Corollaries of weather dependent electricity generation

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Objective of the „Energiewende“ – technology change:
2045: no net-CO_2 emissions

<u>Sectors:</u>

energy generation ⇒ renewable technologies
industry ⇒ CO_2-free technologies (steel, cement)
heating ⇒ heat-pumps instead of gas heating
mobility ⇒ electric vehicles (BEVs)

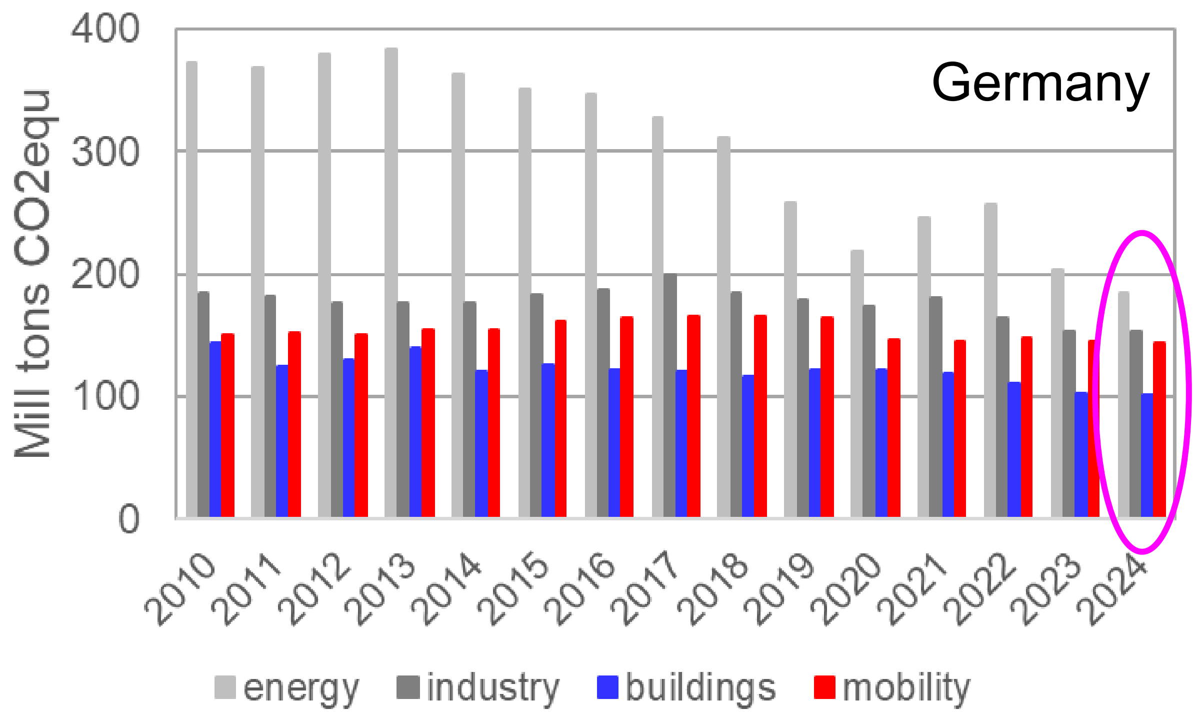
the new primary energy is **electricity** – serves the other sectors
⇒ sector coupling

electricity generation by renewables, REs

- onshore wind, Won
- offshore wind, Woff
- photovoltaic power, PV
- biomass
- hydro-electricity

Status of the transition

CO_{2equ} emissions by sectors
(UBA)



Comments:

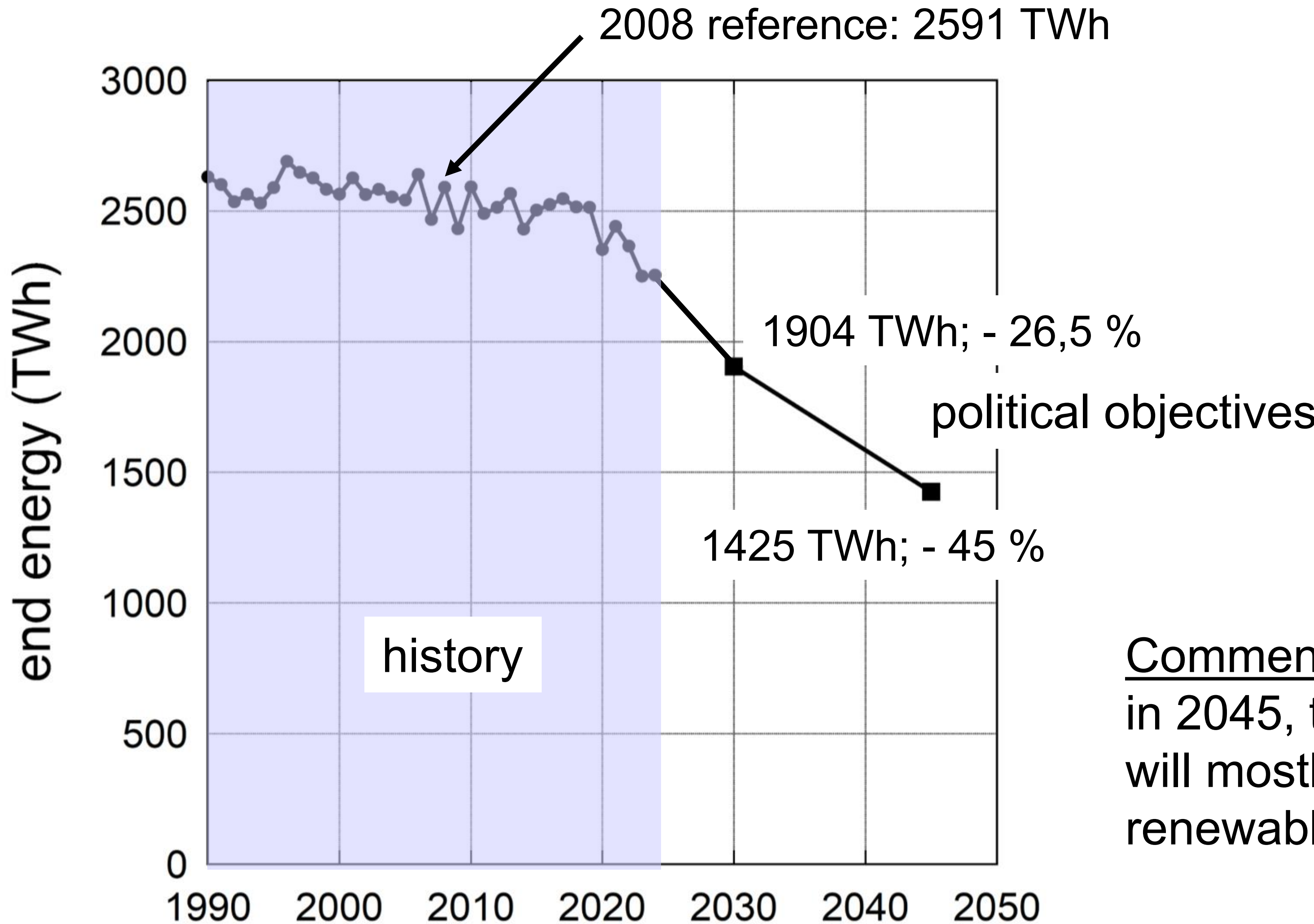
The energy sector has achieved ~50% since 2013

comparatively little reduction in the other sectors:

- extent of the problem:
  - mobility: 644 TWh/y for fuel
  - gas for househoulds: 230 TWh/y
- comparison: electricity consumption: 464 TWh; 130 TWh households

https://www.umweltbundesamt.de/sites/default/files/medien/11867/dokumente/emissionsdaten_2024_-_pressehintergrundinformationen.pdf

End (final) energy, and the political objectives



<u>Comment:</u>
in 2045, the end energy will mostly be provided by renewable electricity

A crucial question: How large is the future electricity demand?

Answer from the Big-5: AGORA, BDI*, Dena**, Fraunhofer ISI, Adriadne/BMBF

* Bundesverband der Deutschen Industrie; ** Deutsche Energie-Agentur; *** Bundesministerium für Forschung, Technologie und Raumfahrt

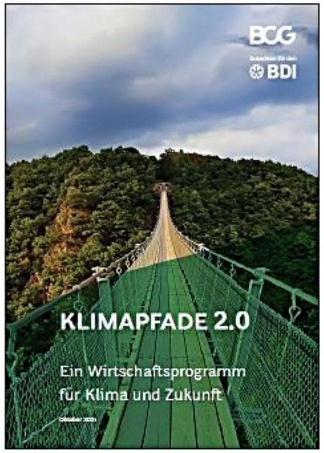
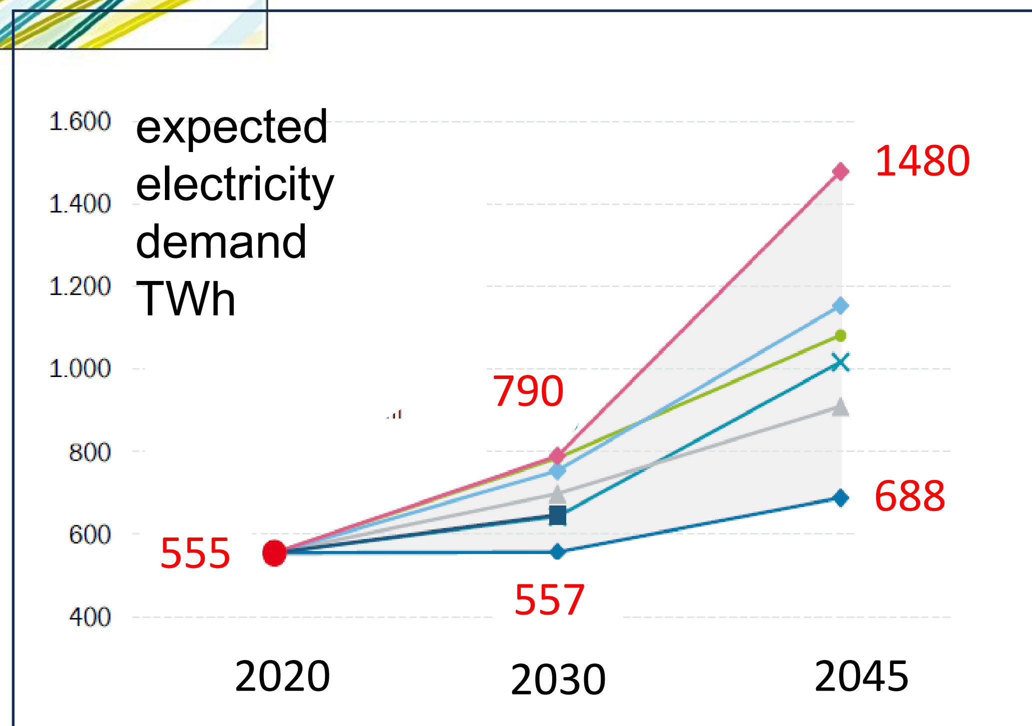


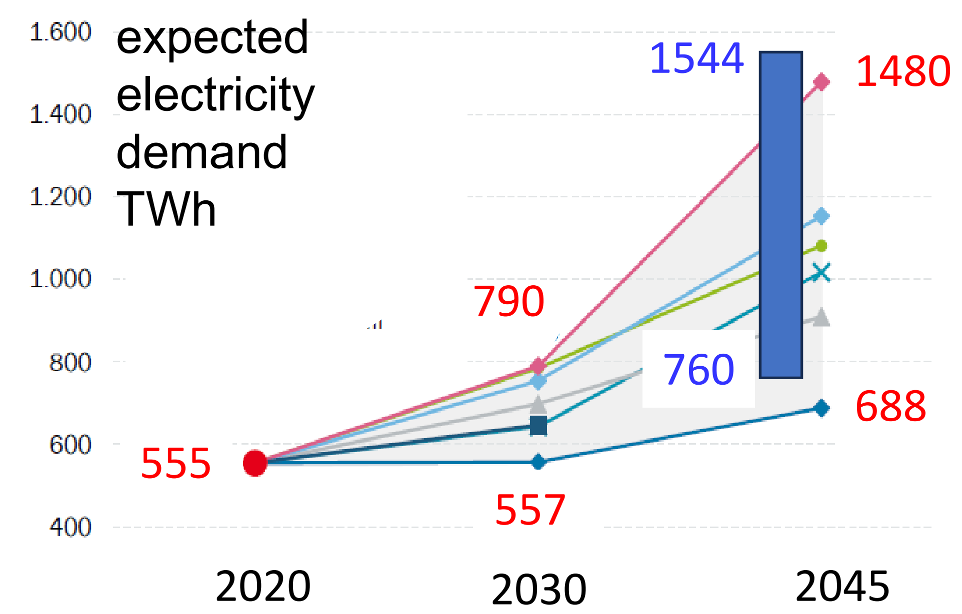
Diagram taken from: https://www.stiftung-klima.de/app/uploads/2022/03/2022-03-16-Big5_Szenarienvergleich_final.pdf



And from 10, partially more recent studies

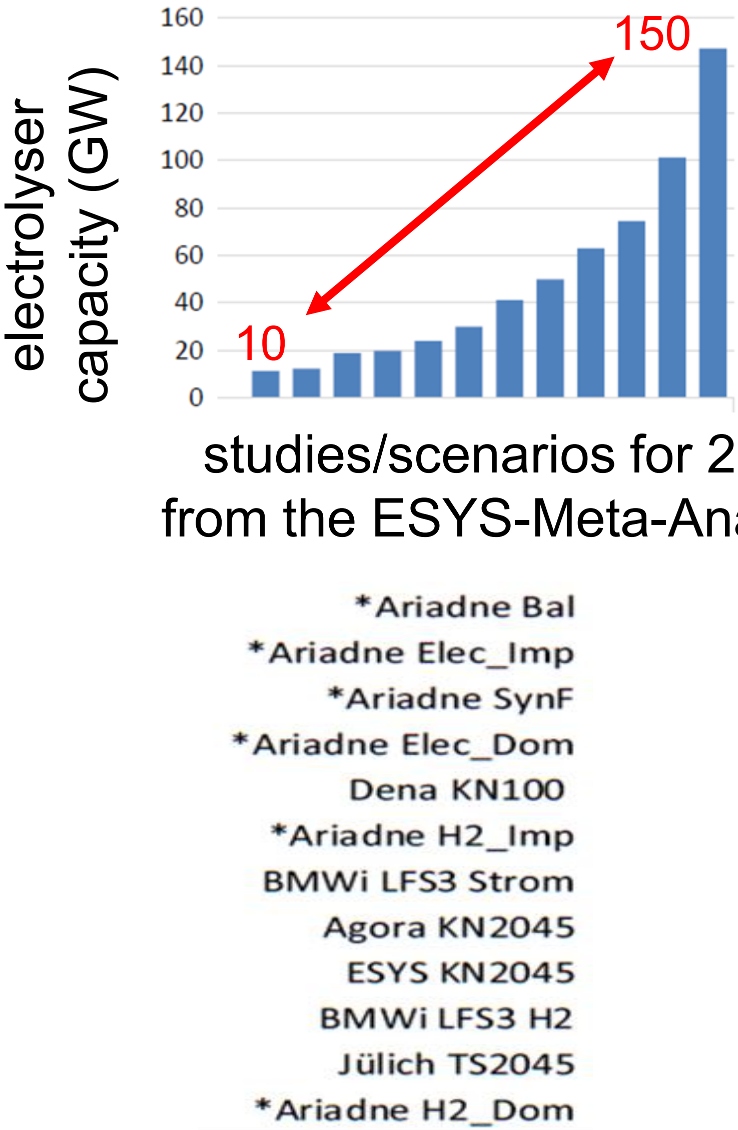
#	Studie	Strombedarf
1	Fraunhofer 2024	1227-1544 brutto
2	BDI/ KLIMAPFADE 2.0	993 netto
3	BMWK, 2024	1100-1300 brutto
4	BDI-Studie	950 netto /0,88
5	BMBF/Ariadne	1037–1423 wohl brutto
6	Agora 2024	1017-1267 brutto
7	Agora 2021	1017 Brutto
8	e-venture	887-1186 netto
9	UBA Treibhausgas	947,2-967,2 brutto
10	Aurora 2025	965 oder 760 brutto

<u>Comment:</u>
No clear answer on the future demand



Why is it so difficult to predict the future electricity demand?

