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

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Research question and scope

- Does the market optimum deviate significantly 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 (azimuth)**

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PV system or market value

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

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

Important factors:
- Supply (cost) curve
- Demand situations/profile
- Installed PV/Res-capacity
- Storage

$e_1^* + e_2^* < e_1 + e_2$ 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
PV angles and market value status quo

Spot market revenue vs. full load hours for different PV installation angels

market optimum ≈ maximum output

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

Source: Kloess, TU Wien

\[
\begin{align*}
\min C & : C = \sum_{i} \sum_{j} P_{j,i} \cdot c_{j} \\
\text{s.t.} & : L_{t} \leq \sum_{j} P_{j,i} + Re_{s_{t}} + \sum_{i} PV_{- profil_{i,t}} \cdot cap_{- pv_{i}} \\
& : \sum_{i} cap_{- pv_{i}} \leq cap_{- pv_{max}}
\end{align*}
\]
Model results: Market value maximizing PV angles

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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

**Vienna University of Technology, EEG**

### Market value [€/kW] change in Market value [%]

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**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

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 competitiveness of PV on wholesale electricity markets.

- Race between cost decreases and market values (including CO₂ prices).
Thanks for your attention!

Link to paper on science direct:

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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

Full load hours and installation angels of a PV system
Location: Vienna - 48.2° N, 16.3° E

Source: own calculations based on data from:
http://www.soda-is.org
Modellierte Merit-order für DE, AT 2012

Verfügbare Netto-Kraftwerksleistung [GW]

Grenzkosten [€/MWh]

Residual Load

residual load [MW]

Verfügbarer Kraftwerkseinsatz [MW]
Residual load in different times of the day

Residual load
- red: hours 8 to 11 - morning
- green: hours 14 to 17 - afternoon

Residual load
- hours 12 and 13

Power [MW]

hours
Ramp Scenario

+ 40 GW

+ 70 GW

+ 100 GW

+ 150 GW

+ 200 GW

+ 300 GW
The graph shows the relationship between additional PV installed (in GW) and PV curtailment in % of total PV output. The curtailment increases linearly with the additional PV installed, indicating a direct proportionality between the two variables.
Volllaststunden der fossilen Kraftwerke in Abhängigkeit des PV-Ausbaus

Installierte Leistung [MW]
Volllaststunden [h]

Hohe Einbußen
Wind Scenario double

+ 40 GW

+ 70 GW

+ 100 GW

+ 150 GW

+ 200 GW

+ 300 GW
PV angles and market value status quo

Source: www.eex.com

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

Residual load evening hours
hours: 18, 19, 20

power [MW]

0 \times 10^4
0
1
2
3
4
5
6
7
8

hours

0
100
200
300
400
500
600
700
800
900
1000

30.09.2016
Vienna University of Technology, EEG
Preliminary results for additional 70GW

Spot market revenue vs. full load hours for different PV installation angles: model output + 70GW