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

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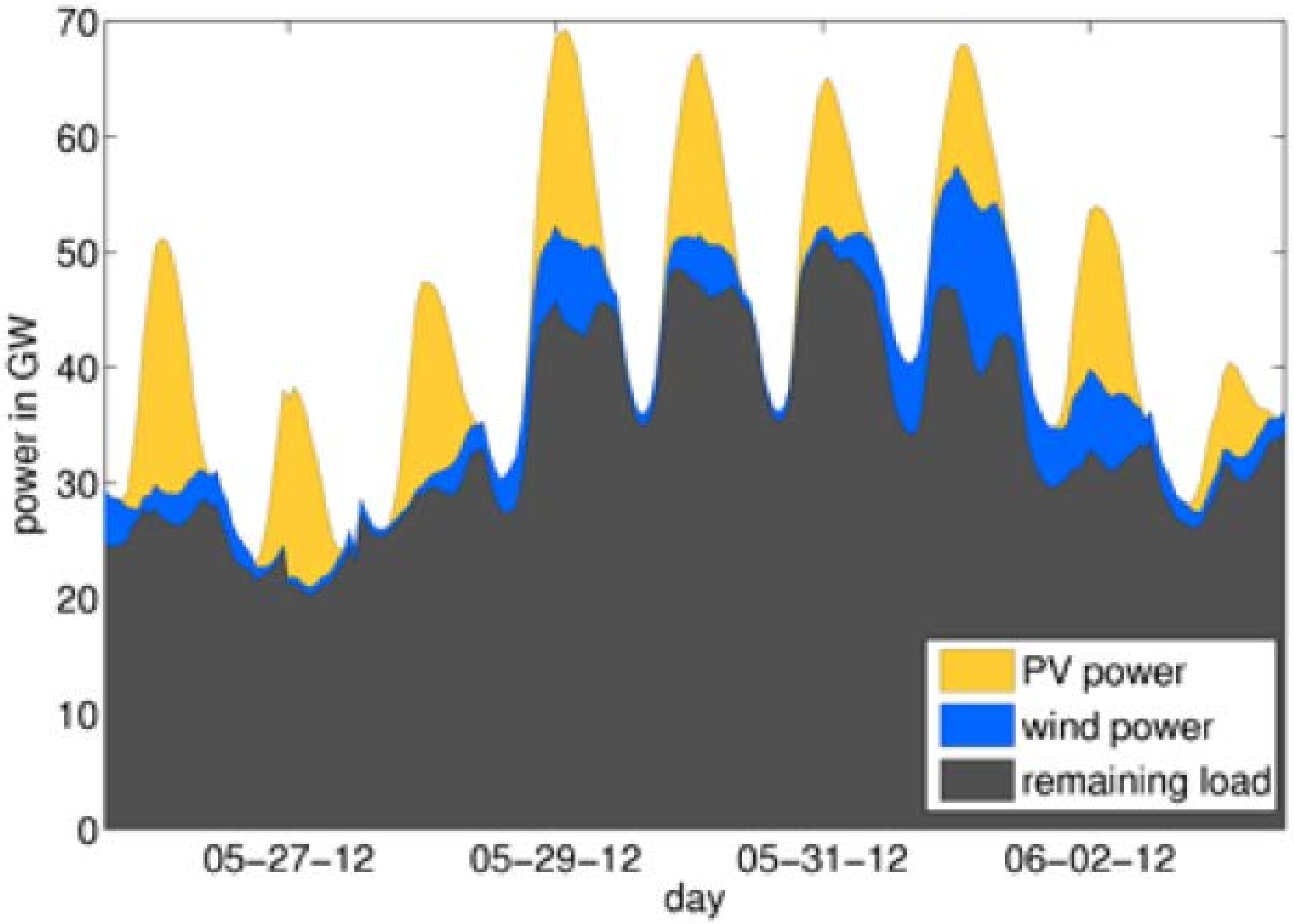
Energy Meteorology Group, Institute of Physics,
University of Oldenburg

