Is fusion still needed ?

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

The **old** time scale for fusion development given by resource limits:
oil: 40 y gas: 60 y coal: 150 y

The **new** time scale determined by environmental concerns:

If the global temperature rise should be limited to 2°C
→ 1000 bn tons of CO_2 can still be emitted

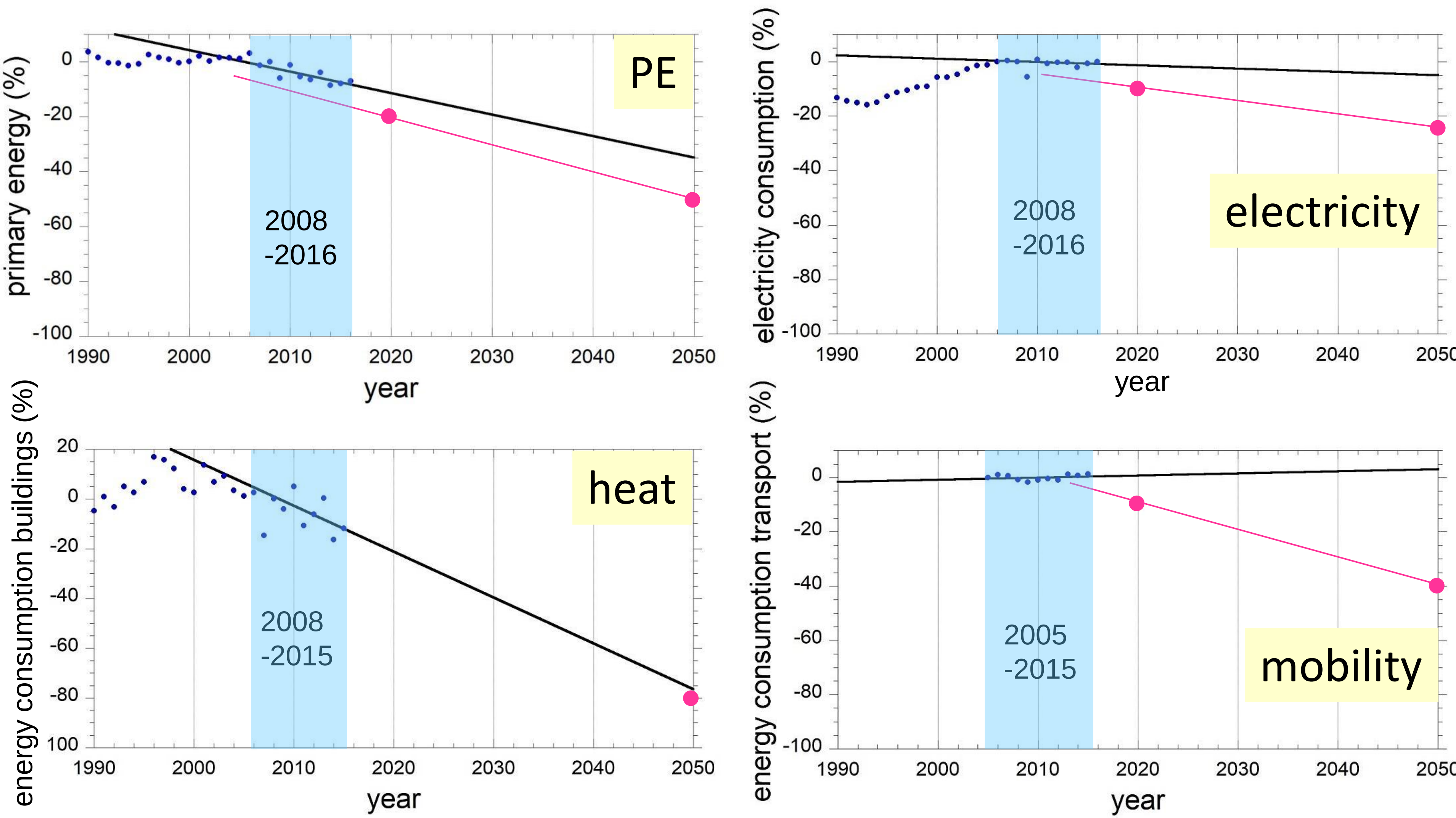
average per-capita GHG* release	= 5 tons/y	→ 25 y
average EU release	= 7.7 t/y	→ 16 y
average German release	= 9.5 t/y	→ 13 y
average US release	= 16.5 t/y	→ 8 y
average Indian release	= 1.7 t/y	→ 74 y

The new situation leads to strongly reduced time scales

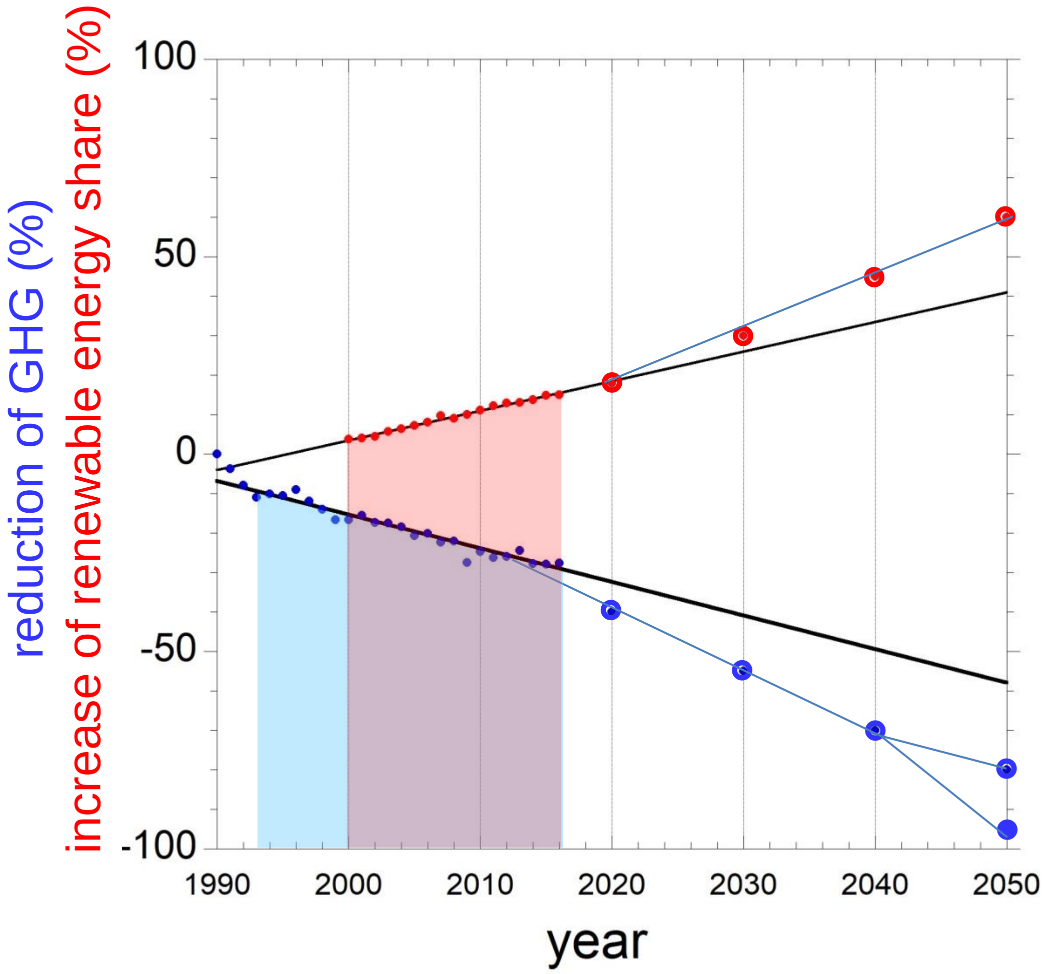
*GHG = green-house-gas

The political response: goals for the next decades

• actual data — fit ▭ range for fit ● political goals — guide for the eye



Goal and method



Fusion seen from the outside

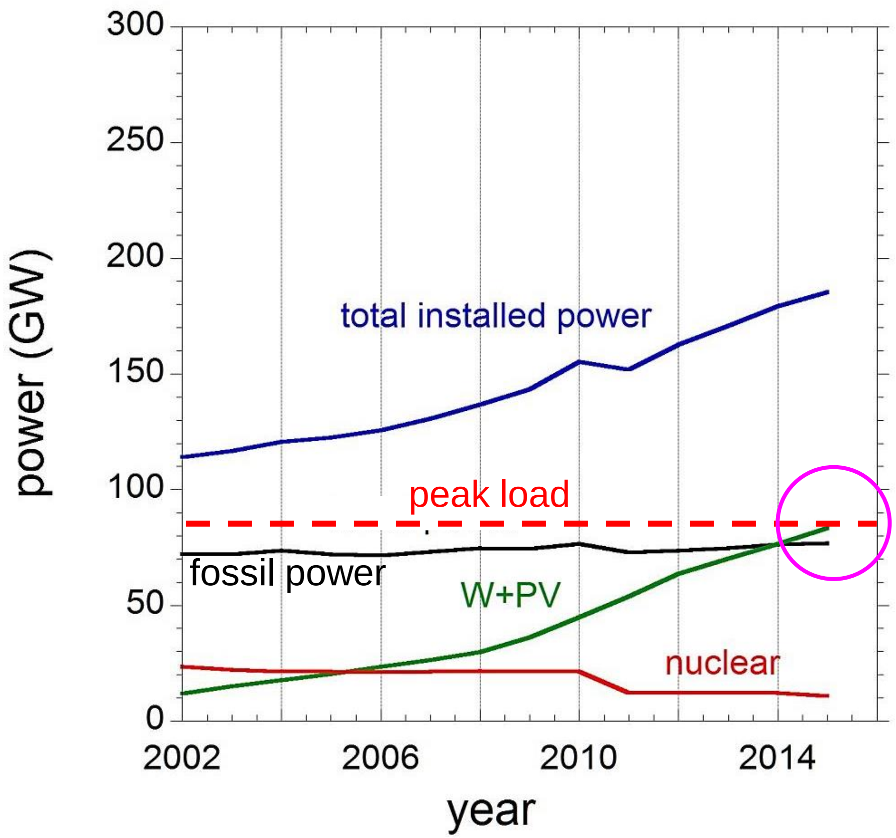
1. Fusion can only enter the market on a meaningful scale after 2100.

2. Fusion will provide a product – continuous electricity – that will at that time not fill the real need, which is dispatchable* electricity and fuel.

3. When fusion is ready to enter the energy mix it will not be competitive with sources like solar and wind in combination with conversion and storage, and therefore will lack the push for deployment.

*to dispatch: deliver according to demand

Renewable energies (RES) in Germany



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

Large overcapacity

Ways to reduce consumption

Heat:

heat-pumps
direct electrical heating

Transportation:

electric cars
Hydrogen cars: electricity-electrolysis-hydrogen
Synthetic fuel: electricity-electrolysis-hydrogen-higher carbon-hydrids

Today: PE: chemical →

Mechanical energy (transport)
Electricity
Heat

Future: PE : electrical →

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

Ways to reduce consumption

Heat:

heat-pumps
direct electrical heating

Transportation:

electric cars
Hydrogen cars: electricity-electrolysis-hydrogen
Synthetic fuel: electricity-electrolysis-hydrogen-higher carbon-hydrids

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

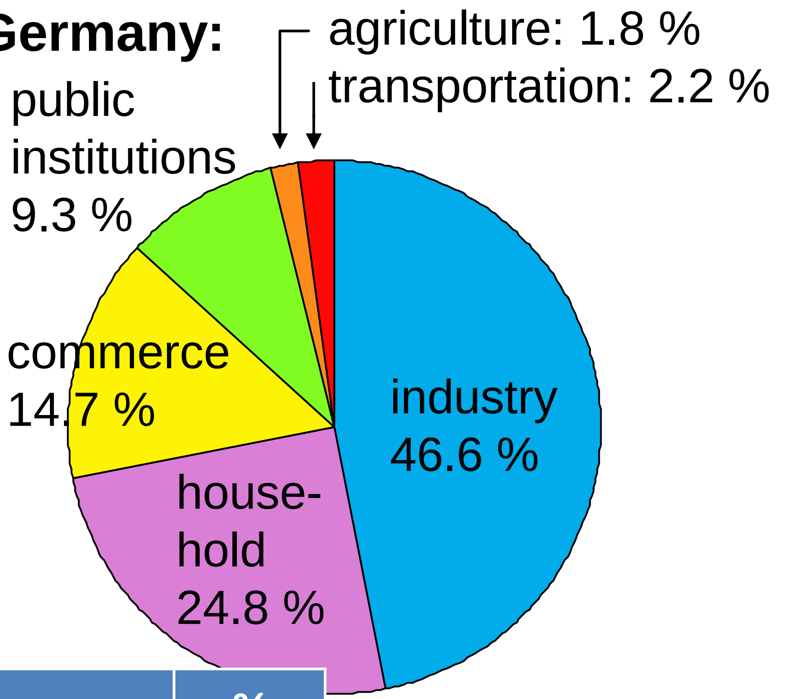
Future: PE : electrical →
Chemical energy (storage)
Heat (heat pump)
Electricity → transport

1. Topic: Electricity

Electricity production and consumption in Germany:

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

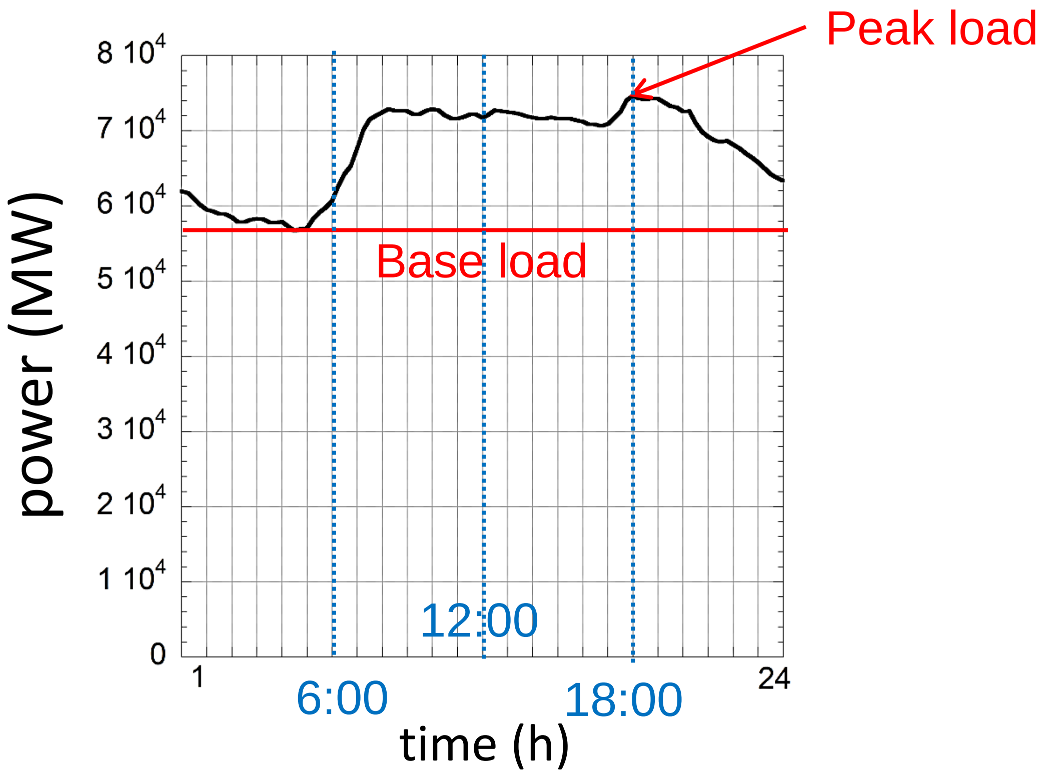
→ net electricity consumption: 540 TWh
per-capita: 6.6 MWh
corresponds to: 752 W



Household electricity consumption	%
refrigerator	29
stove, electric iron, dryer	19
Hot water, washing machine dish washer	17
Heating	15
TV, radio, PC	12
illumination	8

Specifics of electricity consumption

Load* variation during Tue 31.1.2012



* load = demand

Important:

Supply has to meet demand at every moment

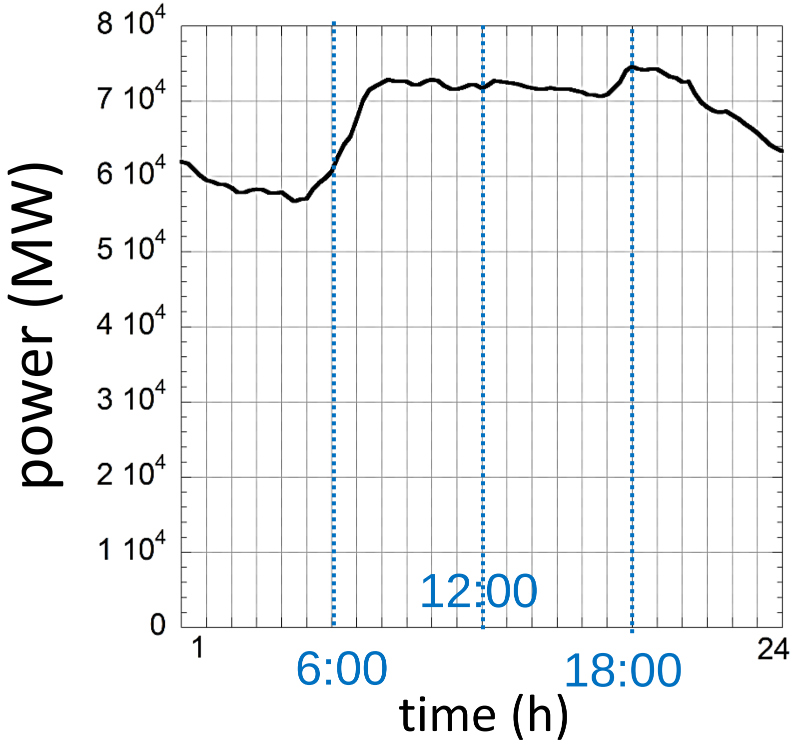
It is not sufficient to talk on integral values of energy only

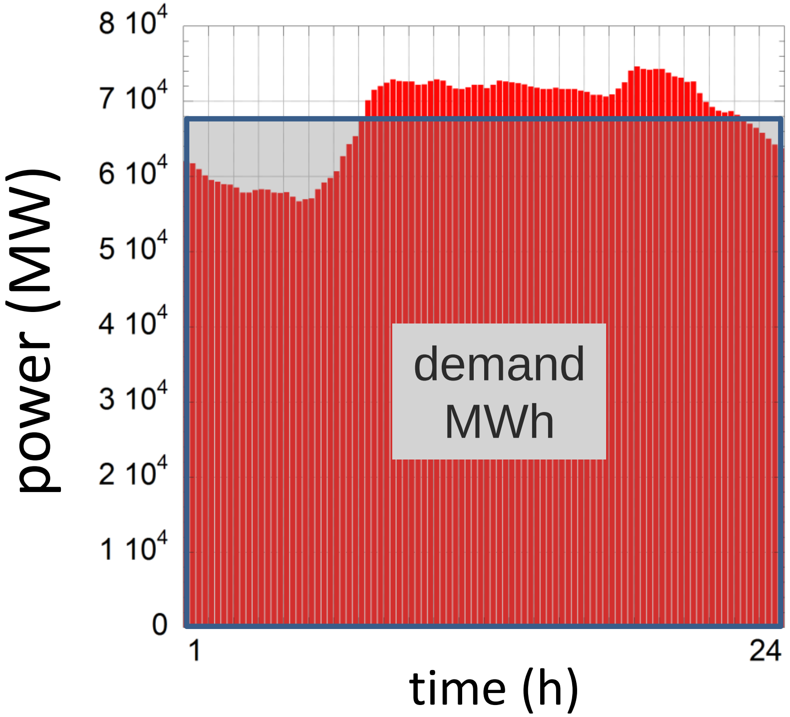
Consumption is very variable e.g. cooking needed: 3800 W for 2 hours average in the day: 320 W