One example: Electrolysers



studies/scenarios for 2045
from the ESYS-Meta-Analysis

Elements of a bottom-up procedure:

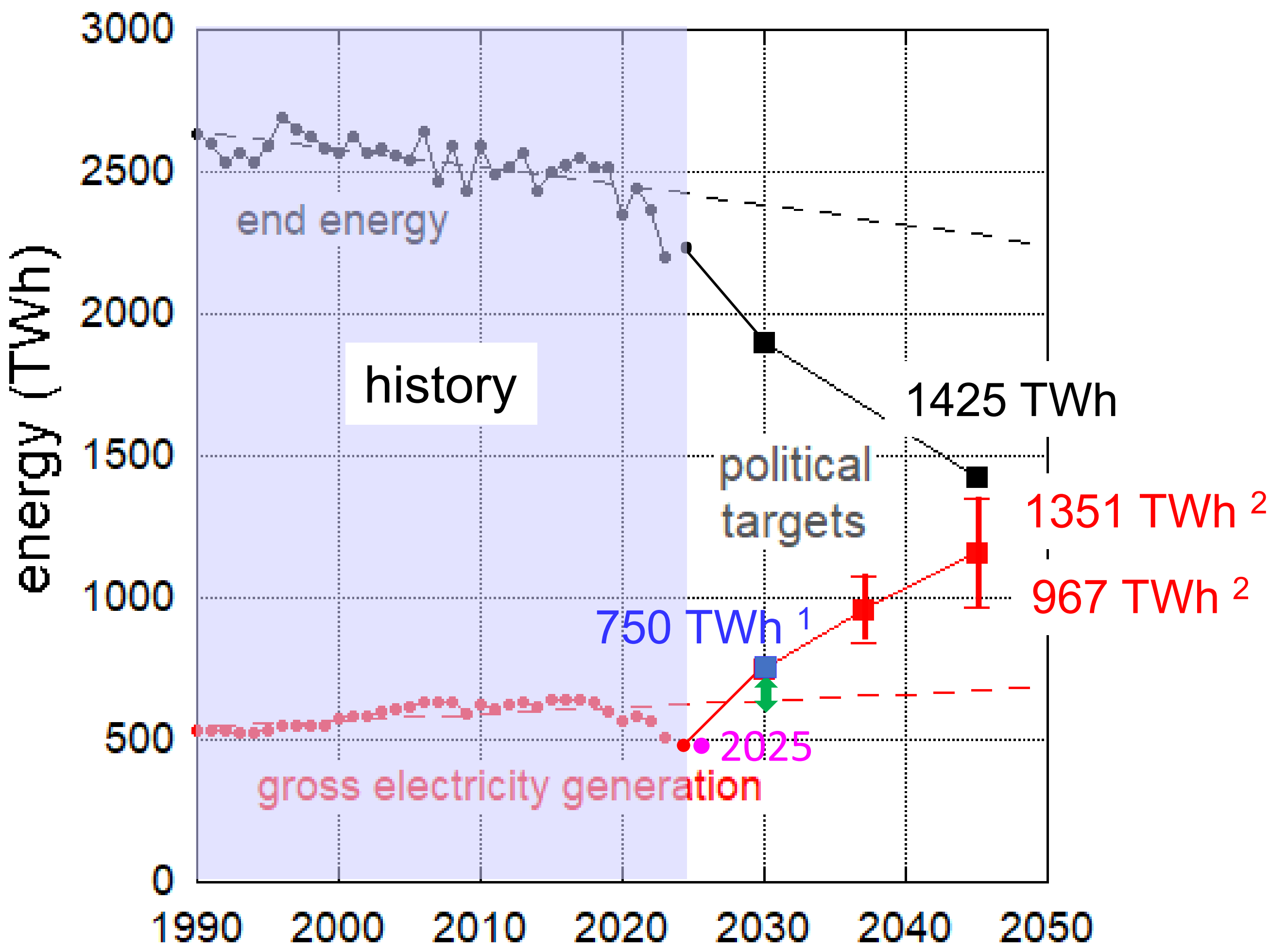
(1) Basic electricity (efficiency, saving)
(2) New consumers: digitisation,
data centers, AI, cooling ...
(3) Sector coupling
mobility, BEVs
heating, heat-pumps
(4) Electrolysers for H2 generation,
(5) Level of import (electricity, H2)
.....

<u>Conclusion:</u>
either: a large corridor of solutions
for the goal – no net emissions

or: no clear guidelines from scenarios

https://energiesysteme-zukunft.de/publikationen/analyse/transformationspfade
Fig. 31

The political objectives



Objective:

share electricity

in end-energy: 0,95

specific cases, I will analyse

year	gross electricity
	TWh
2030	650
2030	750
2045	967
2045	1351

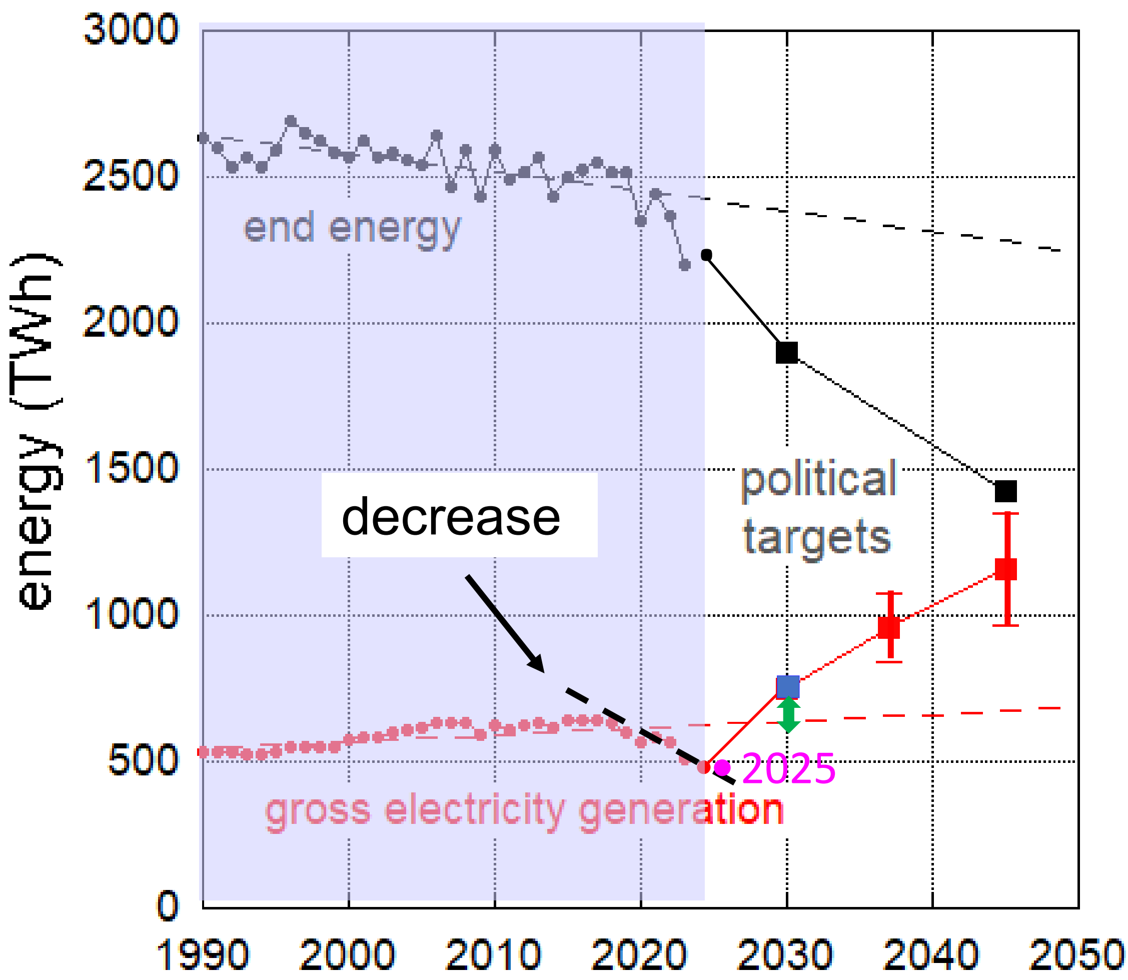
1) Osterpaket of the Ampel-government from 2022

↕ Present government: 600 and 700 TWh

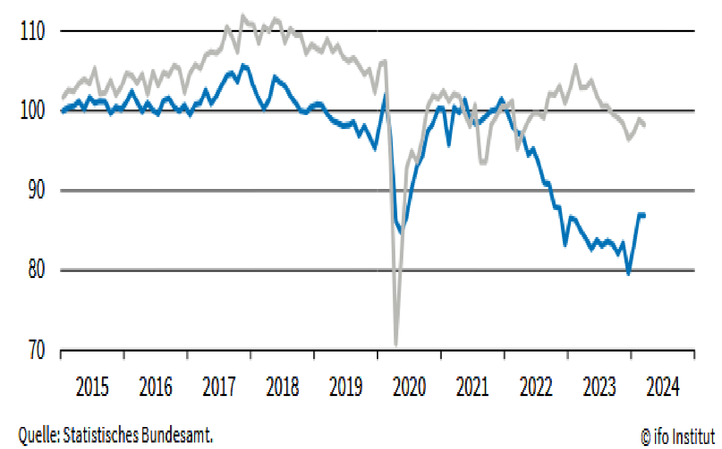
2) NEP-scenarios A and C.

NEP: Grid-development-plan Bundesnetzagentur (German regulatory authority)

Decrease of electricity generation/consumption in recent years



Production index
energy-intensive industry
non-energy-intensive industry



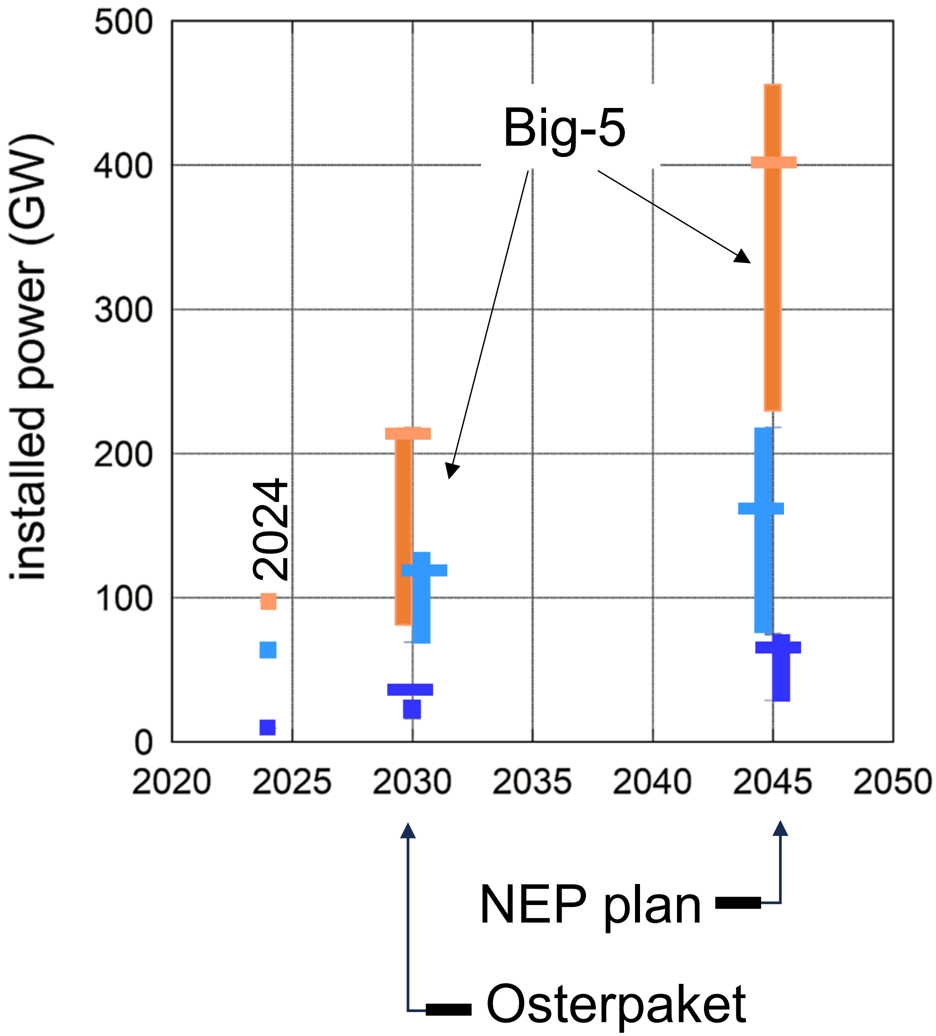
Comment:

Sector coupling is not yet effective; electricity share in the end-energy: 20%
Unexpected consumer-response: instead of clean technology investments, a reduction of domestic economic activities.

Generation: expected capacity (GW) of renewable energies (REs)

Nomenclature

renewabel energies REs = Biomass + Hydro + iREs (i: intermittent)
iREs = onshore wind (Won), offshore Wind (Woff), photovoltaic power (PV)



		„Oster-paket“[1]	NEP Plan [2]
GW	2024	2030	2045
PV	92,4	215	400
Won	63,6	115	160
Woff	9,2	30	70

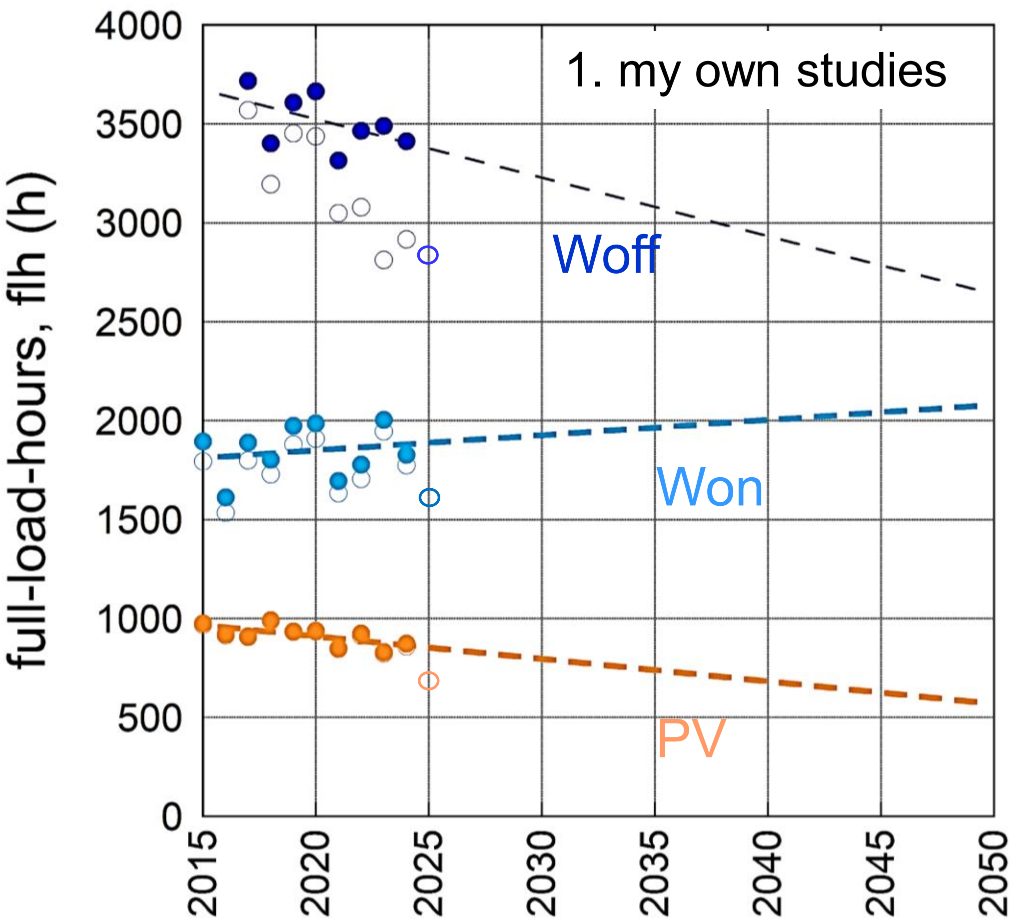
my input data

Comment:
No clear answer on the future installations

1) Ampel-government, 2022
2) NEP: Grid-development-plan Bundesnetzagentur (German regulatory authority)

