short-term storage** (e.g. batteries, pumped-hydro, small thermal storage)
- **demand-side management** (e.g. battery electric vehicles, industry)
- **east-west grids over multiple time zones**



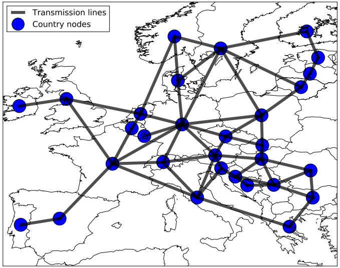
Weekly variations: challenges and solutions



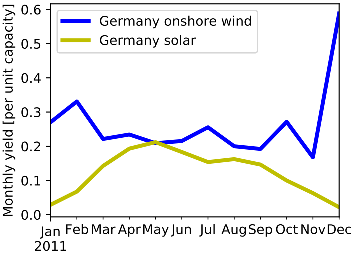


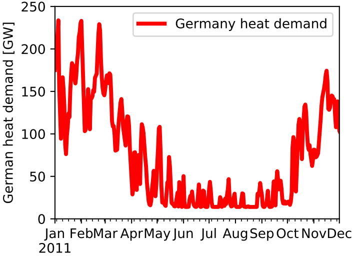
Weekly variations in supply and demand can be balanced by

- **medium-term storage** (e.g. chemically with hydrogen or methane storage, thermal energy storage, hydro reservoirs)
- **continent-wide grids**



Seasonal variations: challenges and solutions

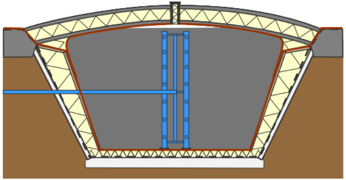




Seasonal variations in supply and demand can be balanced by

- **long-term storage** (e.g. chemically with hydrogen or methane storage, long-term thermal energy storage, hydro reservoirs)
- **north-south grids over multiple latitudes**

Pit thermal energy storage (PTES)
(60 to 80 kWh/m³)



Research approach

Avoid too many assumptions. Fix the **boundary conditions**:

- Meet demand for energy services
- Reduce CO_2 emissions
- Conservative predictions for cost developments
- No/minimal/optimal grid expansion

Then **let the math decide the rest**, i.e. choose the number of wind turbines / solar panels / storage units / transmission lines to minimise total costs (investment **and** operation).

Generation, storage and transmission optimised **jointly** because they are **strongly interacting**.

Linear optimisation of annual system costs

Find the long-term cost-optimal energy system, including investments and short-term costs:

$$\text{Minimise}\left(\textbf{Yearly system costs}\right) = \sum_n \left(\textbf{Annualised capital costs}\right) + \sum_{n,t}\left(\textbf{Marginal costs}\right)$$

subject to

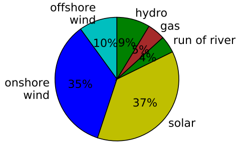
- meeting **energy demand** at each node n (e.g. region) and time t (e.g. hour of year)
- wind, solar, hydro (variable renewables) **availability time series** $\forall\, n, t$
- **transmission constraints** between nodes, **linearised power flow**
- (installed capacity) $\leq$ (**geographical potentials** for renewables)
- **CO_2 constraint** (e.g. 95% reduction compared to 1990)

In short: mostly-greenfield investment optimisation, multi-period with linear power flow.

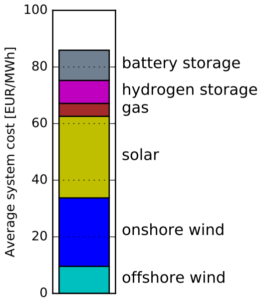
Optimise transmission, generation and storage **jointly**, since they're strongly interacting.

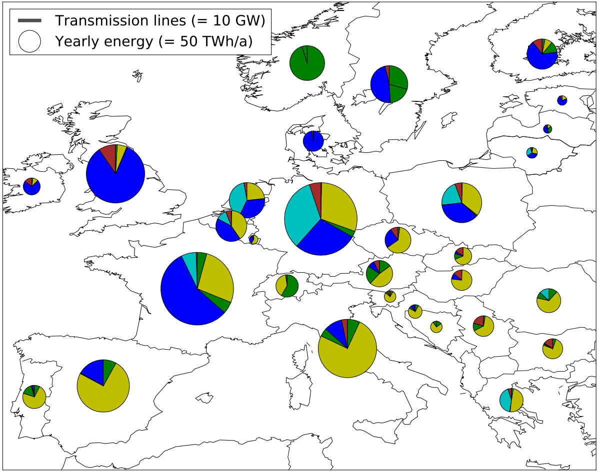
Costs: No interconnecting transmission allowed

Technology by energy:



Average cost **€86/MWh**:

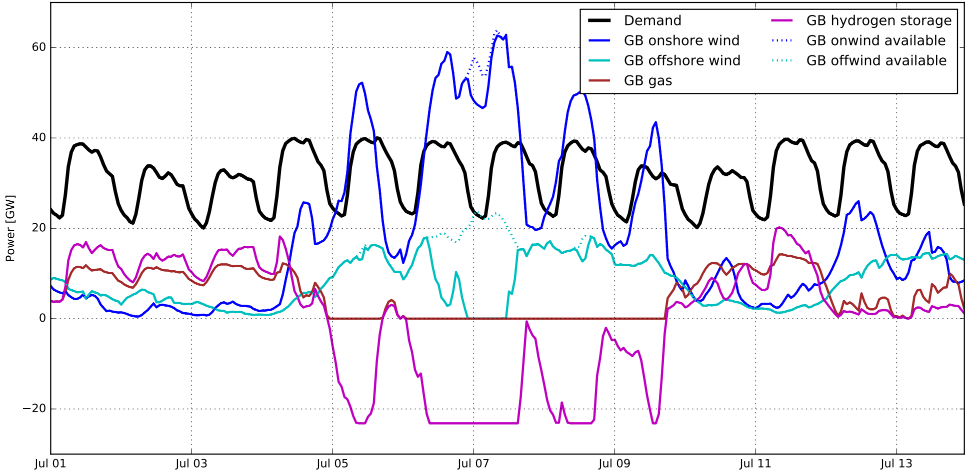




Countries must be self-sufficient at all times; lots of storage and some gas to deal with fluctuations of wind and solar.

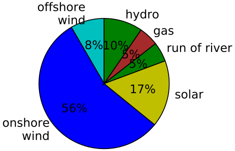
Dispatch with no interconnecting transmission

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

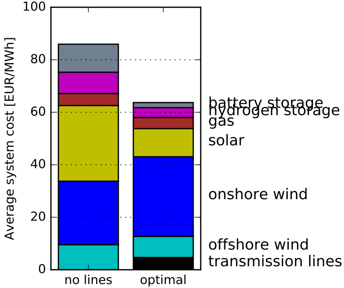


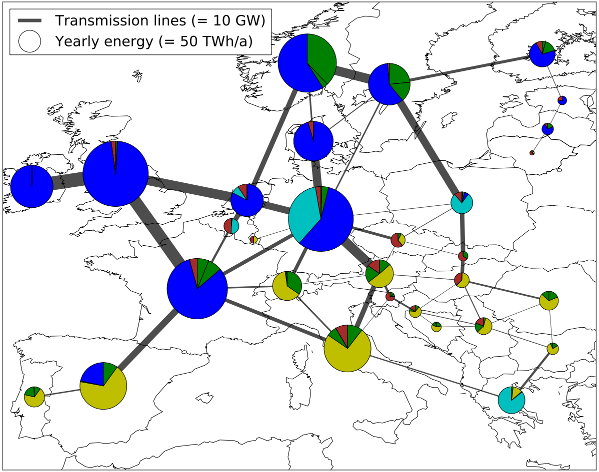
Costs: Cost-optimal expansion of interconnecting transmission