Time-resolved analysis is necessary

Electricity consumption in Germany

Load variation during Tue 31.1.2012

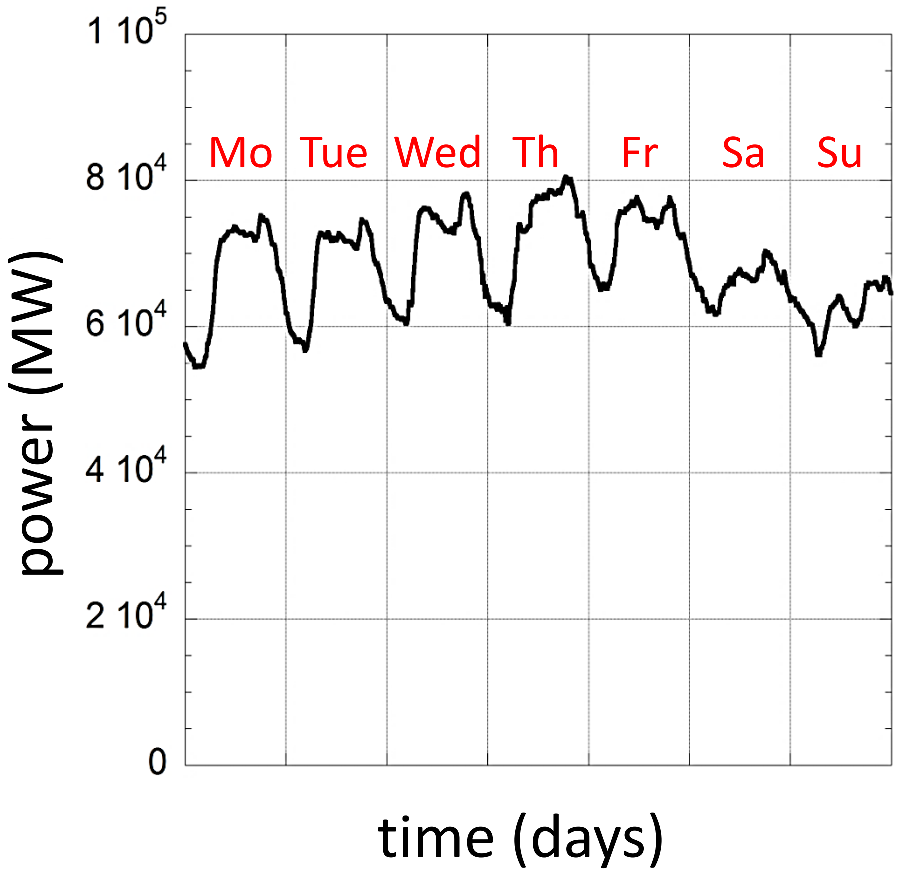




65 GW x 24 h x 365 days =
600 TWh

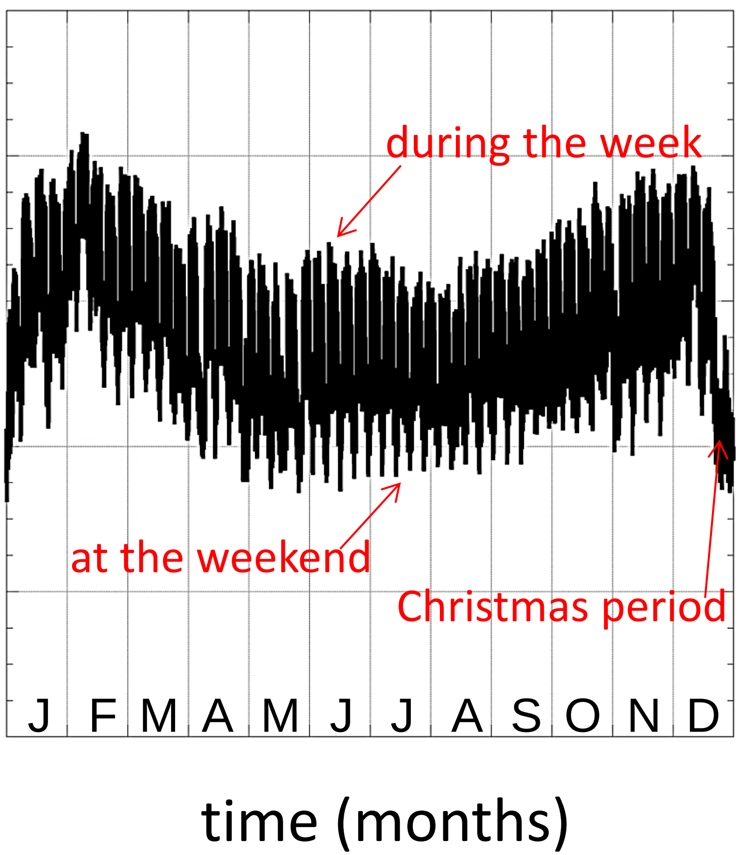
Specifics of electricity consumption

Load variation during the week



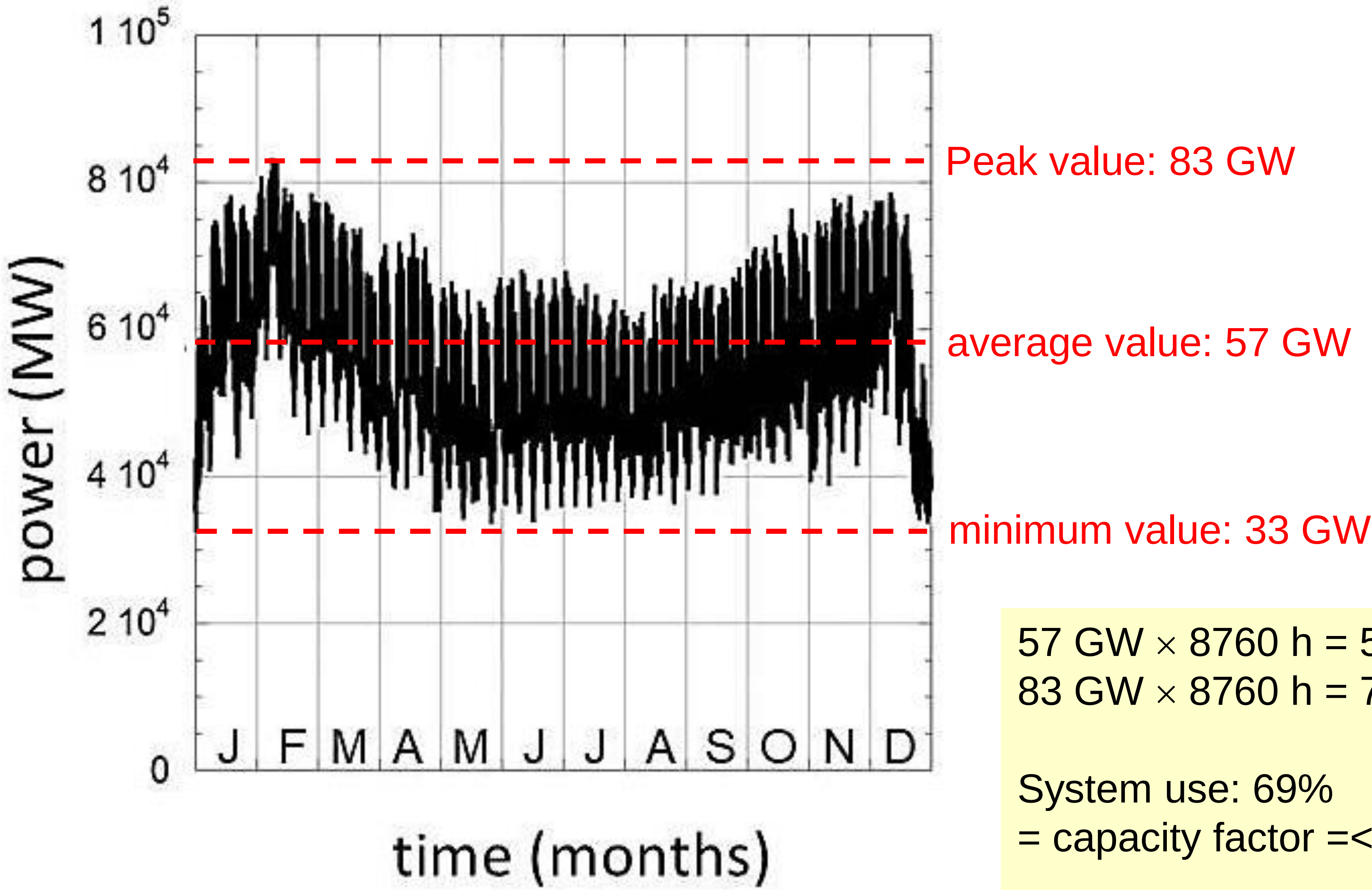
low at weekends

Seasonal variation



high in winter

Descriptive parameters

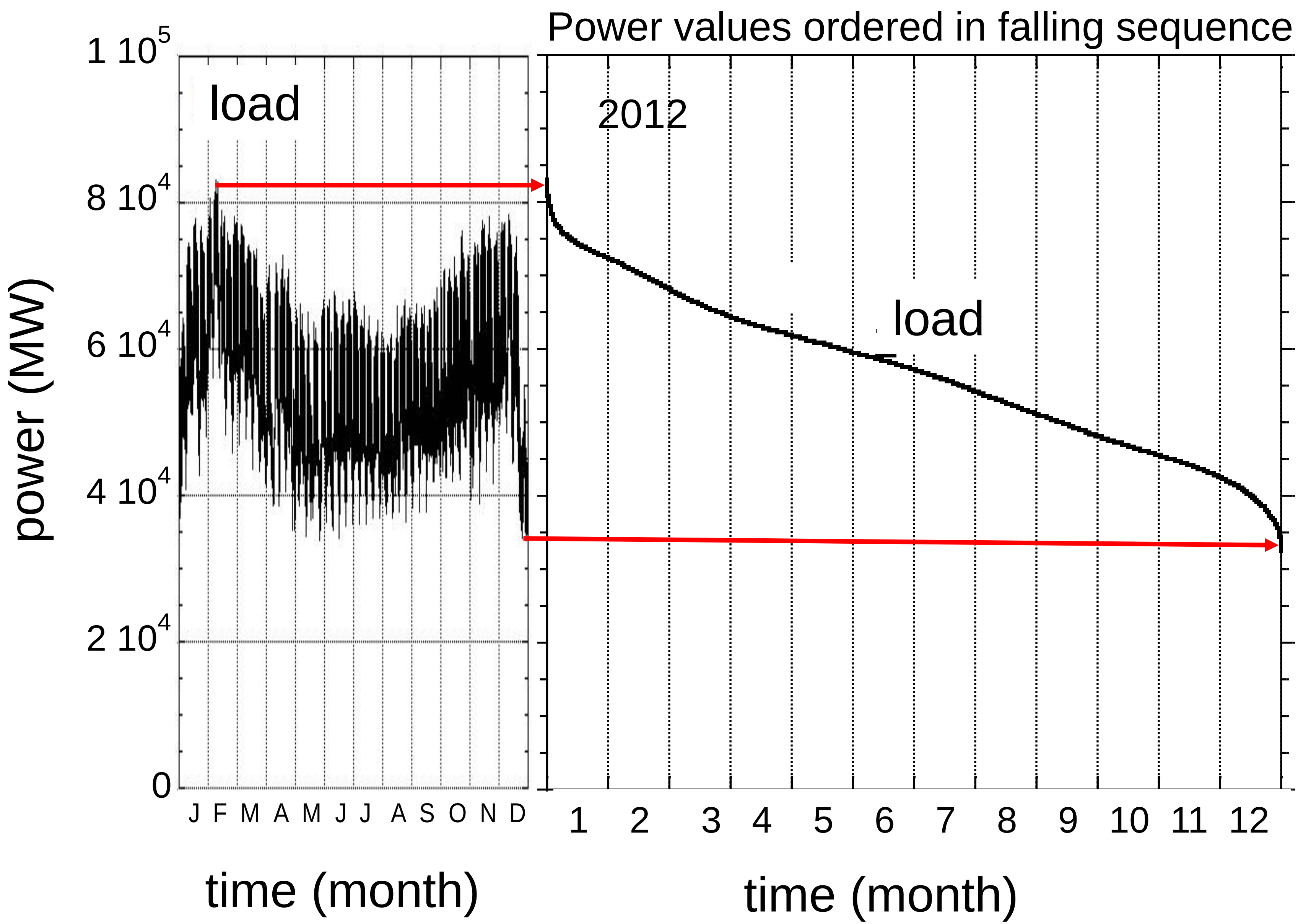


57 GW × 8760 h = 500 TWh
83 GW × 8760 h = 727 TWh

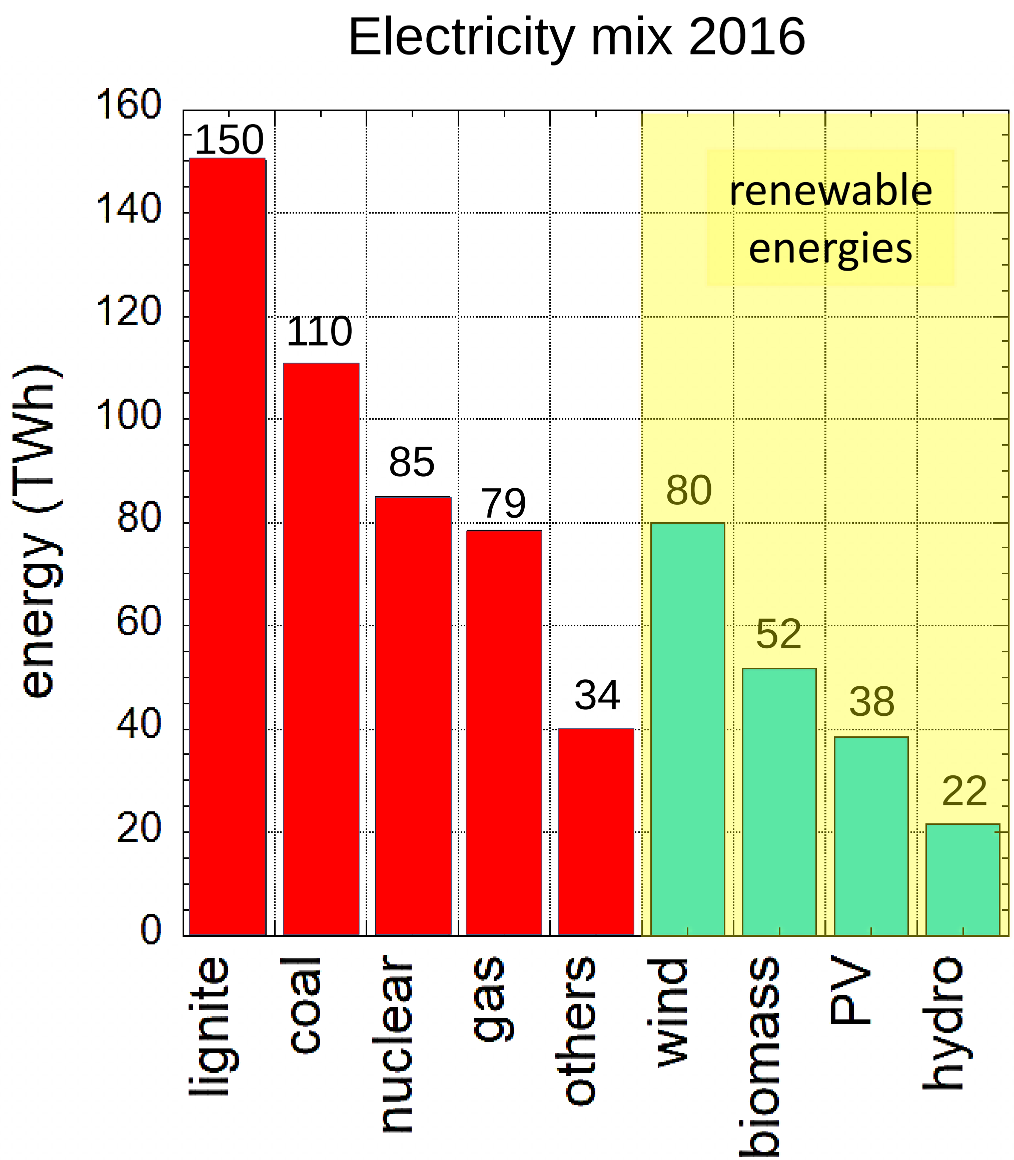
System use: 69%
= capacity factor $=\langle P \rangle / P_{inst}$

Full-load hours flh
$= 8760 \times \langle P \rangle / P_{inst} = 6016$ h

Annual duration curves

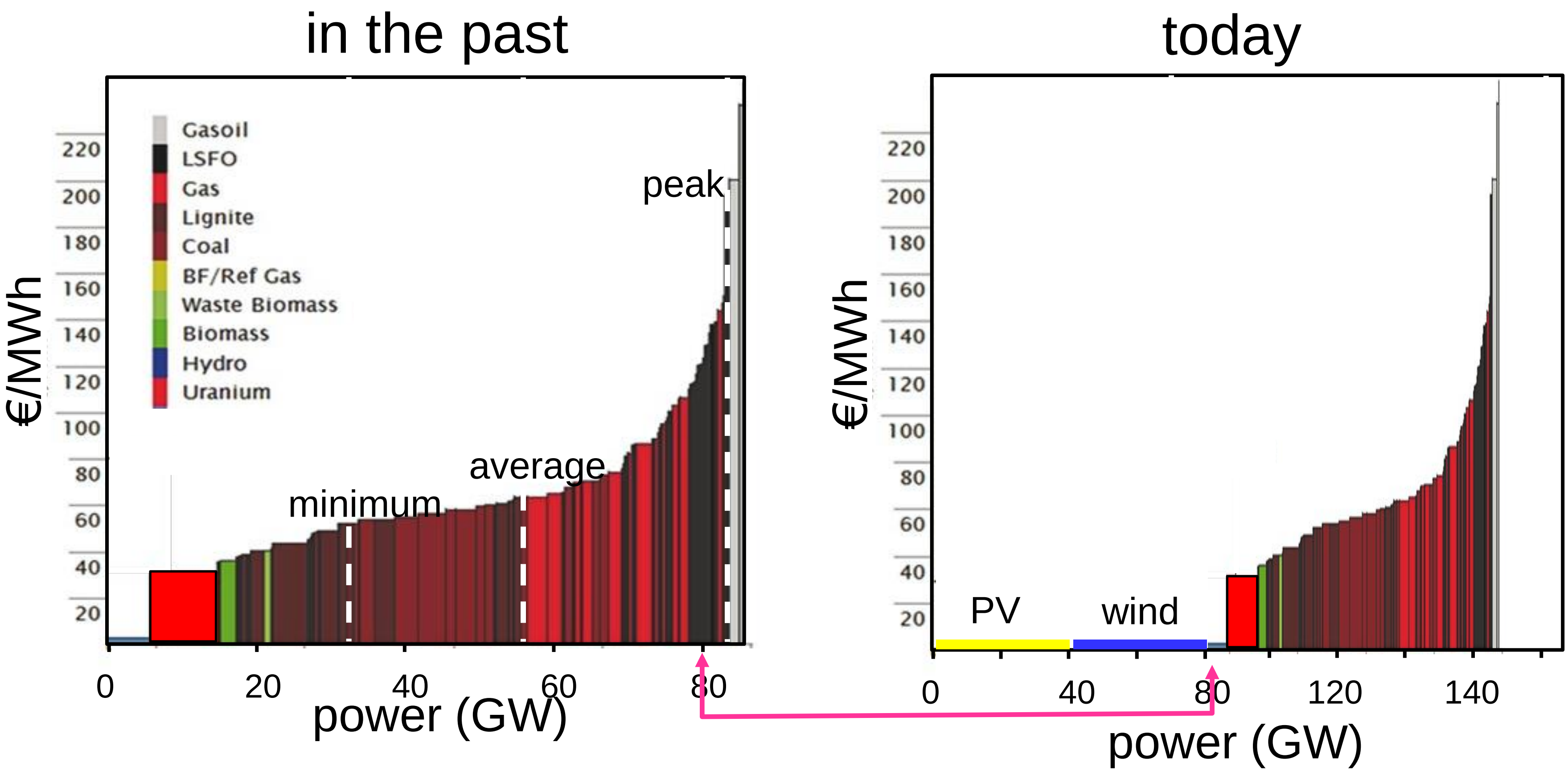


Electricity production of Germany - today



AGEB e.V.

