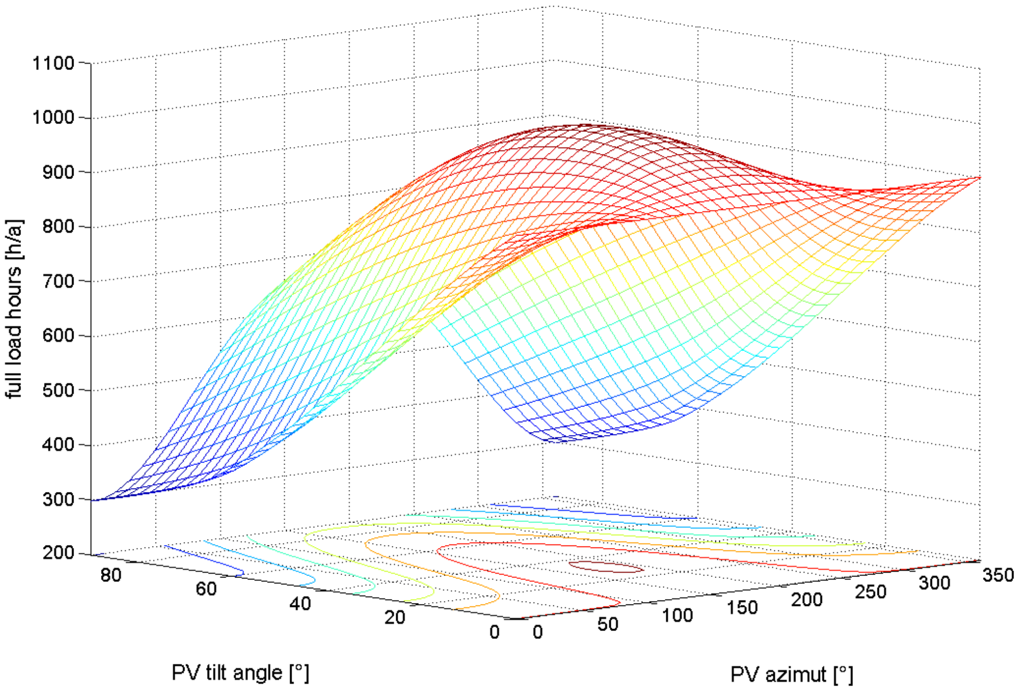
East to west - The optimal tilt angle and orientation of photovoltaic panels from an electricity system



Michael Hartner
André Ortner
Albert Hiesl

TU Wien
Energy Economics Group (EEG)

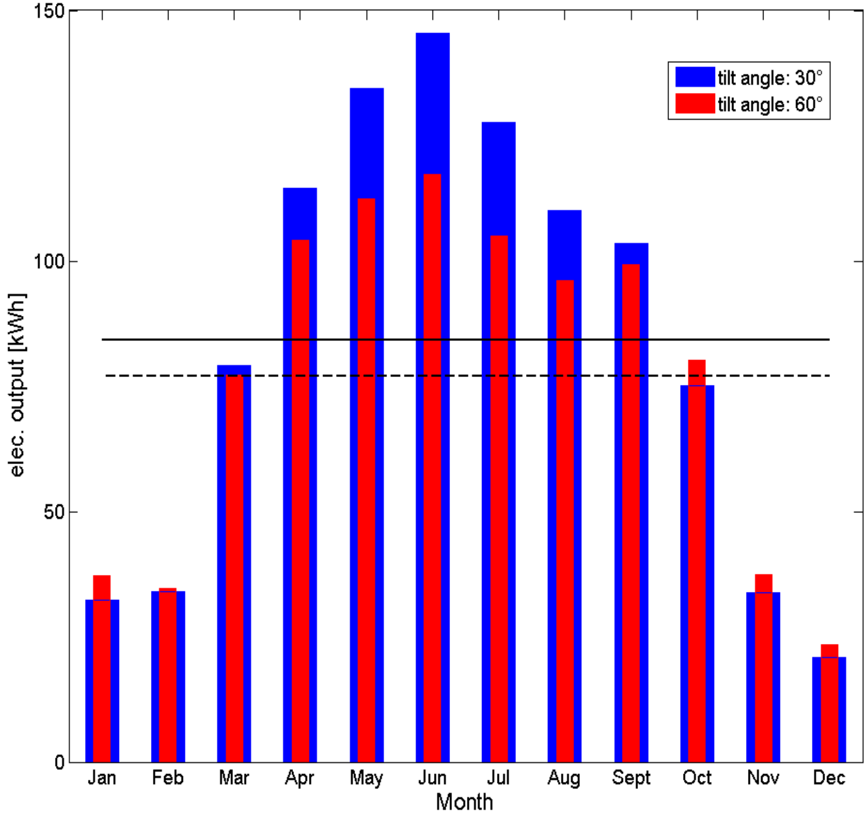
e-mail: hartner@eeg.tuwien.ac.at

Research question and scope

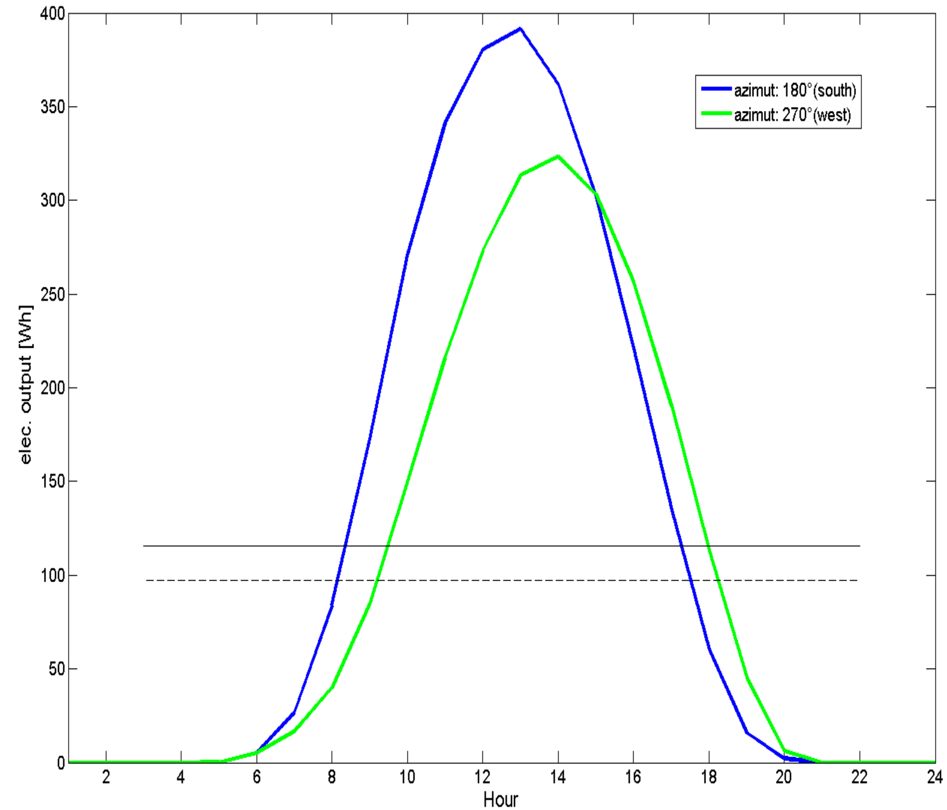
- Does the market optimum deviate stignificantly from the “energetic” optimum of PV-installation angels?
- If yes, what are the effects on electricity generation costs in the system?
- Is there a need for support policy adjustments?

Potential PV-production shifts

- Seasonal shift (tilt angle)

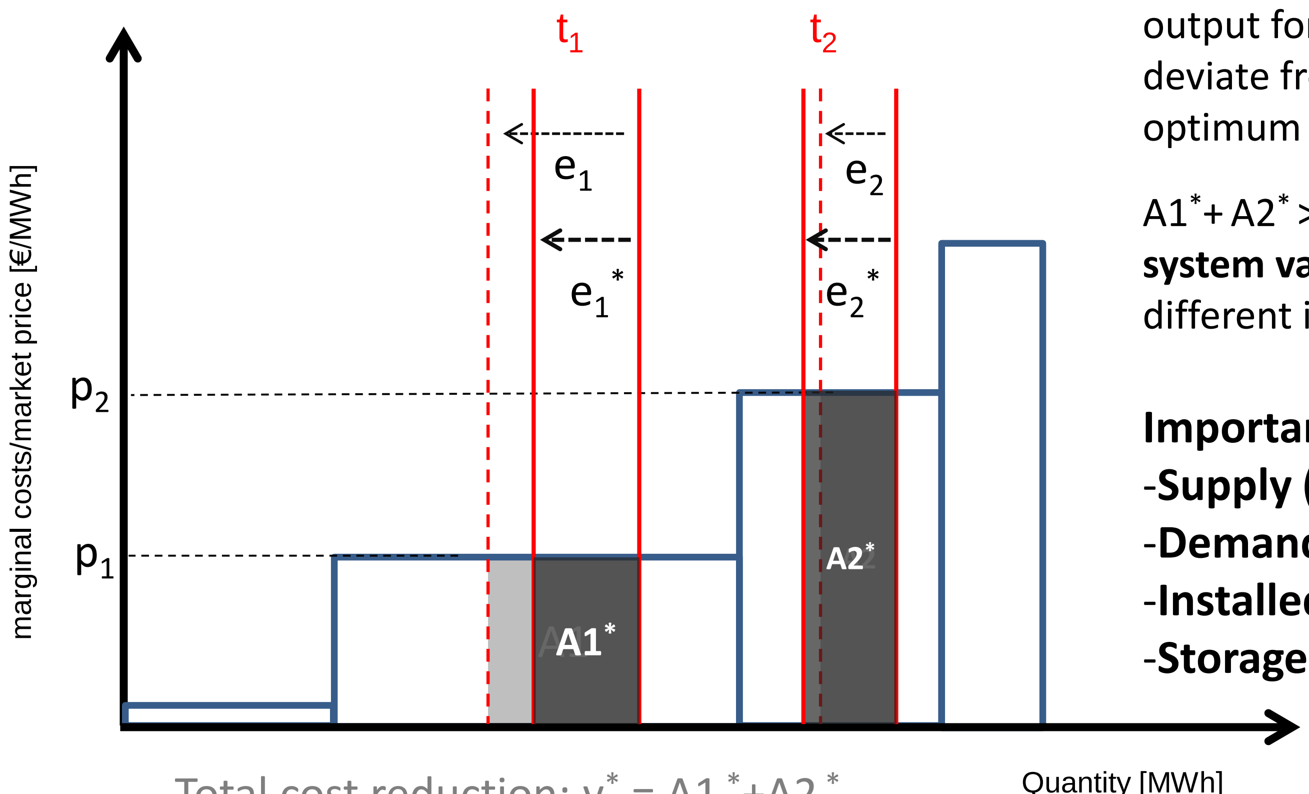


- Hourly shift (azimut)



PV system or market value

System value of a **PV-system** that **deviates from the energetic optimum**



Total cost reduction: $v^* = A1^* + A2^*$

$e_1^* + e_2^* < e_1 + e_2$ lower total output for PV systems that deviate from the energetic optimum

$A1^* + A2^* > A1 + A2$ but the **system value can be higher** for different installation angles

Important factors:

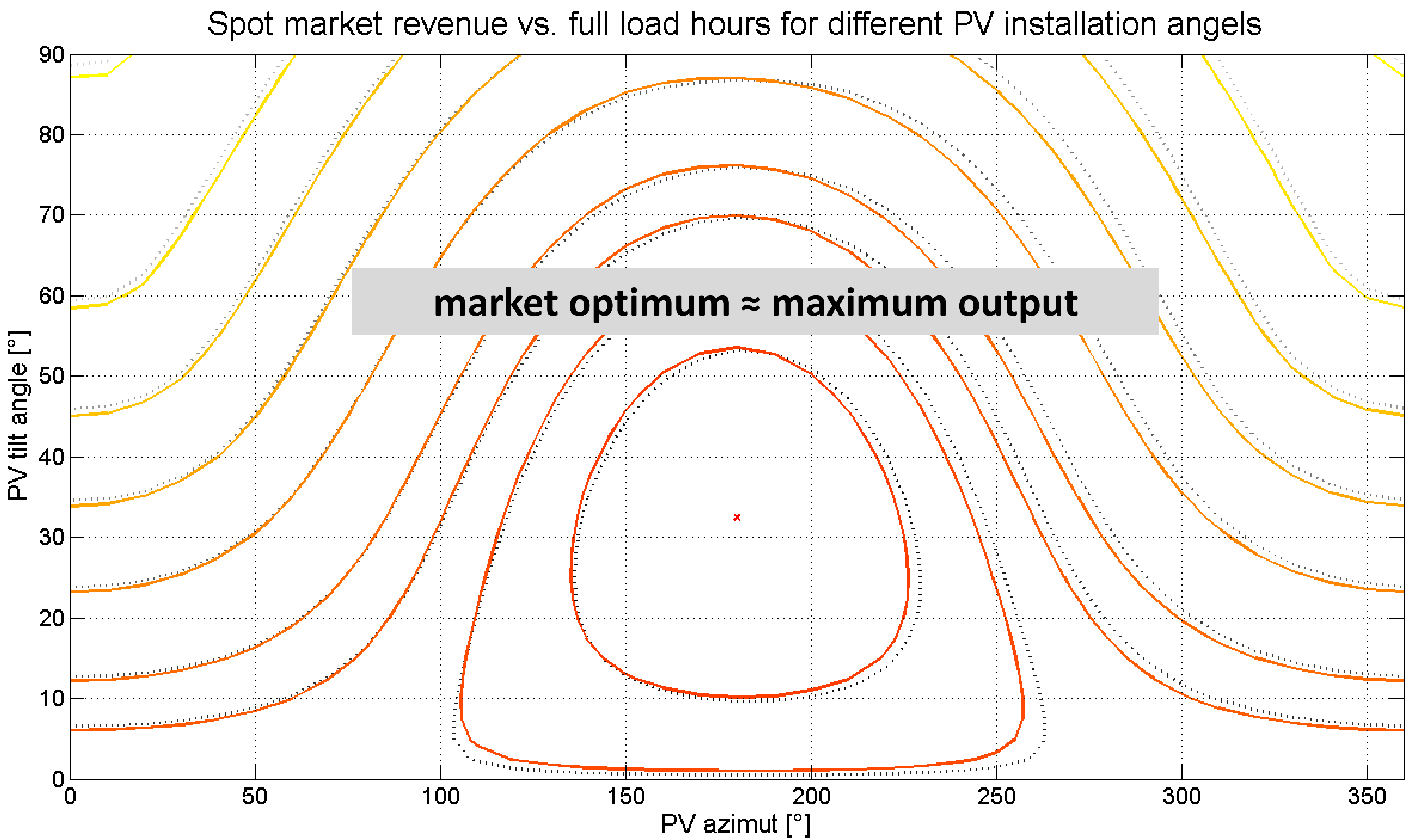
-Supply (cost) curve

-Demand situations/profile

-Installed PV/Res-capacity

-Storage

PV angles and market value status quo



Source: own calculations: for year 2012

PV angles and market value - future

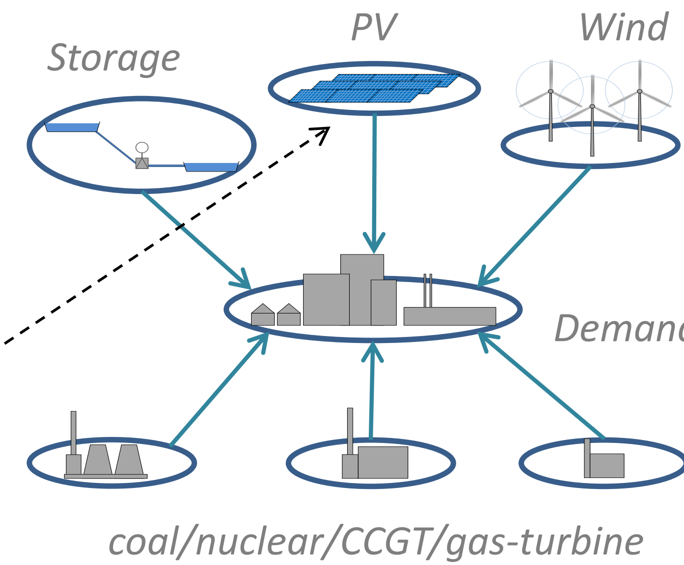
Optimal PV installation angles in a system with high share of PV? – e.g. up to 100 GW installed in Austria and Germany

PV angles and market value - future

Numerical model to estimate relevance for Austria and Germany:

PV-Profiles for 23 regions and different install. angles

hourly dispatch model - linear



Source: Kloess, TU Wien

$$\min C: \quad C = \sum_t \sum_j P_{j,t} \cdot c_j$$

s.t.

$$L_t \le \sum_j P_{j,t} + \mathrm{Res}_t + \sum_i PV\_profil_{i,t} \cdot cap\_pv_i$$

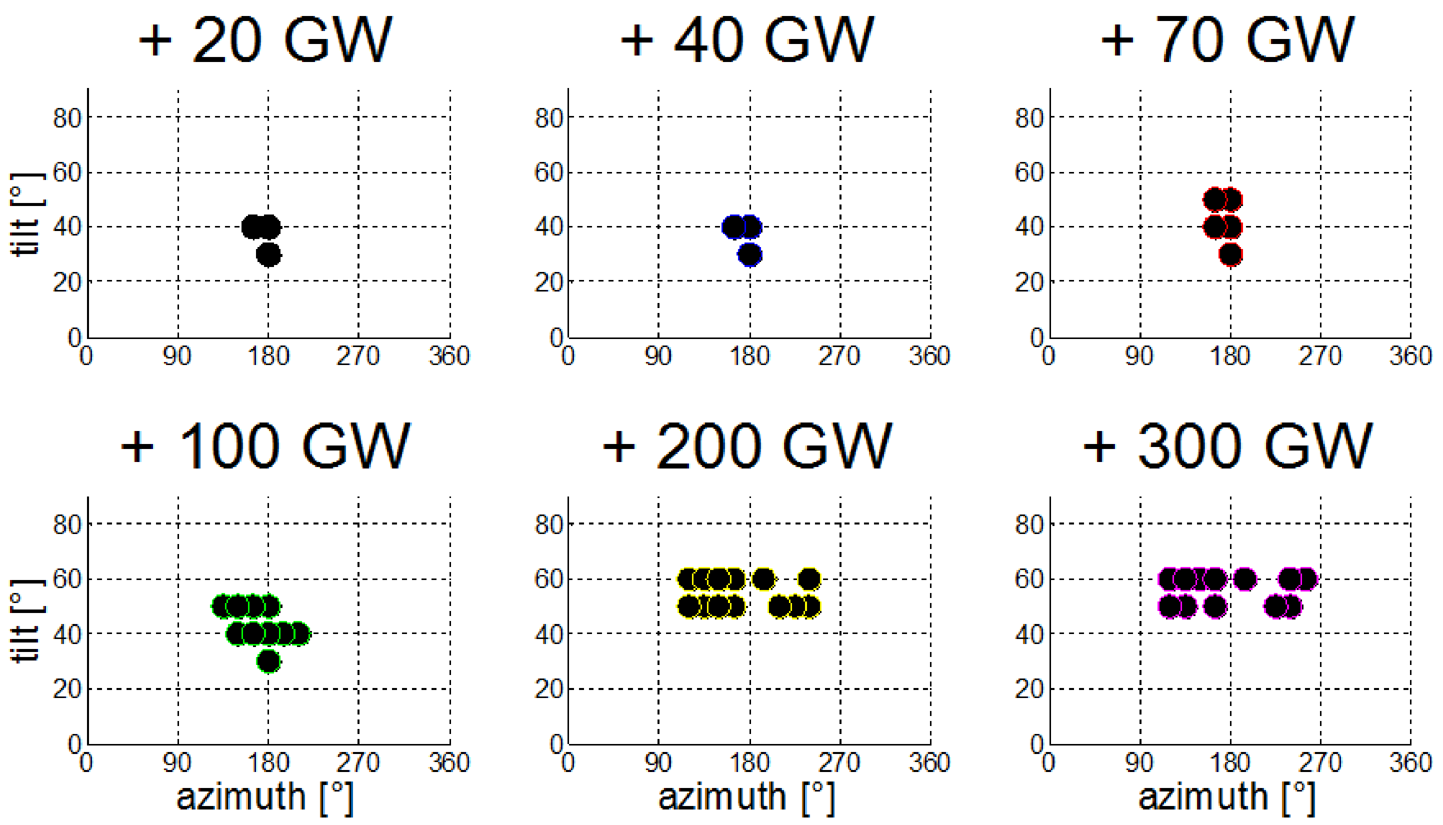
$$\sum_i cap\_pv_i \le cap\_pv\_\max_i$$

Model results: Market value maximizing PV angles

Region	+ 0 GW		+ 20 GW		+ 40 GW		+ 70 GW		+ 150 GW		+ 300 GW	
	Tilt	Azimuth	Tilt	Azimuth	Tilt	Azimuth	Tilt	Azimuth	Tilt	Azimuth	Tilt	Azimuth
1	40	180	40	180	40	180	40	180	50	225	60	255
2	30	180	30	180	30	180	30	180	50	240	60	255
3	40	180	40	165	40	165	40	165	50,50	120,135	50,60	120,255
4	40	180	40	165	40	165	40	165	50,50	120,135	60	120
5	40	180	40	180	40	180	40	180	50	225	60,60	240,255
6	40	180	40	180	40	180	40	180	50	225	60	240
7	40	180	40	165	40	165	40	165	50	135	50,50	135,240
8	40	180	40	165	40	165	40	165	50	135	60	120
9	30	180	40	180	40	180	40	180	50	225	60	255
10	40	180	40	180	40	180	40	180	50	225	60	240
11	30	180	40	180	40	165	40	180	50	150	50	135
12	30	180	30	180	30	180	30	180	50	225	60	255
13	30	180	30	180	30	180	30	180	50	225	50	240
14	30	180	30	180	30	180	30	180	50	135	50	120
15	30	180	30	180	30	180	40	180	50	225	60	240
16	30	180	30	180	40	180	40	180	50	210	50	225
17	40	180	40	180	40	180	40	180	50	165	50	165
18	40	180	40	180	40	180	40	180	50,50	150,165	60	150
19	30	180	40	165	40	165	40	165	50	150	60	135
20	40	180	40	180	40	180	40	180	50	180	60	195
21	40	180	40	180	40	180	50,50	165,180	60	165	60	165
22	40	180	40	180	40	180	50	165	60	165	60	165
23	40	180	40	165	40	165	40	165	50	150	60	135

