Local and regional PV power forecasting based on PV measurements, satellite data and numerical weather predictions

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Outline

- background: grid integration of PV power in Germany
- overview on PV power prediction system
- evaluation:
  - different data and models for different forecast horizons
  - combination of different models
- summary and outlook
Contribution of photovoltaic (PV) systems to electricity supply in Germany

- installed PV power (end 2015): 39.5 GW_{peak}
- up to 50% of electricity demand from PV
Contribution of photovoltaic (PV) systems to electricity supply in Germany

- installed PV power (end 2015): \(39.5 \text{ GW}_{\text{peak}}\)
- up to 50\% of electricity demand from PV
- strong variability of solar power
Grid integration of PV Power: marketing at the European Energy Exchange

- by Transmission System Operators
  - regional forecasts
- direct marketing
  - local forecasts
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- by Transmission System Operators
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  - local forecasts
- forecast horizons

Diagram:
- Forward market
- Day-ahead market
- Intraday market
- historic data
- Day-ahead forecast
- Intraday forecast
- physical balancing
- horizontal load balancing
- actual feed-in
- t
  - 12am previous day
  - 45 minutes before
  - time of delivery
Grid integration of PV Power: marketing at the European Energy Exchange

- by Transmission System Operators
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- forecast horizons
  - forecast errors
  - high price
  - need for balancing power

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- Day-ahead-market
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Grid integration of PV Power: marketing at the European Energy Exchange

- by Transmission System Operators
  - regional forecasts
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  - local forecasts

- forecast horizons
  - need for forecast errors: high price, balancing power

Accurate solar power forecasts important for cost efficient and reliable system integration of solar power
Overview of forecasting scheme

- **PV power measurement**
- **Satellite cloud motion forecast CMV**
- **NWP: numerical weather prediction**

*Forecast horizon* - hours - days
Overview of forecasting scheme

PV power predictions

PV power forecasting: PV simulation and statistical models

PV power measurement

Satellite cloud motion forecast CMV

NWP: numerical weather prediction

Forecast horizon: hours — days
Numerical weather predictions

- global model forecast (IFS) of the European Centre for Medium-Range Weather Forecasts (ECWMF)
- regional model forecasts (COSMO EU) of the German Meteorological service (DWD)
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Post processing:

- bias correction and combination with linear regression
Irradiance prediction based on satellite data

- cloud index from Meteosat images with Heliosat method*
- resolution in Germany:
  - 1.2km × 2.2 km
  - 15 minutes

*Hammer et al 2003
cloud index from Meteosat images with Heliosat method

cloud motion vectors by identification of matching cloud structures in consecutive images

extrapolation of cloud motion to predict future cloud index
Irradiance prediction based on satellite data

- cloud index from Meteosat images with Heliosat method
- cloud motion vectors by identification of matching cloud structures in consecutive images
- extrapolation of cloud motion to predict future cloud index
- irradiance from predicted cloud index images with Heliosat method
Measurement data

- March- November 2013
- 15 minute values
- 921 PV systems\(^1\) in Germany
- information on PV system tilt and orientation

\(^1\)Monitoring data base of Meteocontrol GmbH
Overview of forecasting scheme

PV power predictions

PV power forecasting:
PV simulation and statistical models

PV power measurement

satellite cloud motion forecast CMV

NWP: numerical weather prediction

Forecast horizon: hours, days
Overview of forecasting scheme

**persistence:** constant ratio of measured PV power $P_{\text{meas}}$ to clear sky PV power $P_{\text{clear}}$

$$P_{\text{pers}}(t) = \frac{P_{\text{meas}}(t-\Delta t)}{P_{\text{clear}}(t-\Delta t)} \times P_{\text{clear}}(t)$$
Different input data and models

PV simulation:
- global horizontal irradiance
- irradiance on plane of array: tilt conversion model
- PV Power output: parametric model for MPP efficiency
- post processing: linear regression

Forecast horizon:

- Persistence
- PV power measurement
- Satellite cloud motion forecast CMV
- NWP: numerical weather prediction
Different input data and models

PV power predictions

- Persistence
- PV simulation
- PV simulation

PV power measurement

Satellite cloud motion forecast CMV

NWP: numerical weather prediction

Forecast horizon: hours, days
Different input data and models

PV power predictions

- Persistence
- PV simulation
- PV simulation

Evaluation:
Here forecast horizons 15 min to 5 hours ahead

Forecast horizon: hours, days

Evaluation:
Forecast horizons 15 min to 5 hours ahead

- PV power measurement
- Satellite cloud motion forecast CMV
- NWP: Numerical weather prediction
Regional forecasts: persistence, CMV and NWP based forecasts

Prediction horizon 0.25 h

- NWP
- CMV
- persistence

Predicted power [%]

Measured power [%]
Regional forecasts: persistence, CMV and NWP based forecasts
Regional forecasts: persistence, CMV and NWP based forecasts

Prediction horizon 2.0 h

- NWP
- persistence

Prediction horizon 2.0 h

- NWP
- CMV
Regional forecasts: persistence, CMV and NWP based forecasts
Regional forecasts: persistence, CMV and NWP based forecasts

Prediction horizon 4.0 h

- NWP
- CMV
- Persistence

predicted power [%]

measured power [%]
Rmse in dependence of forecast horizon

German average

\[ \text{rmse} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( \frac{P_{\text{meas}}}{P_{\text{inst}}} - \frac{P_{\text{pred}}}{P_{\text{inst}}} \right)^2} \]

15 minute values
normalization to installed power \( P_{\text{inst}} \)
only daylight values, calculation time of CMV: sunel > 10°
only hours with all models available included in dependence of forecast horizon
**Rmse in dependence of forecast horizon**

- **German average**

![Graph showing RMSE in dependence of forecast horizon for German average.](image)

The graph shows the Root Mean Square Error (RMSE) of predictions for both NWP and CMV methods, normalized by installed power $P_{inst}$, over different forecast horizons. The RMSE is calculated as:

$$ \text{rmse} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( \frac{P_{meas}}{P_{inst}} - \frac{P_{pred}}{P_{inst}} \right)^2} $$

- CMV forecasts better than NWP based forecast up to 4 hours ahead.

