# Integration of variable electricity sources



F. Wagner, Max-Planck-Institut für Plasmaphysik, Greifswald/Garching

## Out of environmental reasons:
## Transformation of the energy system

Today: PE: chemical ➡ Mechanical energy (transport)
Electricity
Heat

Future: PE: electrical ➡ Chemical energy (storage)
Heat (heat pump)
Electricity → transport

# Energy production by variable sources



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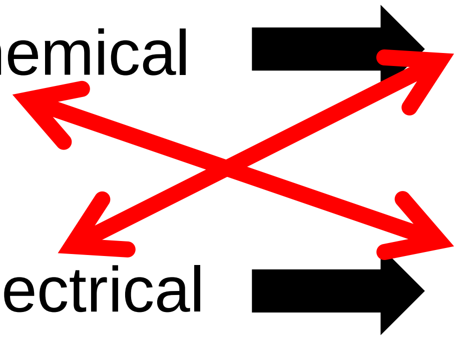
## Out of environmental reasons:
## Transformation of the energy system

Today: PE: chemical

Future: PE: electrical



Mechanical energy (transport)
Electricity
Heat

Chemical energy (storage)
Heat (heat pump)
Electricity → transport

# Electricity consumption



**Germany:**

electricity production: 648 TWh (2016)
- internal needs of power stations
- transformation, transportation losses
- export

→ net electricity consumption: 540 TWh

per-capita: 6.6 MWh
corresponds to: 752 W

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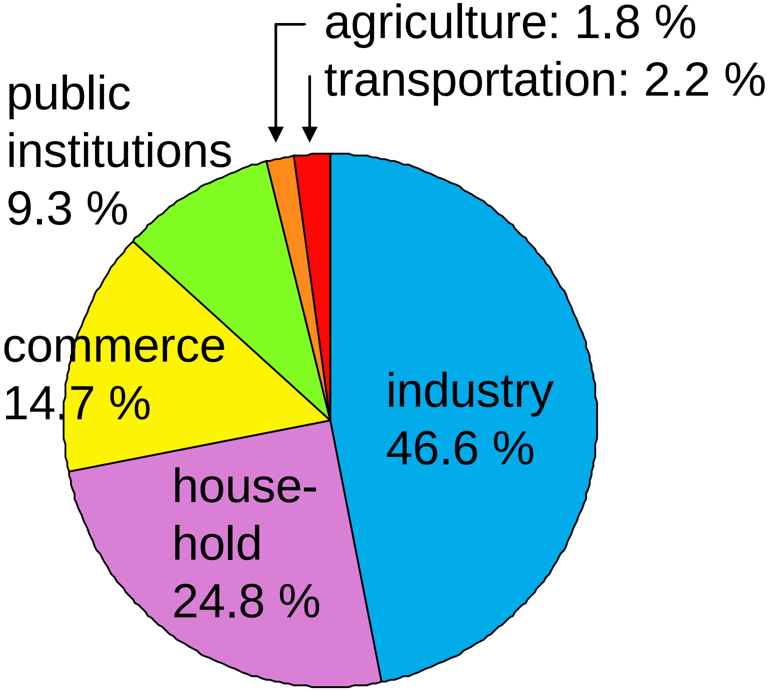
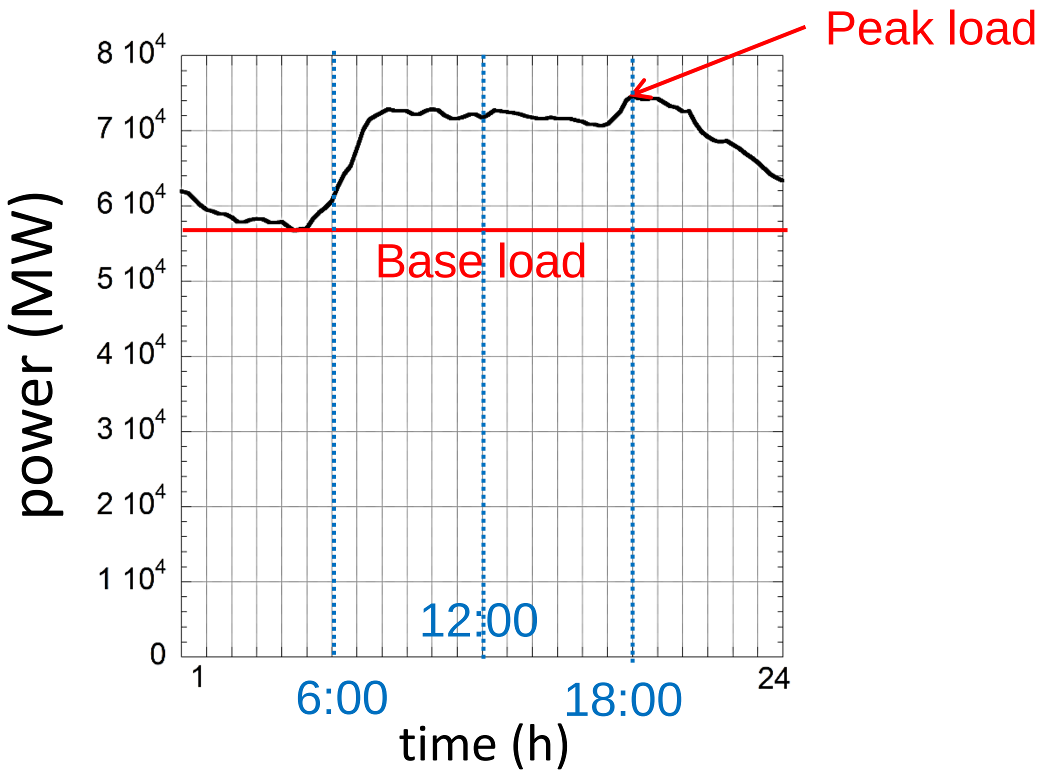


# Specifics of electricity consumption



Load variation during Tue 31.1.2012




Important:

Supply has to meet demand at every moment

It is not sufficient to talk on integral values of energy only

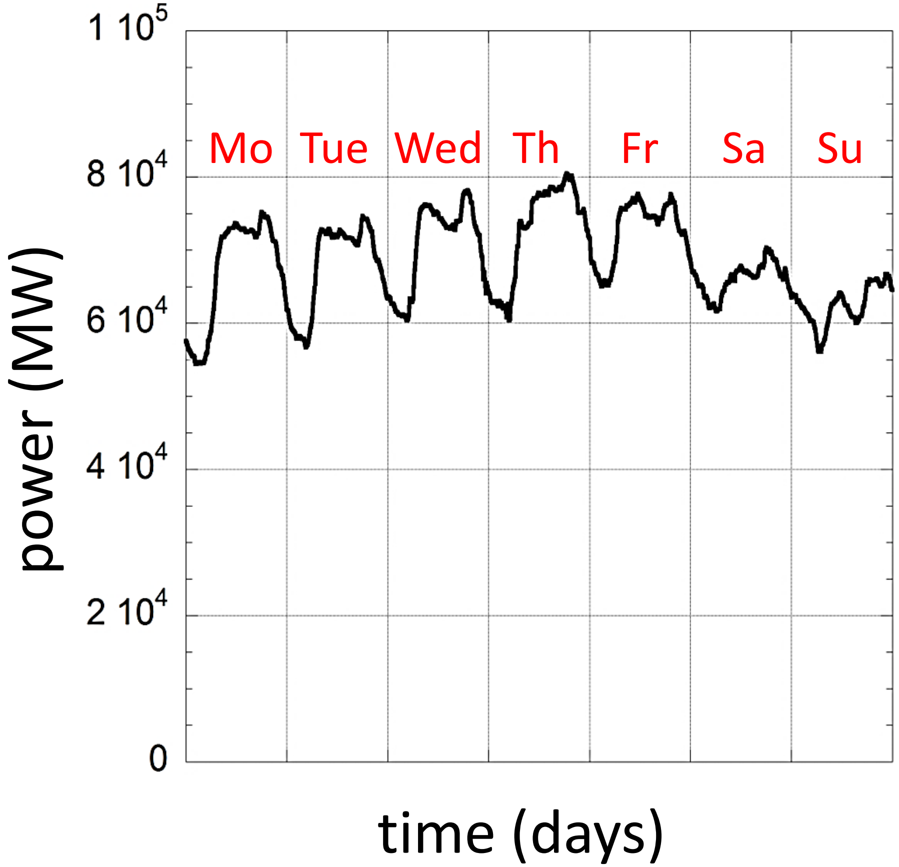
Consumption is very variable
e.g. cooking
needed: 3800 W for 2 hours
average in the day: 320 W