From installation (GW) to generation (TWh): full-load-hours (flh)

flh = annual generation (TWh) / installed power (GW)
depends on weather conditions during the year
and on the future technological progress

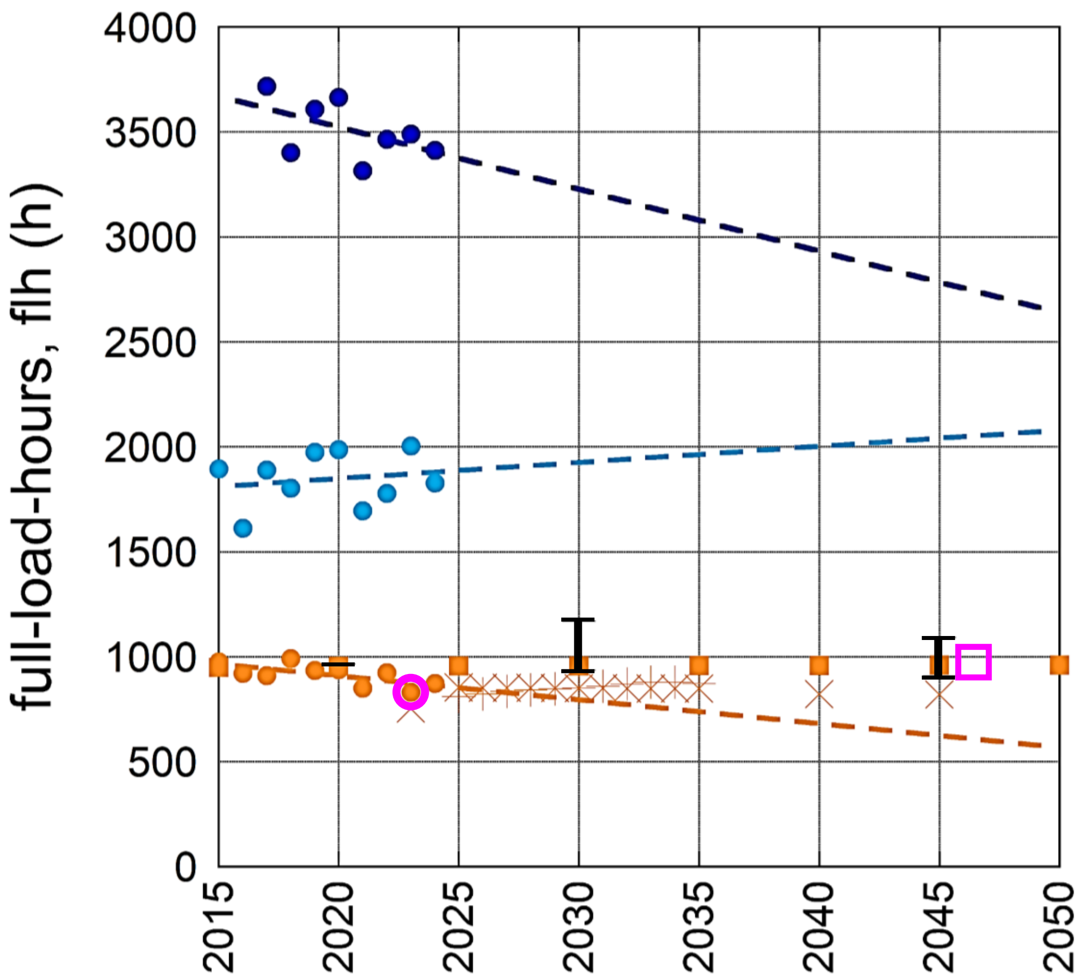


Data handling:
- open symbols: raw data
- closed symbols: corrected for shut-down periods

Comments:
Won: increase as qualitatively expected.
Woff: possibly shadow-effects.
PV: impact of less efficient roof-top + balcony panels?

Dashed lines: linear extrapolation $\Rightarrow$ reference

flh-values from different studies: PV



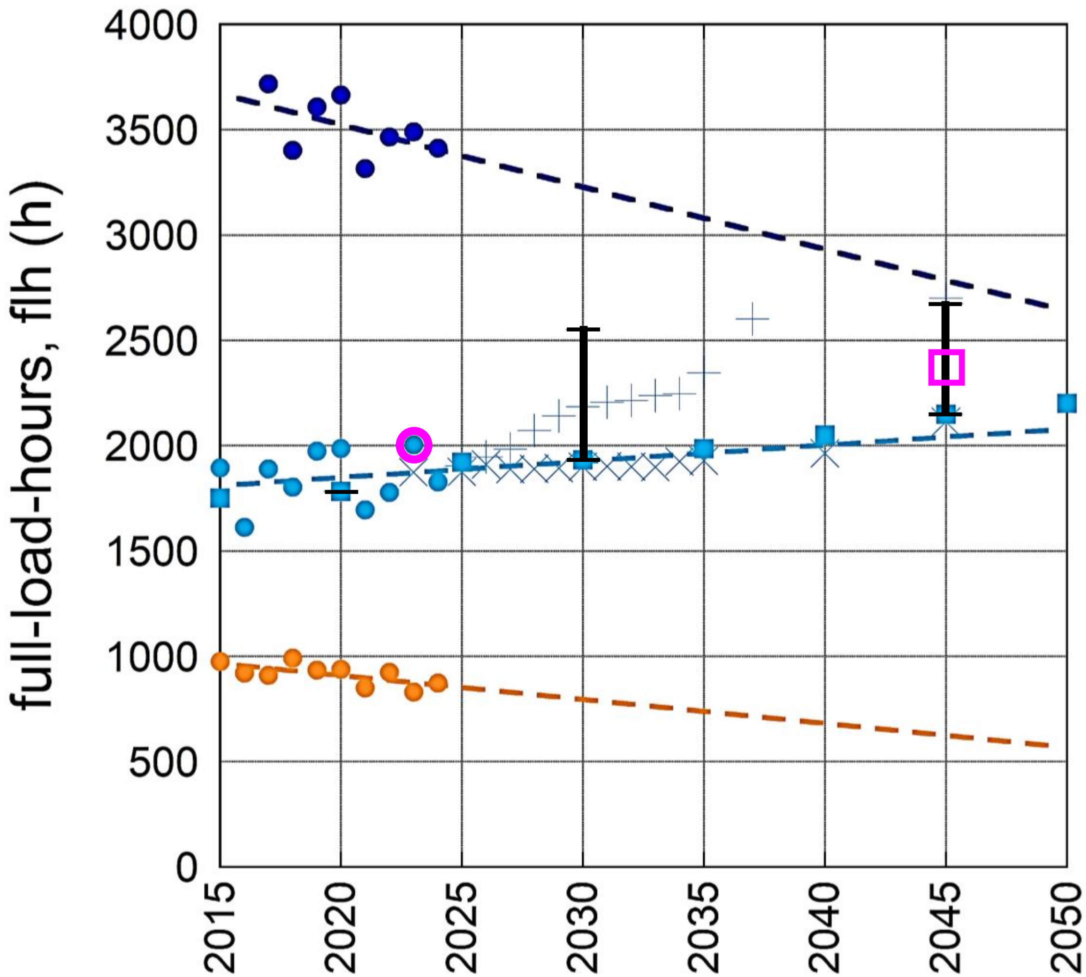
■ AGORA*
× UBA**
+ NEP
I Big-5
* Thinktank
** Federal Environment Agency

○ the 2023-value for my projections
□ average study-value for 2045 projections

Comments:
- no improvement expected
- negative trend not considered

AGORA: https://www.agora-energiewende.de/daten-tools/klimaneutrales-deutschland-2045-datenanhang
UBA: Tabelle Datenbasis projektionen-2025-kernindikatoren-ap1.master_20250527
NEP 38/45: https://www.netzentwicklungsplan.de/sites/default/files/2024-07/Szenariorahmenentwurf_NEP2037_2025_1.pdf?utm_source=chatgpt.com
NEP Vers. Sich.: https://daten.bundeswirtschaftsministerium.de/ODP/Redaktion/DE/OpenData/20250903-Daten-Versorgungssicherheit-OpenData.html
Big-5: https://www.prognos.com/de/projekt/vergleich-der-big-5-klimaneutralitaetsszenarien

flh-values from different studies: Won



- ■ AGORA*
- × UBA**
- + NEP
- I Big-5

* Thinktank

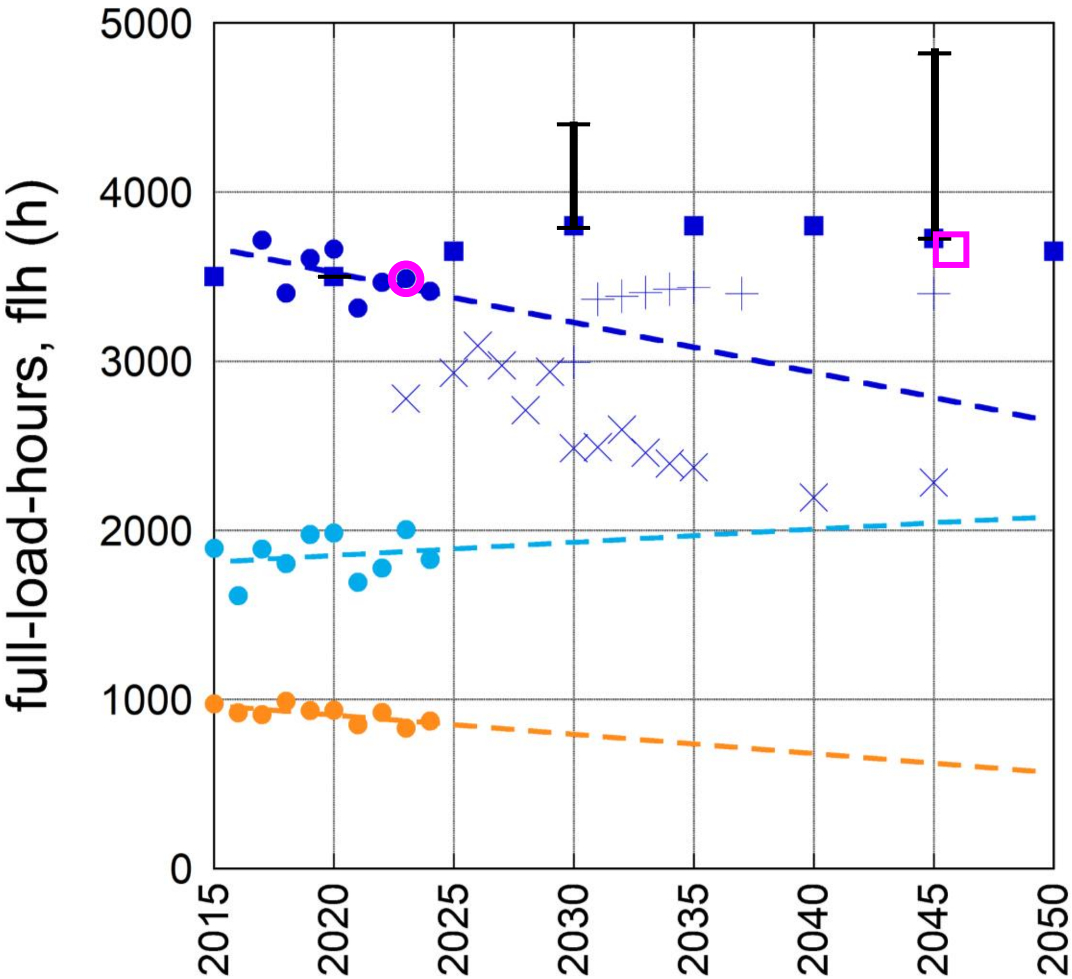
** Federal Environment Agency

○ the 2023-value for my projections

□ average study-value for 2045 projections

Comments:
larger spreading;
positive trend;
NEP-assumption:
⇒ ~ 25% more energy
at specified capacity

flh-values from different studies: Woff

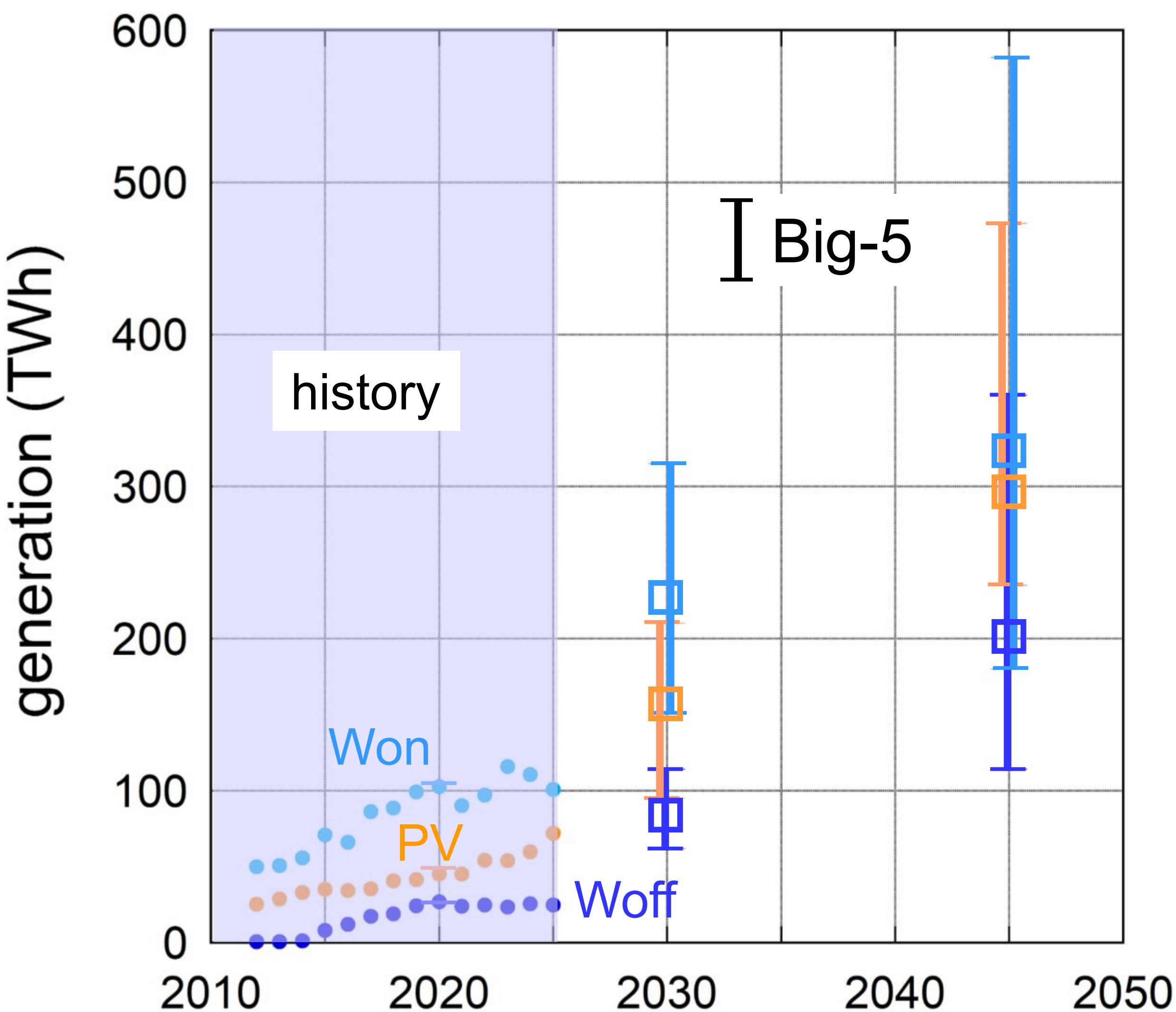


■ AGORA*
× UBA**
+ NEP
I Big-5
* Thinktank
** Federal Environment Agency

○ the 2023-value for my projections
□ average study-value for 2045 projections

<u>Comments:</u>
no agreement;
AGORA considers shadow effects
UBA-values: reduced use of installed capacity.