15 minute values

normalization to installed power $P_{inst}$

only daylight values, calculation time of CMV: sunel > 10°

only hours with all models available included in dependence of forecast horizon.
Rmse in dependence of forecast horizon

German average

\[ \text{rmse} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( \frac{P_{\text{meas}}}{P_{\text{inst}}} - \frac{P_{\text{pred}}}{P_{\text{inst}}} \right)^2} \]

- CMV forecasts better than NWP based forecast up to 4 hours ahead
- Persistence better than CMV forecasts up to 1.5 hour ahead

15 minute values
Normalization to installed power \( P_{\text{inst}} \)
Only daylight values, calculation time of CMV: sunel > 10°
Only hours with all models available included in dependence of forecast horizon
Rmse in dependence of forecast horizon

German average

single sites

comparison of German average and single site forecasts:

- German average RMSE about 1/3 of single site RMSE for NWP forecasts
Rmse in dependence of forecast horizon

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- German average RMSE about 1/3 of single site RMSE for NWP forecasts
Rmse in dependence of forecast horizon

**German average**

![Graph showing RMSE in dependence of forecast horizon for German average.](image)

**single sites**

![Graph showing RMSE in dependence of forecast horizon for single sites.](image)

**Comparison of German average and single site forecasts:**
- German average RMSE about 1/3 of single site RMSE for NWP forecasts
Rmse in dependence of forecast horizon

**German average**

- pers
- NWP
- CMV

**single sites**

- CMV
- NWP
- pers

**comparison of German average and single site forecasts:**
- German average RMSE about 1/3 of single sites RMSE for NWP forecasts
- improvements with persistence and CMV larger for regional forecasts
Rmse in dependence of forecast horizon

German average

single sites

different models suitable in dependence of forecast horizon and spatial scale

- German average RMSE about 1/3 of single sites RMSE for NWP forecasts
- improvements with persistence and CMV larger for regional forecasts
Different input data and models

PV power predictions

- persistence
- PV simulation
- PV simulation

Different input data and models:

- PV power measurement
- satellite cloud motion forecast CMV
- NWP: numerical weather prediction

Forecast horizon:

- hours
- days

*) PV simulation with bias correction
Combination of different models

- Persistence
- PV simulation
- PV simulation

PV power predictions

Forecast horizon:
- PV measurement
- Satellite cloud motion forecast CMV
- NWP: Numerical weather prediction

Forecast horizon:
- Hours
- Days
Combination of forecasting methods

combination of forecast models with linear regression:

\[ P_{\text{combi}} = a_{\text{NWP}}P_{\text{NWP}} + a_{\text{CMV}}P_{\text{CMV}} + a_{\text{persist}}P_{\text{persist}} + a_0 \]

coefficients \( a_{\text{NWP}}, a_{\text{CMV}}, a_{\text{persist}}, a_0 \) are fitted to measured data in dependence of

- forecast horizon
- hour of the day
Combination of forecasting methods

combination of forecast models with linear regression:

\[ P_{\text{combi}} = a_{\text{NWP}}P_{\text{NWP}} + a_{\text{CMV}}P_{\text{CMV}} + a_{\text{persist}}P_{\text{persist}} + a_0 \]

daytime coefficients \( a_{\text{NWP}}, a_{\text{CMV}}, a_{\text{persist}}, a_0 \) are fitted to measured data in dependence of

- forecast horizon
- hour of the day

training data:

daily update with measurements of last 30 days

- for single site forecasts: each PV system separately
- for regional forecasts: average of sites
Regional forecasts

regression coefficients in dependence of forecast horizon

regression coefficients (weights) reflect horizon dependent forecast performance of different models
Regional forecasts

Rmse in dependence of forecast horizons

Considerable improvement with combined model over single model forecasts
Regression coefficients

German average

Single sites

Horizon dependent regression coefficients **different** for regional and single site forecasts
Rmse in dependence of forecast horizon

- forecast combination outperforms single model forecasts for all horizons
- improvements with combination larger for regional forecasts
Rmse in dependence of forecast horizon

- forecast combination outperforms single model forecasts for all horizons
- improvements with combination larger for regional forecasts

considerable improvement by combining different models with statistical learning
Summary

- PV power prediction contributes to successful grid integration of more than 39 GW_{peak} PV power in Germany
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- PV power forecasts based on satellite data (CMV) significantly better than NWP based forecasts up to 4 hours ahead
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- PV power prediction contributes to successful grid integration of more than 39 GW$_{\text{peak}}$ PV power in Germany
- PV power forecasts based on satellite data (CMV) significantly better than NWP based forecasts up to 4 hours ahead
- Significant improvement by combining different forecast models with PV power measurements, in particular for regional forecasts
Thank you for your attention!