Technology by energy:



Average cost **€64/MWh**:

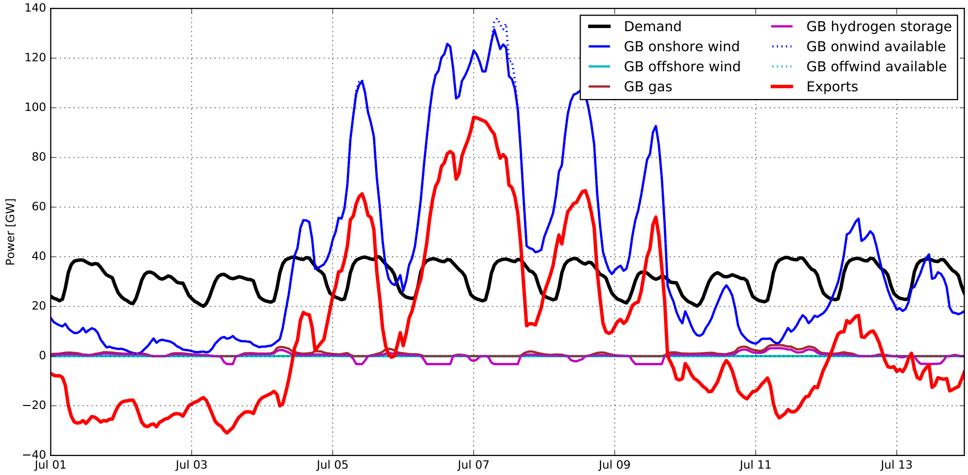




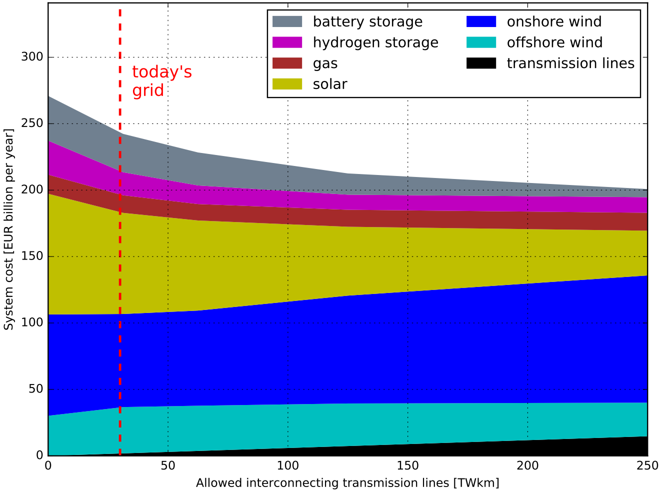
Large transmission expansion; onshore wind dominates. This optimal solution may run into public acceptance problems.

Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can be now be exported:

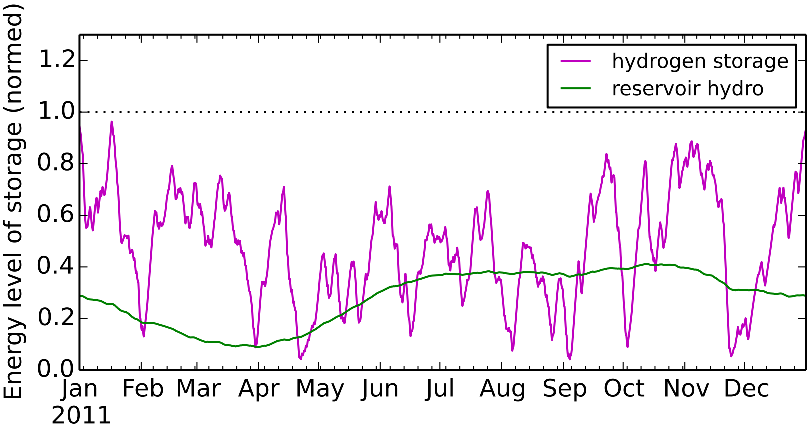


Electricity Only Costs Comparison



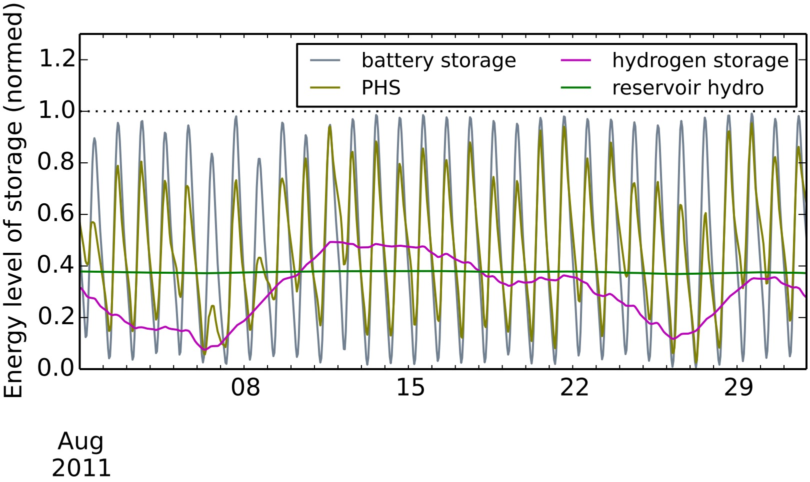
- Average total system costs can be as low as € 64/MWh
- Energy is dominated by wind (64% for the cost-optimal system), followed by hydro (15%) and solar (17%)
- Restricting transmission results in more storage to deal with variability, driving up the costs by up to 34%
- Many benefits already locked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

Different flexibility options have difference temporal scales



- Hydro reservoirs are **seasonal**
- Hydrogen storage is **weekly/synoptic**

Different flexibility options have difference temporal scales



- Pumped hydro and battery storage are **daily**

Features of this example

This example has several features which will accompany us through this lecture:

1. We have to account for the variations of wind and solar in **time** and **space**.
2. These variations take place at **different scales** (daily, synoptic, seasonal).
3. We often have a choice between balancing in **time** (with storage) or in **space** (with networks).
4. Optimisation is important to increase cost-effectiveness, but we should also look at **near-optimal** solutions.

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: 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

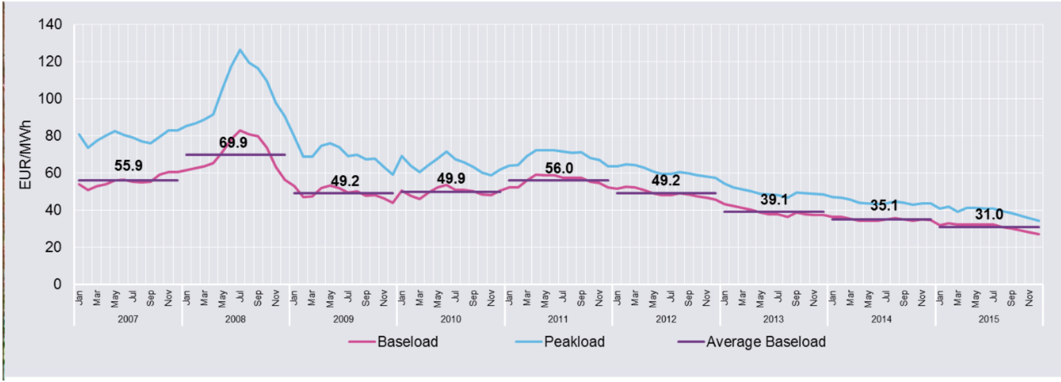
10 W * 2 h = 20 Wh

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 30-40 €/MWh, but sinking thanks to renewables and the **merit order effect**:



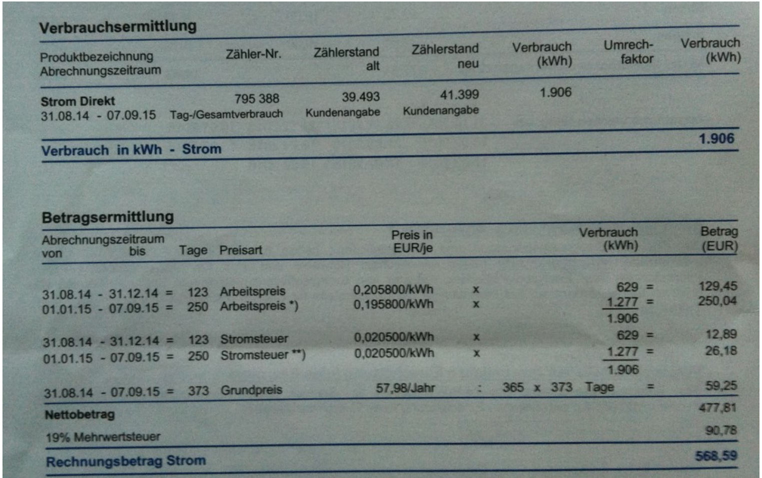
Source: Agora Energiewende

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	Tag-/Gesamtverbrauch	795 388	39.493 Kundenangabe	41.399 Kundenangabe	1.906		
Verbrauch in kWh - Strom							**1.906**

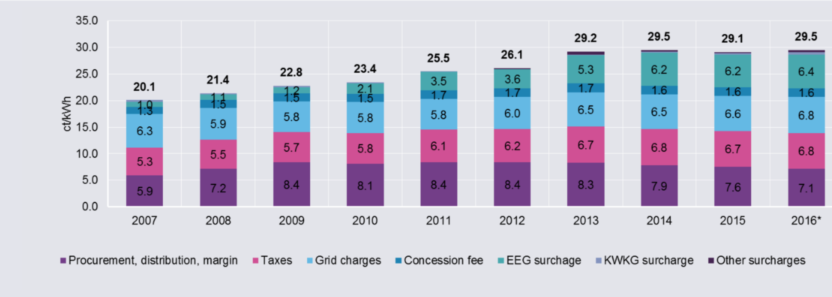
Betragsermittlung

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 power prices 2007-2016



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

Yearly energy to power

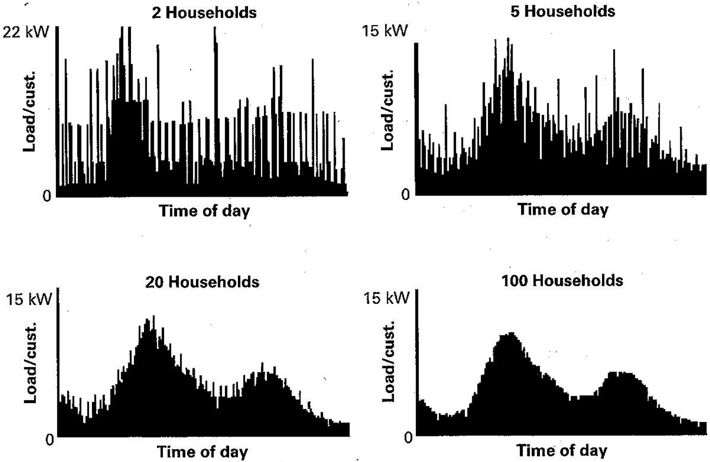
Germany consumes around 600 TWh per year, written 600 TWh/a.

What is the *average* power consumption?

