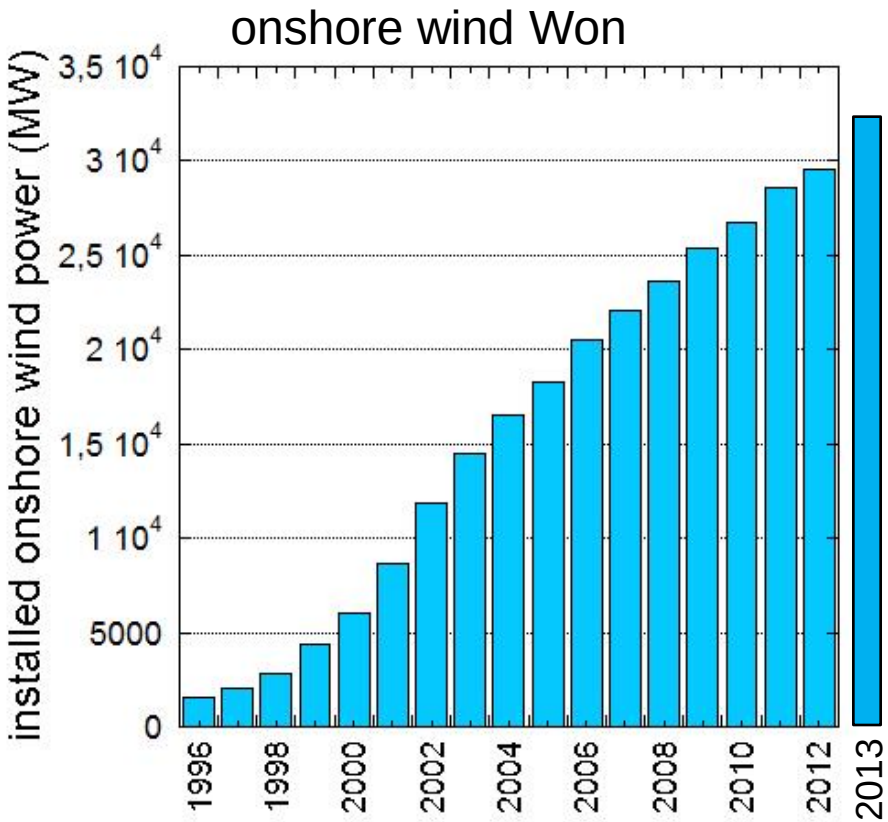
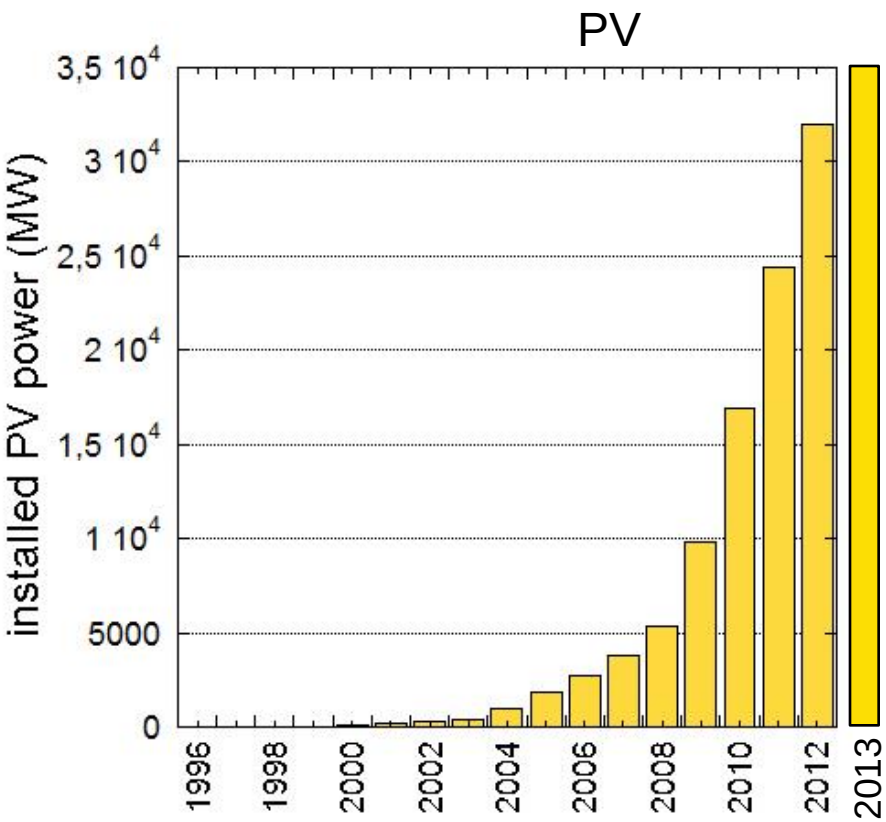
Properties of an electricity system with intermittent sources

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

Showcase for RE development: Growth of wind and PV in Germany





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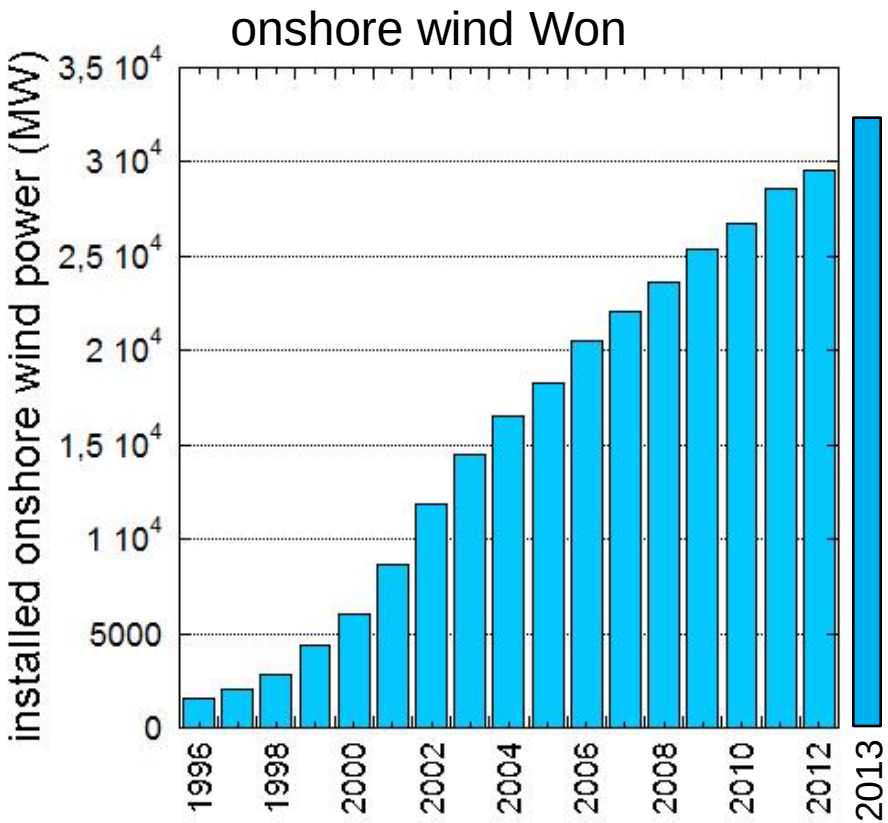
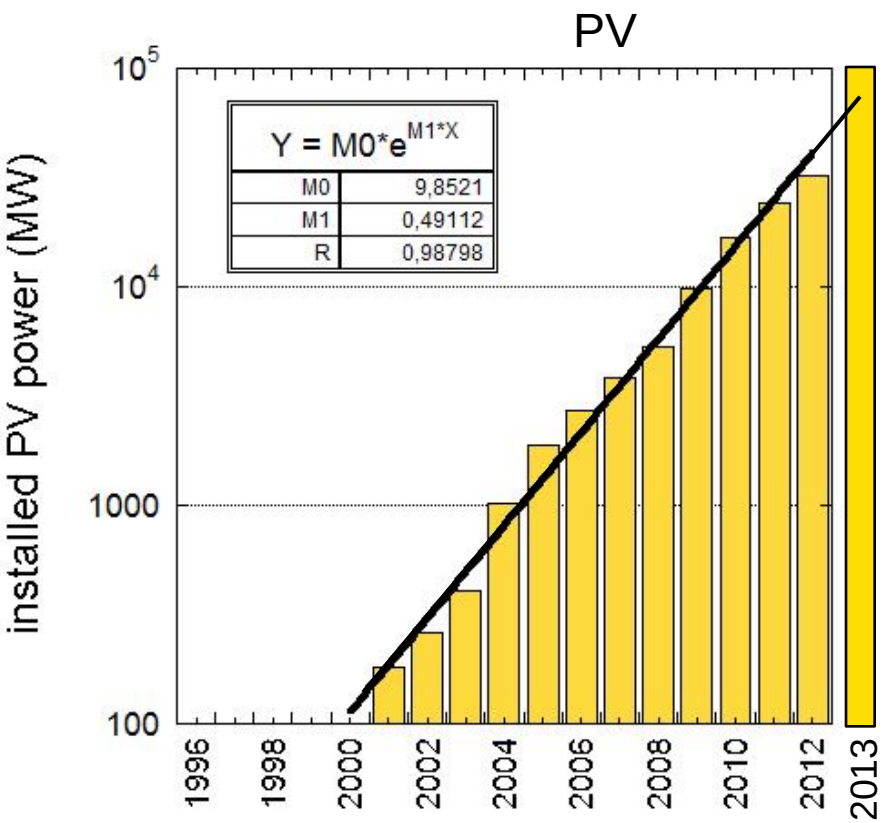
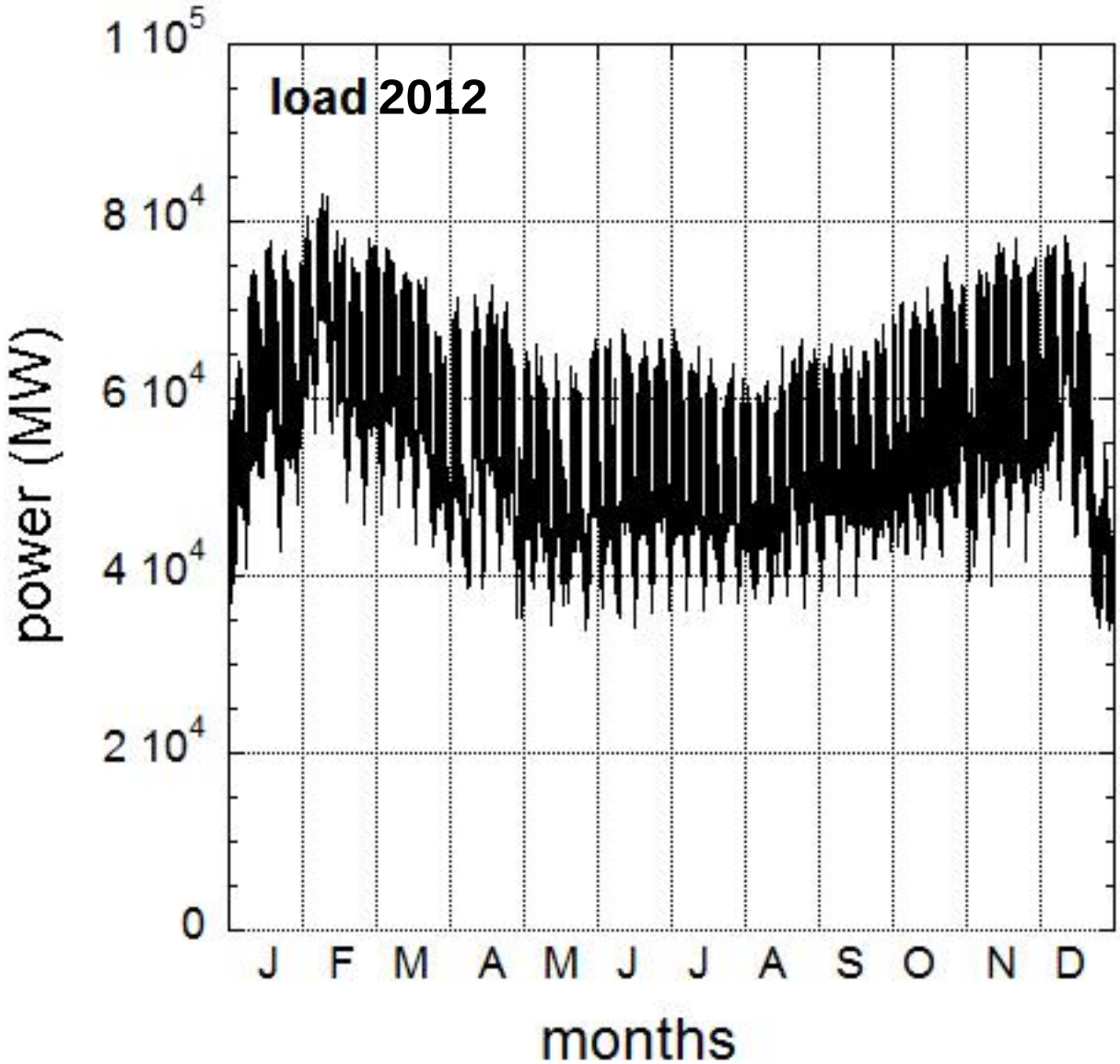
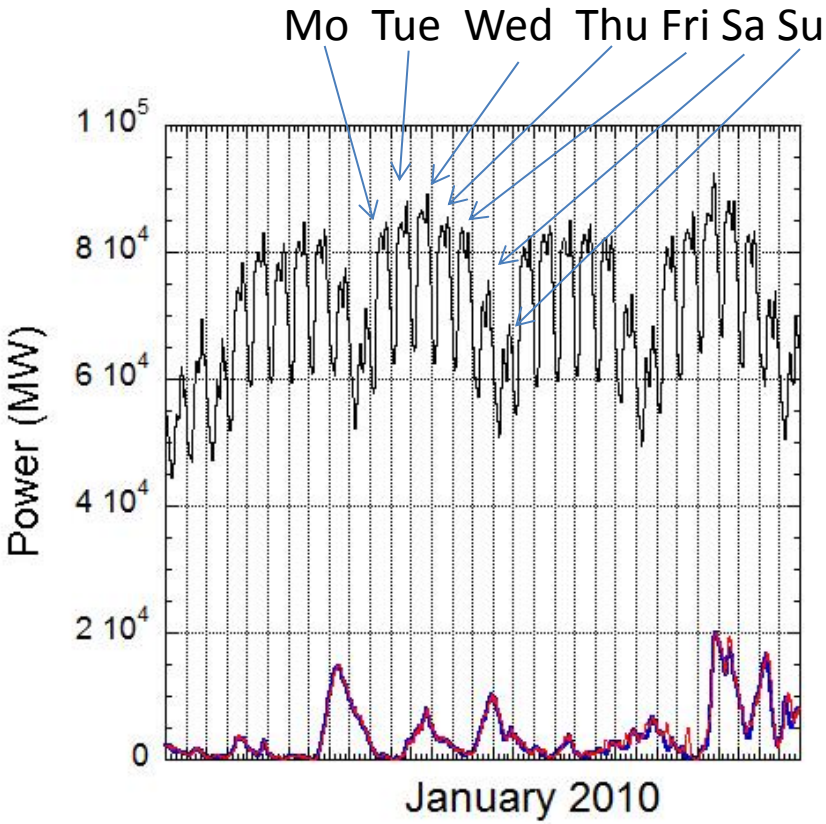


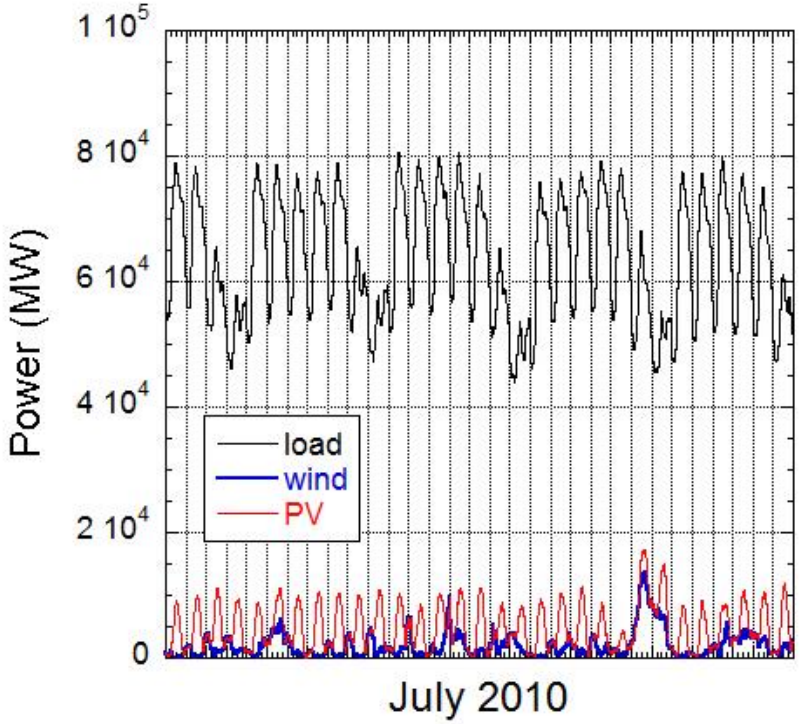


Comparison: load – installed RE power



Input in more detail: January and July 2010





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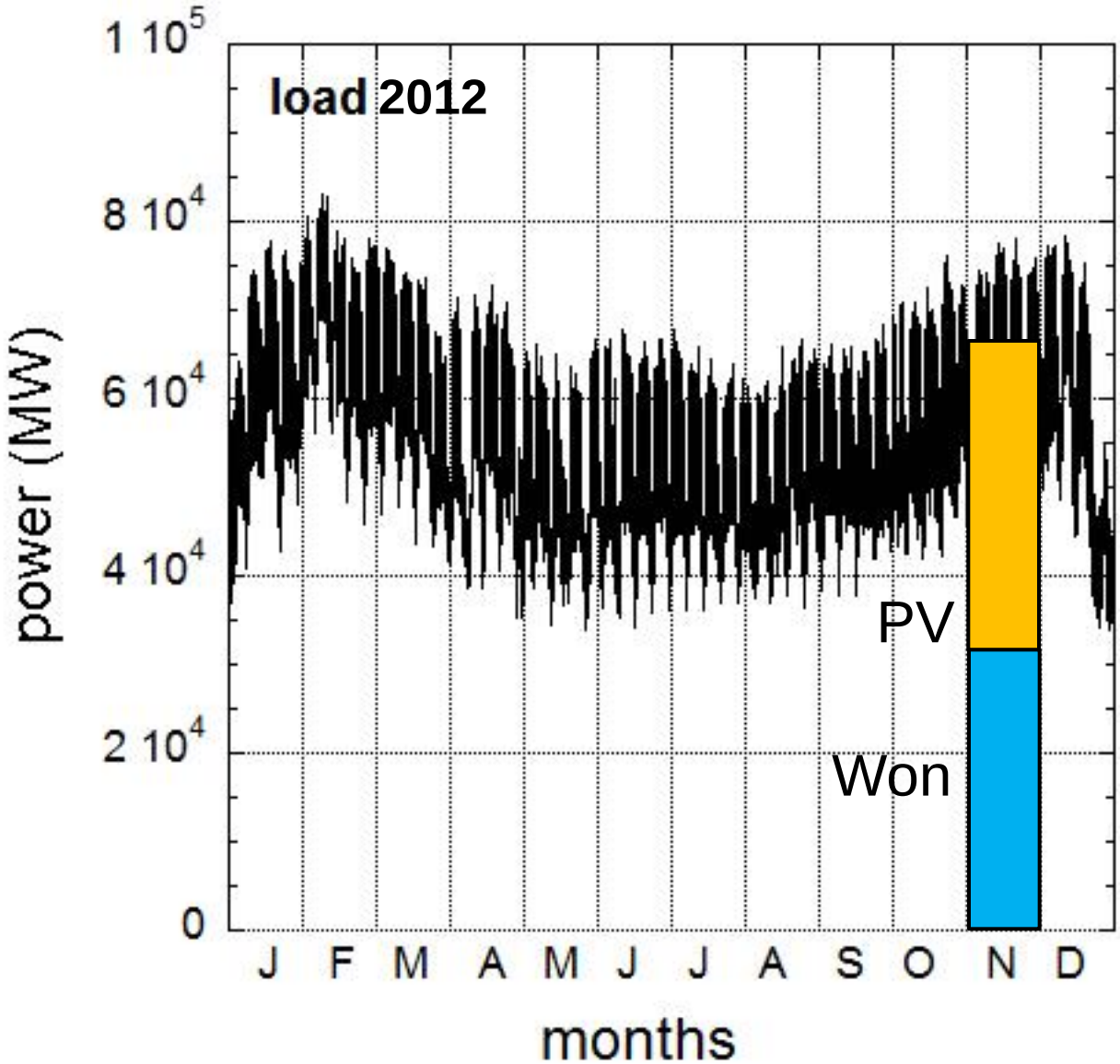
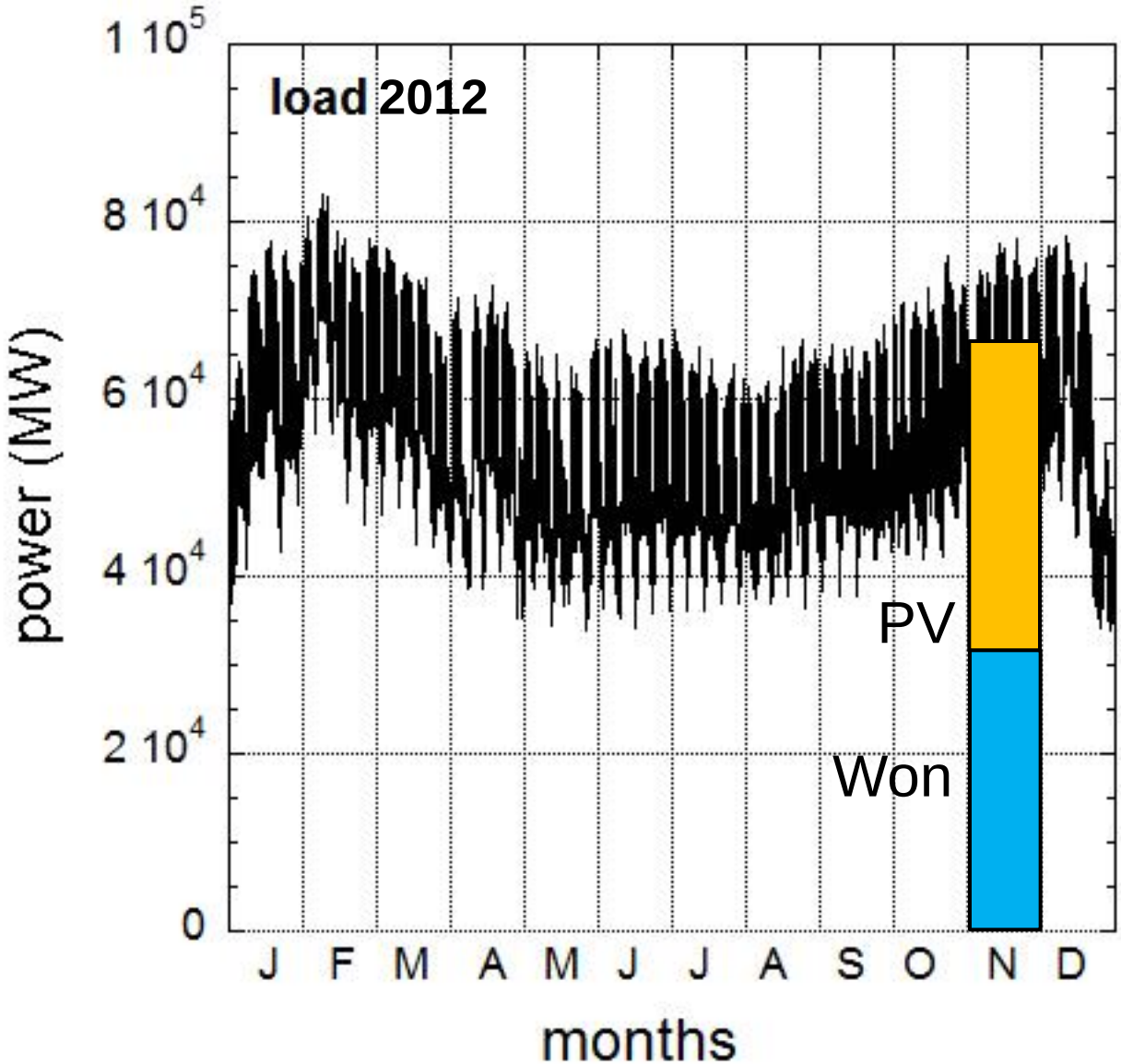


