Energy System Modelling
Summer Semester 2018, Lecture 1

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

11th July 2018

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Administration

Contact Details

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`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

The course will take place over five days: 11.7, 13.7, 16.7, 17.7 and 18.7.

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

09:45-11:15	Lecture 1
11:30-13:00	Lecture 2
14:00-15:30	Exercise Class
15:45-17:15	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: 50.41 Raum 145/146

Course Website

You can find the course website here:

`https://nworbmot.org/courses/esm-2018/`

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 August on a single date. The date will be decided during the final lecture, based on when we are all available.

MA Thesis: Industrial Demand in a Fossil-Free European Energy System

We have some exciting opportunities in the Energy System Modelling group at IAI to look at the integration of industrial demand and emissions in our European energy system model.

See the advert:

`https://nworbmot.org/courses/esm-2018/esm-ma-bio-industry.pdf`

Objectives:

- Collect sustainable biomass potentials for each European country by fuel type (forest residues, agricultural residues, municipal waste, etc.) based on existing sources.
- Collect energy use and emissions per country per industry from standard statistical sources.
- Build the different energy pathways into an existing model of the European energy system.
- Simulate the optimal mix of energy sources and technologies to eliminate CO2 emissions from the industrial sector.

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

Course outline

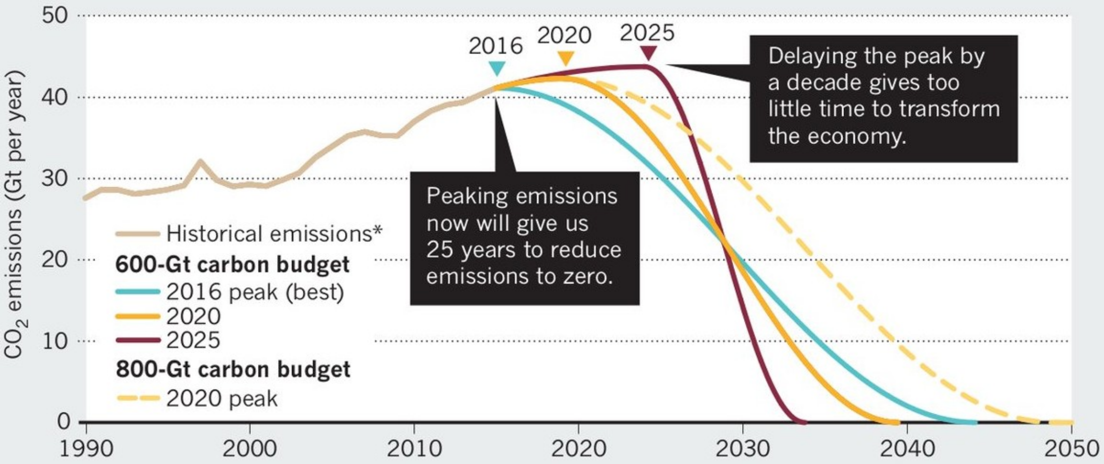
This course will cover the following topics:

- 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.)

Introduction: Balancing Variable Renewable Energy

The Global Carbon Dioxide Challenge: Budgets from 2016

600 Gt budget gives 33% chance of 1.5°C (Paris: ‘pursue efforts to limit [warming] to 1.5°C’)
800 Gt budget gives 66% chance of 2°C (Paris: hold ‘the increase...to well below 2°C’)

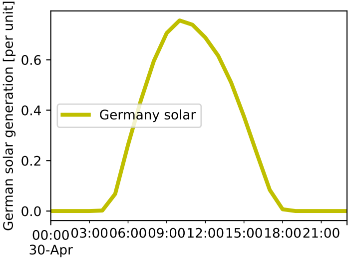


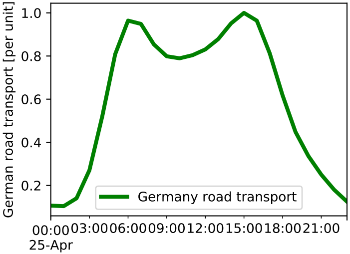
Source: ‘Three years to safeguard our climate,’ Nature, 2017

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?

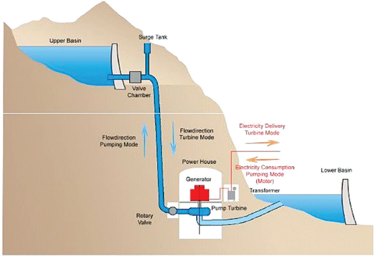
Daily variations: challenges and solutions



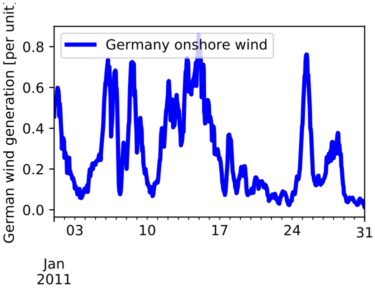


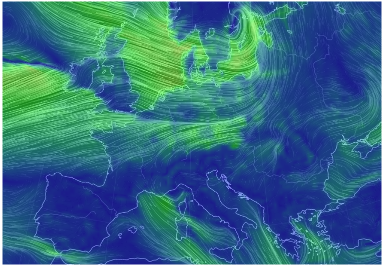
Daily variations in supply and demand can be balanced by

- **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**



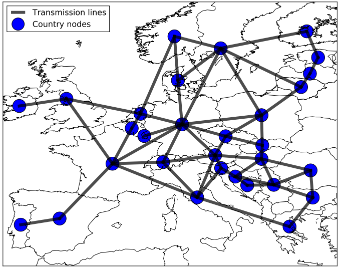
Synoptic variations: challenges and solutions



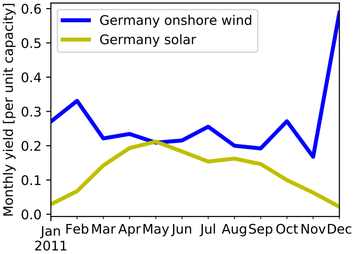


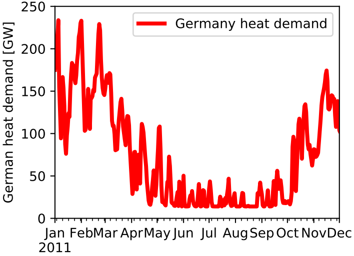
Synoptic variations in supply and demand can be balanced by

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



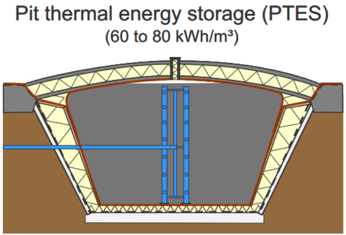
Seasonal variations: challenges and solutions





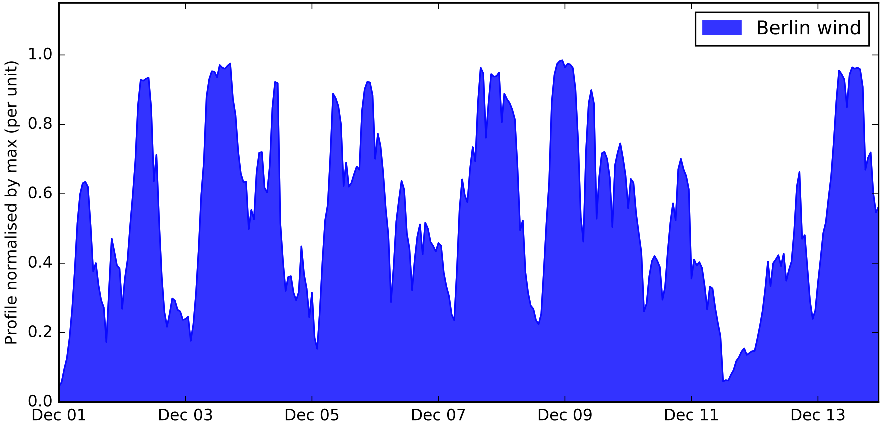
Seasonal variations in supply and demand can be balanced by

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



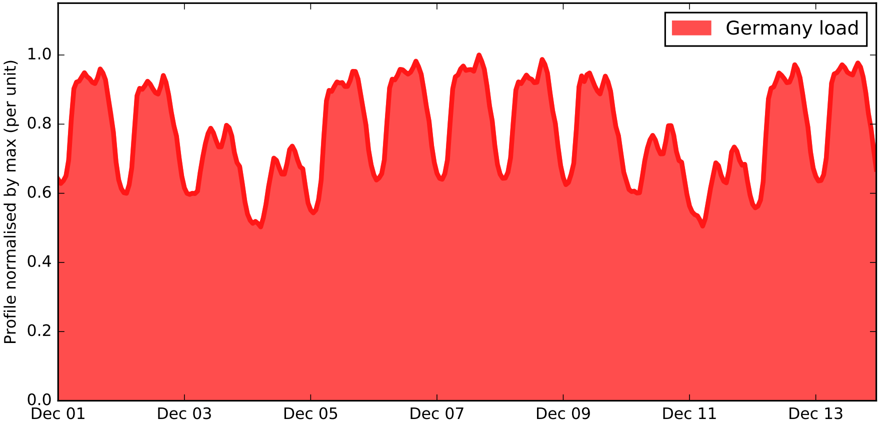
Variability: Single wind site in Berlin

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.