Time-resolved analysis is necessary

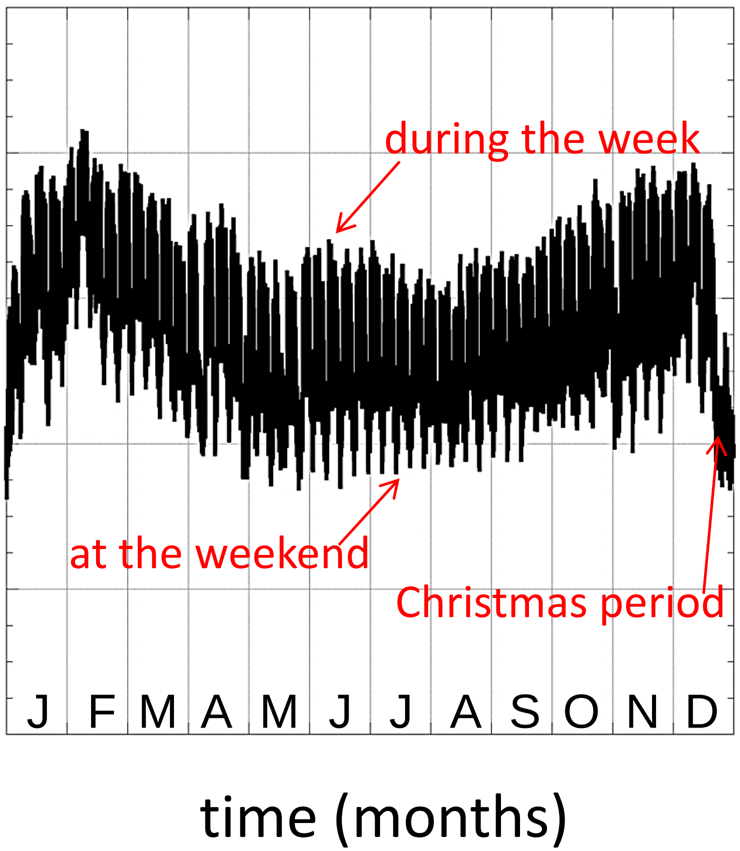
# Specifics of electricity consumption



## Load variation during the week

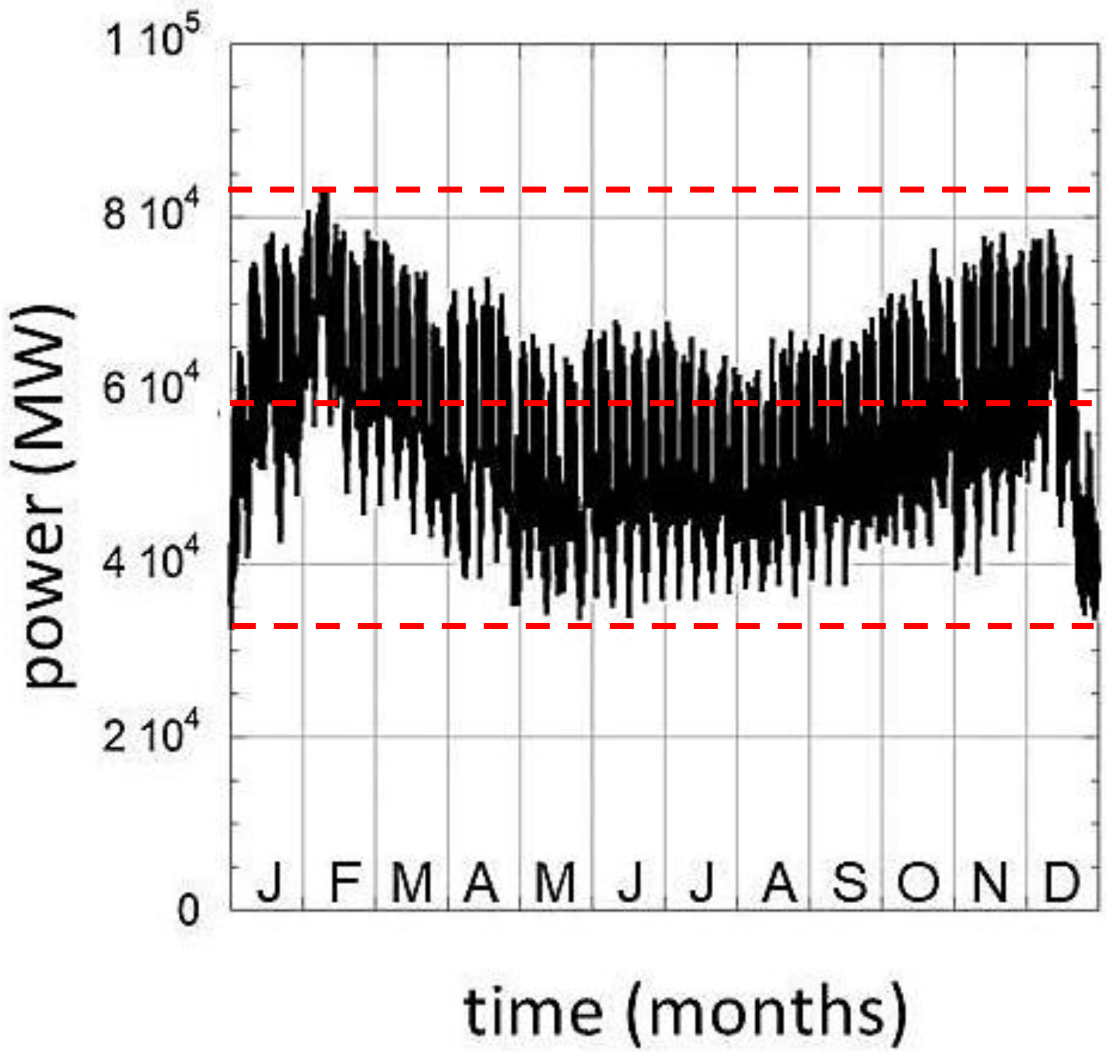



## Seasonal variation



# Descriptive parameters





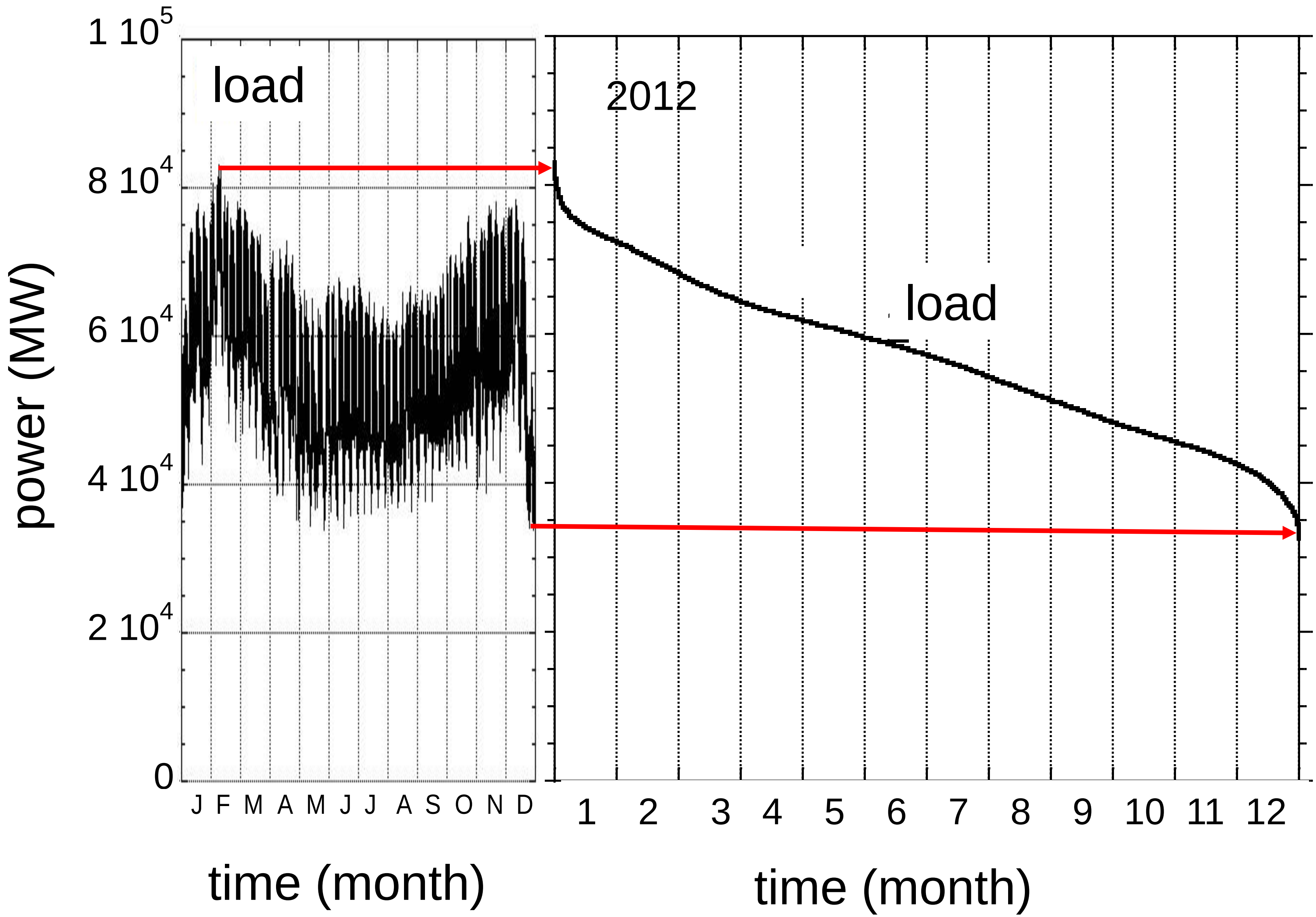

57 GW × 8760 h = 500 TWh
83 GW × 8760 h = 727 TWh

System use: 69%
= capacity factor

Full-load hours flh
$= 8760 \times \langle P \rangle / P_{max} = 6000$ h

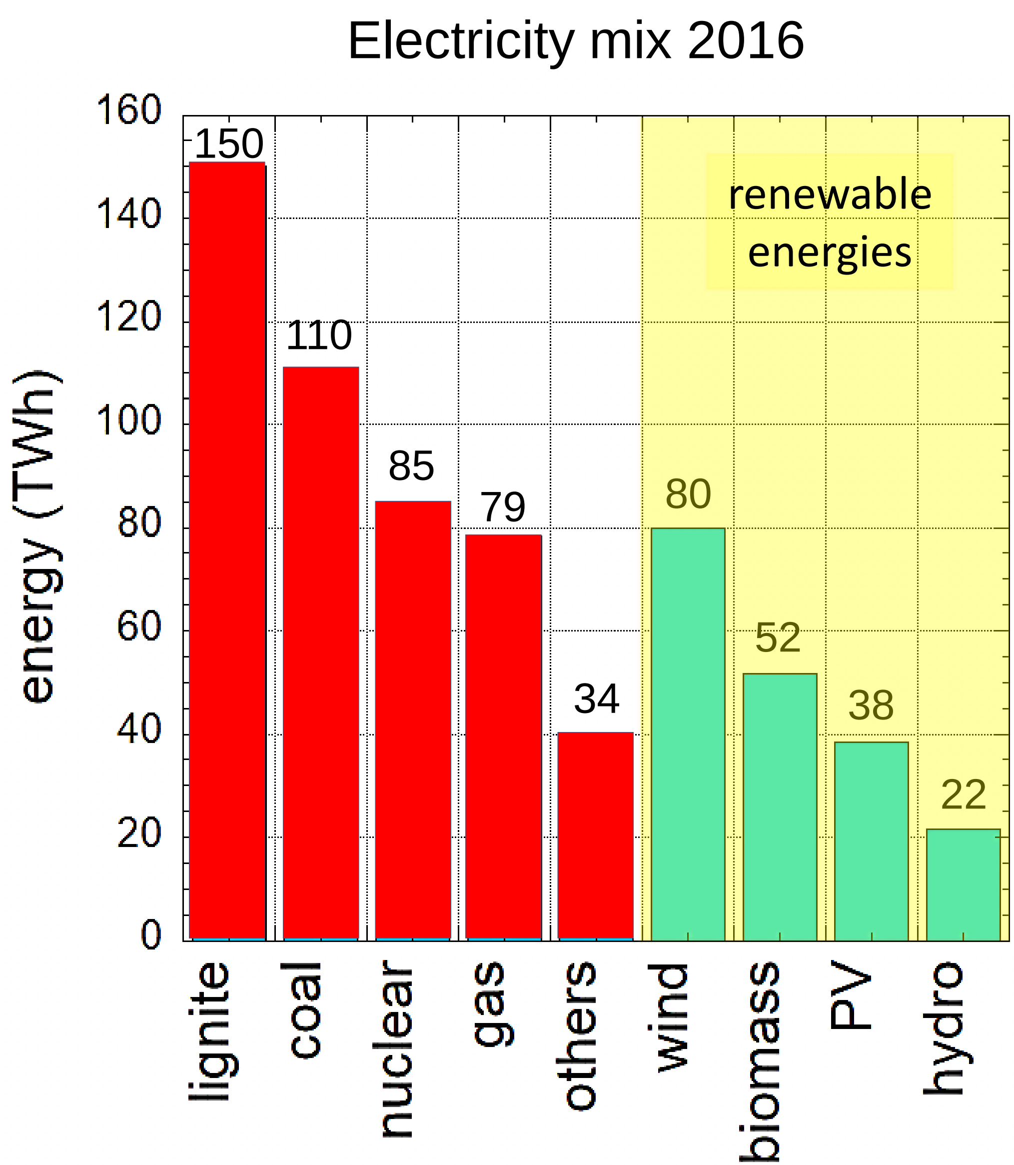
# Annual duration curves





# Electricity production - today



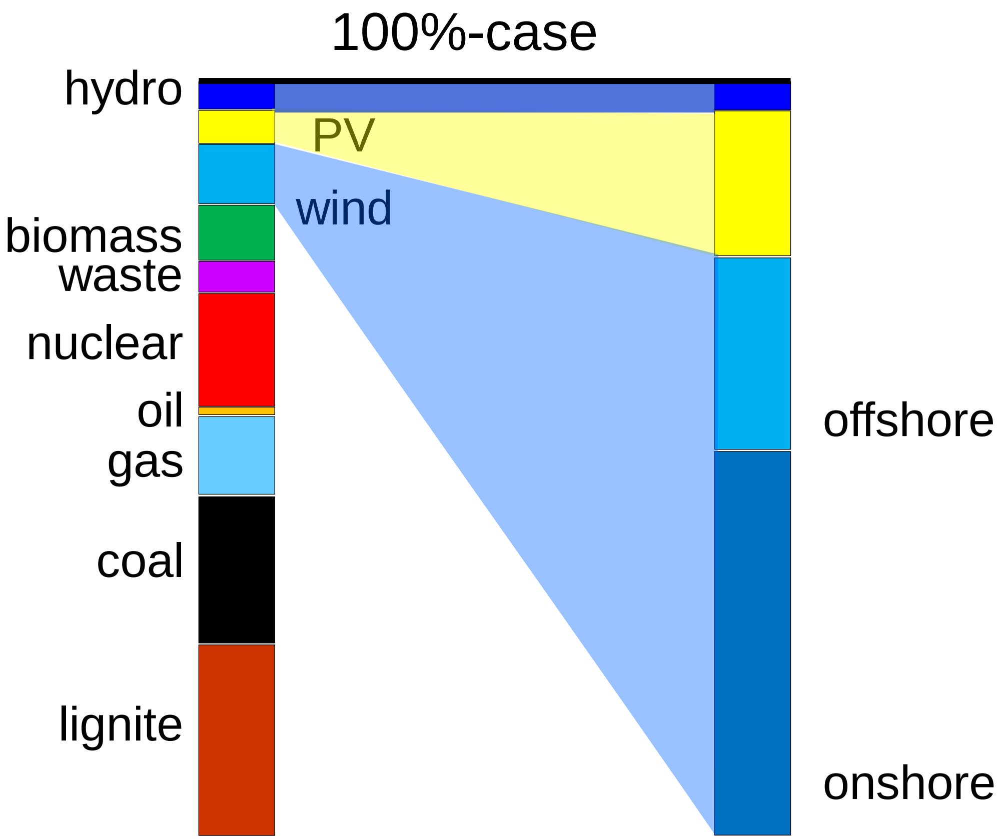



AGEB e.V.

# The transition to renewable energies only



## 2012: 520 TWh endenergy




Hydro + Biomass
are limited

Only onshore, offshore wind
and
photovoltaik power (PV)
are scalable

# The characteristics of wind and PV power



Low power density

Wind: 2-3 $W/m^2$

PV: 5 $W/m^2$

Large areas needed

Large material investments

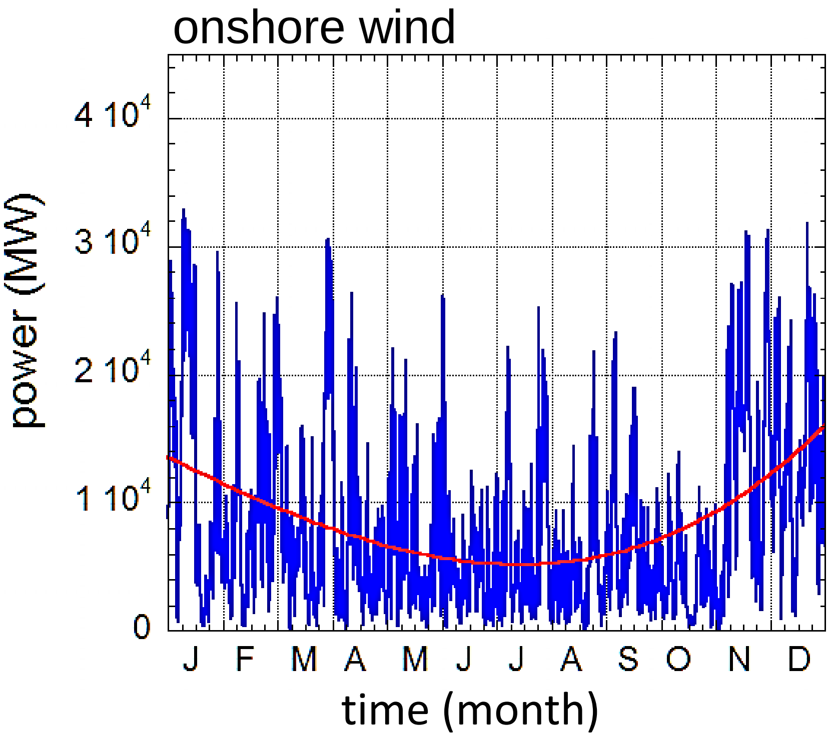
For comparison:

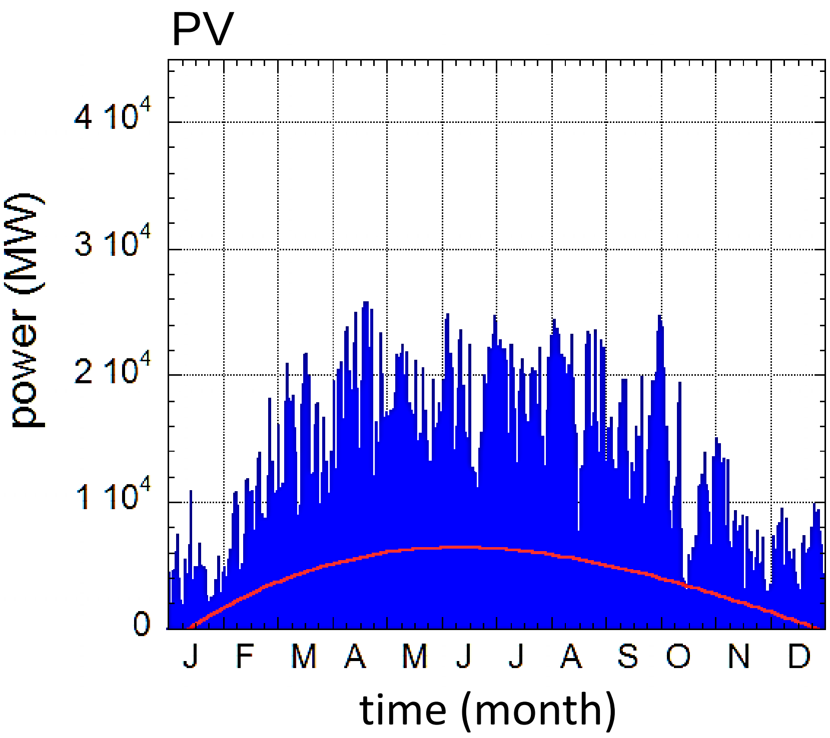
Germany
total energy density: 1.1 $W/m^2$
Munich
only electricity: 2.5 $W/m^2$

# Intermittency of power production



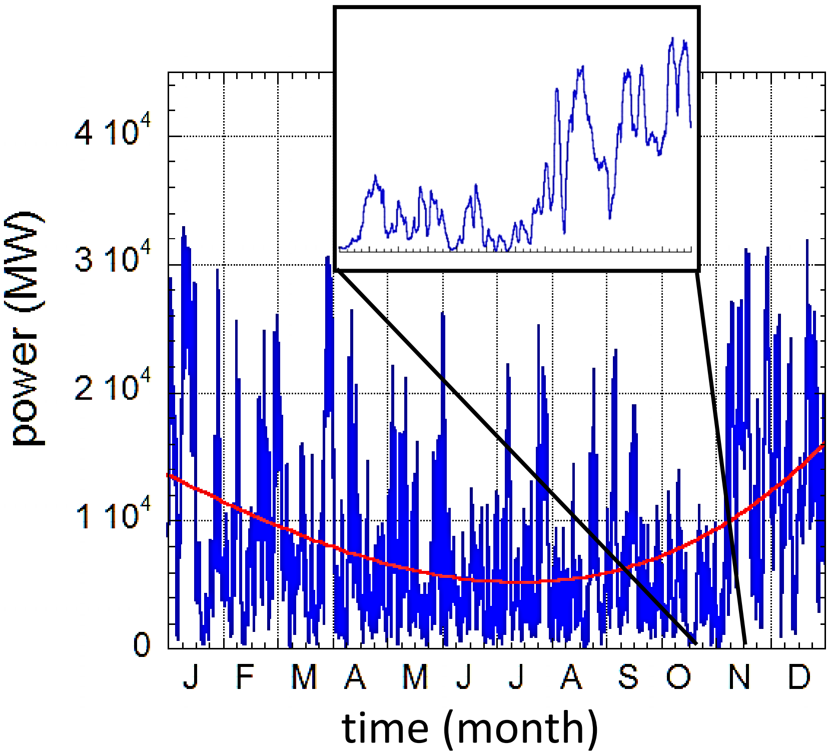
Data of 2015

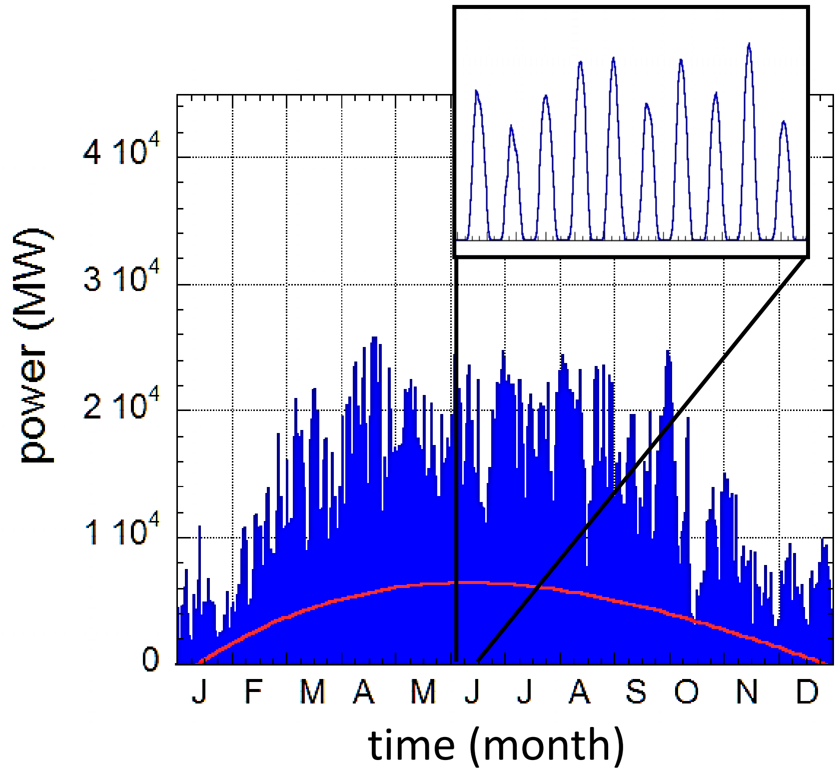


# Intermittency of power production

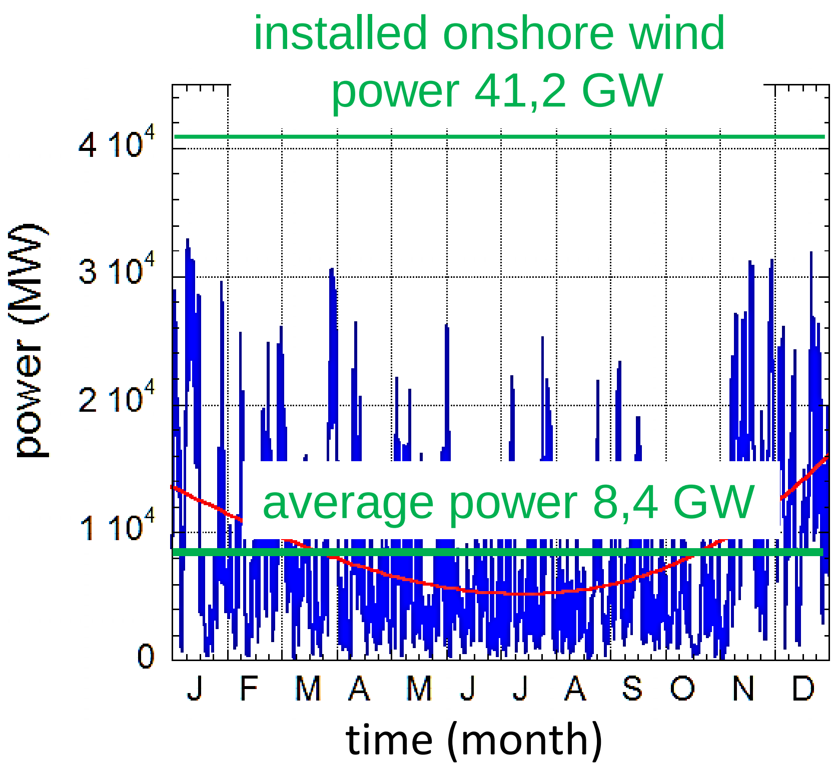


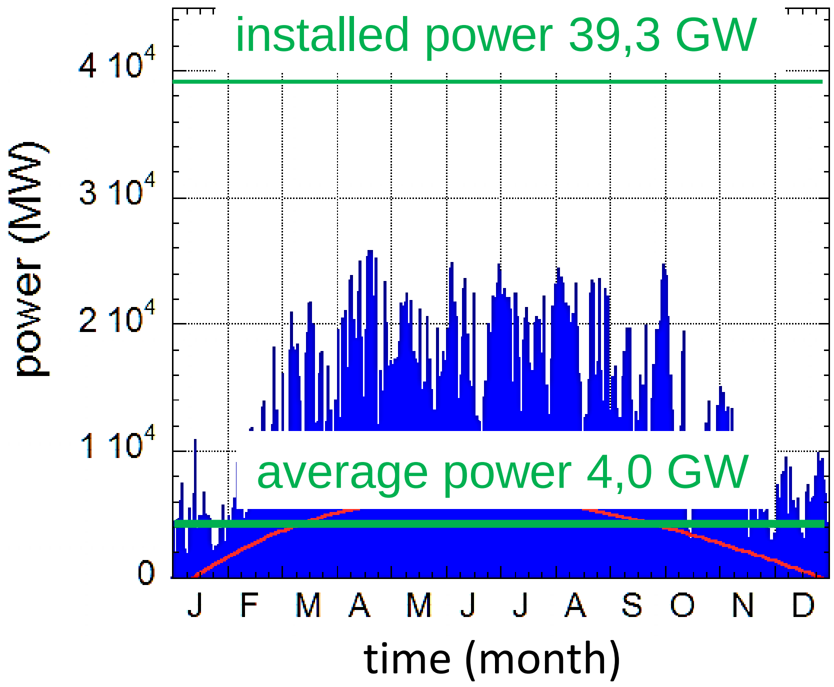


# The consequences of intermittency






flh = 1786 h

892 h

Offshore: 3300 h

# The consequences of intermittency



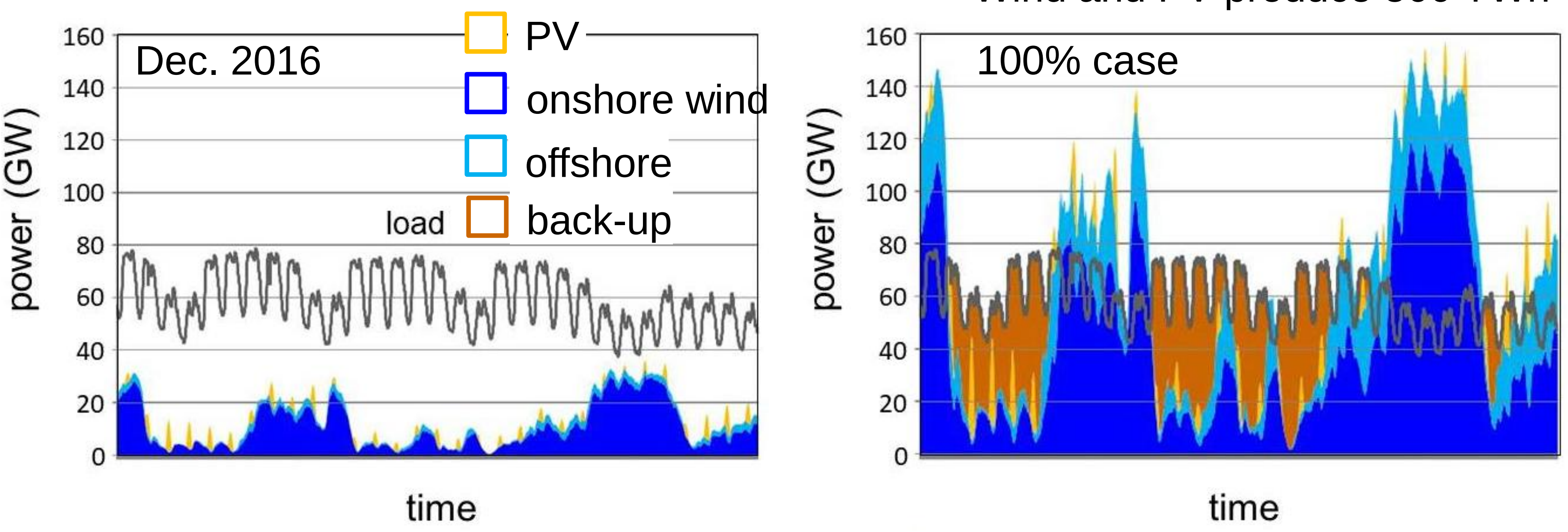
Intermittent renewable power iRES is not always available