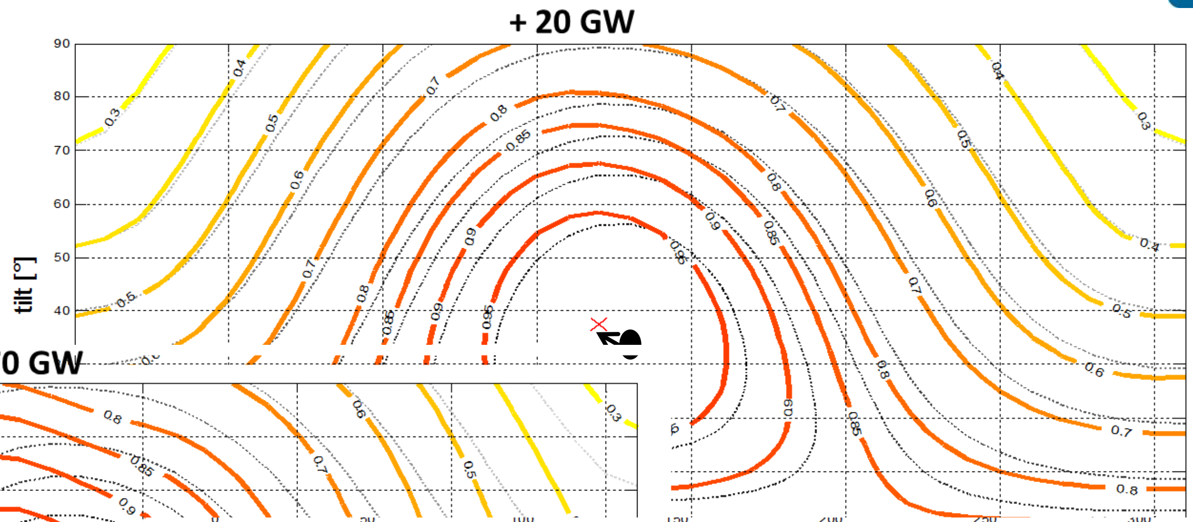
Model results

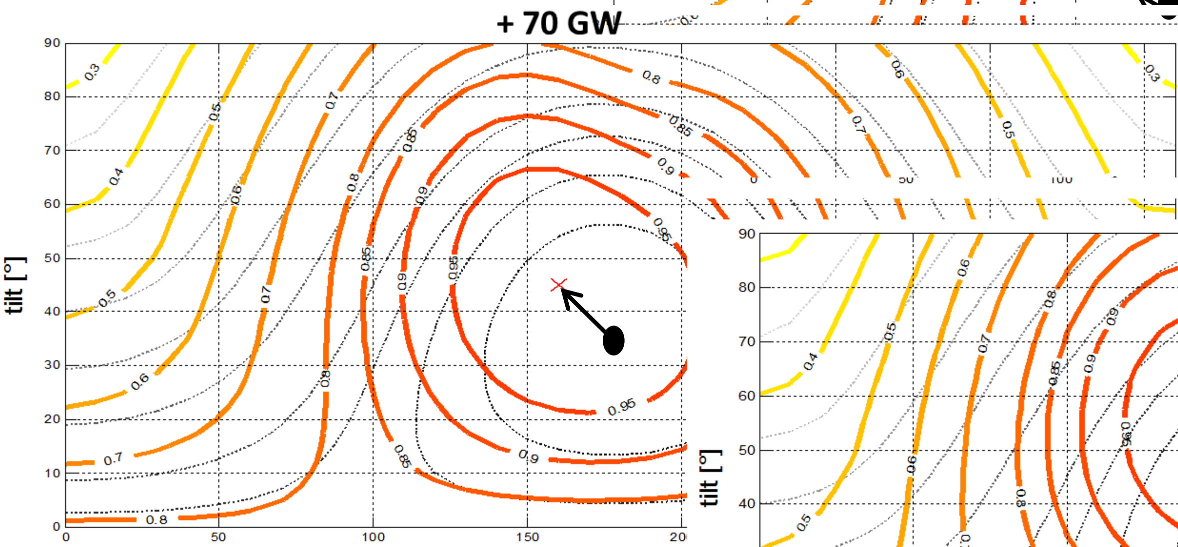
- For lower penetration levels (up to +40 GW compared to 2012 ≈ 70 GW in total) angle shifts towards east are observed but most sights stay at the energetic optimum
- for higher penetration levels the optimal angles start to deviate into all directions

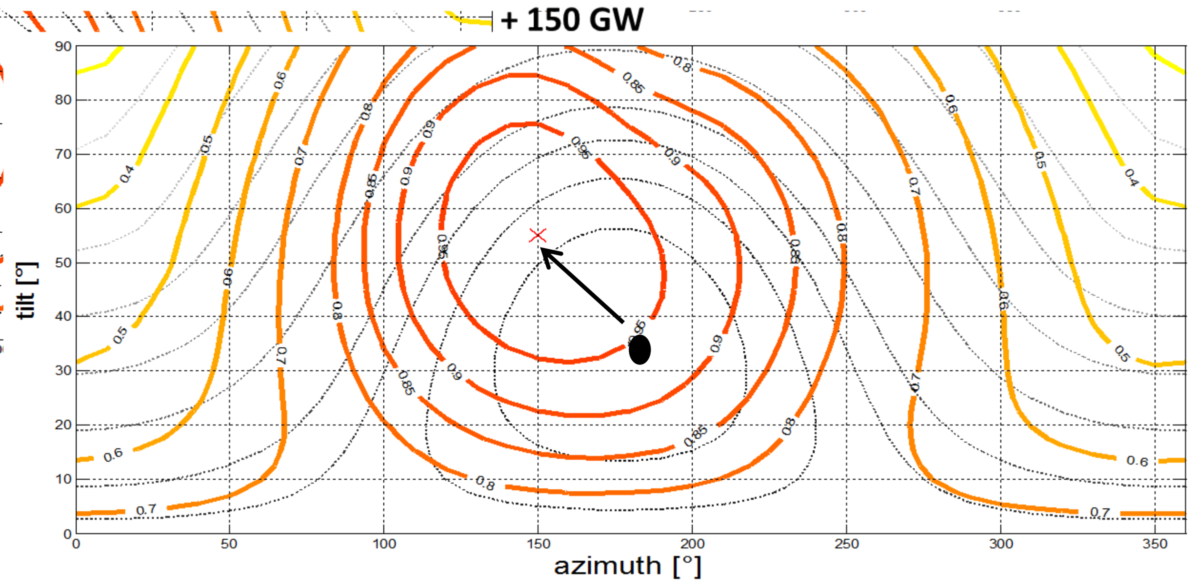


Model results

Results for a PV system in Vienna: 48,2° N, 16,3° E







Change in market values (per kWp) for market optimum vs. energetic optimum

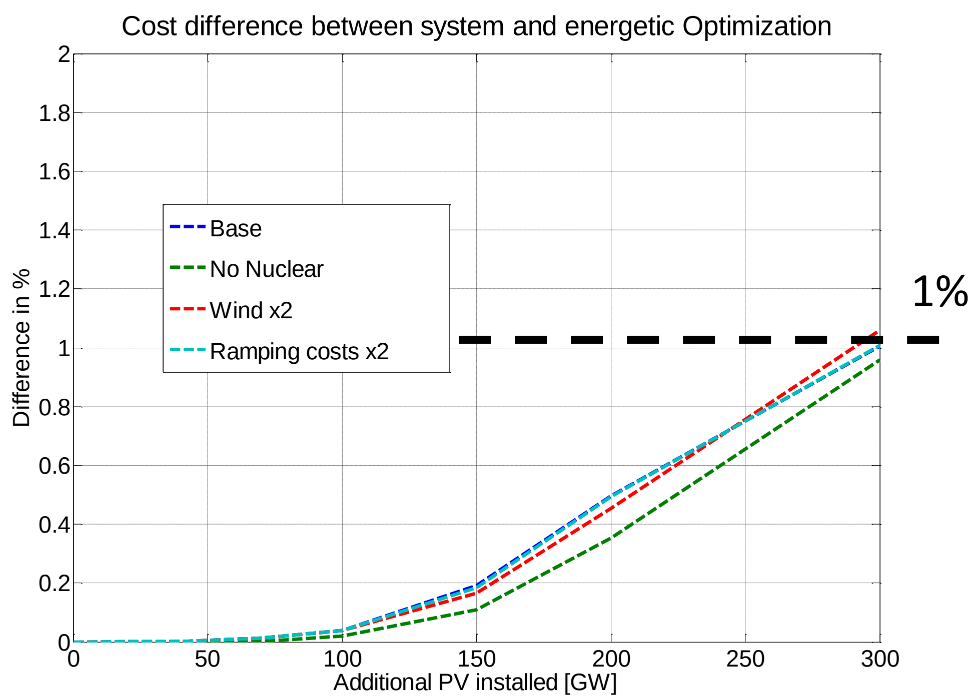
Region	+ 20 GW		+ 40 GW		+ 70 GW		+ 100 GW		+ 150 GW		+ 300 GW	
	Market value [€/kW]	change in Market value [%]	Market value [€/kW]	change in Market value [%]	Market value [€/kW]	change in Market value [%]	Market value [€/kW]	change in Market value [%]	Market value [€/kW]	change in Market value [%]	Market value [€/kW]	change in Market value [%]
1	34.8	0.0	25.9	0.0	13.9	0.0	8.4	1.0	4.9	4.7	1.6	20.3
2	33.5	0.0	24.7	0.0	12.9	0.0	7.5	0.0	4.1	2.3	1.2	16.6
3	35.0	0.1	25.9	0.2	13.6	0.3	7.9	0.4	4.4	3.5	1.2	11.6
4	37.5	0.0	28.0	0.3	14.8	0.6	8.7	1.4	4.9	5.6	1.5	17.8
5	36.2	0.0	27.0	0.0	14.7	0.0	9.0	0.3	5.1	1.7	1.6	12.8
6	36.8	0.0	27.4	0.0	14.7	0.0	8.7	0.0	4.8	0.9	1.4	8.1
7	36.9	0.0	27.4	0.1	14.5	0.0	8.5	0.1	4.7	0.9	1.3	6.0
8	38.0	0.0	28.4	0.2	15.1	0.5	8.9	1.2	5.0	5.1	1.5	15.2
9	36.7	0.1	27.3	0.2	14.9	0.4	9.1	1.2	5.2	4.1	1.6	19.6
10	37.5	0.0	27.9	0.0	15.0	0.0	8.9	0.0	4.9	0.9	1.5	7.0
11	37.8	0.1	28.1	0.2	15.0	0.3	8.7	0.5	4.8	1.4	1.4	6.3
12	38.8	0.0	29.0	0.0	15.7	0.0	9.5	0.6	5.5	3.8	1.7	17.9
13	38.7	0.0	28.8	0.0	15.3	0.0	8.9	0.0	4.9	1.5	1.4	10.2
14	39.0	0.0	28.9	0.0	15.2	0.0	8.8	0.0	4.8	1.2	1.4	6.9
15	42.5	0.0	32.2	0.0	18.1	0.3	11.3	1.3	6.7	3.5	2.2	15.0
16	42.8	0.0	32.4	0.1	17.9	0.4	11.0	0.9	6.4	1.9	2.0	8.3
17	43.3	0.0	32.8	0.0	18.2	0.0	11.2	0.0	6.6	0.1	2.1	1.9
18	44.6	0.0	33.9	0.0	19.3	0.0	12.2	0.1	7.3	1.5	2.4	6.1
19	41.6	0.2	31.7	0.7	18.0	[illegible]	[illegible]	[illegible]	[illegible]	7.6	2.6	18.0
20	47.6	0.0	37.2	0.0	22.5	[illegible]	[illegible]	[illegible]	[illegible]	1.5	3.4	5.1
21	48.8	0.0	38.2	0.0	23.4	[illegible]	[illegible]	[illegible]	[illegible]	2.2	3.7	5.6
[illegible]	[illegible]	[illegible]	[illegible]	0.0	22.5	[illegible]	[illegible]	[illegible]	[illegible]	3.1	3.6	7.2
[illegible]	[illegible]	[illegible]	[illegible]	0.4	21.3	[illegible]	[illegible]	[illegible]	[illegible]	5.0	3.3	12.1