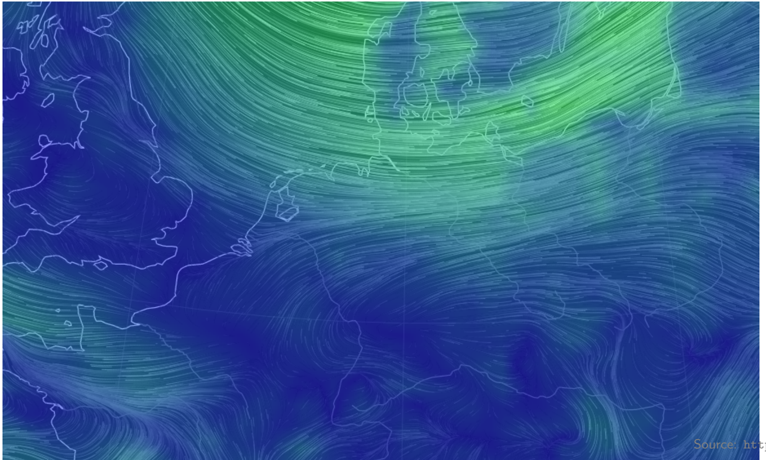
Electricity consumption is much more regular

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

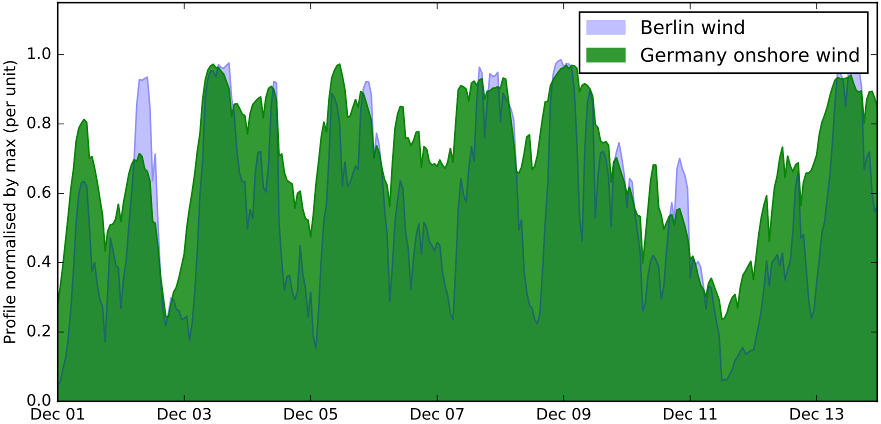
But the wind does not blow the same at every site at every time: at a given time there are a variety of wind conditions across Germany. These differences **balance out over time and space**.



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

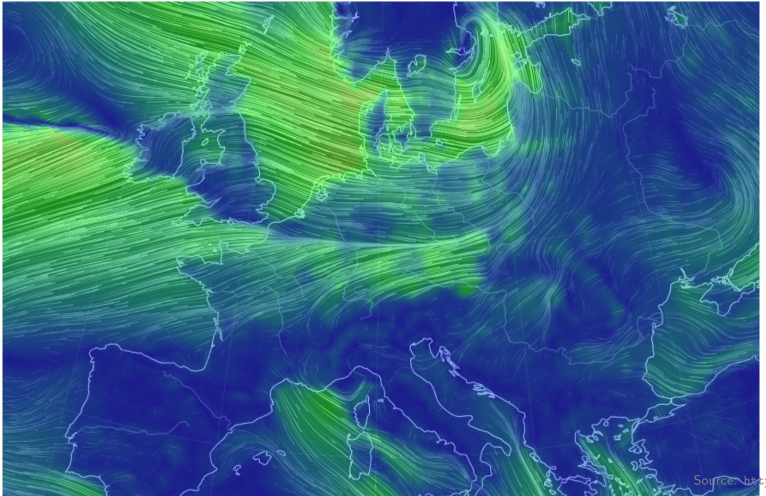
Variability: Single country: Germany

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

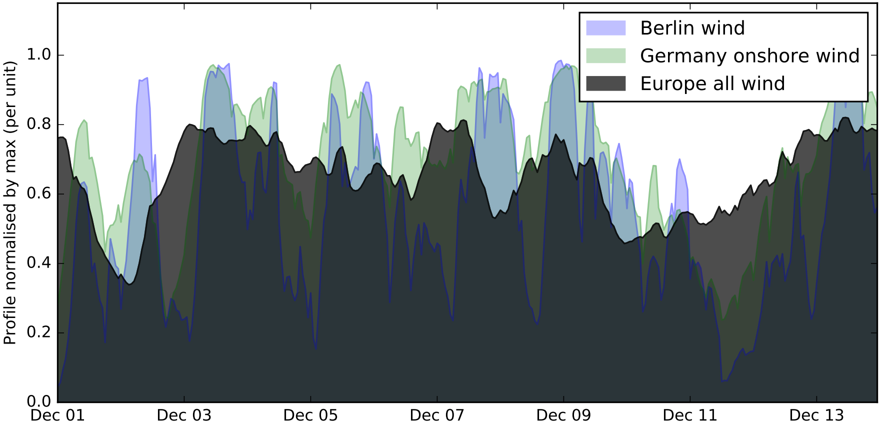
The scale of the weather systems are bigger than countries, so to leverage the full smoothing effects, you need to integrate wind at the **continental scale**.



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

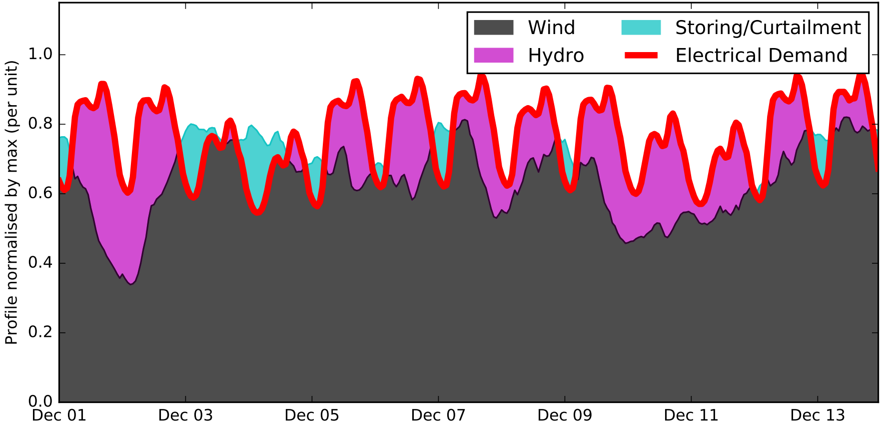
Variability: A continent: Europe

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.



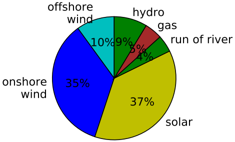
Variability: A continent: Wind plus Hydro

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.

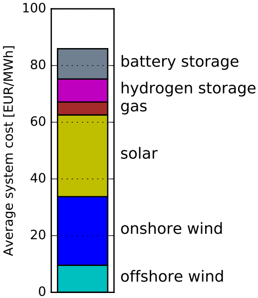


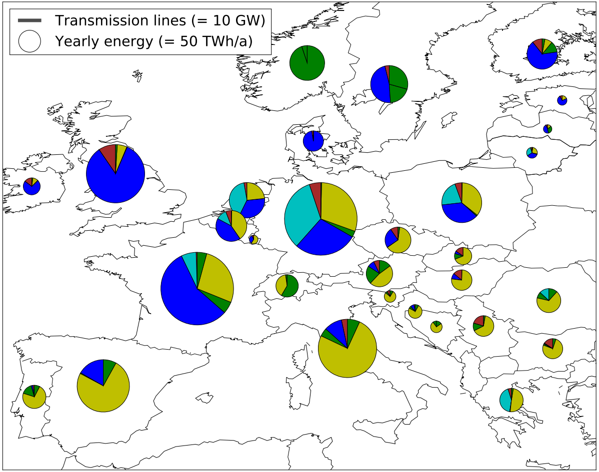
Costs: No interconnecting transmission allowed

Technology by energy:



Average cost **€86/MWh**:

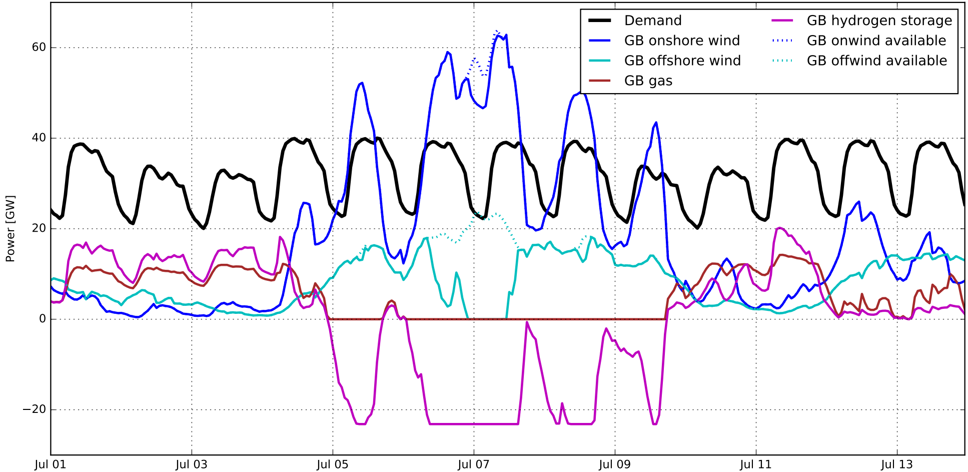




Countries must be self-sufficient at all times; lots of storage and some gas to deal with fluctuations of wind and solar.