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

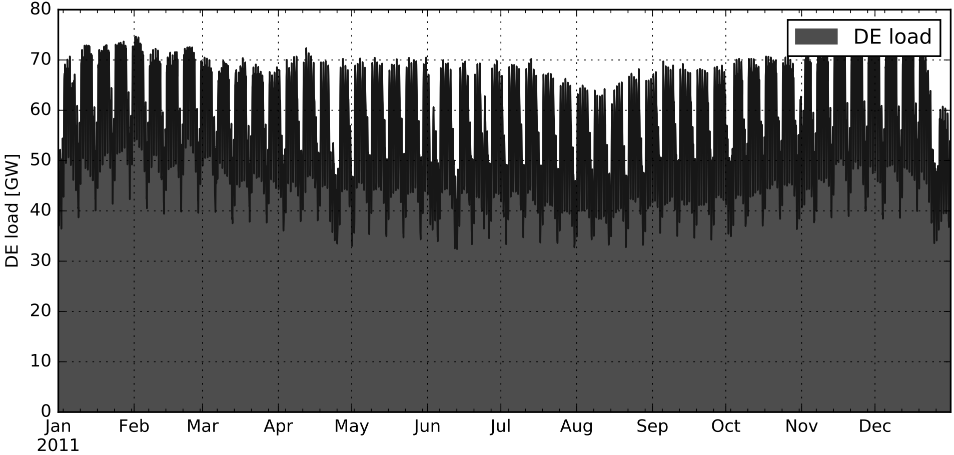
Discrete Consumers Aggregation

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



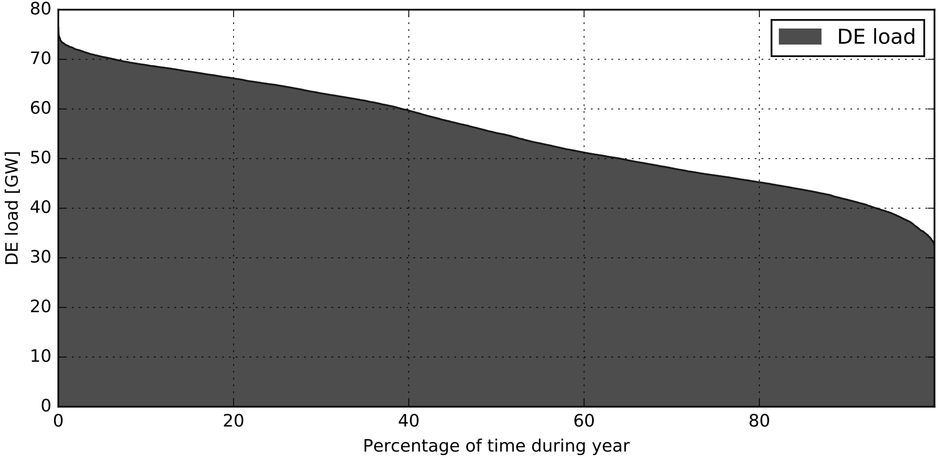
Load curve properties

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



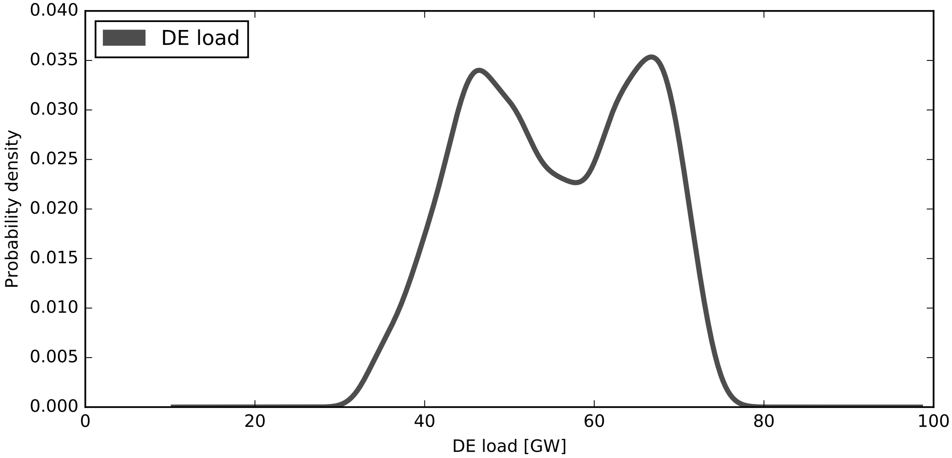
Load duration curve

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

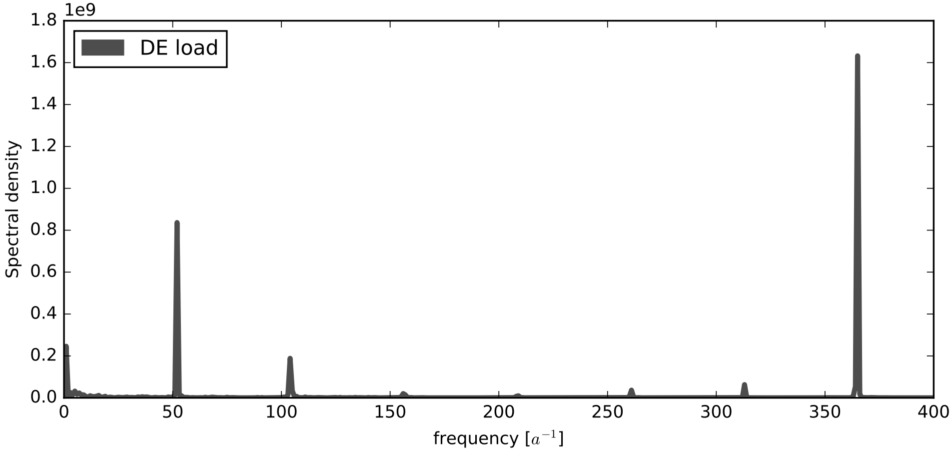
$$a_n = \frac{1}{T} \int_0^T dt \left[f(t) e^{\frac{i2\pi nt}{T}} \right]$$

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).

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.

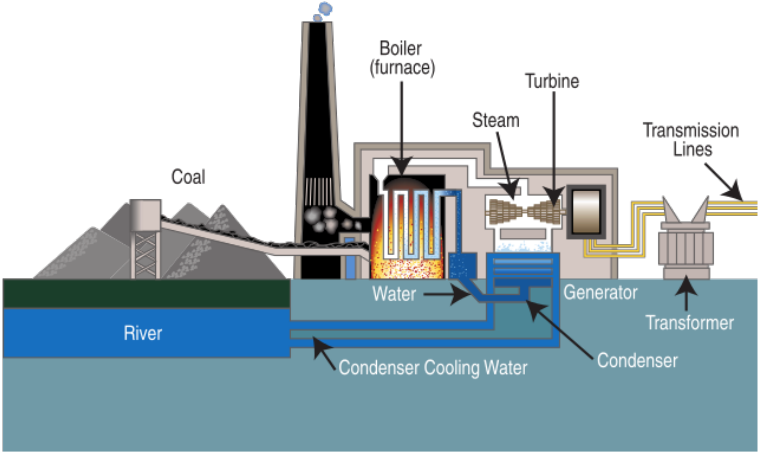
Power: Examples of generation

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

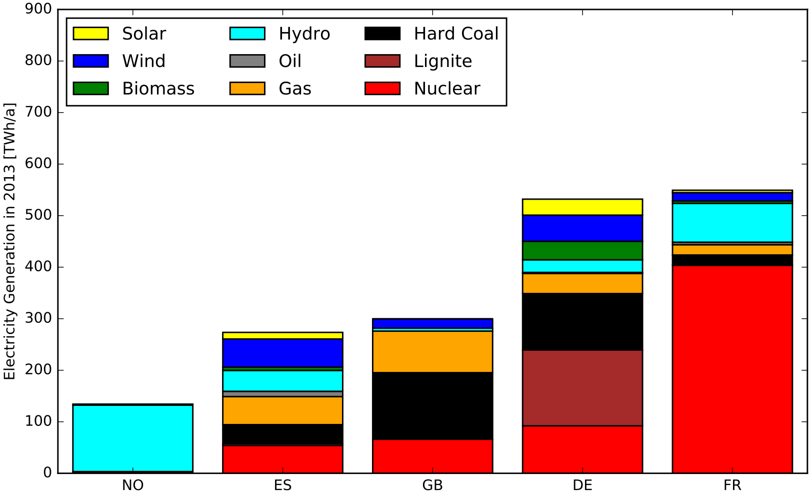
Generators

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*.