Generation: historical values and Big-5 expectations



Conclusions:

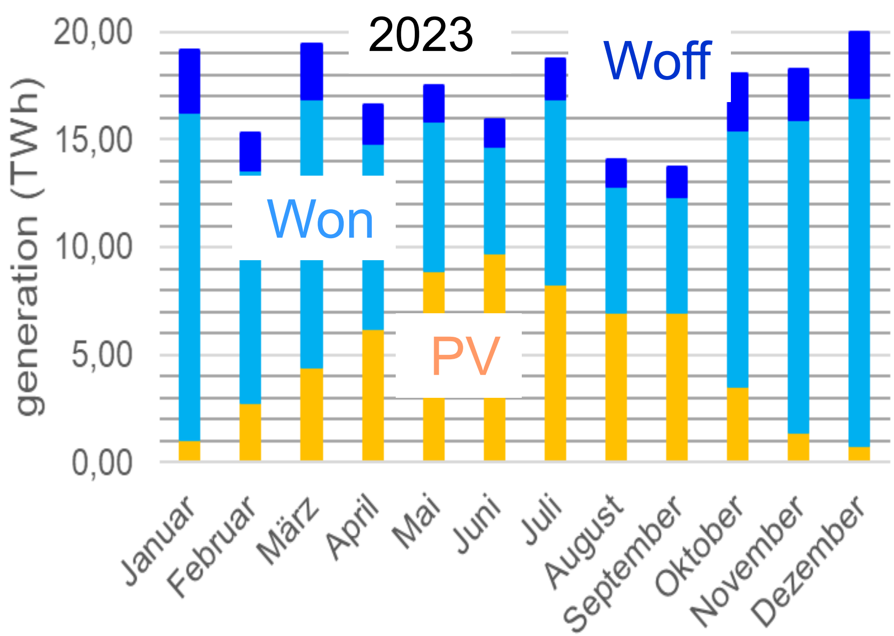
either:
the goals can be met in a large parameter range.

or:
scenario-studies hardly deliver clear guide-lines.

□ for my projections

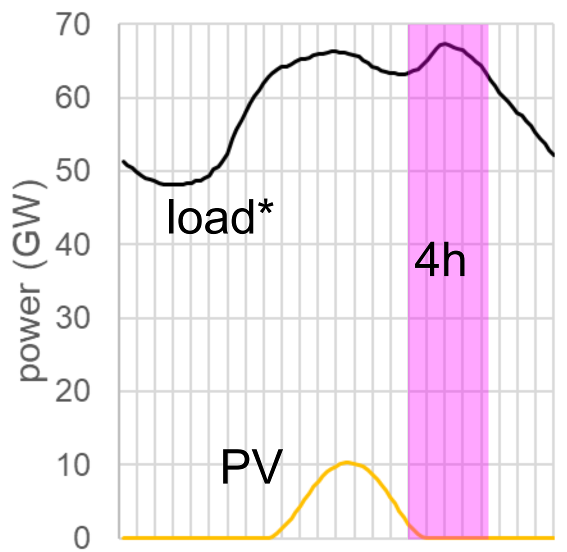
Variation of wind and solar power

1. intermittency on short time scale
2. seasonal variation



3. daily variation

averaged over January 2024



* load: electricity distributed via the grid

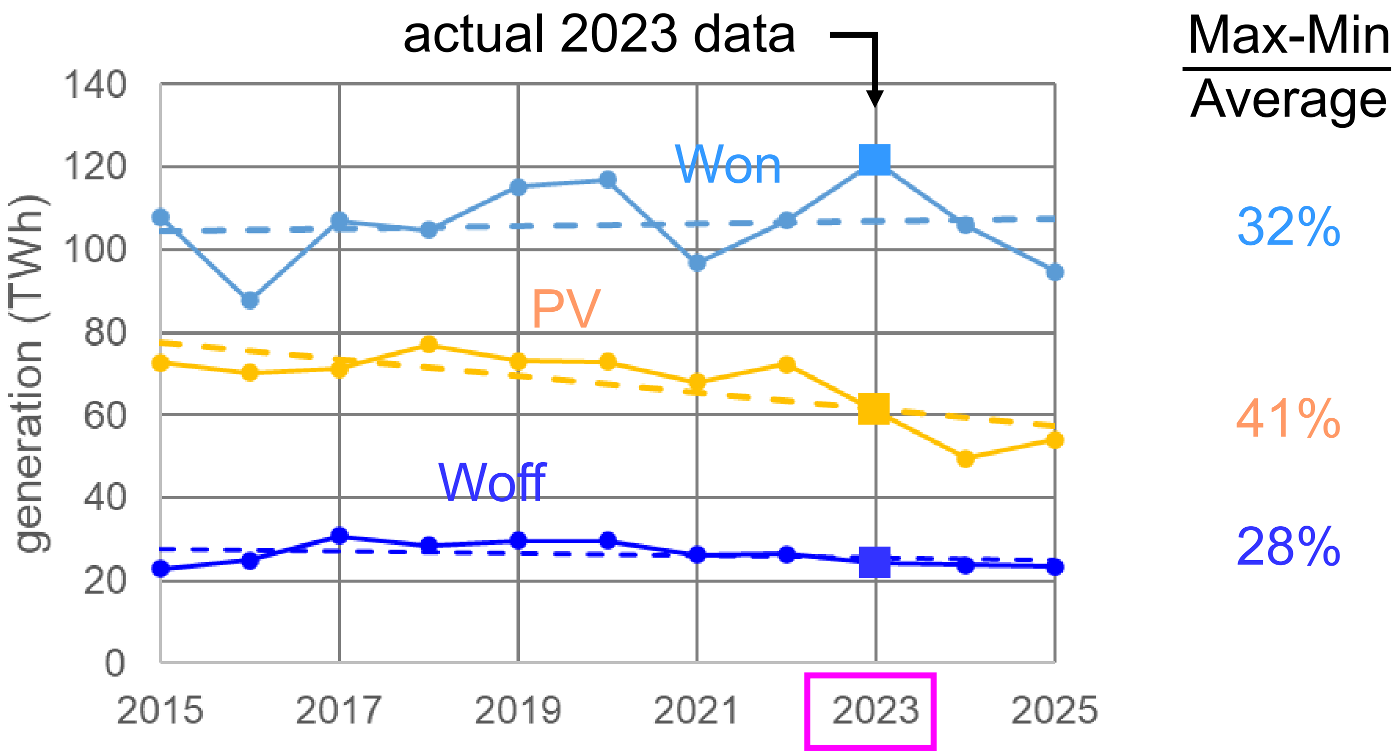
Comments:

PV in summer high, in winter lower
wind in winter high, in summer lower
⇒ iREs generation: rather constant;
scatter from month to month
PV (Jan, Dec) ~ 10% of PV (June, July)

PV does not contribute to the evening peak of the load

Year-to-year variation of iREs generation

Annual generation BUT with the installations of 2023 to allow comparison
2023: PV = 76,9 GW, Won = 61 GW, Woff = 8,5 GW

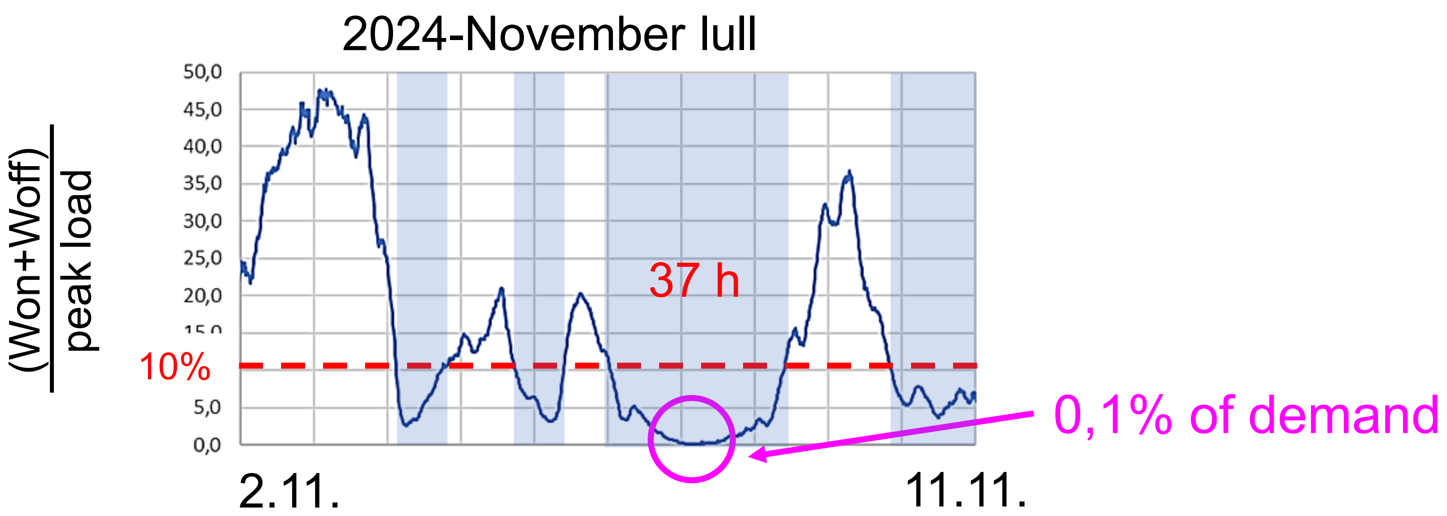


Conclusions:

30-40% variation from year to year has to be expected
variation of wind+solar: 24% ⇒ complementarity of wind and PV
projections into the future of limited precision

The infamous „Dunkelflaute“

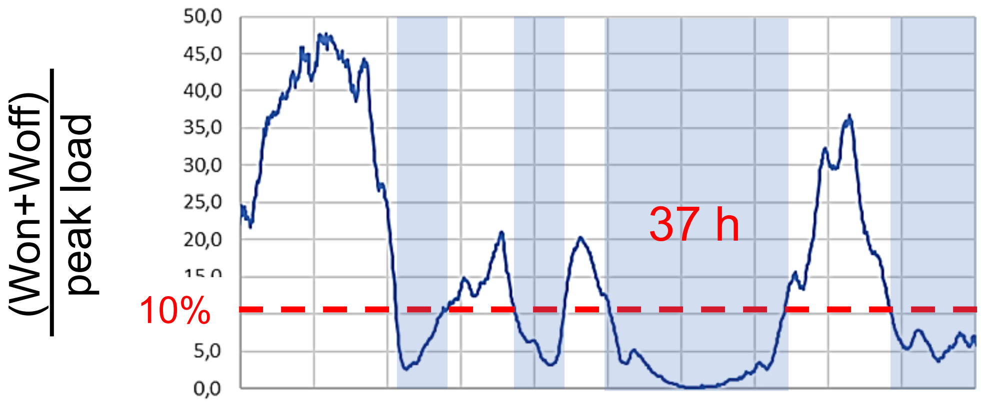
My definition: Won+Woff < 10% of peak-load



The infamous „Dunkelflaute“

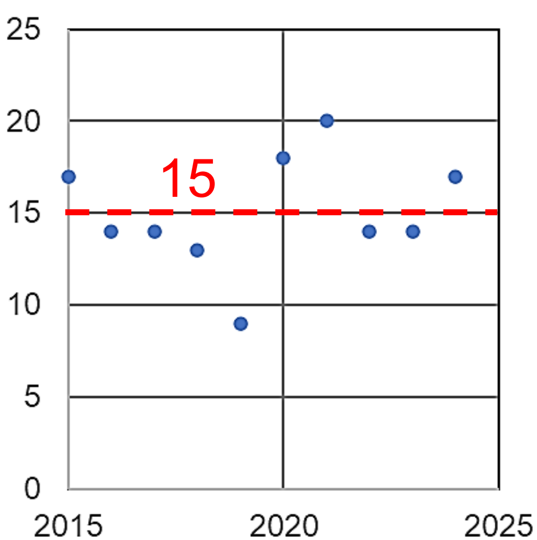
My definition: Won+Woff < 10% of peak-load

2024-November lull

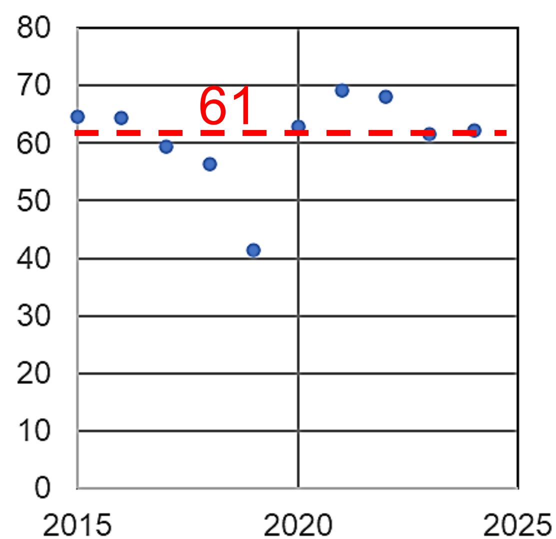


Dunkelflaute features - with the iREs installations of 2030

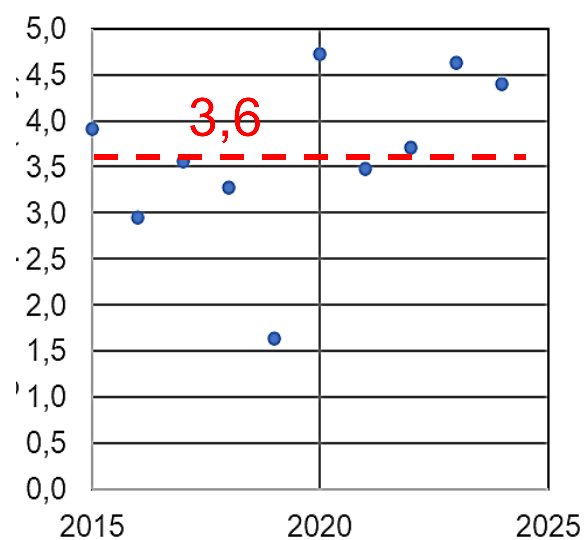
number of lulls per year



total duration of all lulls (days)