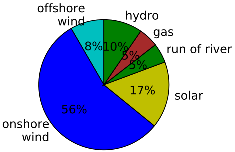
Dispatch with no interconnecting transmission

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

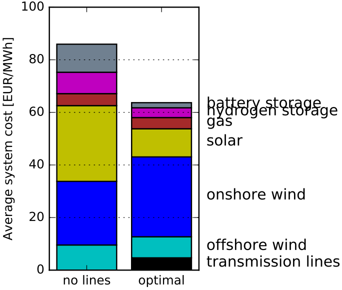


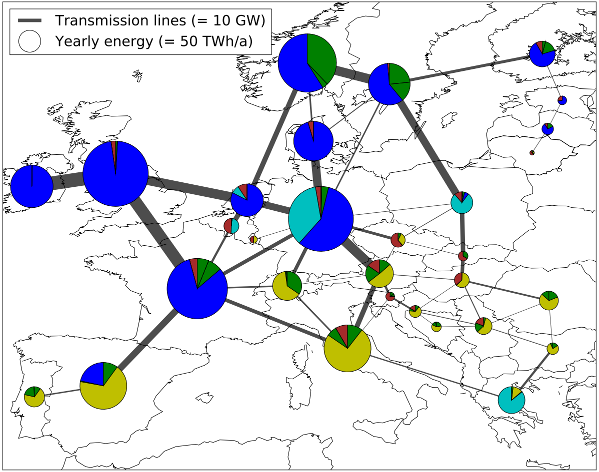
Costs: Cost-optimal expansion of interconnecting transmission

Technology by energy:



Average cost **€64/MWh**:

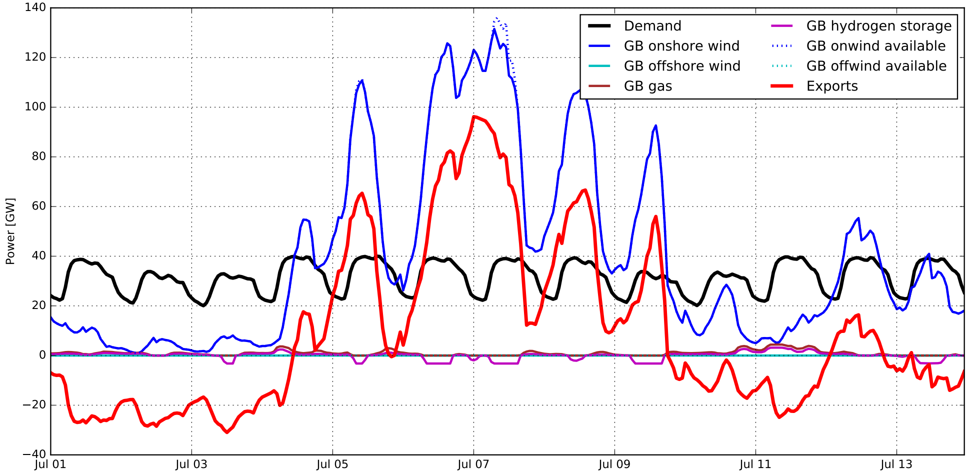




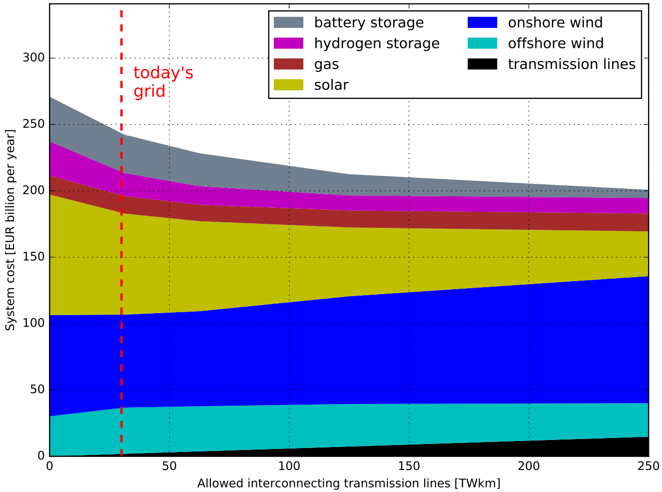
Large transmission expansion; onshore wind dominates. This optimal solution may run into public acceptance problems.

Dispatch with cost-optimal interconnecting transmission

Almost all excess wind can be now be exported:

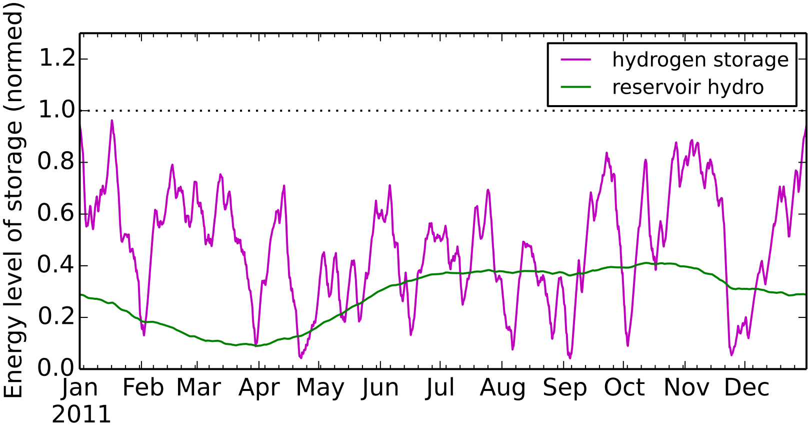


Electricity Only Costs Comparison



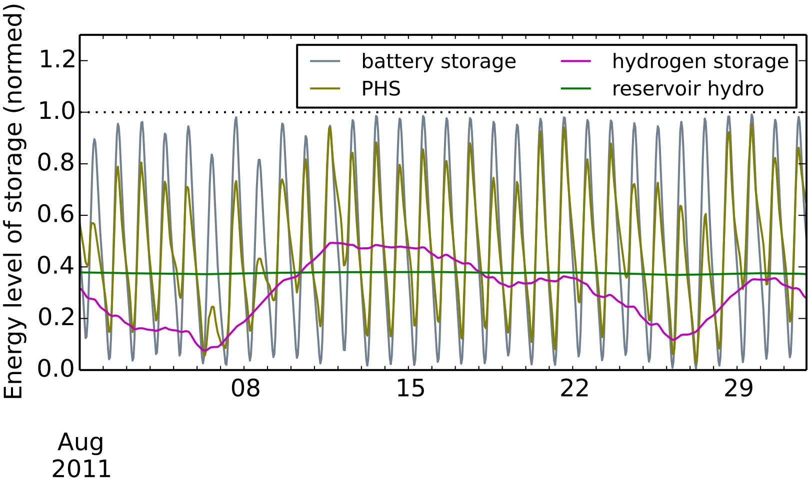
- Average total system costs can be as low as € 64/MWh
- Energy is dominated by wind (64% for the cost-optimal system), followed by hydro (15%) and solar (17%)
- Restricting transmission results in more storage to deal with variability, driving up the costs by up to 34%
- Many benefits already locked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

Different flexibility options have difference temporal scales



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

Different flexibility options have difference temporal scales



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

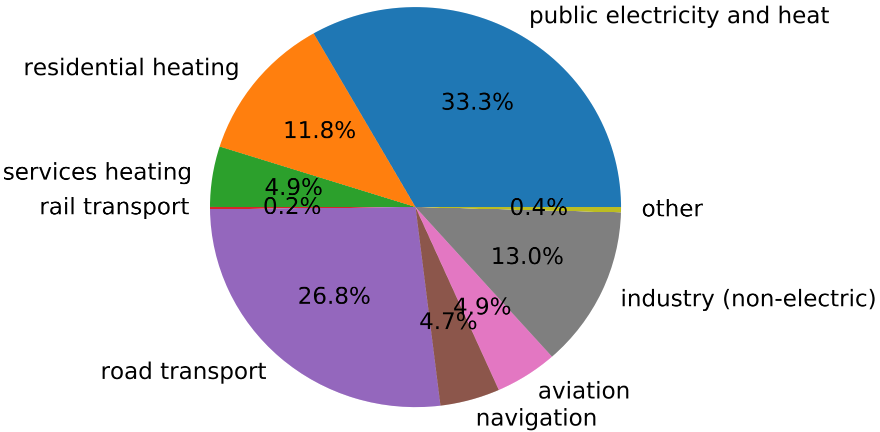
Features of this example

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.

It's not just about electricity demand...