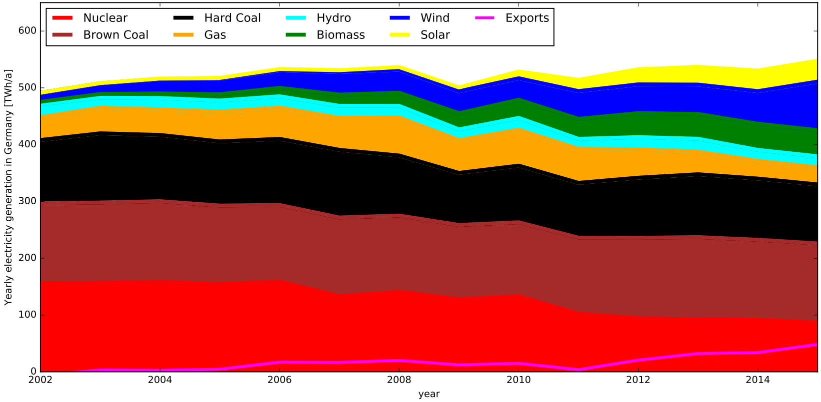
Source: Wikipedia

Example of electricity generation across major EU countries in 2013



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

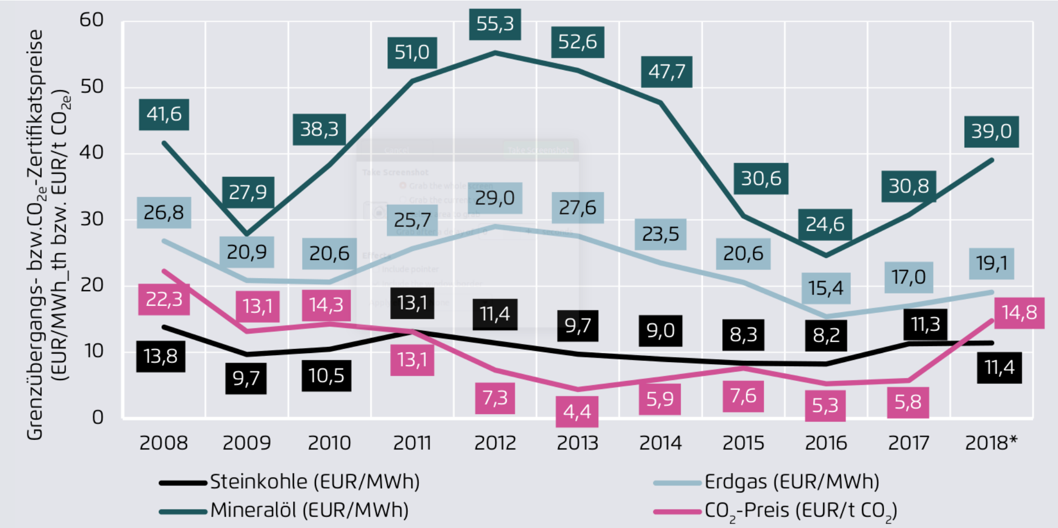
CO2 emissions per MWh

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

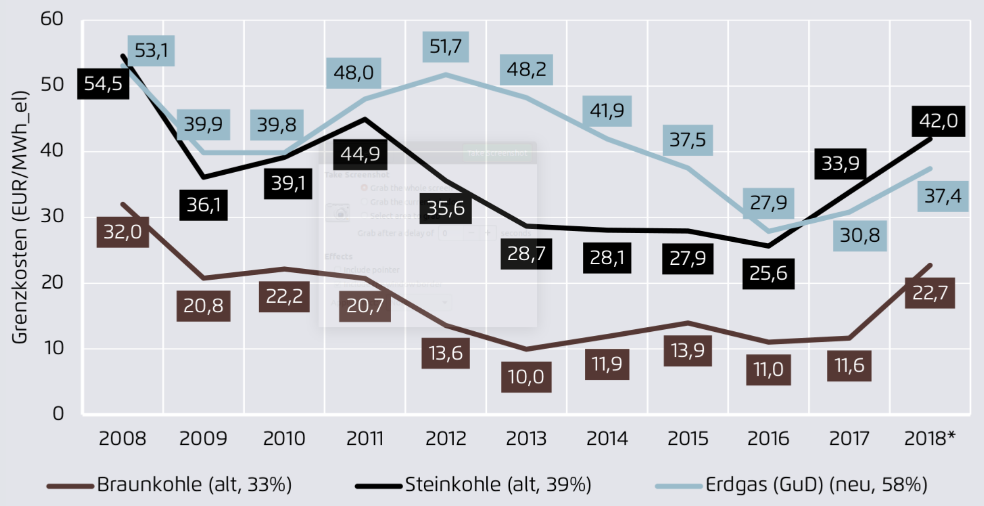
Current CO_2 price in EU Emissions Trading Scheme (ETS) is around €25/t_{CO2}

CO2 and import costs change over time...



Source: Agora Energiewende Jahresrückblick 2018

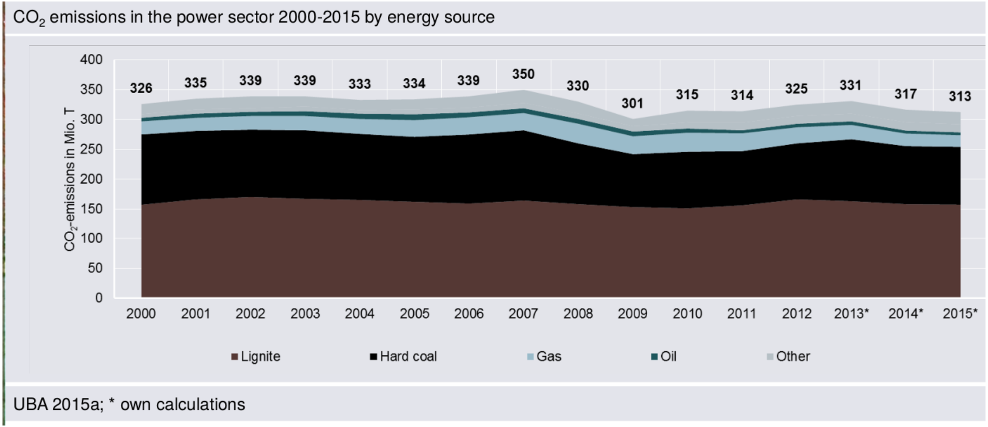
...which affects the marginal costs of generation



Source: Agora Energiewende Jahresrückblick 2018

CO2 emissions from electricity sector

Despite the increase in renewables in the electricity sector, CO_2 emission have not been reduced substantially in Germany in recent years. This is partly because German exports have also increased. Also, other sectors havent not succeeded in reducing emissions.



Source: Agora Energiewende

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:

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

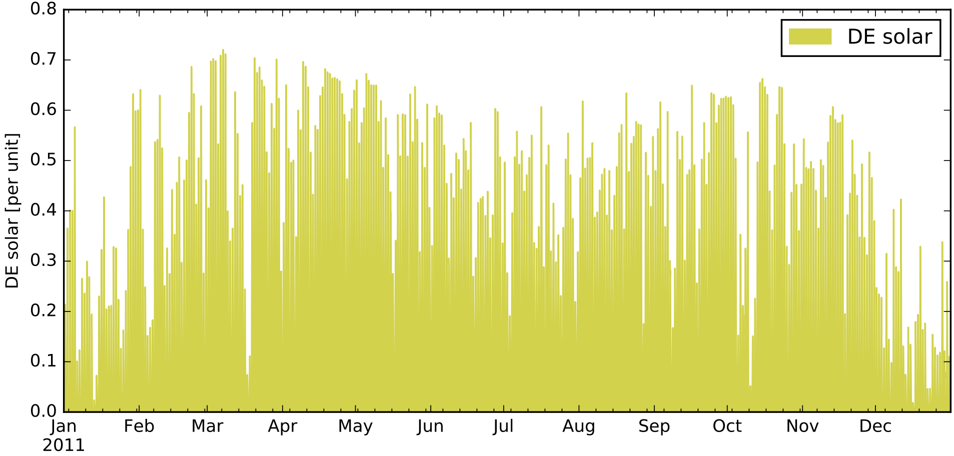
Typical values for Germany:

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)

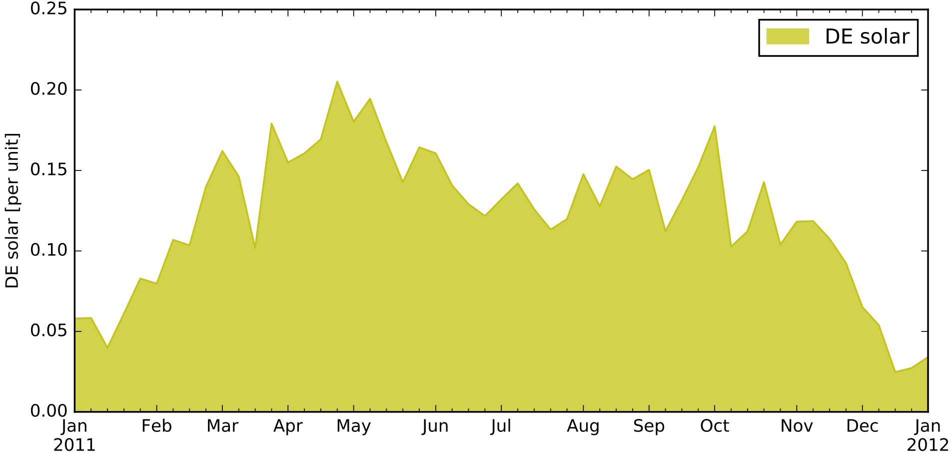
Solar time series

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).