2013:

Won: 32 GW
Woff: 0.508 GW
PV: 35.7 GW

Fraunhofer ISE

Comparison: load – installed RE power



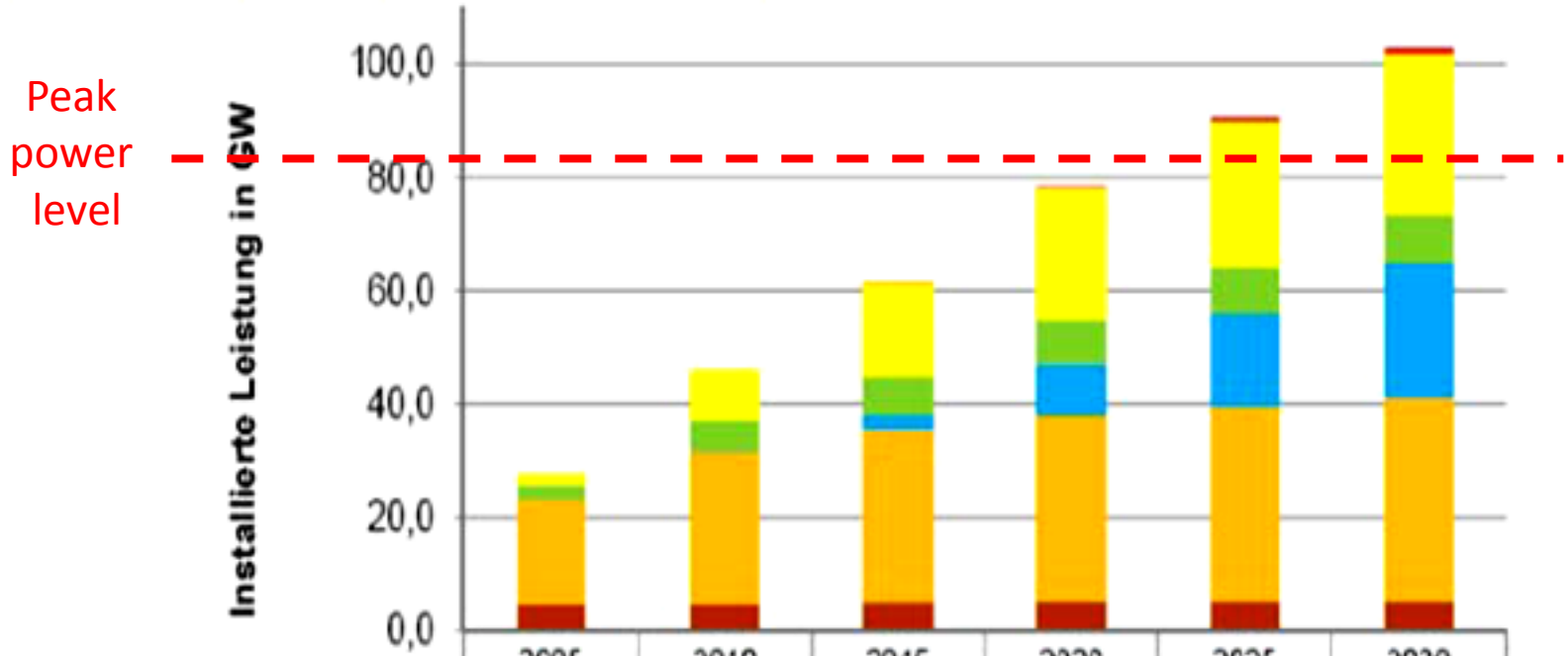
RE have feed-in priority

Already now:

periods w/o thermal power

periods with surplus

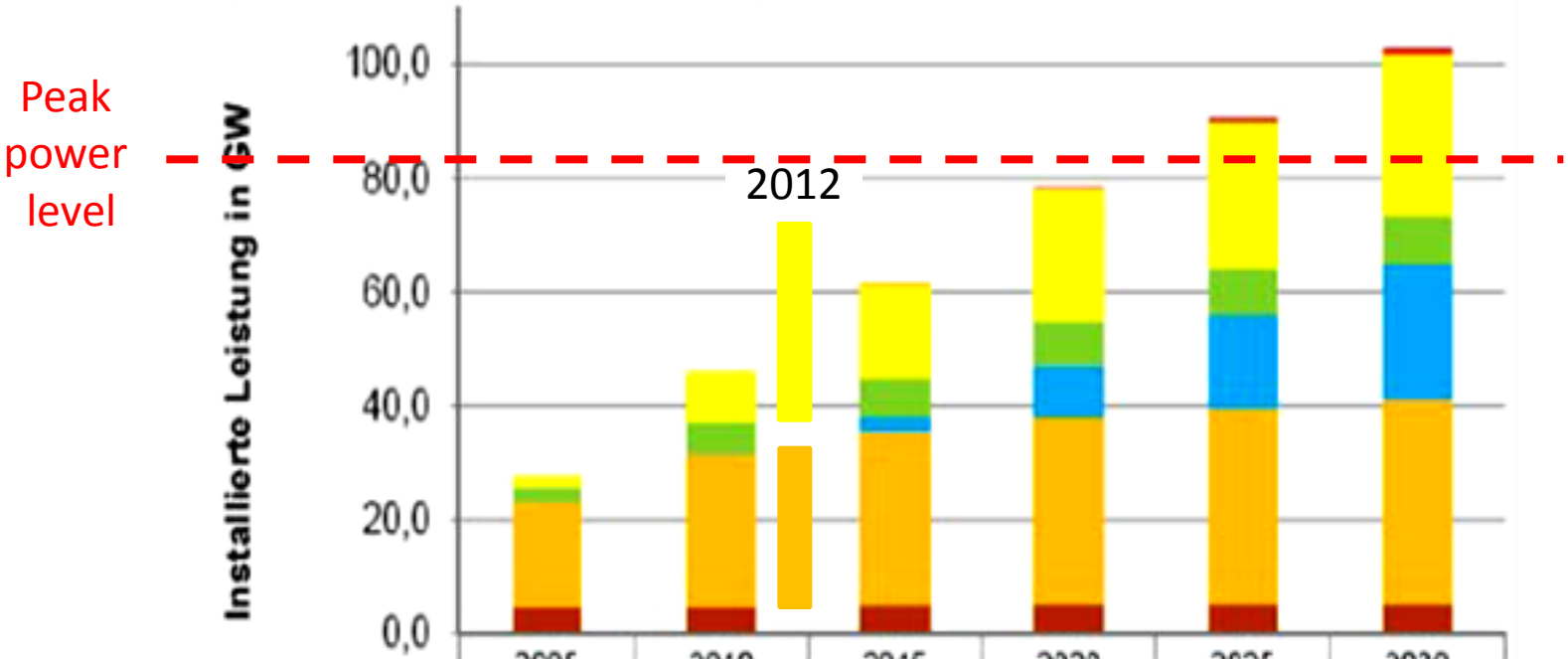
Expected development



	2005	2010	2015	2020	2025	2030
Geothermie	0,0	0,0	0,1	0,3	0,65	1,0
Photovoltaik	1,9	8,9	16,6	23,2	25,8	28,4
Biomasse	2,6	5,3	6,8	7,9	8,2	8,5
Offshore	0,0	0,2	2,5	9,0	16,4	23,8
Onshore	18,4	26,8	30,5	32,9	34,4	35,9
Wasser (ohne Pumpspeicher)	4,7	4,8	5,0	5,1	5,15	5,2
Summe	**27,6**	**46,0**	**61,5**	**78,4**	**90,6**	**102,8**

Quelle: Leitszenario 2009 (BMU 2009).

Expected development



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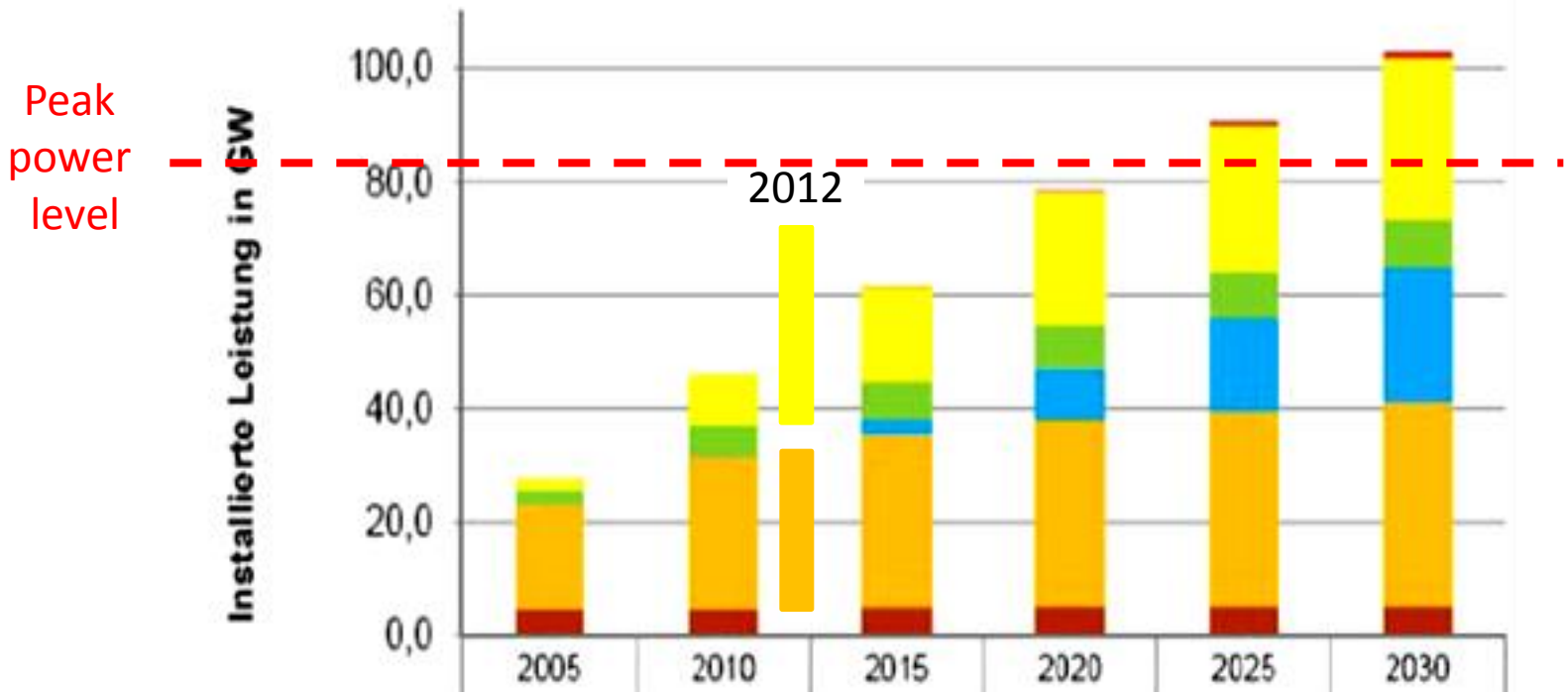

Consequences of rapid development:

high costs (22 B€ fit-in-tarif costs in 2013 – 2 B€ market value)
unbalanced development (sources, no new grids, no technical solution e.g. for storage)

Electricity production

Total production 2012: 629 TWh

Source	2010	2011	2012	2013	%
Coal	117	112,5	116,4	124	19,7
lignite	145,9	150,1	160,7	162,0	25,8
nuclear	140,6	108	99,5	97	15,4
Gas	89,3	86,1	76,4	66	10,5
oil	8,7	7,2	7,6	7,0	1,1
Wind onshore	37,8	48,9	50,7	49,8	7,9
Photovoltaic	11,7	19,6	26,4	28,3	4,5
Biomass	29,6	32,8	39,7	42,6	6,8
Hydro	21	17,7	21,8	21,2	3,4
waste	4,7	4,8	5,0	5,2	0,8
others	26,7	25,6	25,7	25,9	4,1

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waste	4,7	4,8	5,0	5,2	0,8
others	26,7	25,6	25,7	25,9	4,1

mix	%
PV+wind	12,4
RE	23,4
Nuclear	15,4
Fossil	57,1

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Strong growth of RE

Electricity production

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Decrease of nuclear energy

Electricity production

Source	2010	2011	2012	2013	%
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others	26,7	25,6	25,7	25,9	4,1

Increase of coal use

Electricity production

Source	2010	2011	2012	2013	%
Coal	117	112,5	116,4	124	19,7
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others	26,7	25,6	25,7	25,9	4,1

Decrease of gas

Electricity production

Source	2010	2011	2012	2013	%
Coal	117	112,5	116,4	124	19,7
lignite	145,9	150,1	160,7	16	
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Gas	89,3	86,1	76,4	6	
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Hydro	21	17,7	21,8	2	
waste	4,7	4,8	5,0	5	
others	26,7	25,6	25,7	25,9	4,1

Reaction of economy:

Gas too expensive
(in spite of benefical properties of turbines);
gas power stations mothballed

Cheap coal replaces gas in spite of higher specific CO_2 production

Environmental consequence:
CO_2 emission increases:
2011: 798 Mt; 2013: 834 Mt; increase: 4.5 %

Scaling to higher RE powers

Data of 2012 of all 4 suppliers (Tennet, 50Hertz, Amprion, Transnet)
Data base for load, Won, Woff, PV, 15 min resolution, 35136 time points

Procedure: Scale 2012 data to higher installed powers and analyse

Assumptions:
electricity demand will not change
Hydro and waste will not change
reduced load is the reference: **500 TWh**

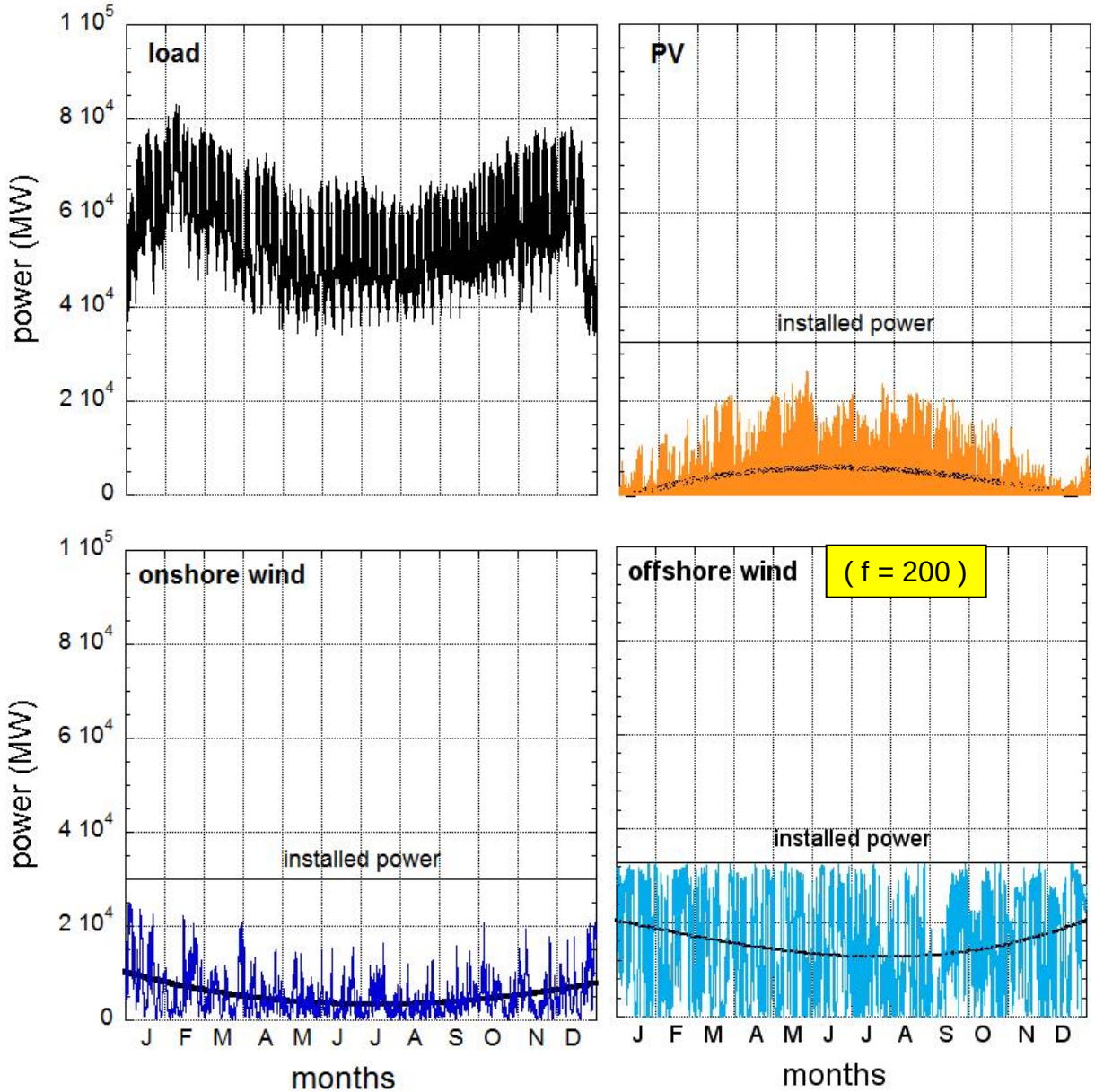
Biomass will be used for transportation and not for electricity production
(1/10 of demand could maximally be covered by bio-gas into electricity)

no losses considered

no nuclear or import considered

Windshare: W_{on} = 2/3 W; W_{off} = 1/3 W (mix is uncritical)

2012 input data

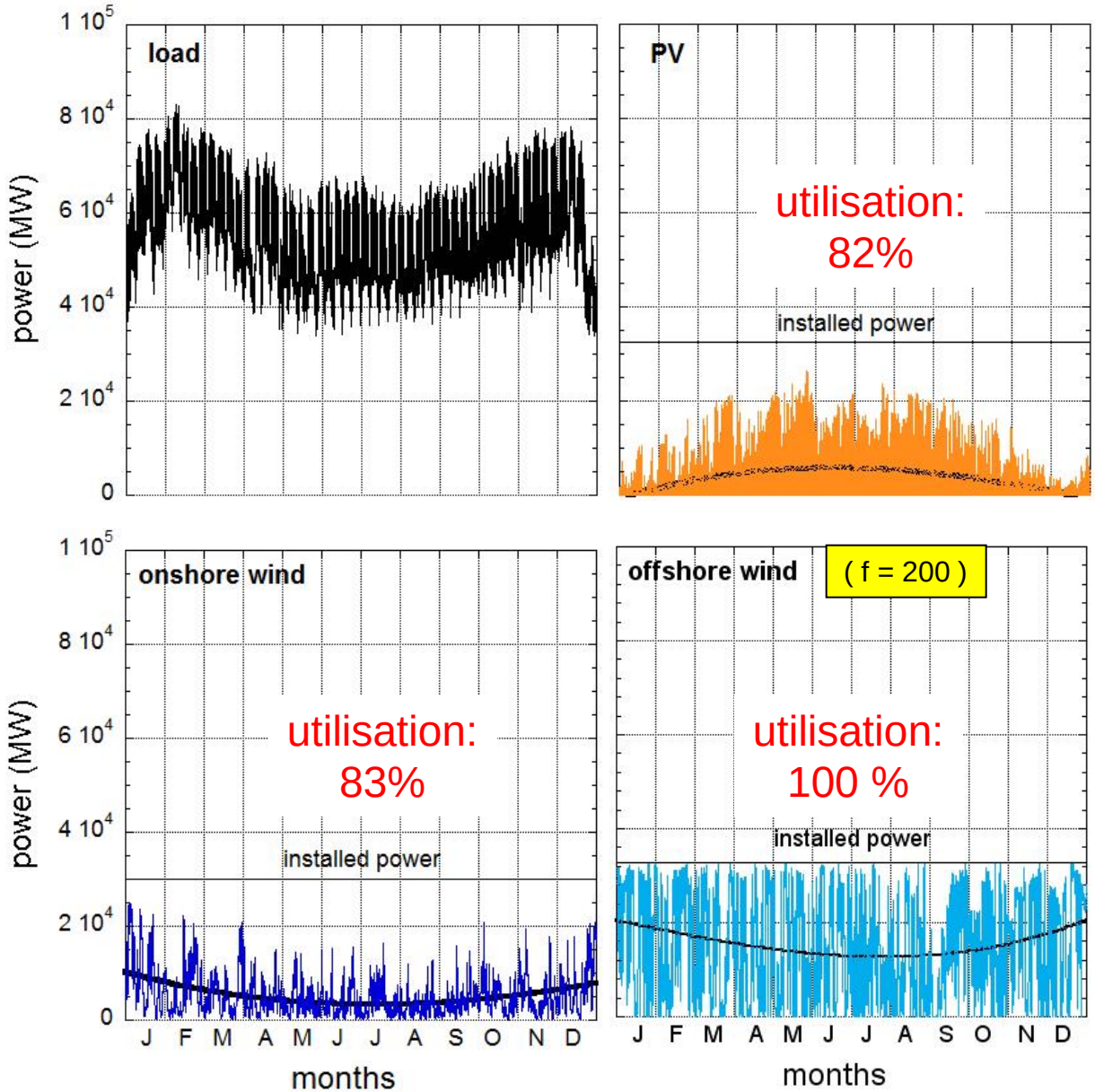


Constant RE power (end of 2012)