EU28 CO_2 emissions in 2015 (total 3.2 Gt CO_2, 8% of global):



Source: Brown, data from EEA

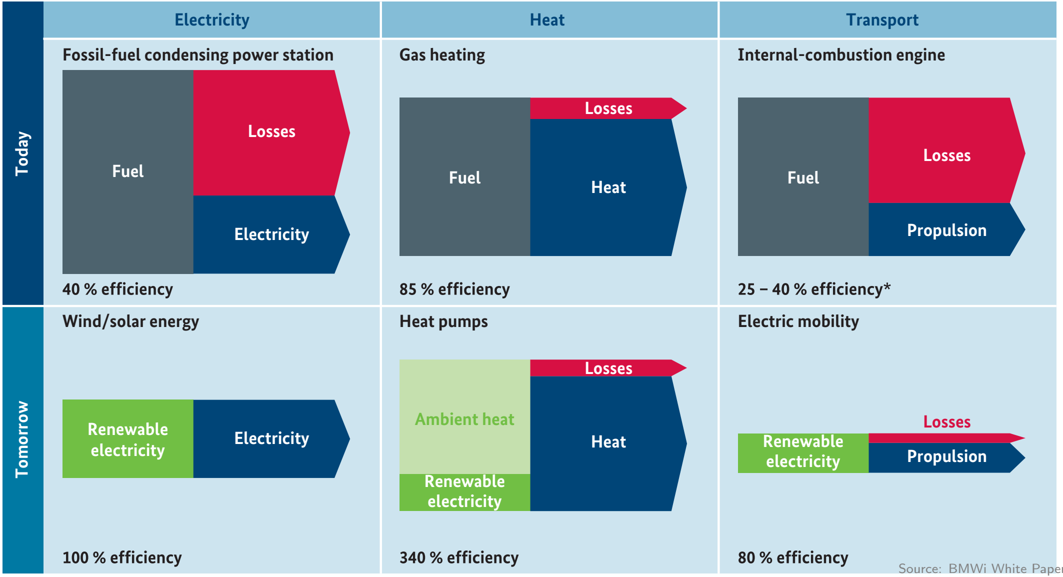
...but electification of other sectors is critical for decarbonisation

Wind and solar dominate the expandable potentials for low-carbon energy provision, so **electrification is essential** to decarbonise sectors such as transport and heating.

Fortunately, these sectors can also offer crucial **flexibility** back to the electricity system.

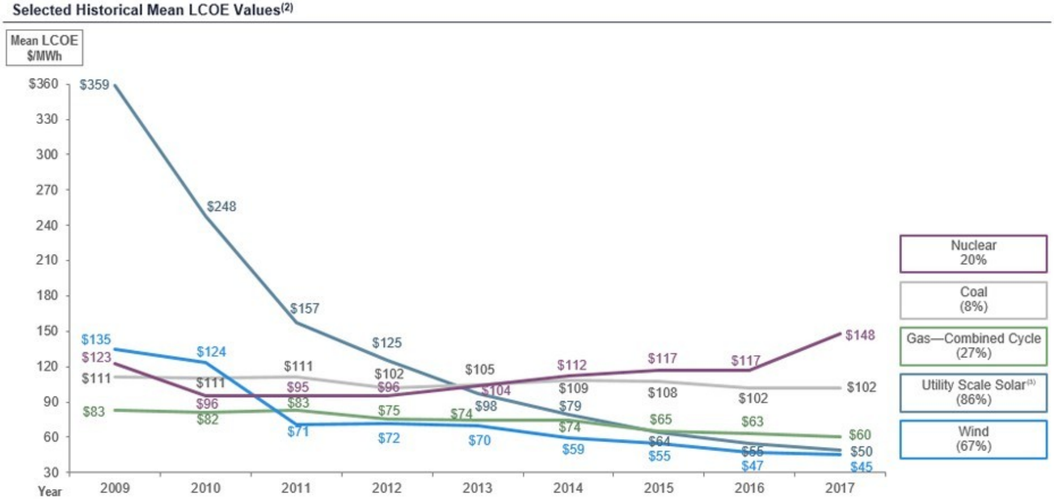
Source: Tesla; heat pump: Kristoferb at English Wikipedia

Efficiency of renewables and sector coupling



Source: BMWi White Paper 2015

Low cost of renewable energy 2017 (NB: ignores variability)



Source: Lazard's LCOE Analysis V11

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

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.

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

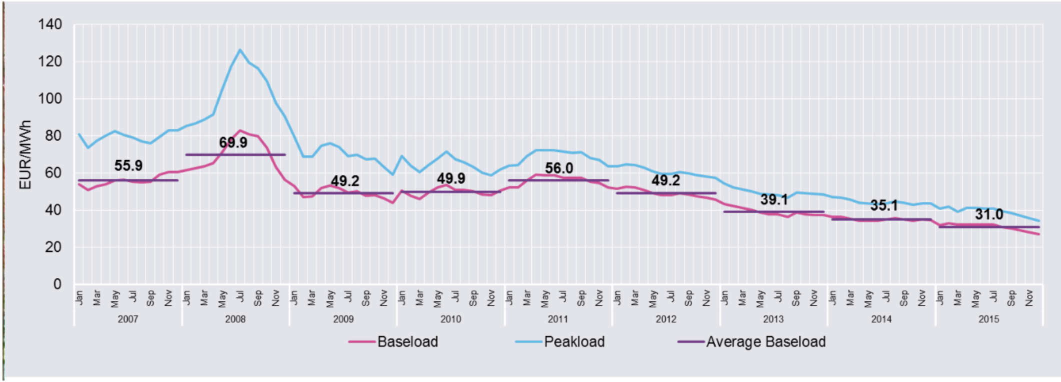
10 W * 2 h = 20 Wh

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**:



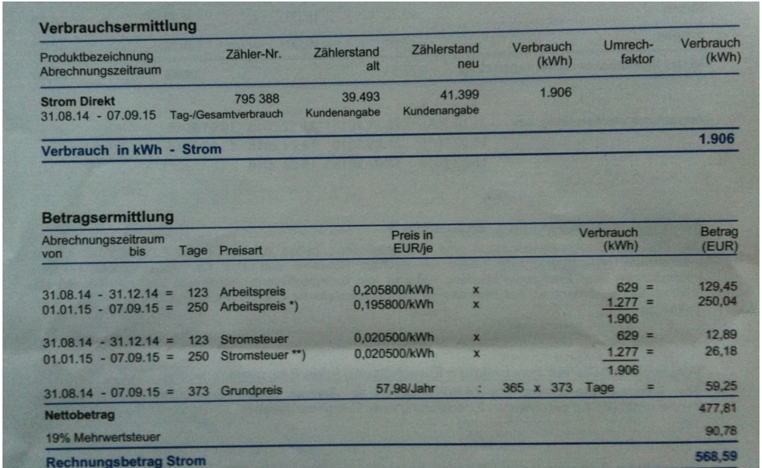
Source: Agora Energiewende

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

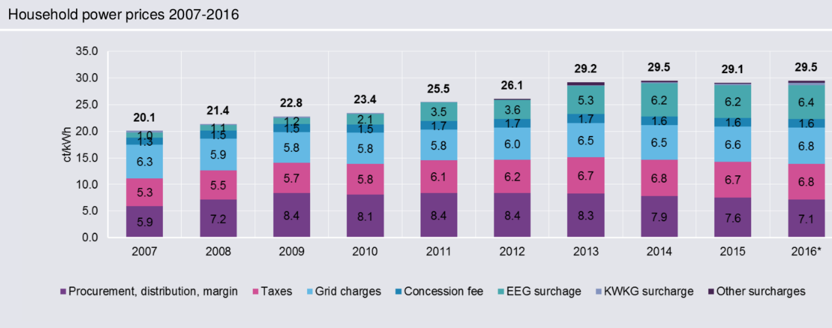
Produktbezeichnung Abrechnungszeitraum	Zähler-Nr.	Zählerstand alt	Zählerstand neu	Verbrauch (kWh)	Umrech-faktor	Verbrauch (kWh)
Strom Direkt 31.08.14 - 07.09.15	795 388 Tag-/Gesamtverbrauch	39.493 Kundenangabe	41.399 Kundenangabe	1.906		
Verbrauch in kWh - Strom						**1.906**

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.



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

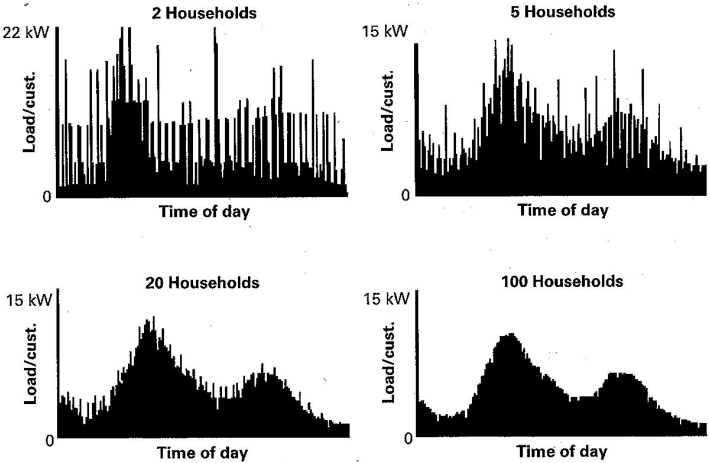
Germany consumes around 600 TWh per year, written 600 TWh/a.

What is the *average* power consumption?