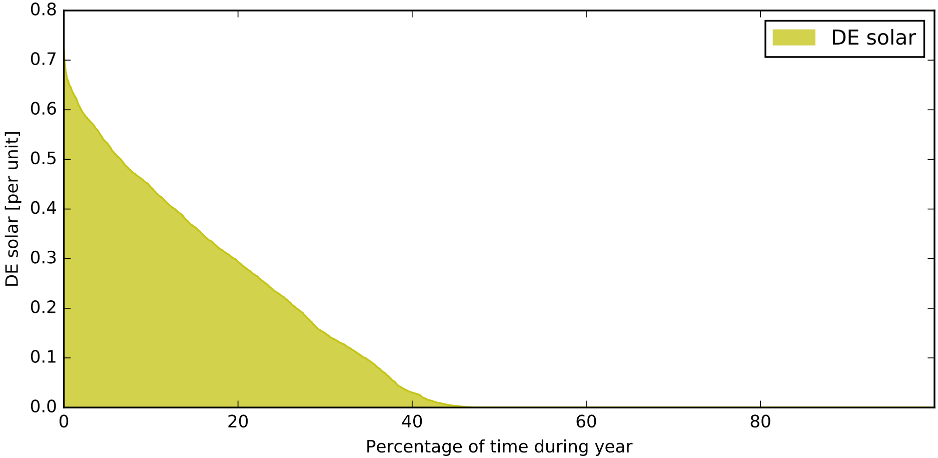


Solar time series: weekly

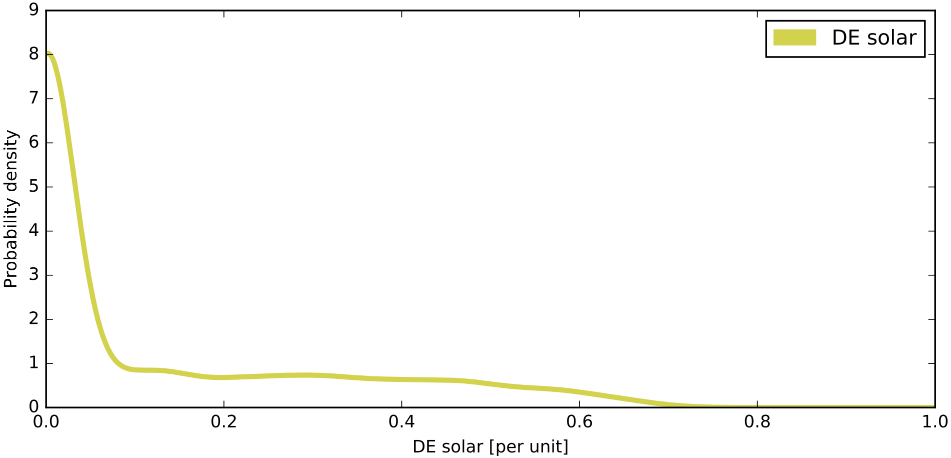
If we take a weekly average we see higher solar in the summer.



Solar duration curve

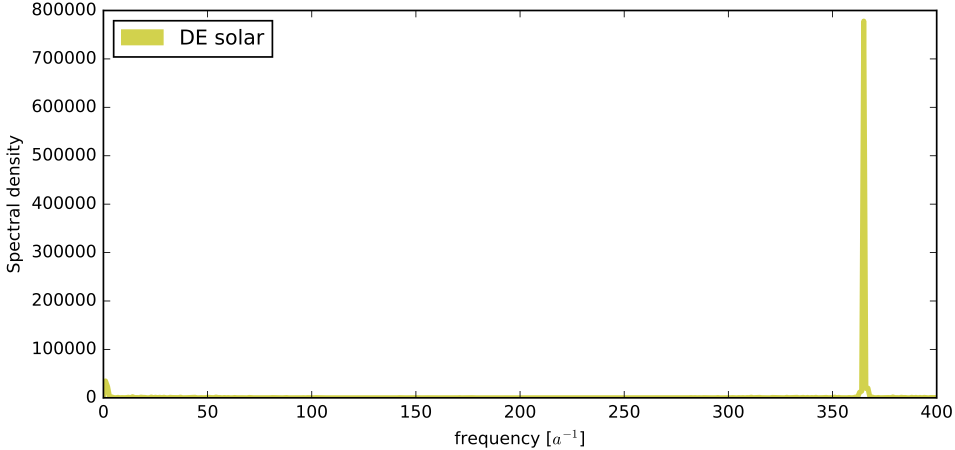


Solar density function



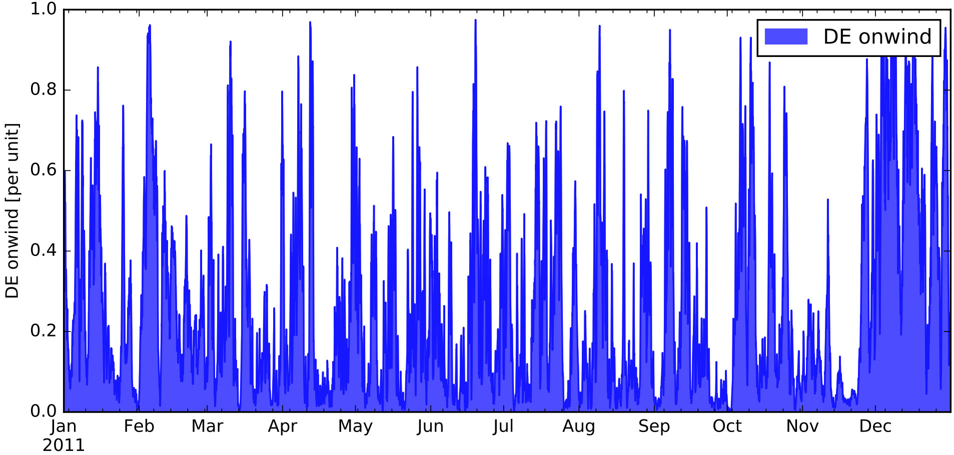
Solar spectrum

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



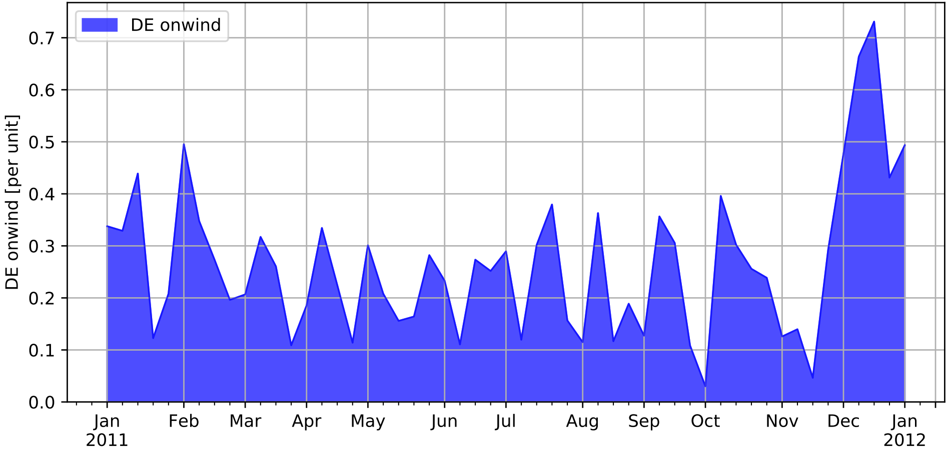
Wind time series

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).