W_{off}: 160 MW

Multiplied by f=200

2012 input data



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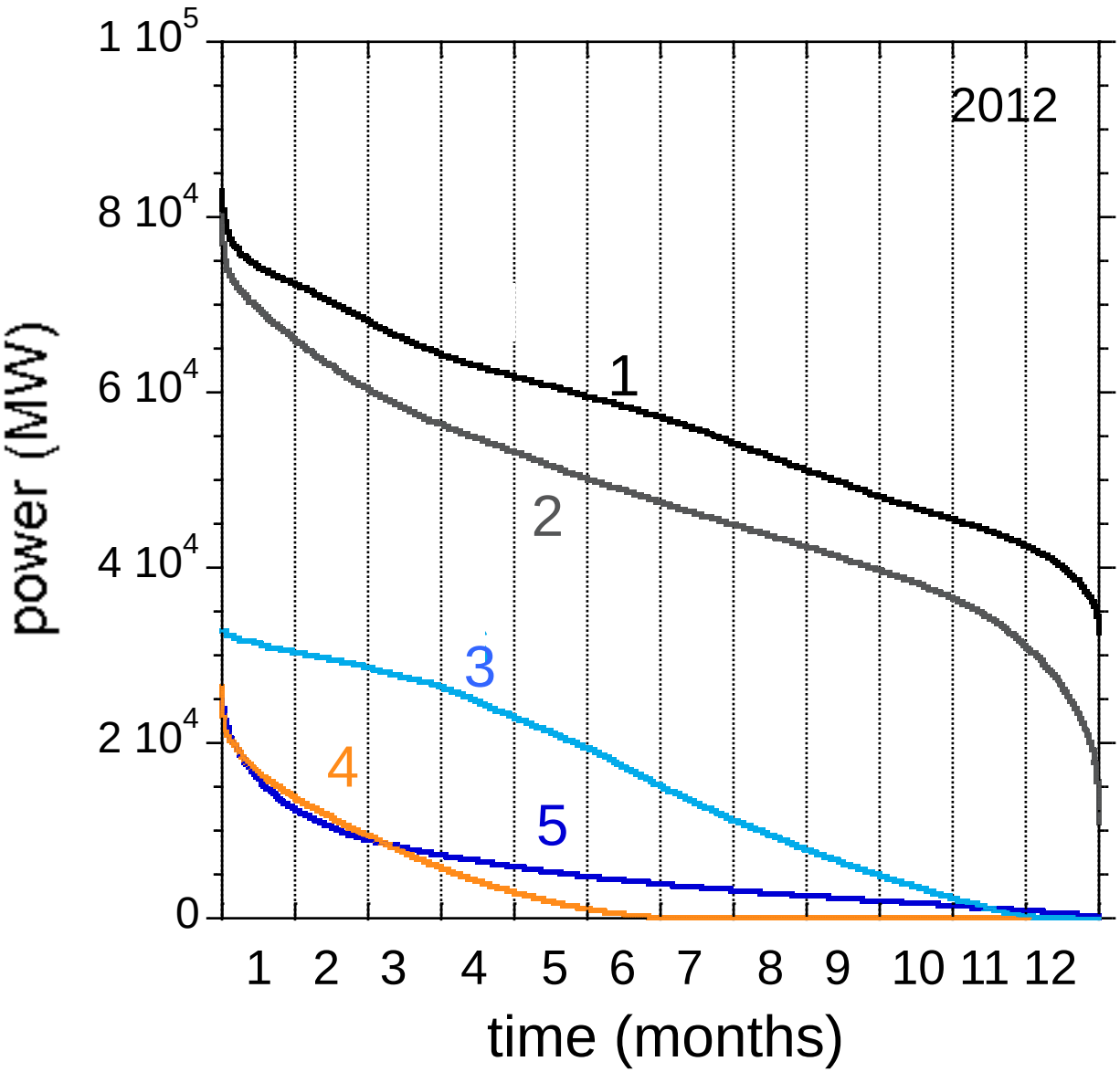
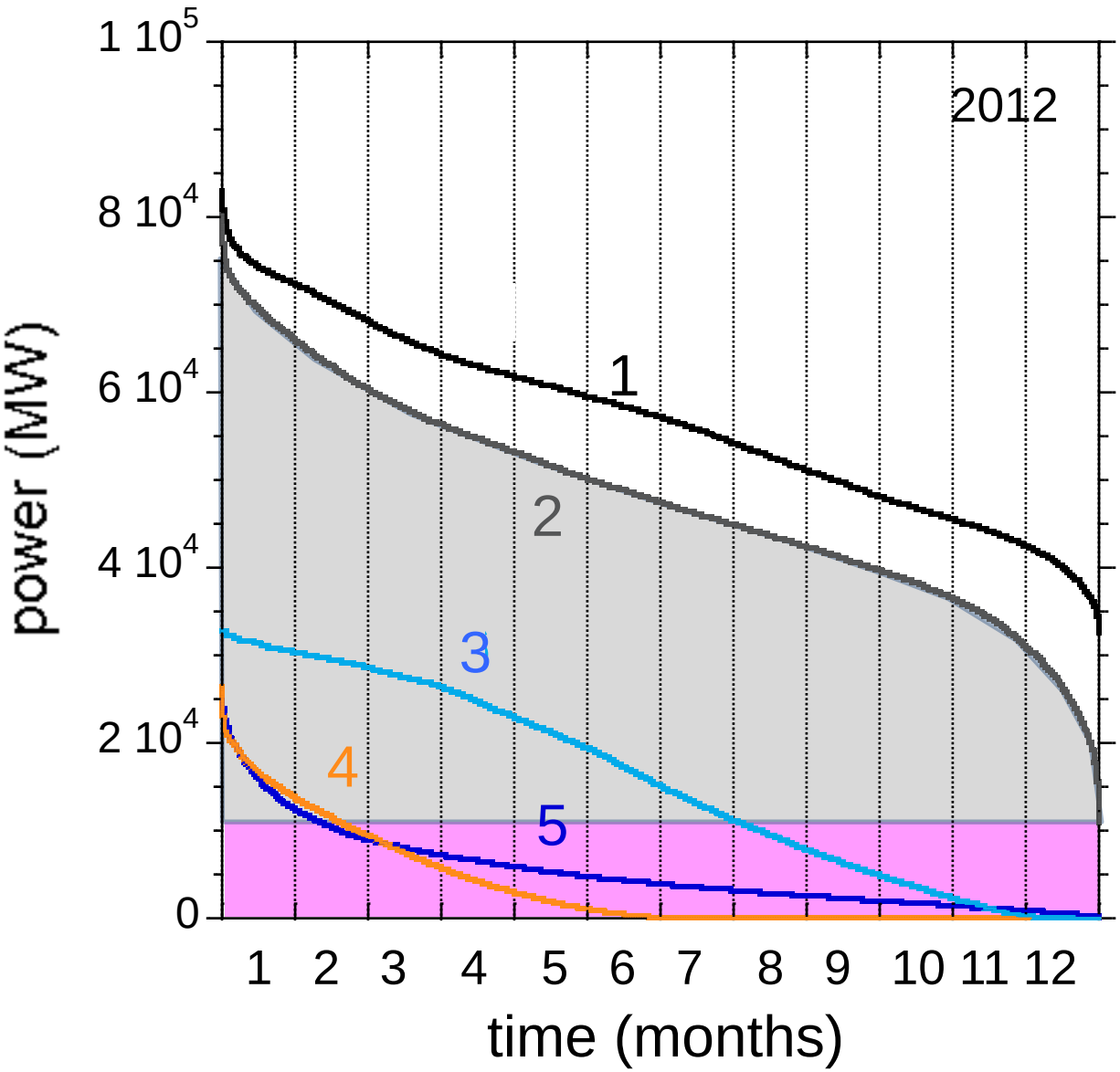
Duration curve



1: reduced load
2: back-up
3: Woff x 200
4: PV
5: Won

Duration curve



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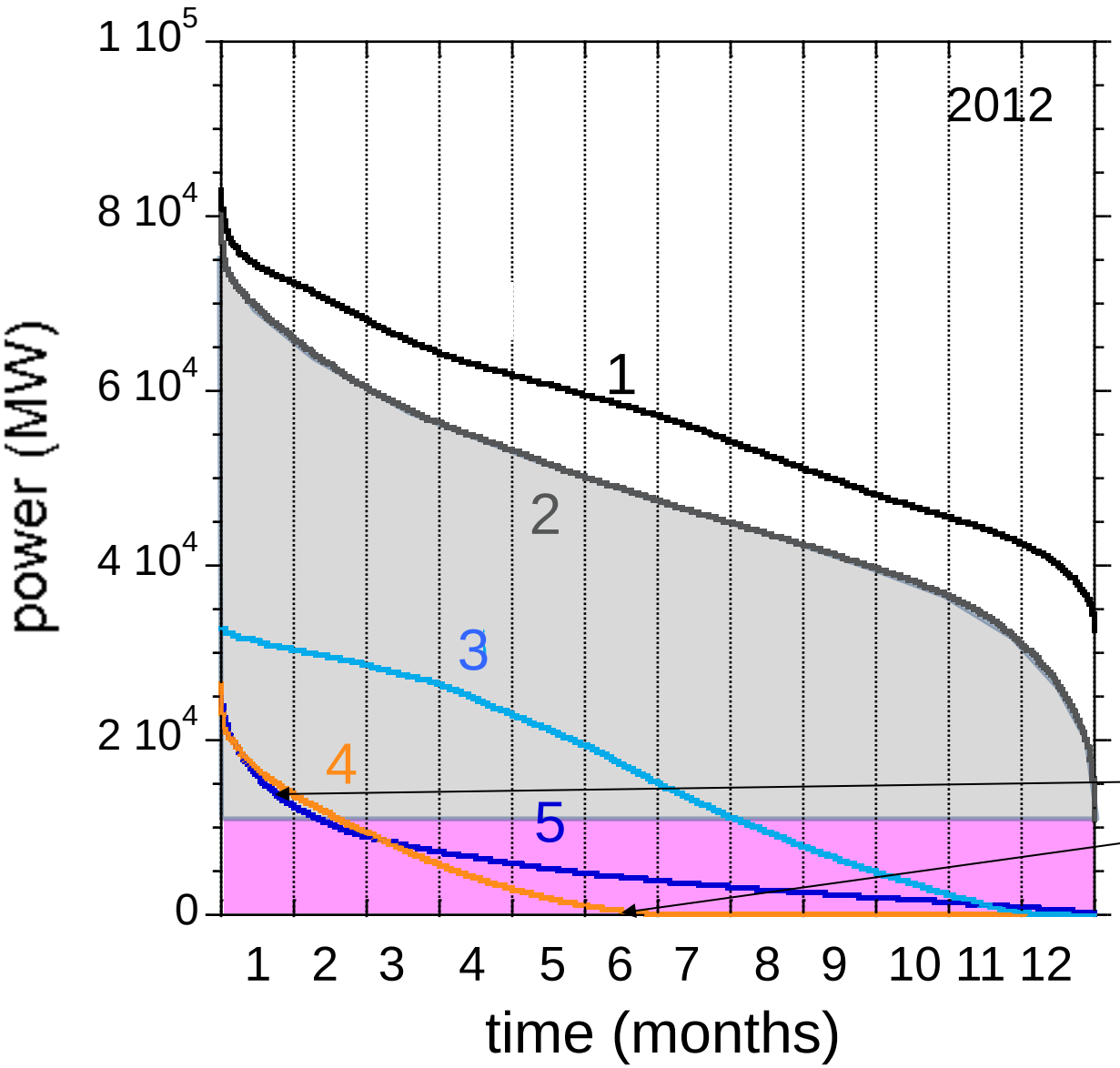
Grey: fossil power
Red: nuclear power

Duration curve

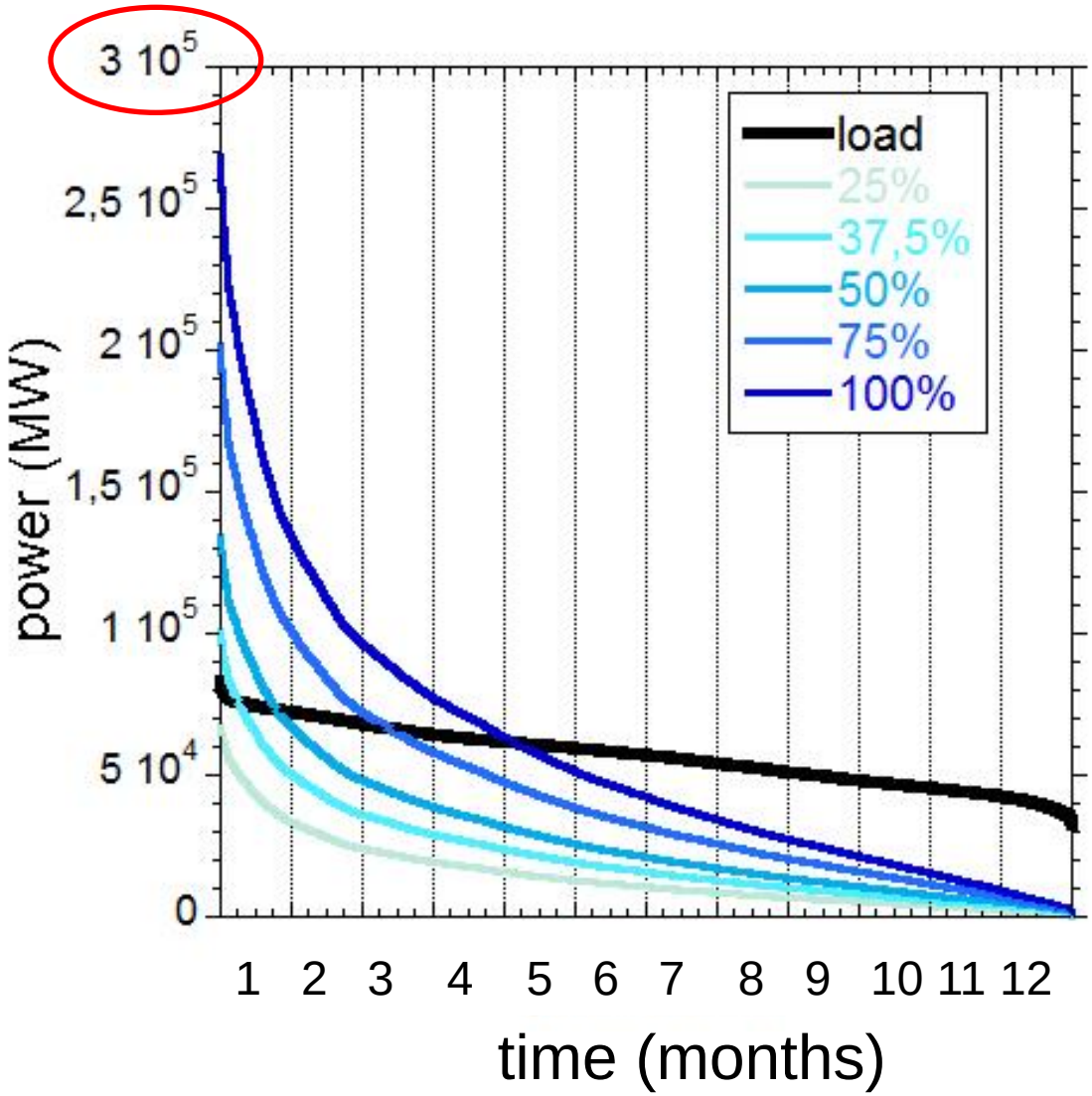


1: reduced load
2: back-up
3: Woff x 200
4: PV
5: Won

Grey: fossil power
Red: nuclear power

Won: > 50% for a month
PV: for half a year only

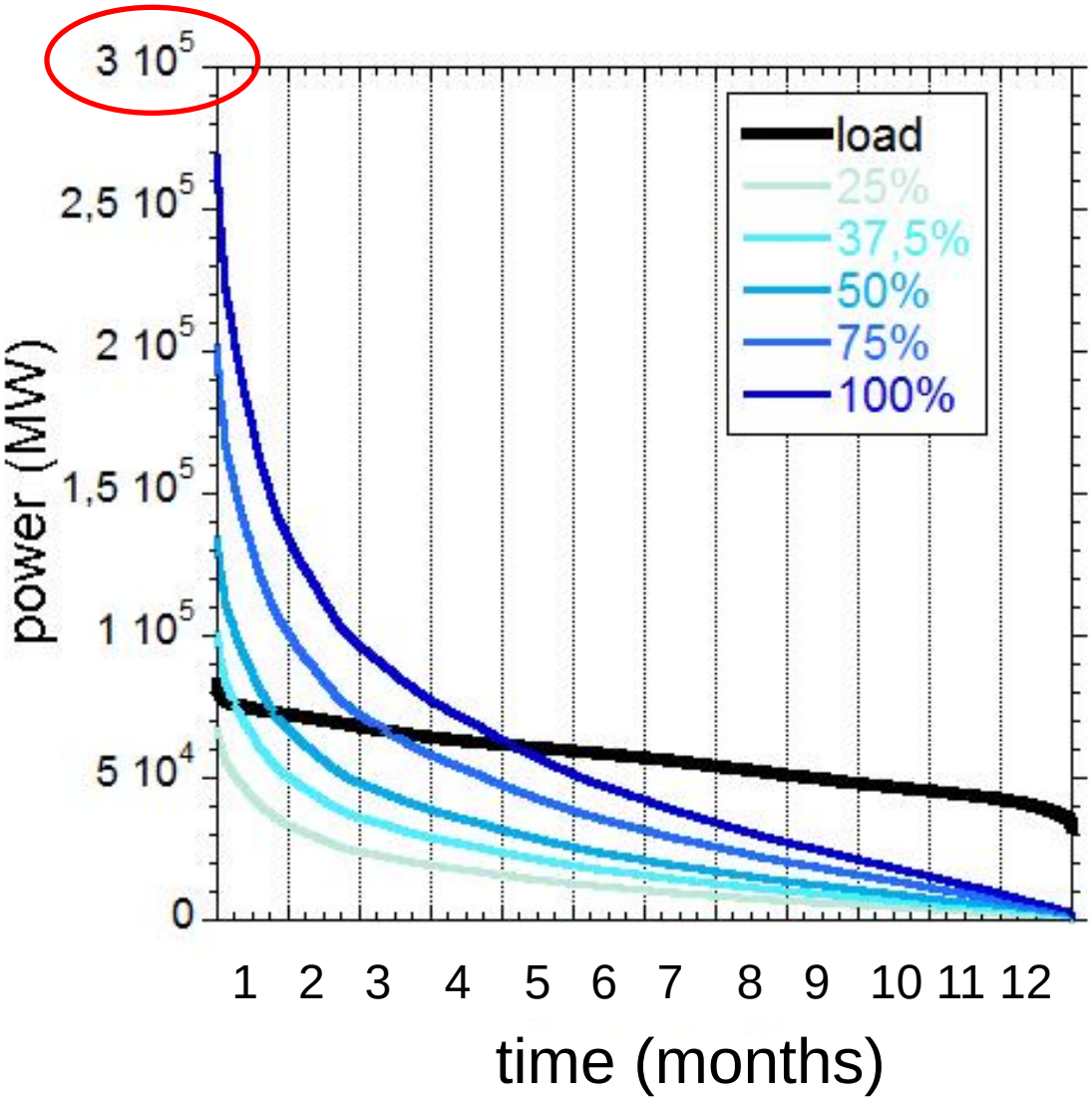
Scaling of Won

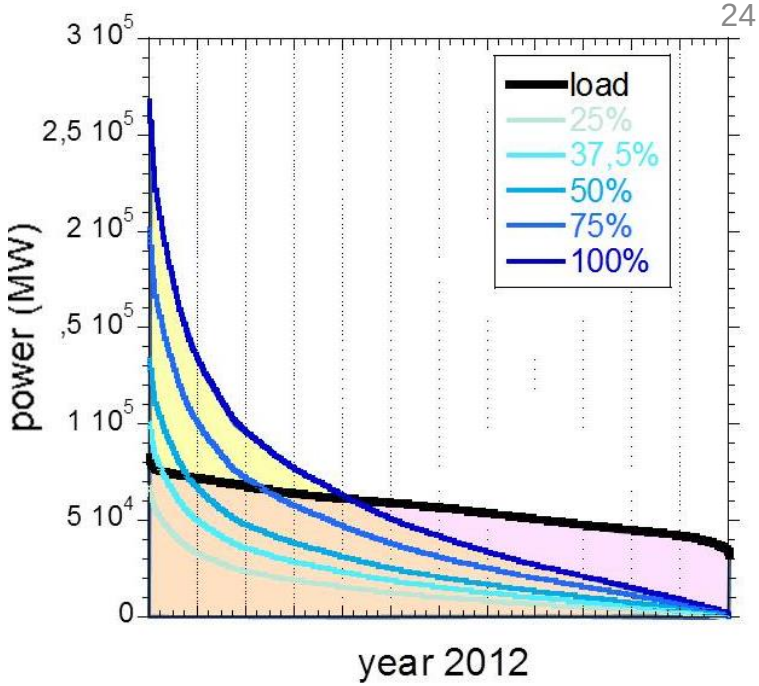


Problem:

Large capacities necessary

Scaling of Won



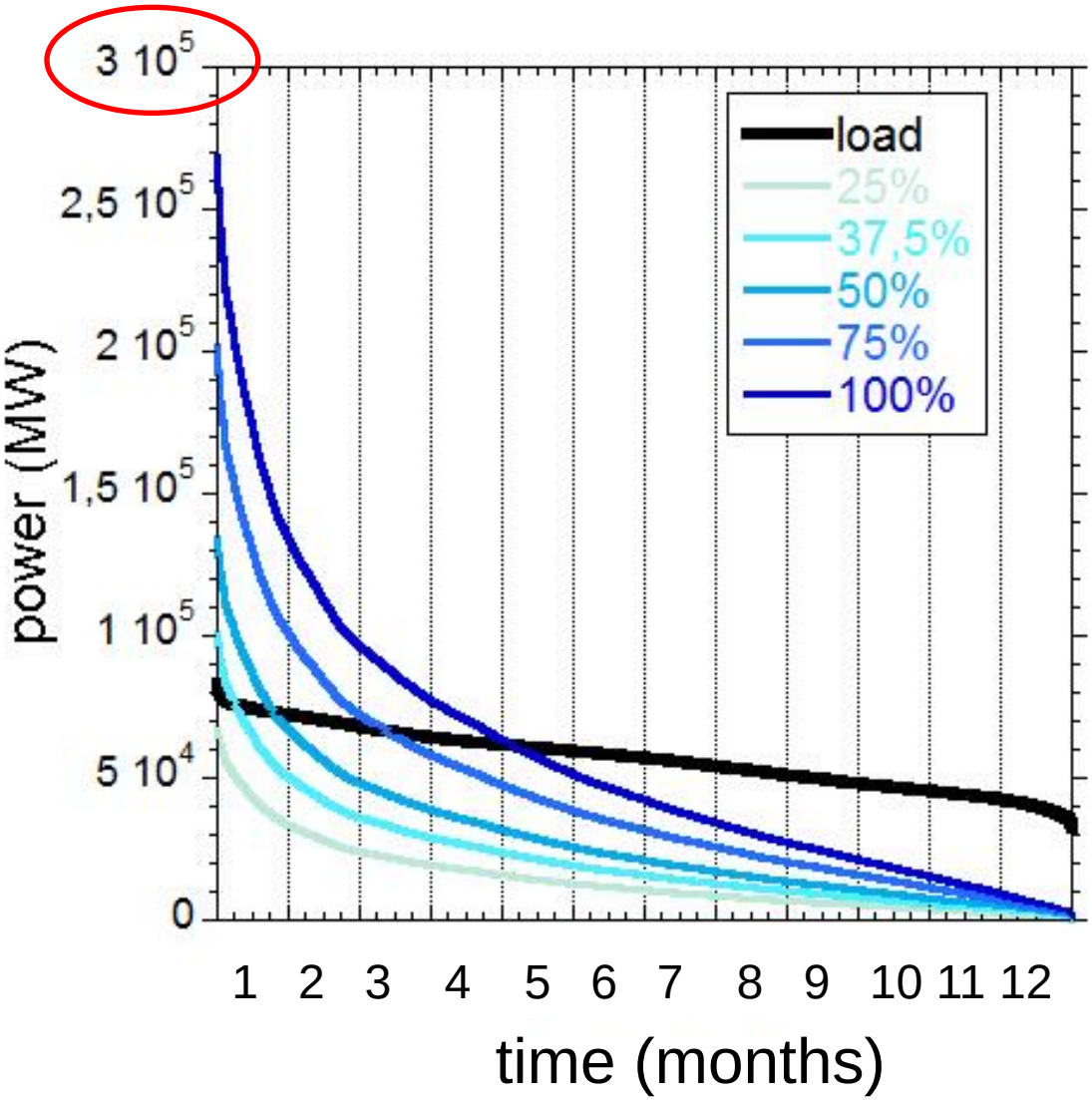


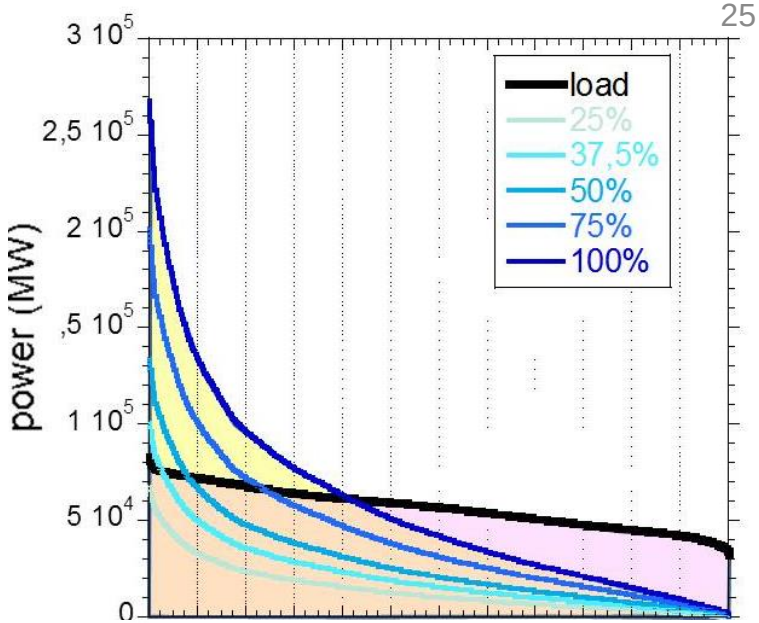
Problems:

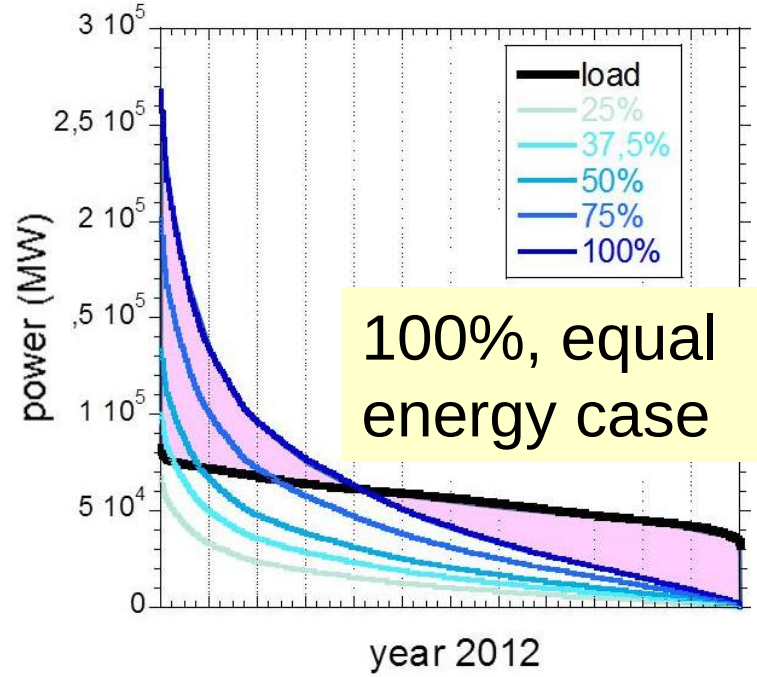
Production of surplus energy

Back-up power needed

Scaling of Won

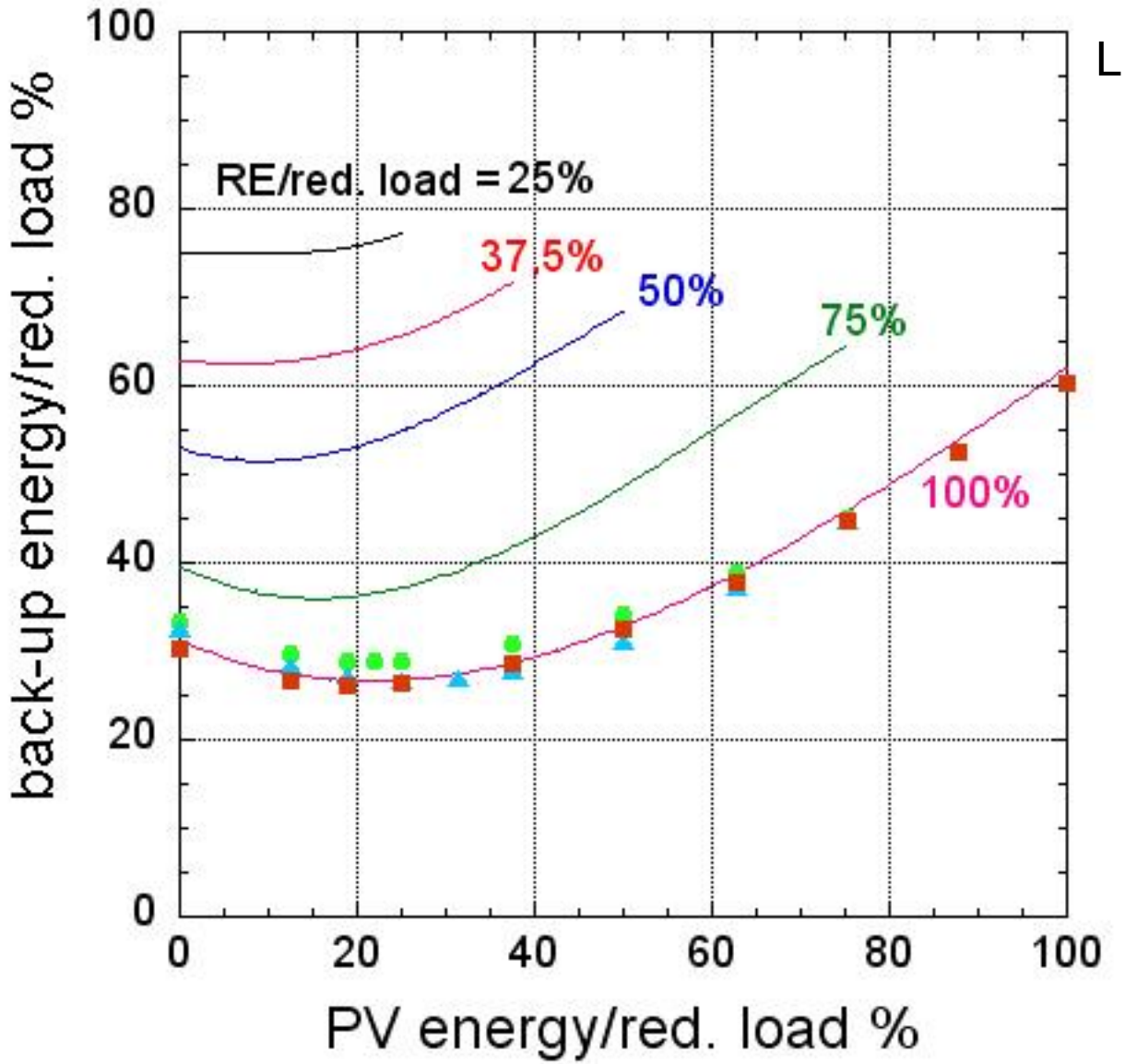






100%, equal energy case

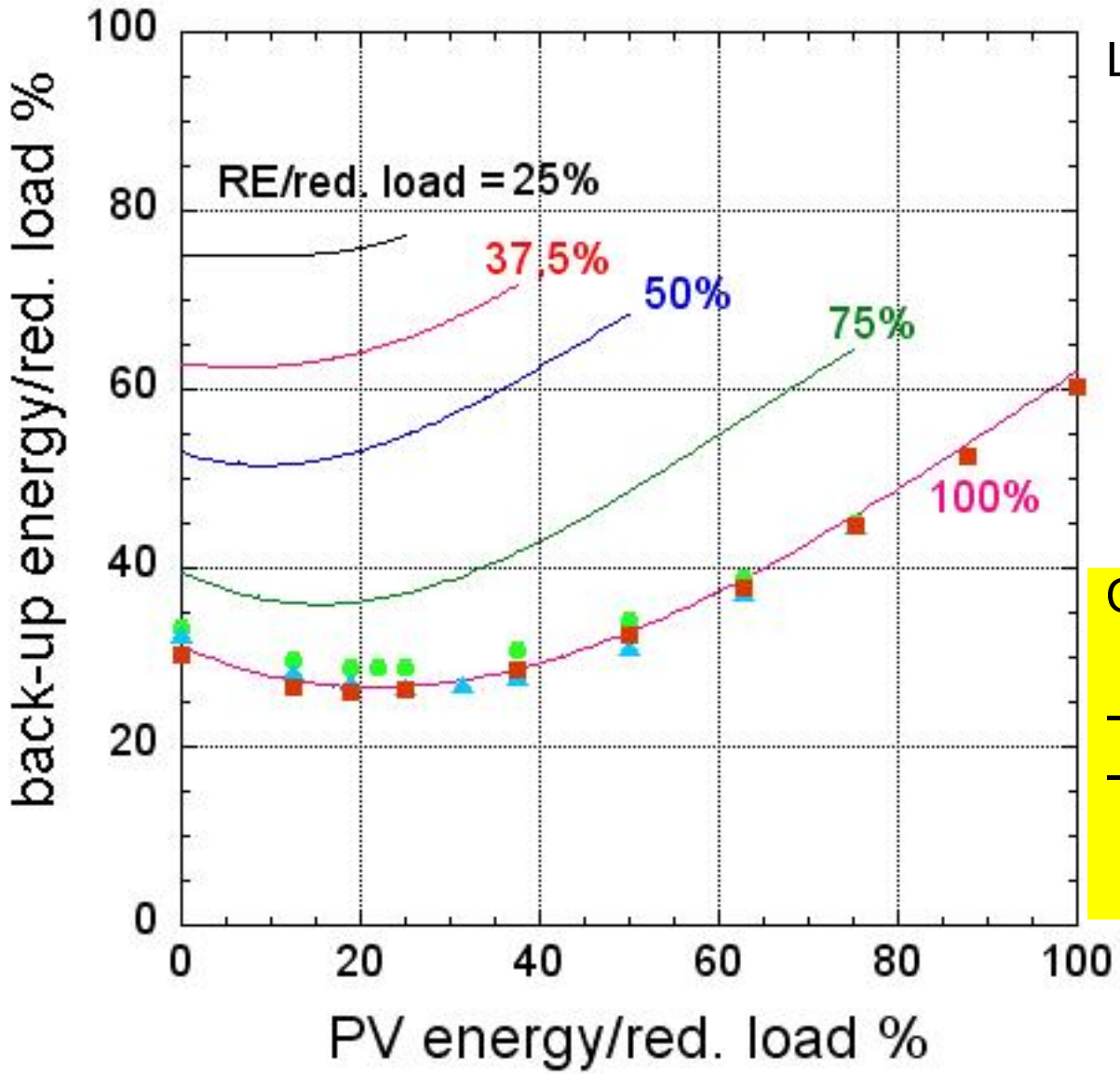
The optimal mix case: minimal back-up



Lines: 2010 data

- 2012 data; W_{off} = 1/3V
- only W_{on}
- only W_{off}

The optimal mix case: minimal back-up



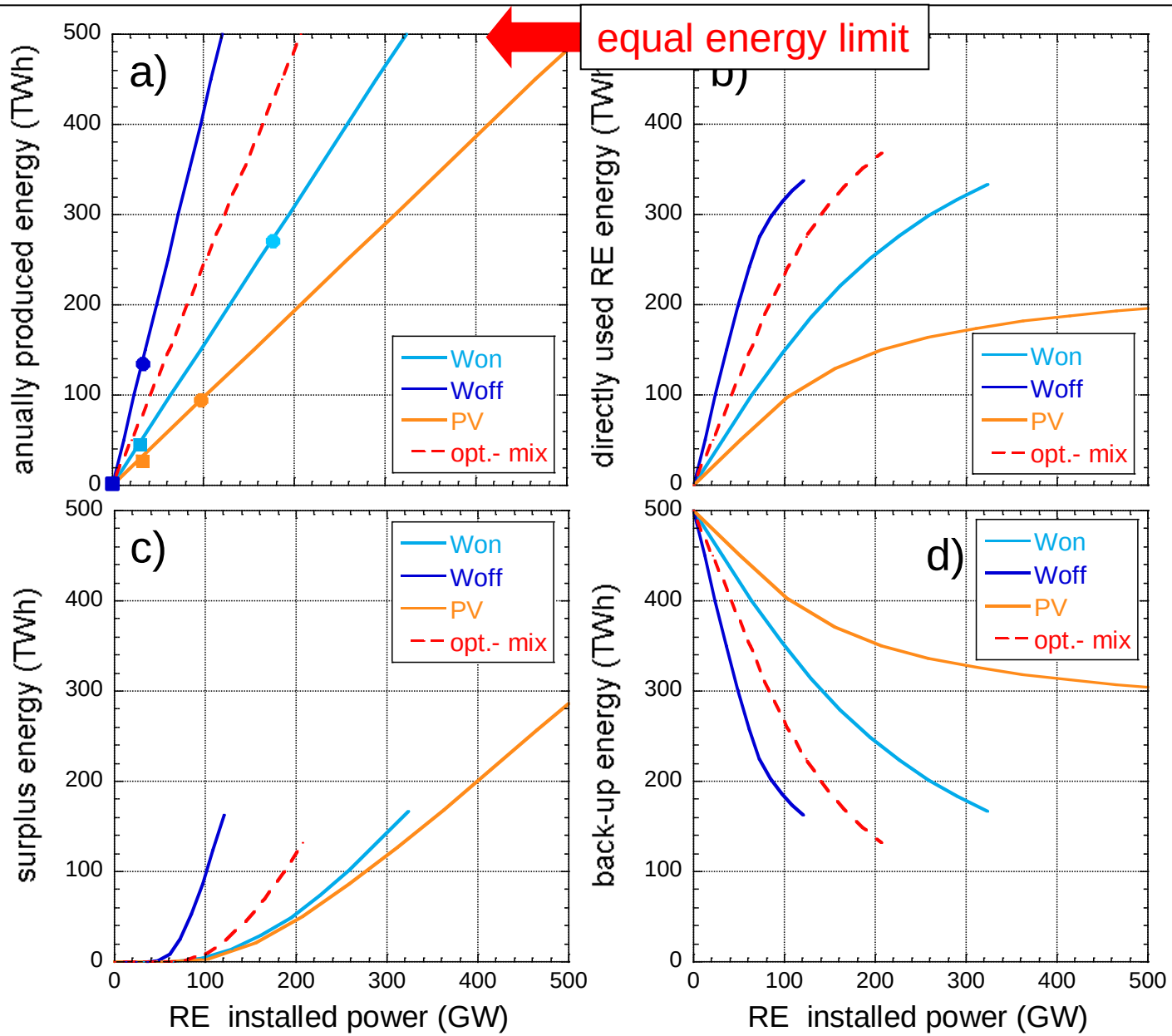
Lines: 2010 data

- 2012 data; W_{off} = 1/3W
- only W_{on}
- only W_{off}

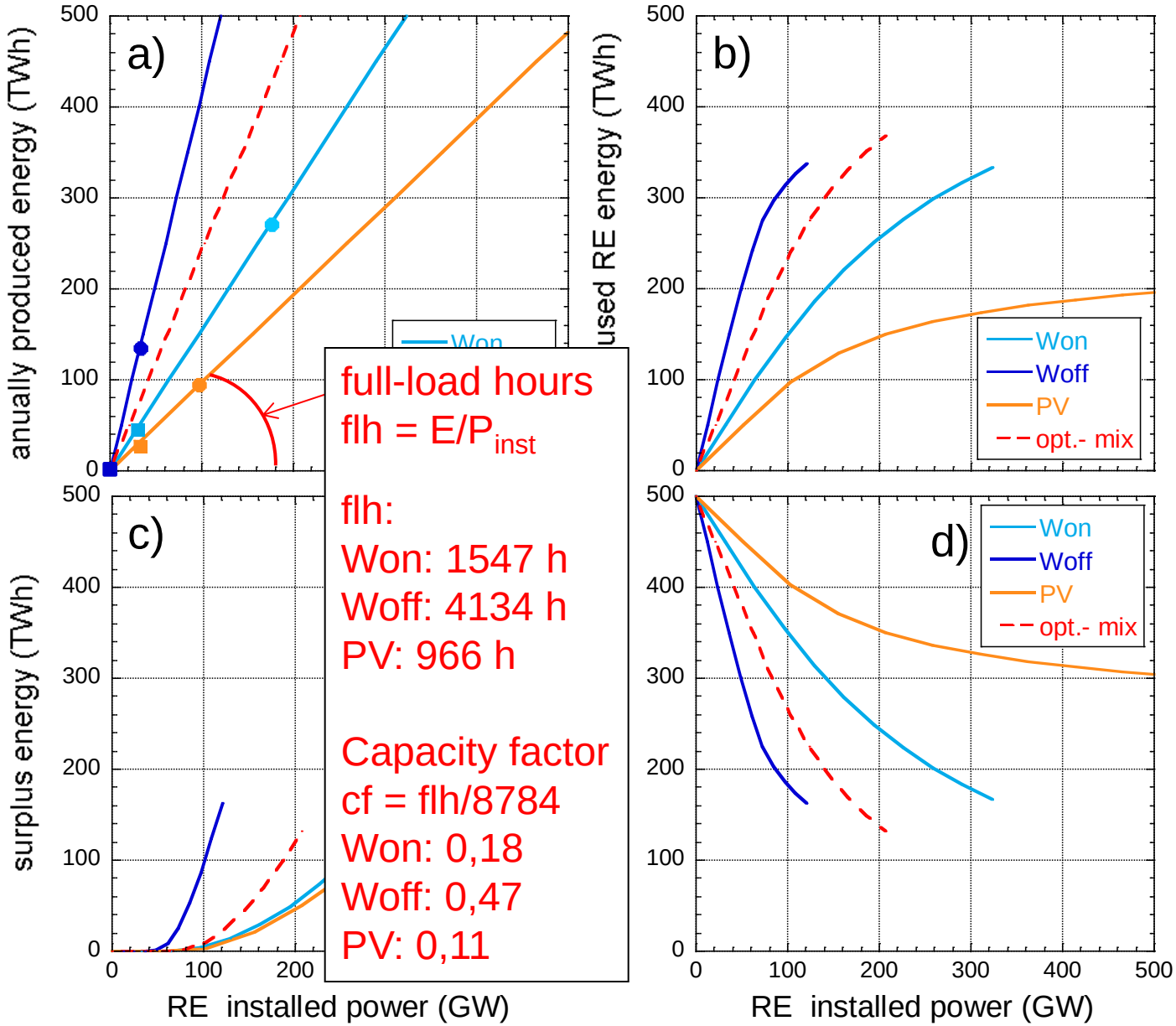
Optimal mix case:

- not a development scenario
- rather a reference case with minimal side effects

Scaling with installed power



Scaling with installed power

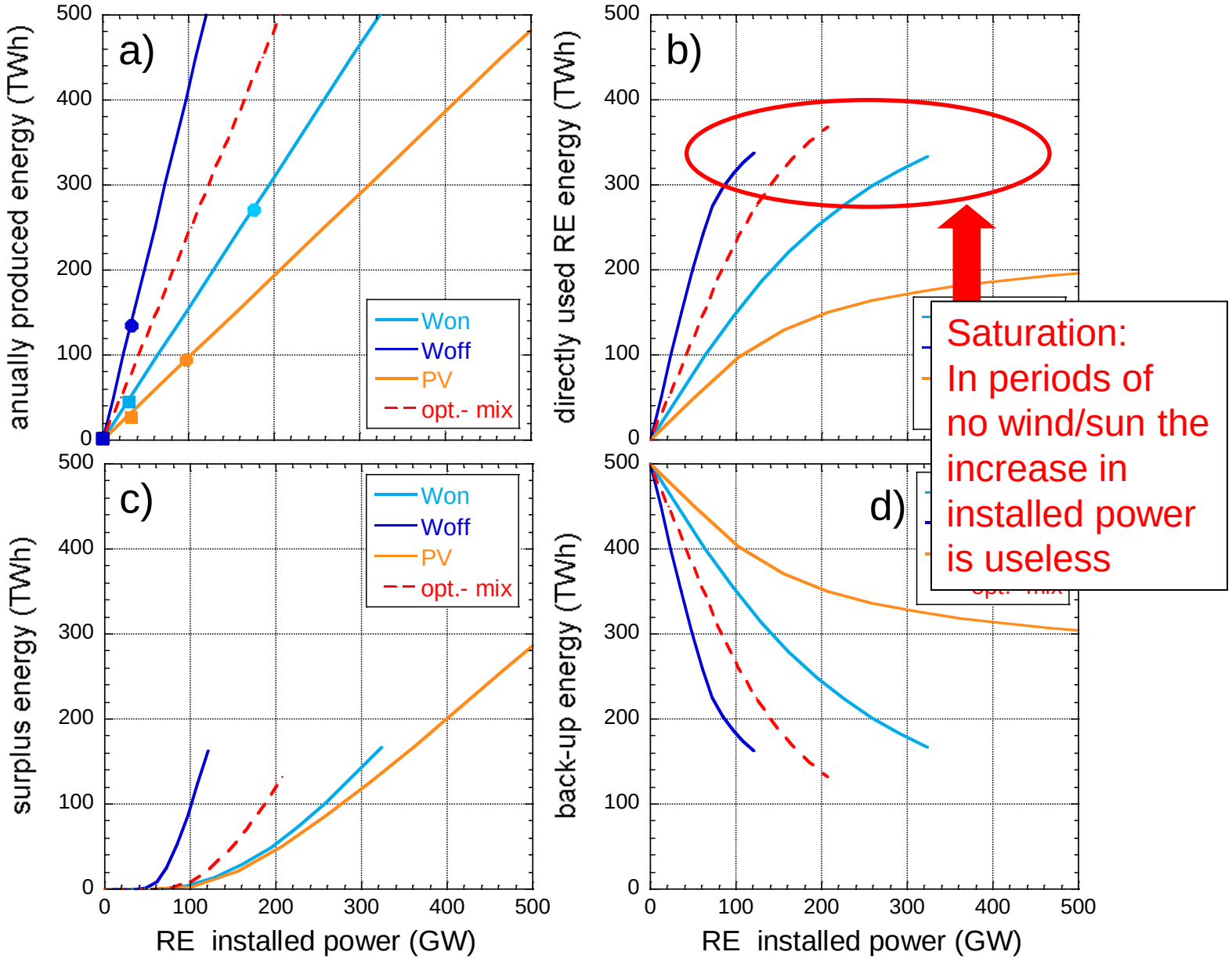


full-load hours
flh = E/P_{inst}

flh:
Won: 1547 h
Woff: 4134 h
PV: 966 h

Capacity factor
cf = flh/8784
Won: 0,18
Woff: 0,47
PV: 0,11

Scaling with installed power



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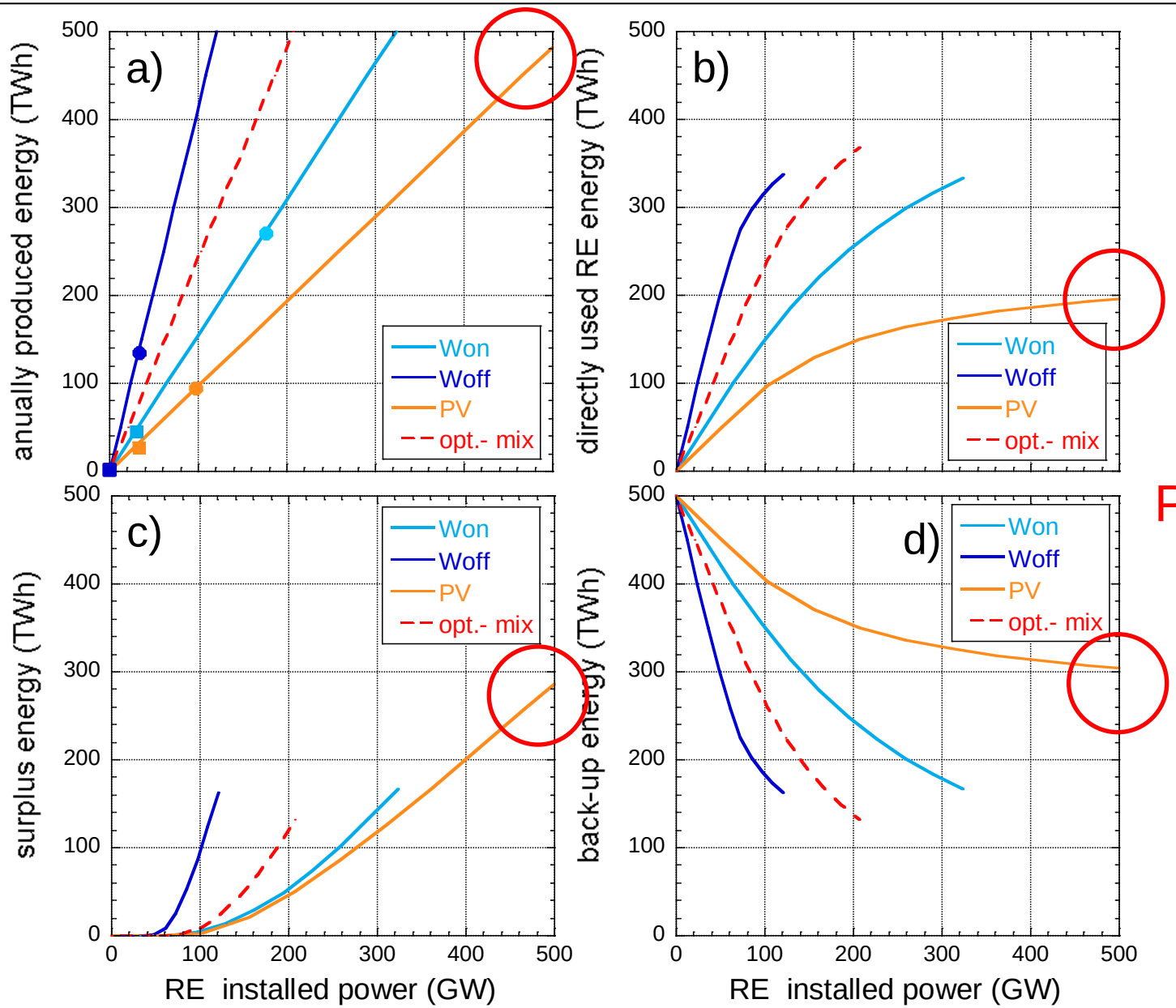
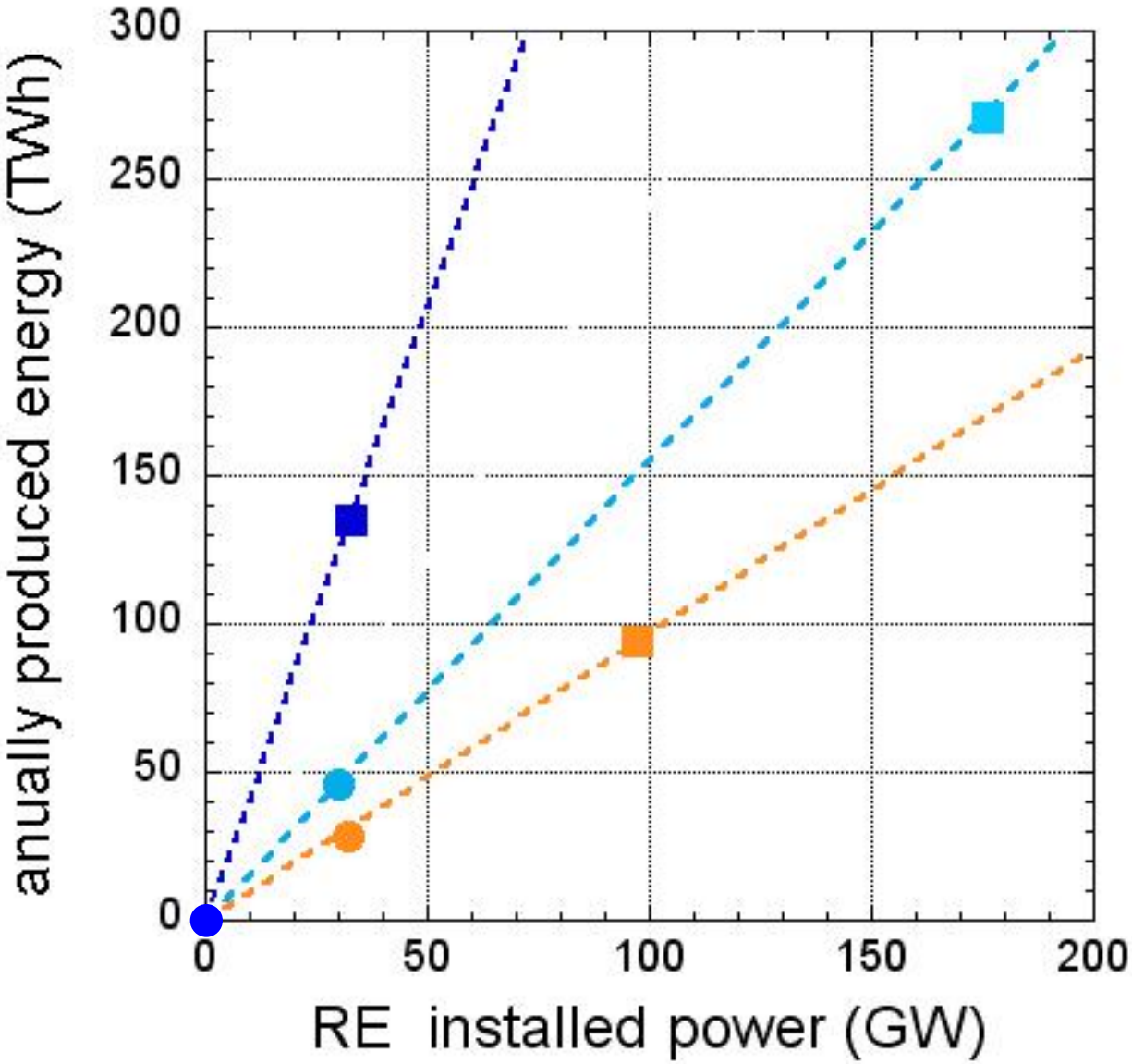


PV ???

2012 compared to „opt. mix, 100%-case“



The „Energiewende“ is still in its infancy

● situation 2012
■ optimal mix, 100% case

2012 experience:

- technology change outside market
- high costs for consumers
- insufficient grids
- destruction of PV industry
- economic problems of wind industry
- transformation of landscape

Specification of 100%, optimal mix case

Assumptions:
net electricity production/demand: 500 TWh

100% case: RE produce 500 TWh; $W_{surplus} = W_{back\text{-}up}$
Optimal mix: ~ 20% PV

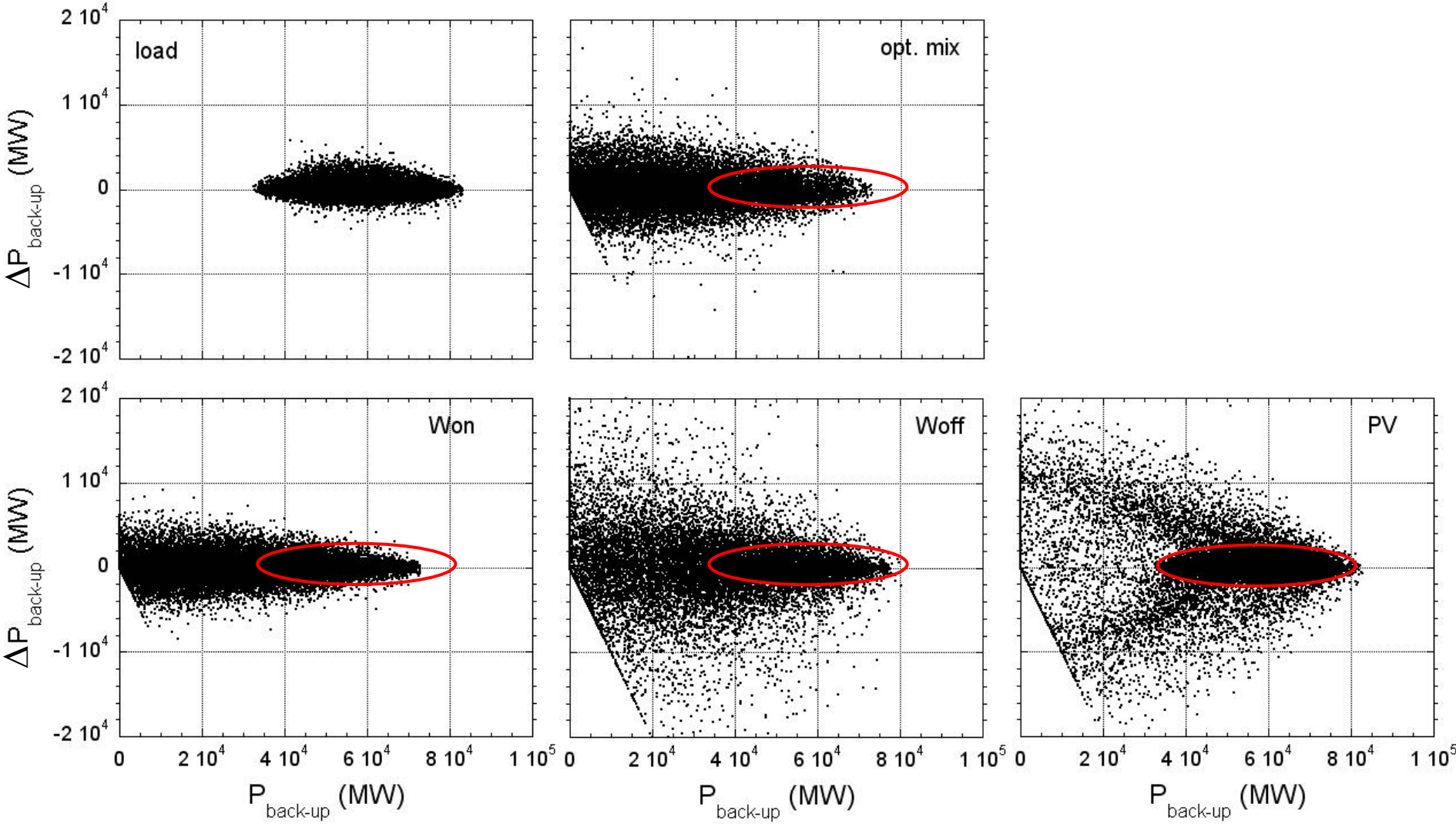
Specification:
W_{Won} = 271 TWh ; W_{Woff} = 135 TWh ; W_{PV} = 94 TWh;
$W_{back\text{-}up}$ = 131 TWh; $W_{surplus}$ = 131 TWh

P_{won} = 176 GW ; P_{woff} = 33 GW; P_{PV} = 97 GW; $P^{RE}_{installed}$ = 306 GW
P_{load} = 84 MW; $P_{back\text{-}up}$ = 73 GW;

The total installed power compares with the load of the EU: ~ 400 GW
The surplus corresponds to the annual demand of Poland
Not much saving in back-up power