→ **backup** system necessary

High power installation necessary to produce required energy

→ **surplus** production

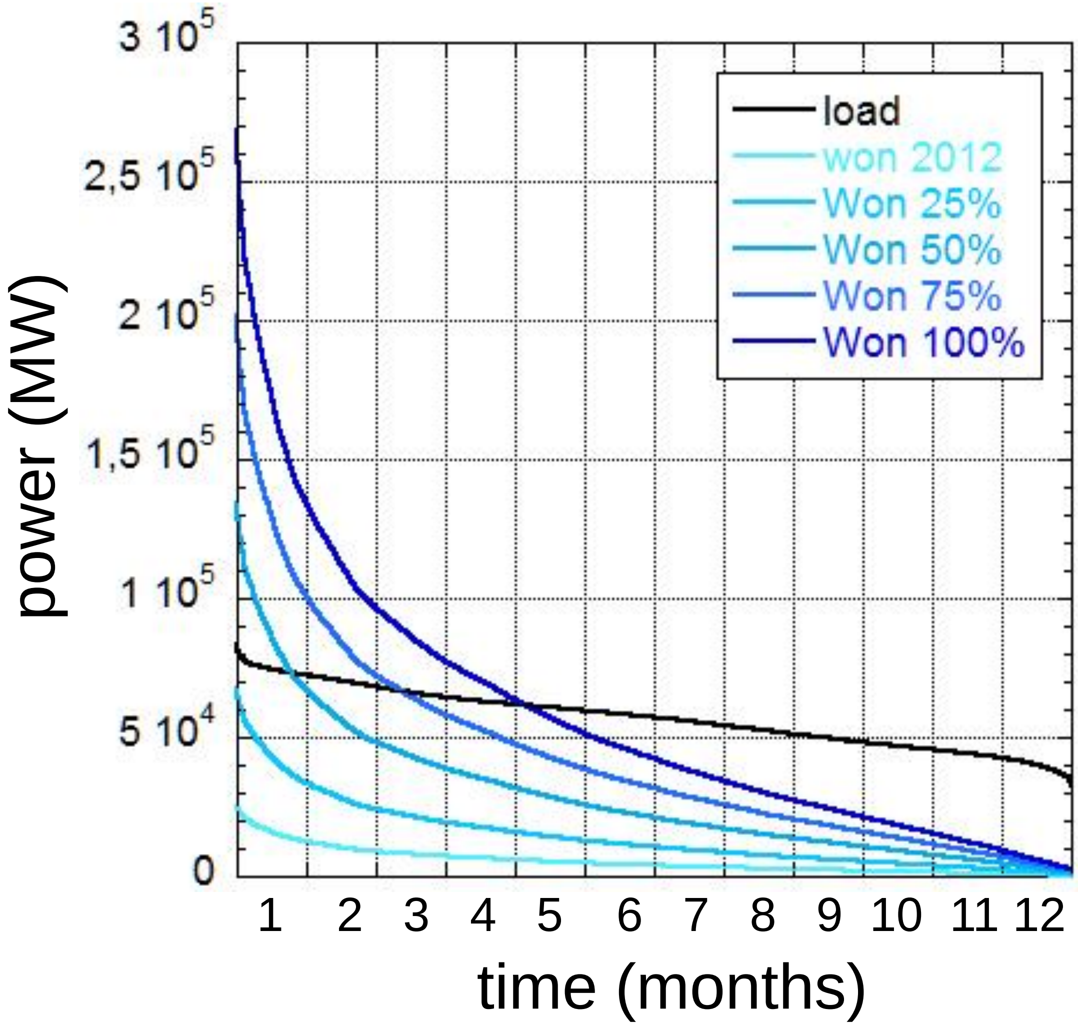
Wind and PV produce 500 TWh



# The basic problem of iRES



Annual Duration Curve ADC



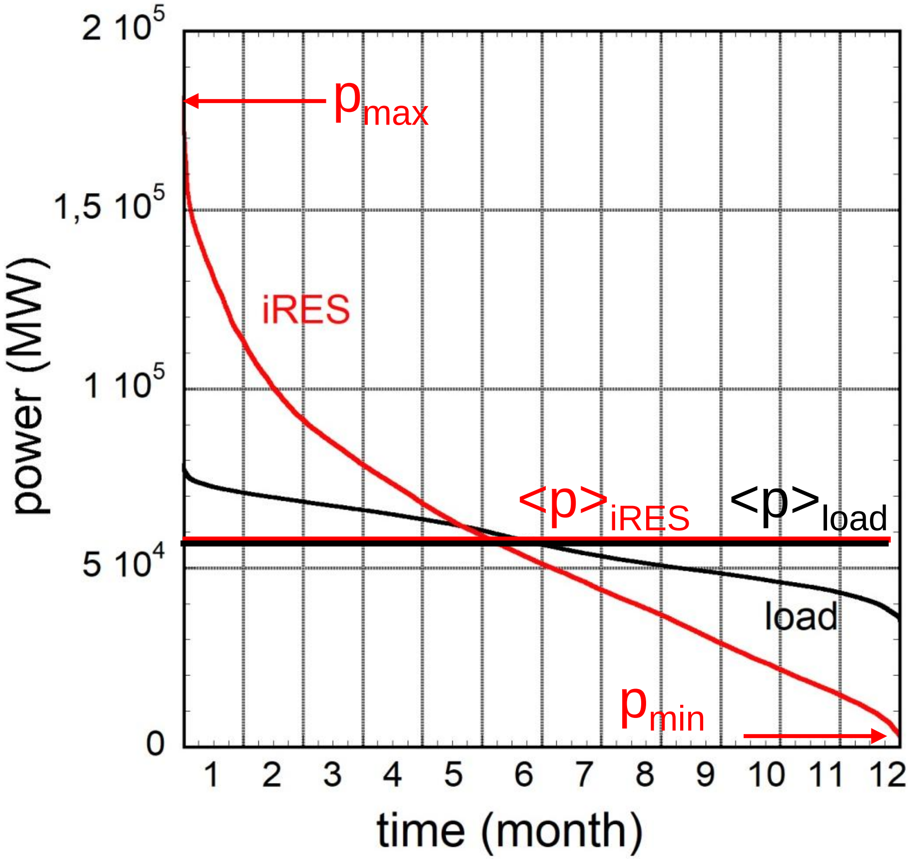

Load and production curve do not fit

To gain energy:
large capacities
high power levels

# The basic problem of iRES



annual duration curves for 100% case



# The basic problem of iRES



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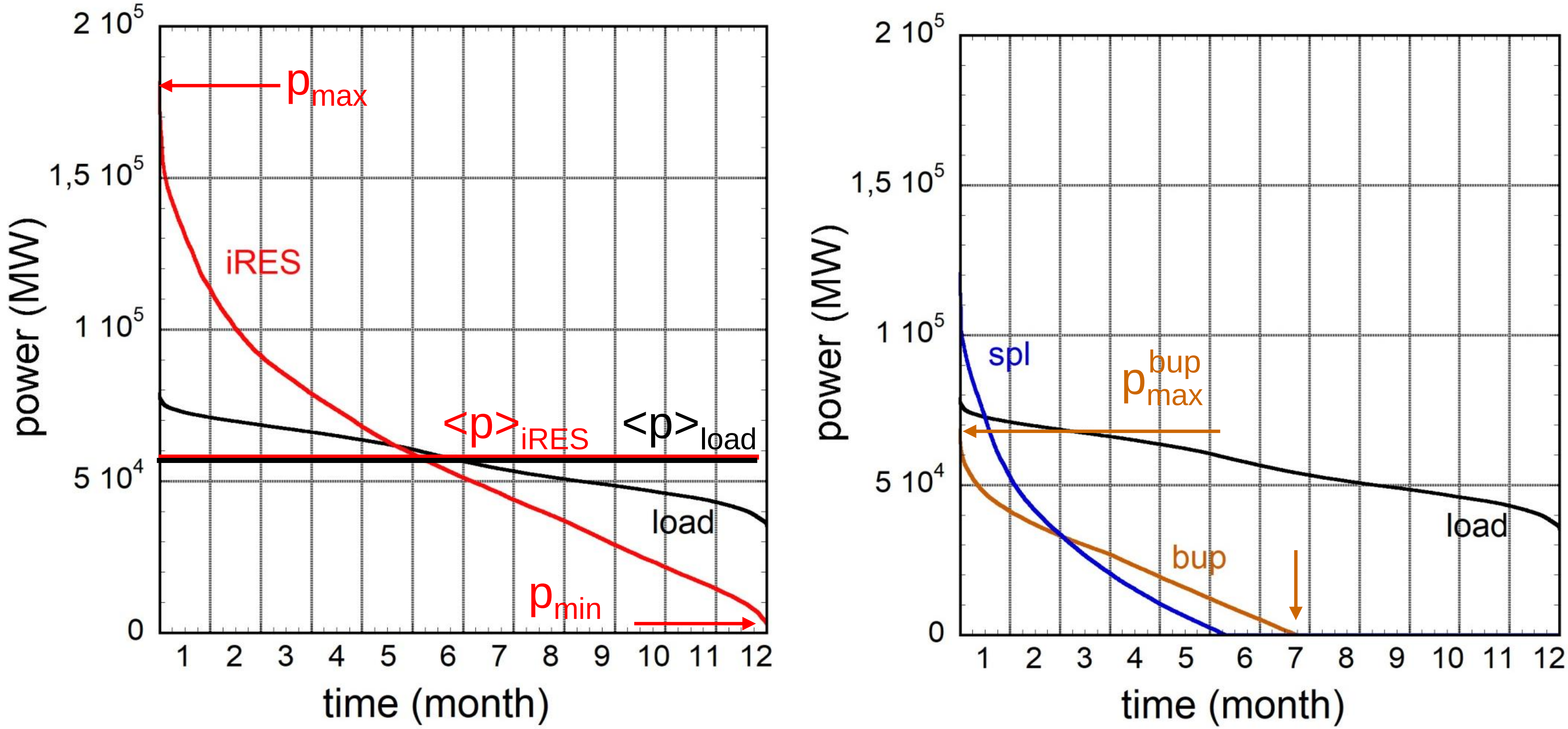
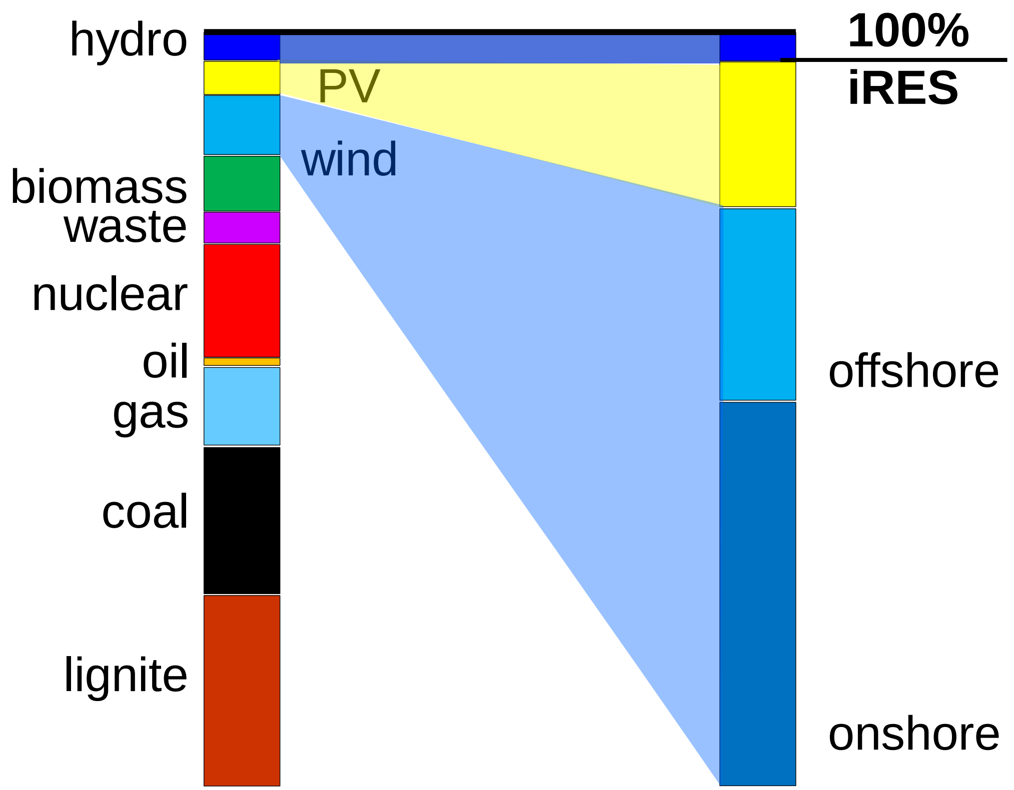


# Transition in energy technology






Endenergy: 520 TWh

**Analysis method:**

scale wind and PV to 100%

100%-case = 500 TWh

**Assumptions**

hydro limited to 20 TWh

no nuclear power

no bio-gas (at present: 50TWh)

no export, import

wind and PV ratio: optimal mix

1. analysis step: **no losses**

# Public data source

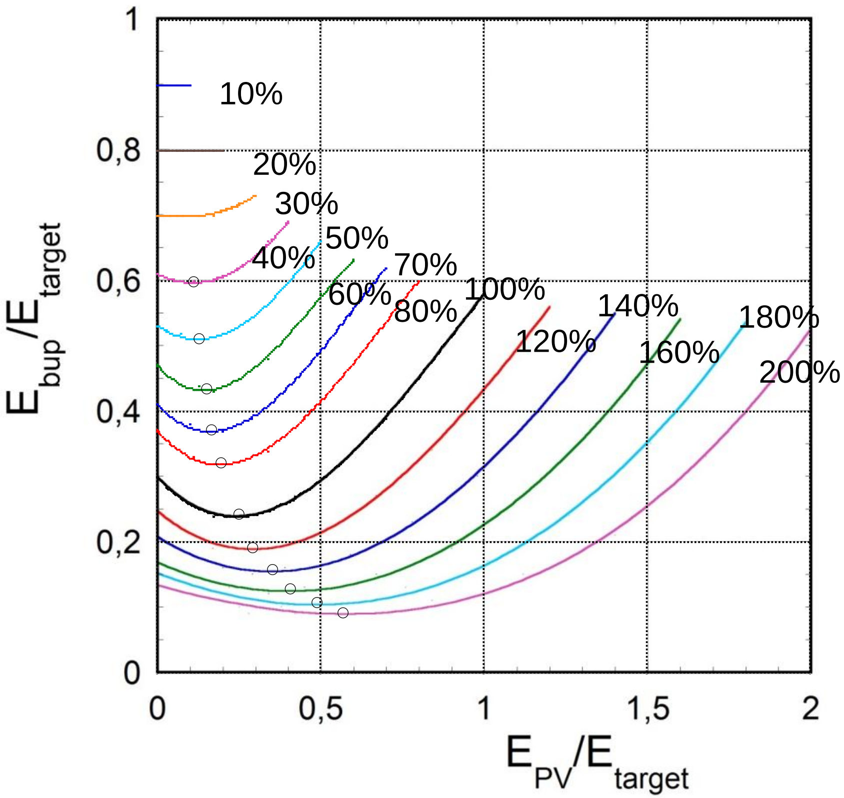


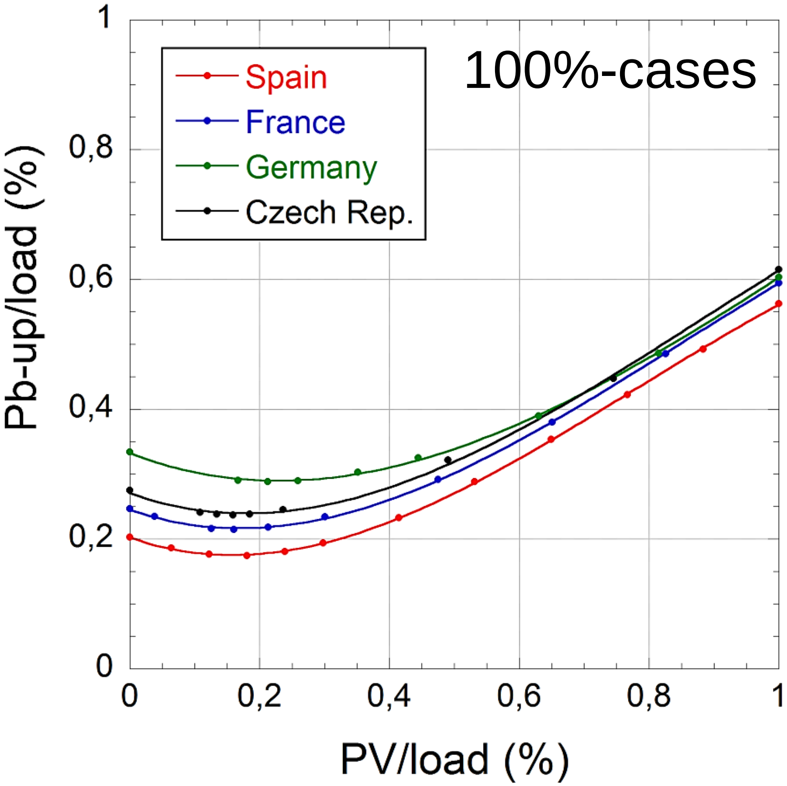
From the four German grid operators
http://www.tennettso.de/;
http://www.50hertz-transmission.net/;
http://www.amprion.de/;
http://transnet-bw.de/.

From the EU organisation ENTSOE
http://www.entsoe.net/

# Optimal mix between wind and PV





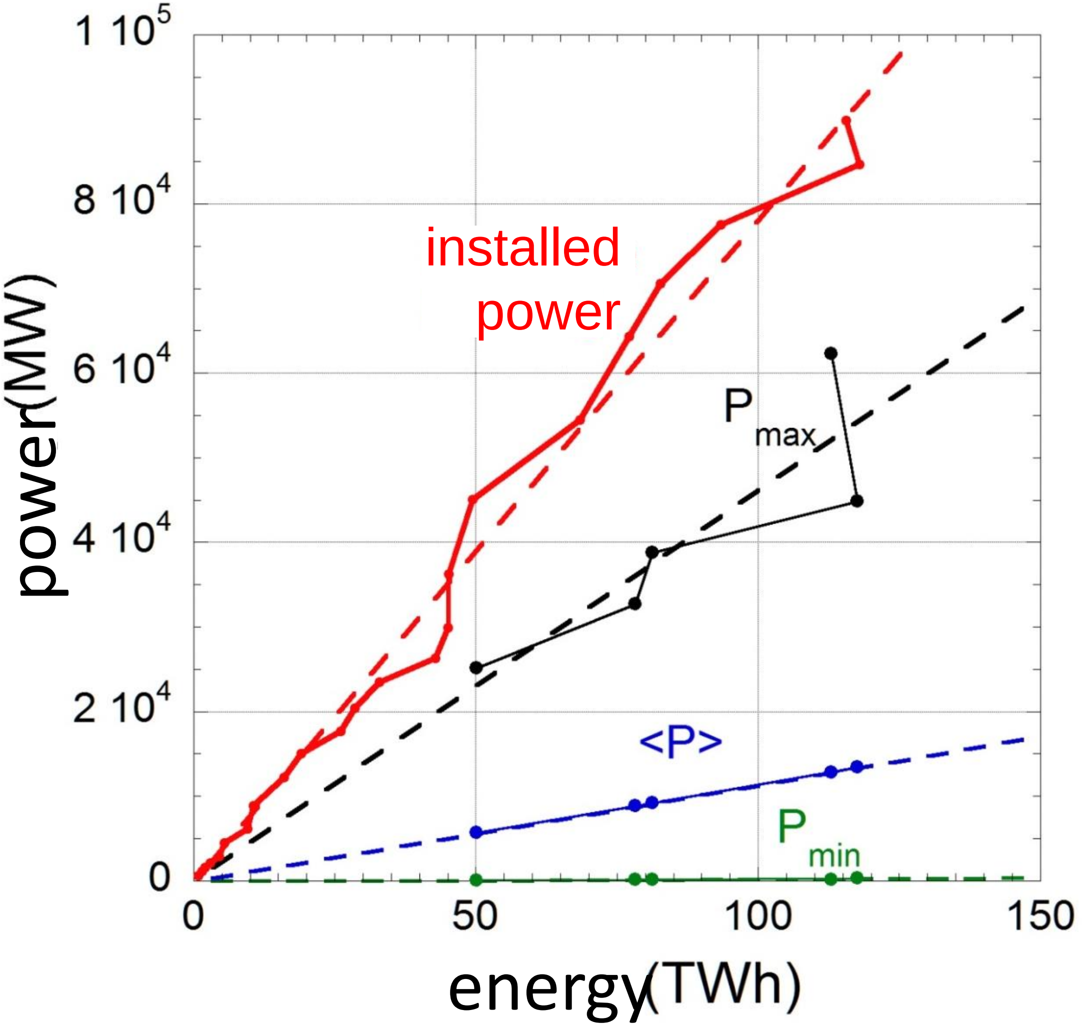




$E_{PV}$ ~ 20%; $E_{wind}$ ~ 80%

$P_{PV} = E_{PV}/flh_{PV}$; $P_{wind} = E_{wind}/flh_{wind} \rightarrow P_{PV}$ ~ 30%