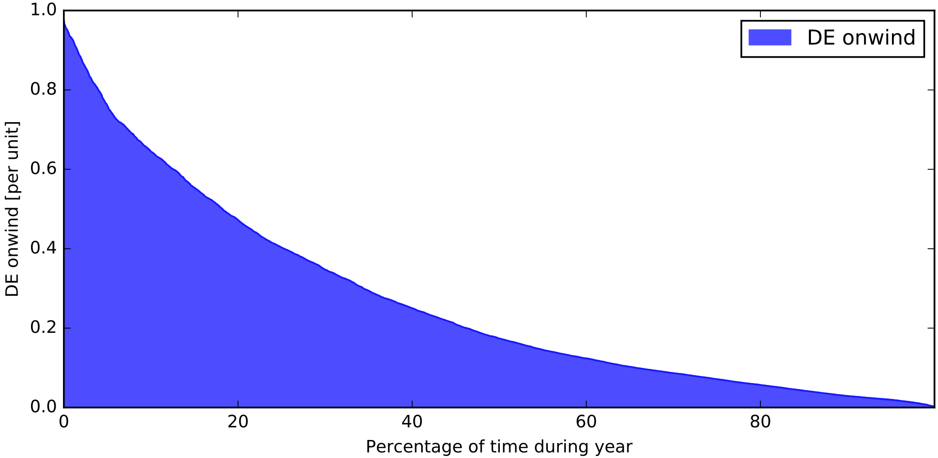


Wind time series: weekly

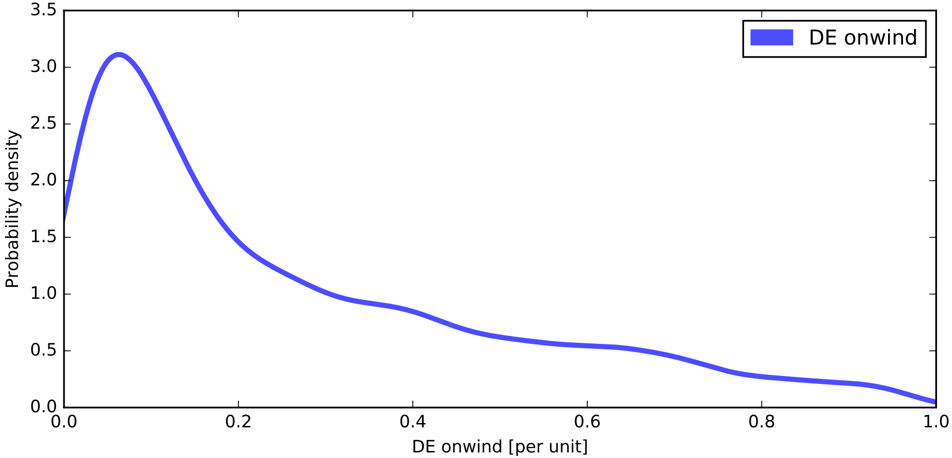
If we take a weekly average we see higher wind in the winter and some periodic patterns over 2-3 weeks (**synoptic scale**).



Wind duration curve

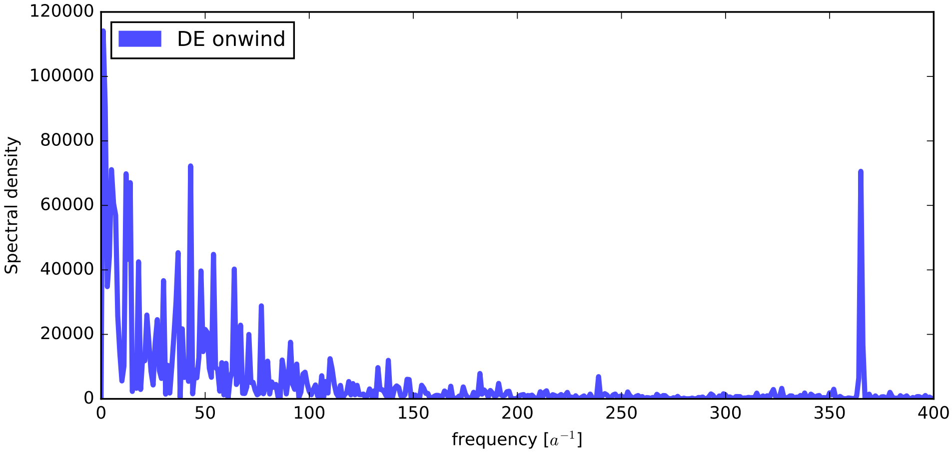


Wind density function



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 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