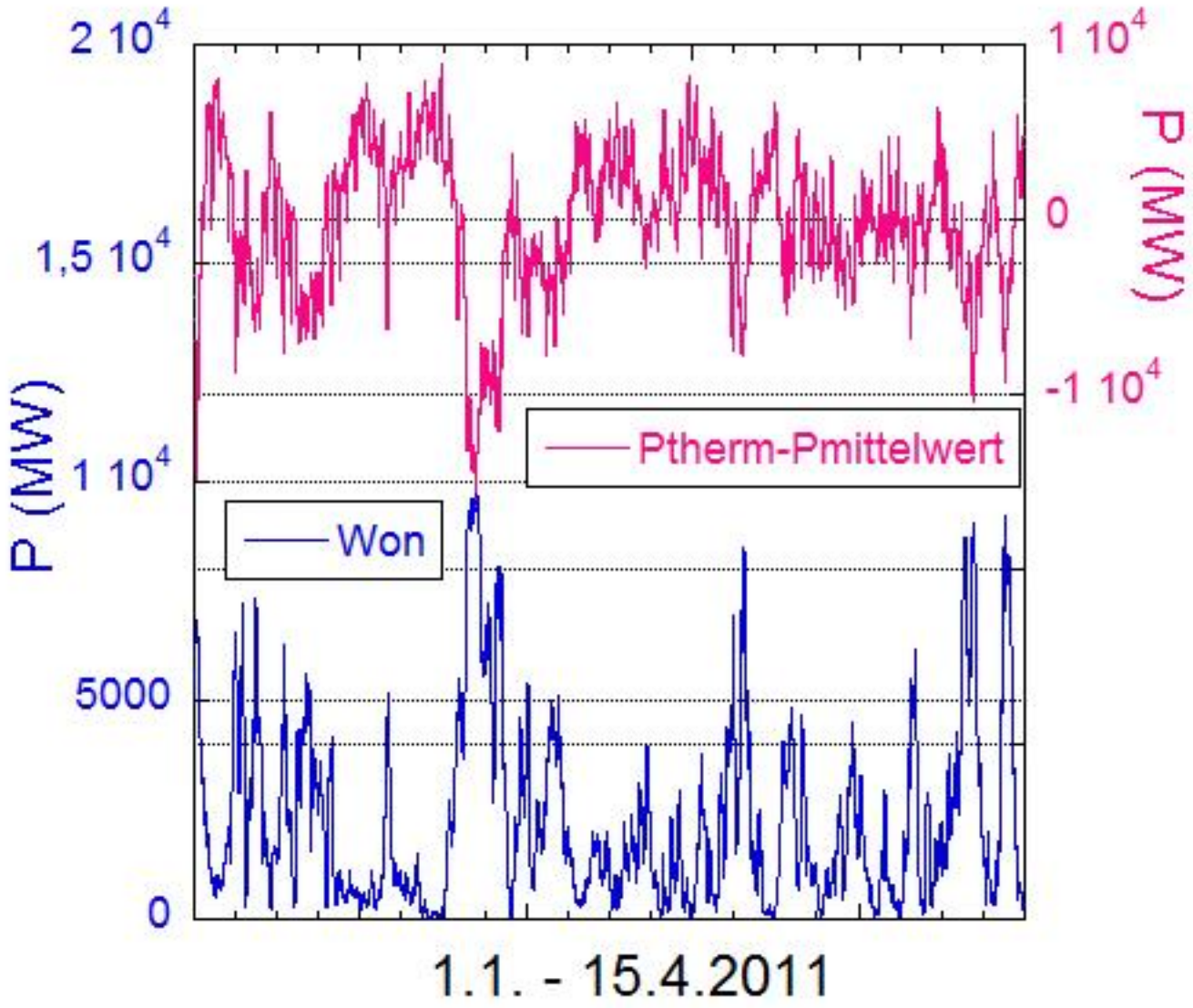
Challenges for the back-up system

Power jumps within 15 min



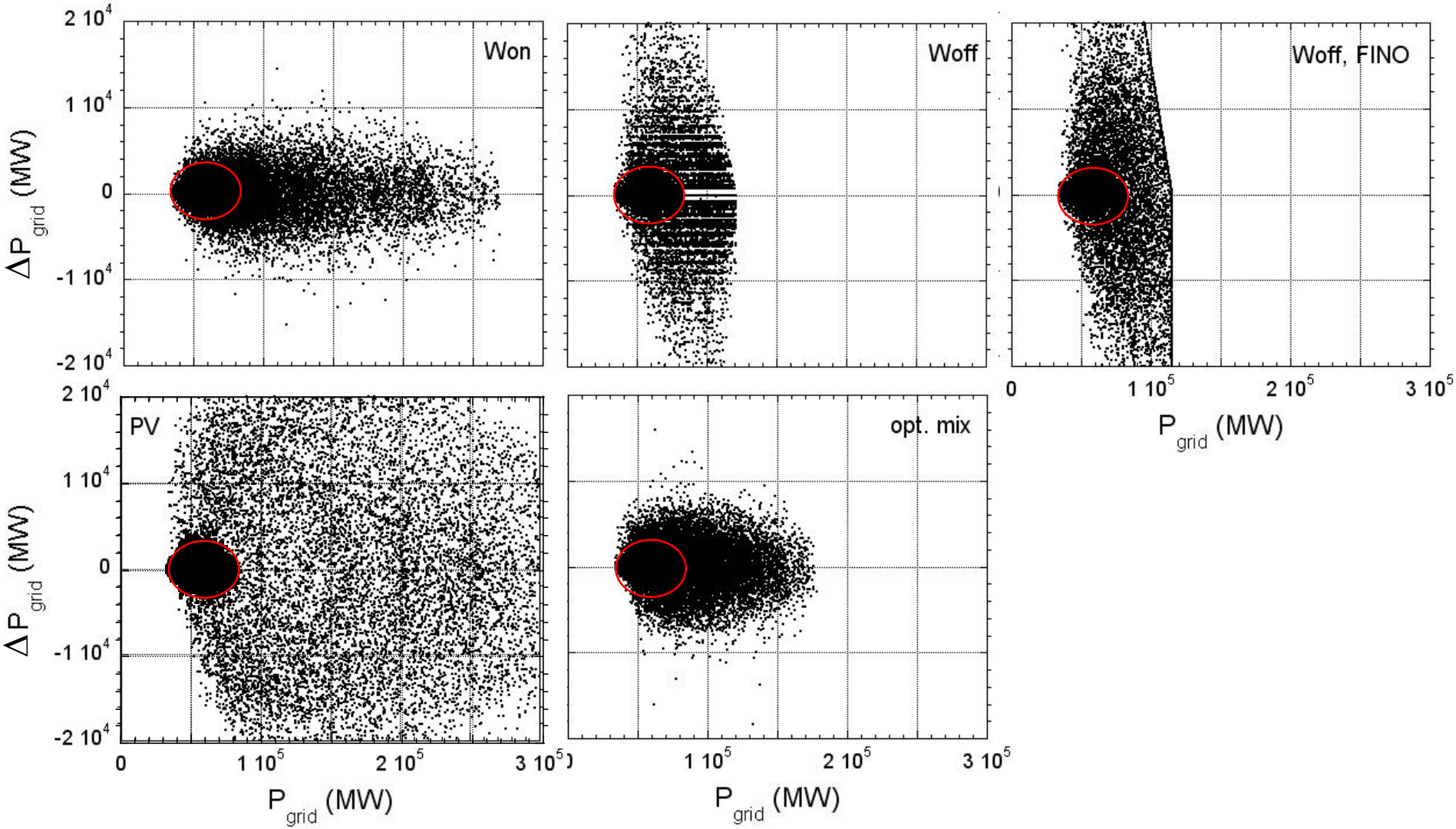
Situation 50Hertz, East Germany

Operation of thermal power station



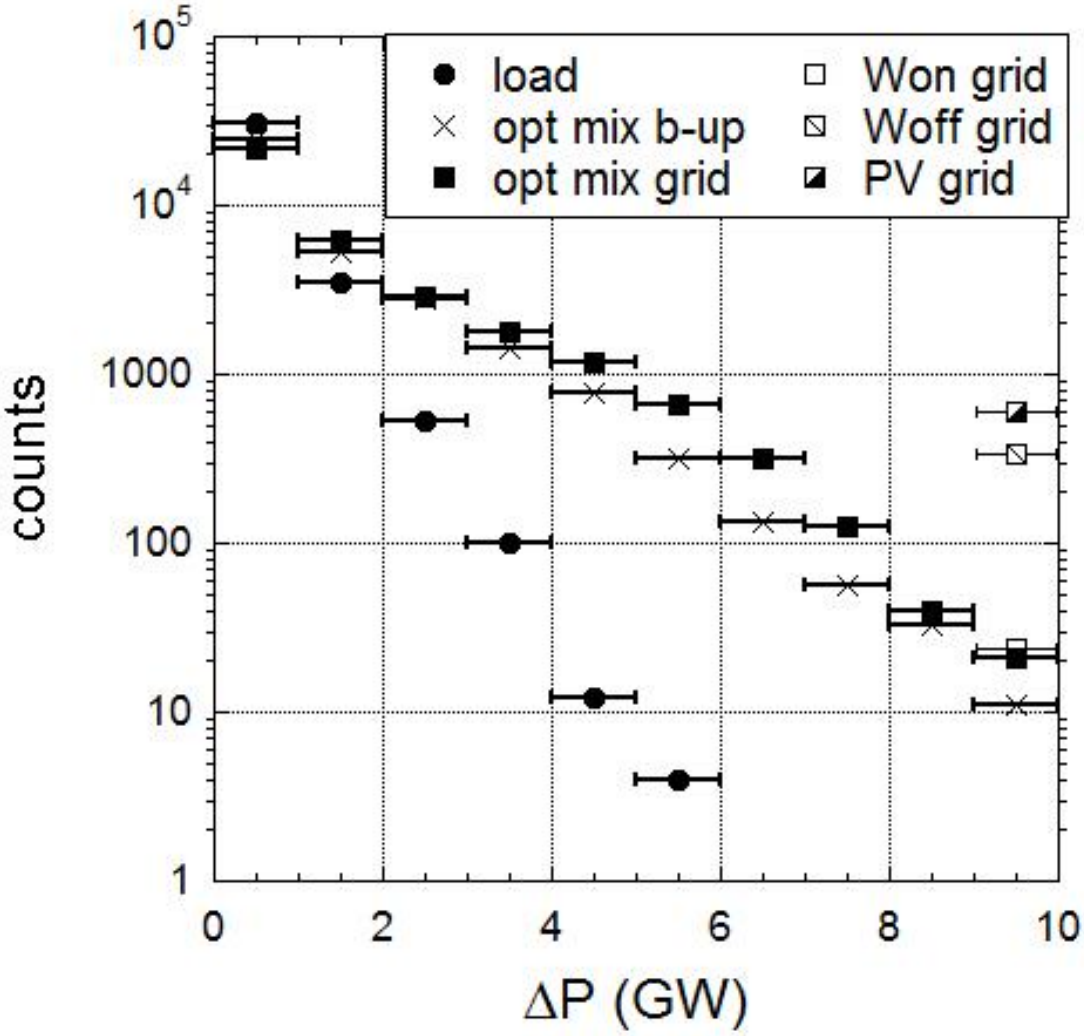
Challenges for the grid

Power jumps within 15 min



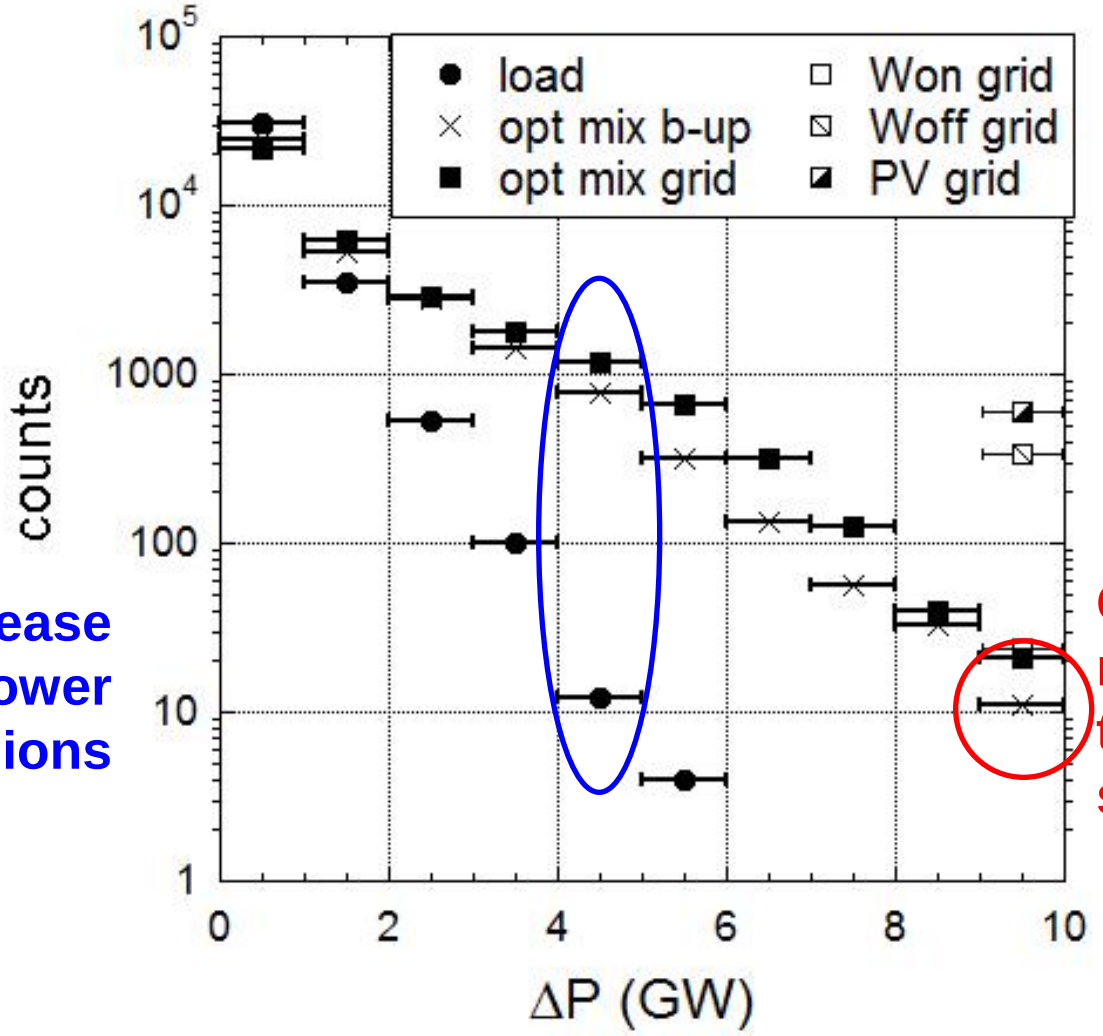
Challenges for the system

Frequency of power jumps



Challenges for the system

Frequency of power jumps



Strong increase of large power excursions

Coherent action of many large-scale thermal power stations necessary

Storage

Present pumped water storage situation: ~ 50 GWh, ~ 7 GW

To replace the back-up system, the 100%, optimal mix case demands a storage of 33 TWh = 650 x presently installed capacity of Germany

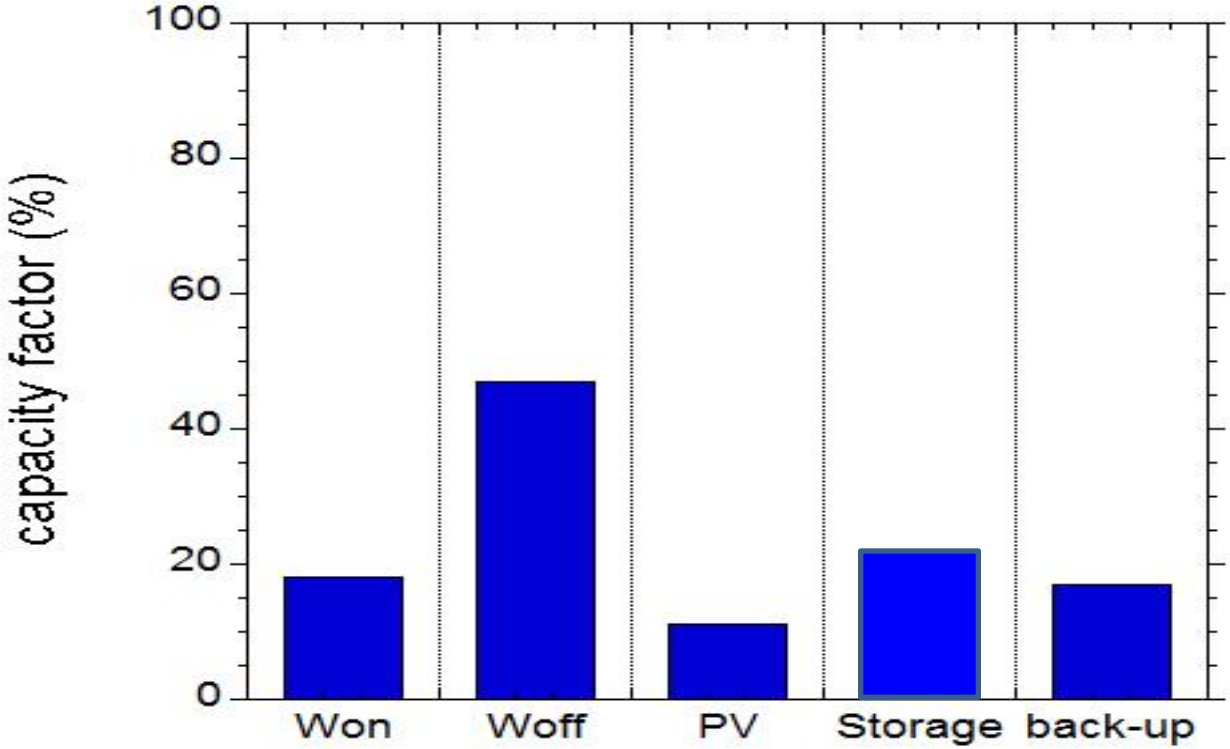
A target storage value could be: 5 TWh.
Only chemical storage possible; technology not available at large scales

Such a system would consist of:

P_{won} = 176 GW ; P_{woff} = 33 GW; P_{PV} = 97 GW

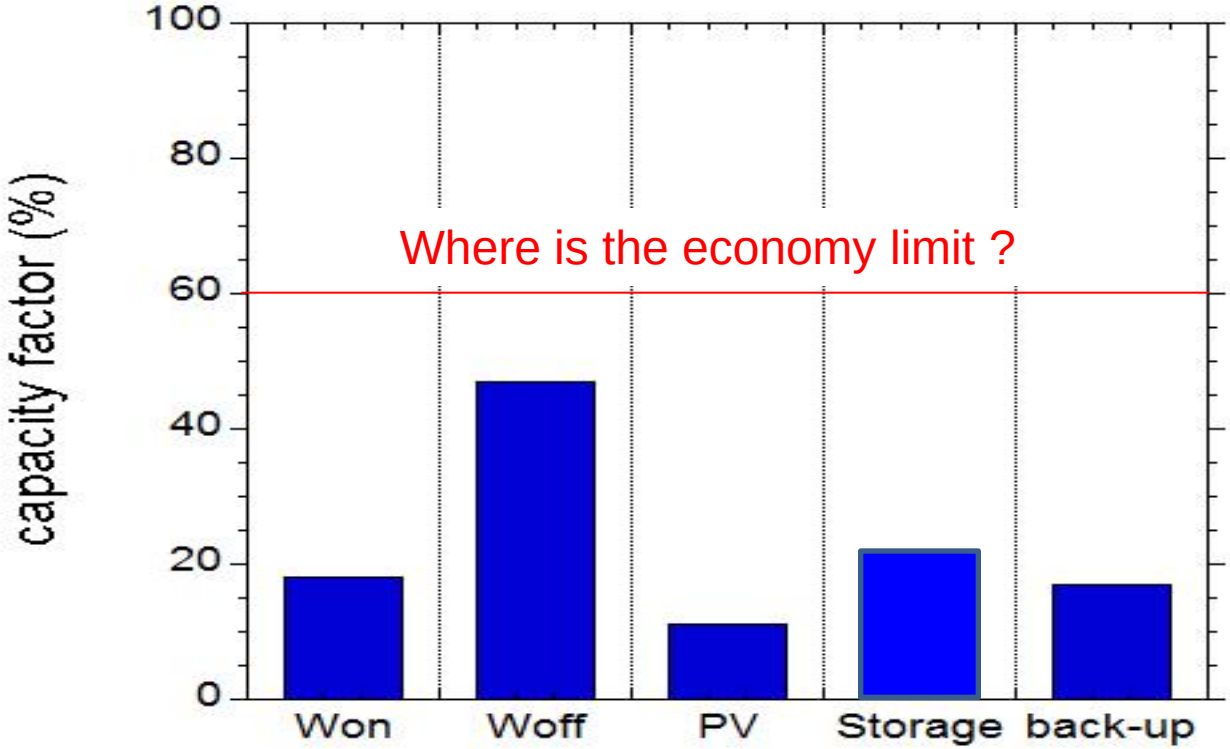
$P_{storage}$ = -123 (+73) GW; $P_{back\text{-}up}$ = 71 GW for 42 TWh

Economy of the 100%, optimal mix case with storage



Problem: all components operate under low cf conditions

Economy of the 100%, optimal mix case with storage



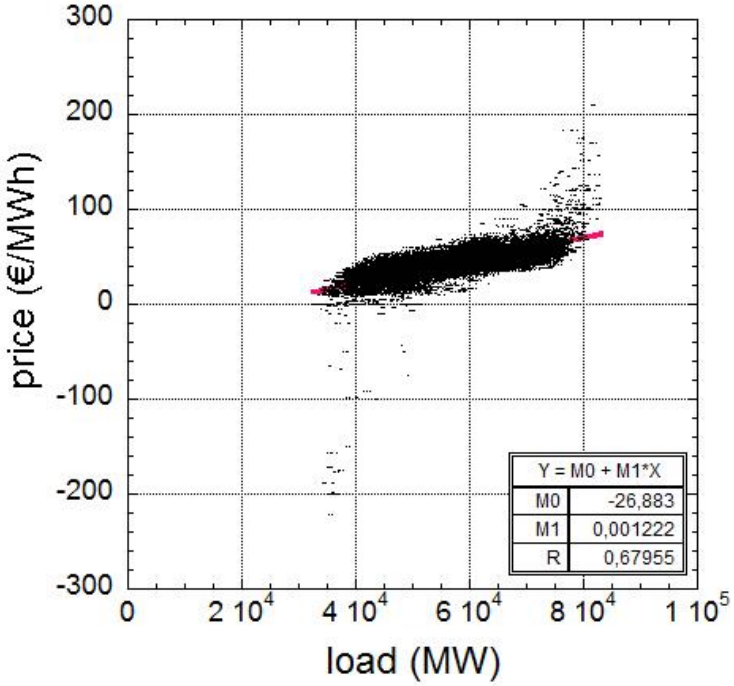
Problem: all components operate under low cf conditions

Structure of electricity costs: C = α/**cf** + OC

α/cf: capital costs

OC: operational costs: fuel, maintenance..

Spot market electricity costs and RE



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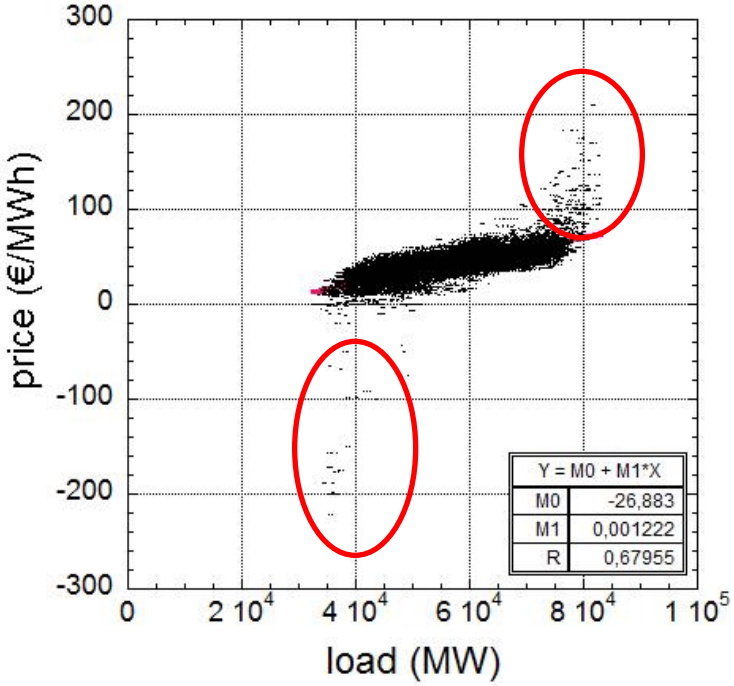
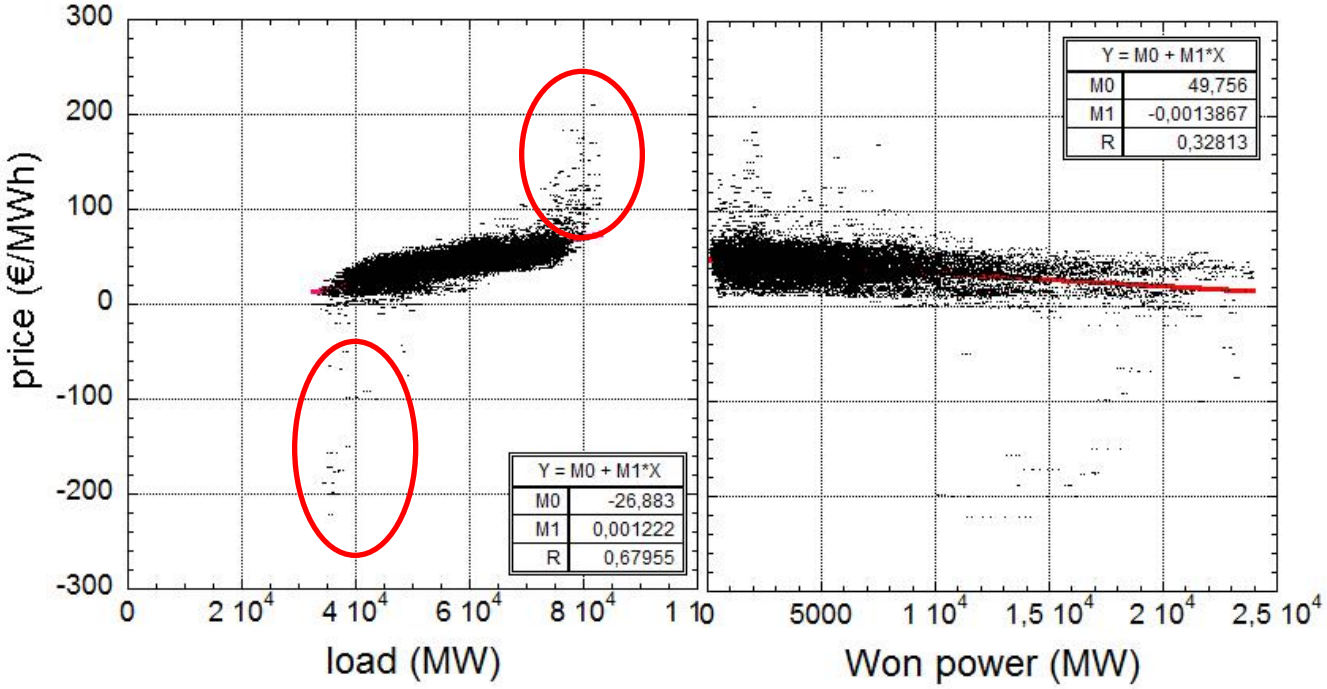


Neg prices at low load possible
Highest prices at highest load

Spot market electricity costs and RE



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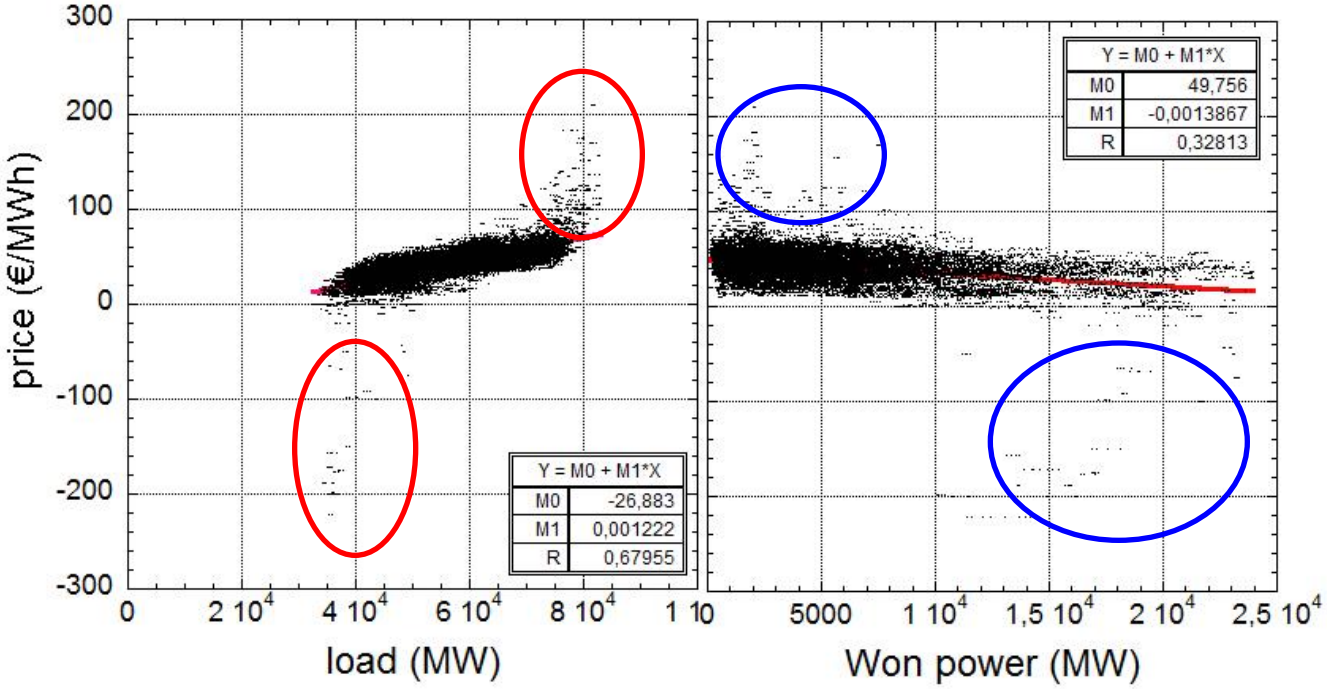
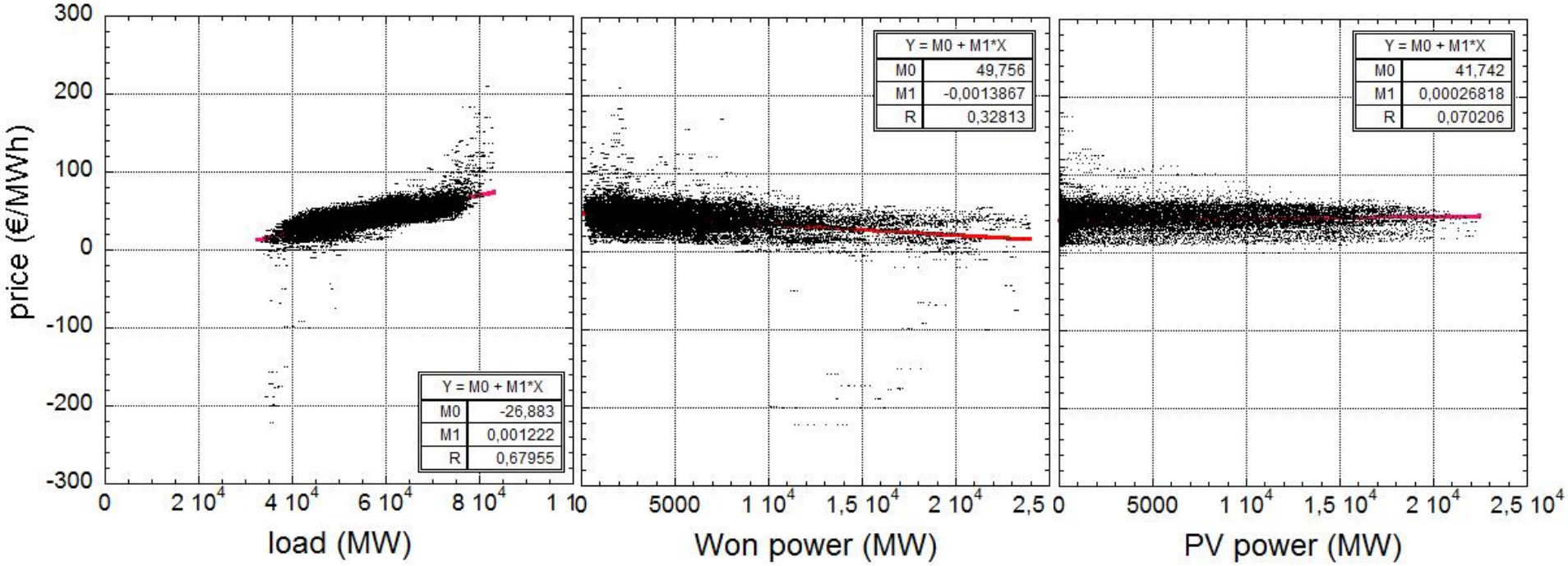