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

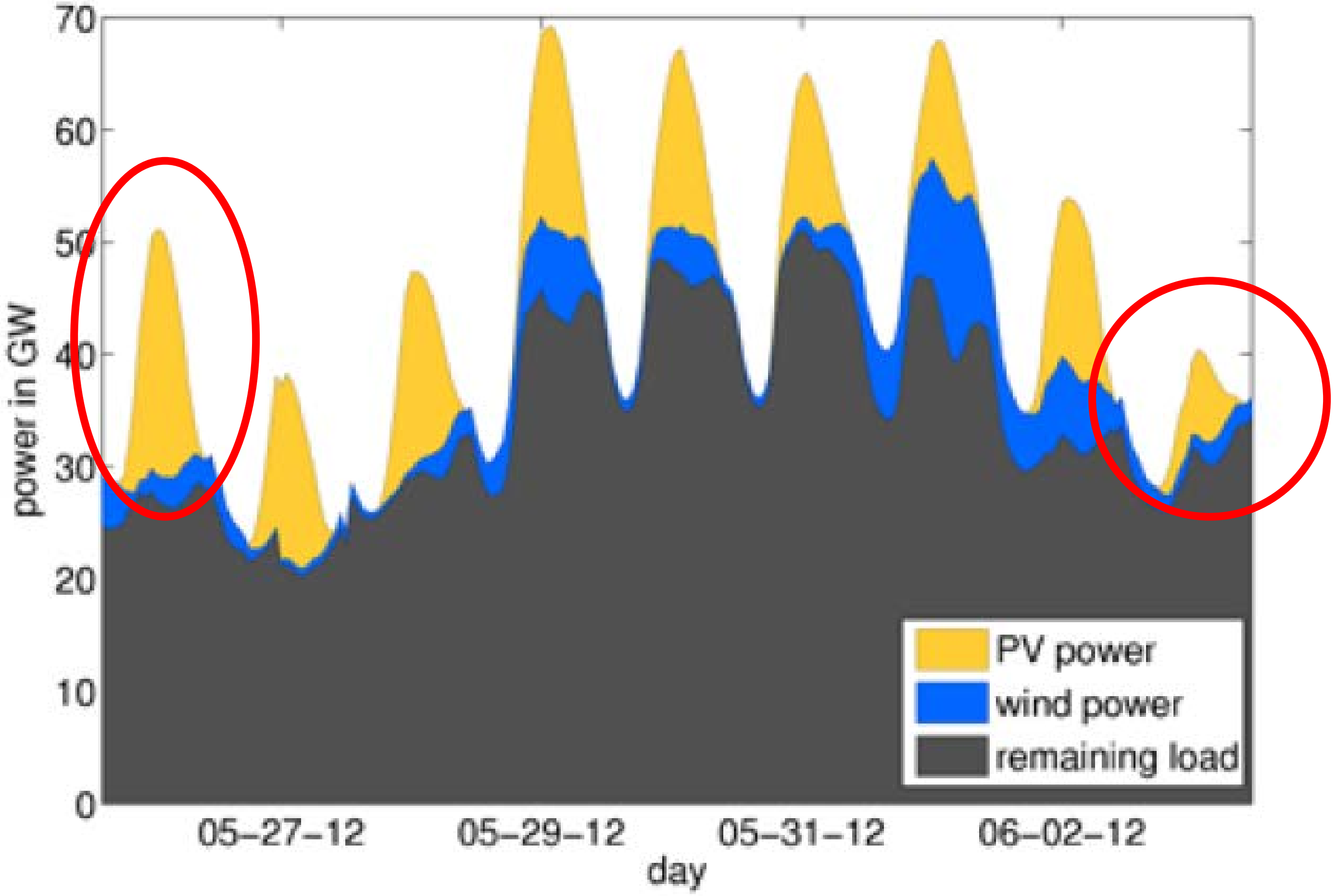
Contribution of photovoltaic (PV) systems to electricity supply in Germany

- 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 GW_{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