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

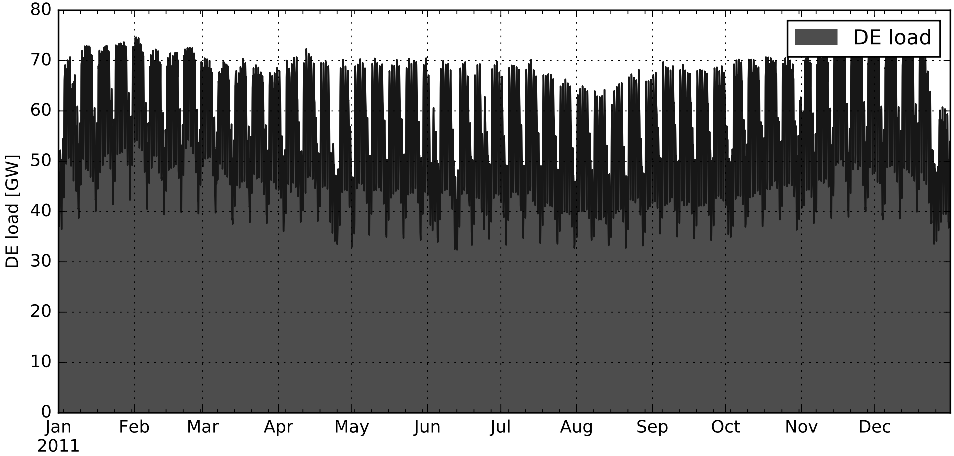
Discrete Consumers Aggregation

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



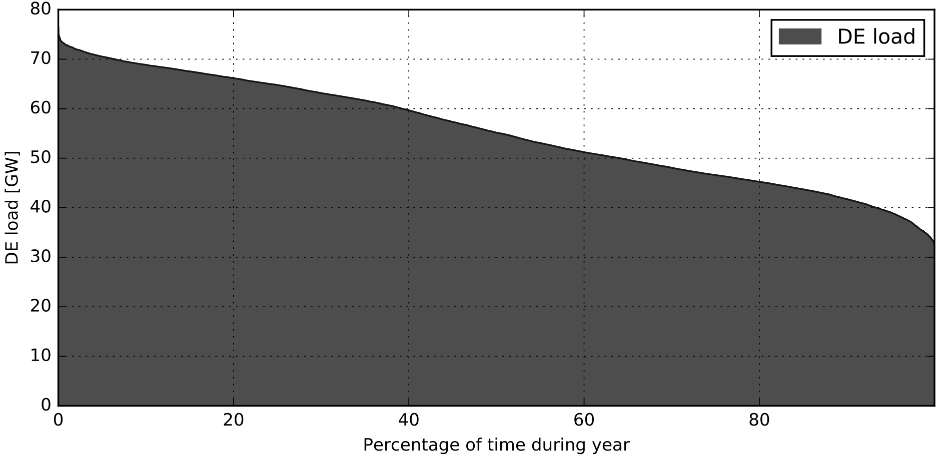
Load curve properties

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



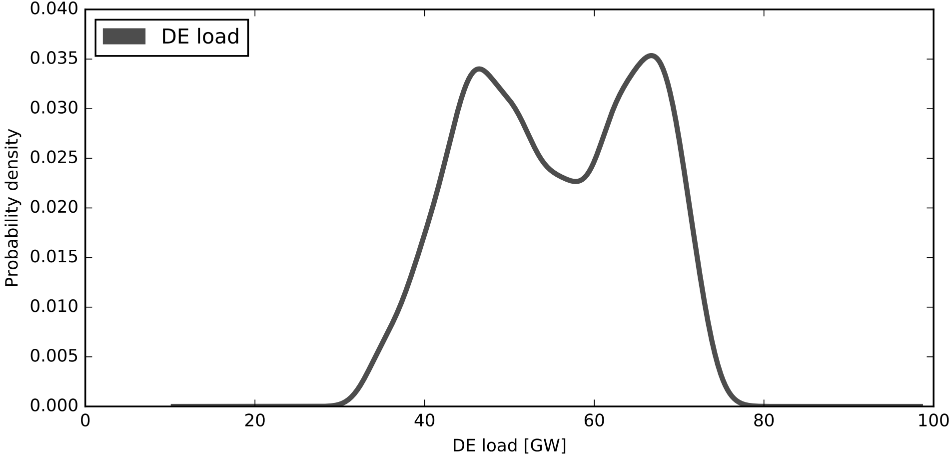
Load duration curve

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



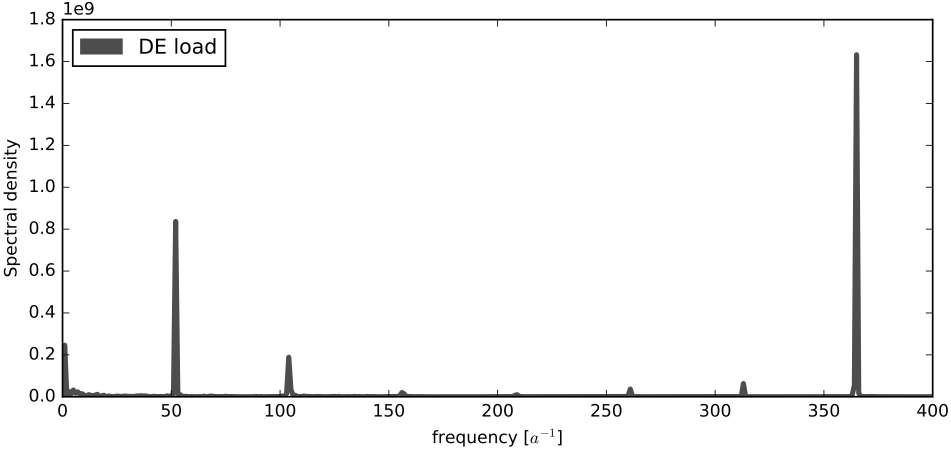
Load density function

Similarly we can also build the probability density function:



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.

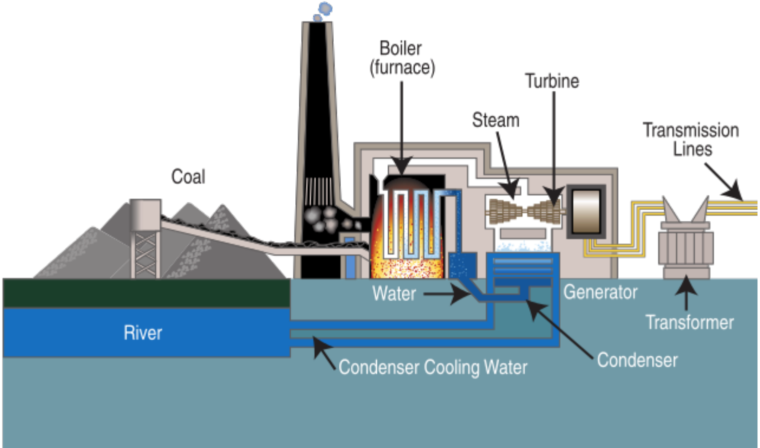
Power: Examples of generation

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

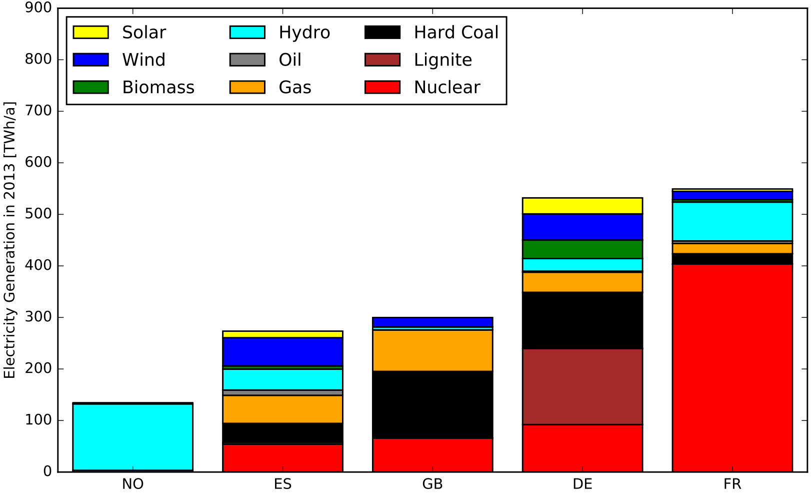
Generators

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*.



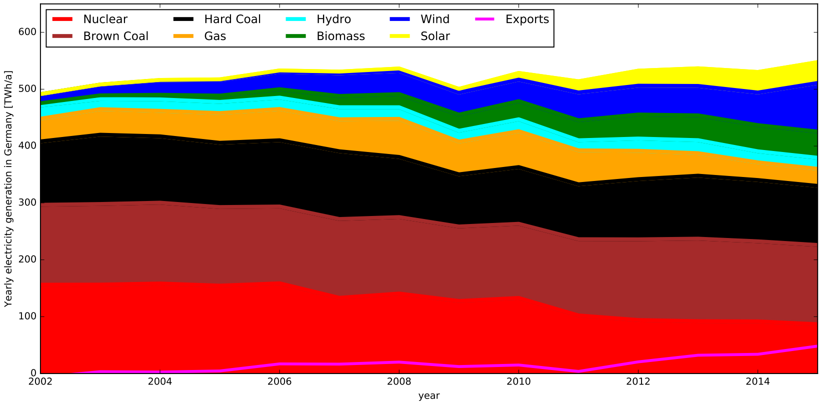
Source: Wikipedia

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 $\mathrm{MWh}_{\mathrm{th}}$, 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	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 €/$\mathrm{MWh_{th}}$.

Using the efficiency, we can convert this to €/$\mathrm{MWh_{el}}$.

Fuel	Per unit efficiency $\mathrm{MWh_{el}/MWh_{th}}$	Cost per thermal €/$\mathrm{MWh_{th}}$	Cost per elec. €/$\mathrm{MWh_{el}}$
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.