# Analysis Examples

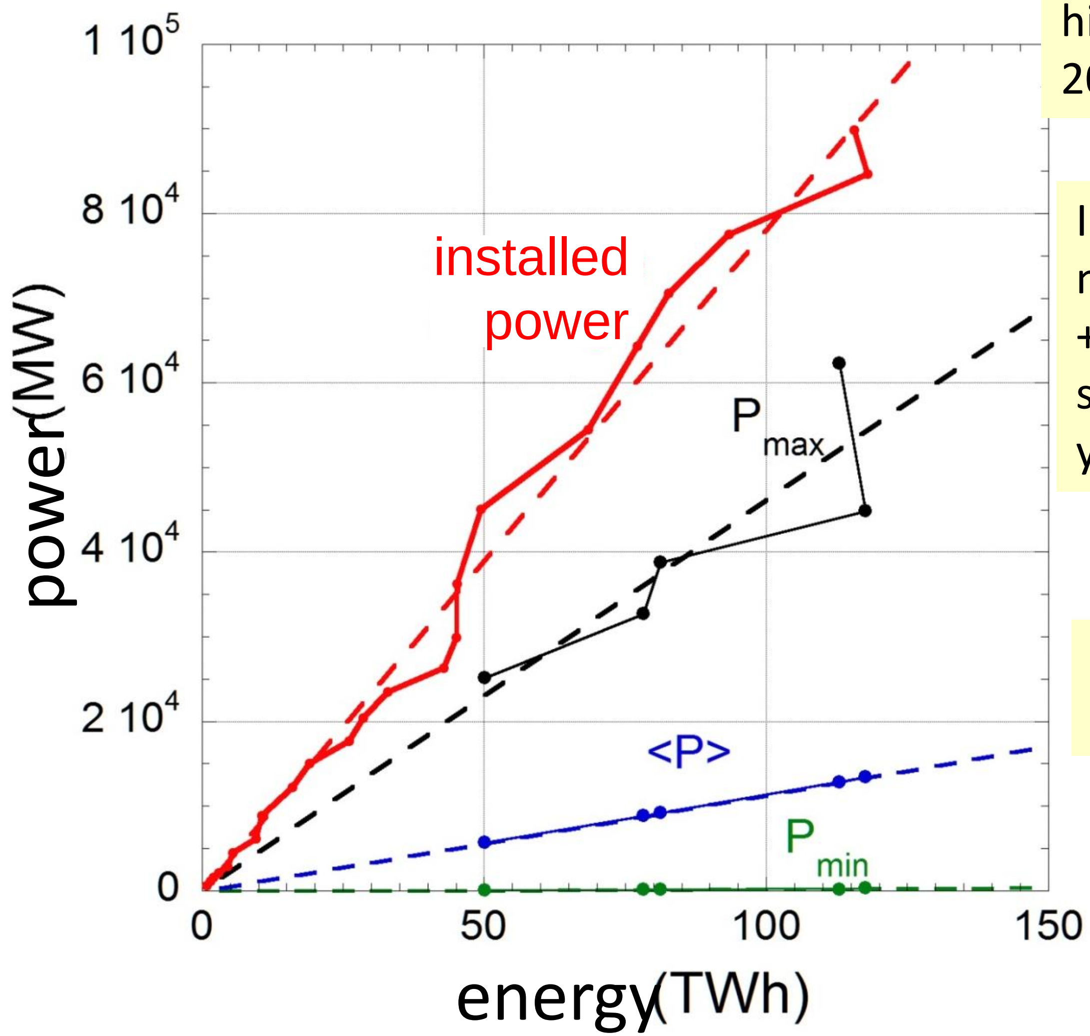
Germany as role-model for the “Energiewende”



# Analysis Examples



## Germany as role-model for the "Energiewende"



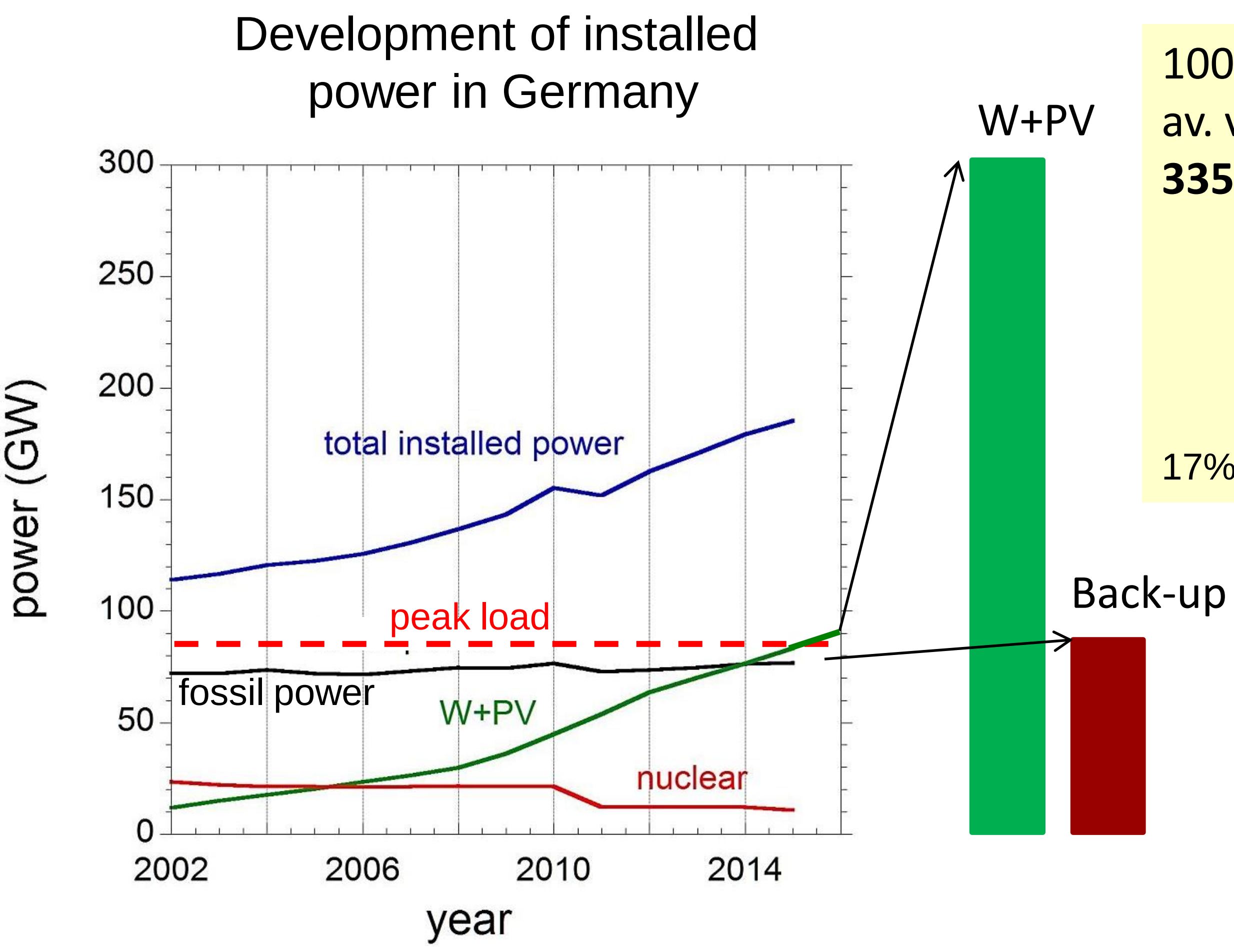

Because of intermittency: high installed power 2016: ~ 28000 windmills

Installed power level never reached
+
strong variation from year to year

Low capacity factor: cf ~ 15%

Back-up system required

# 1. example: How much power has to be installed?




100%, optimal mix case:
av. value 2010-2015:
**335 GW** (= 4kW/person;
4x peak load)
$P_{won}$ =174GW
$P_{woff}$ =43GW
$P_{PV}$ =118GW

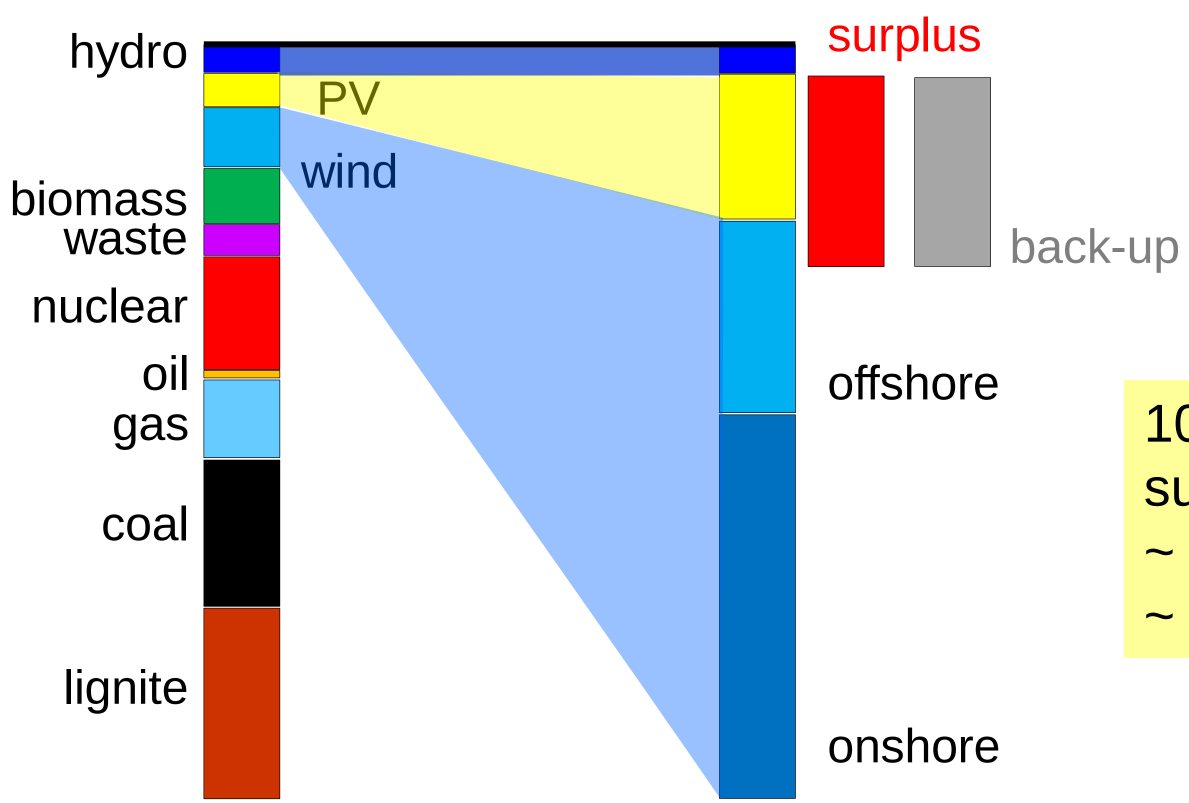
17% energy variation from year to year

**73 GW to produce 132 TWh**
the needed back-up power is larger than the fossil power of today

Build-up of tremendous overcapacity
No economic use of back-up investment

# Surplus and back-up production





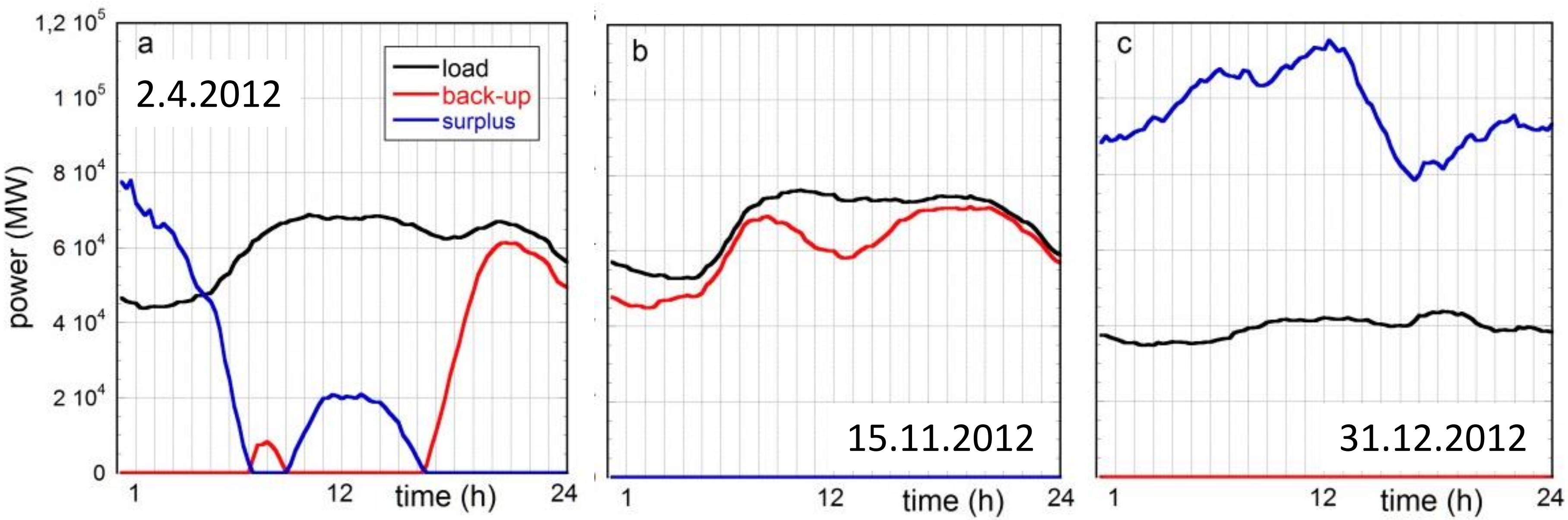

100% case:
surplus = back-up energy
~ 25% of total generation
~ 125 TWh

# 2. Example: Scenarios for using surplus



100%, optimal mix case

day with highest transfer | highest back-up need | largest surplus




**Quantitatively:**

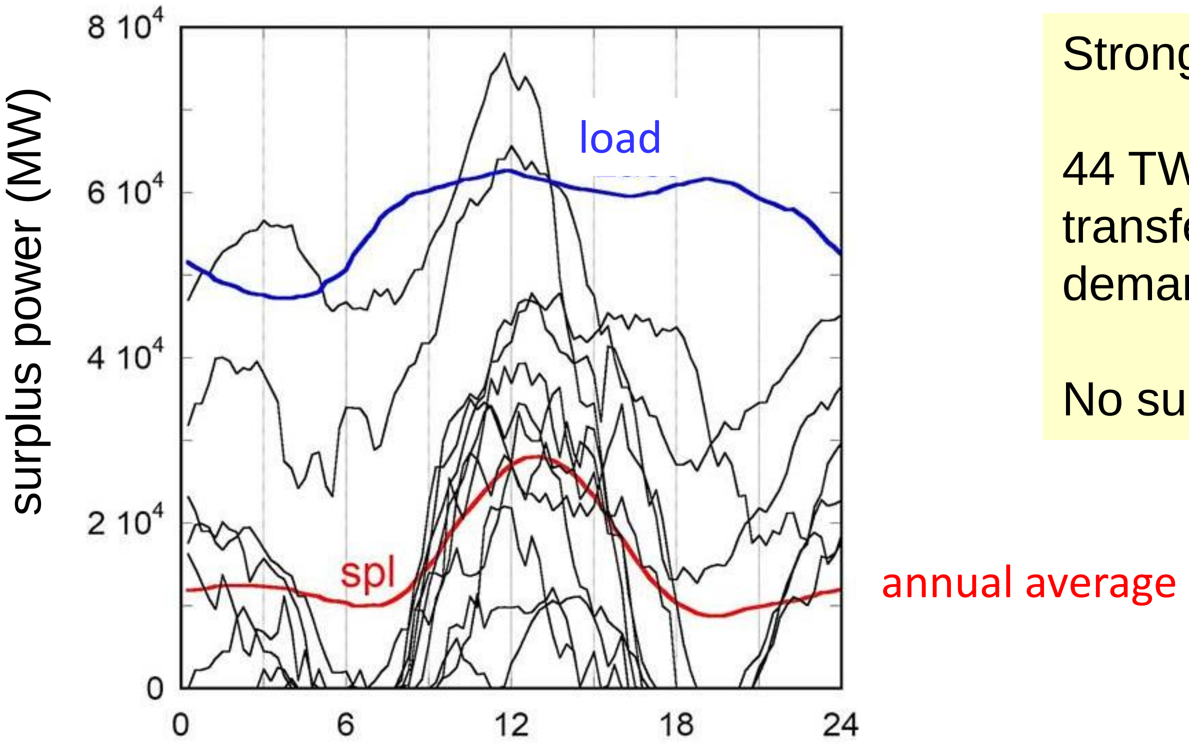
average daily need: 1.36 TWh

| day with highest transfer | highest back-up need | largest surplus |
| --- | --- | --- |
| 0.47 TWh surplus | 0 TWh surplus | 2.33 TWh surplus |
| 0.37 TWh back-up | 1.47 TWh back-up | 0 TWh back-up |

# Problems of Demand-side management



surplus power for the 100%, optimal mix case for 21 days in April 2012




Strong variation of surplus power

44 TWh out of 131 TWh could be transferred from surplus to demand periods

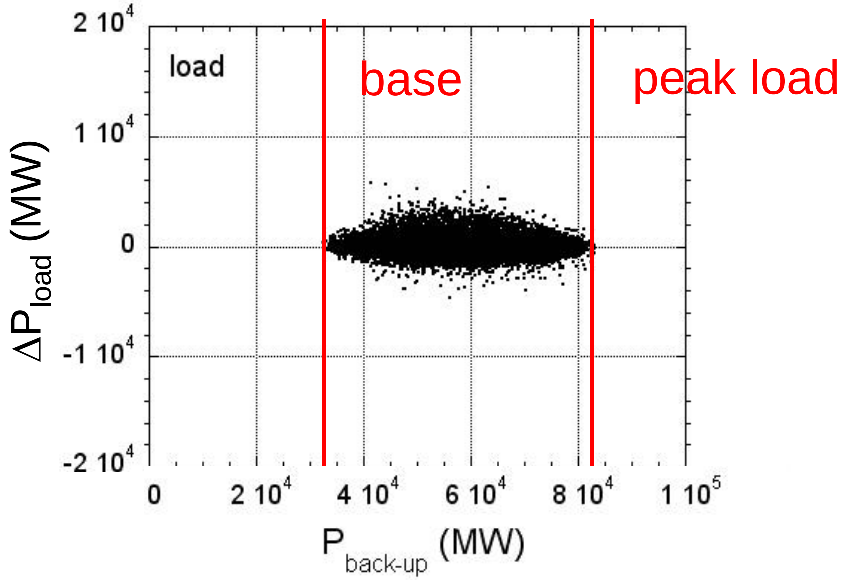
No surplus for 134 days

# 3. Example: Fluctuation level



Power jumps within 15 min

$$\Delta P_i = P_{i+1} - P_i$$



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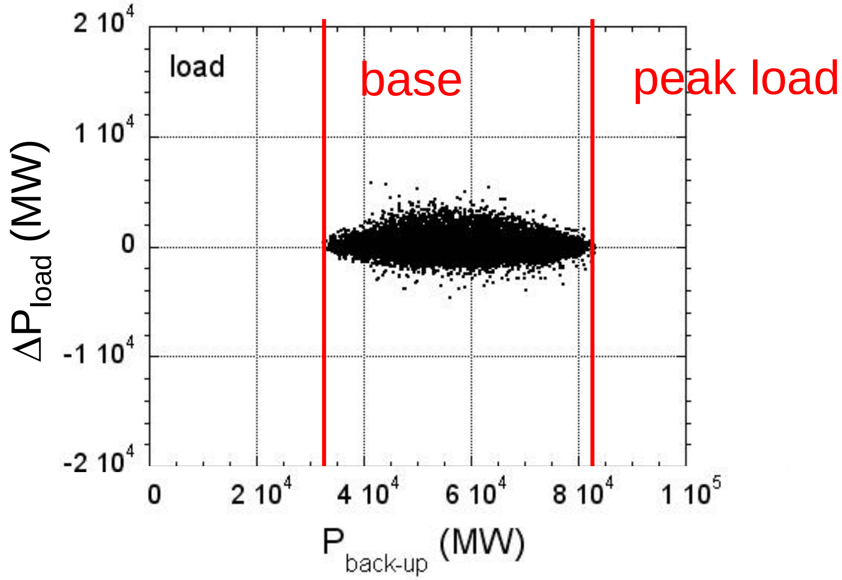
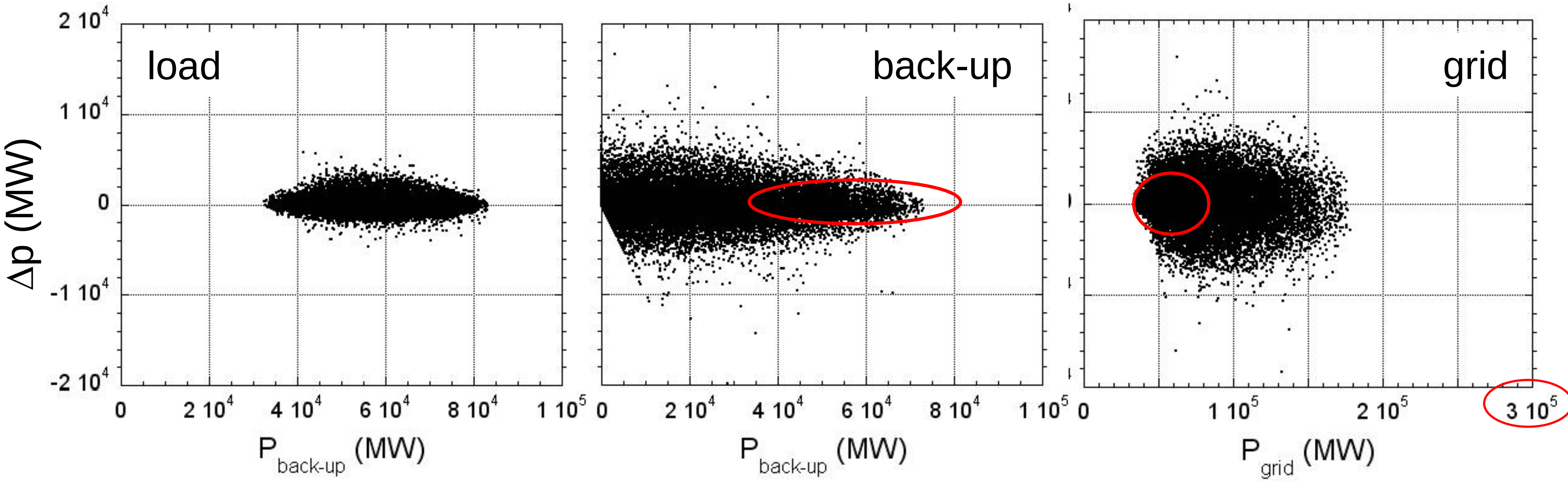