Electricity price structure in the past



strong economic consequences on thermal systems

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

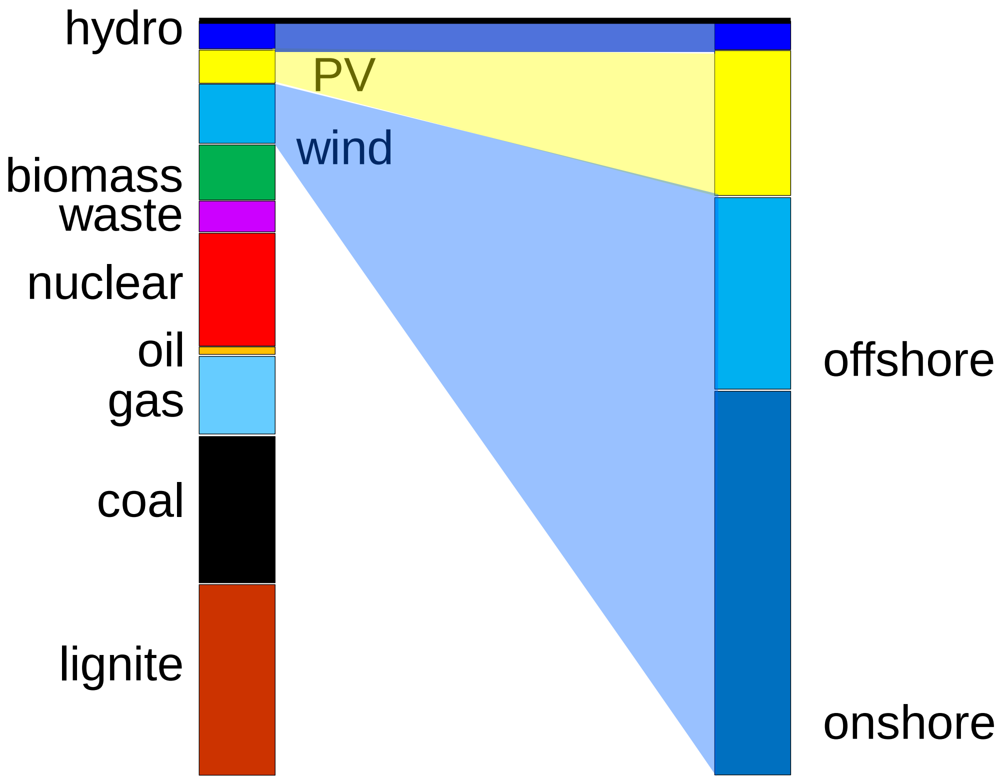
The transition to renewable energies only

Limited and scalable RES forms

hydro + biomass + others
are limited

only onshore, offshore wind
and
photovoltaic power (PV)
are scalable

2012: 520 TWh electricity use



The characteristics of wind and PV power

wind farm

PV park

1. Problem: low power density:

Wind: 2-3 W/m^2

PV: 5 W/m^2

Consequences:
Large areas needed
Large material investments

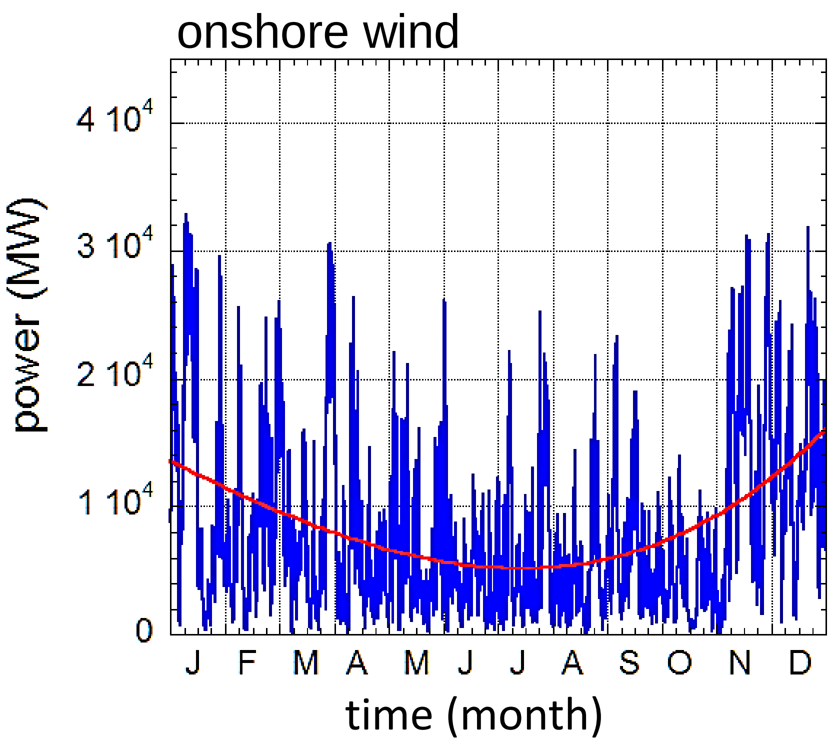
For comparison:

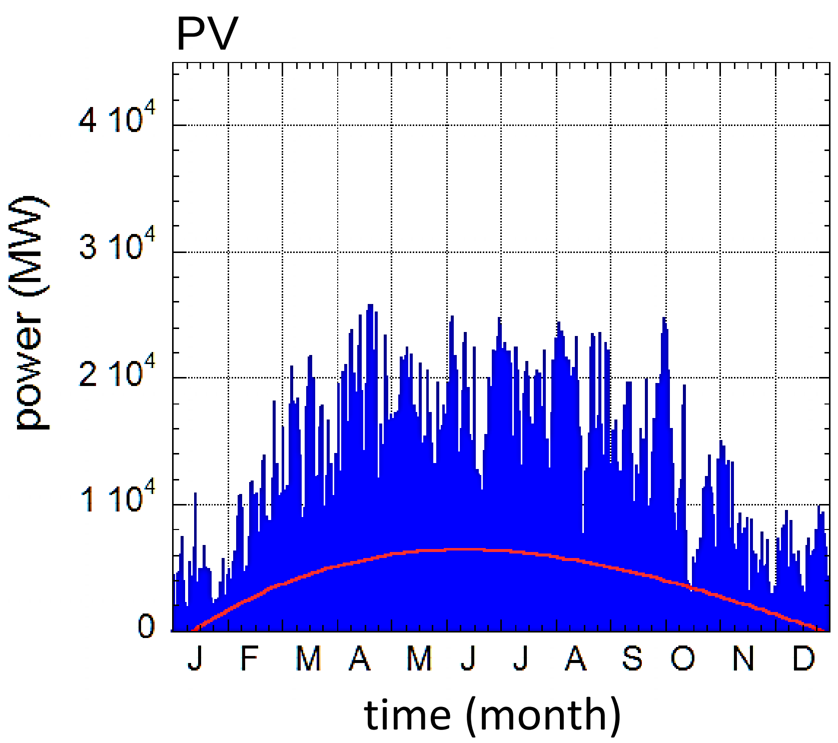
Germany
total energy density: 1.1 W/m^2

Munich
only electricity: 2.5 W/m^2

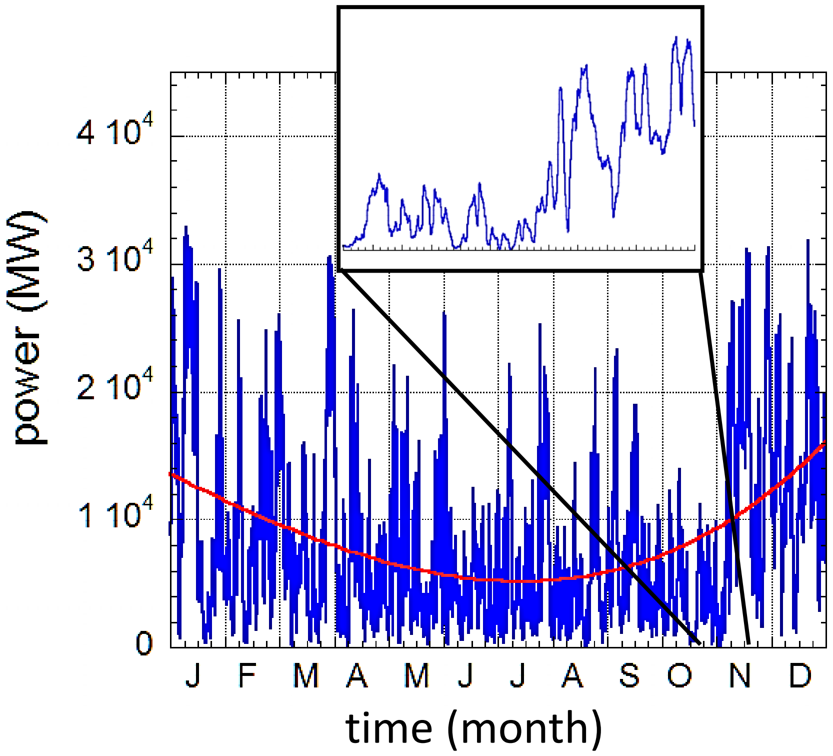
2. Problem: Intermittency of power production