control areas

Grid integration of PV Power: marketing at the European Energy Exchange

- by Transmission System Operators
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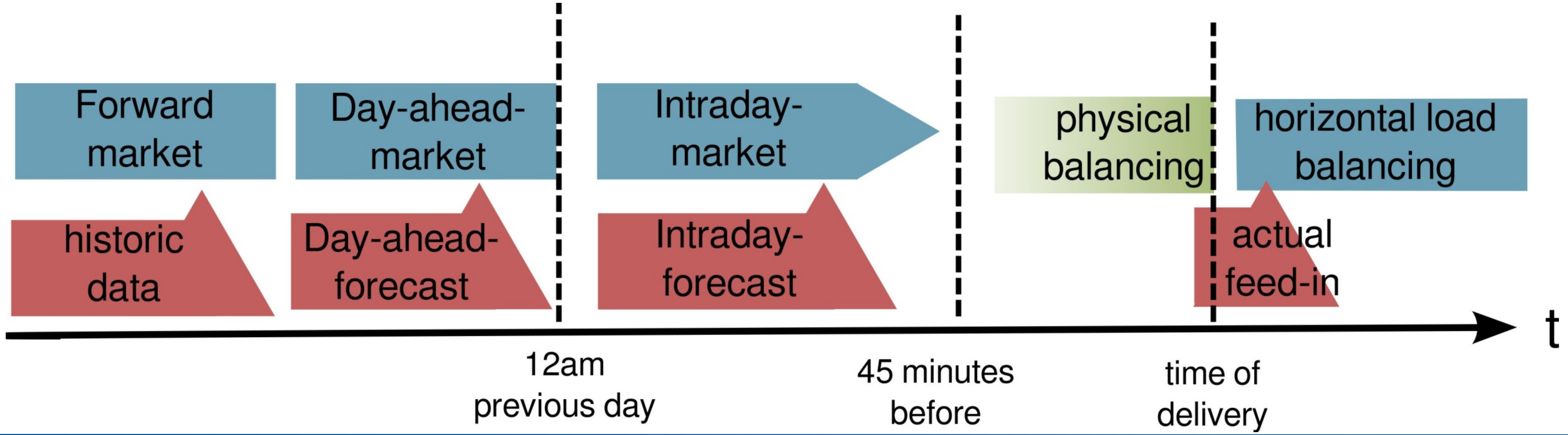
- forecast horizons



Grid integration of PV Power: marketing at the European Energy Exchange

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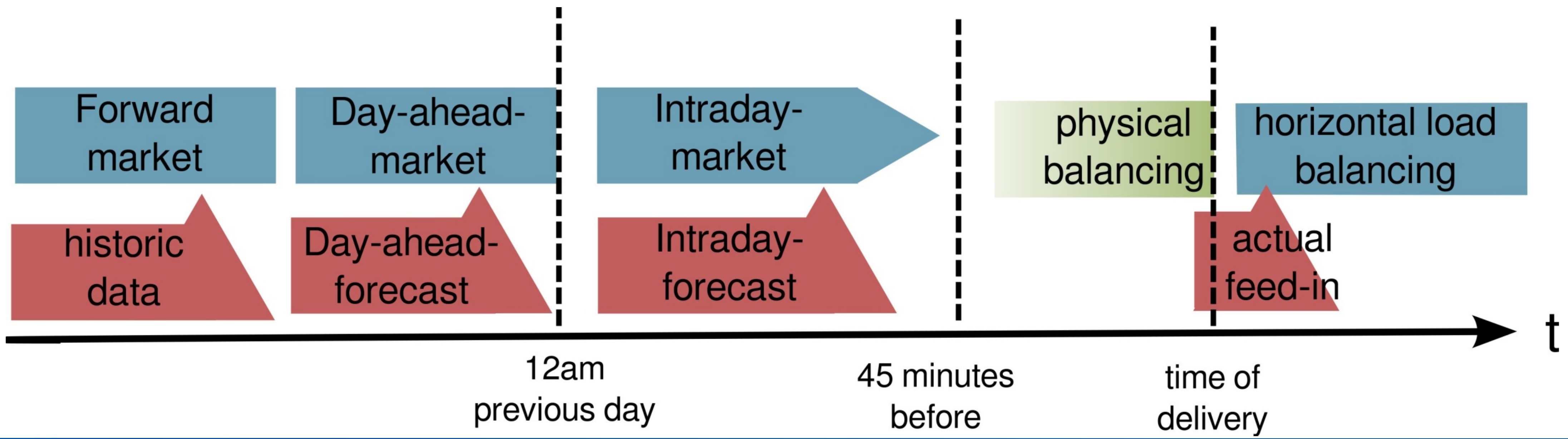
forecast errors *high price* *need for balancing power*