100%, optimal mix case



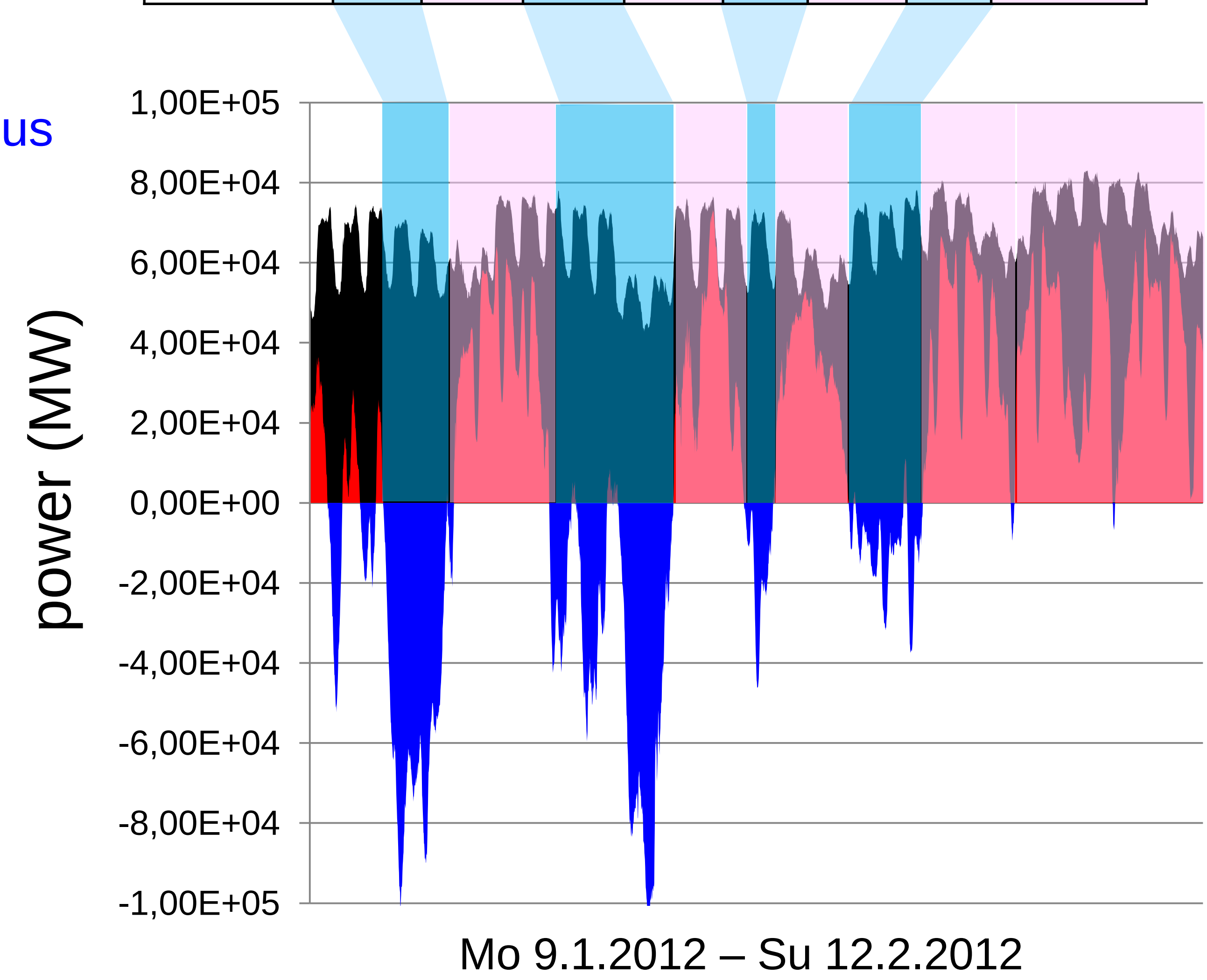
# 4. Example: Seasonal storage



100%, optimal mix case

black: load
red: back-up
blue, negative: surplus

| h | 66 | 90 | 117 | 67 | 27 | 71 | 70 | 264 |
|---|---|---|---|---|---|---|---|---|
| TWh | 3.7 | -3.5 | 4.5 | -2.5 | 0.5 | -2,4 | 0.8 | -10.4 |



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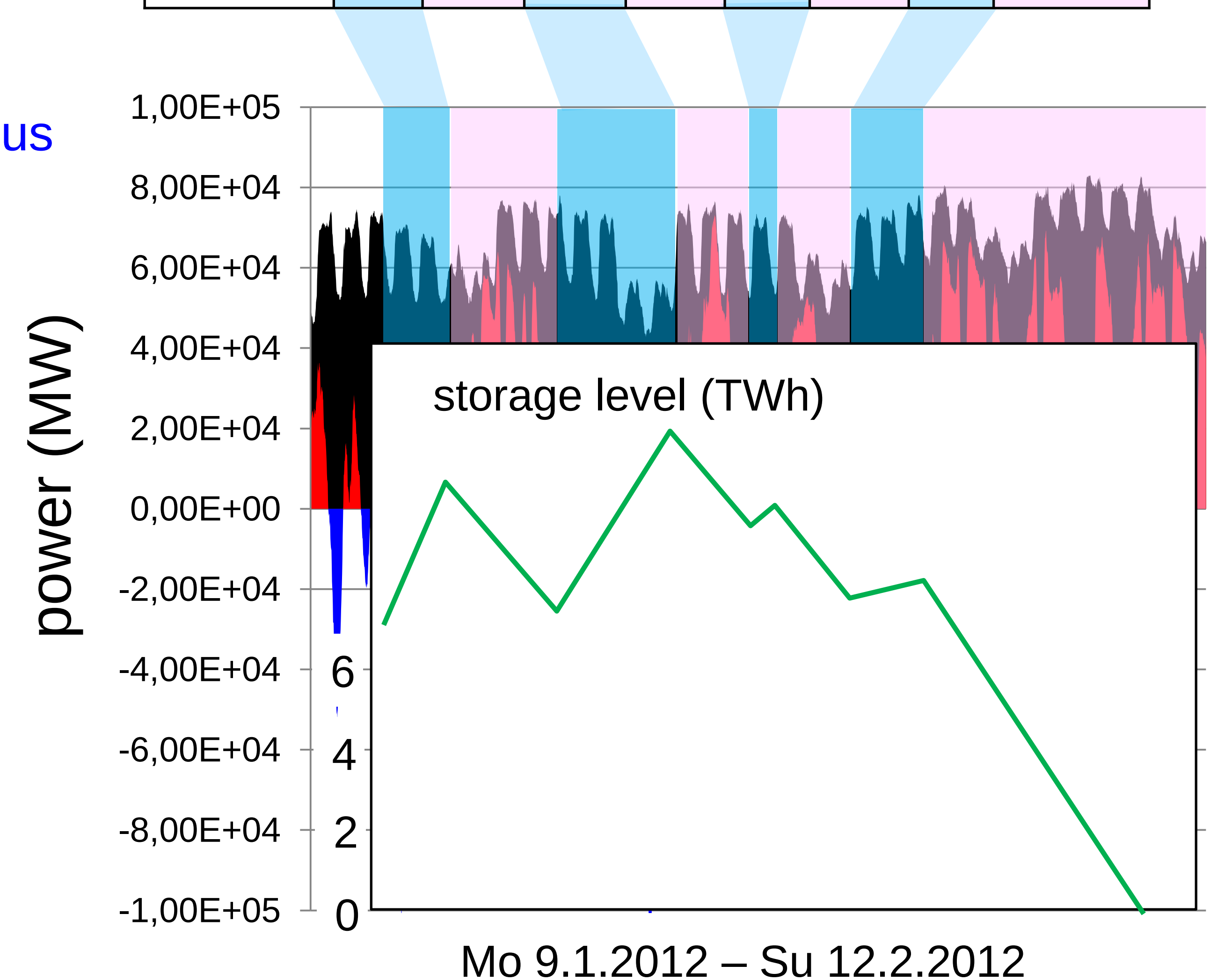
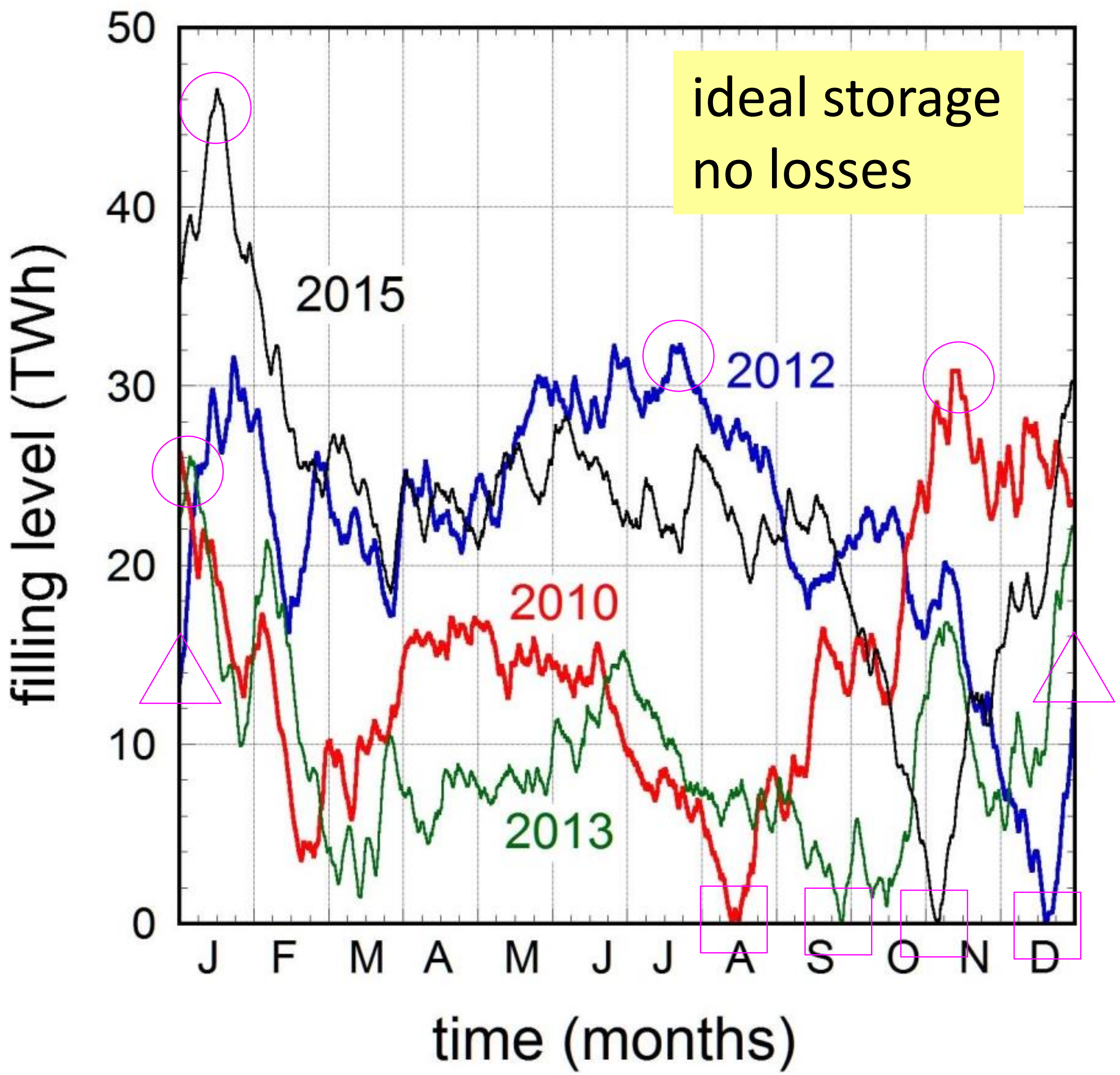


# Variation from year to year




Periodic boundary conditions

Maximum = capacity

Once empty during the year

# The effect of efficiencies



Assume: chemical storage and power-to-gas-to-power

1. step: electrolysis with surplus: $\eta \sim 0.65-0.7$
2. step: electricity from $H_2$: $\eta \sim 0.5$ (fuel cell)

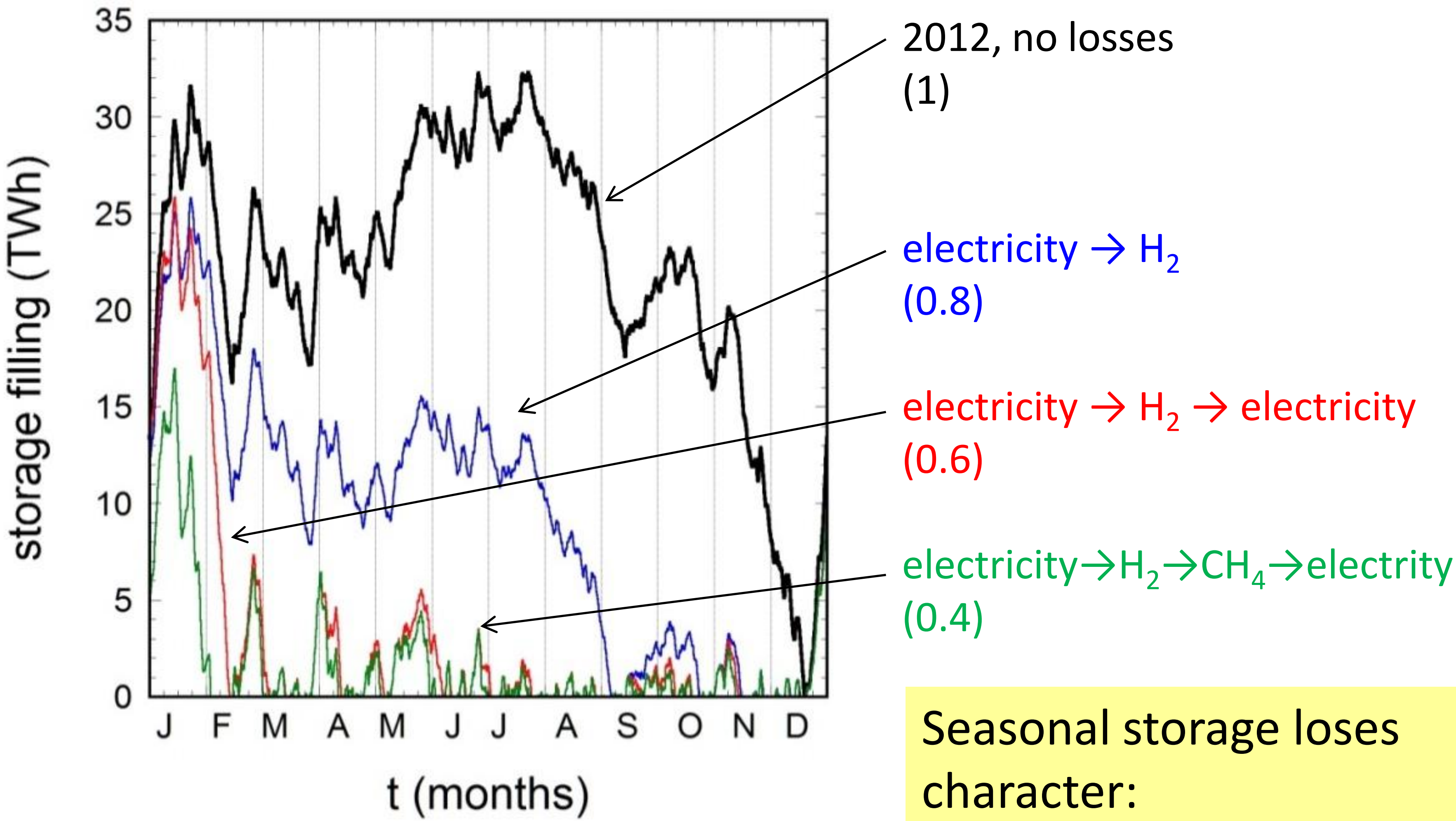
Alternatively
2. step: $H_2$ to $CH_4$: $\eta \sim 0.65$
3. step: $CH_4$ to electricity: $\eta \sim 0.5$

Total efficiencies: $\eta \sim 0.2 – 0.35$ → for 1 kWh output, 3 - 5 kWh input

From 131 TWh surplus, 25 - 45 TWh can be recovered

# Transformation losses: power-to-gas



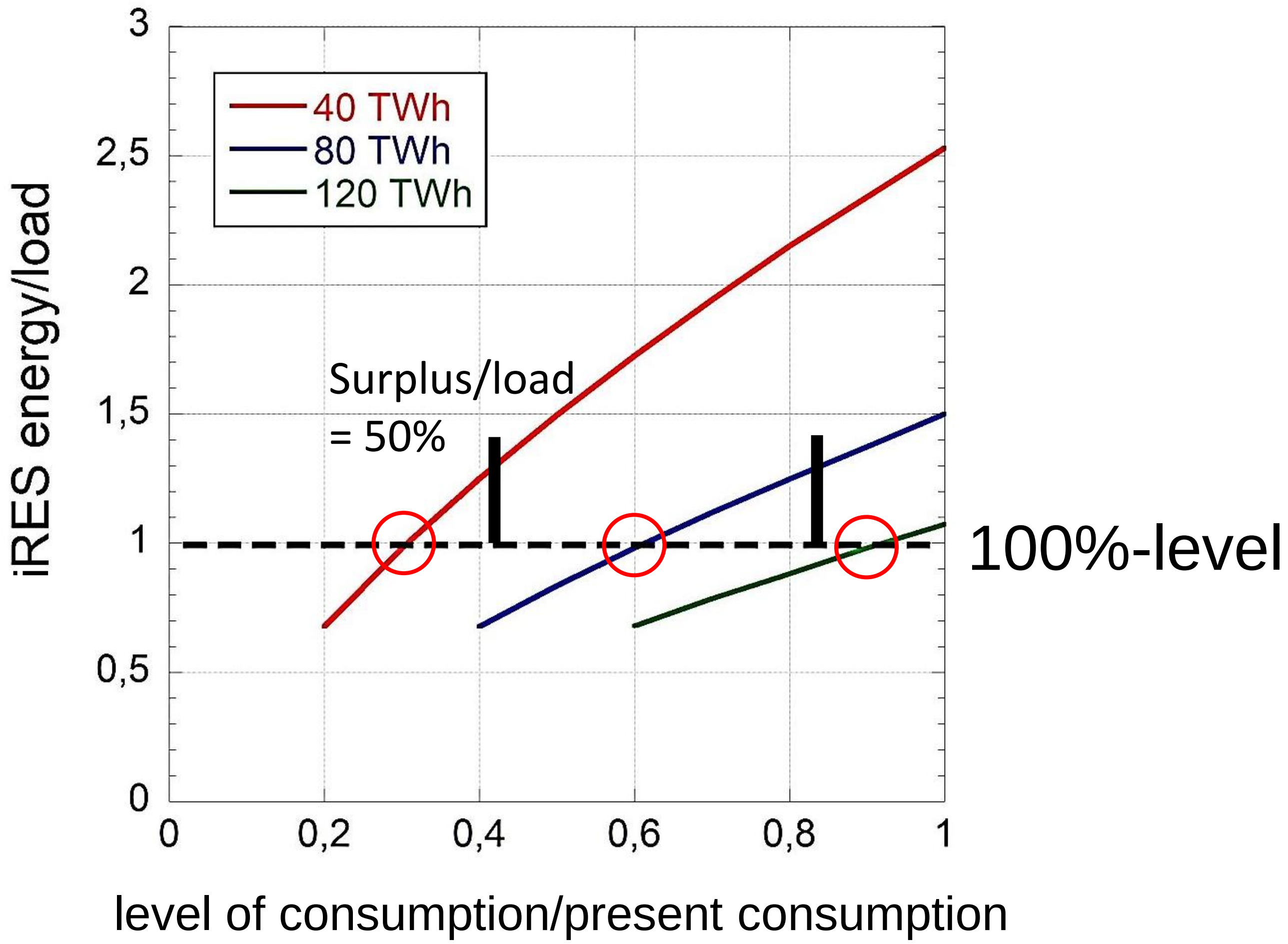



Seasonal storage loses character:
short operational periods after bursts of surplus