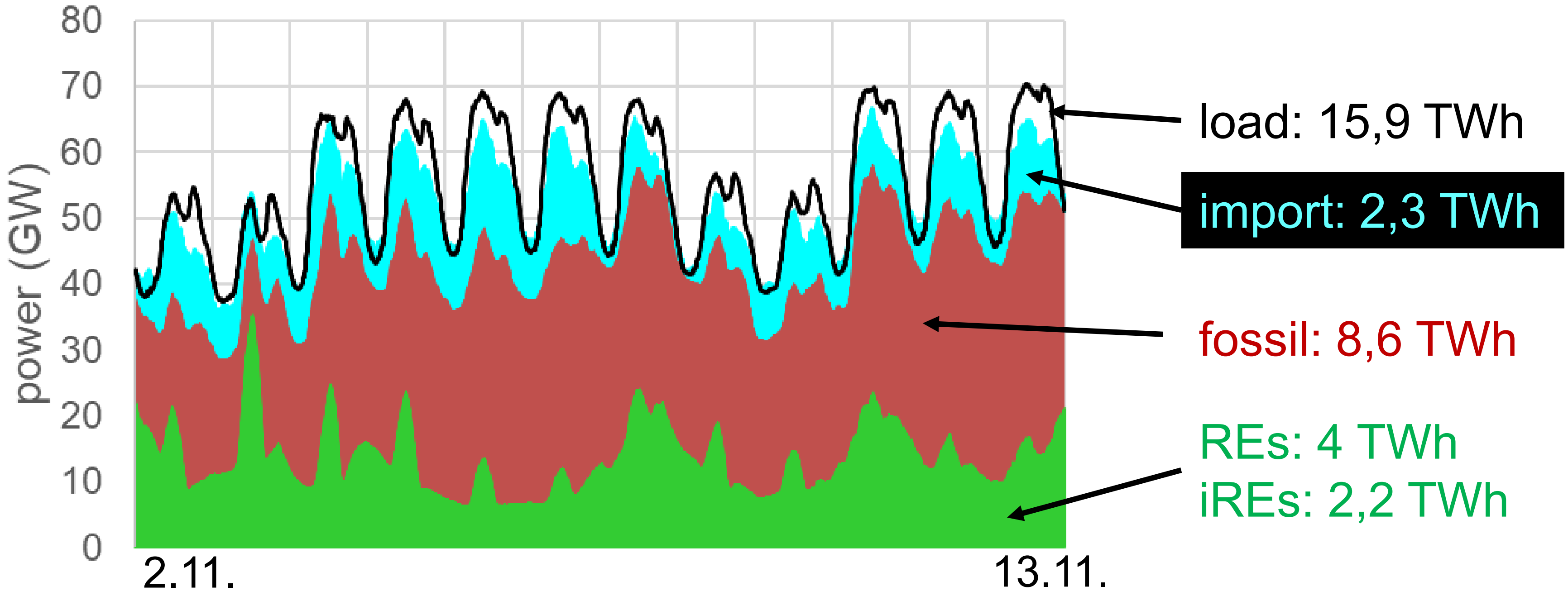
longest lull period (days)



The November 2024 lull

It lasted for 11 days. It was the longest since 1982 [1]

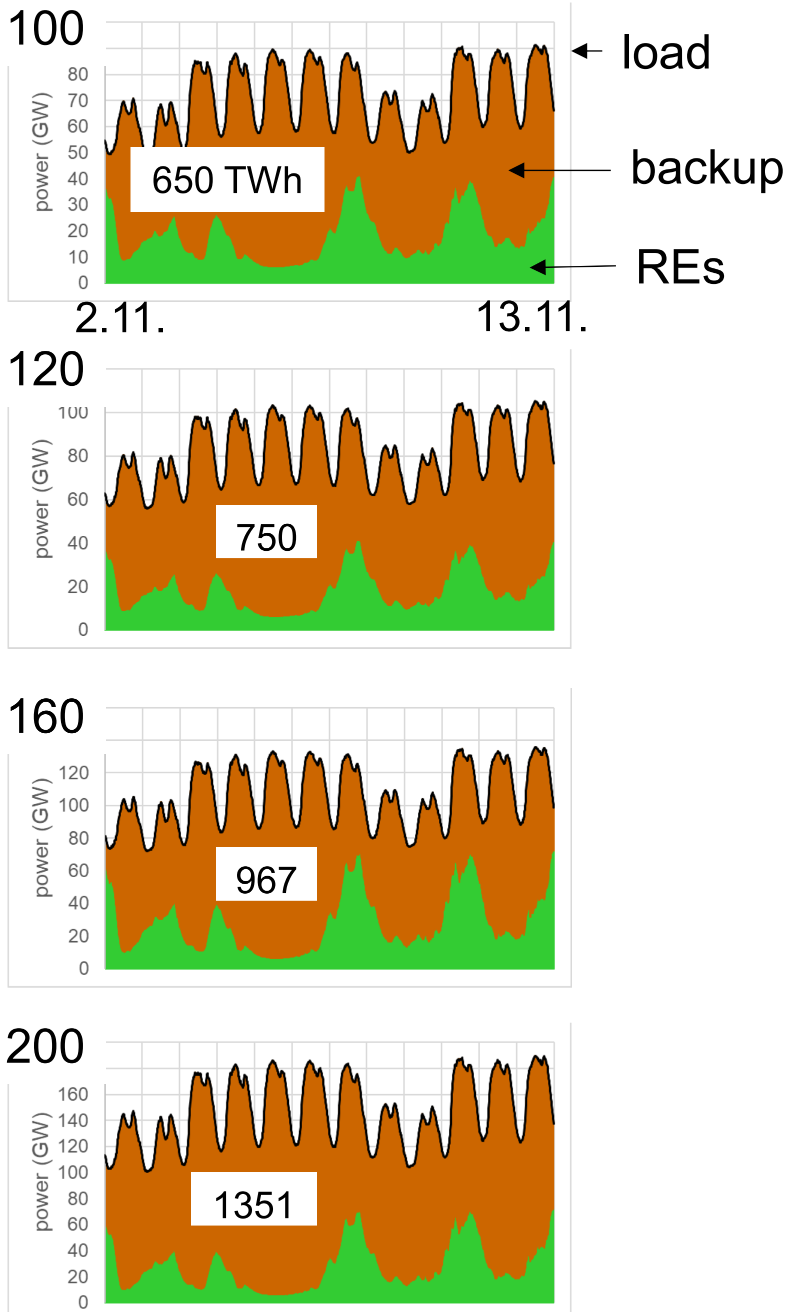
1 Amprion



Dunkelflaute - scaled to 2030 and 2045

2030

PV	215
Won	115
Woff	30



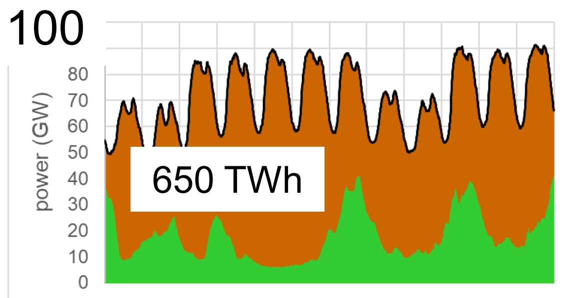
2045

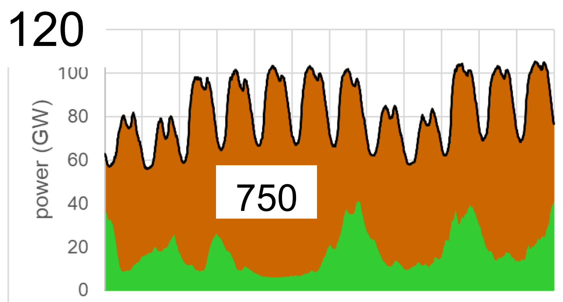
PV	400
Won	160
Woff	70

Dunkelflaute - scaled to 2030 and 2045

2030

PV	215
Won	115
Woff	30





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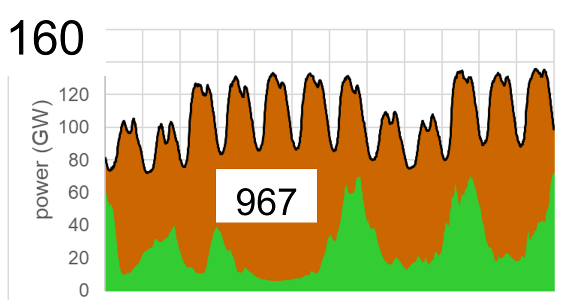
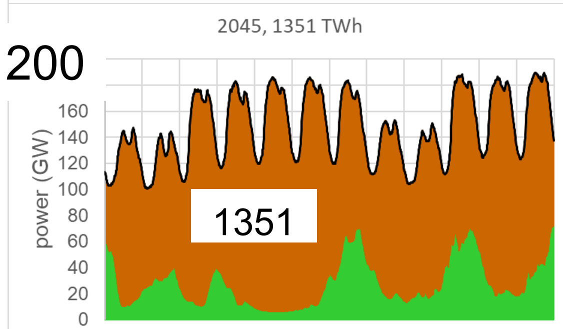




specification of the backup system

year	gross electricity	annual load	backup demand	backup power
	TWh	TWh	TWh	GW
2024	501	466	8,6	39,3
2030	650	606	15,2	83
2030	750	697	18,4	97
2045	967	896	22,3	127
2045	1351	1255	35	180

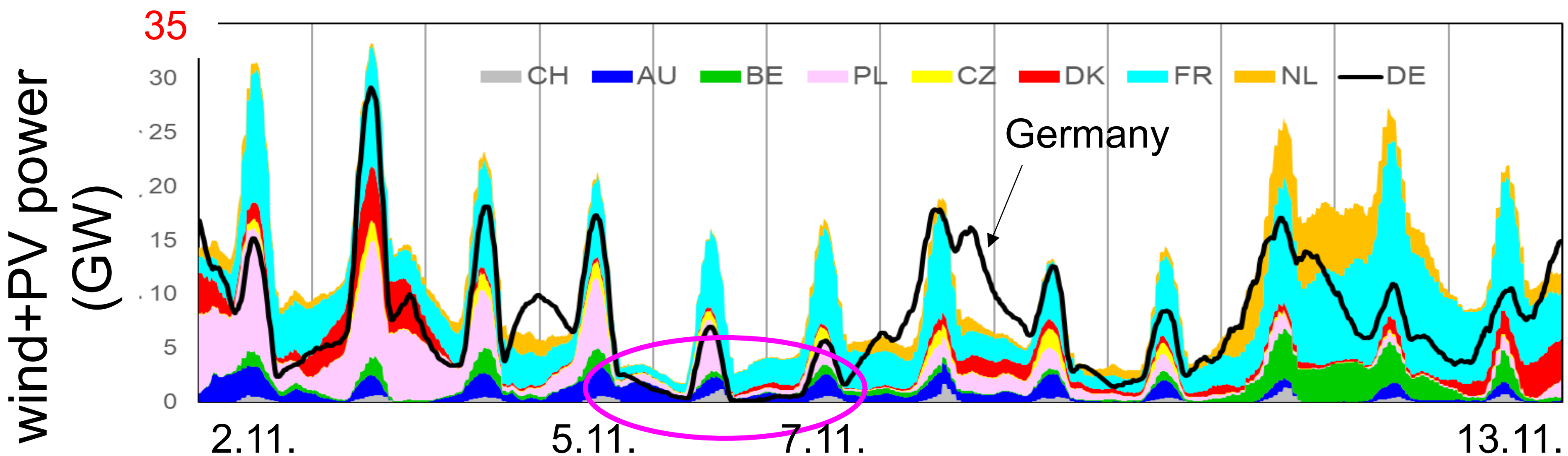
<u>conclusions:</u>

need for an independent system
delivering dispatchable power

cannot be fully covered by
pumped hydro-storage
batteries

Are our neighbours able to help with iREs?

2. – 13. November 2024



installed iREs power: sum neighbours: ~ 170 GW; DE: 165 GW

<u>Conclusions:</u>
our neighbours cannot help with renewable power
they themselves need to employ a separate system

<u>Comment:</u> all neighbours together have similar state of iREs development

New topic: Projections to 2045 on the basis of 2023

from 2023 ⇒ 2045:

PV: 77 ⇒ 400 GW; Won: 61 ⇒ 160 GW; Woff: 8,5 ⇒ 70 GW

biogas, hydro = const.

Problem: electricity demand is not known ⇒ variable

4 cases considered

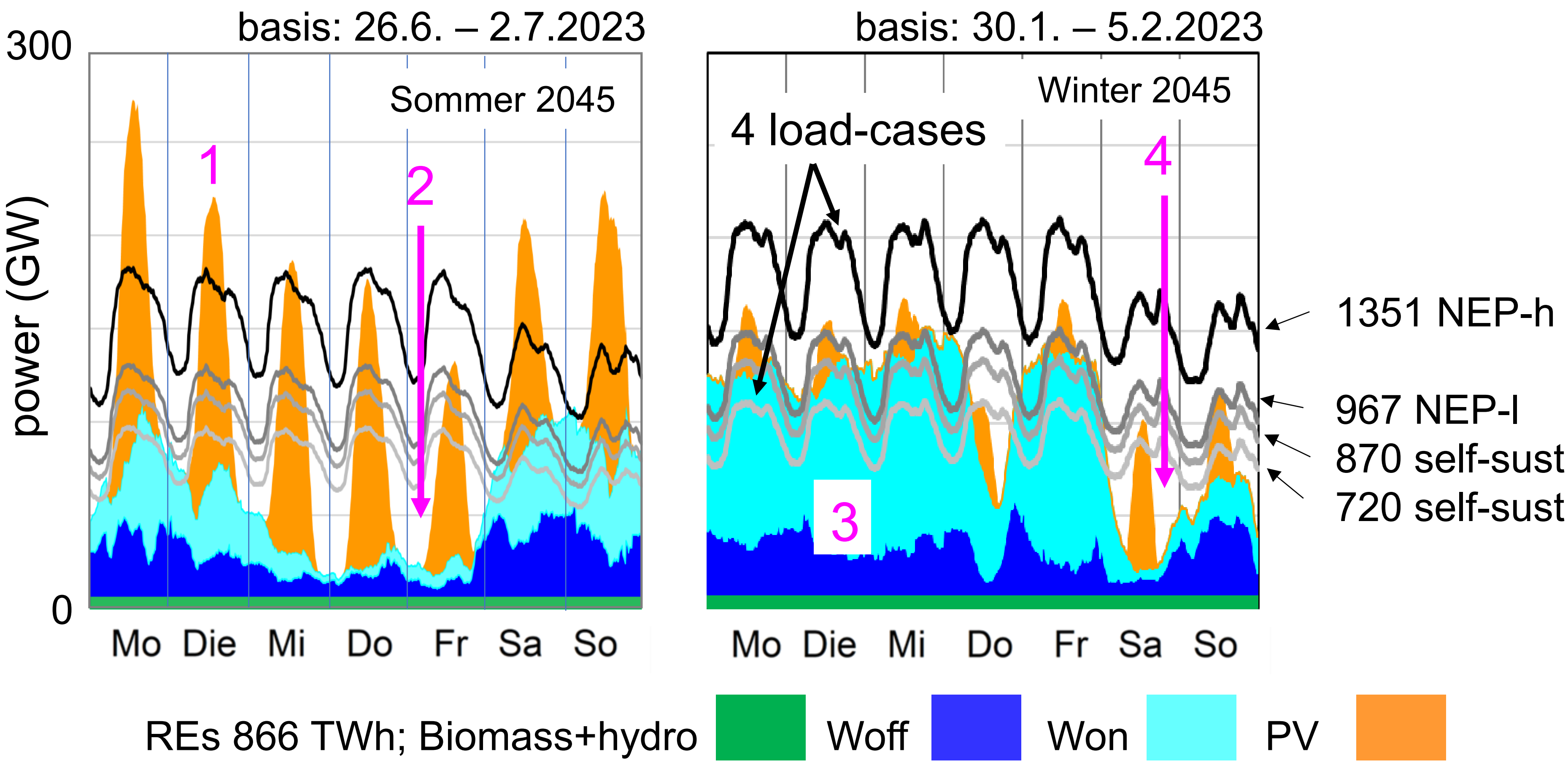
1) NEP-high: 1351 TWh; REs generation: 866 TWh

2) NEP-low: 967 TWh; REs generation: 866 TWh

3) self-sustained case-high: 870 TWh
(flh: average value □ ⇒ REs: 1063 TWh)

4) self-sustained case-low: 720 TWh
(flh: 2023 ○ ⇒ REs: 866 TWh)

Generation and consumption – summer and winter week



Observations:

1 surplus in summer even at highest loads

2 backup in summer during nights

3 complete coverage apart from highest loads; surplus in winter possible for low load

4 backup in winter necessary even for lowest load case

Storage 2045

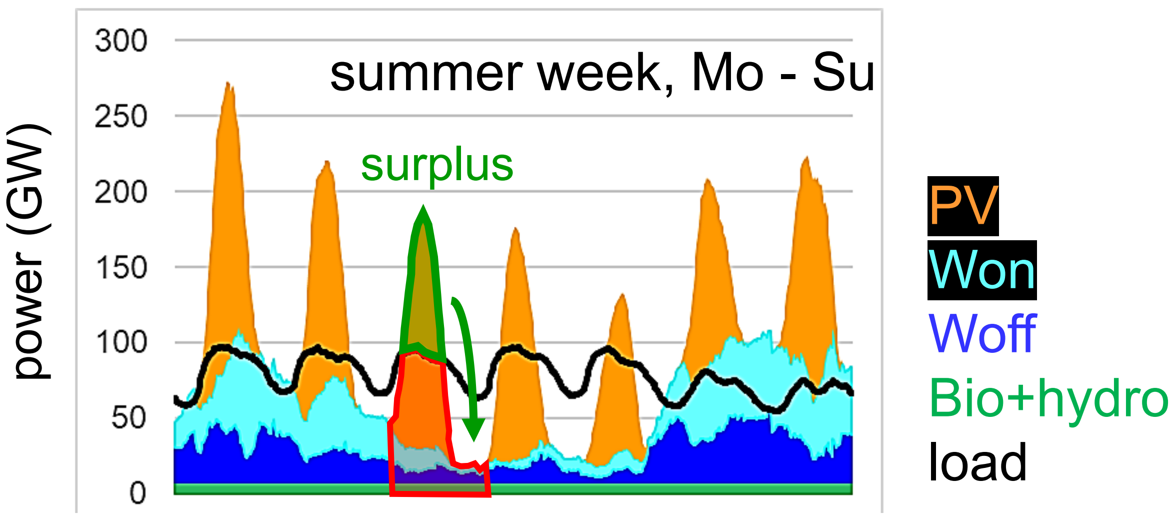
Concept: surplus in storage, from there secondary electricity when needed

2 types of storages

TSp (short-term storage, e.g. batteries ⇒ secondary electricity)

SSp (saisonal storage, e.g. electrolysers ⇒ hydrogen ⇒ gas-power station ⇒ secondary electricity)

principle of short-term storage TSp



TSp = 0,35 TWh ~ average backup in summer (1.5. – 30.9.)

