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

Elke Lorenz, Jan Kühnert, Björn Wolff, Annette Hammer, Detlev Heinemann

1) Energy Meteorology Group, Institute of Physics, University of Oldenburg
Outline

- 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
Grid integration of PV in Germany

- installed Power: $38.5\text{GW}_{\text{peak}}$ (end of 2014)
Grid integration of PV in Germany

- installed Power: \(38.5\text{GW}_{\text{peak}}\) (end of 2014)
- marketing of PV power at the European Energy Exchange
Grid integration of PV in Germany

- installed Power: $38.5\text{GW}_{\text{peak}}$ (end of 2014)
- marketing of PV power at the European Energy Exchange
  - by transmission system operators
  - regional forecasts
Grid integration of PV in Germany

- installed Power: $38.5\text{GW}_{\text{peak}}$ (end of 2014)
- marketing of PV power at the European Energy Exchange
  - by transmission system operators  
    ➔ regional forecasts
  - direct marketing  
    ➔ local forecasts
Grid integration of PV in Germany

- installed Power: \(38.5\text{GW}_{\text{peak}}\) (end of 2014)
- marketing of PV power at the European Energy Exchange
  - by transmission system operators → regional forecasts
  - direct marketing → local forecasts
  - day ahead: for the next day
Grid integration of PV in Germany

- installed Power: $38.5\text{GW}_{\text{peak}}$ (end of 2014)
- marketing of PV power at the European Energy Exchange
  - by transmission system operators
    - regional forecasts
  - direct marketing
    - local forecasts
- day ahead: for the next day
- intraday: until 45 minutes before delivery
Grid integration of PV in Germany

- installed Power: \(38.5\text{GW}_{\text{peak}}\) (end of 2014)
- marketing of PV power at the European Energy Exchange
  - by transmission system operators
    - regional forecasts
  - direct marketing
    - local forecasts
  - day ahead: for the next day
  - intraday: until 45 minutes before delivery
    - here: 15 min to 5 hours ahead
Overview of forecasting scheme
Overview of forecasting scheme

- PV power measurement
- Satellite cloud motion forecast CMV

Forecast horizon: hours
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)
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)

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 x 2.2 km
  - 15 minutes

*Hammer et al 2003
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 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

October 22nd 2015, 4th PV Modelling Workshop, Köln, Germany
Overview of forecasting scheme

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

$$P_{\text{pers}}(t) = \frac{P_{\text{meas}}(t-\Delta t)}{P_{\text{clear}}(t-\Delta t)} P_{\text{clear}}(t)$$

**PV power predictions**

**Panel:** PV power measurement

**Forecast:** satellite cloud motion forecast CMV

**NWP:** numerical weather prediction

**Forecast horizon:**
- hours
- days
Different input data and models

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

PV simulation:
- Diffuse fraction model: Skartveith et al, 1998
- Tilt model: Klucher 1970
- Parametric model for MPP efficiency: Beyer et al 2004
- Linear regression

forecast horizon: hours, days
Different input data and models

- Persistence
- PV simulation
- PV simulation

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

Forecast horizon: hours, days
Regional forecasts: persistence, CMV and NWP based forecasts

![Graph showing predicted vs. measured power for different models](image)

- **Prediction horizon 0.25 h**
  - NWP
  - Persistence
  - CMV
Regional forecasts: persistence, CMV and NWP based forecasts

Prediction horizon 0.5 h

- NWP
- Persistence

Prediction horizon 0.5 h

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

Prediction horizon 1.0 h

- NWP
- Persistence

Prediction horizon 1.0 h

- NWP
- CMV
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

Prediction horizon 3.0 h

---

October 22nd 2015, 4th PV Modelling Workshop, Köln, Germany
Regional forecasts: persistence, CMV and NWP based forecasts

Prediction horizon 4.0 h

- NWP
- Persistence
- CMV
Rmse in dependence of forecast horizon

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

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**

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

**forecasts for German average**

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

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

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

- NWP
- CMV
- pers

**single sites**

- CMV
- NWP
- pers

Comparison of German average and single site forecasts:
- Rmse for German about 1/3 of single sites 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:**

- rmse for German 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*

- 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

PV power predictions

Combination

Persistence

PV simulation

PV simulation

PV power 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:

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

coefficients \( a_{NWP}, a_{CMV}, a_{\text{persist}}, a_0 \) are fitted to measured data
Combination of forecasting methods

combination of forecast models with linear regression:

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

coefficients \( a_{NWP} \), \( a_{CMV} \), \( a_{persist} \), \( a_0 \) 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:

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

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:

- for single site forecasts: each PV system separately
Combination of forecasting methods

combination of forecast models with linear regression:

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

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

- forecast horizon
- hour of the day

training data:

- for single site forecasts: each PV system separately
- for regional forecasts: average of sites
Combination of forecasting methods

How many days to train forecast combination?

Improvement score:

\[
\frac{\text{rmse}_{\text{ref}} - \text{rmse}_{\text{combi}}}{\text{rmse}_{\text{ref}}}
\]

with respect to best single model

all sites average, May to November, 2012
Combination of forecasting methods

How many days to train forecast combination?

Improvement score:

$$\frac{rmse_{ref} - rmse_{combi}}{rmse_{ref}}$$

with respect to best single model

all sites average, May to November, 2012

independent test year for model configuration
Combination of forecasting methods

How many days to train forecast combination?

Improvement score:

$$\frac{rmse_{ref} - rmse_{combi}}{rmse_{ref}}$$

with respect to best single model

→ last 30 days

all sites average, May to November, 2012
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
Single site forecasts

regression coefficients in dependence of forecast horizon

regression coefficients (weights) reflect horizon dependent forecast performance of different models for single sites
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
Summary

- PV power prediction contributes to successful grid integration of more than 38 GW_{peak} PV power in Germany
Summary

- PV power prediction contributes to successful grid integration of more than 38 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.
Summary

- PV power prediction contributes to successful grid integration of more than 38 GW_{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.
Outlook

- **combination of machine learning with PV simulation** for integration of **additional data sources:**
  - additional meteorological parameters
  - additional NWP systems

- **uncertainty information**
Thank you for your attention!