# 5. Example: Conditions of a 100% **electricity** supply by RES

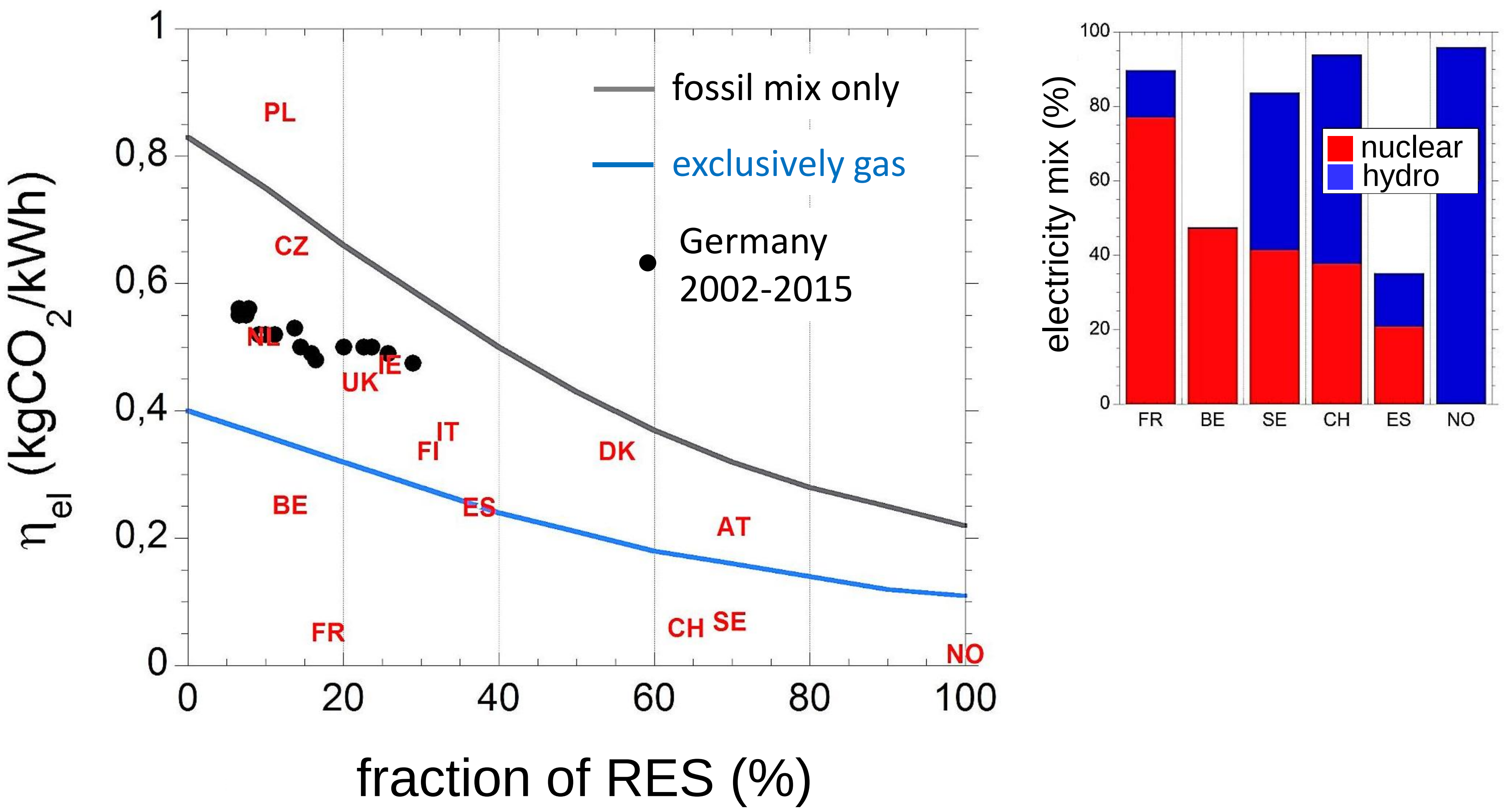


Main knobs: savings/efficiency + use of biomass
Minor knobs: decrease of population, import (dispatchable power), geo-th-power



# 6. Example: $CO_2$ emissions





# 7. Example: Benefits from an EU-wide RES field

Construction of an EU-wide RES field

| |
|---|
| Germany, wind+PV<br>Denmark, wind<br>Belgium, wind<br>France, wind+PV<br>UK, wind<br>Ireland, wind<br>Spain, wind+PV<br>Czech Rep., wind+PV<br><br>Sweden, wind+PV |

Distribution of wind field expressed as regression coefficient

# The benefit of working with an EU-wide RES field



the back-up energy is reduced by 24%,

the maximal back-up power by 9%,

the maximal surplus power by 15%,

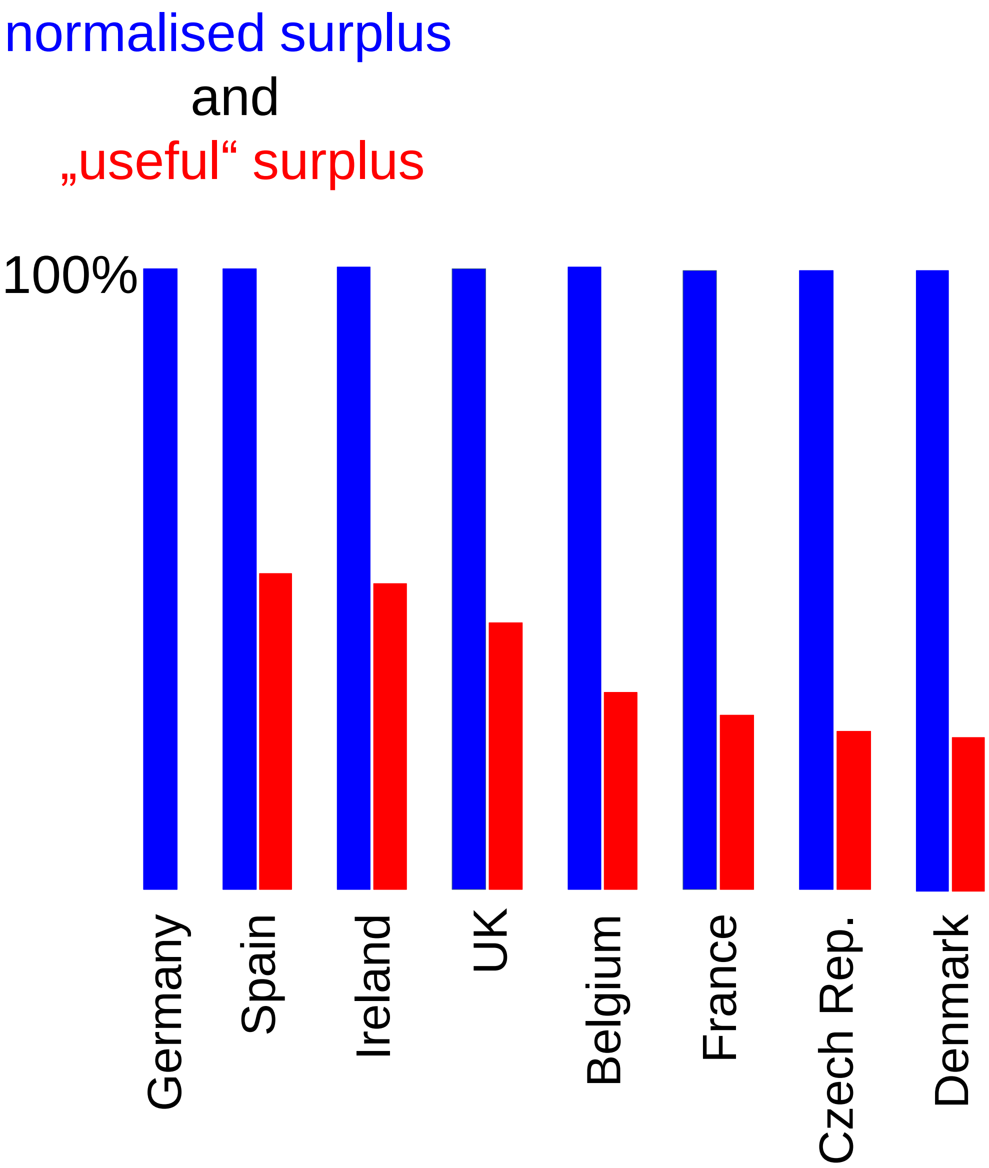
the maximal grid power by 7%,

the typical grid fluctuation level by 35%

the maximal storage capacity by 28%

# Useful surplus (from German point of view)

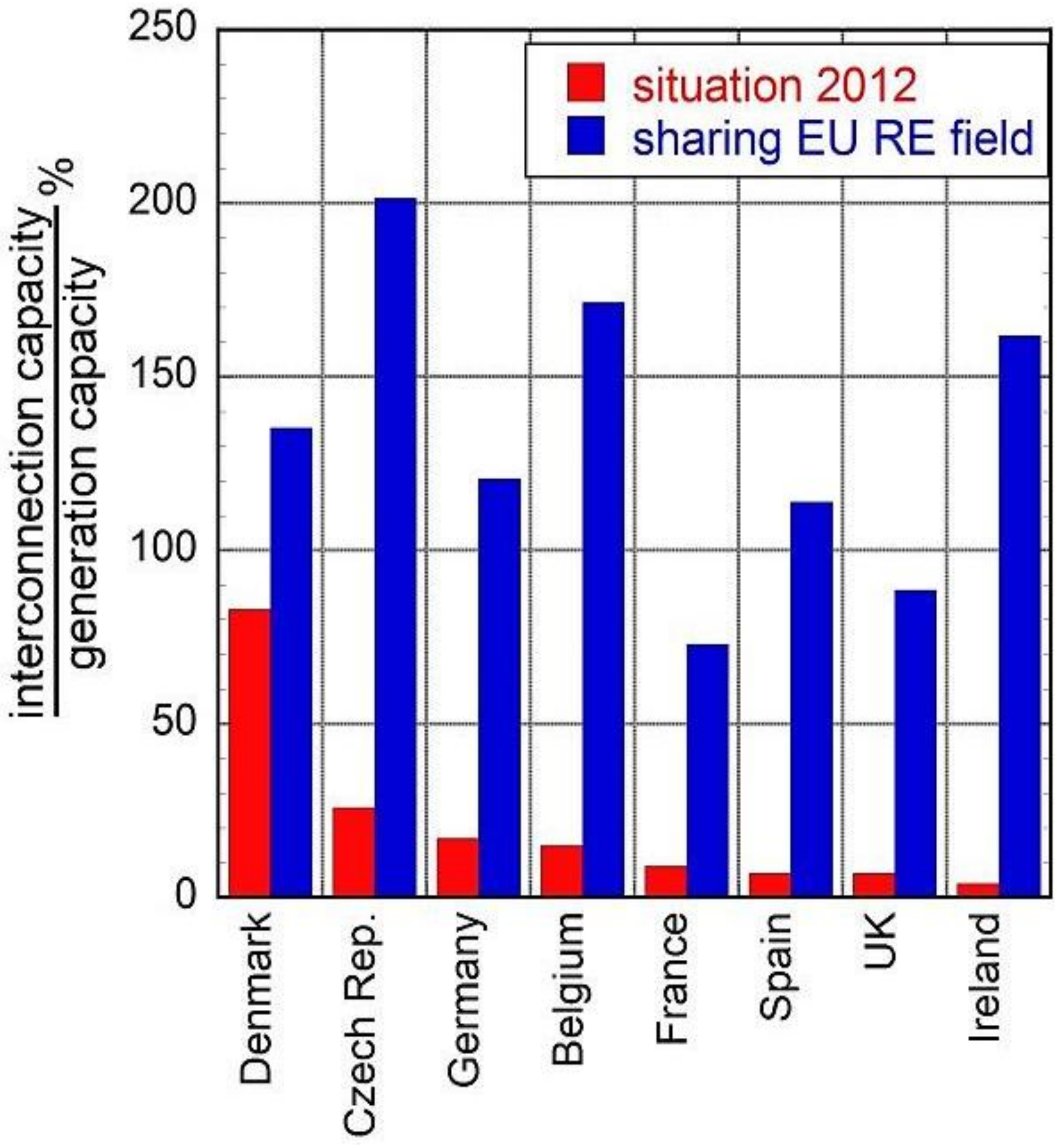





**In case of surplus – also the neighbours produce it**

# Interconnector capacity





# Conclusion



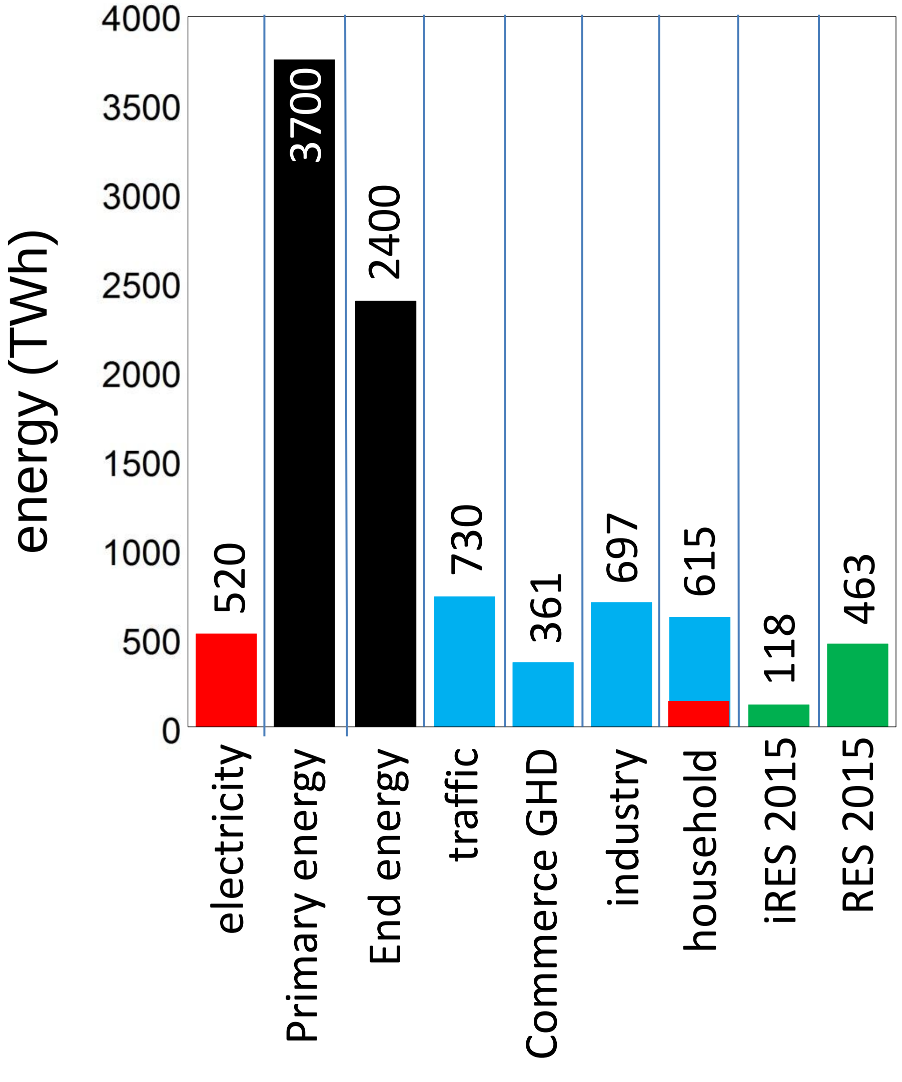
EU-wide consequences

- Large  RES power necessary for all countries
- National RES use demands typically north-south grids
- Cross-border exchange requires east-west grids
- Exchange over large distances beneficial
- Large interconnector capacities needed
- Not all countries benefit from an EU-wide RES field