Nur geringer Effekt selbst bei +40 GW im Vergleich zu 2012

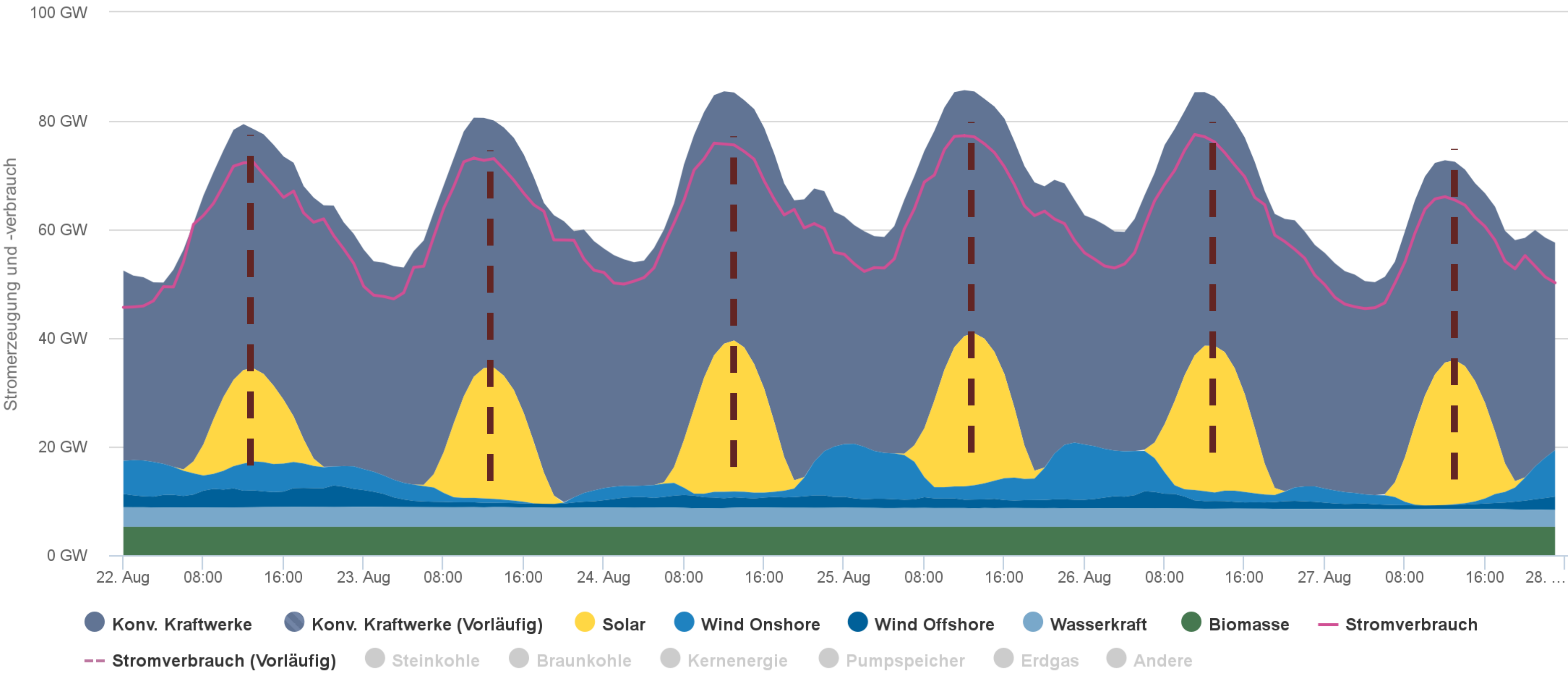
Bei sehr hohen PV Anteil werden die Unterschiede größer, allerdings bei sehr geringen Marktwerten

Model results

- Although the model suggests that adjustments can increase the market value, the **effect is very low** at least for total installed PV capacities of less than 100 GW in Austria and Germany
- Improvements of revenues for PV systems with adjusted installation angles are **below 0.7%** even if the installed capacity in Austria and Germany doubles
- Even for extremely high PV shares the differences in total system costs are below 1%



Explanations for low impact of angle adjustments

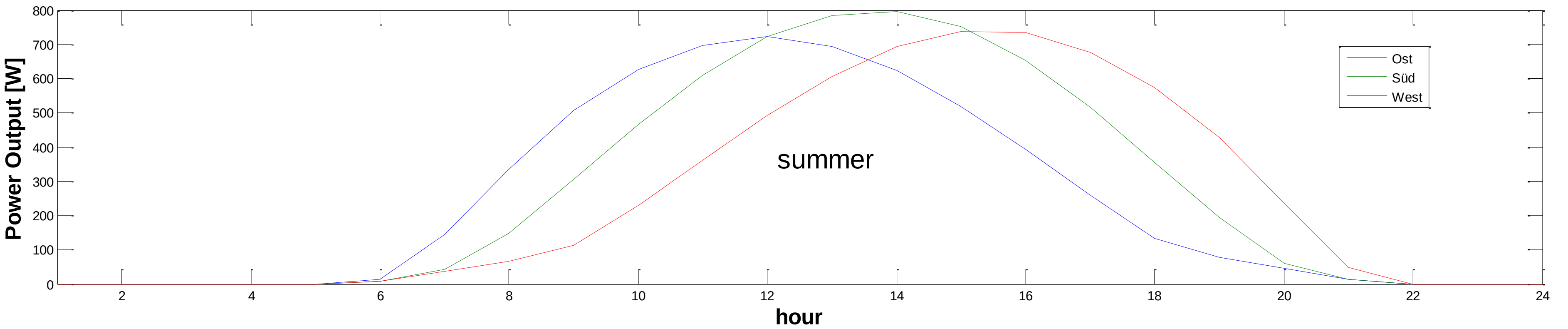


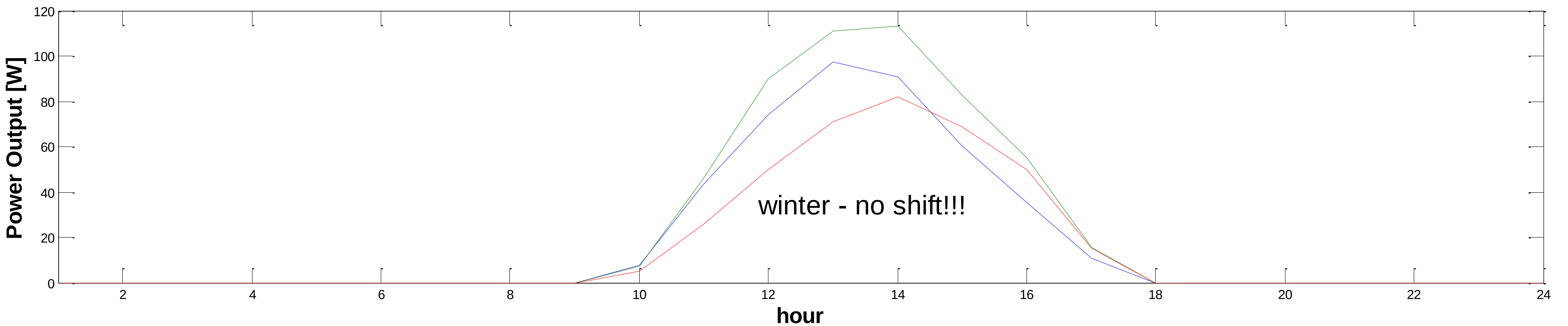
Source: Agora Energiewende - https://www.agora-energiewende.de/de/themen/-agothem-/Produkt/produkt/76/Agorameter/

Agora Energiewende; Stand: 29.

There is an almost perfect match between demand peaks and PV feed in and there is still space to decrease residual demand in those times – Only if PV regularly exceeds those peaks around noon adjustments of angles make sense

Explanations for low impact of angle adjustments

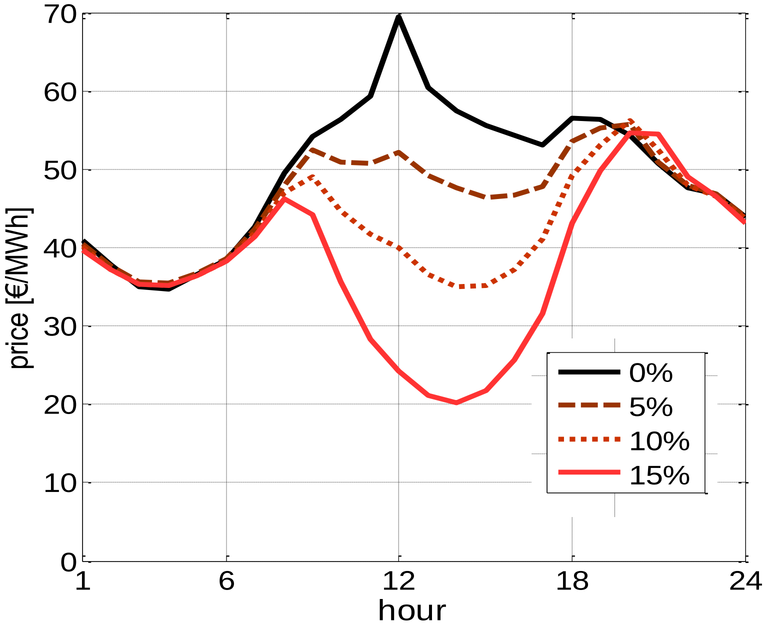




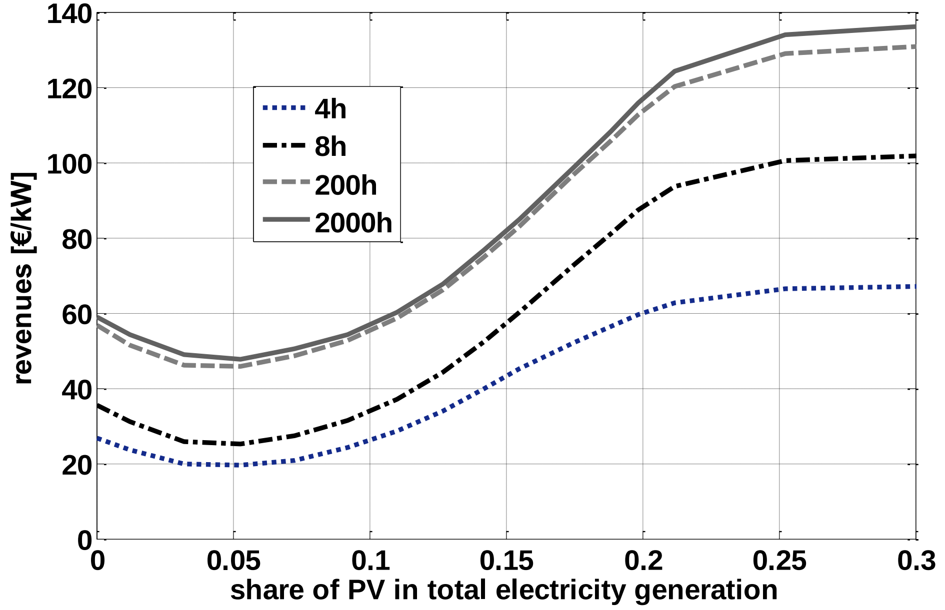
- Production shifts are not happening throughout the year for PV systems without tracking
- Shifts of azimuth angles without adjustments of tilt angles lead to significant shifts in summer, but would have almost no effect in winter when the sun is low and the share of diffuse radiation is higher
- losses around noon in winter month which are peak price hours are significant

Additional insights:

Average prices for each hour



Effects storage revenues



- As expected the market value of PV drops significantly – below 50% of initial value for PV shares >15% of total generation
- Revenues of storage systems decrease for low shares and are only positively affected for PV shares >10%
- Marginal emission reductions (not shown here) also decrease but are slightly less affected as PV starts to cut into coal and lignite

Conclusions

- Model results show that in the near future the maximum output in terms of full load hours still provides a sensible benchmark for optimal PV installation angles
- With very high shares (>100 GW) the optimum deviates significantly from the energetic optimum but the effect on total system costs are still small.
- Direct marketing or feed-in-premium would provide the right incentives for investors – but not relevant at current PV penetration levels (depends on desired PV share)
- Significant drops in market values are very likely with increasing shares of PV affecting the competiveness of PV on wholesale electricity markets
- Race between cost decreases and market values (including CO_2 prices)

Thanks for your attention!