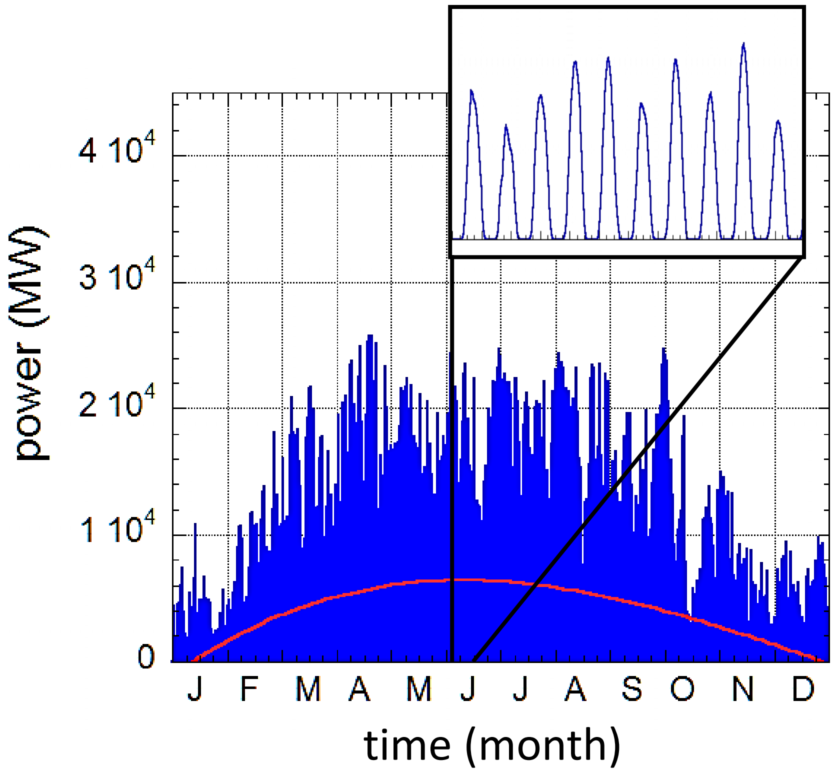
Data of 2015



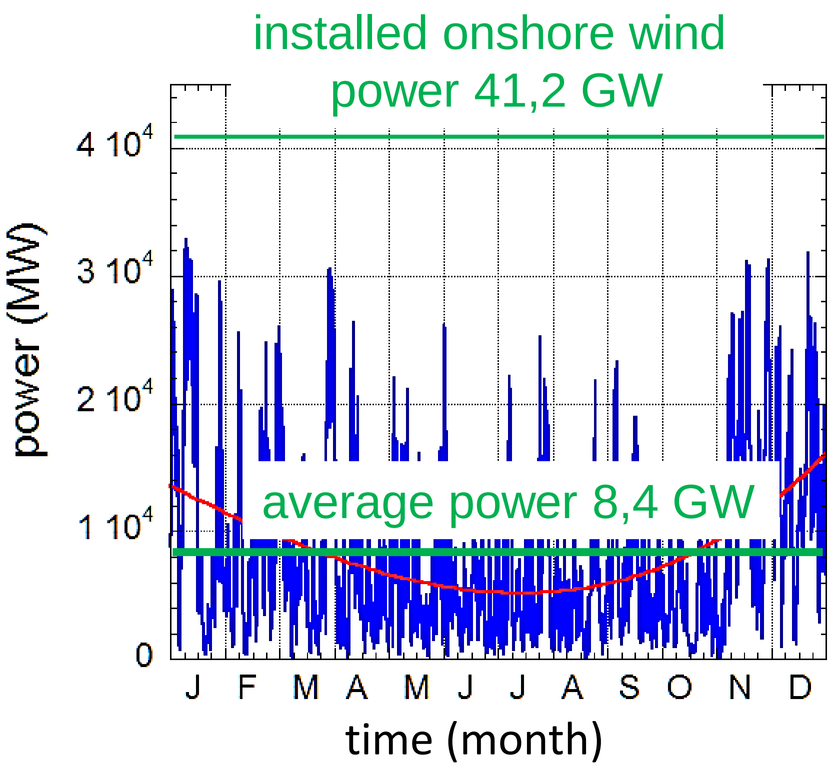


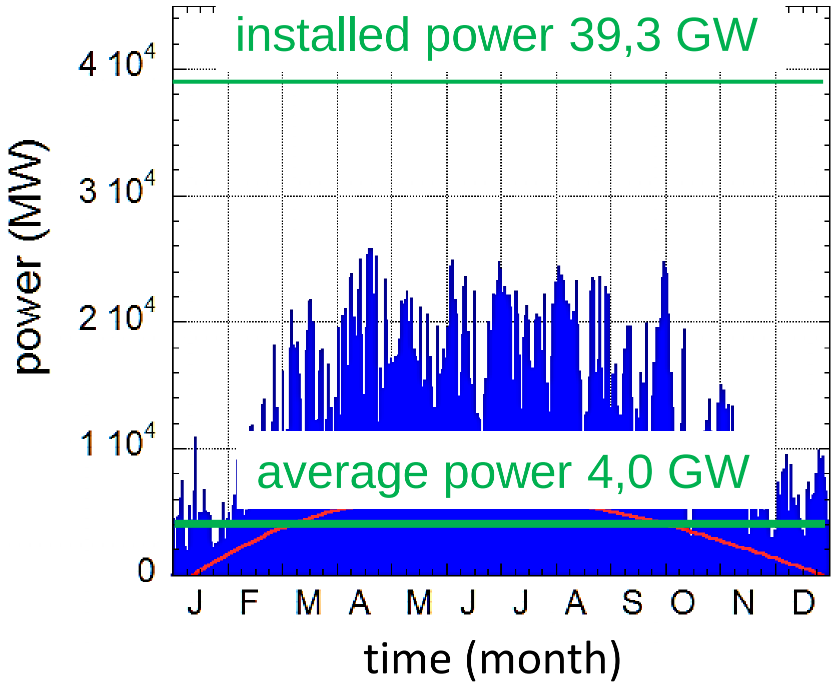
Intermittency of power production





The consequences of intermittency





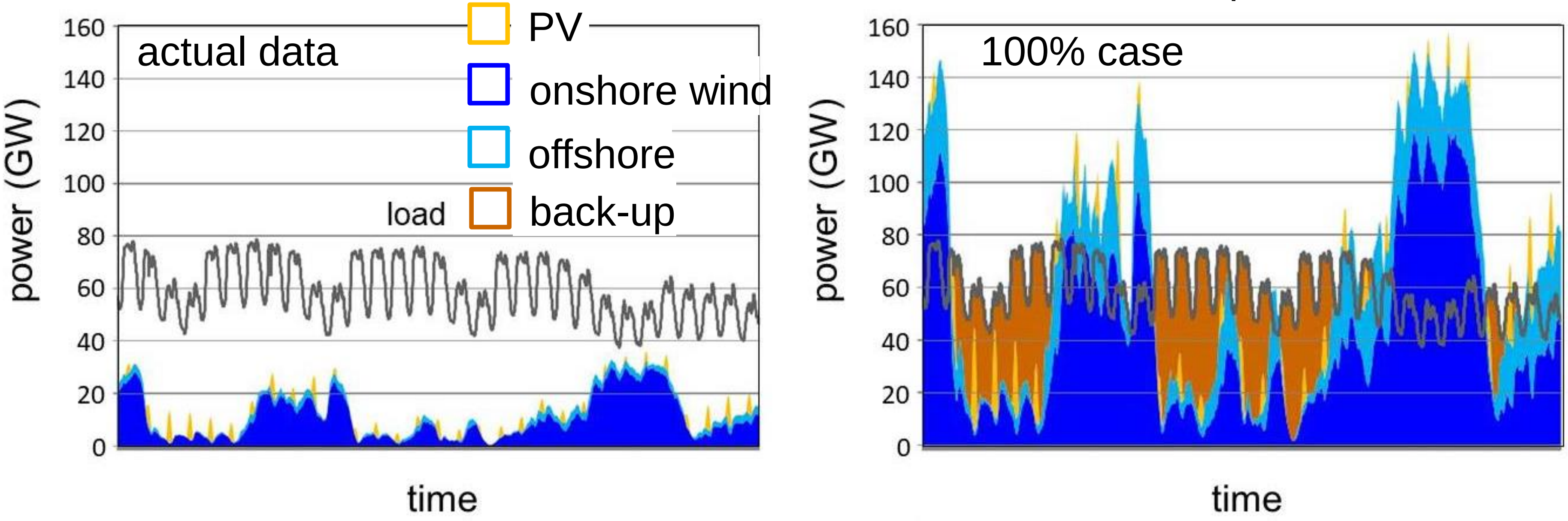
flh* = 1786 h

892 h

* Definition: full-load-hours, flh = 8760h*average/installed power

The consequences of intermittency

Wind and PV produce 500 TWh



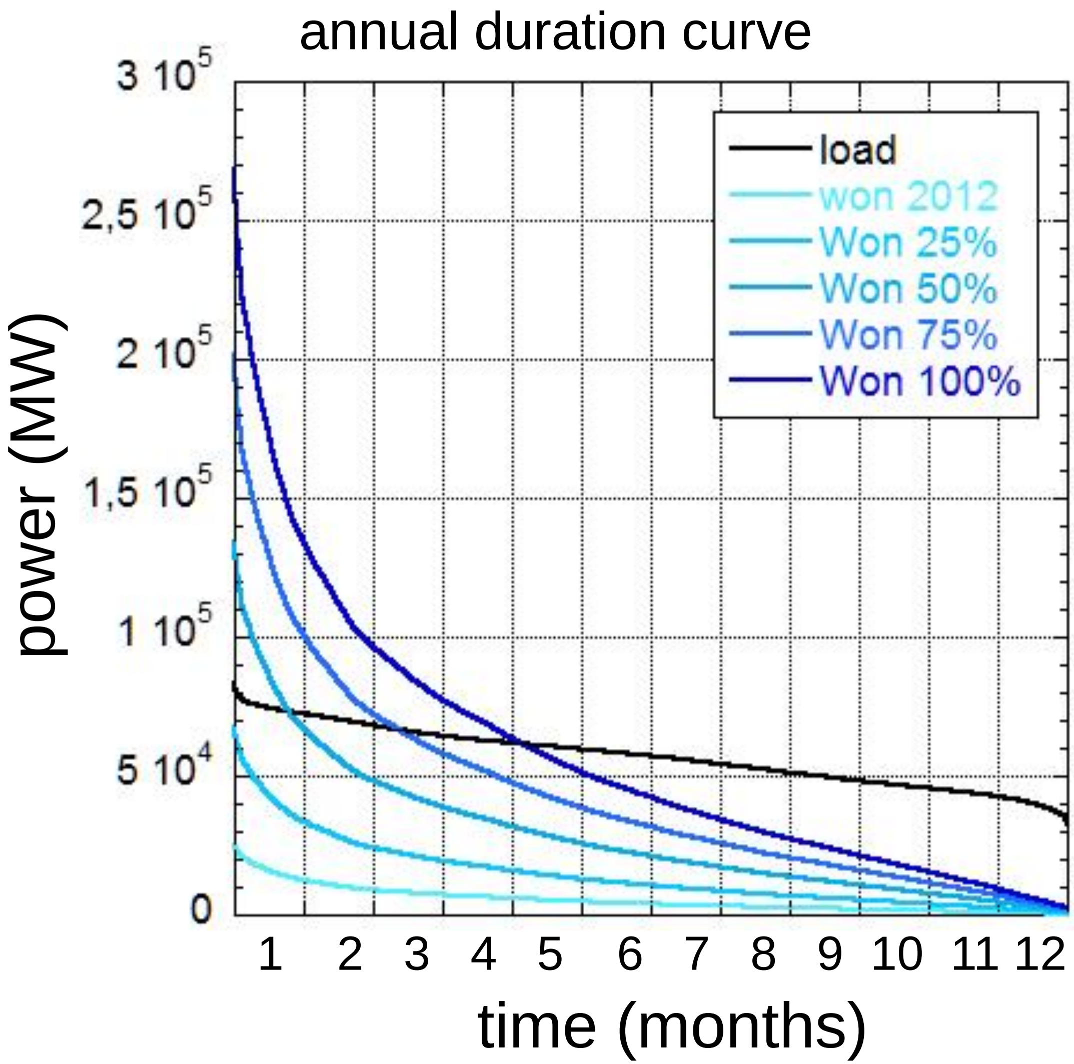
Intermittent renewable power **iRES** is not always available

→ **backup** system necessary

High power installation necessary to produce required energy

→ **surplus** production

The basic problem of iRES



load and production curve do not fit

to gain energy:

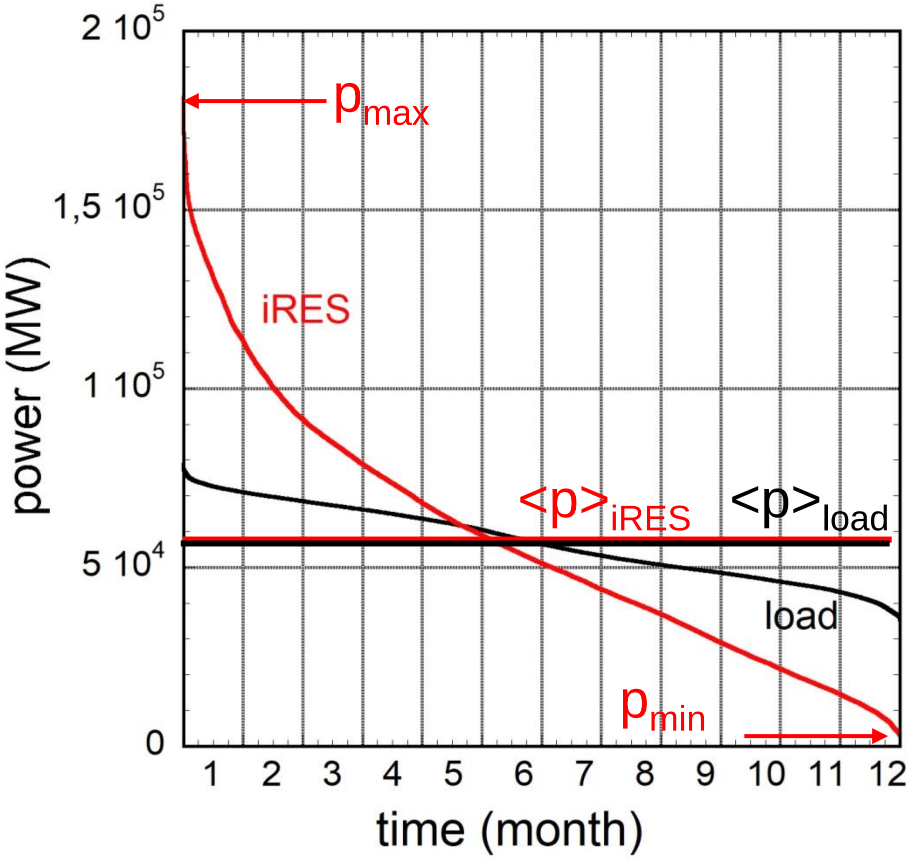
high power levels

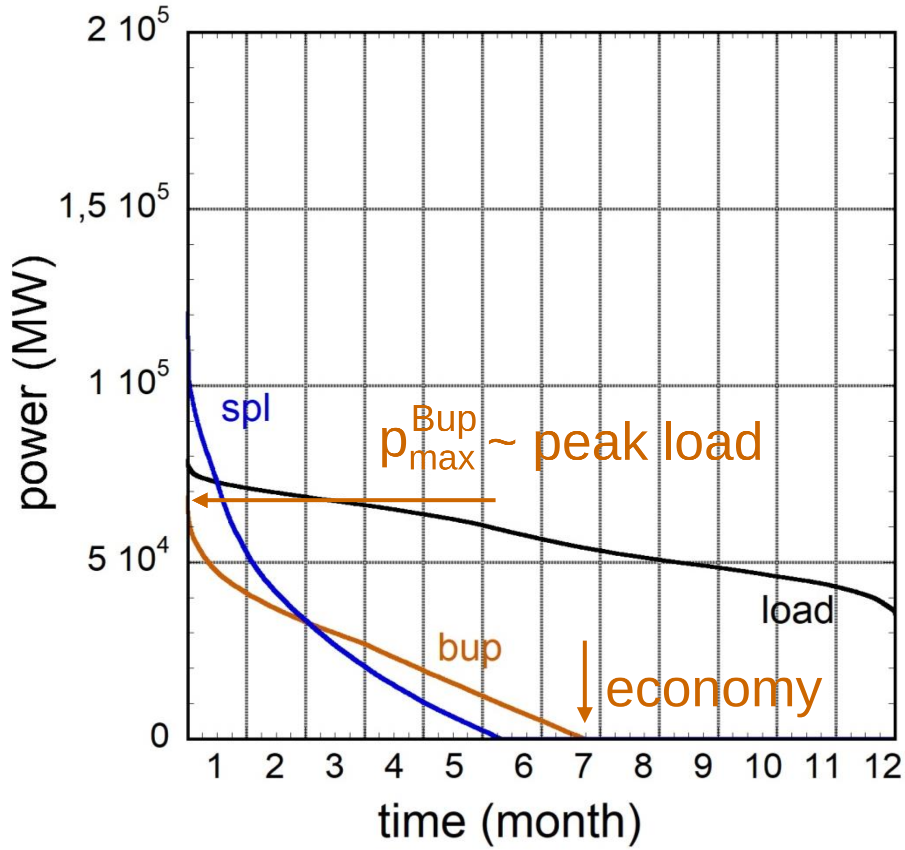
large installations

have to be accepted

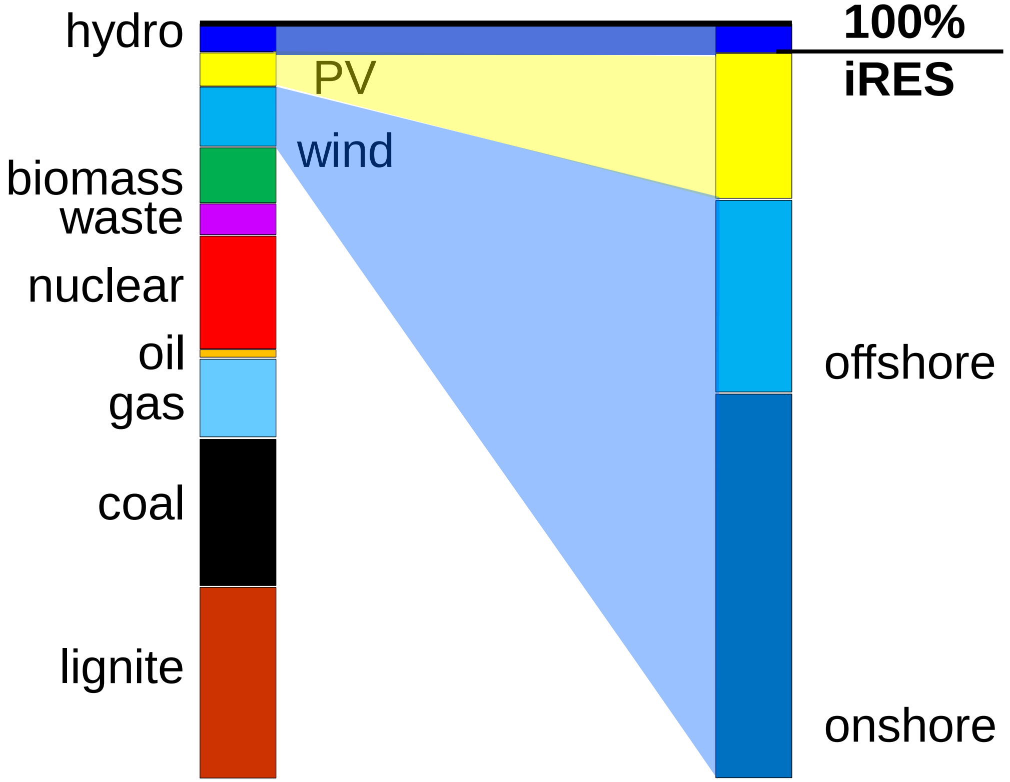
The basic problem of iRES

annual duration curves for 100% case





Transition in energy technology



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**

Analysis method:

scale wind and PV to 100%

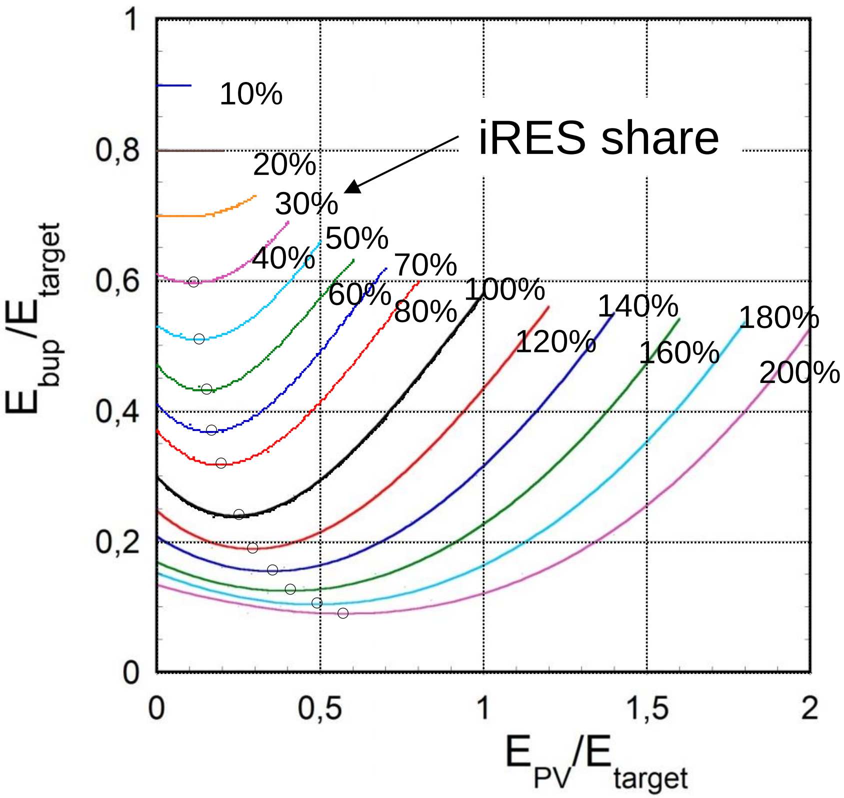
100%-case = 500 TWh

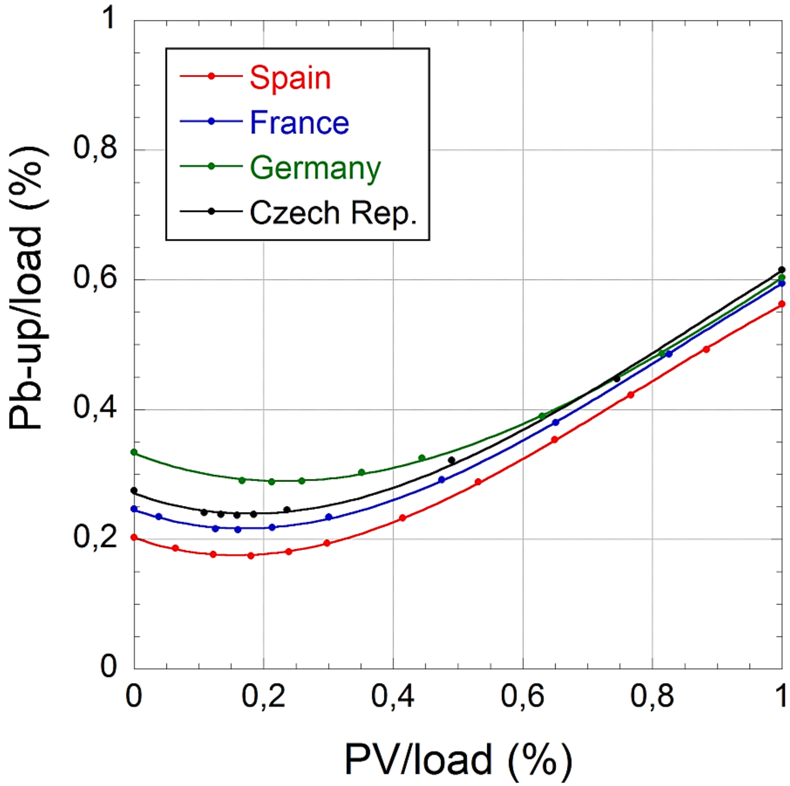
Public data source

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



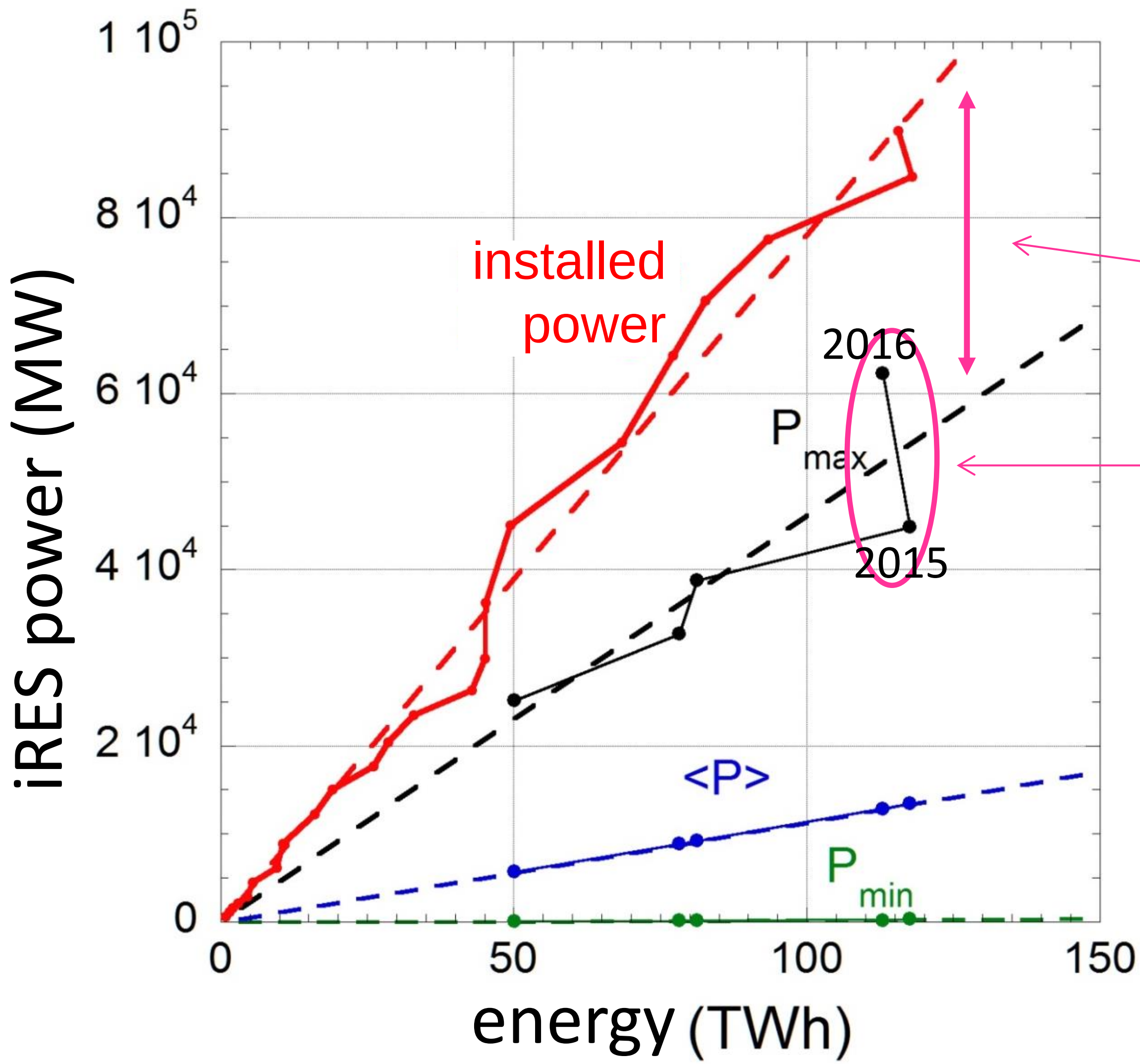


100%-case: E_{PV} ~ 20%; E_{wind} ~ 80%

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

Analysis examples from Germany

Relevant power values versus produced energy



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

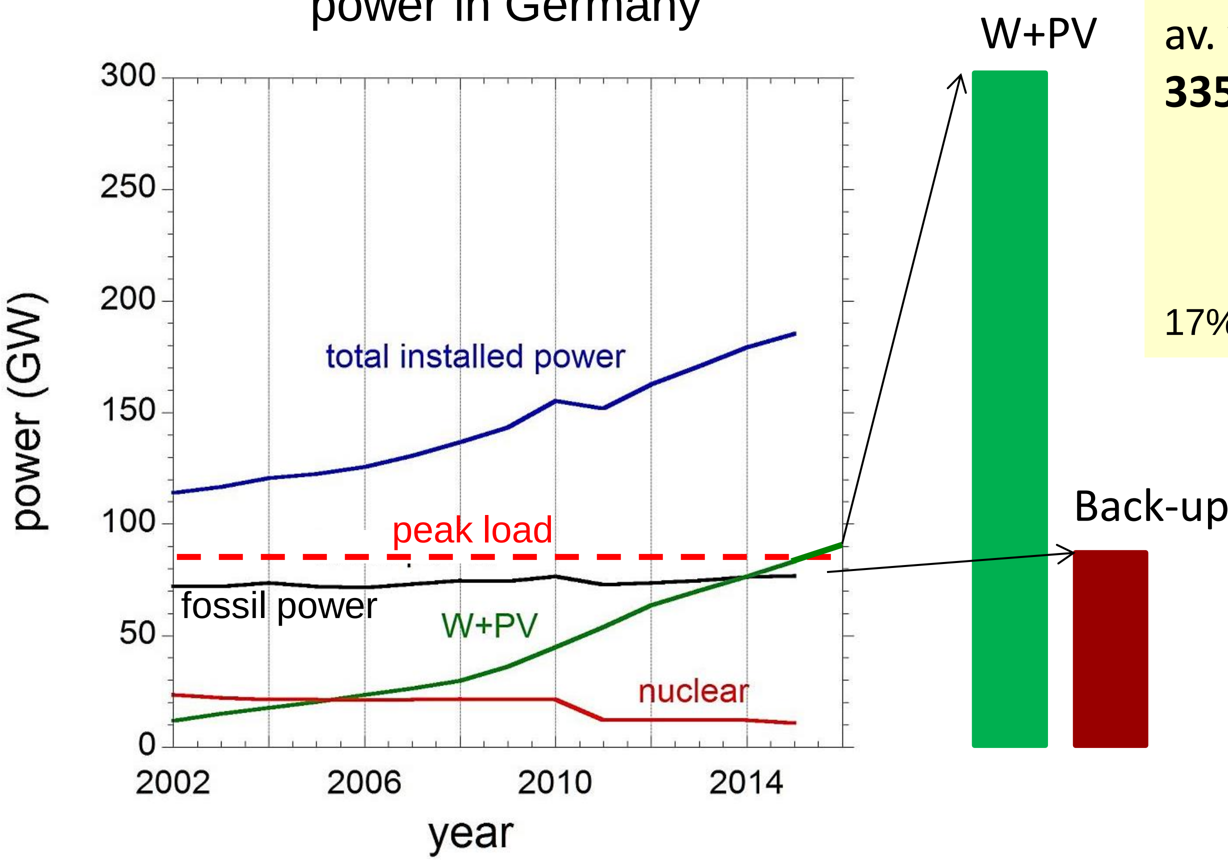
Installed power level never reached
+
strong variation from year to year

Low capacity factor: cf = <P>/P_{inst} ~ 15%

Back-up system required

1. question: How much power has to be installed?

Development of installed power in Germany



100%, optimal mix case:
av. value 2010-2015:
335 GW (= 4kW/P; 4x peak load)

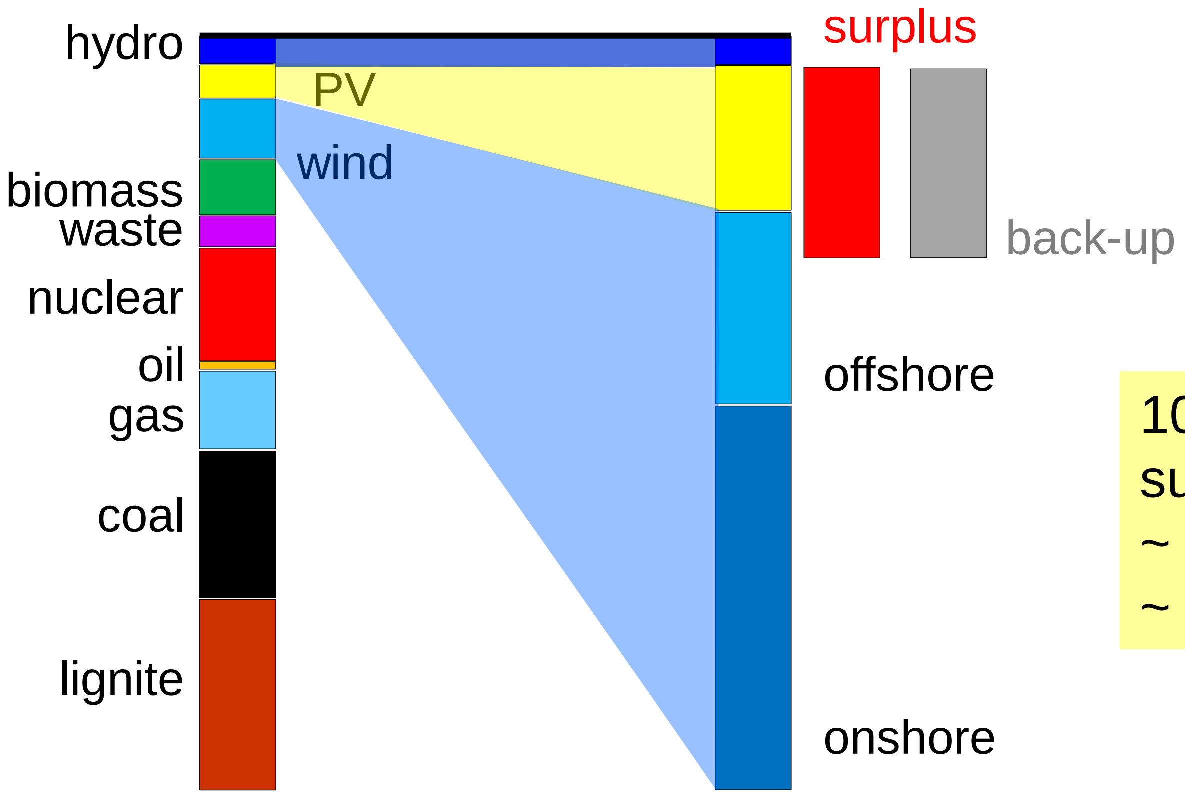
P_{won} =174GW
P_{woff} =43GW
P_{PV} =118GW

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

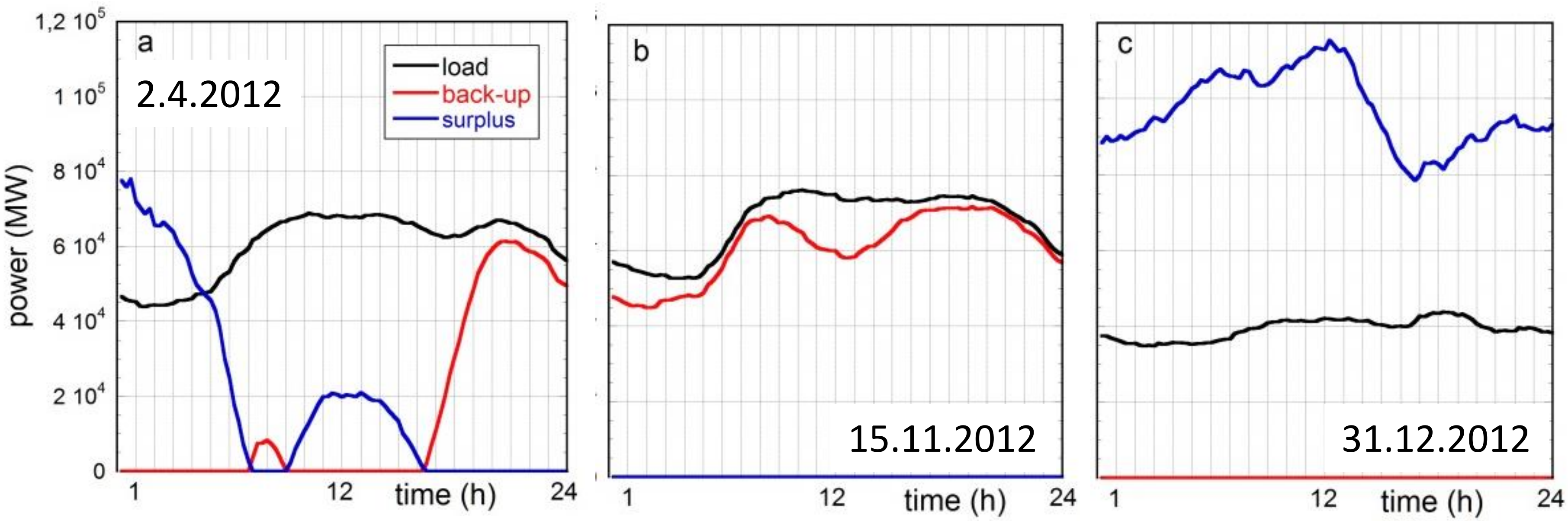


100% case:
surplus = back-up energy
~ 25% of total generation
~ 125 TWh

2. Scenarios for using surplus

100%, optimal mix case

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



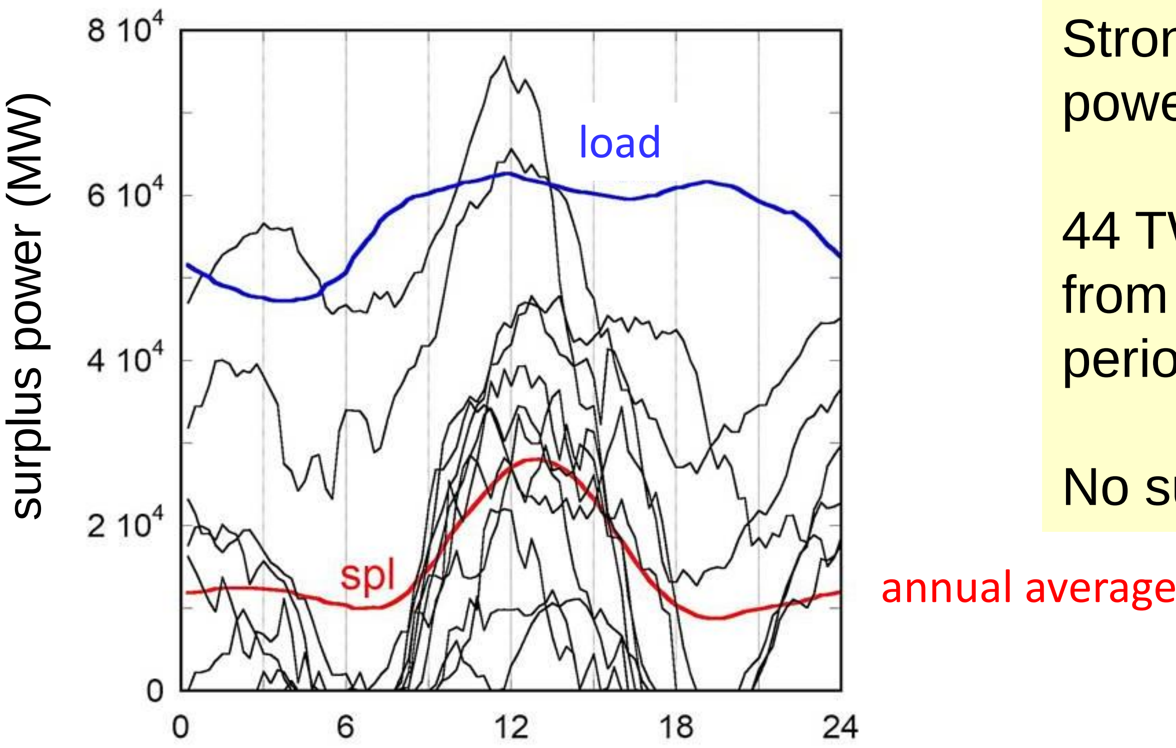
Quantitatively:

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 could be transferred from surplus to demand periods