# 6. Example: Going beyond electricity

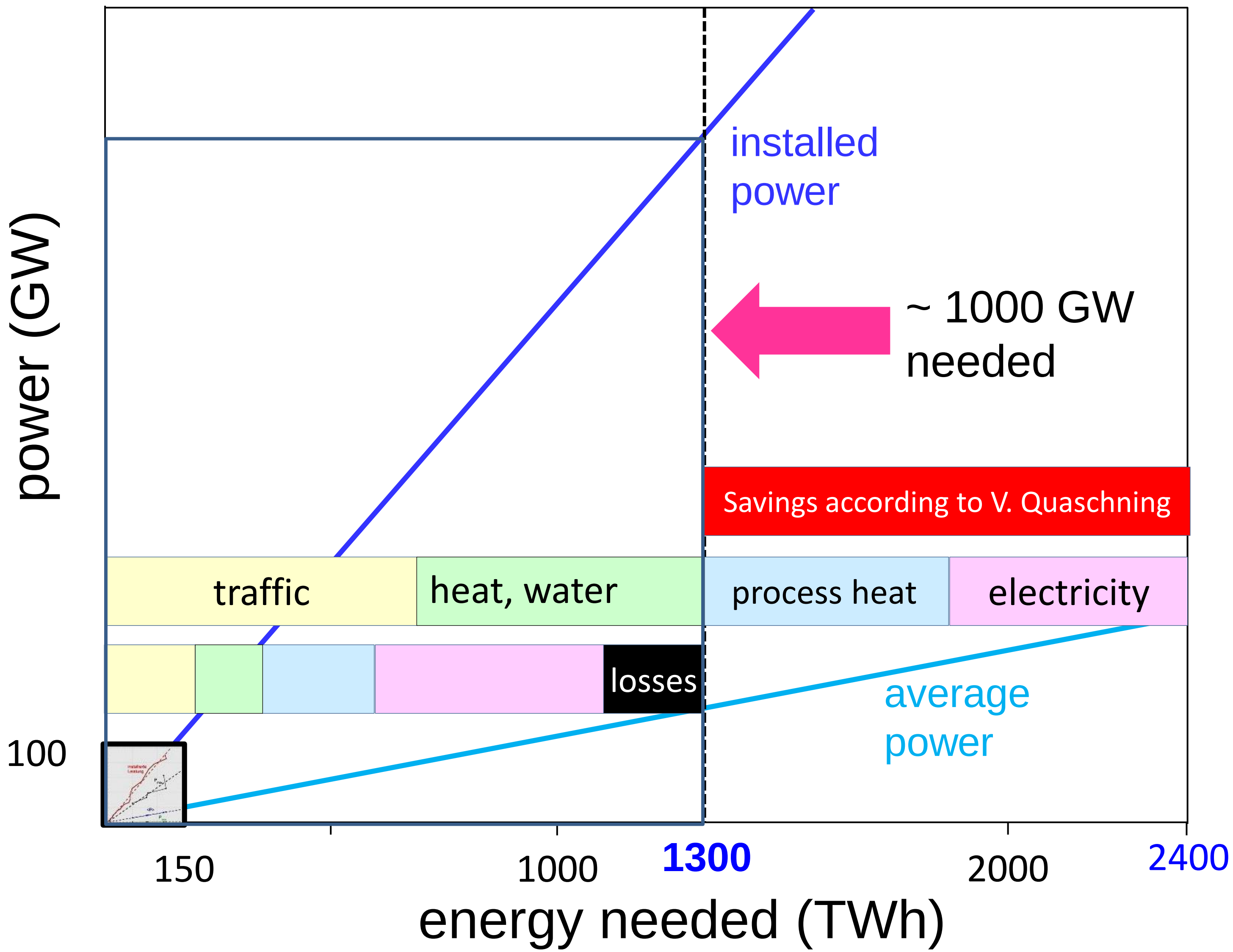


Energy production and needs of all energy sectors



# Issues of full de-carbonisation



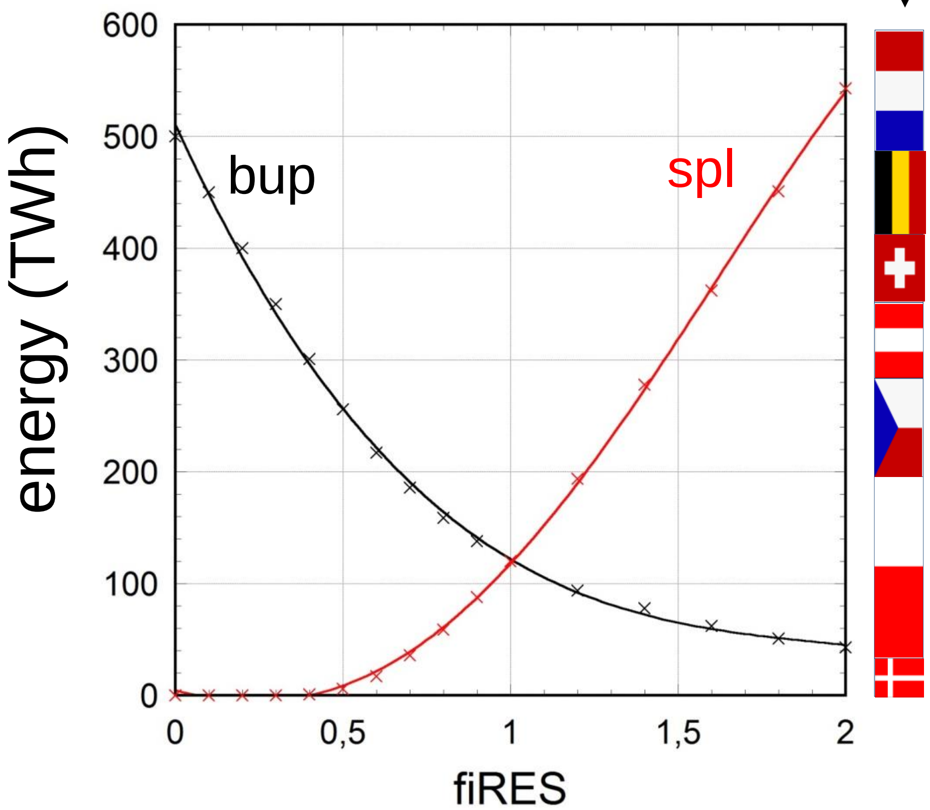


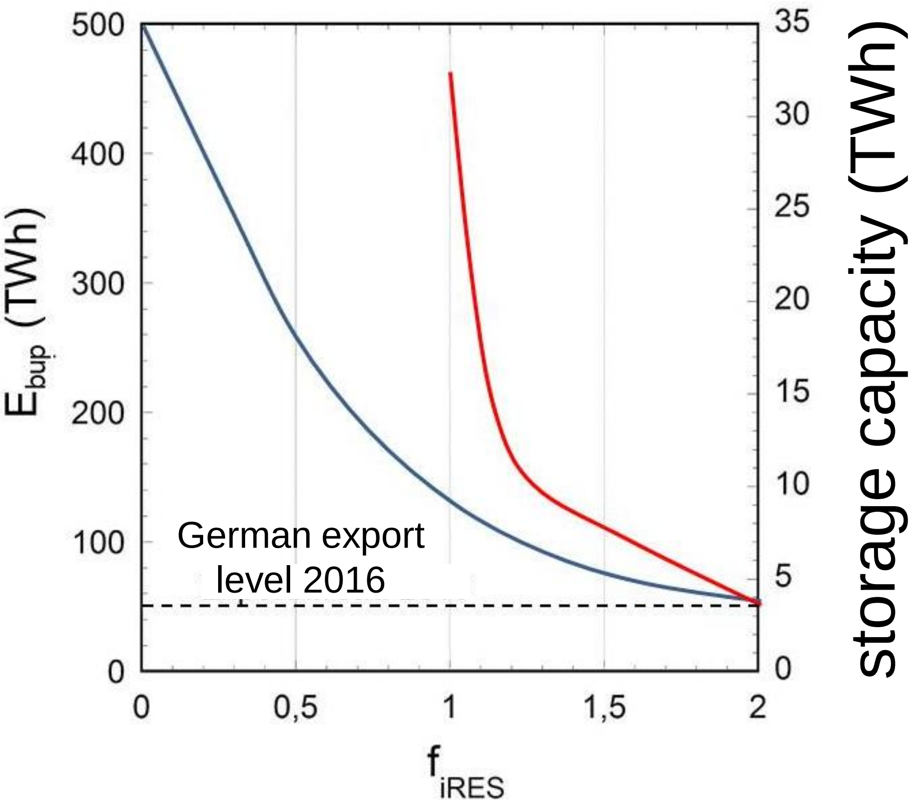
# Overproduction of electricity



back-up and surplus production

Germany´s neighbours



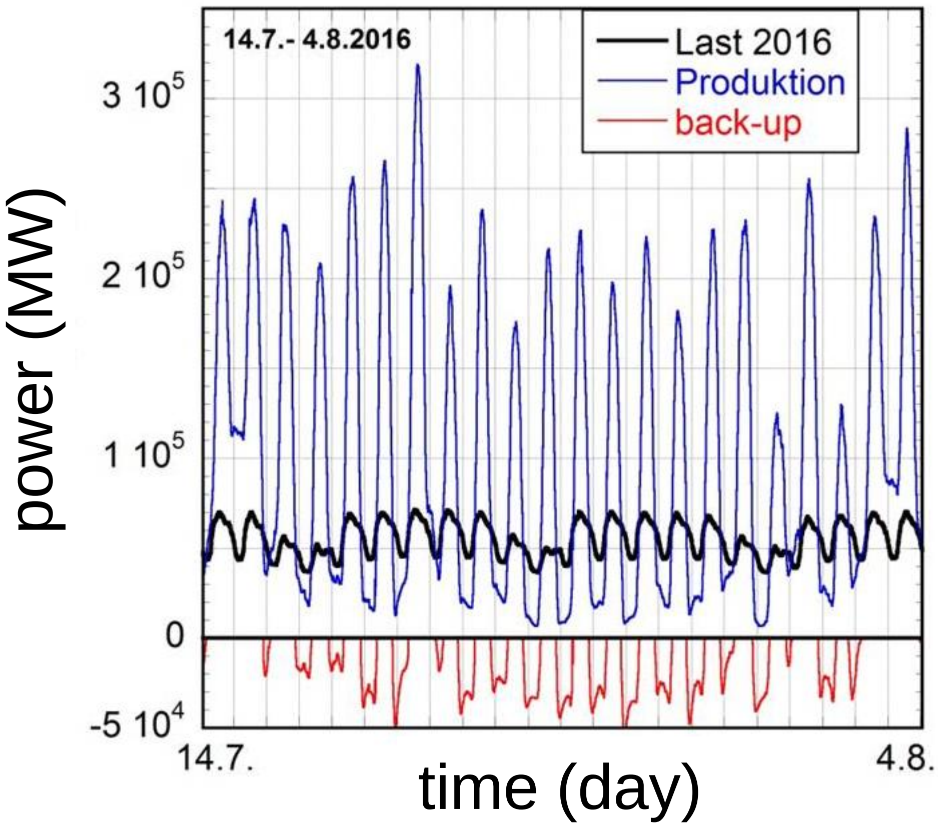



# Overproduction of electricity



- a good example for the need of time-resolved studies

Still periods where electricity demand cannot be met



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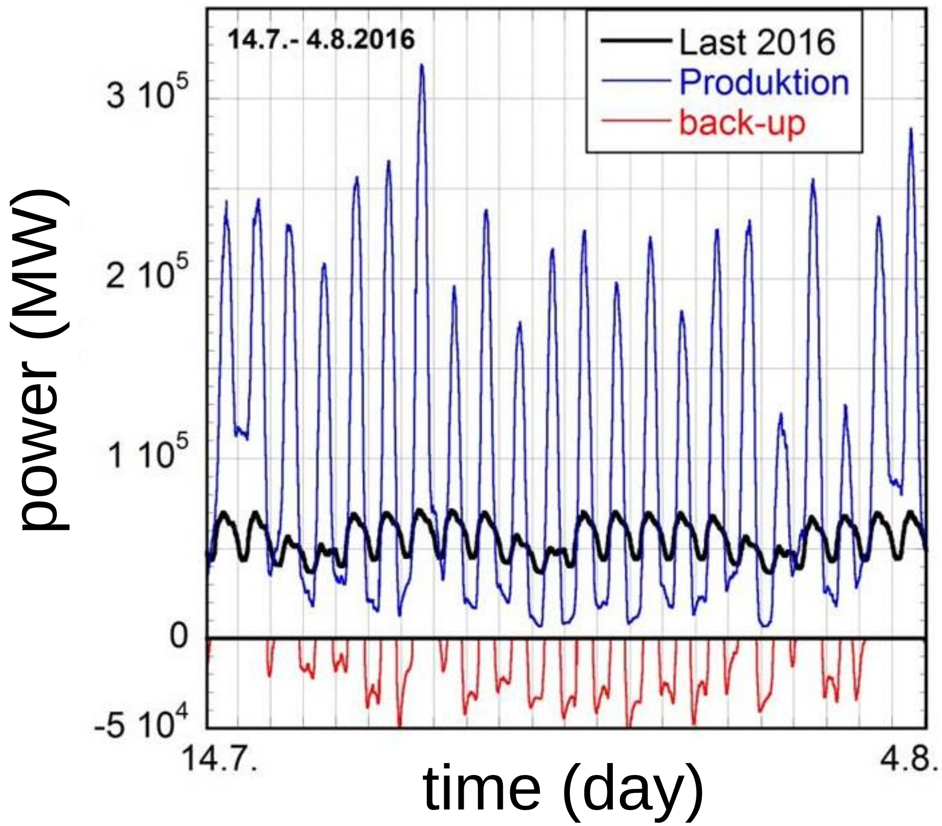
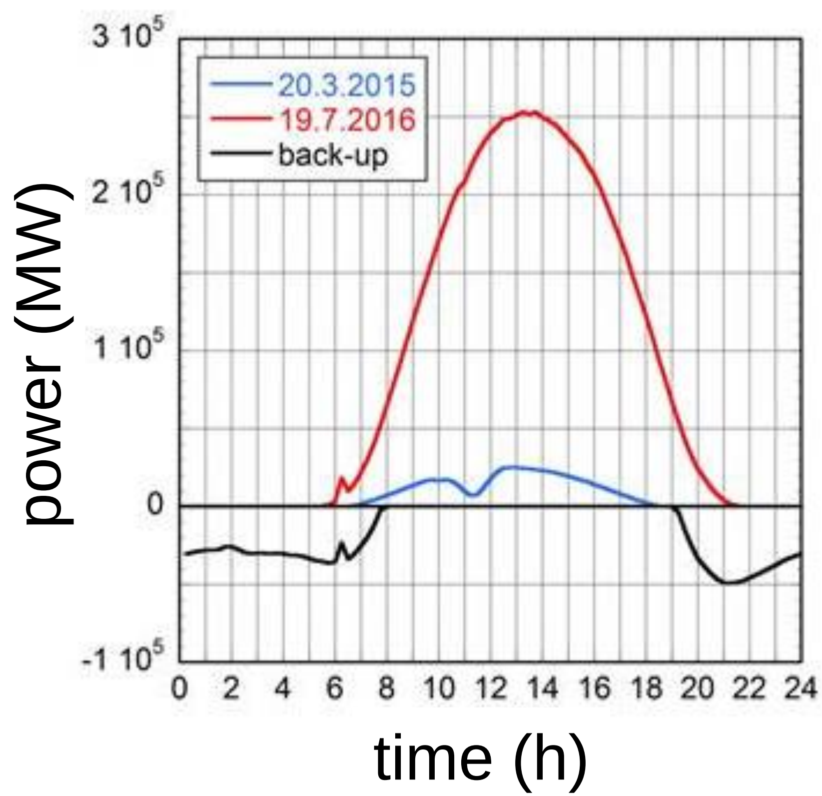



Strong grid dynamics



# Conclusions



Data on electricity production and consumptions are easily available.

They can be used in a simple and transparent form to analyse the energy transition using mostly intermittent sources.

# Publications along this line




**Germany**

F. Wagner "*Electricity by intermittent sources : An analysis based on the German situation 2012*", Eur. Phys. J. Plus 129 (2014) 20.

F. Wagner "*Surplus from and storage of electricity generated by intermittent sources*", Eur. Phys. J. Plus 131 (2016) 445.

H. W. Sinn "*BUFFERING VOLATILITY: A STUDY ON THE LIMITS OF GERMANY'S ENERGY REVOLUTION",* accepted for publication in European Economy Review.

**France**

D. Grand, et al. "*Electricity production by intermittent renewable sources: a synthesis of French and German studies"* Eur. Phys. J. Plus 131 (2016) 329.

**Italy**

F. Romanelli *"Strategies for the integration of intermittent renewable energy sources in the electrical system"* Eur. Phys. J. Plus 131 (2016) 53.

**Czech Republic**

F. Wagner and F. Wertz *„Characteristics of electricity generation with intermittent sources depending on the time resolution of the input data"* Eur. Phys. J. Plus 131 (2016) 284.

**Sweden**

F. Wagner and E. Rachlew "*Study on a hypothetical replacement of nuclear electricity by wind power in Sweden"* Eur. Phys. J. Plus 131 (2016) 173.

**Spain**

R. Gómez-Calvet et al. "*Present state and optimal development of the renewable energy generation mix in Spain*" to be published in Renewable and Sustainable Energy Reviews

**EU**

F. Wagner "*Considerations for an EU-Wide use of renewable energies for electricity generation*", Eur. Phys. J. Plus 129 (2014) 219.

# Major Results



How much power has to be installed?
Enough to serve Europe in good days

The remaining need for back-up power?
12% saving in power;
2 parallel systems are needed

The extent of surplus energy?
Formally enough to serve Poland

Dimension of seasonal storage?
For the 100% case: 660 x present capacity

The dynamics of the back-up system?
From 0 up to the load; strong gradients

The conditions for DSM (demand-side management)?
Cheap electricity prices during the day

The amount of $CO_2$ reduction?
Not to the level of France, Sweden, Switzerland...

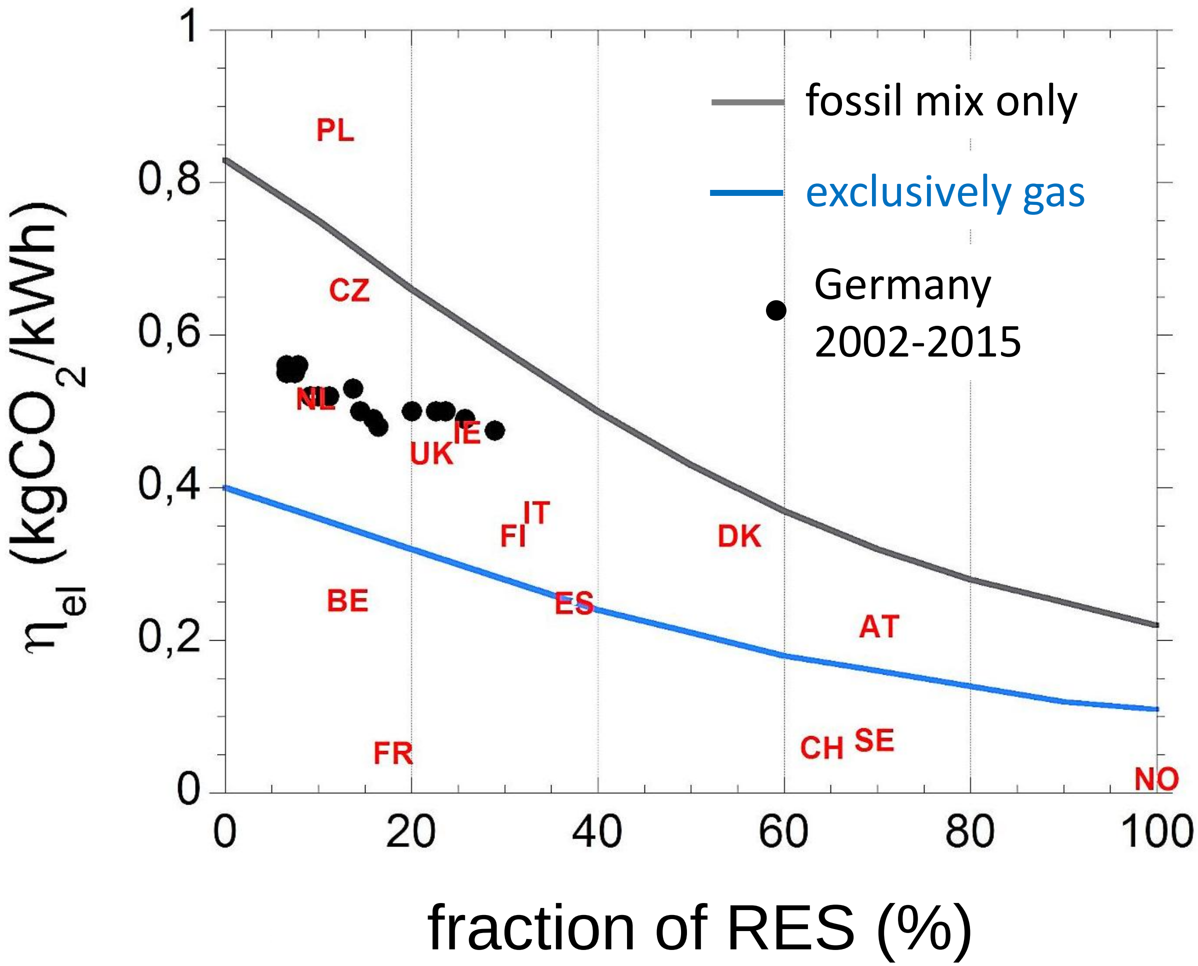
Conditions of a 100% supply by RES?
Use of biogas (e.g. 40 TWh) and savings (down to 30%)

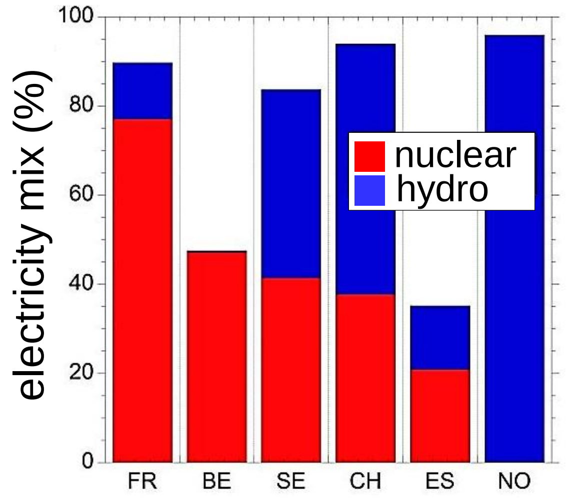
What could be a reasonable share by iRES?
40%