Link to paper on science direct:

http://www.sciencedirect.com/science/article/pii/S0306261915010338

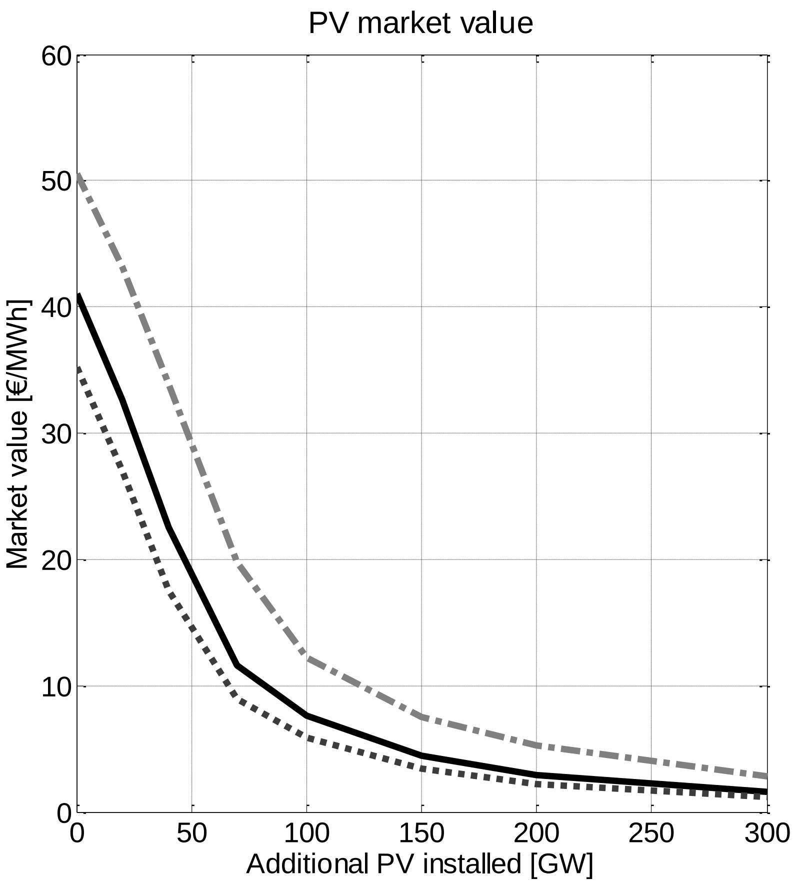
Contact:
Michael Hartner
hartner@eeg.tuwien.ac.at

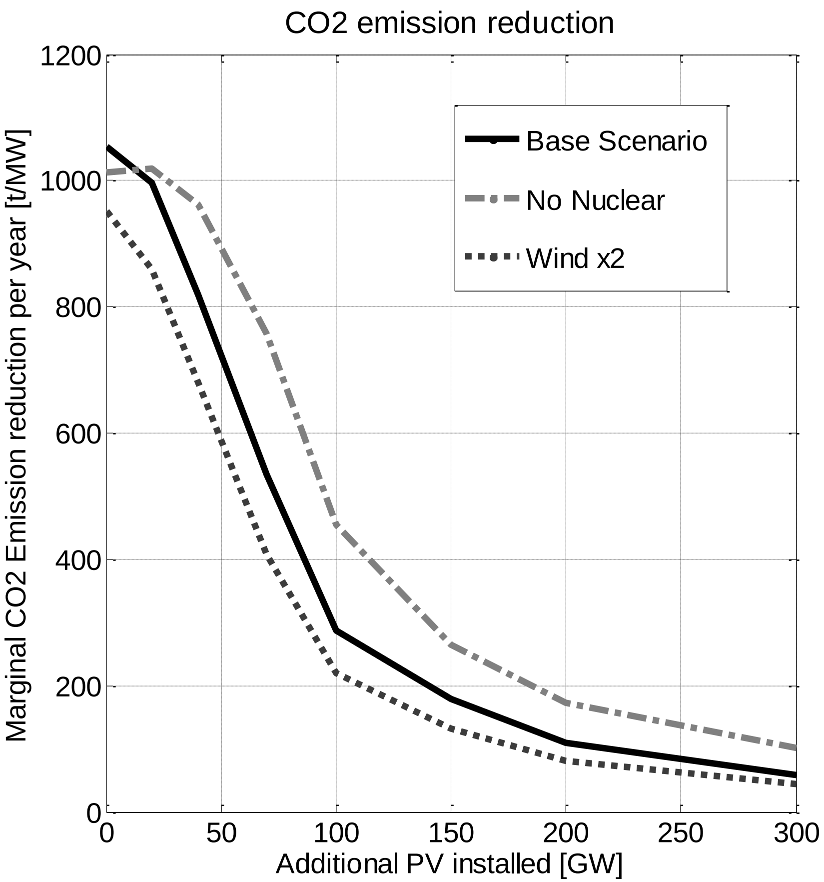
Vienna University of Technology
Institute of Energy Systems and Electrical Drives
Energy Economics Group – EEG
Tel: +43(0)-1-58801-370379
Web: http://eeg.tuwien.ac.at/

Additional insights:

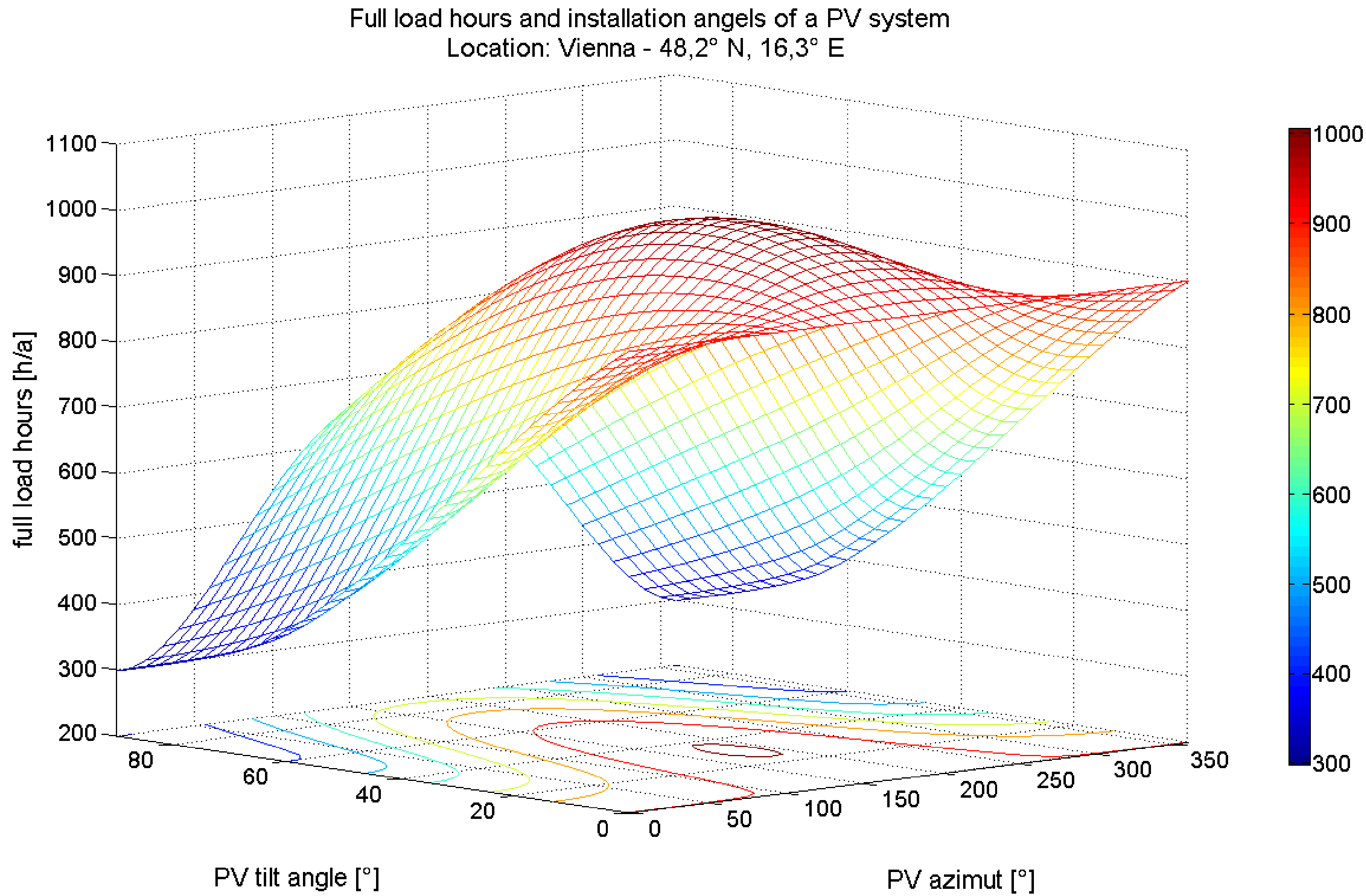
Market value drops to very low levels – no competitiveness in energy only markets?

Marginal emission reductions are rather constant until up to 100 GW because PV starts to cut into coal