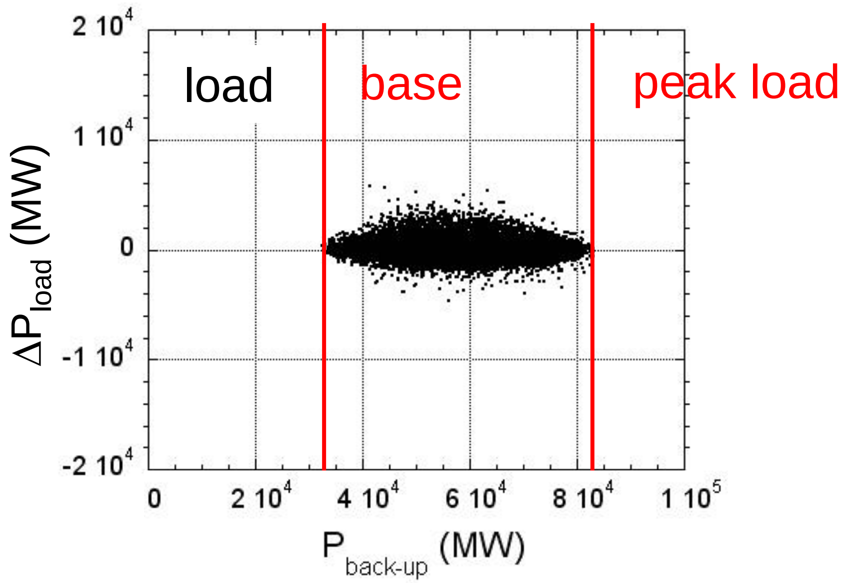
No surplus for 134 days

* DMS-management: adjust demant to supply

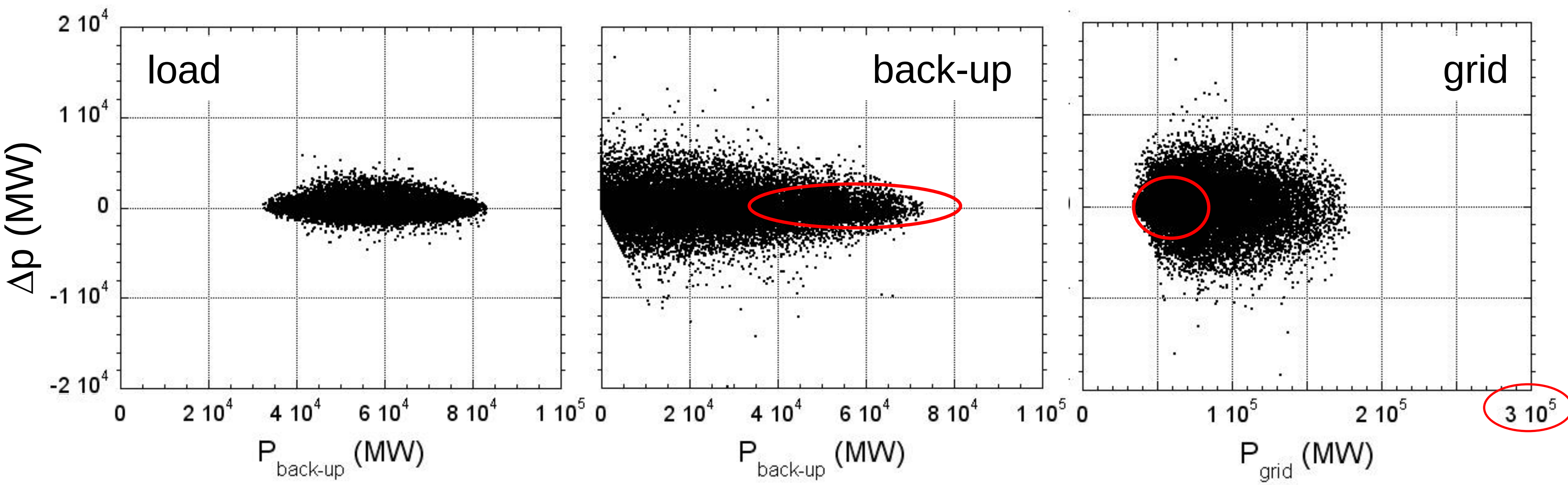
3. Fluctuation level

Power jumps within 15 min

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



100%, optimal mix case

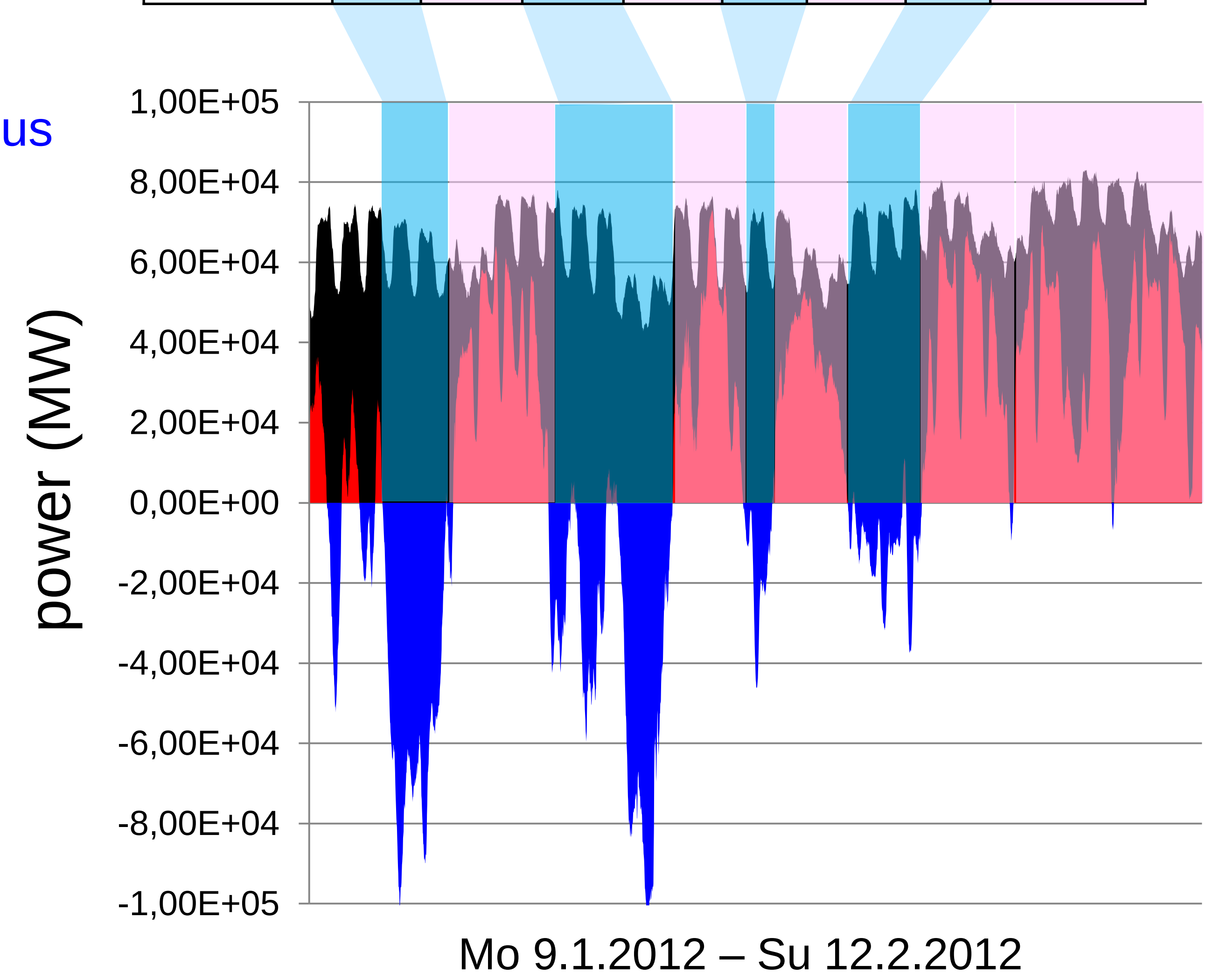


4. Seasonal storage

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



Seasonal storage

100%, optimal mix case

black: load
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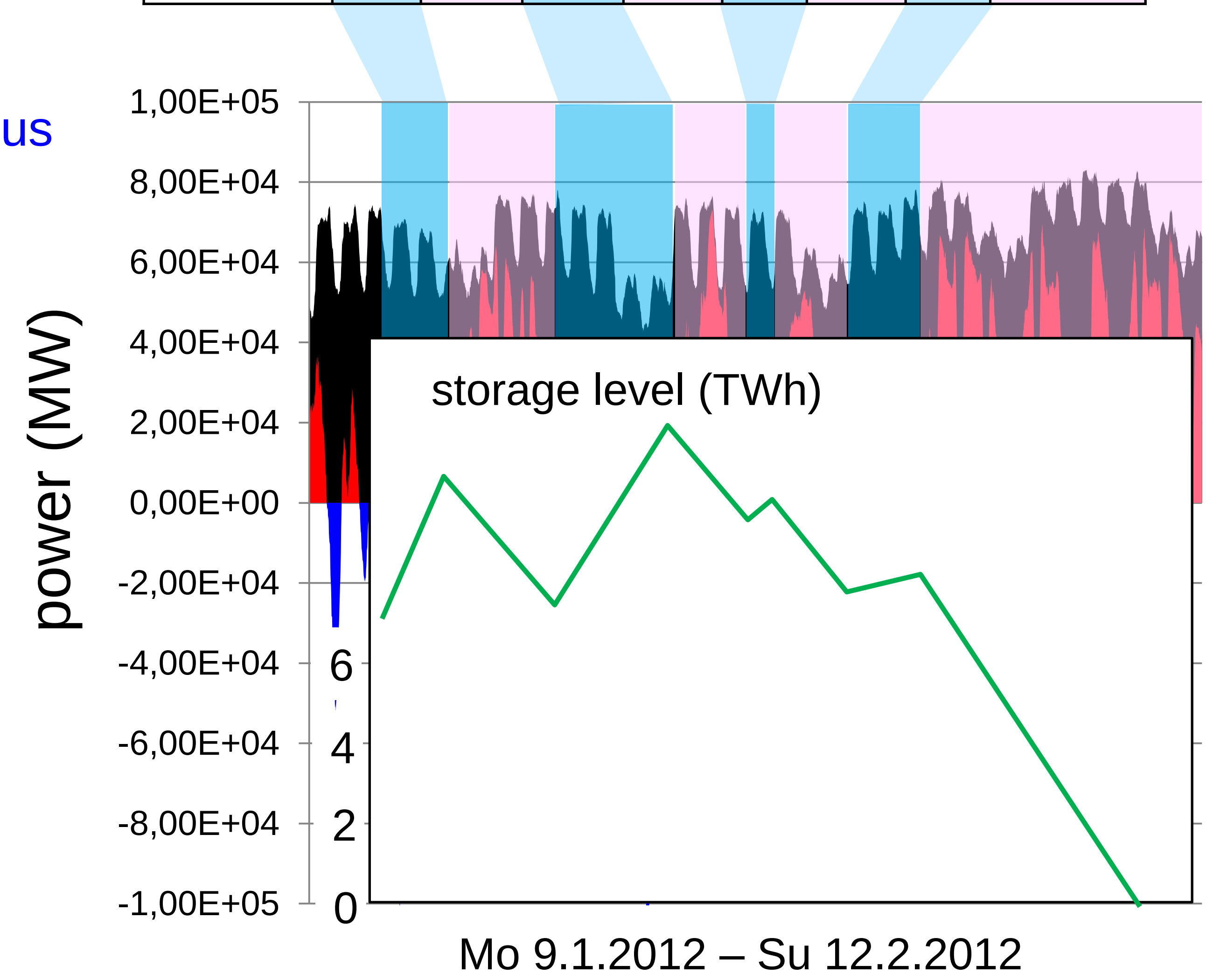
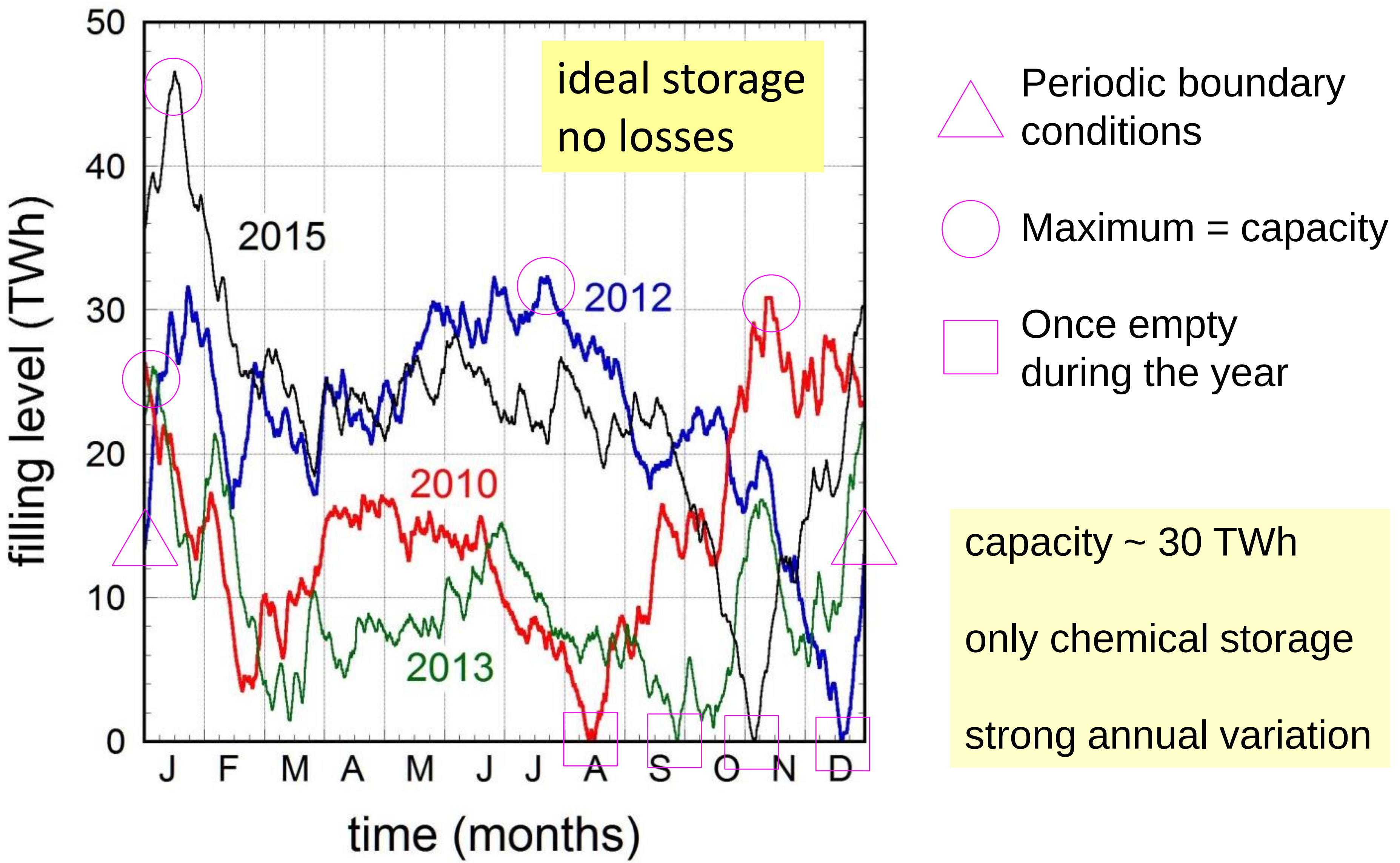
blue, negative: surplus

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



Variation from year to year



capacity ~ 30 TWh

only chemical storage

strong annual variation

The effect of efficiencies

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

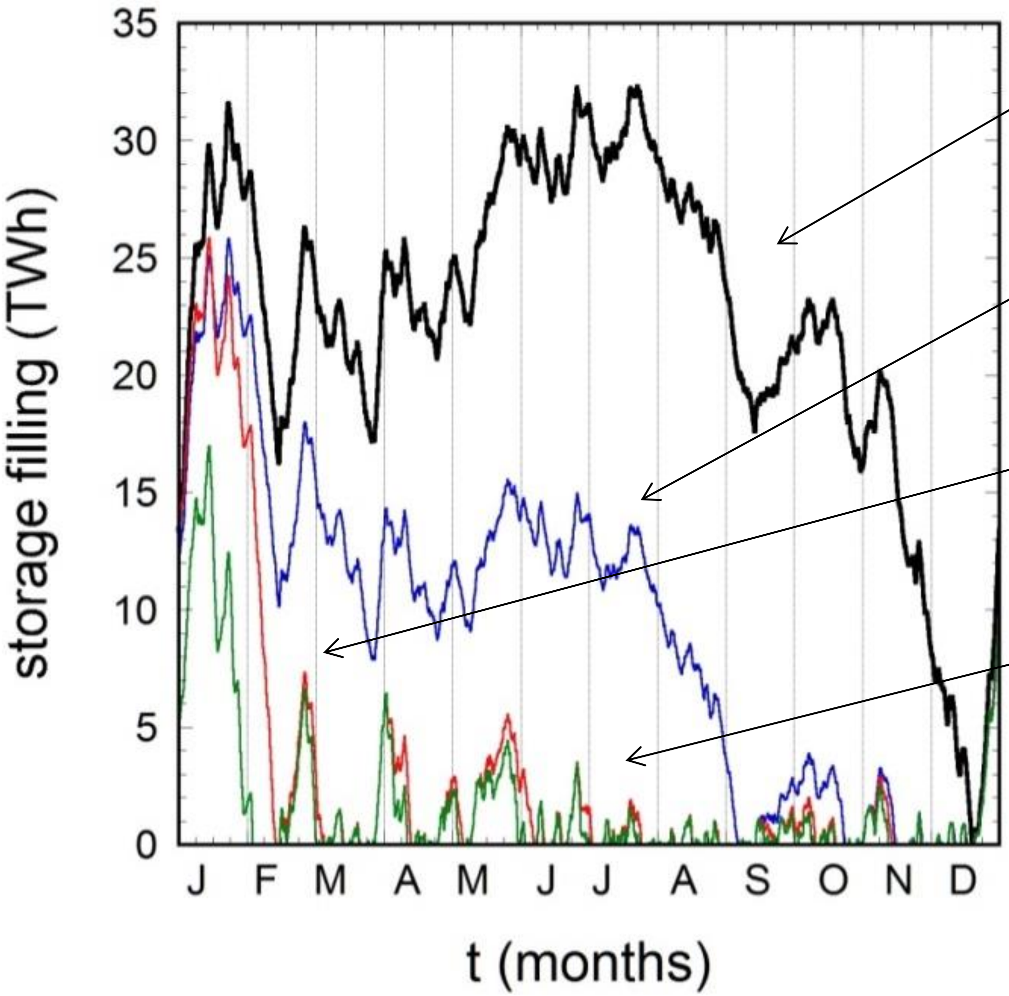
1. step: electrolysis with surplus: η ~ 0.65-0.7
2. step: electricity from H_2: η ~ 0.5 (fuel cell)

Alternatively
2. step: H_2 to CH_4: η ~ 0.65
3. step: CH_4 to electricity: η ~ 0.5

Total efficiencies: η ~ 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



2012, no losses (1)

electricity → H_2 (0.8)

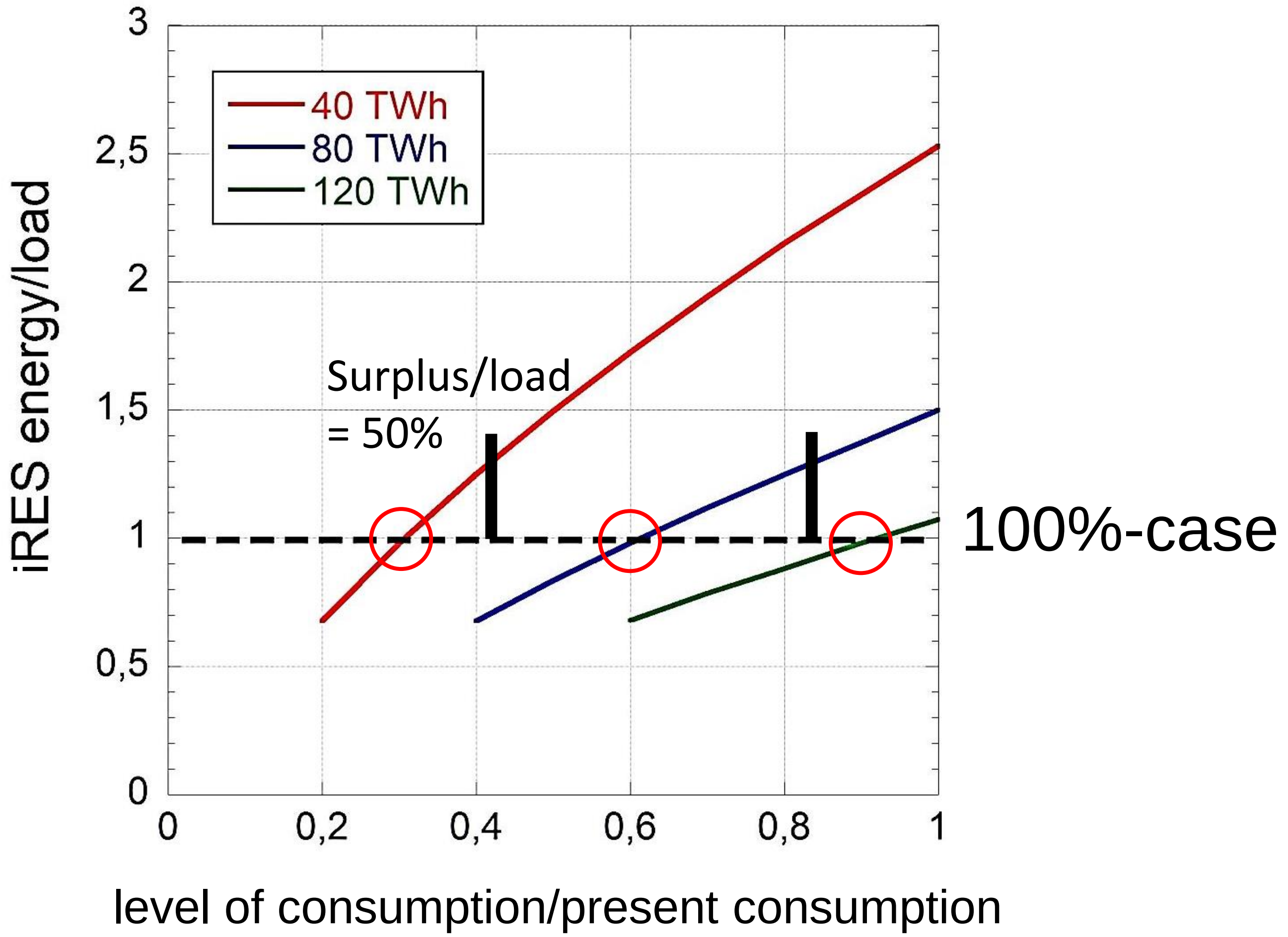
electricity → H_2 → electricity (0.6)

electricity → H_2 → CH_4 → electrity (0.4)

Seasonal storage loses character:
short operational periods
after bursts of surplus
Storage does not liberate from weather dependence

5. 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



The use of biomass

Crops = raps (diesel), corn+cereal (biogas → electricity, 50 TWh),
Cereal+sugar beets (ethanol; 50% import)
Wood: 19% (2015) of German wood harvest for energetic use (burned)