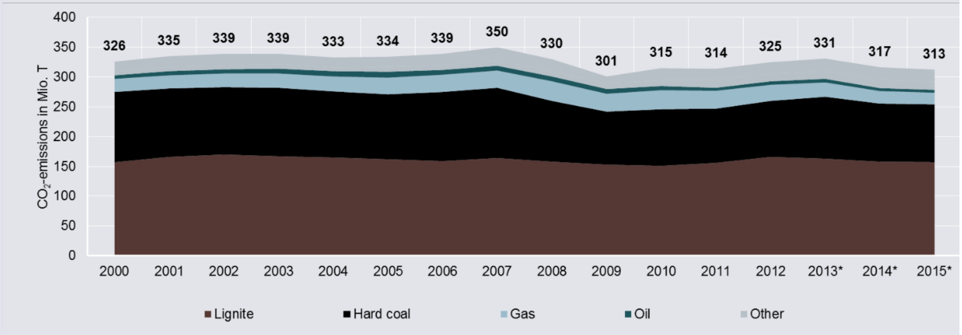
Fuel	t_{CO2}/t	t_{C02}/MWh_{th}	t_{CO2}/MWh_{el}
Lignite	0.9	0.36	0.9
Hard Coal	2.4	0.36	0.8
Gas	3.1	0.2	0.5
Uranium	0	0	0

Current CO_2 price in EU Emissions Trading Scheme (ETS) is around €16/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



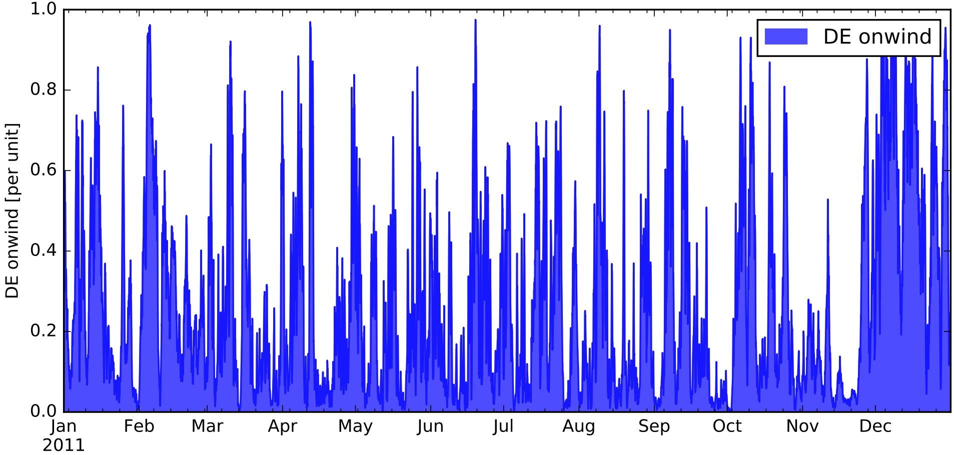
UBA 2015a; * own calculations

Source: Agora Energiewende

Variable Renewable Energy (VRE)

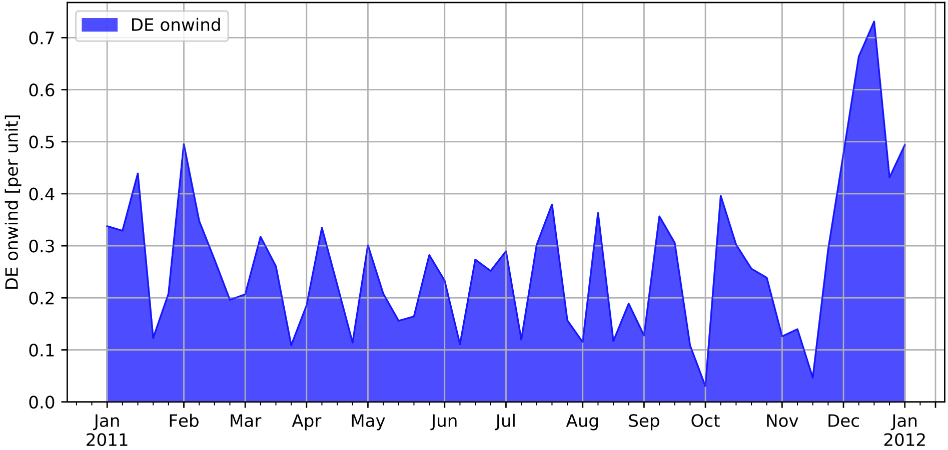
Wind time series

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).

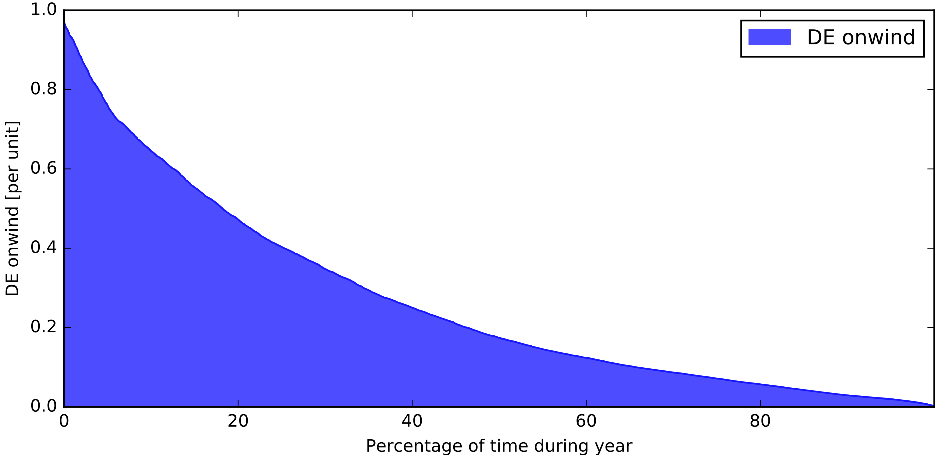


Wind time series: weekly

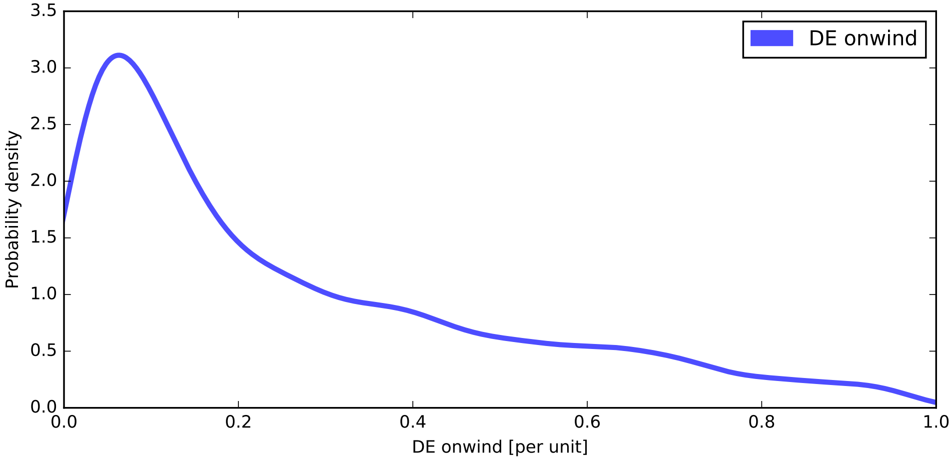
If we take a weekly average we see higher wind in the winter and some periodic patterns over 2-3 weeks (**synoptic scale**).