Max of neg. correlation of PV and TSp work at night

Storage 2045

Concept: surplus in storage, from there secondary electricity when needed

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TSp (short-term storage, e.g. batteries ⇒ secondary electricity)

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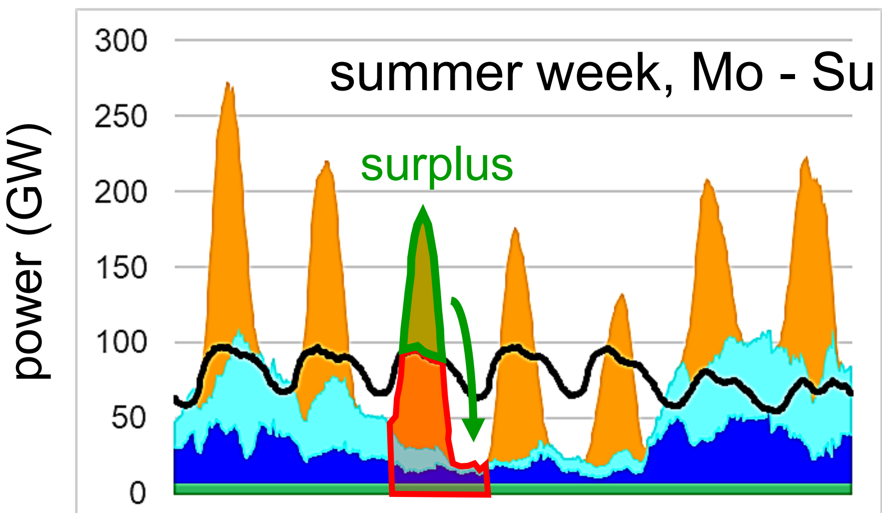
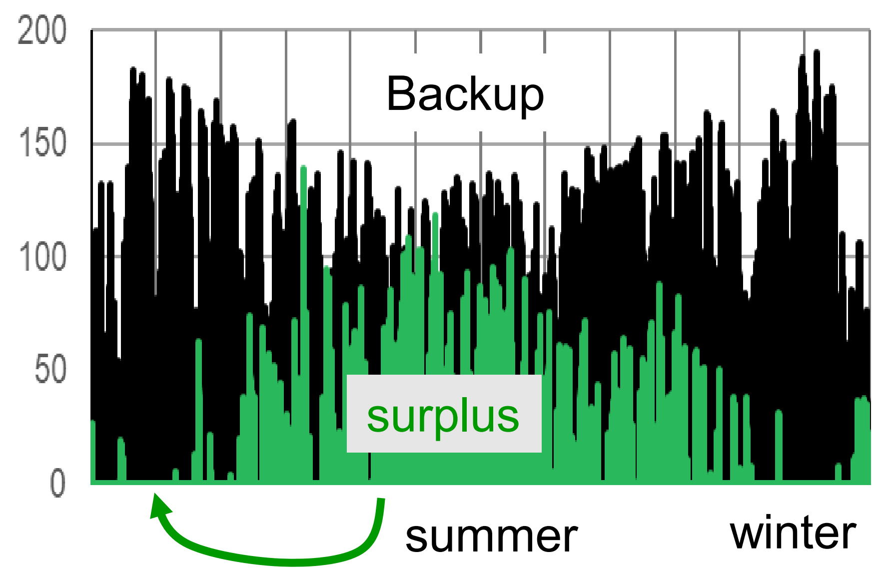
principle of short-term storage TSp

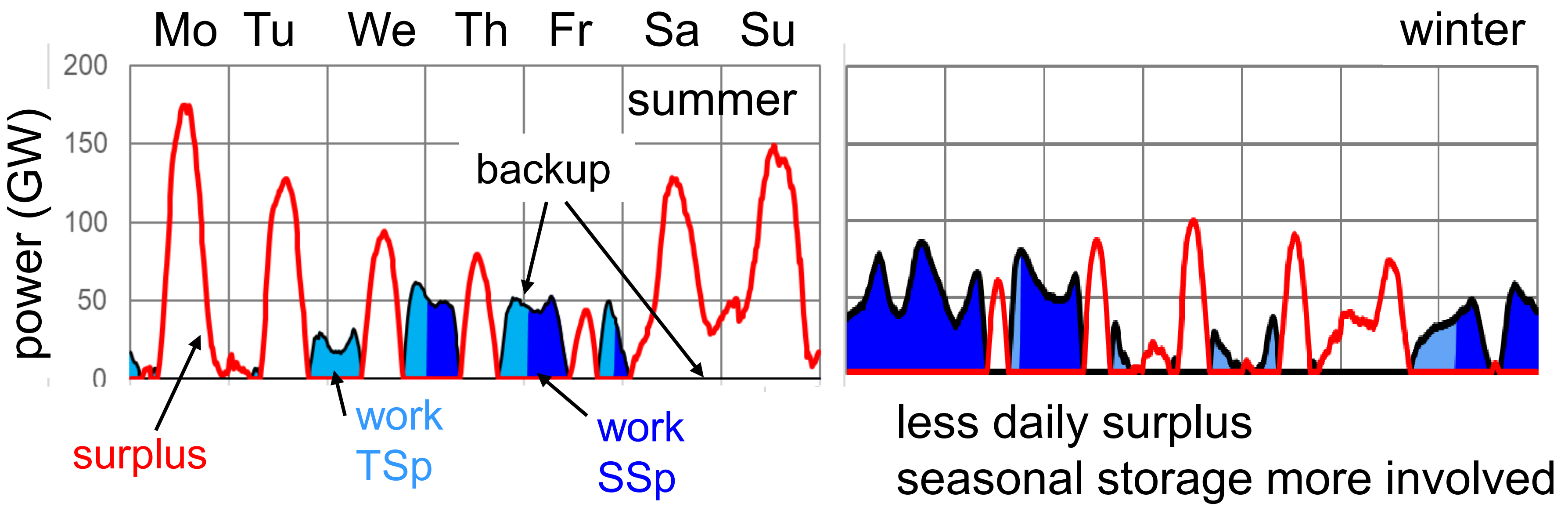


seasonal storage SSp
for the complete year



Action of TSp and SSp represented by surplus and backup

plotted: surplus and backup

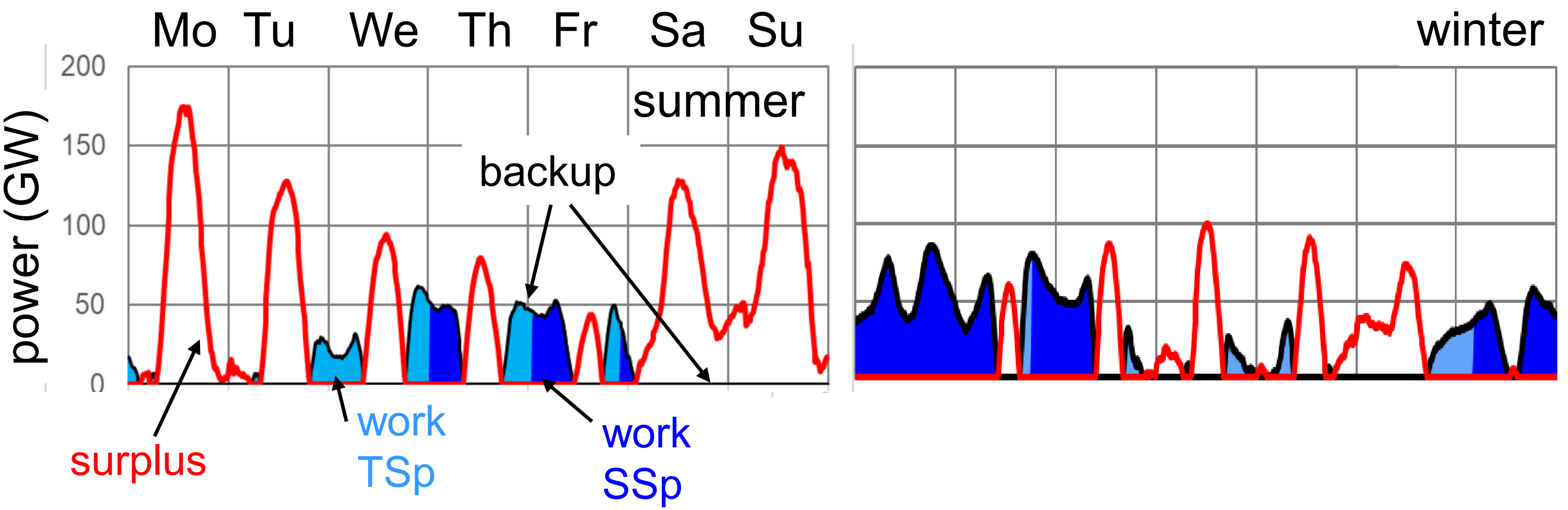


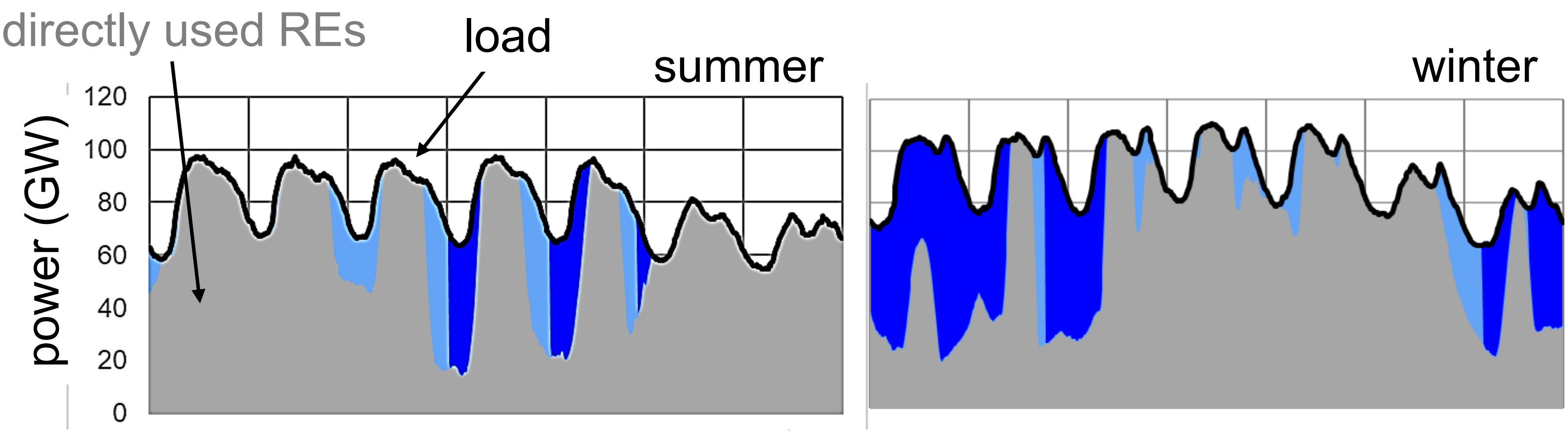
less daily surplus
seasonal storage more involved

surplus > 0: backup = 0
backup > 0: surplus = 0

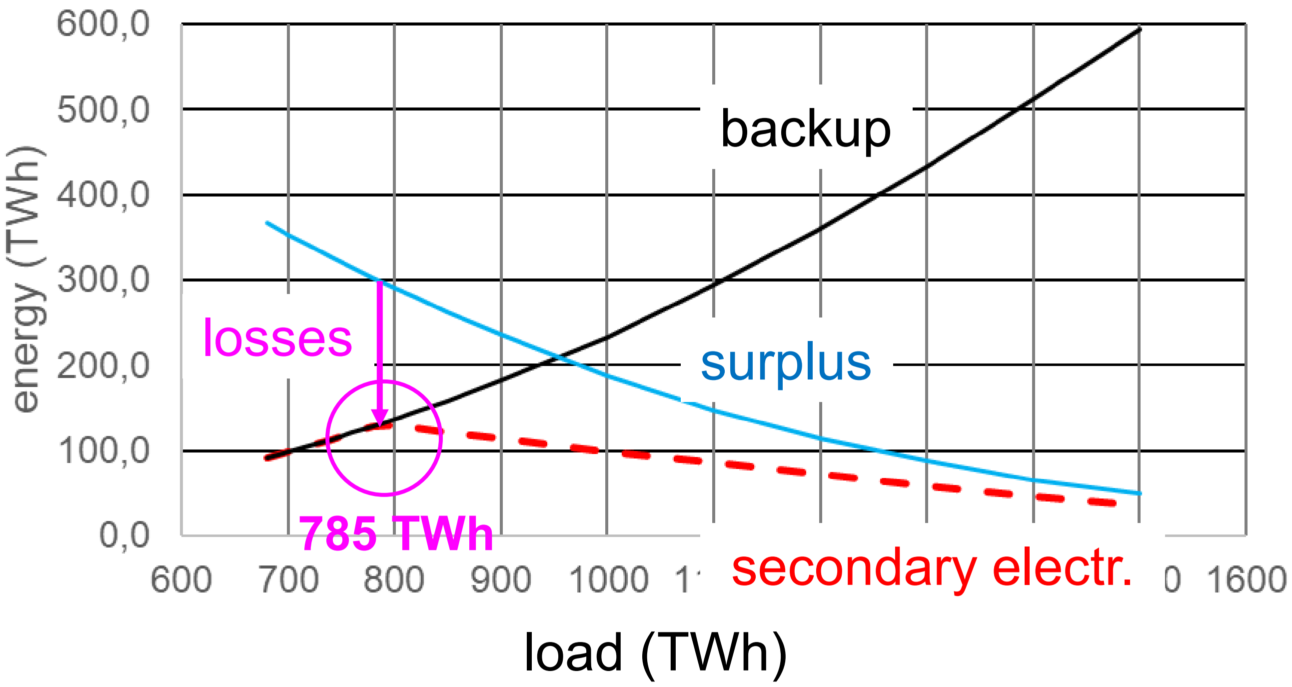
Action of TSp and SSp represented by surplus and backup

plotted: surplus and backup





The role of the load



2045; basis 2023.