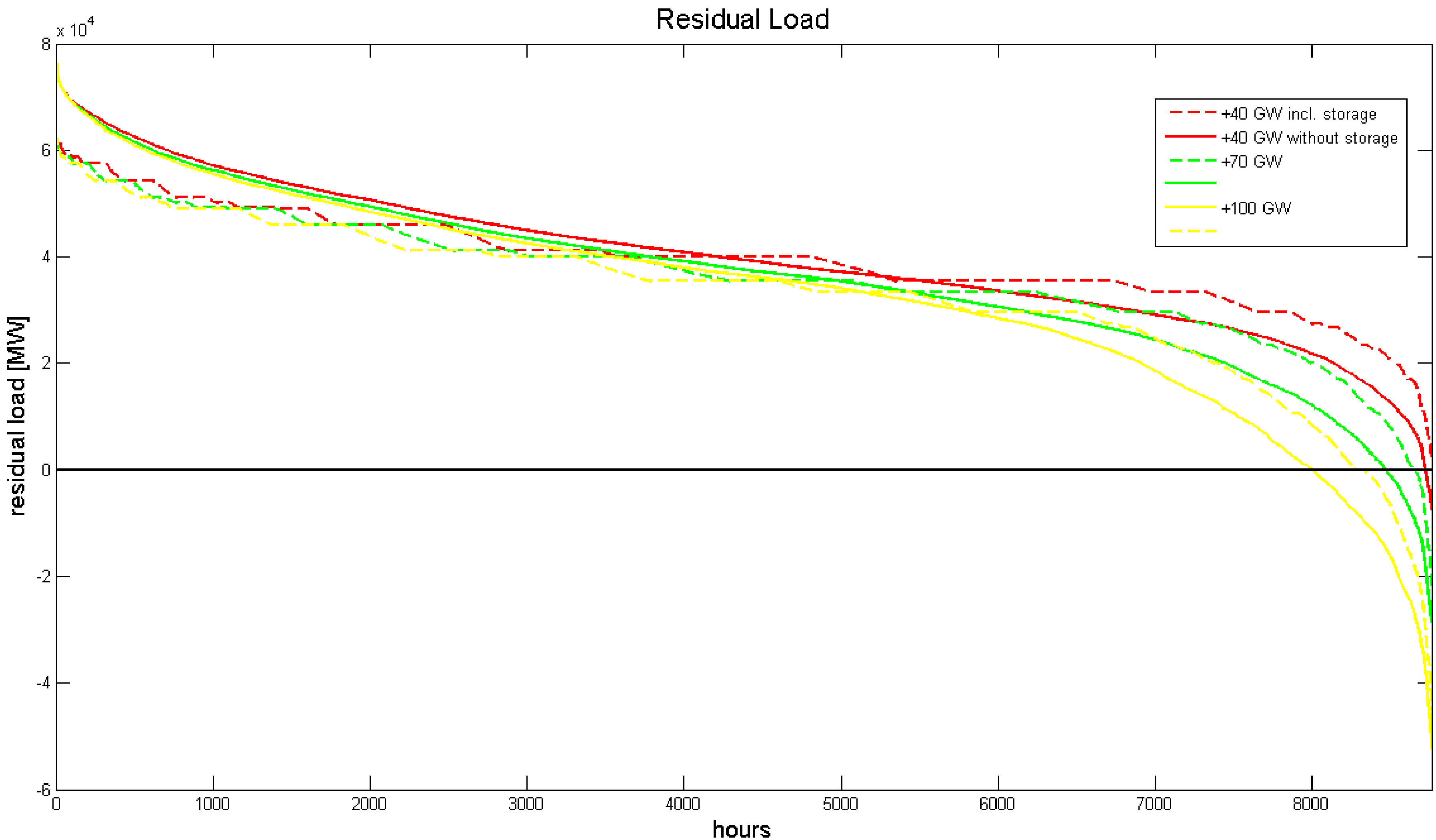


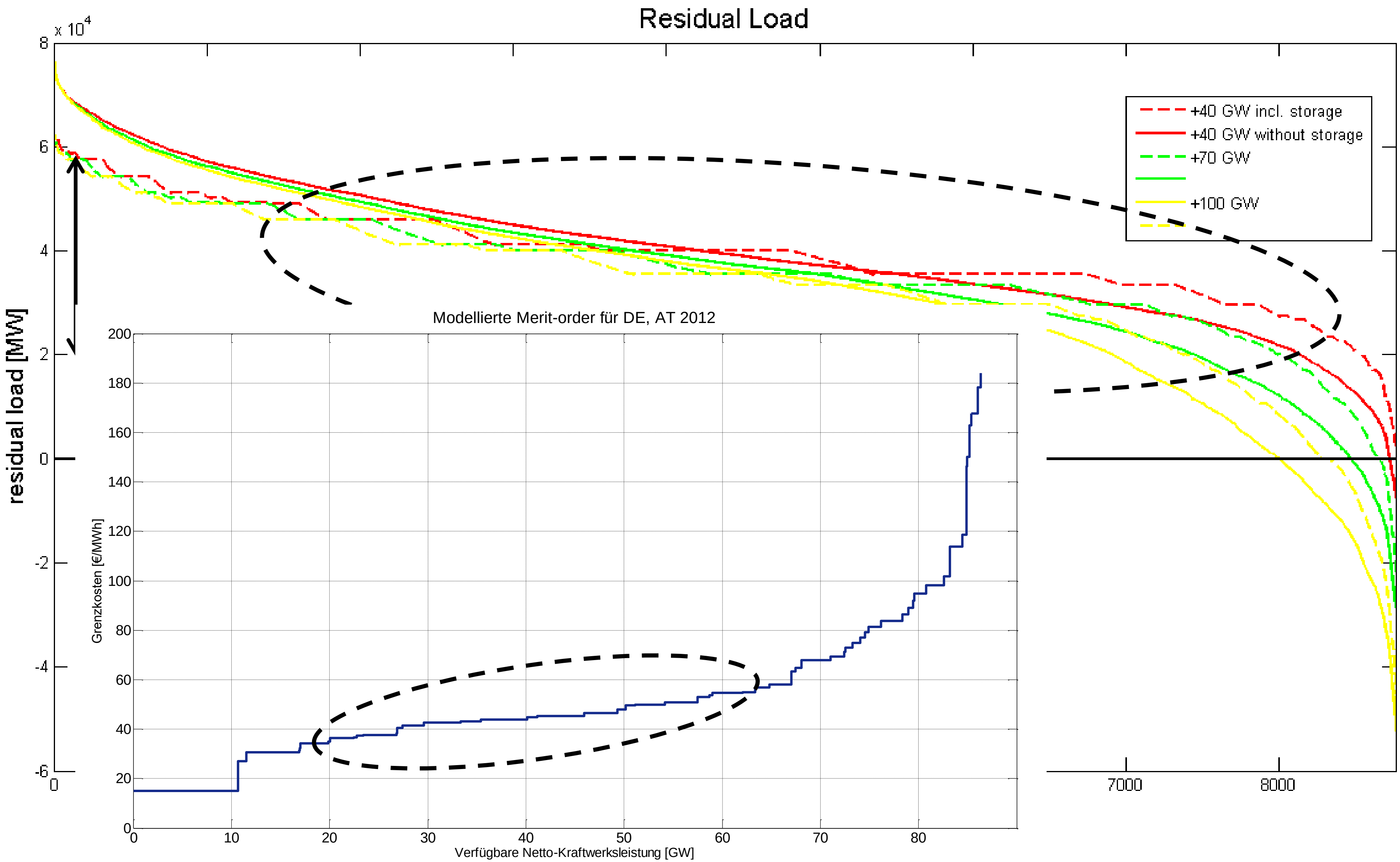


PV – maximum output

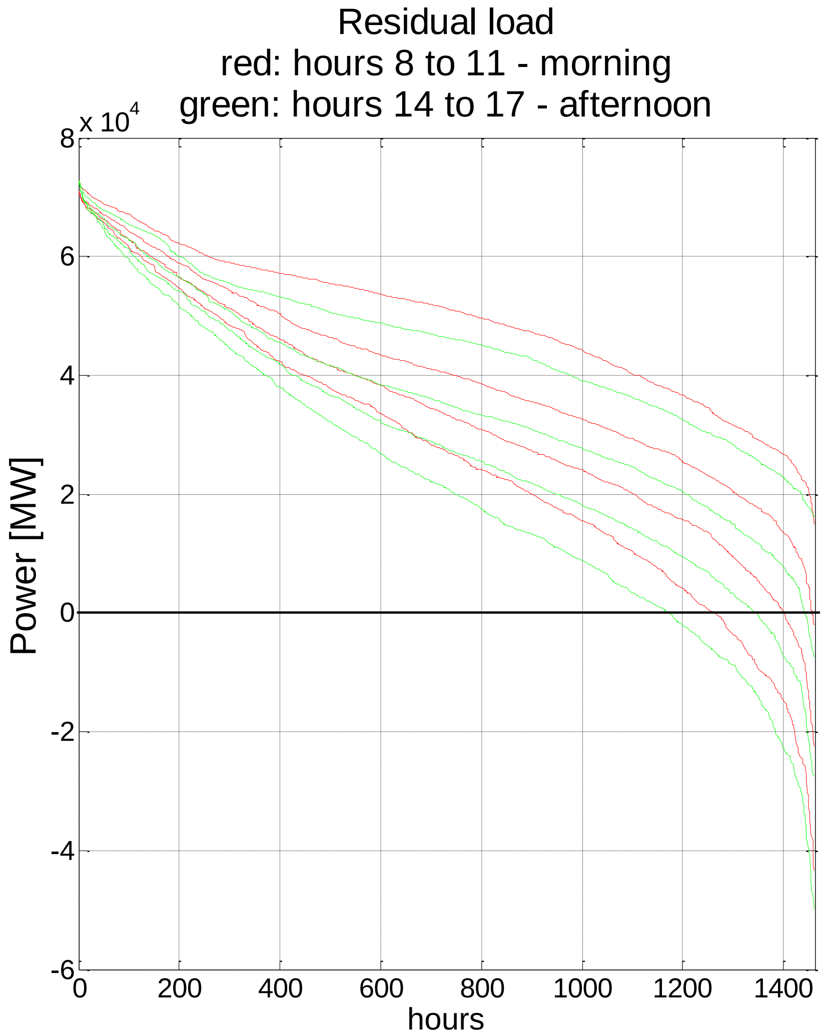


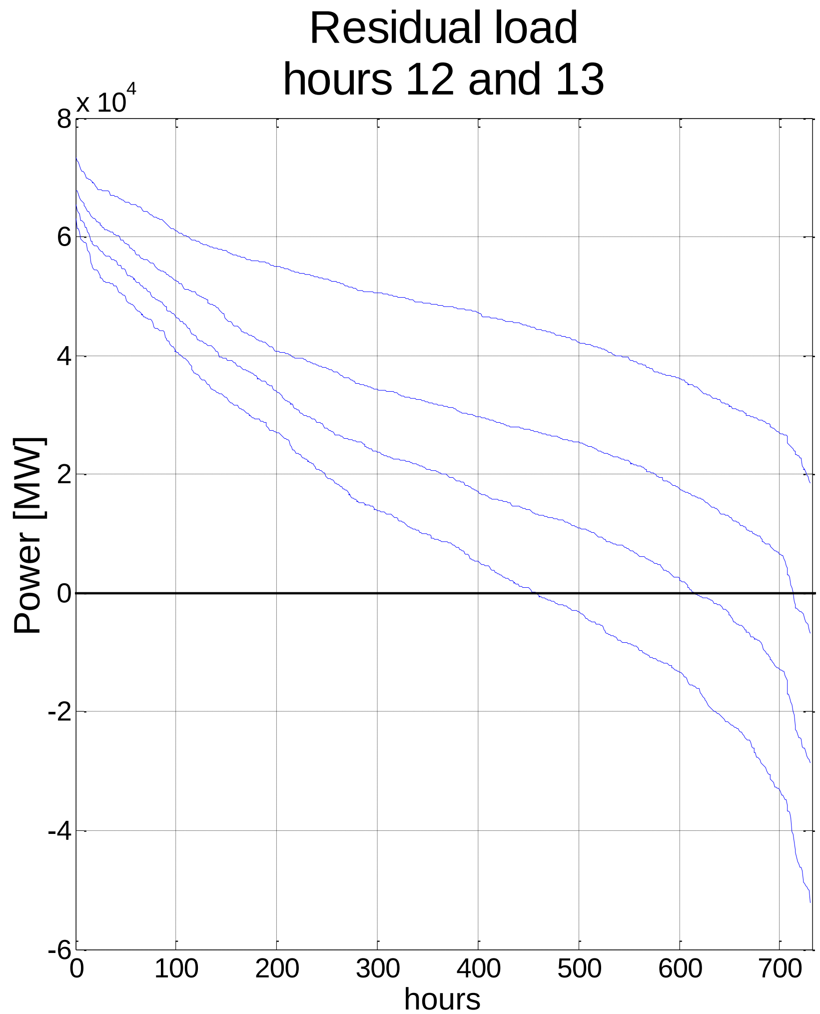
Source: own calculations based on data from: http://www.soda-is.org


Residual Load
x 10^4
8
6
4
2
0
-2
-4
-6
residual load [MW]
0
1000
2000
3000
4000
5000
6000
7000
8000
hours
+40 GW incl. storage
+40 GW without storage
+70 GW
+100 GW