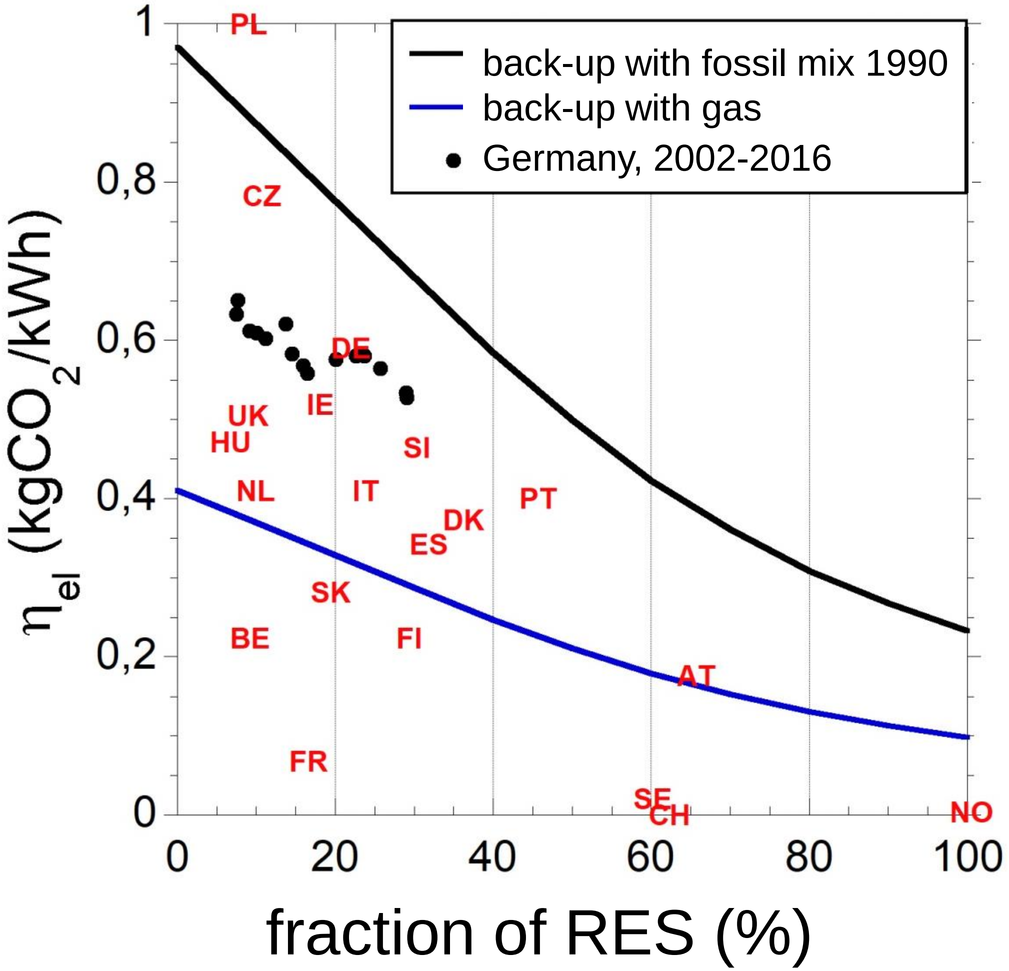
Involved areas:
agriculture total: 18 Mill ha
animal food: 10.2 Mill ha; food: 4.5 Mill ha; forest: 10.7 Mill ha
bioenergy: 2.1 Mill ha →PE of 270 TWh

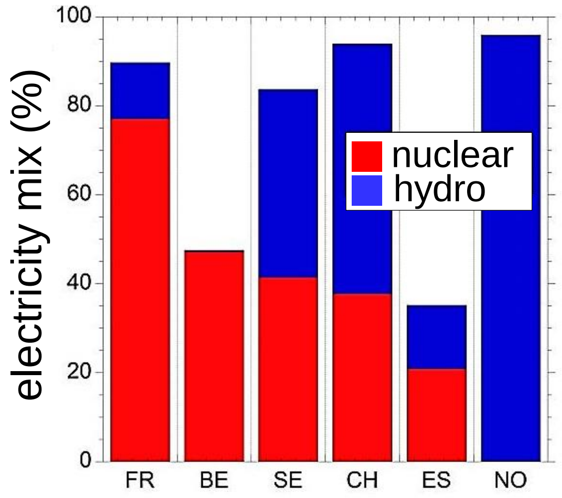
Limiting factors:
Waste: about 2/3 is already used
All generation 1 bio-energies (crops) have low (or no) GHG savings
Agriculture: 1/3 of animal food proteins imported as Soya beans. Would need 3 Mill ha
Forest: total use of wood: 120 Mill m^3; national production ~ 55 Mill m^3; carbon content of forests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

Conclusion: Biomass is strongly limited and its present use is not sustainable

Future: Biomass = Residual material, biogenic waste →aviation, ships, heavy machinery

6. Specific CO_2 emissions

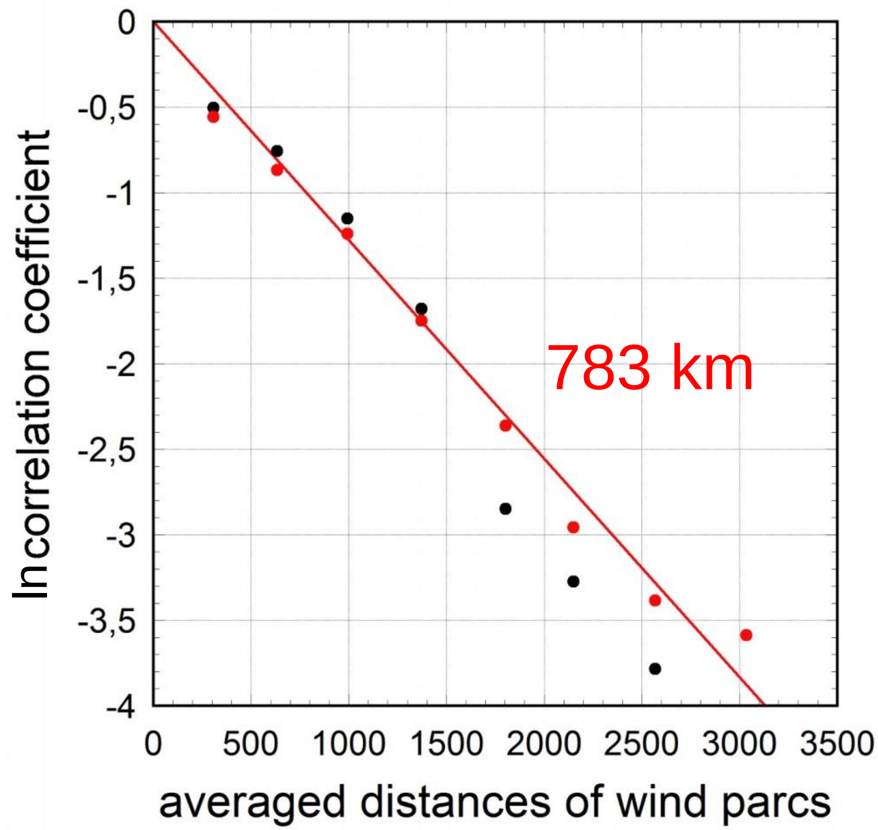




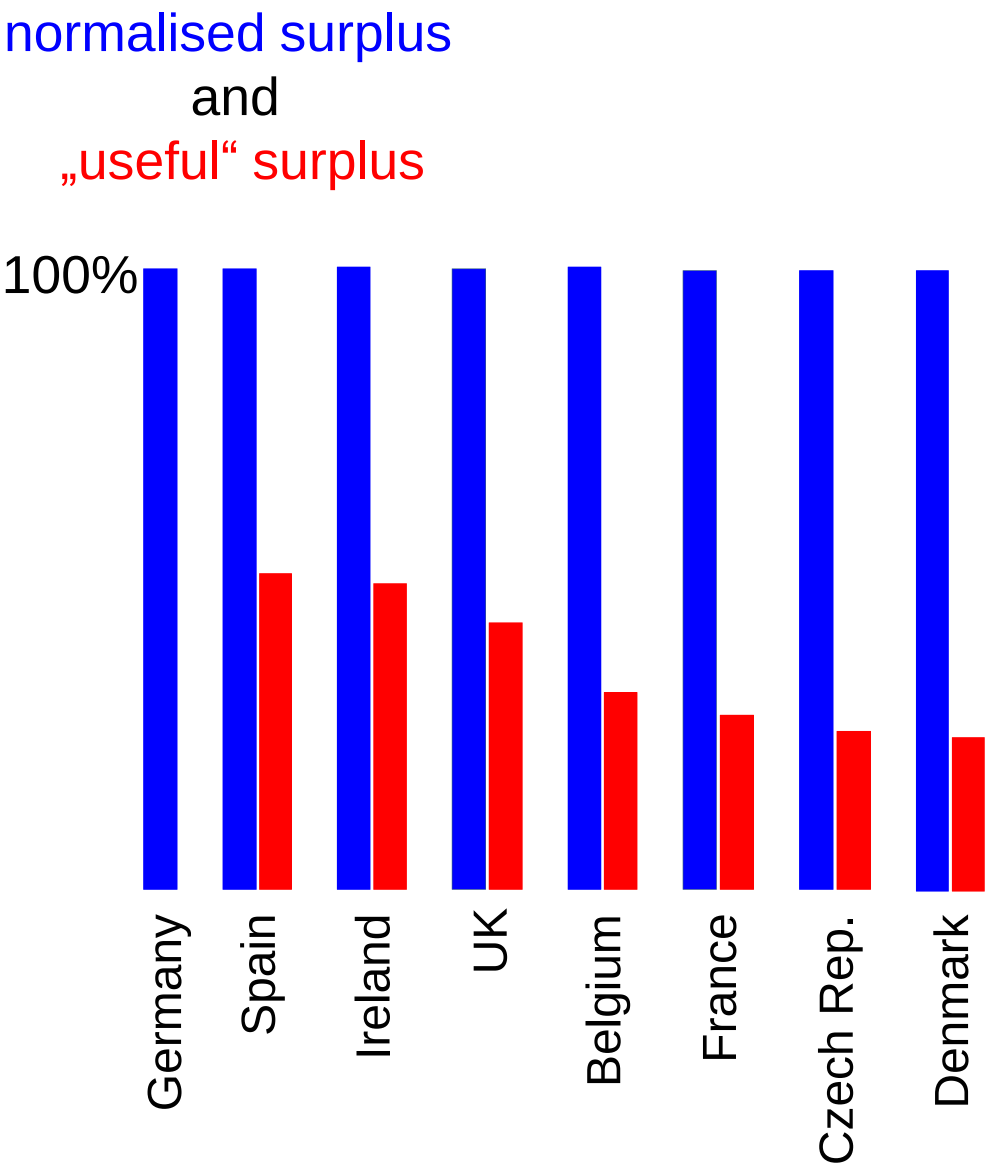
7. Benefits from an EU-wide RES field

Distribution of wind field
expressed as
regression coefficient

18 EU countries
average corr. coefficient
averaged in steps of 400 km



Useful surplus (from German point of view)



In case of surplus – also the neighbours produce it

Summary of benefits (based on 8* countries)

the back-up energy is reduced by 24%,

the maximal back-up power by 9%,

the maximal surplus power by 15%,

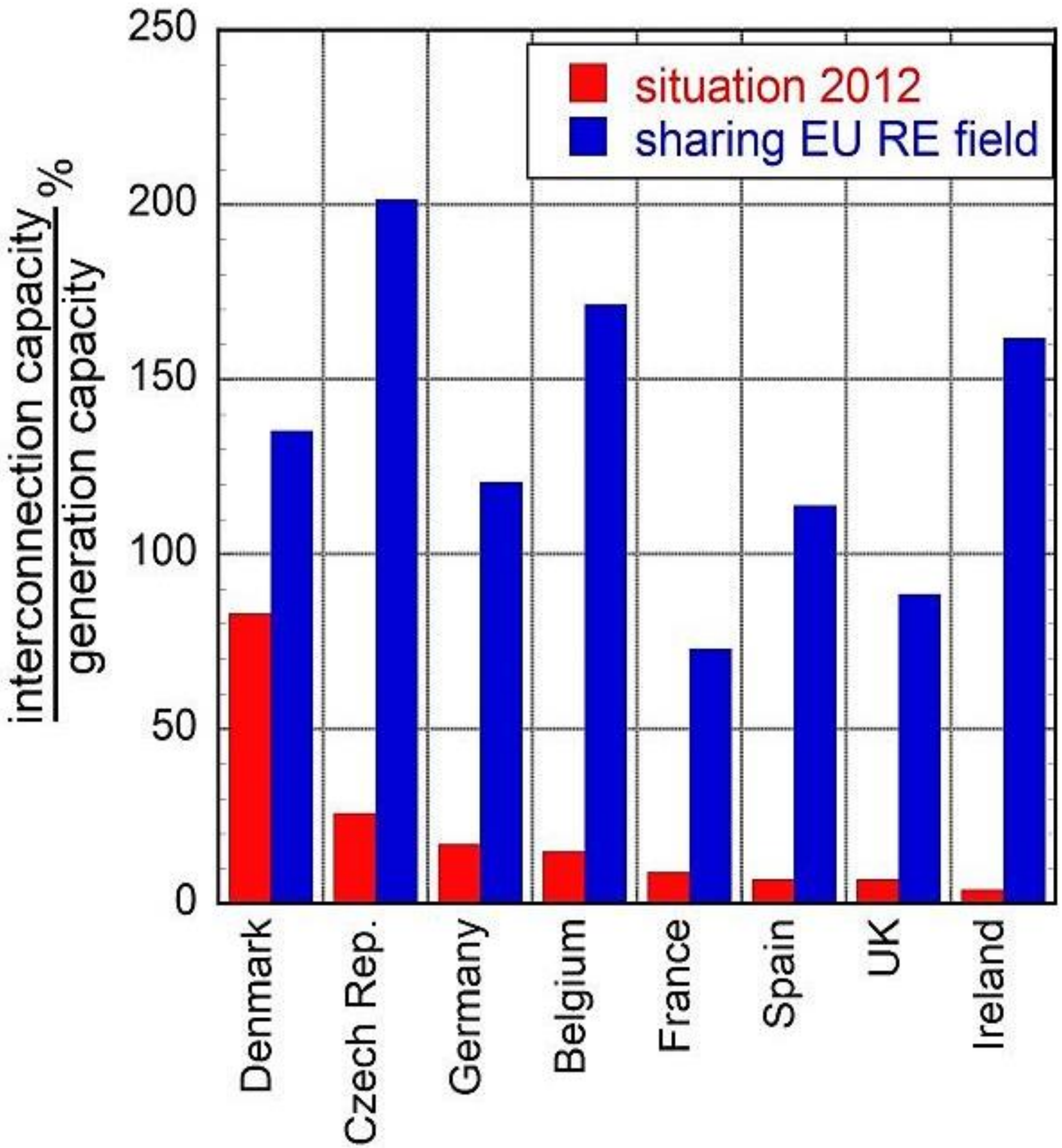
the maximal grid power by 7%,

the typical grid fluctuation level by 35%

the maximal storage capacity by 28%

* only tendency given

Interconnector capacity



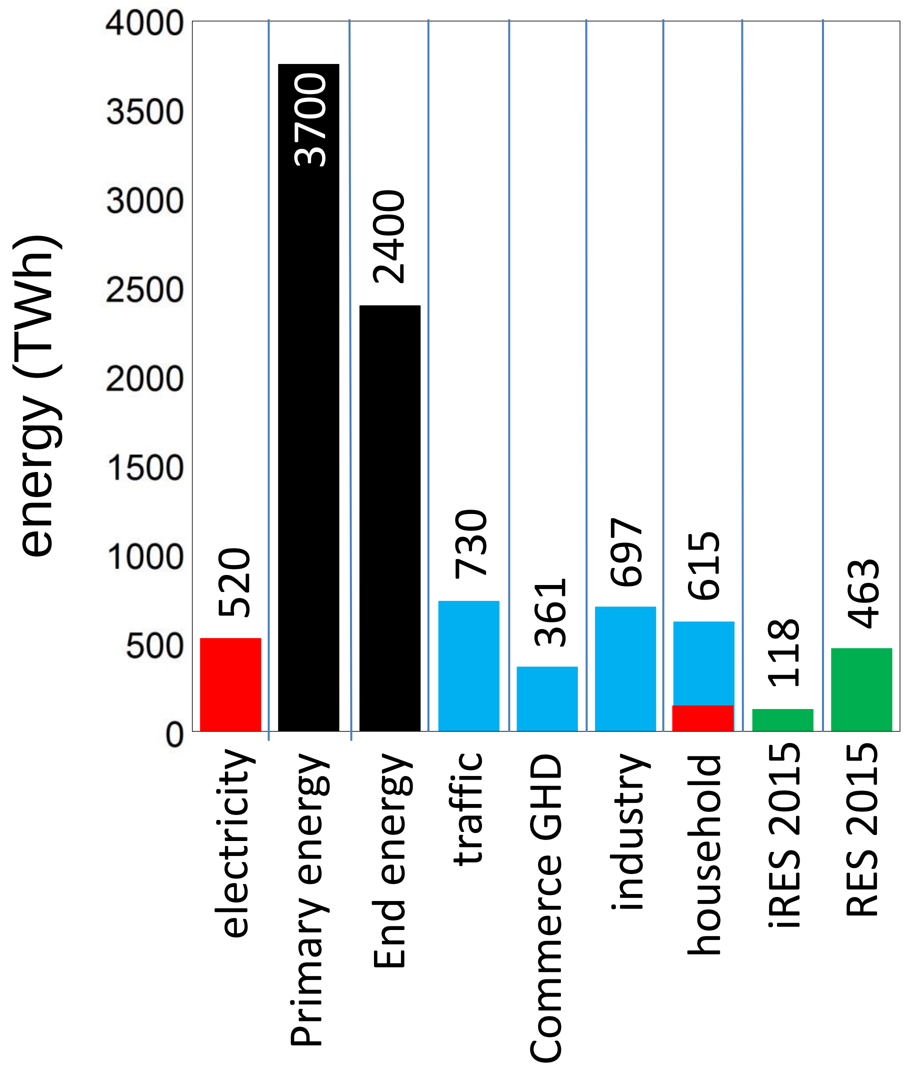
Conclusion

EU-wide consequences

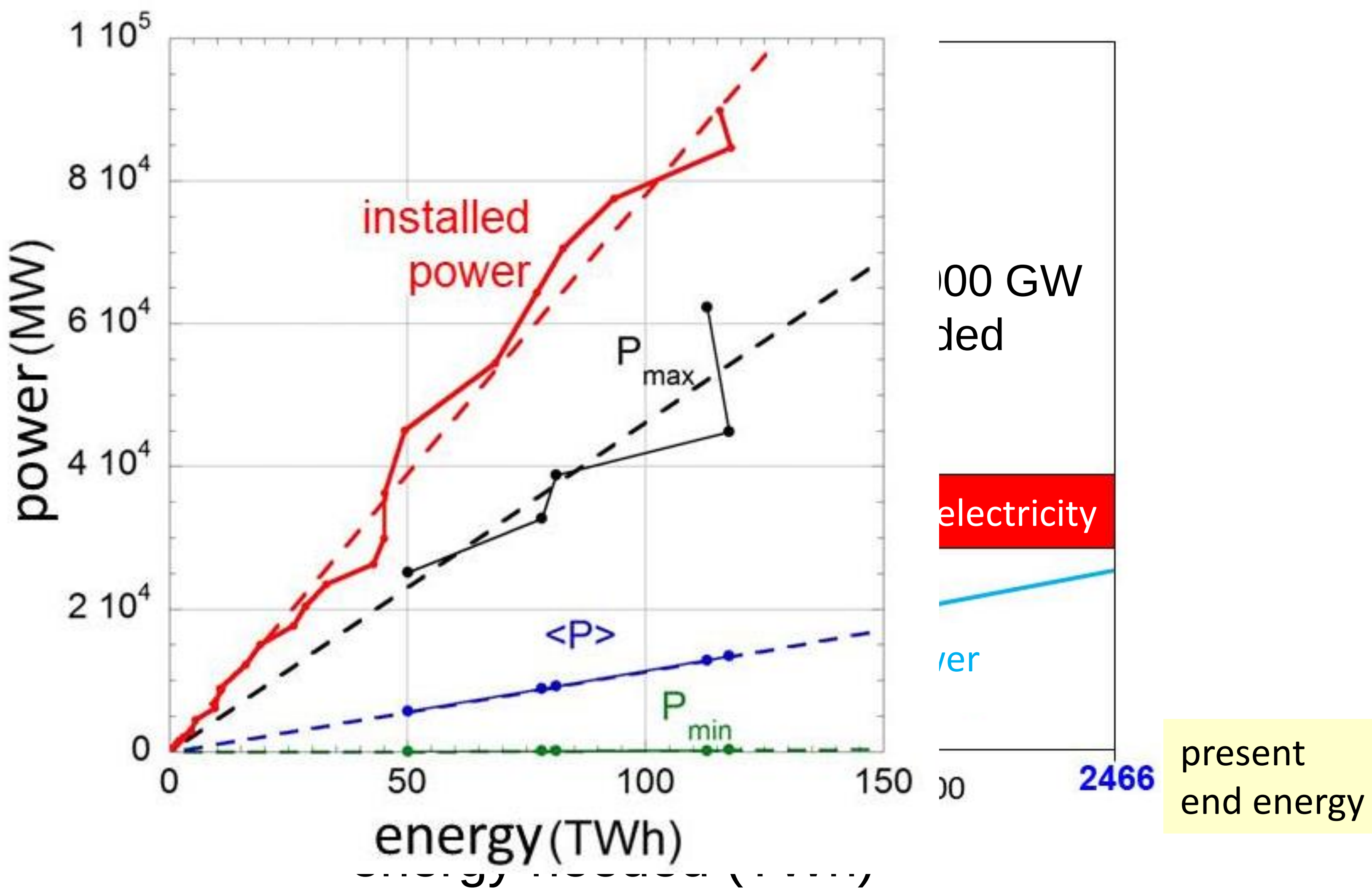
- Large iRES power necessary for all countries
- National iRES use demands typically north-south grids
- Cross-border exchange requires east-west grids
- Exchange over large distances beneficial
- Large interconnector capacities needed
- Not all countries benefit from an EU-wide iRES field