flh: of 2023, with shutdown-corrections

E_{iREs} = 870 TWh; E_{REs} = 920 TWh

Sensitivity of the self-sustained load and conclusions

The self-sustained case depends on the flh-assumptions

720 TWh with flh-2023

786 TWh with flh 2023 but with shut-off correction (○)

870 TWh with flh as average value of the different scenarios quoted (□):

goal: 1351 TWh with 1425 TWh end-energy

<u>Under these circumstances:</u>

Electricity to end-energy ratio: 0,5 – 0,6; goal: 0,95; presently: 0,21

missing electricity (several 100 TWh) cannot be imported from European grid

TSp economic (turnover rate = work/capacity); SSp by far not economic;

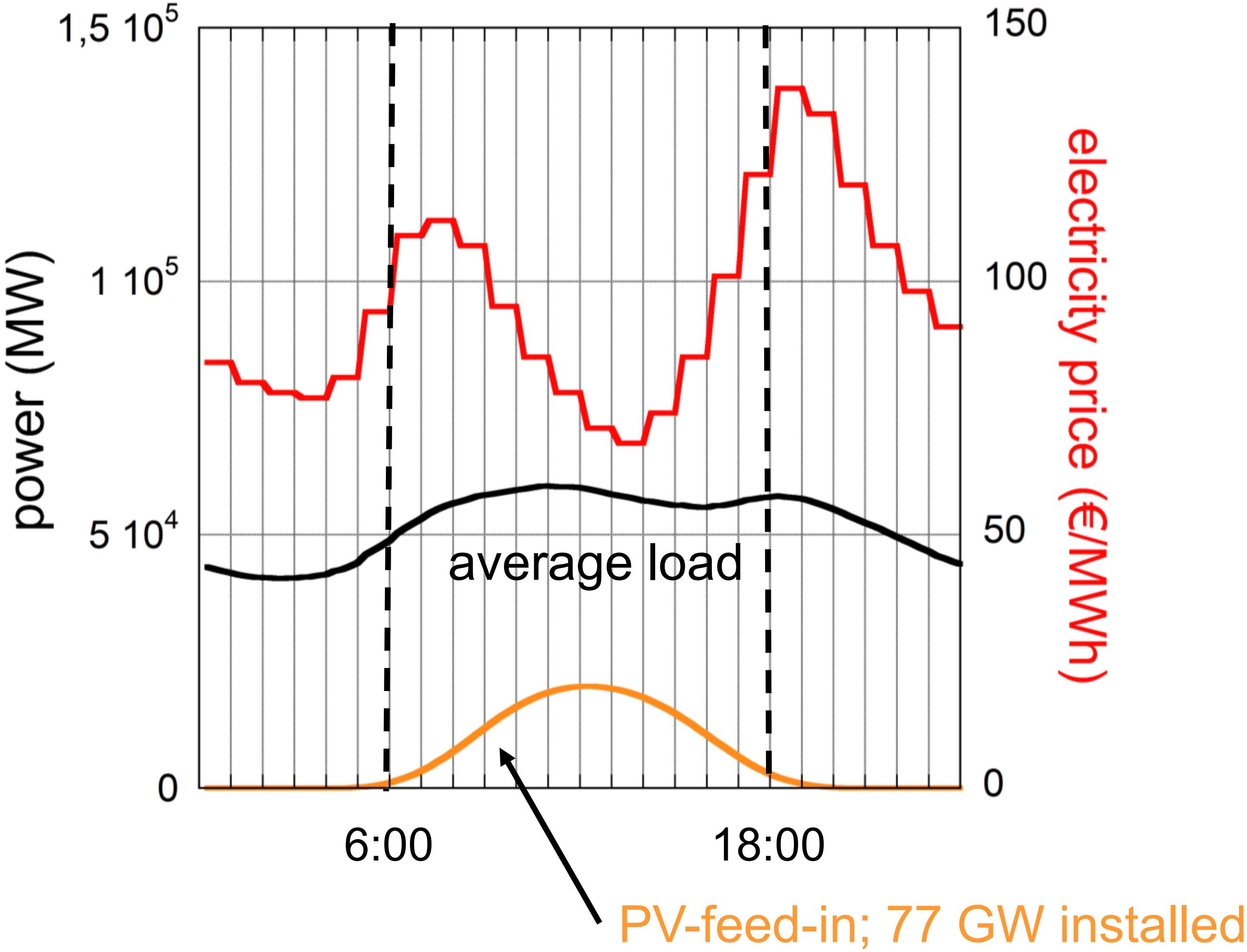
Seasonal balance with domestic hydrogen from surplus is questionable

H2 import: 500 TWh electricity gap ⇒ 1000 TW H2 ⇒ 1400 TWh primary

electricity at generation site: a challenge

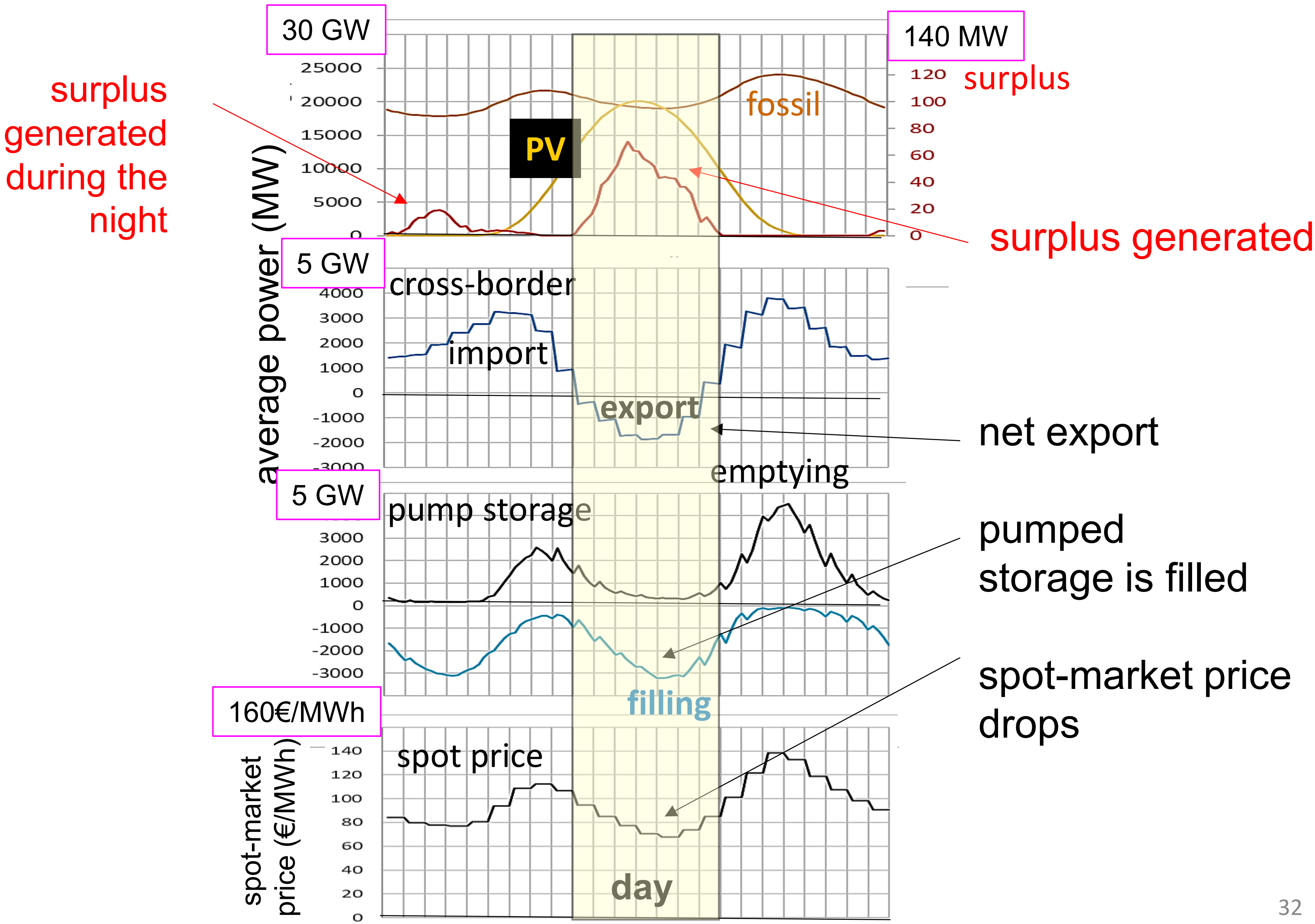
Weather-influence on electricity prices: the „Hellbrise“

2023; day-development, **averaged over the year**



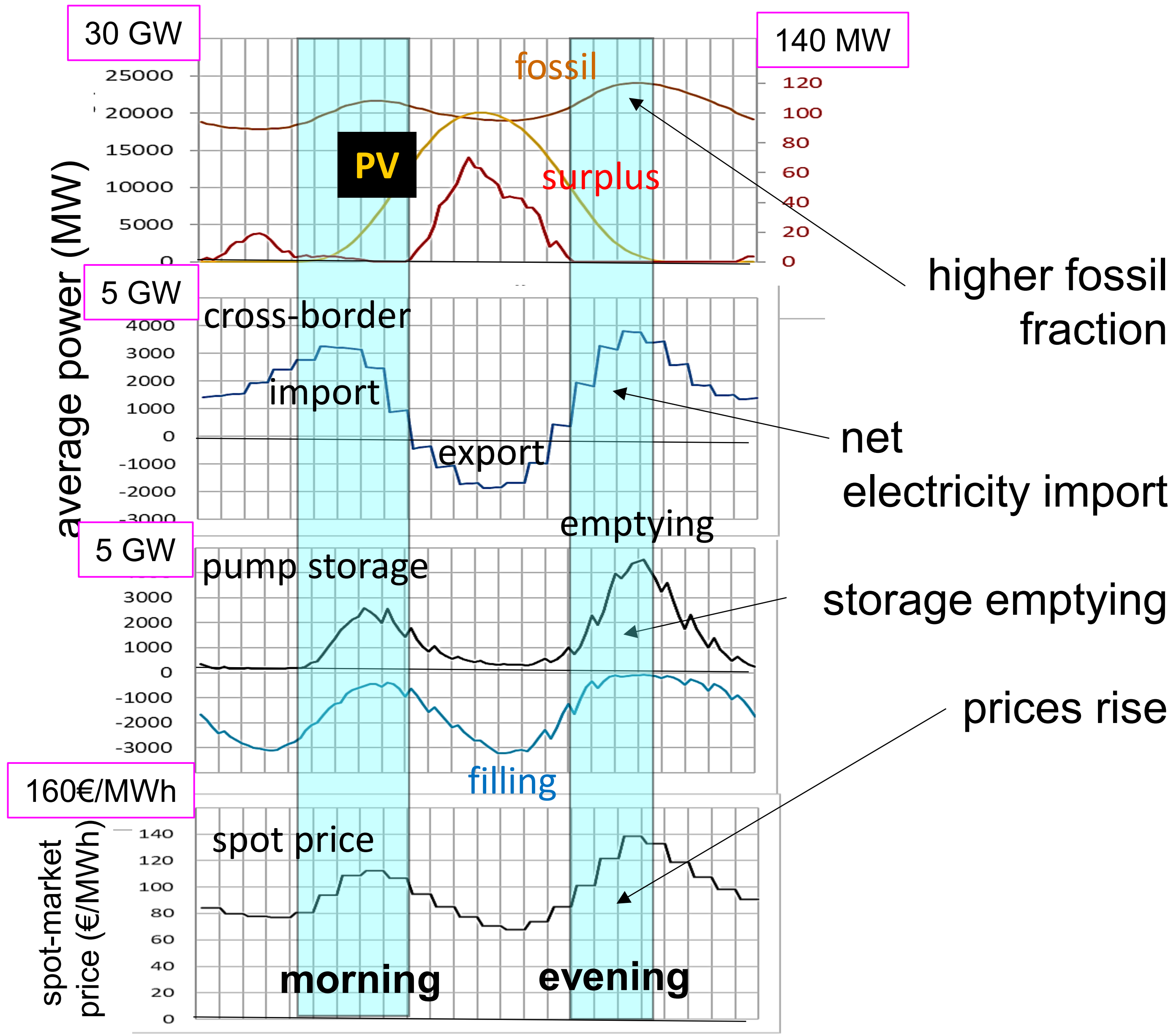
Parameters, which affect the electricity price: with PV

2023; day-development, **averaged over the year**

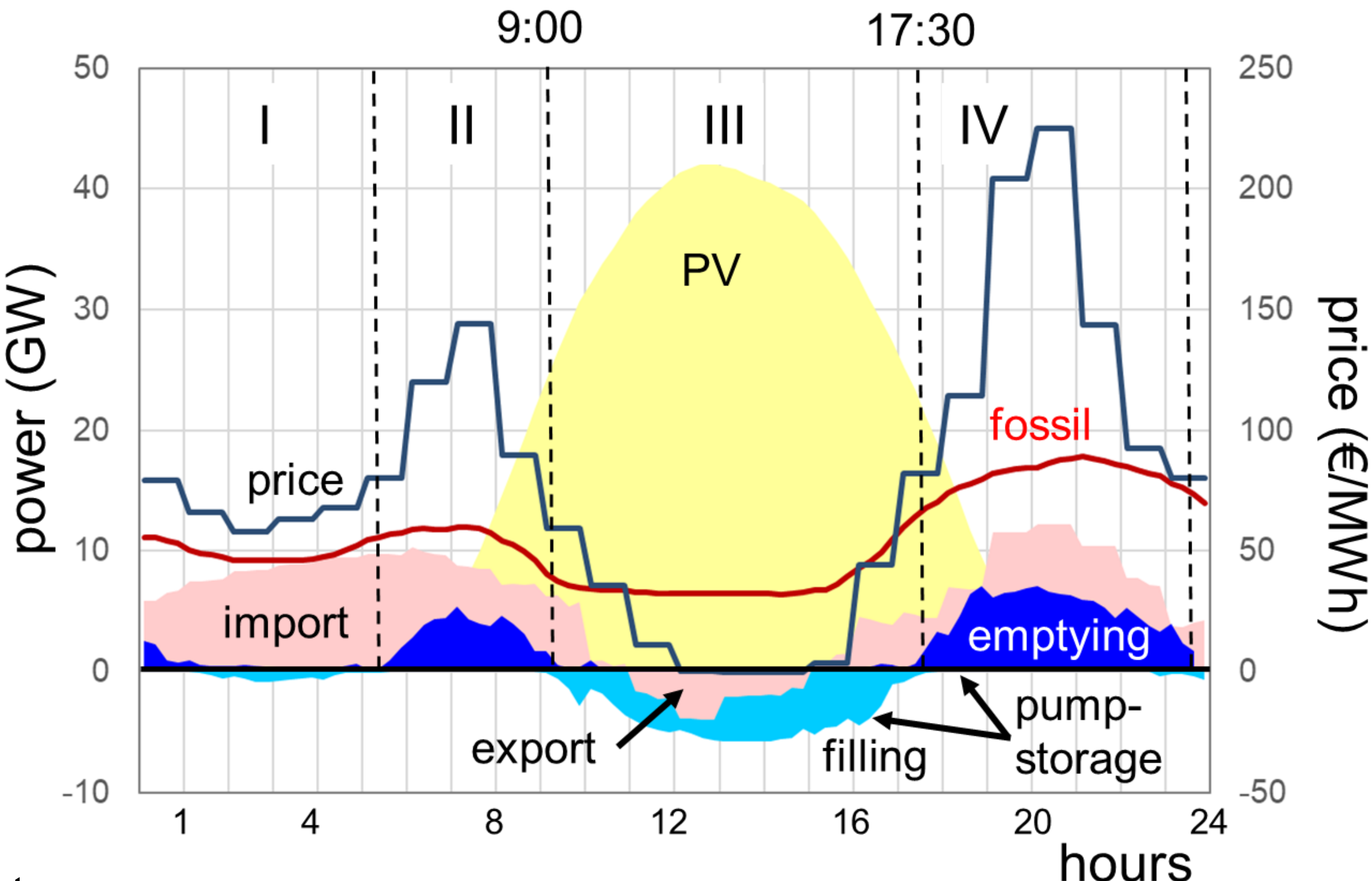


Parameters, which affect the electricity price: w/o PV

2023; day-development, **averaged over the year**



A day in summer: 15.7.2024



Comments:

4 price periods: I morning, II day, III evening, IV night

will change life- and work conditions

will affect demand-side-management and load-shedding

will change load-profile during day/week/year ⇒ all scenarios and projections

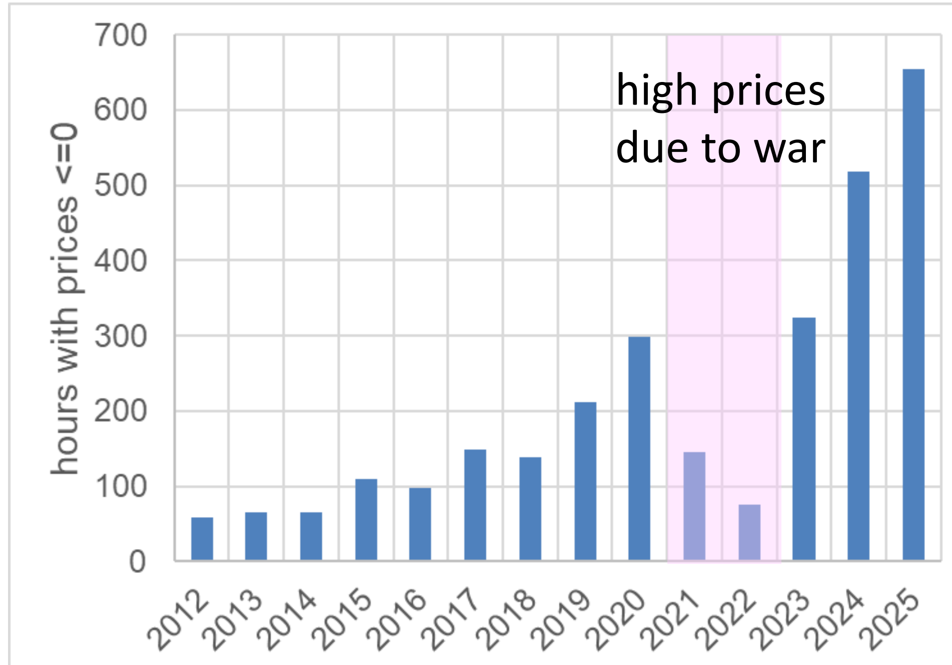
Economic consequences on prices

average prices
in the 4 periods
in 2024
€/MWh

morning	86
day	71
at PV-peak	52
evening	125
night	75

consequence:
more economic and private activities will be squeezed into the day

number of hours with negative prices

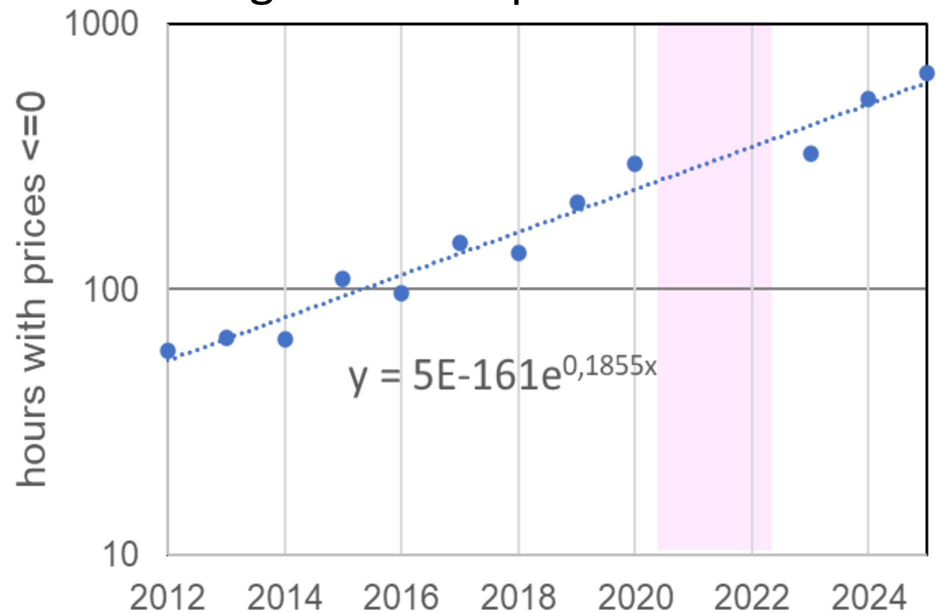


Economic consequences on prices:

average prices
in the 4 periods
In 2024
€/MWh

morning	86
day	71
at PV-peak	52
evening	125
night	75

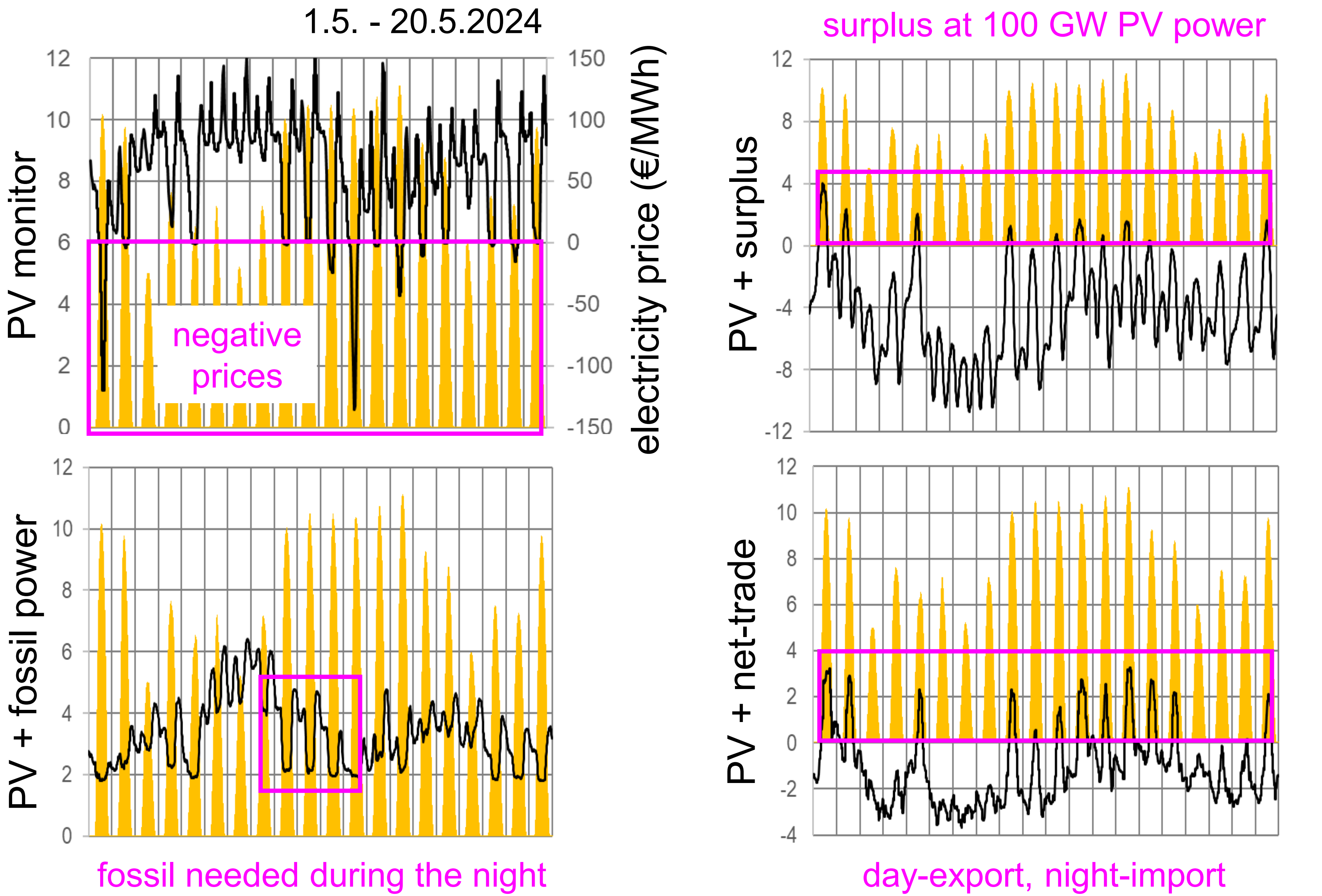
number of hours with negative prices
logarithmic representation



price gap in import and export of electricity

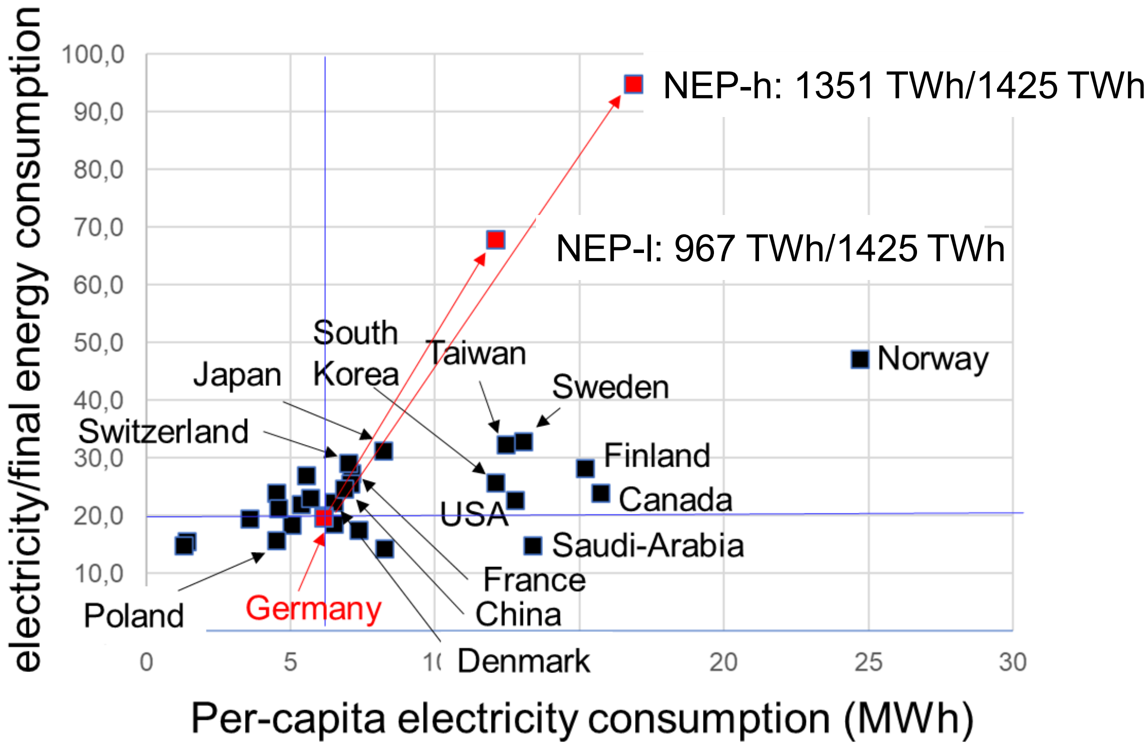
	Net export (TWh)	# net-import hours	average annual price (€/MWh)	average import price (€/MWh)	average export price (€/MWh)	export profit Mrd€	import expenses Mrd€
2017	60	303	34,2	38	34	3,2	0,1
2024	-28	6366	79	92	58	0,4	4,1

The „Hellbrise“



Status compared to others

share of electricity in final energy consumption
versus per-capita electricity consumption



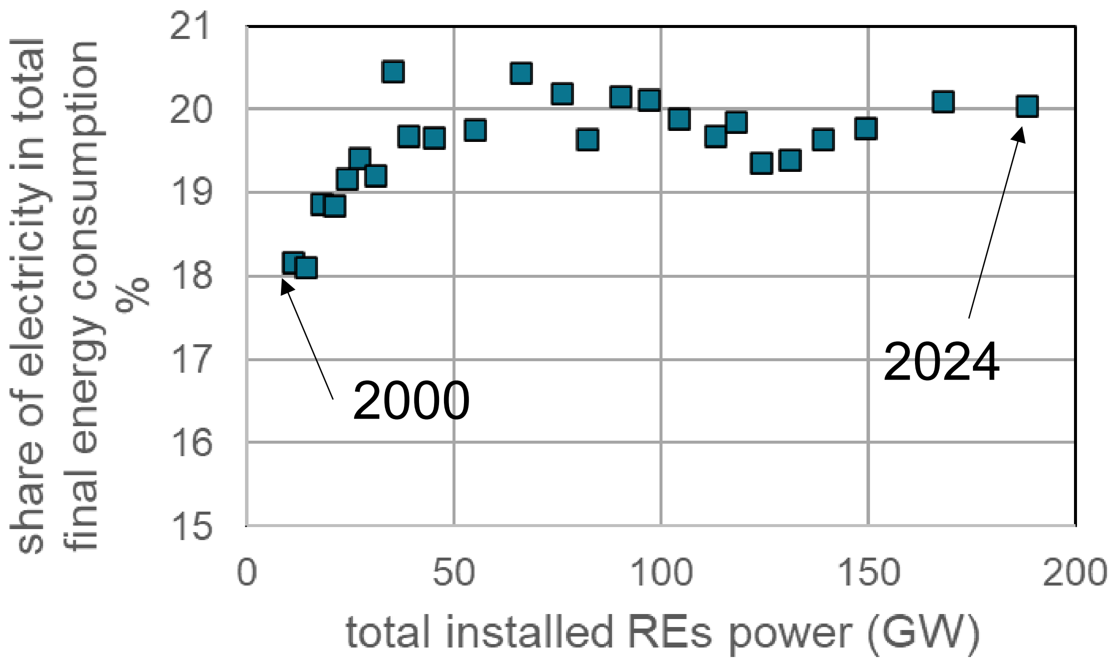
<u>Comments:</u> electricity generation is not basic problem – but most of the more advanced countries employ nuclear power

The problem is the use of electricity in the frame of sector coupling

https://www.iea.org/data-and-statistics
https://ourworldindata.org/grapher/per-capita-electricity-demand?tab=table
https://yearbook.enerdata.net/

The difficulty to increase the electricity share in final energy

example Germany



Comment: no progress with REs installation in the last 15 years

enerdata yearbook 2025
https://www.bdew.de/media/documents/Installierte_Leistung_D_ab_2000_online_o_jaehrlich_Ba_13012025.pdf

Conclusions: Critical impact of the weather on ....

Major weather effects:

- Intermittency and low power density
- PV: strong daily and seasonal variation
- the utilisation of PV cannot be judged as stand-alone electricity technology
- - insufficient supply during Dunkelflaute; - excessive supply during Hellbrise
- strong impact on electricity prices ⇒ will change life- and work conditions

Two separate technologies needed:

- spontaneous electricity will be cheap - dispatchable electricity will be expensive
  - Germany will remain a high electricity price region ⇒ modern applications

2045: Self-sustained electricity generation insufficient for the environmental goals

- in detail: not enough surplus generation
  - secondary electricity: not to the required level
  - domestic hydrogen generation: not sufficient ⇒ no or little electricity for electrolysers, low overall domestic H2 generation
  - BUT: Large import of H2 necessary: from where and when?