Neg prices at low load possible
Highest prices at highest load

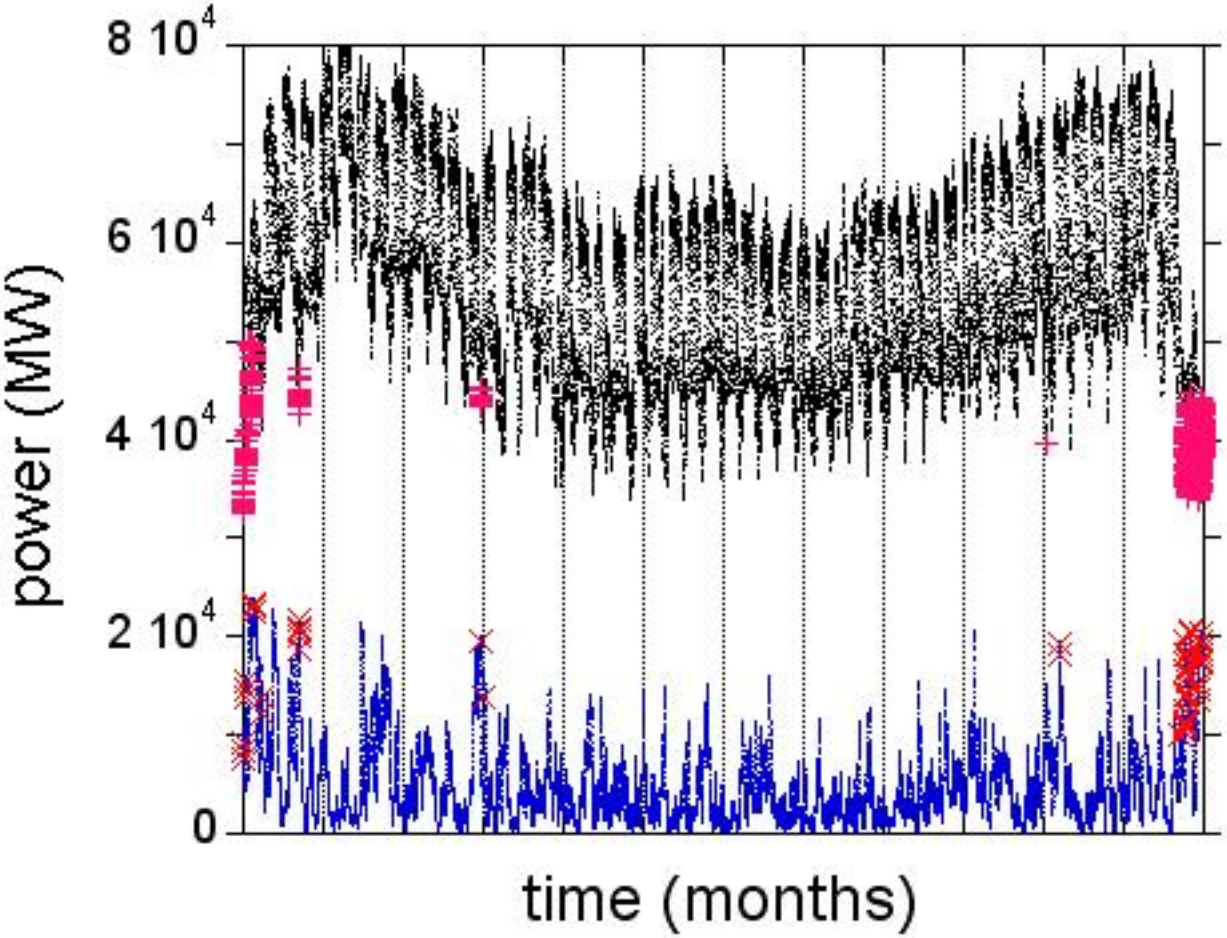
Neg prices at high wind power
Highest prices at low wind power

Spot market electricity costs and RE



PV does not show any price effect

Identification of periods with neg. prices

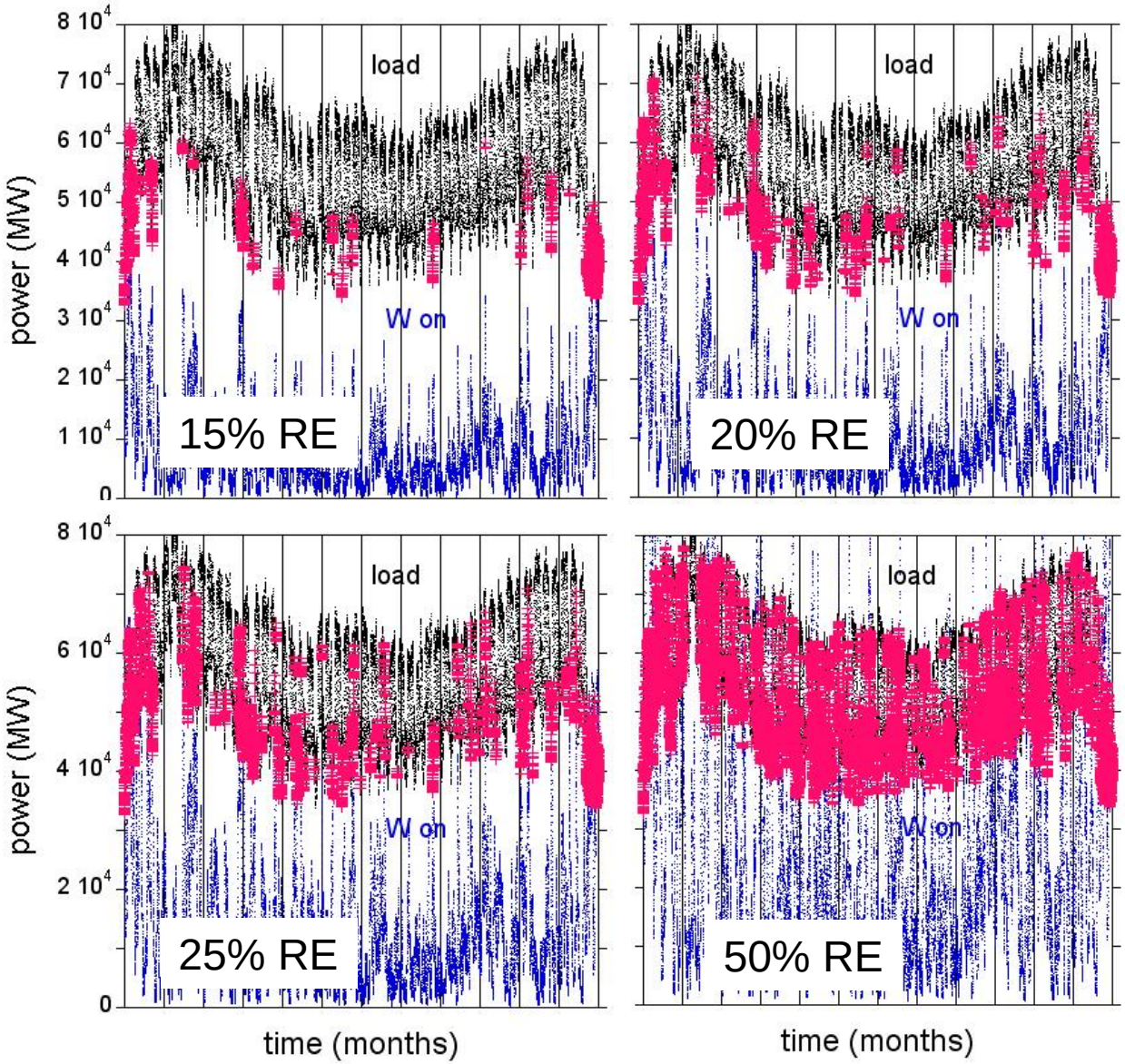


Periods with neg. prices:
low load, high wind

Criterion for neg. prices:
P_{load}-P_{Won} < 26.3 GW

x: actual periods
+ predicted periods

Scaling of periods with neg. prices



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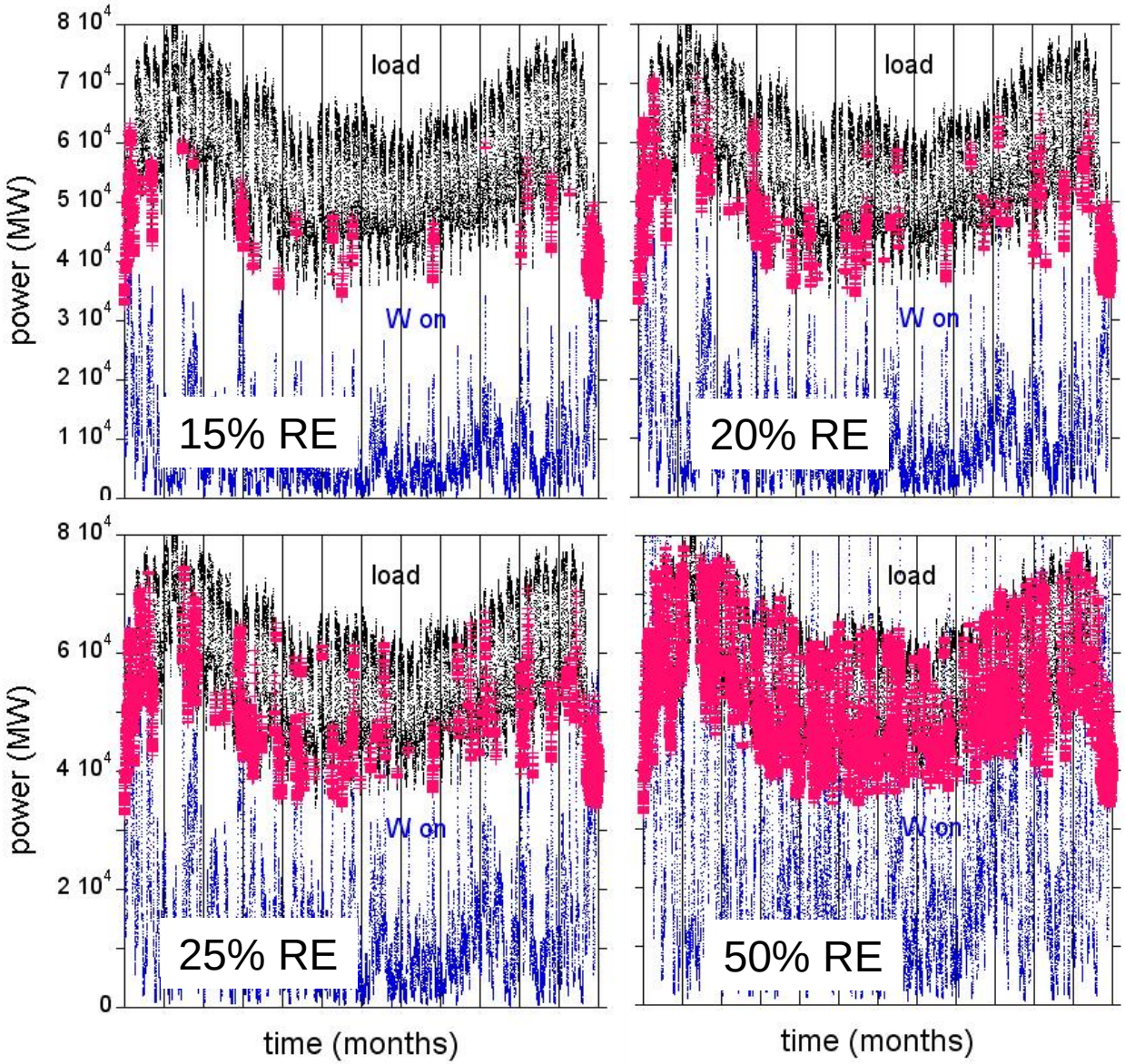
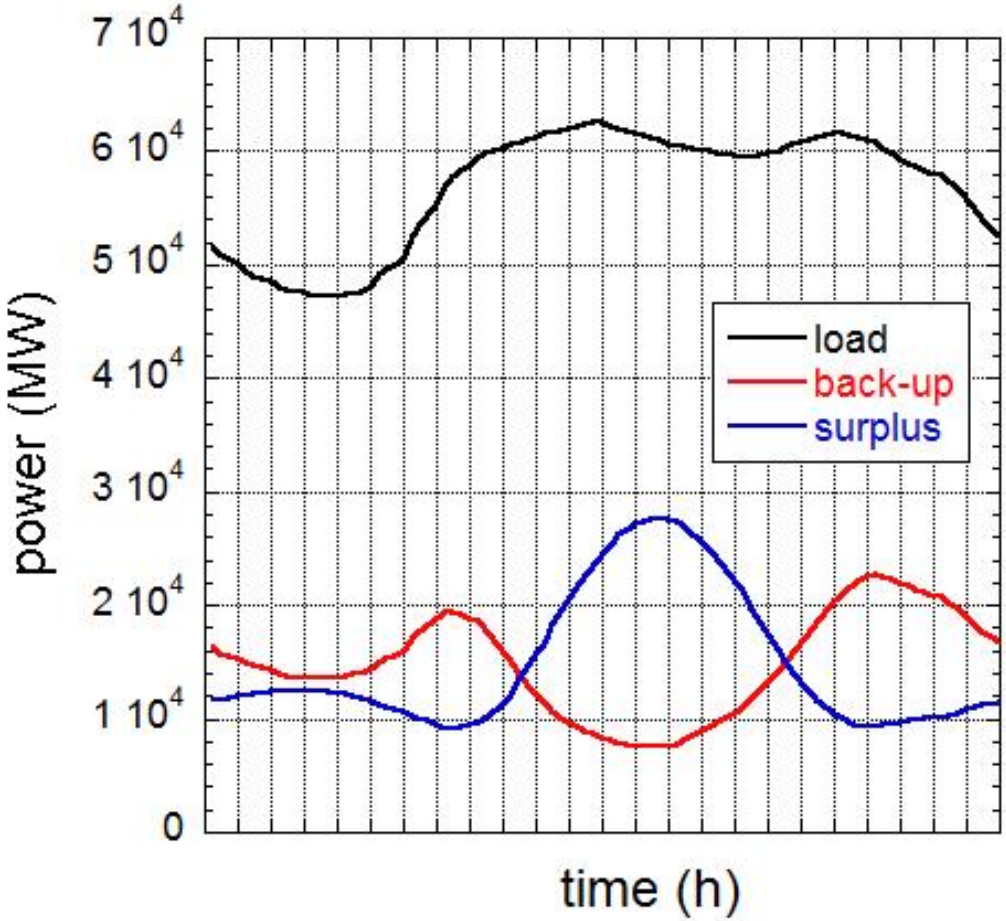


% RE	h with neg prices
15	446
20	825,5
25	1218
50	3359
100	5662

Demand-side management

Principle: avoid high-cost periods –
shift economic activities into low-cost periods

Average of daily variation of load, back-up and surplus



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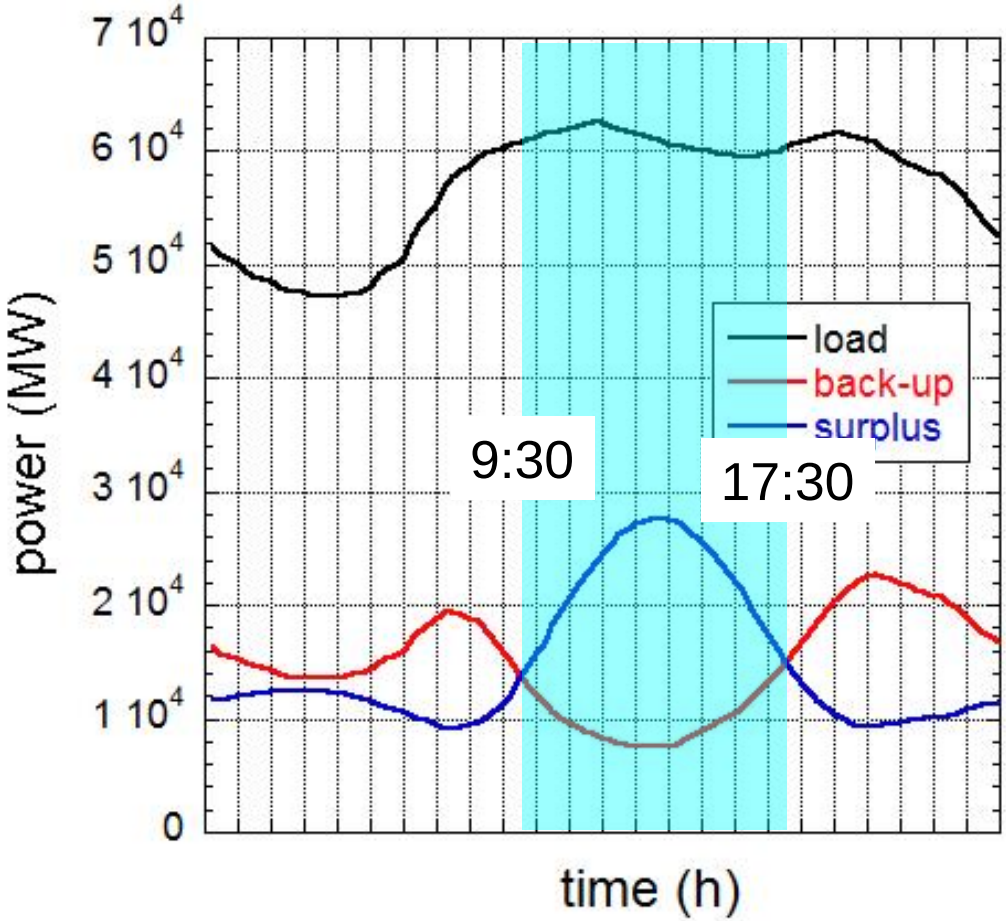
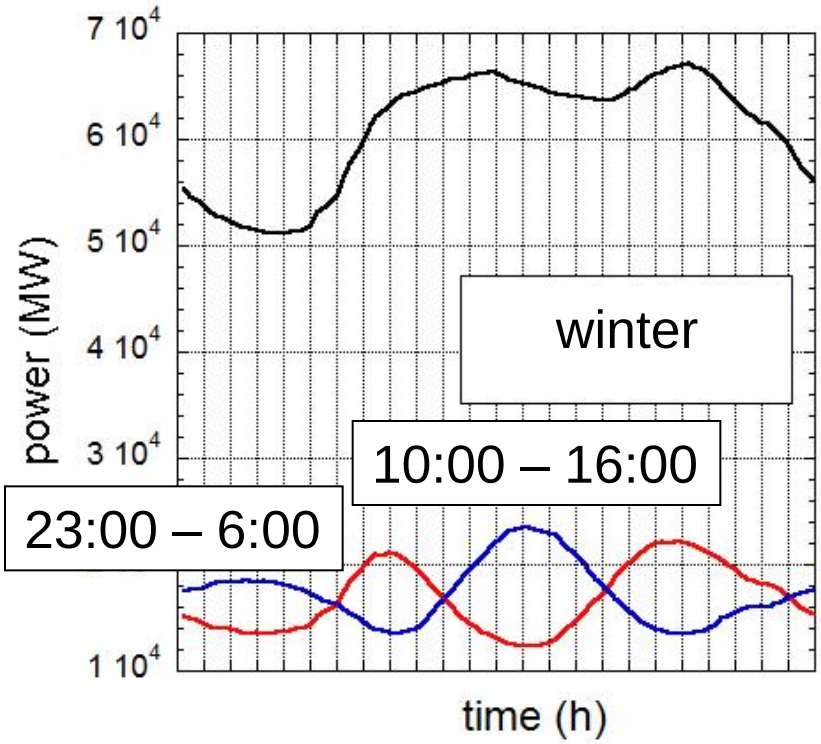
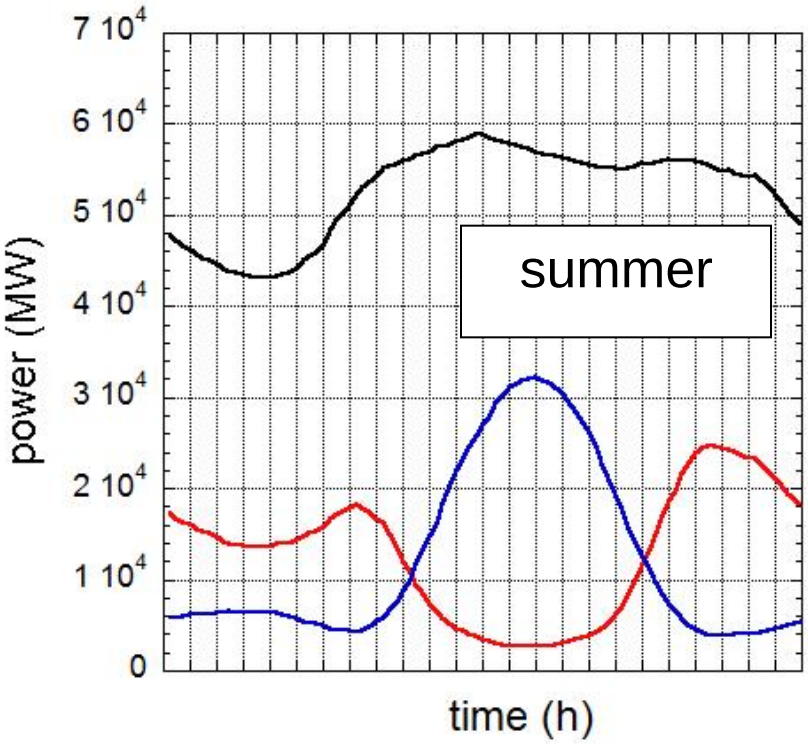