Wind duration curve

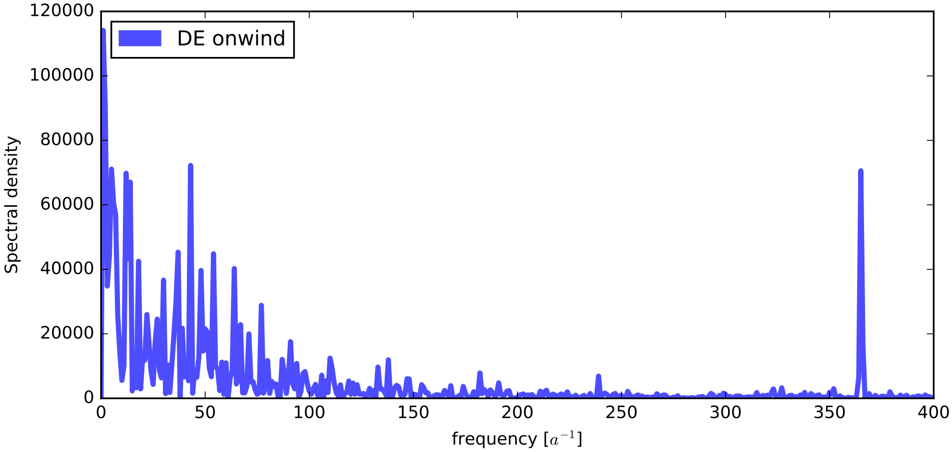


Wind density function



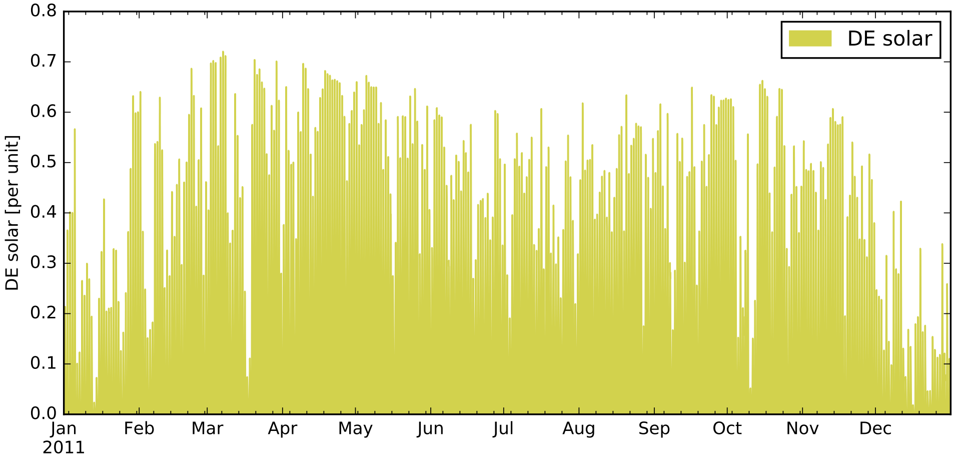
Wind spectrum

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



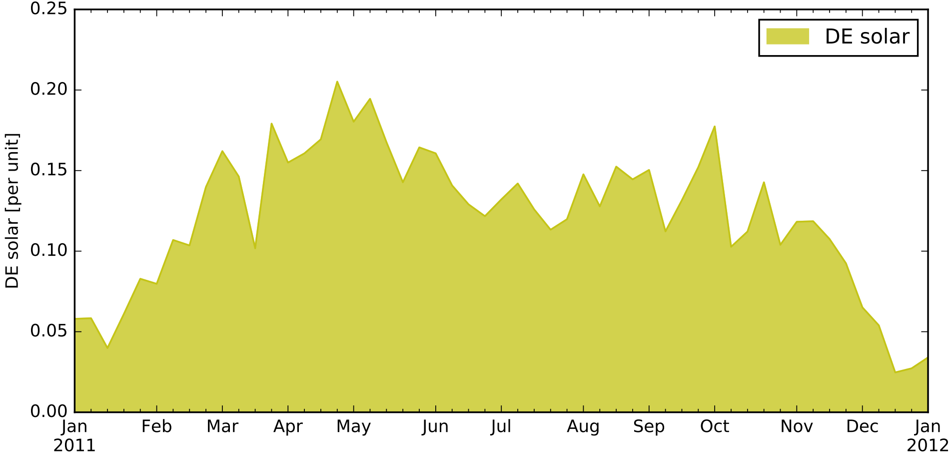
Solar time series

Solar is variable, but more predictable than wind.

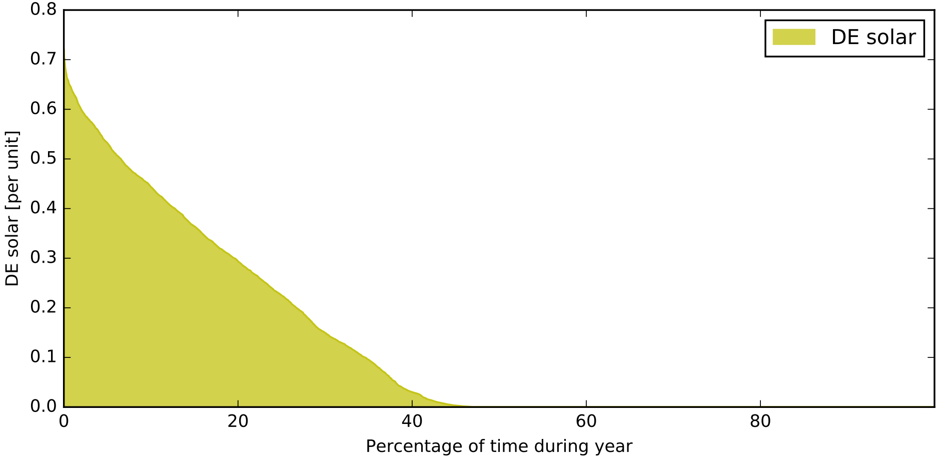


Solar time series: weekly

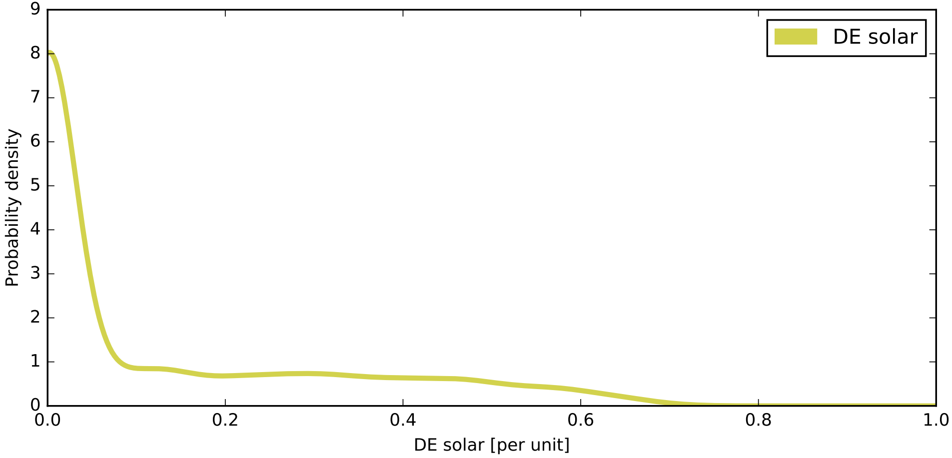
If we take a weekly average we see higher solar in the summer.



Solar duration curve

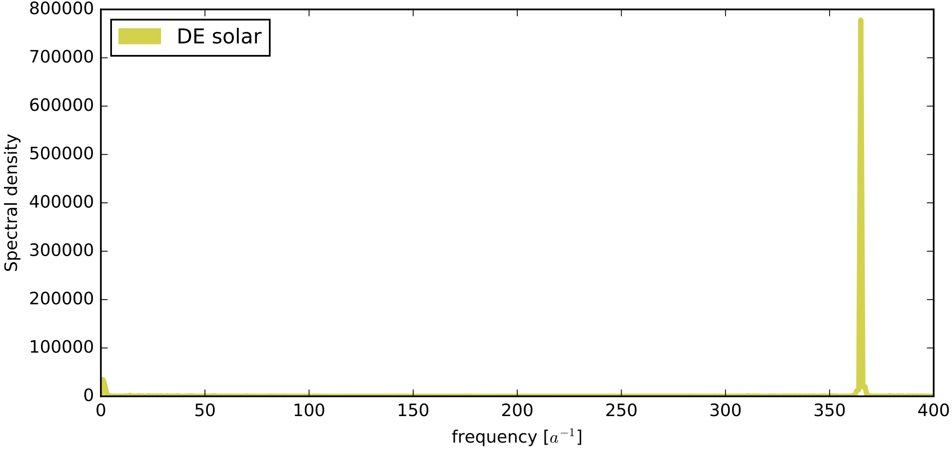


Solar density function



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:

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

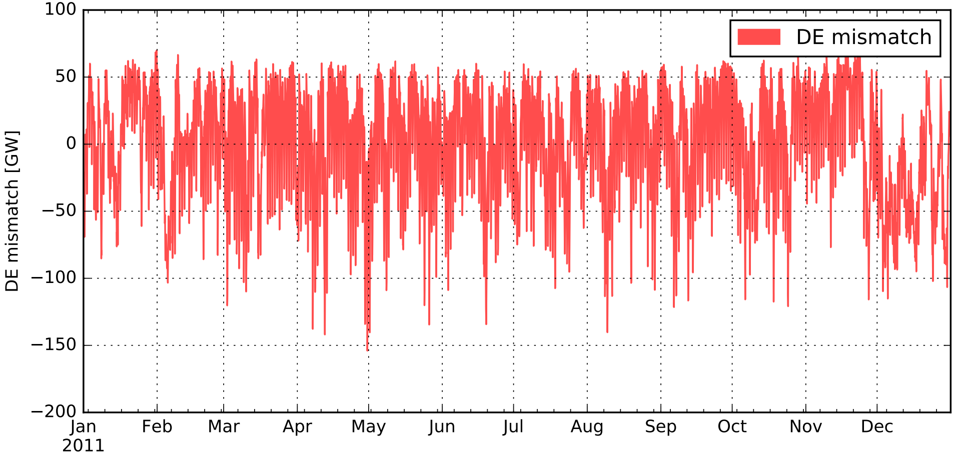
$$m_t = d_t - Ww_t - Ss_t$$

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

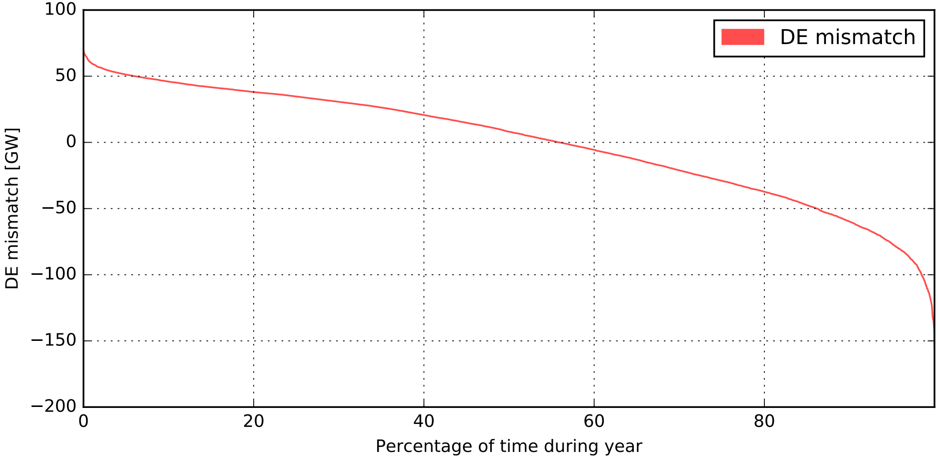
$$\langle m_t \rangle = 0$$

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

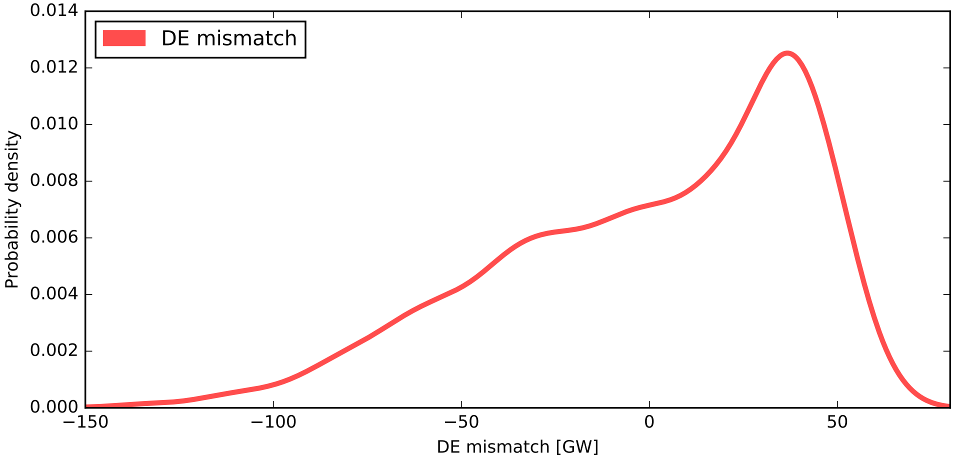
Mismatch time series



Mismatch duration curve

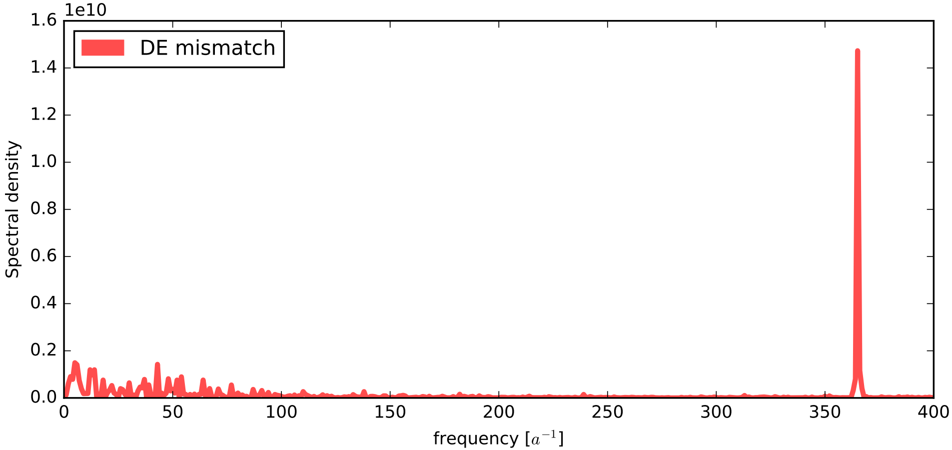


Mismatch density function



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

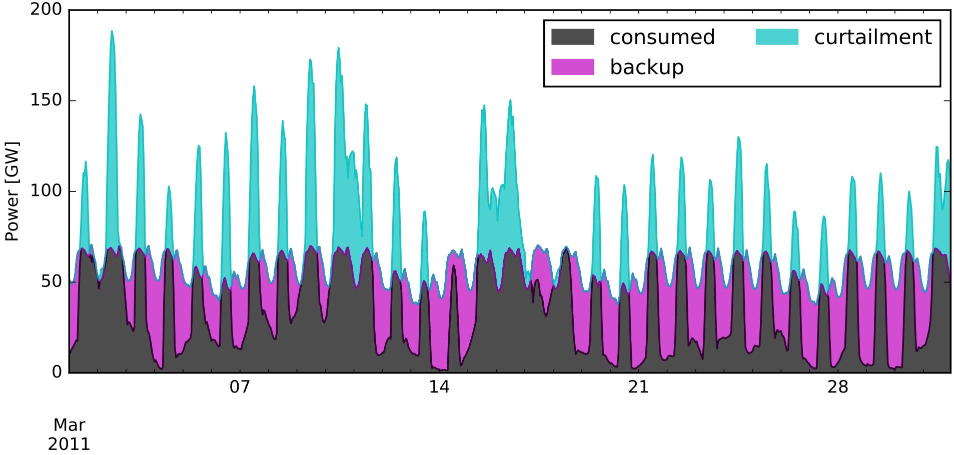
$$\langle m_t \rangle = 0$$

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

This means:

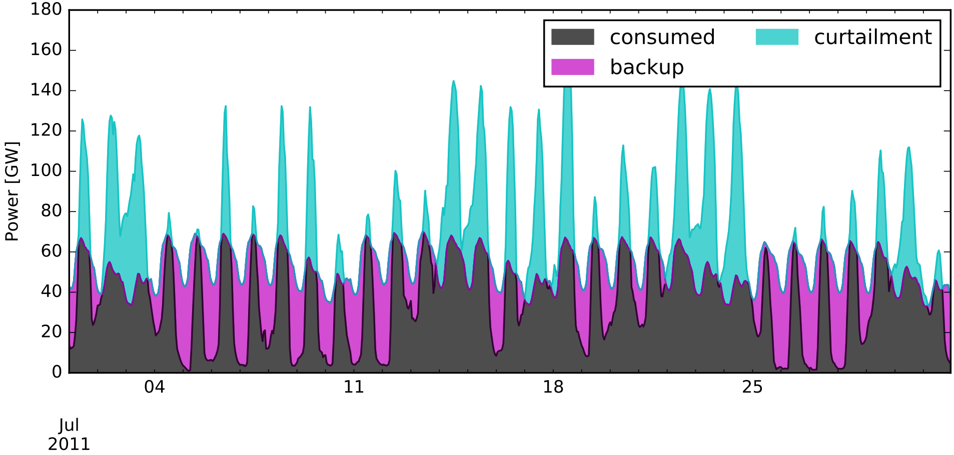
- If $m_t > 0$, i.e. we have unmet demand, then we need backup generation from **dispatchable** sources e.g. hydroelectricity reservoirs, fossil/biomass fuels.
- If $m_t < 0$, i.e. we have over-supply, then we have to shed / spill / **curtail** the renewable energy.

Mismatch



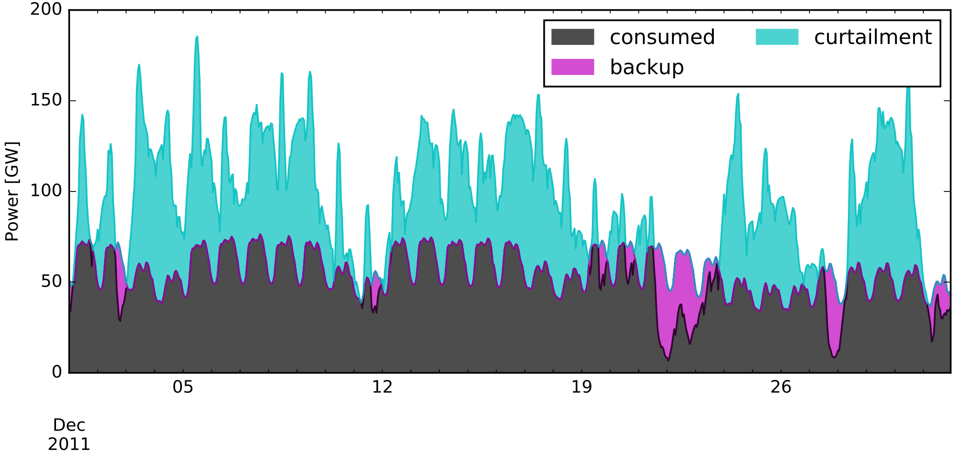
consumed
curtailment
backup
Power [GW]
200
150
100
50
0
07
14
21
28
Mar
2011

Mismatch



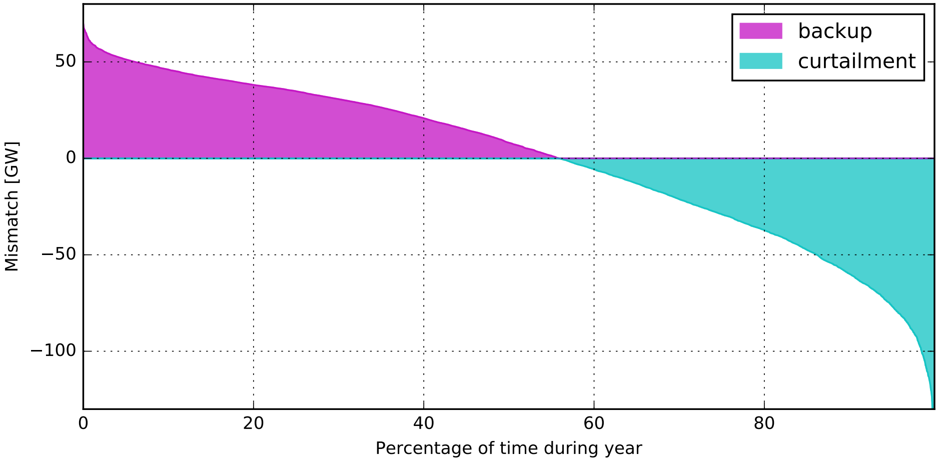
consumed
curtailment
backup
Power [GW]
180
160
140
120
100
80
60
40
20
0
04
11
18
25
Jul
2011

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 4 solutions:

1. Smoothing stochastic variations of renewable feed-in over larger areas, e.g. the whole of Europe.
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.