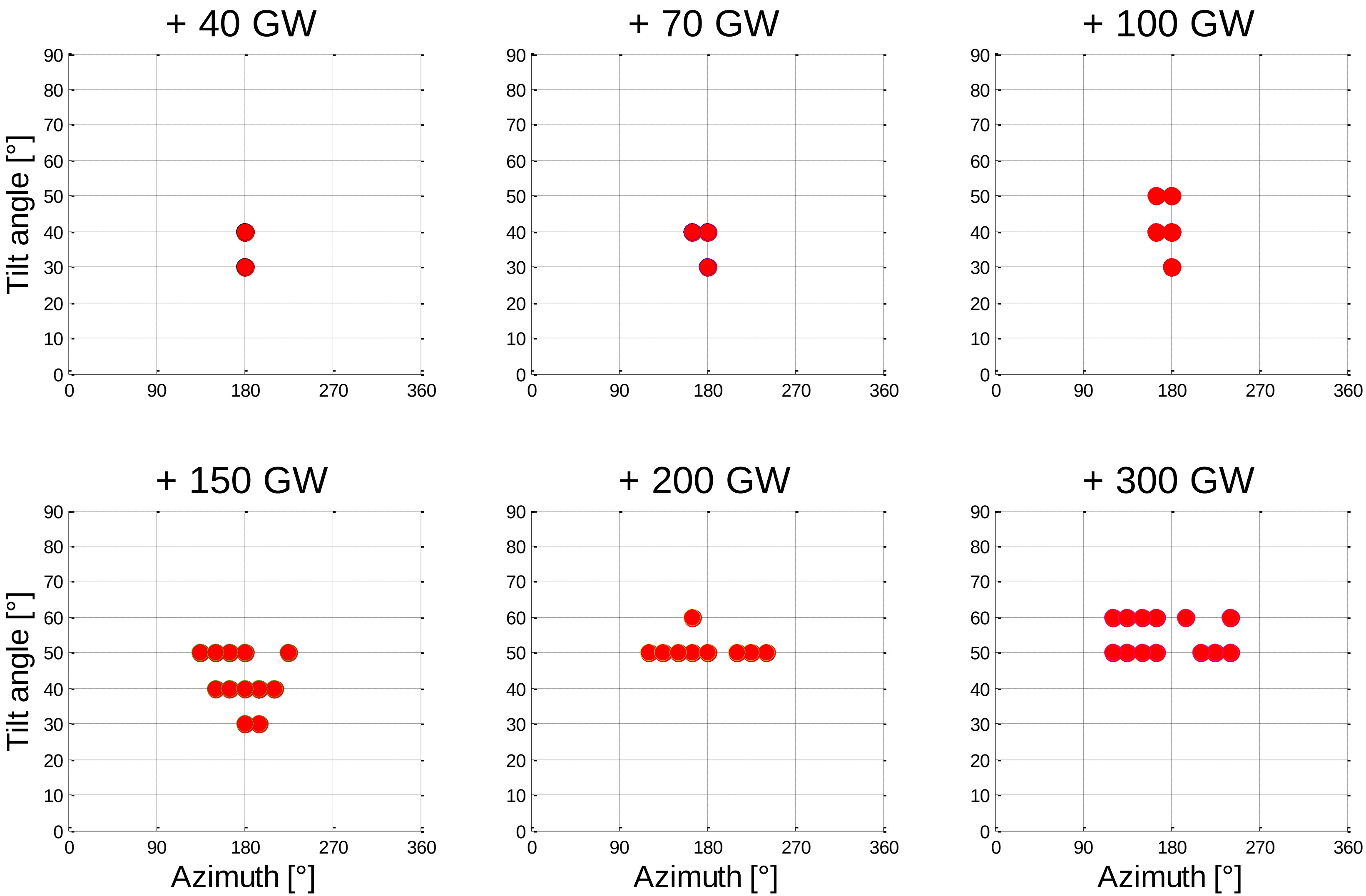

Residual Load
x 10^4
8
6
4
2
0
-2
-4
-6
residual load [MW]
+40 GW incl. storage
+40 GW without storage
+70 GW
+100 GW
7000
8000
Modellierte Merit-order für DE, AT 2012
Grenzkosten [€/MWh]
Verfügbare Netto-Kraftwerksleistung [GW]
200
180
160
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80

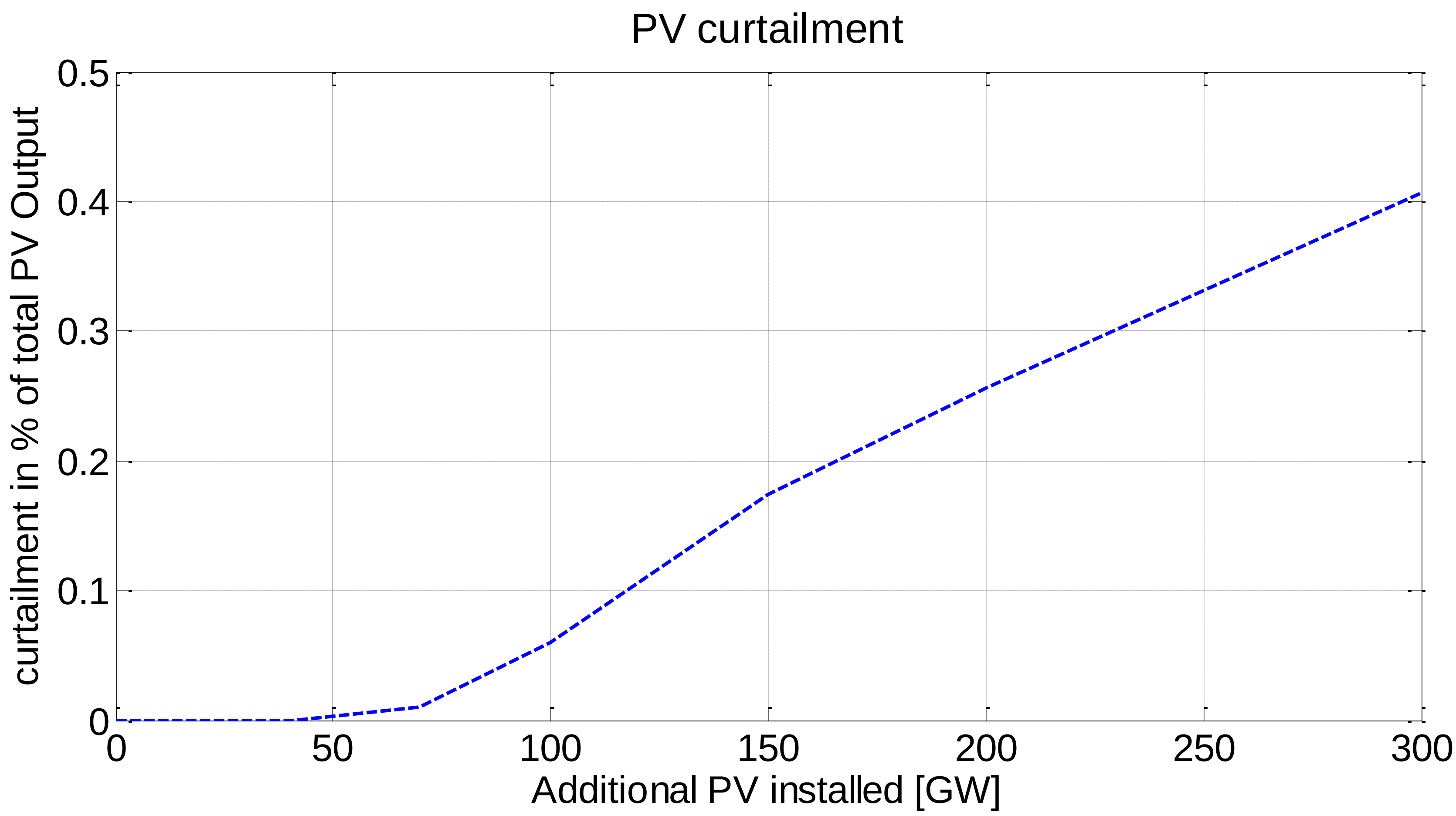
Residual load in different times of the day