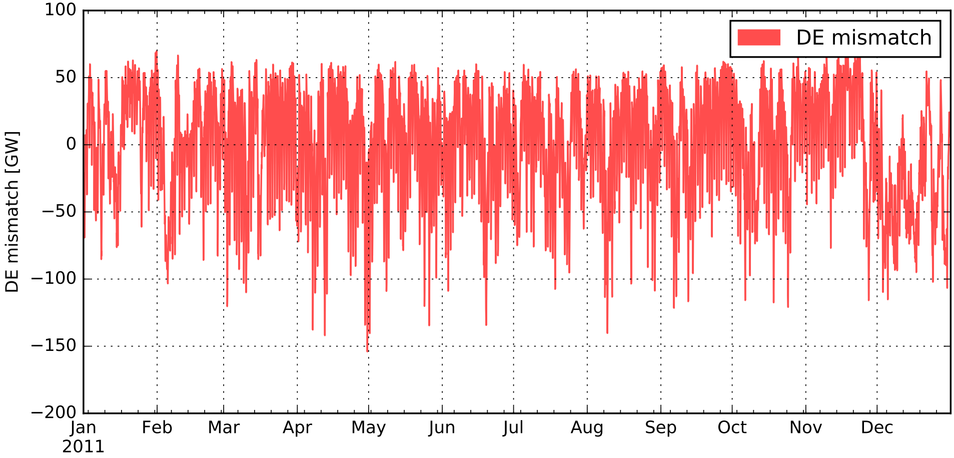
$$m_t = d_t - Ww_t - Ss_t$$

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

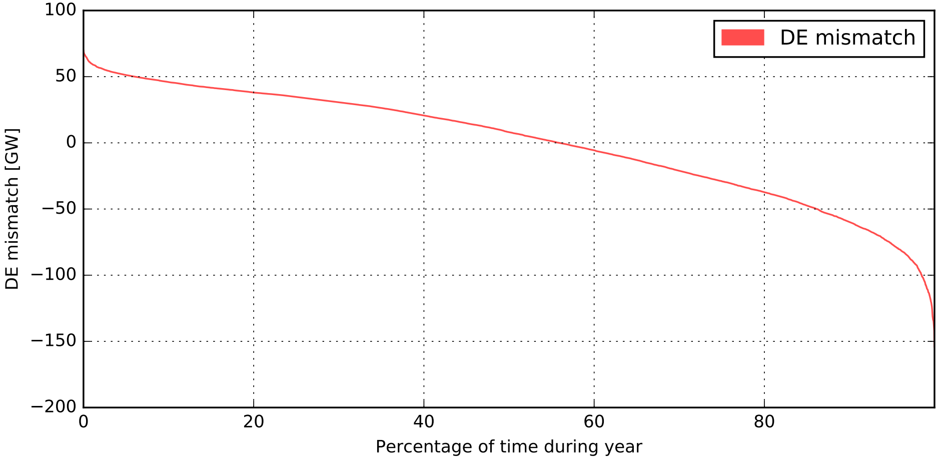
$$\langle m_t \rangle = 0$$

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

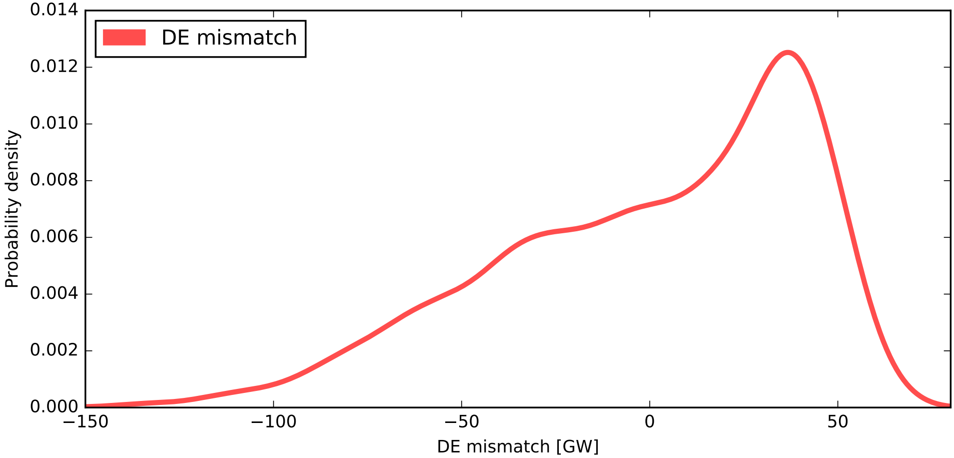
Mismatch time series



Mismatch duration curve

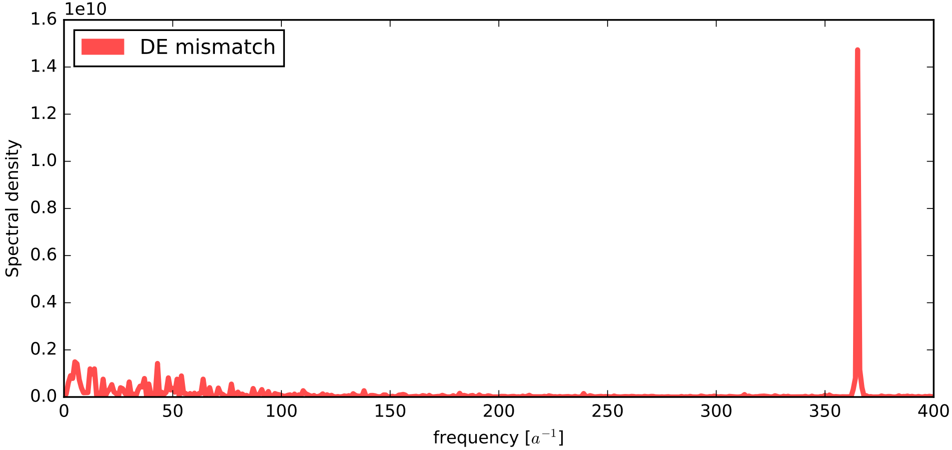


Mismatch density function



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

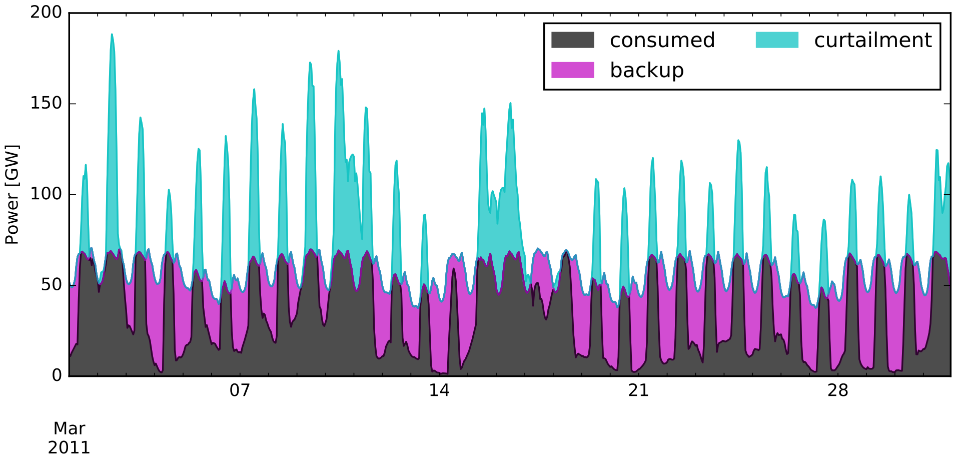
$$\langle m_t \rangle = 0$$

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

This means:

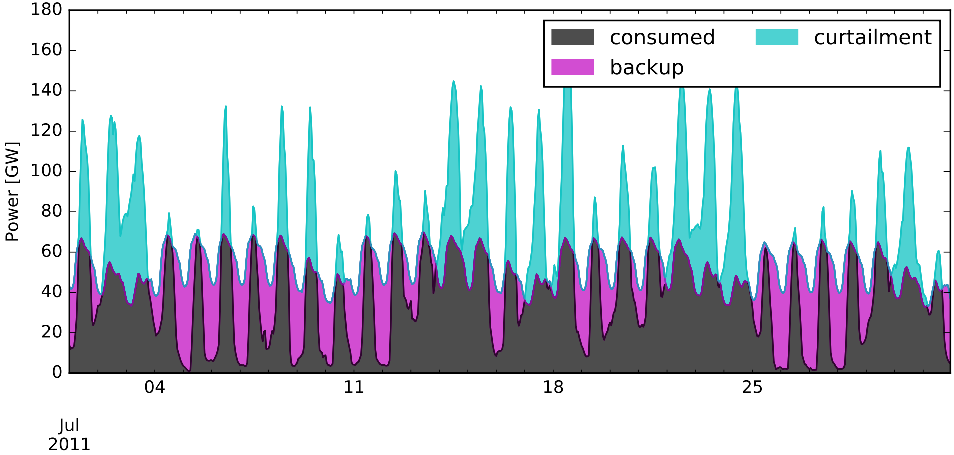
- If $m_t > 0$, i.e. we have unmet demand, then we need backup generation from **dispatchable** sources e.g. hydroelectricity reservoirs, fossil/biomass fuels.
- If $m_t < 0$, i.e. we have over-supply, then we have to shed / spill / **curtail** the renewable energy.

Mismatch



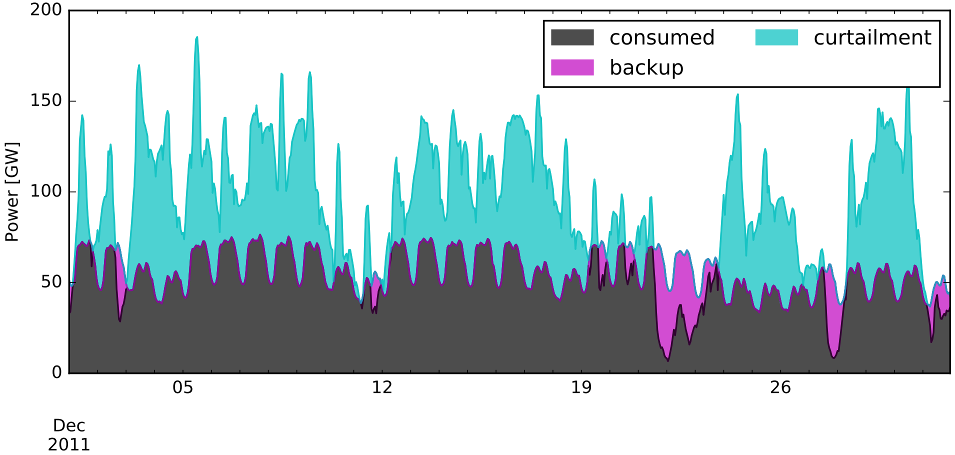
consumed
curtailment
backup
Power [GW]
200
150
100
50
0
07
14
21
28
Mar
2011

Mismatch



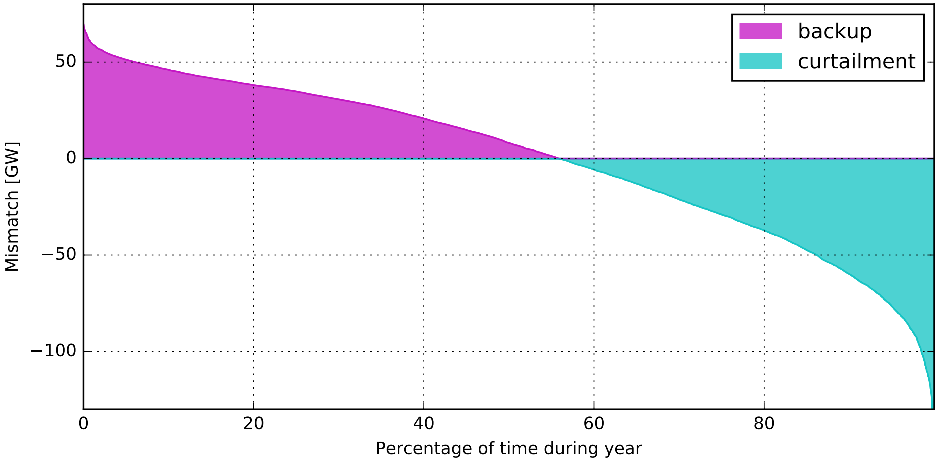
consumed
curtailment
backup
Power [GW]
180
160
140
120
100
80
60
40
20
0
04
11
18
25
Jul
2011

Mismatch



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

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 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).