Demand-side management

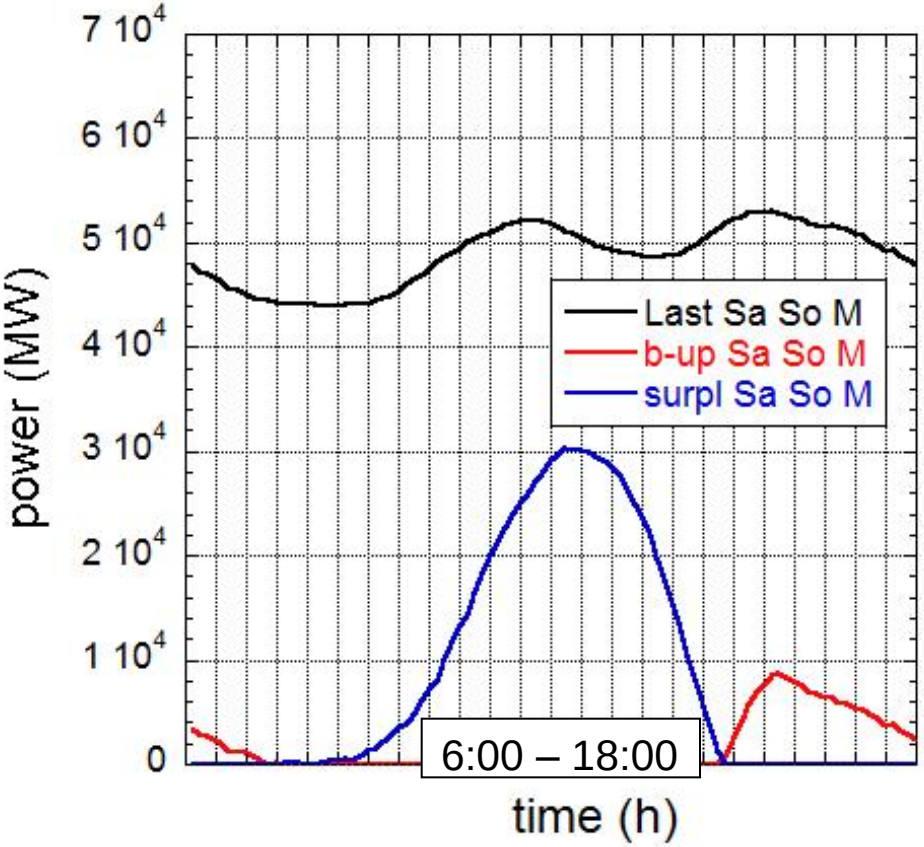
Comparison winter - summer





Demand-side management

Situation during weekend

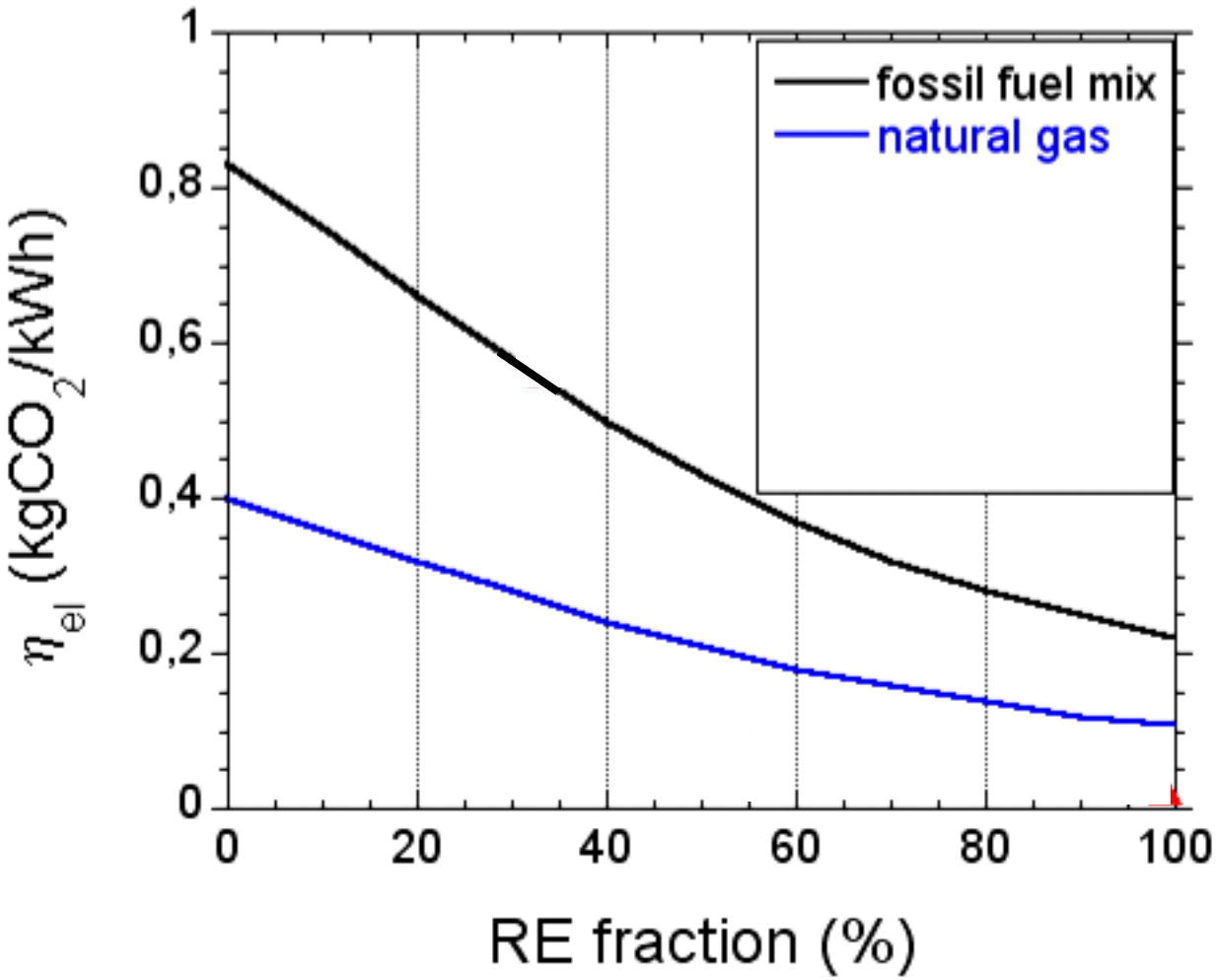


Biggest effect : Integration of weekend

Additional use of RE: 7.5 TWh
Peak-load: 83 → 71 MW
Back-up system: 131 → 123 TWh

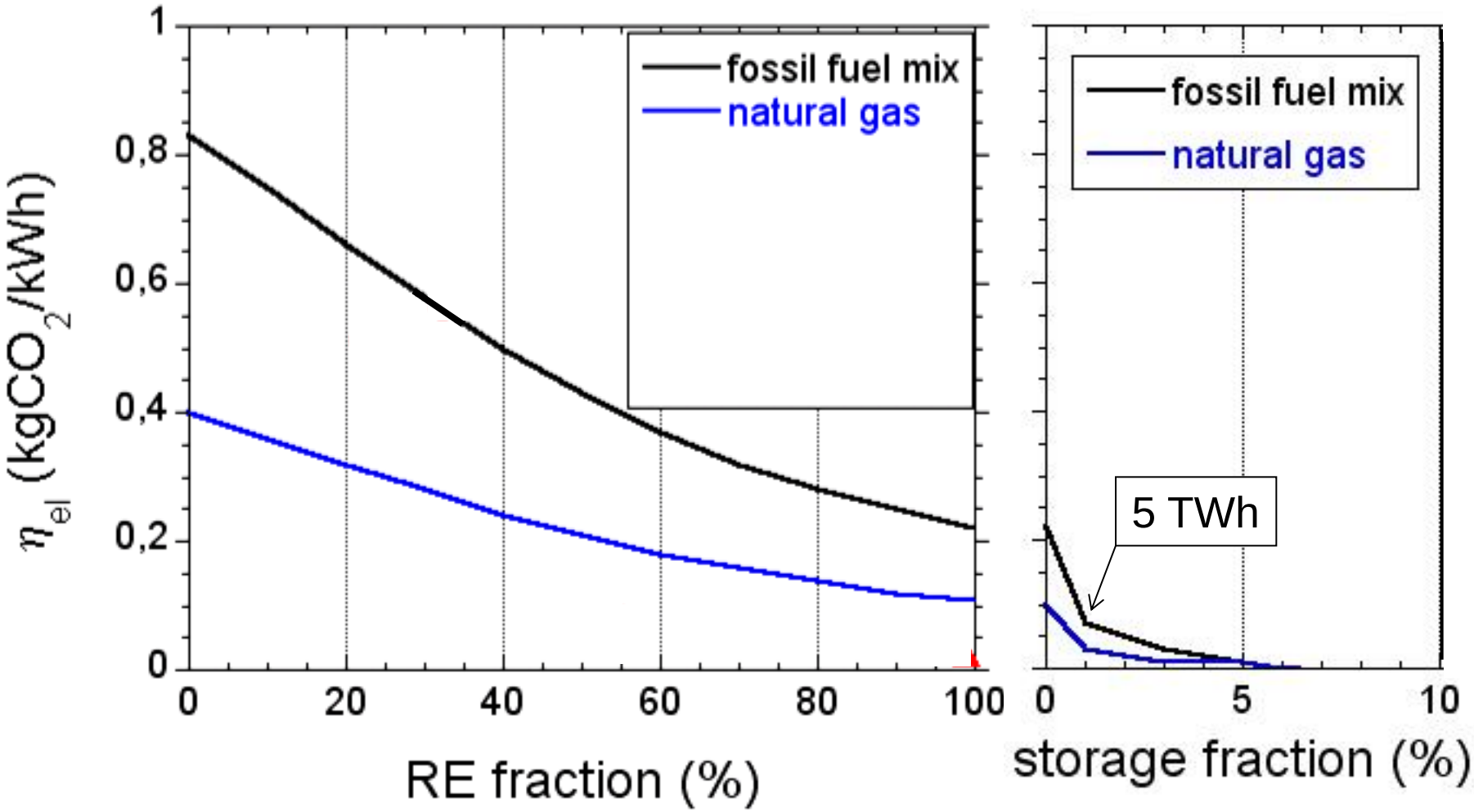
CO_2 reduction by RE

Optimal mix conditions



CO_2 reduction by RE

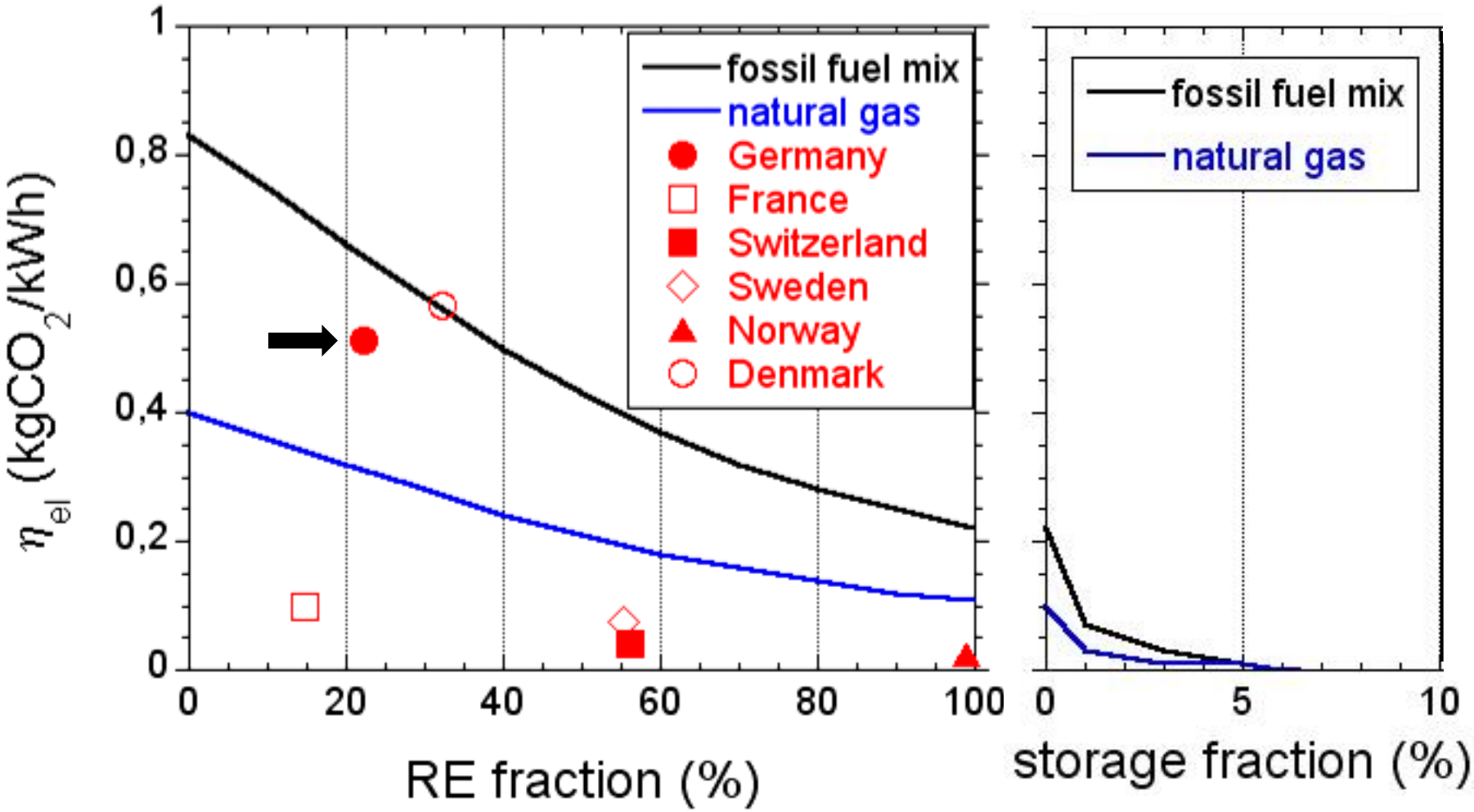
Optimal mix conditions



Storage is hardly motivated by CO_2-saving

CO_2 reduction by RE

Comparison with others



Conclusions w.r.t. intermittend sources

Large power – comparable to the load of Europe - to be installed → high **costs**

A supply system exclusively by wind and PV: **does not seem to be possible**

Back-up system required in all scenarios:

- **little saving in thermal power**
- **power-heat-coupling: maybe, in winter in the morning and evening**
- **probably not very attractive: see experience Denmark**

High surplus power peaks and energies: **what to do with ?**

- **Suppress → further degradation of economic operation**
- **Use for power-to-gas: high prices of secondary electricity**
- **Use for heating: winter production: 76 TWh (private heating: 550 TWh)**
- **Use for cooling: summer production: 55 TWh (cooling needs: 20 TWh)**

Conclusions w.r.t. intermittend sources

Storage (for surplus):

large-scale technology, not available

operation not economic

difficult to motivate from the CO_2 point of view

Components operation not economic → today: **no new gas power stations**

Electricity supply cannot be organised under market rules → **capacity market**

Unfavourable operation of all technical systems → **increased costs and CO_2**

CO_2 reduction: **not to the levels as already achieved by others in EU**

No favourable conditions for demand-side management:

day-time activities will intensify; maybe, new markets will develop

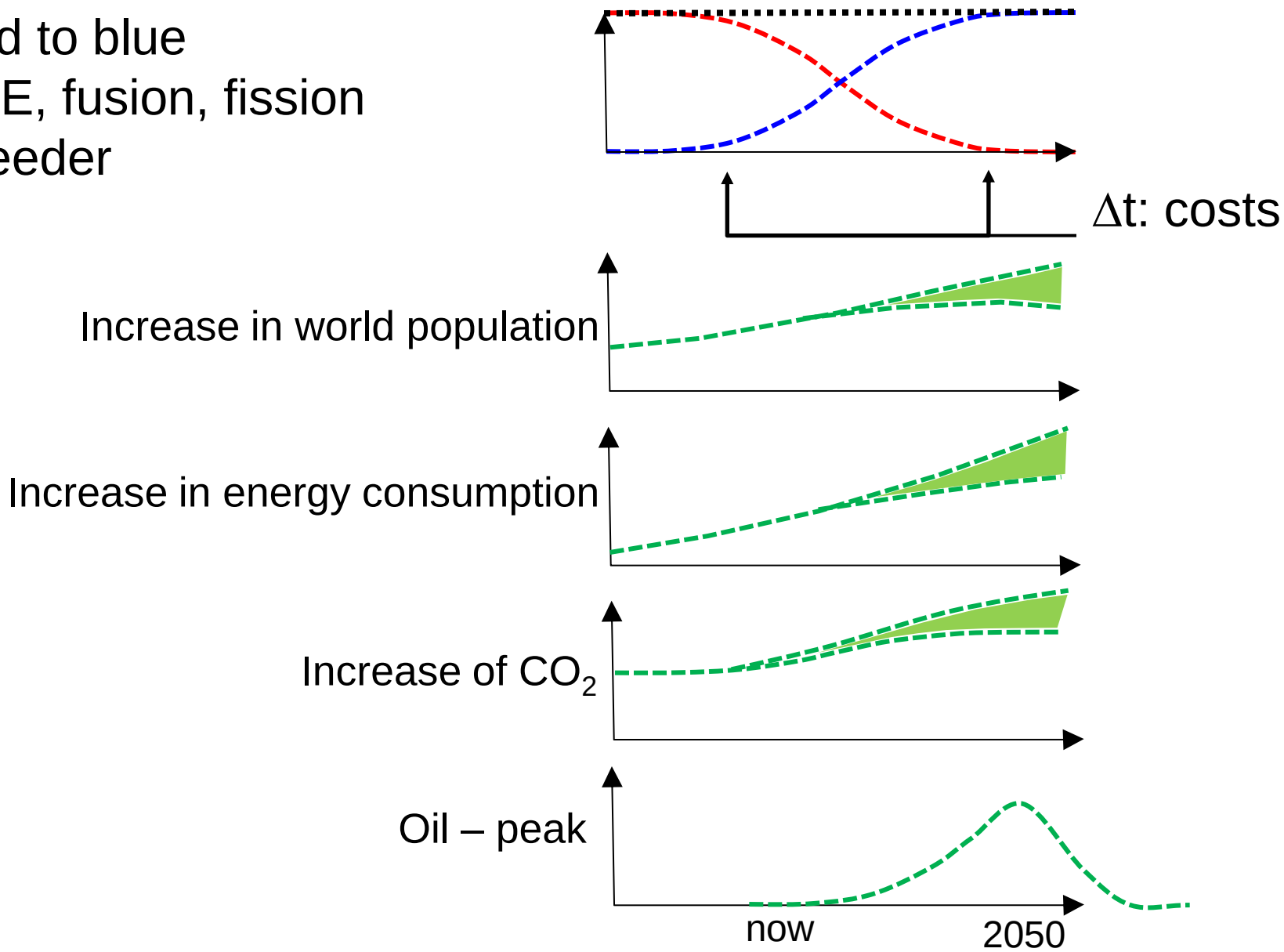
best options: use of weekends

storage by car batteries: surplus during the day not the night

Supra-national grid improves situation: **not probable in near future**

Technology change

from red to blue
Blue: RE, fusion, fission
with breeder



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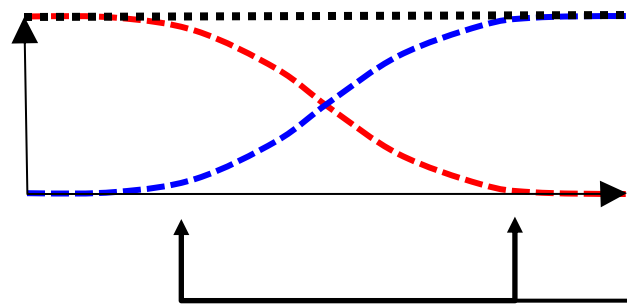
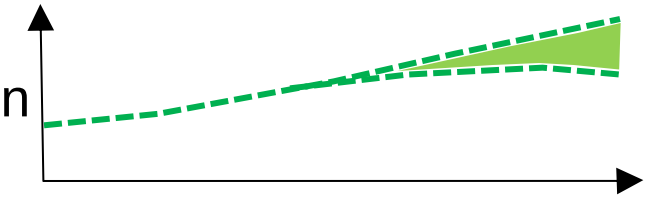
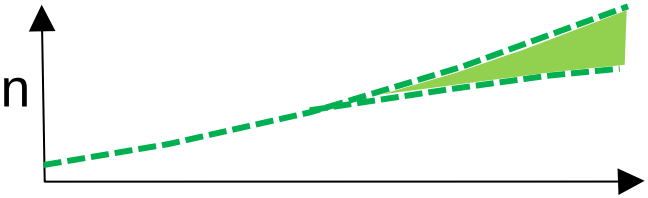


Δt: costs

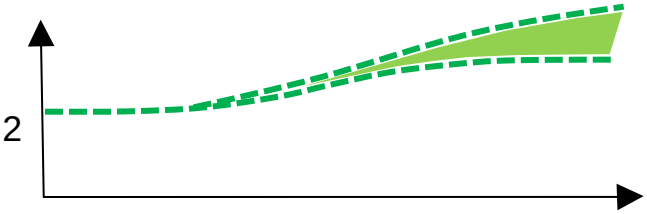
Increase in world population



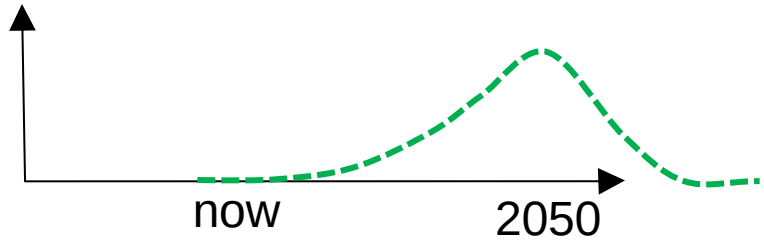
Increase in energy consumption



Increase of CO_2



Oil – peak



Keep all options open

Conclusions

The exclusive use of RE has limitations and leads to shortcomings.

Therefore, the most obvious question will be whether and how an electricity system based on variable sources can be improved or supplemented.

This will be a question classically posed to research and engineering because these disciplines have found the ways in the past to liberate mankind from the imponderabilities and perils of nature.