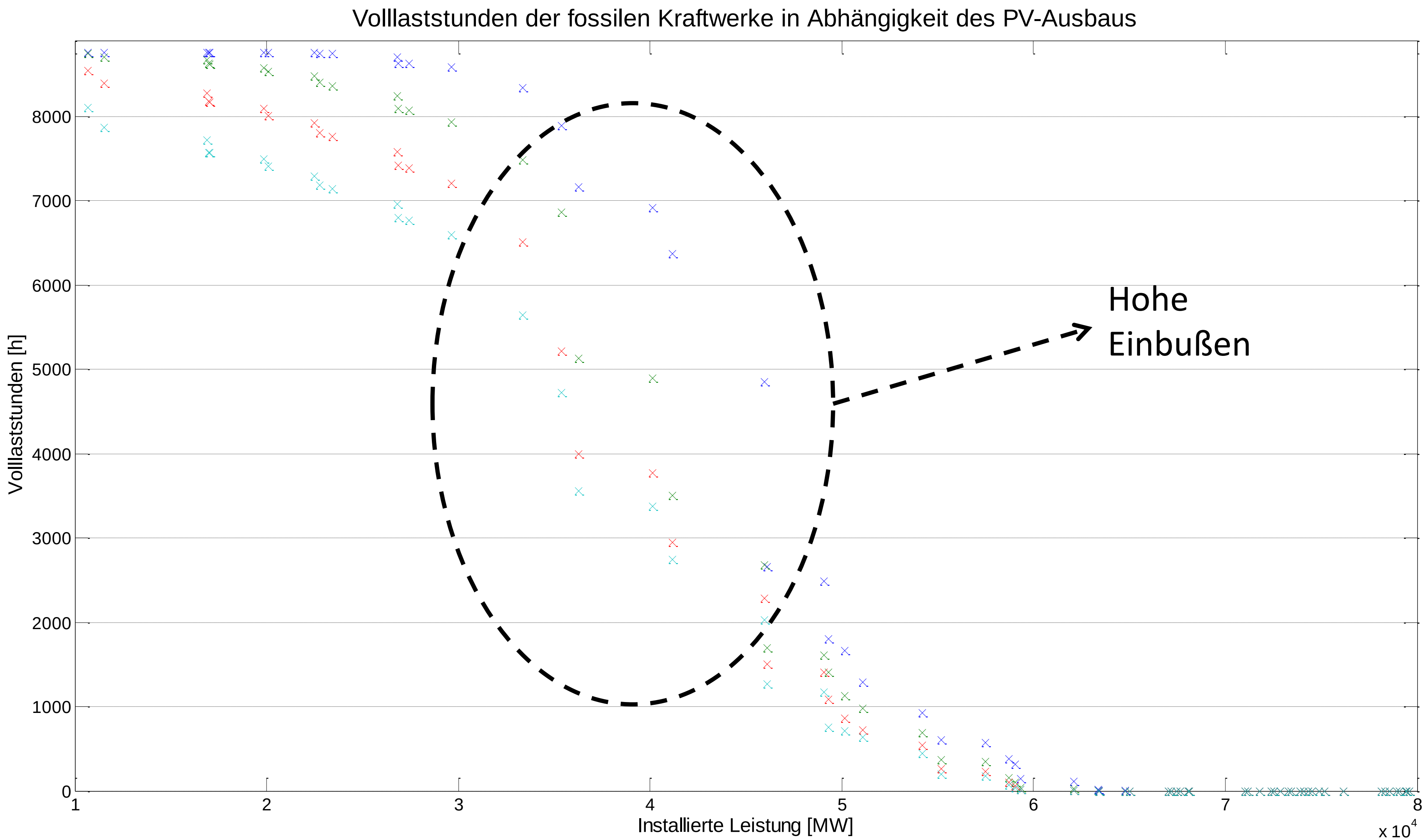




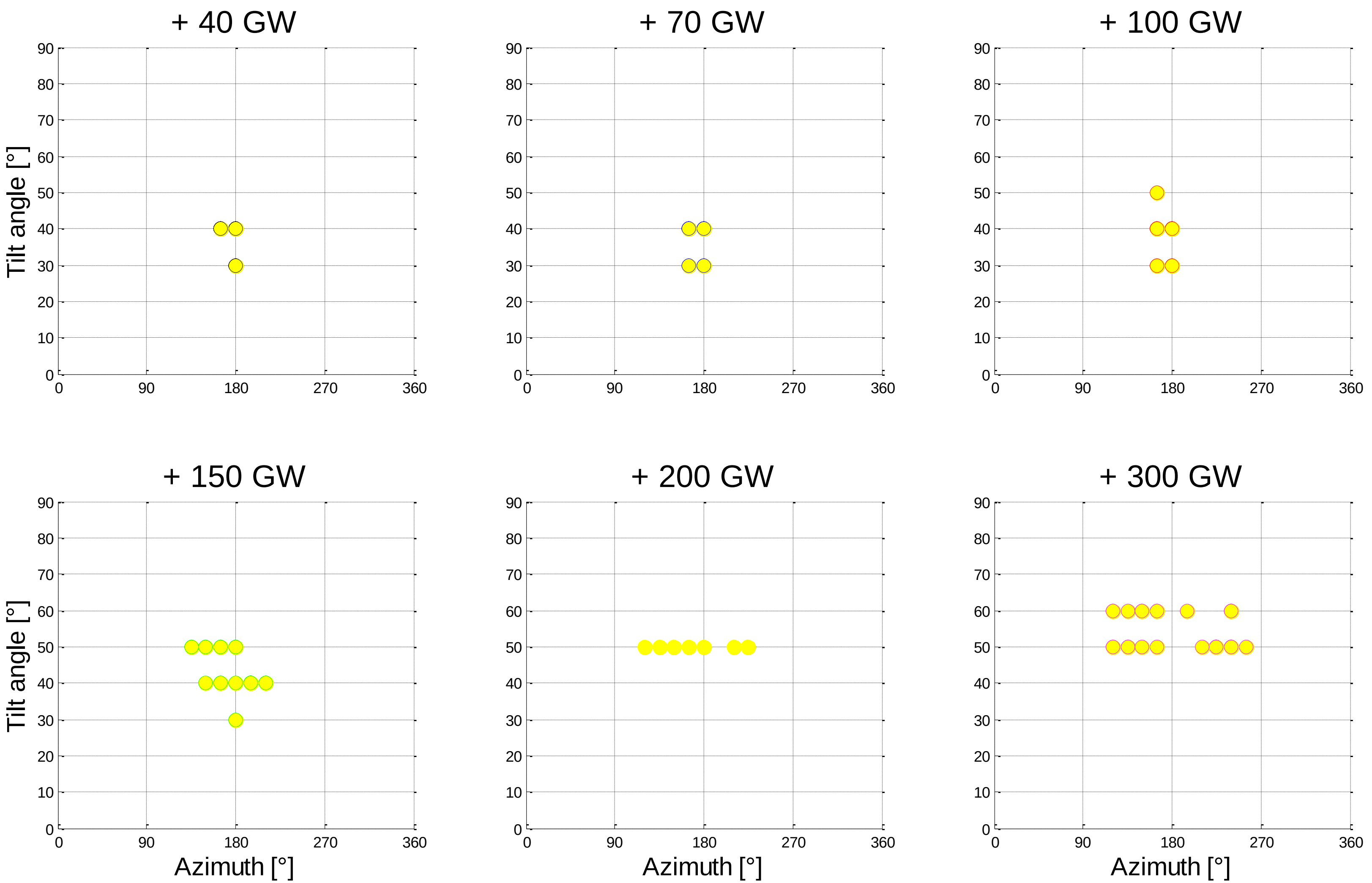
Ramp Scenario



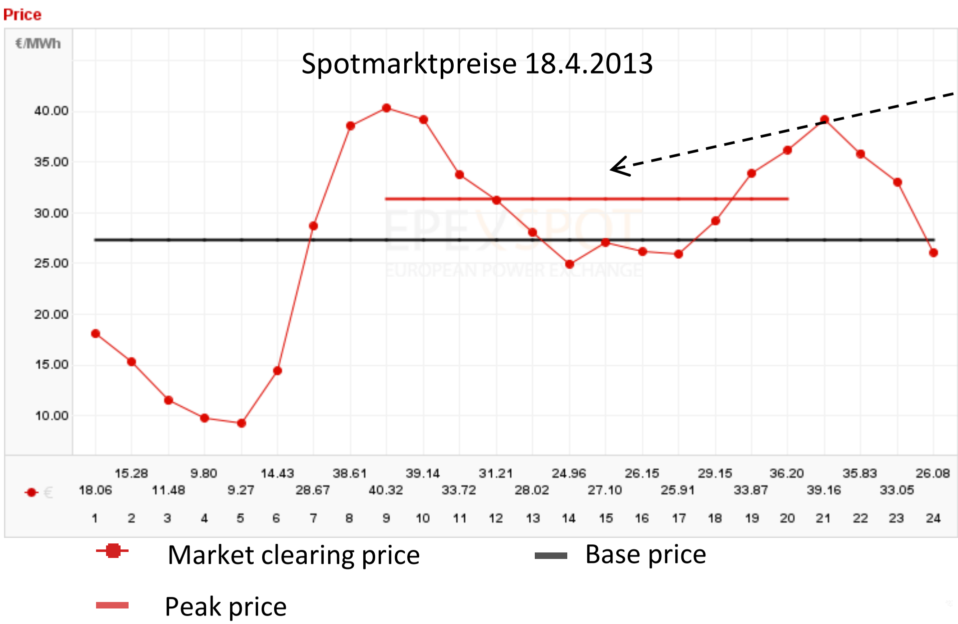

PV curtailment
0.5
0.4
0.3
0.2
0.1
0
curtailment in % of total PV Output
0
50
100
150
200
250
300
Additional PV installed [GW]


Volllaststunden der fossilen Kraftwerke in Abhängigkeit des PV-Ausbaus
Volllaststunden [h]
0
1000
2000
3000
4000
5000
6000
7000
8000
1
2
3
4
5
6
7
8
Installierte Leistung [MW]
x 10^4
Hohe
Einbußen

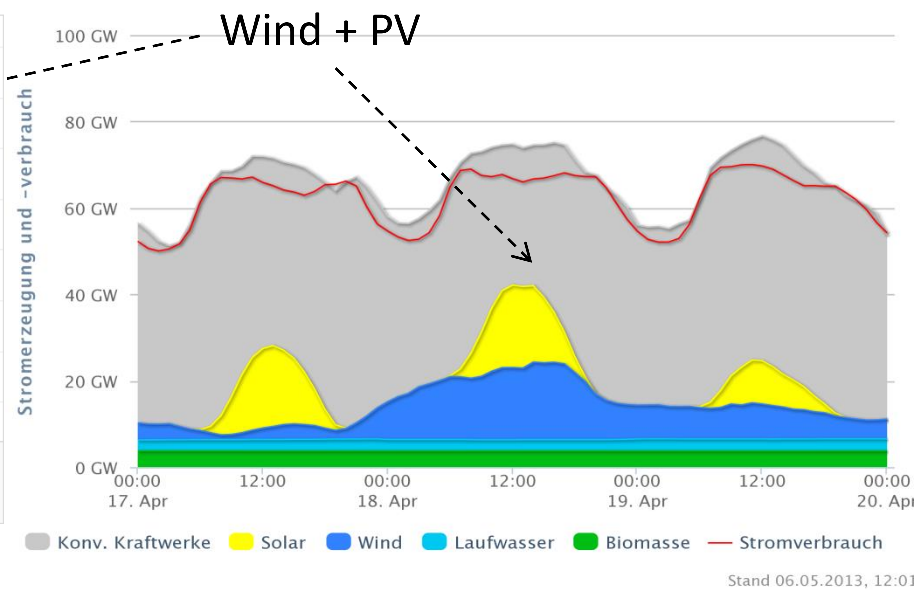
Wind Scenario double



PV angles and market value status quo

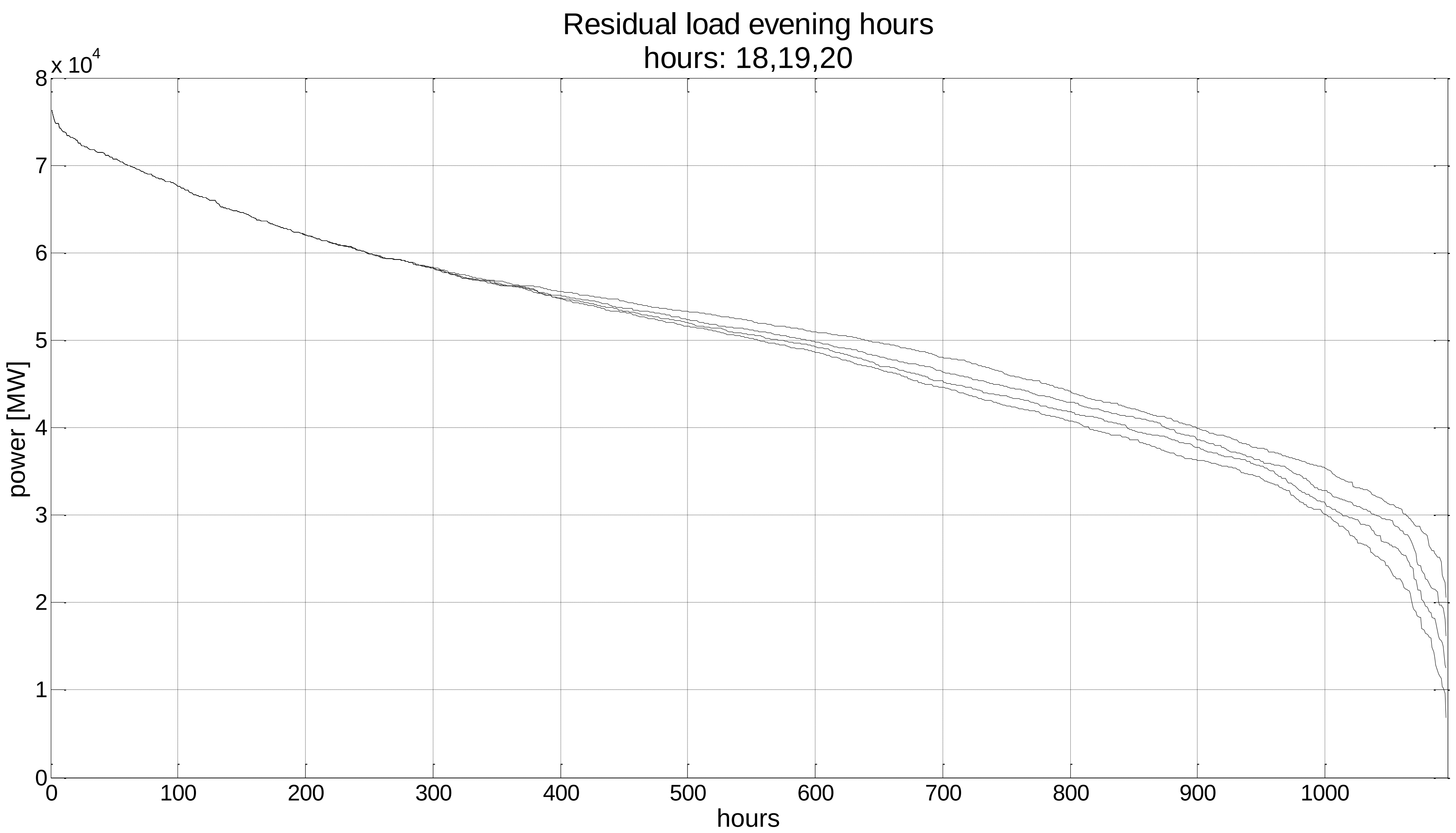


Source: www.eex.com



Source: http://www.agora-energiewende.de/service/aktuelle-stromdaten

Residual load - evening



Preliminary results for additional 70GW