# Thank you

# Comparison of specific $CO_2$ emissions

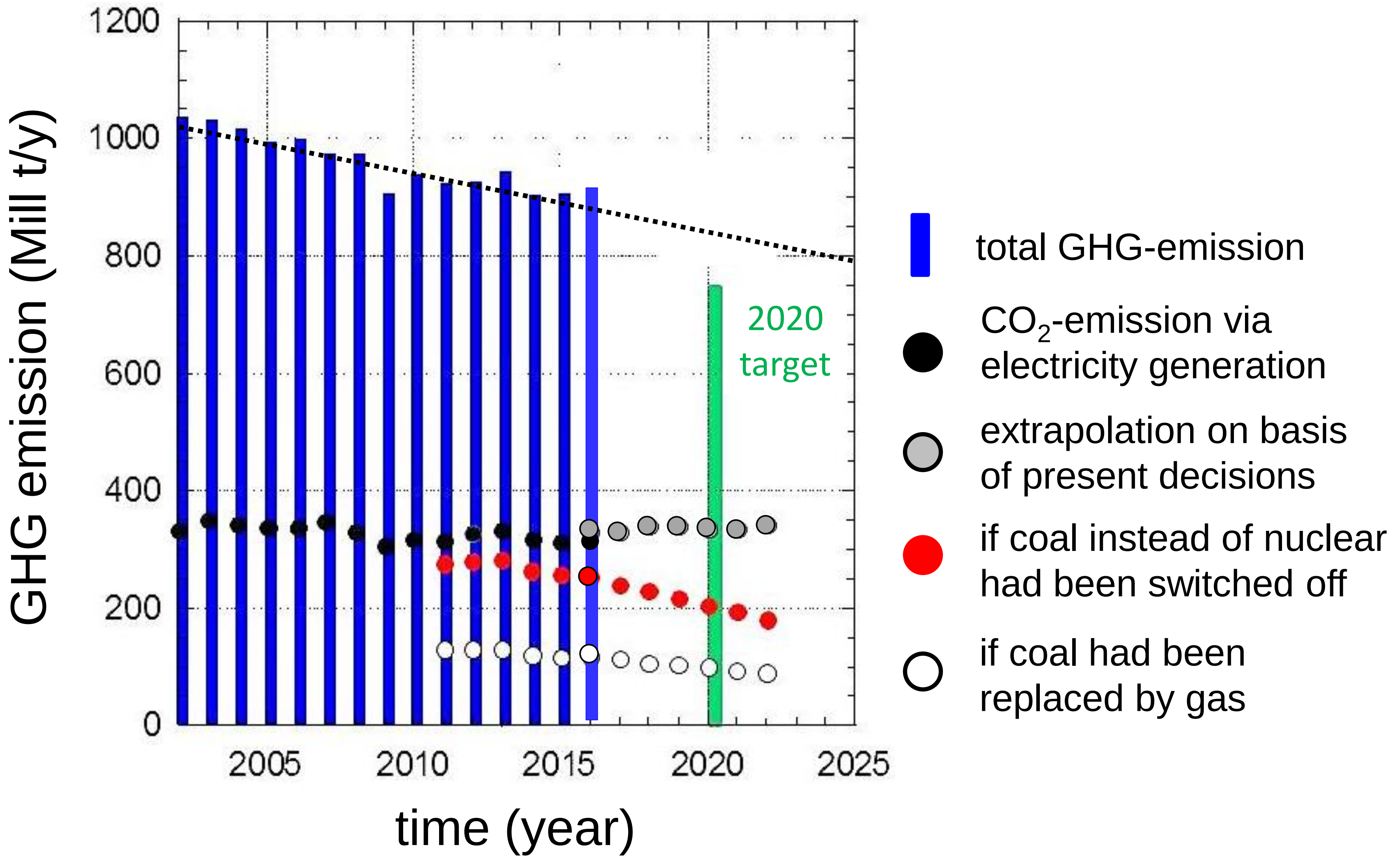




# GHG and $CO_2$ emissions from Germany

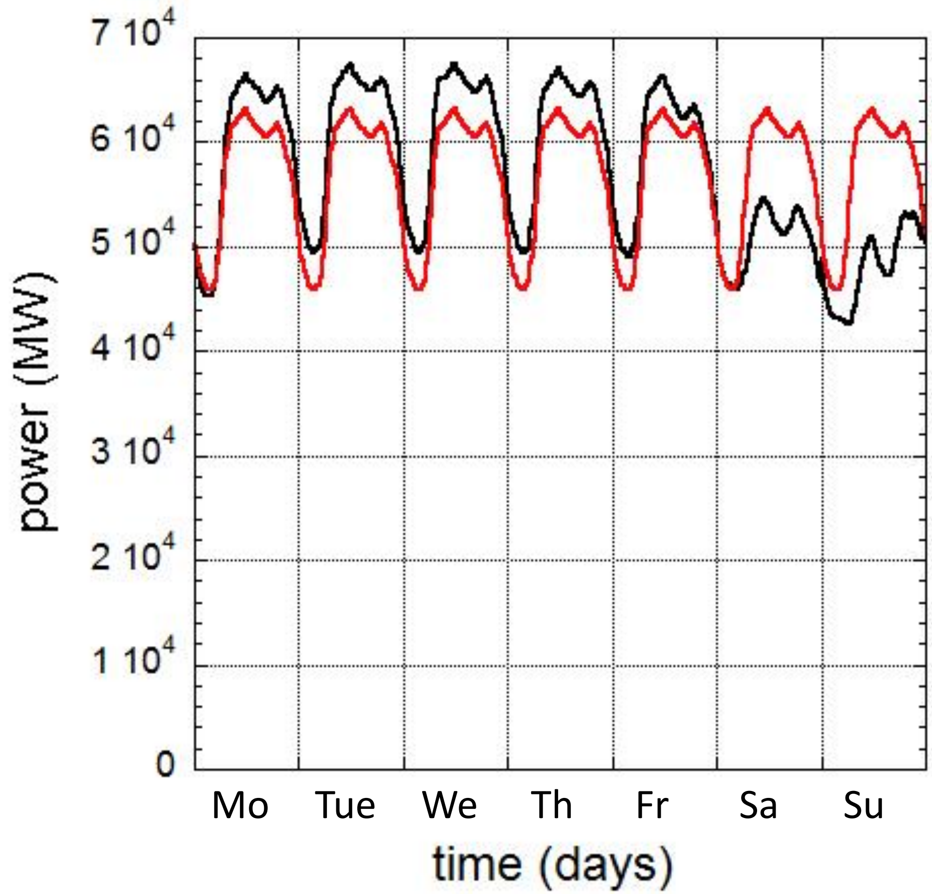




# Demand-side management



Integration of weekends into economic activities




Additional use of iRES: 7.9 TWh

Peak-load: 83 → 63 MW

Reduction of back-up system:
131 → 123 TWh

# Other uses of surplus energy

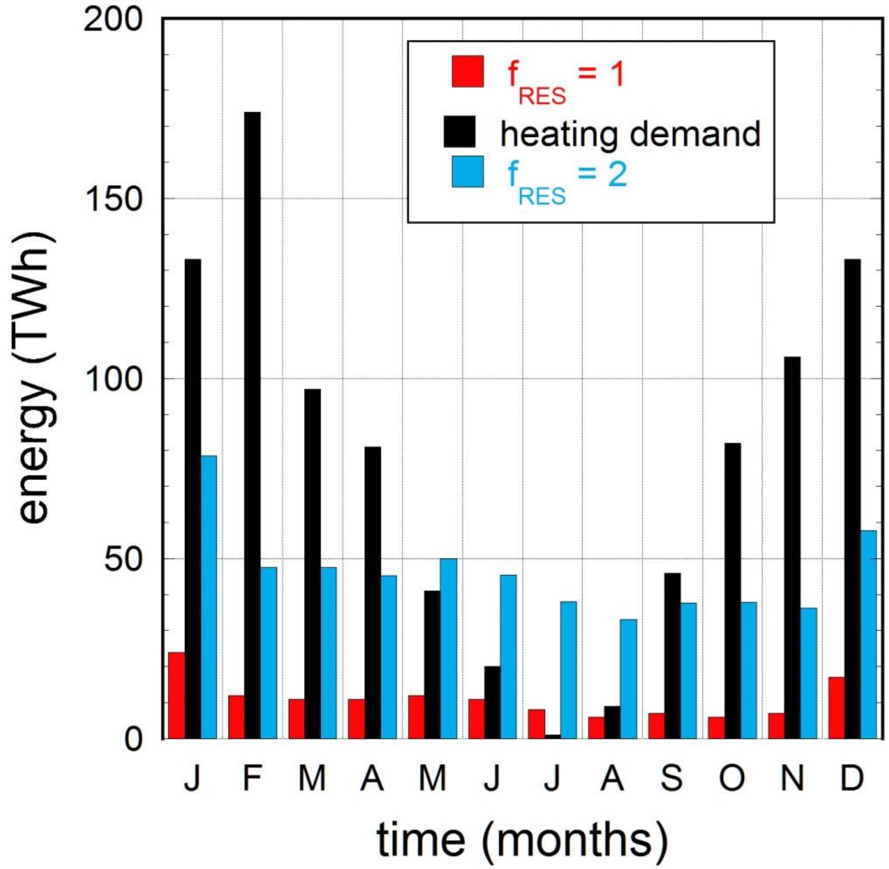


1. Production of $H_2$ for industrial purposes

2 MW → ~ 360 $m^3$/h: 130 TWh ($f_{RES}$=1) → ~ 20 Mrd $m^3$ $H_2$ ~ use in German industry

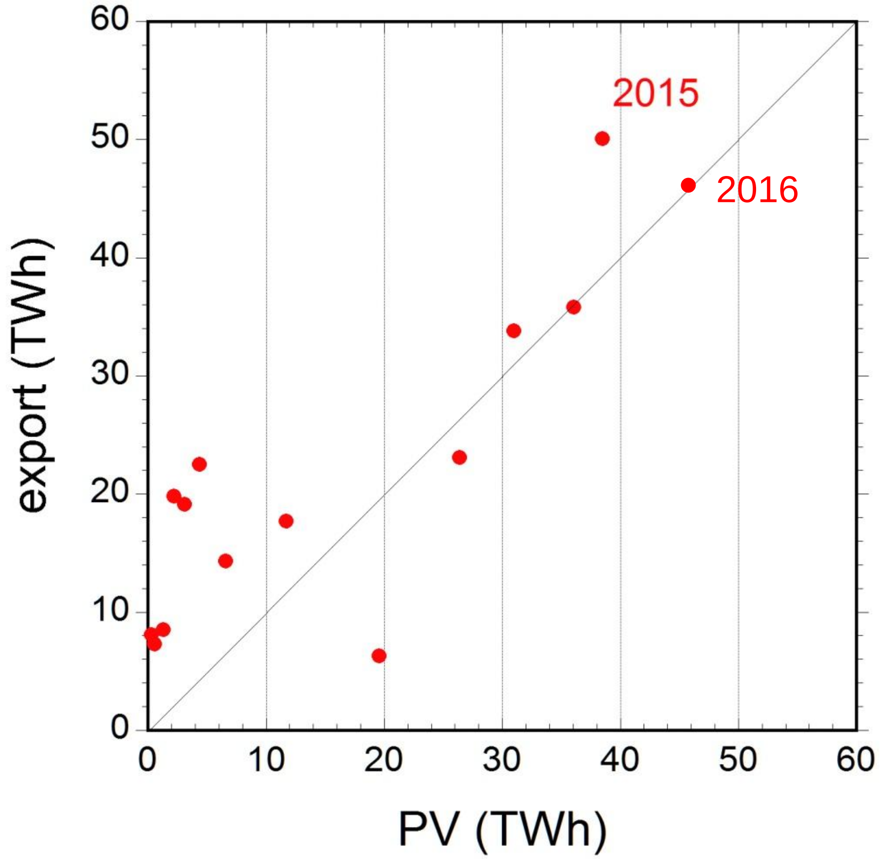
2. For heating

- a substantial share is possible
- for $f_{RES}$=1 not sufficient
- for $f_{RES}$=2 heat insulation needed



# Surplus production today






**Today:**

The electricity export strongly increases and agrees **nominally** with the PV energy generated

# The use of biomass



Biomass =
Residual material, biogenic waste
Crops = raps (diesel), corn+cereal (biogas→electricity, 50 TWh),
cereal+sugar beets (ethanol)
Wood: 19% (2015) of German wood harvest for energetic use (burned)

Involved areas:
agriculture total: 18 Mill ha
animal food: 10.2 Mill ha; food: 4.5 Mill ha; bioenergy: 2.1 Mill ha →PE of 270 TWh
forest: 10.7 Mill ha

Limiting factors:
Waste: about 2/3 is already used
All gen. 1 bioenergies (crops) have low (or no) GHG savings
Agriculture: 1/3 of animal food proteins imported as Soja beans. Would need 3 Mill ha
Forest: total use of wood: 120 Mill $m^3$; national production ~ 55 Mill $m^3$; Carbon content of forests critical
Signs of losing bio-diversity in Germany

**Conclusion: Biomass is strongly limited and has to be used for transportation**

# Conclusion #2



The concept of demand-side-management has restricted potential

A direct use of surplus electricity is advisable

Transformation of surplus electricity into $H_2$ could be useful

The production of secondary electricity is doubtful

- storage is a thermal system with high losses
- its operation also depends on weather conditions

# Conclusion #4



In the future, the discussion on energy savings will complement, maybe replace the one on energy production.

I doubt that a complete decarbonisation with intermittent RES will be possible:

from 180 TWh today to 1300 TWh

from 82 GW today to more than 1000 GW installed power

with more than ½ million wind-turbines

# Conclusion #5 and summary



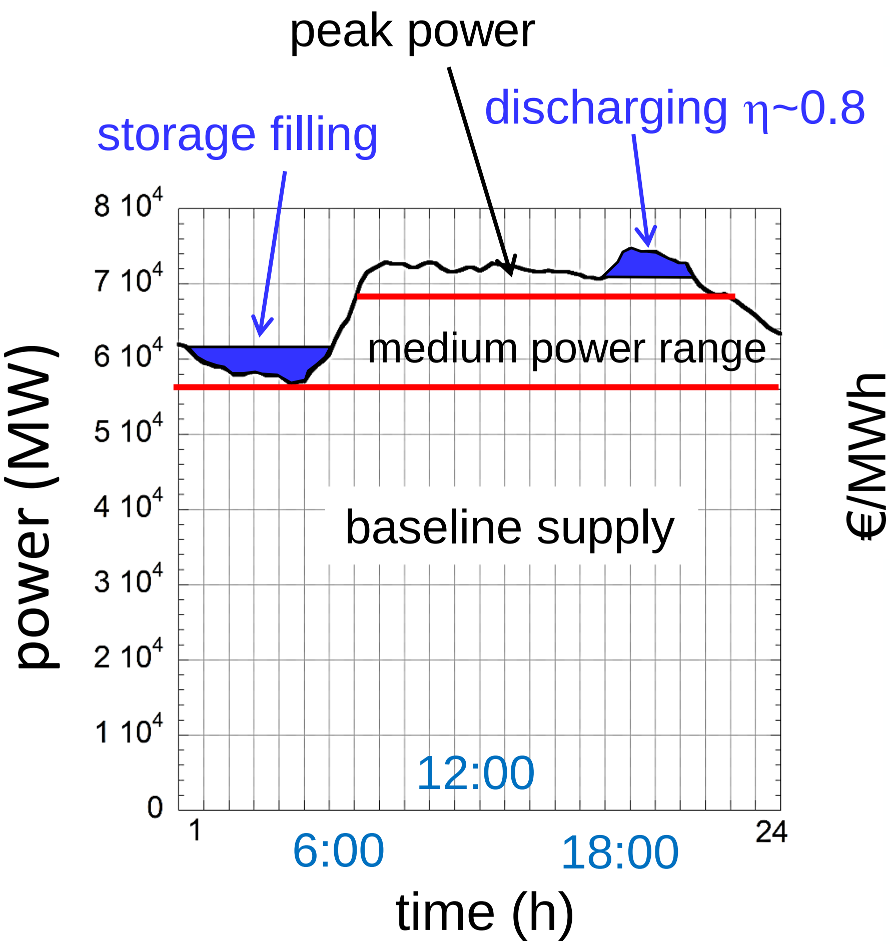
The consequences of the “Energiewende”

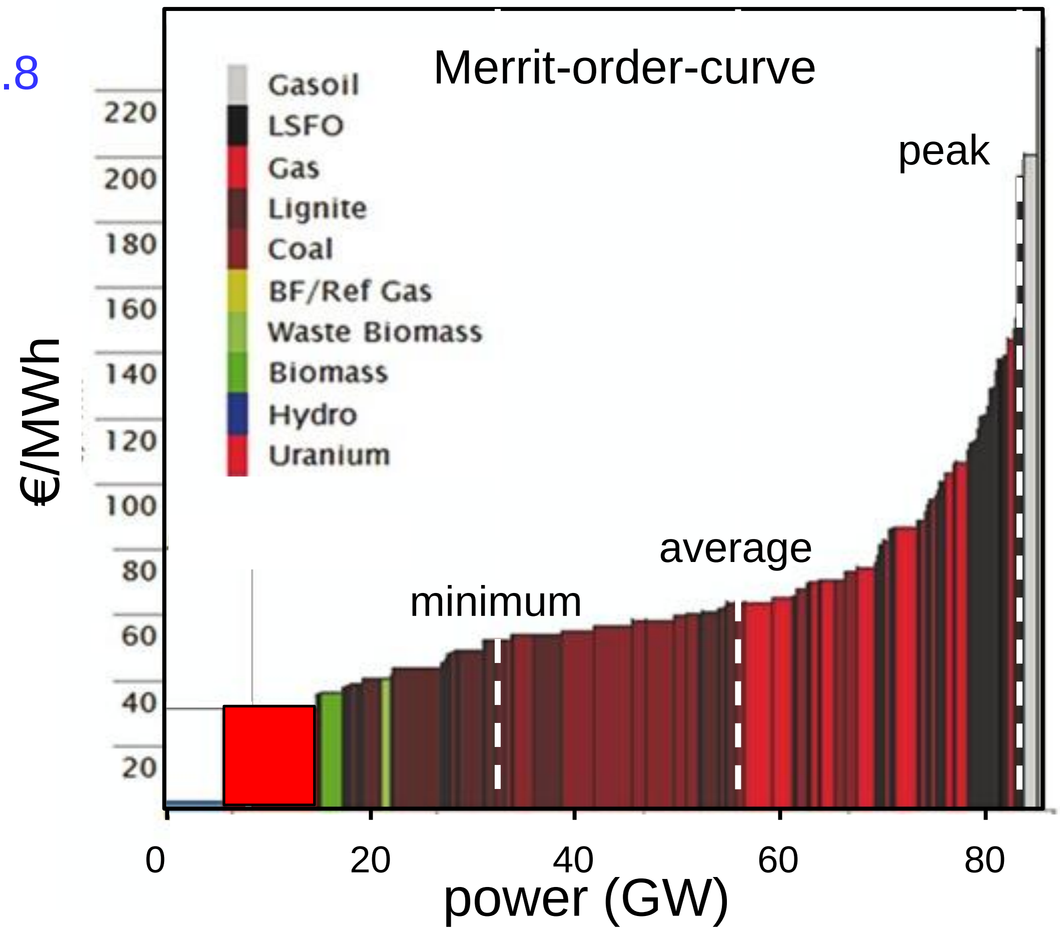
Production in 2016:

78 TWh by wind
37.6 TWh by PV
20.5 TWh by hydro
47 TWh via biomass

the highest electricity price in Europe together with Denmark
24 b€ feed-in subsidy for an electricity value of 3 b€
Electricity export at the level of PV production
2016: 97 h with negative spot-market prices
Chain of phase-shift transformers around Germany
Partial destruction of traditional suppliers – stock market value, lay-offs
No creation of new technologies – PV producers went into insolvency
Polarisation of the general public because of high windmill density
No rewarding effect on Germany´s GHG emissions

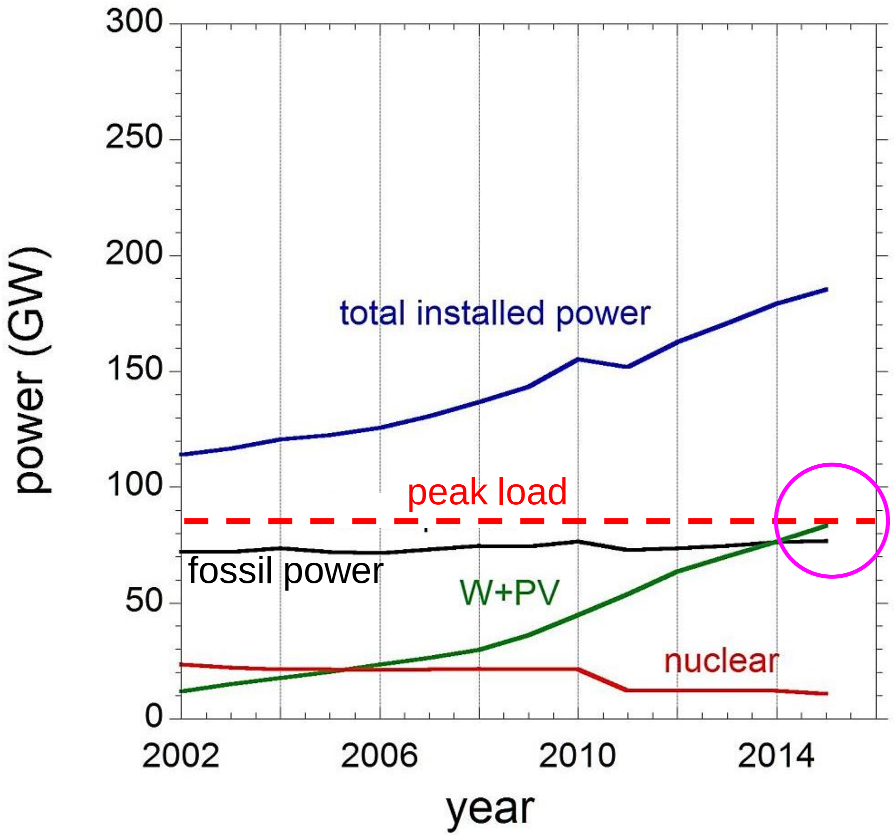
# Selection of supply technology




http://et-energie-online.de/Portals/0/PDF/zukunftsfragen_2013_01_kranner.pdf

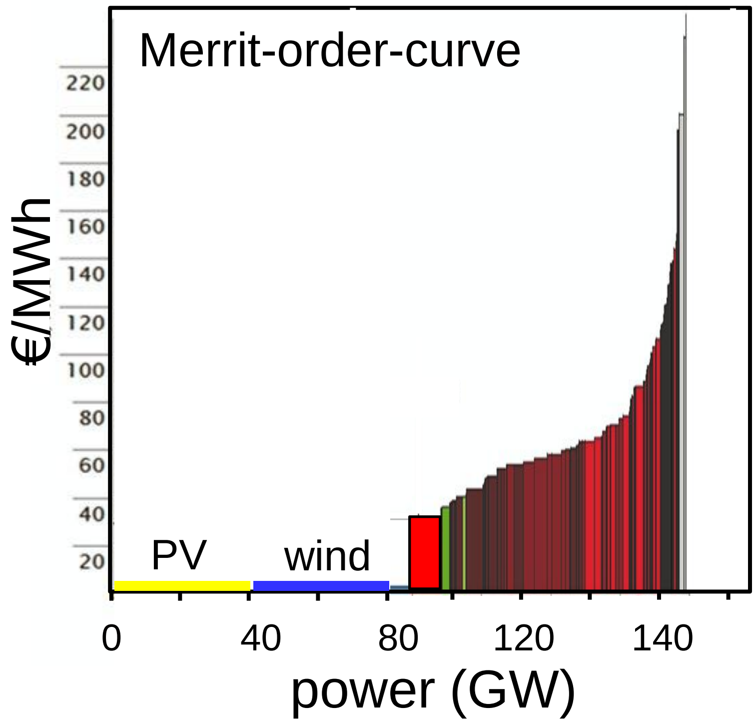
# Power levels to be installed




Wind+PV power ~ peak load
Wind+PV ~ fossil + nuclear

Large overcapacity

## Economic consequences

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# Conclusion #1

Wind- and PV-power suffer from

low power density

intermittency

Consequences:

large power capacities necessary

surplus production

back-up needed → 2 separate systems of largely different technology

the back-up system requires a new economic model

→ capacity market