2. Topic: Beyond electricity: Sector coupling

Energy production and needs of all energy sectors



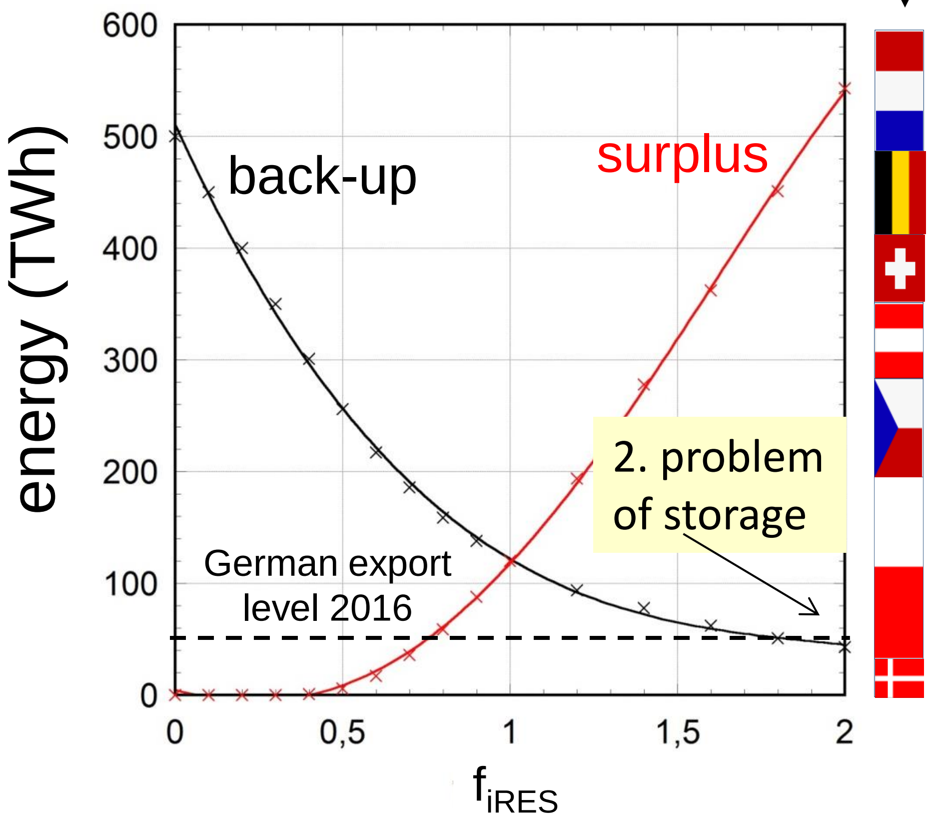
Present end energy situation and future one

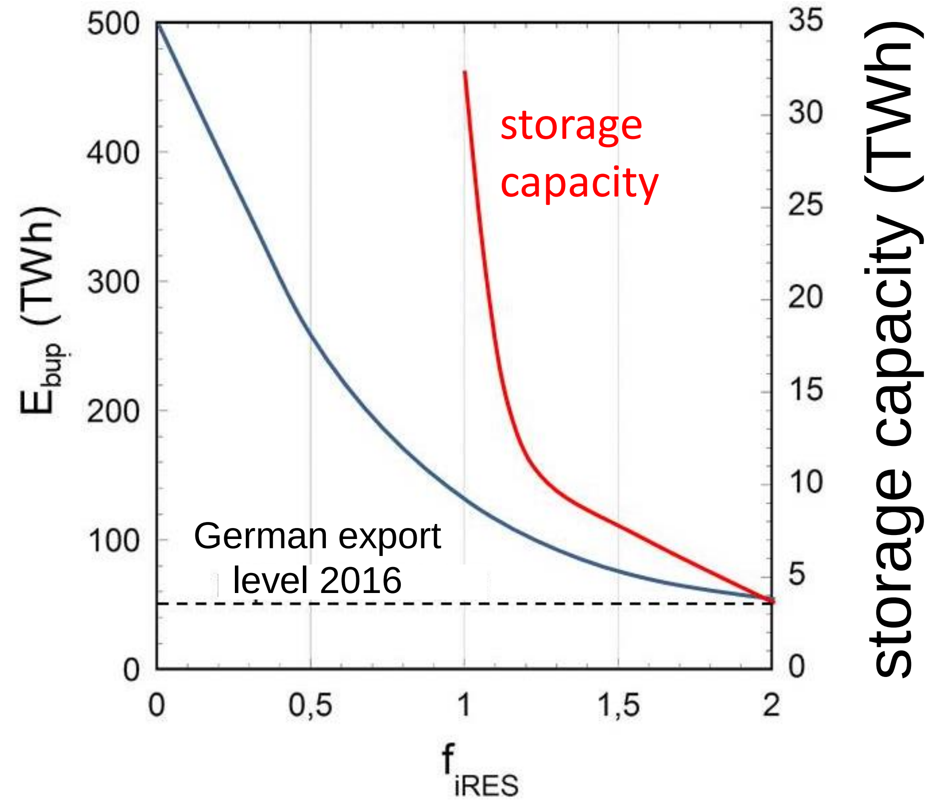


Overproduction of electricity

back-up and surplus production

Germany´s neighbours



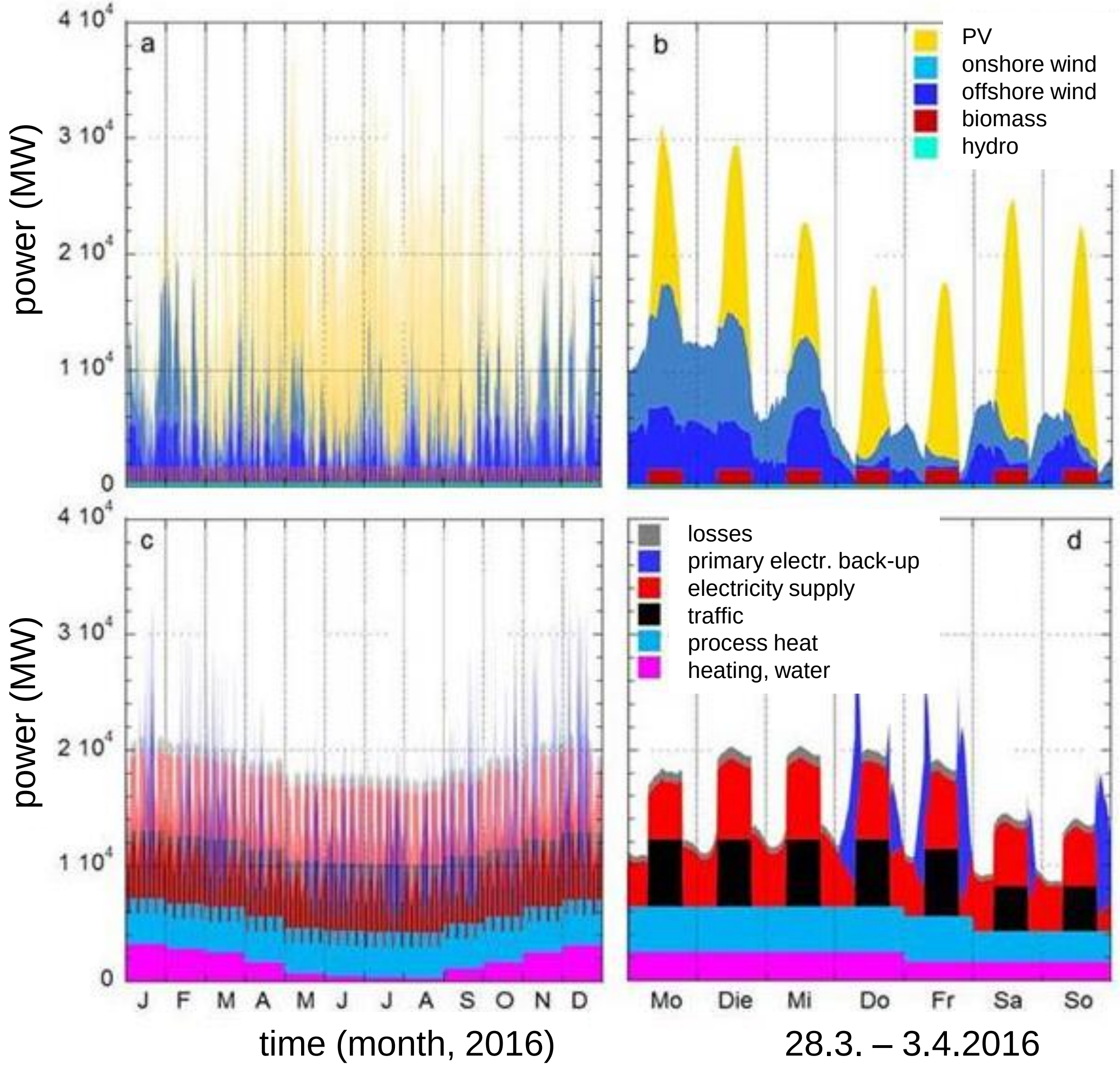


$f_{iRES} = E_{iRES}/E_{target\,=\,500\,TWh}$

Model for supply and consumption needed

Supply:
- wind and PV + hydro
- 58 TWh electricity from biomass; power limited to 20 GW

Consumption:
- electricity according to present load curve
- room heating according to heat consumption of Munich
- Process heat: reduced at weekends
- Loading of electro cars during the day and reduced at weekends



100% case for all electricity consuming sectors

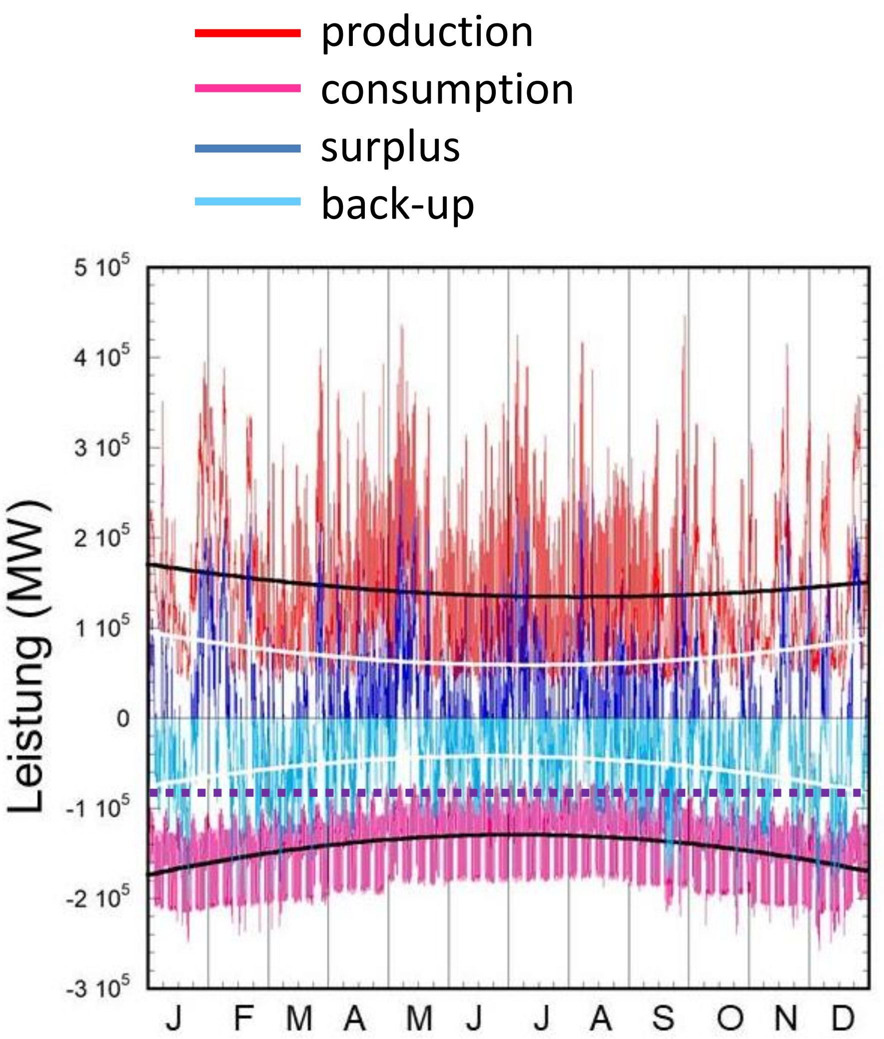
Energy balance:

1177 TWh wind and PV
58 TWh from biomass
27 TWh from hydro
others, import… not considered

Optimal mix of wind and PV
Onshore 574 TWh from 397 GW
Offshore 287 TWh from 87 GW
PV 315 TWh from 363 GW

Surplus, back-up: 270 TWh

Total consumption still characterized by base-load

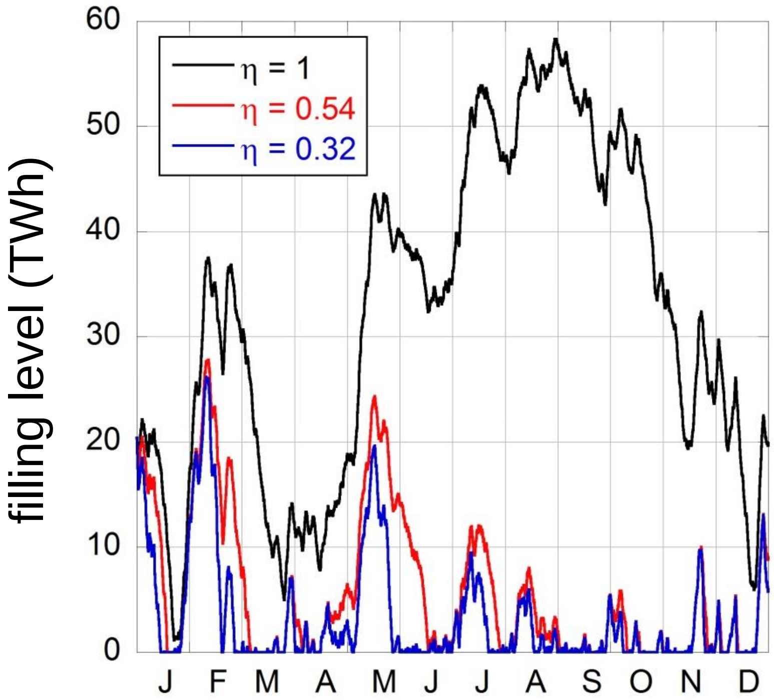


Consequences

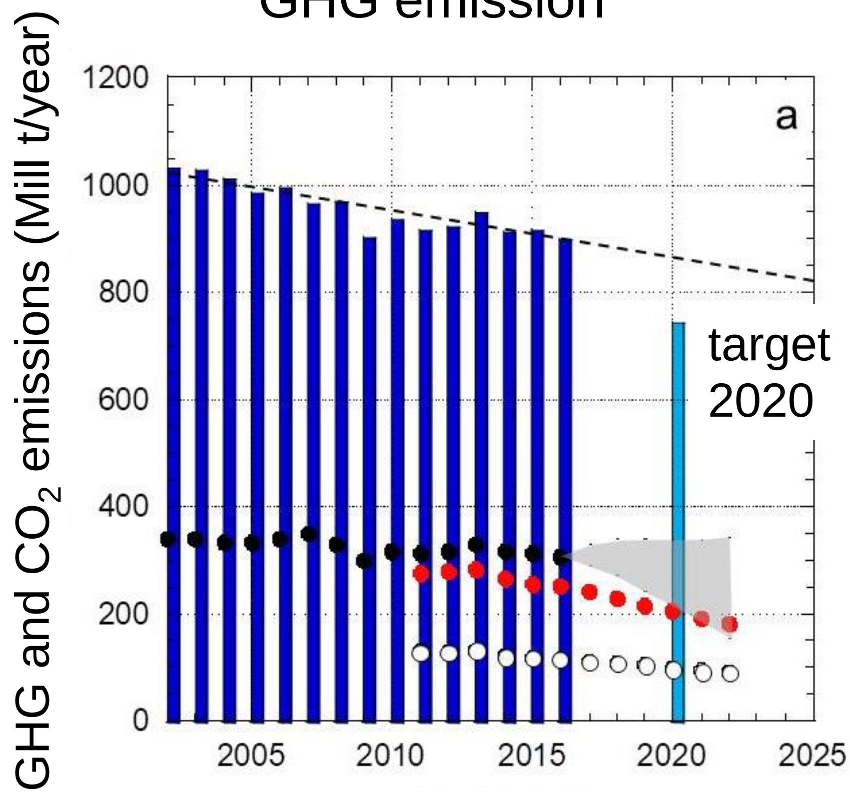
At present: 28000 wind converters
For 397 GW onshore wind: 300000 wind converters; distance: 1.2 km

For 363 GW PV: with the highest net-installation rate of Germany of 7.5 GW/2012:
It takes to 2065, and the target is met with the 2nd – 3rd PV module generation

Storage: déjà-vu



GHG emission



Major Results

Electricity:

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 conditions for DSM
Cheap electricity prices during the day

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

Reasonable share by iRES?
40%

Sector coupling:

Saving:
the future public discussion on energy savings will domintate the one on energy production by iRES.

Power
High density of wind converters needed

Storage
large capacity

uneconomic use
like for electricity storage:
Storage does not free supply from weather conditions

Reduction of GHG emission
Slow and expensive

Observations

The consequences of the “Energiewende”

to produce 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
little rewarding effect on Germany´s GHG emissions

Conclusion for fusion

I doubt that a complete decarbonisation with mostly intermittent RES will be possible: A second system is needed

- fission, on basis of fast neutron reactors of Gen. IV
- CCS (carbon capture and sequestration)
- fusion (interesting: in case of sector coupling, a base-line supply is still required)

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.

Thank you