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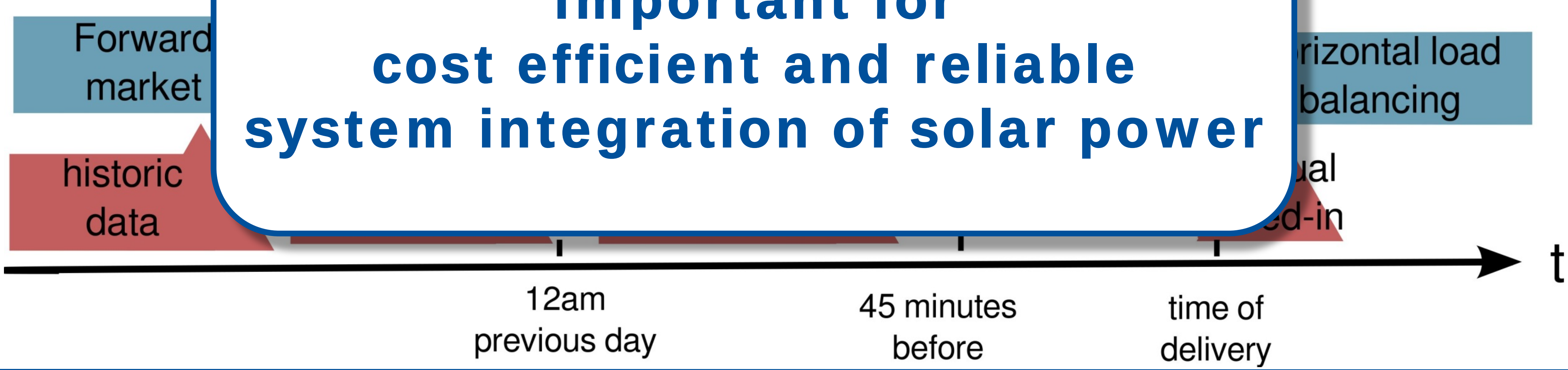
Grid integration of PV Power: marketing at the European Energy Exchange

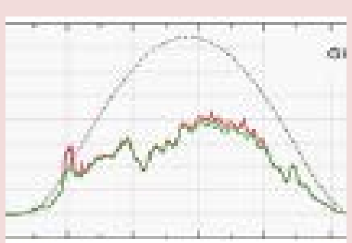
- by Transmission System Operators
  ➡ regional forecasts
- direct marketing
  ➡ local forecasts
- forecast horizons *need for*
  forecast



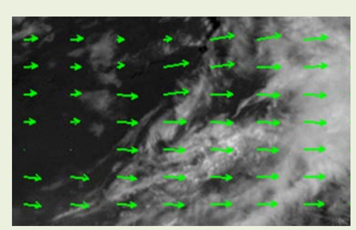
accurate solar power forecasts important for cost efficient and reliable system integration of solar power

Overview of forecasting scheme

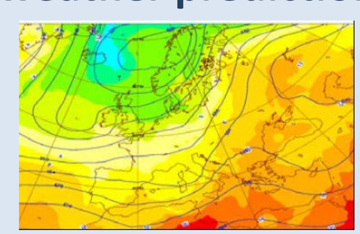
PV power measurement



satellite cloud motion forecast CMV



NWP: numerical weather prediction



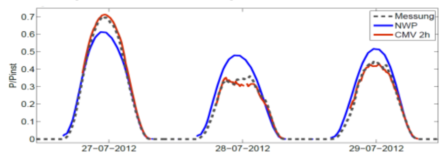
forecast horizon

hours

days

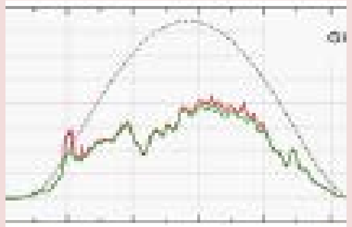
Overview of forecasting scheme

PV power predictions



PV power forecasting: PV simulation and statistical models

PV power measurement



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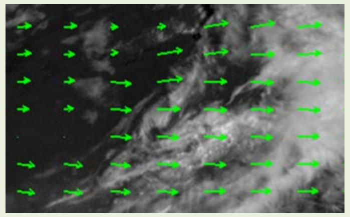

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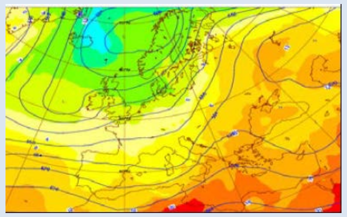
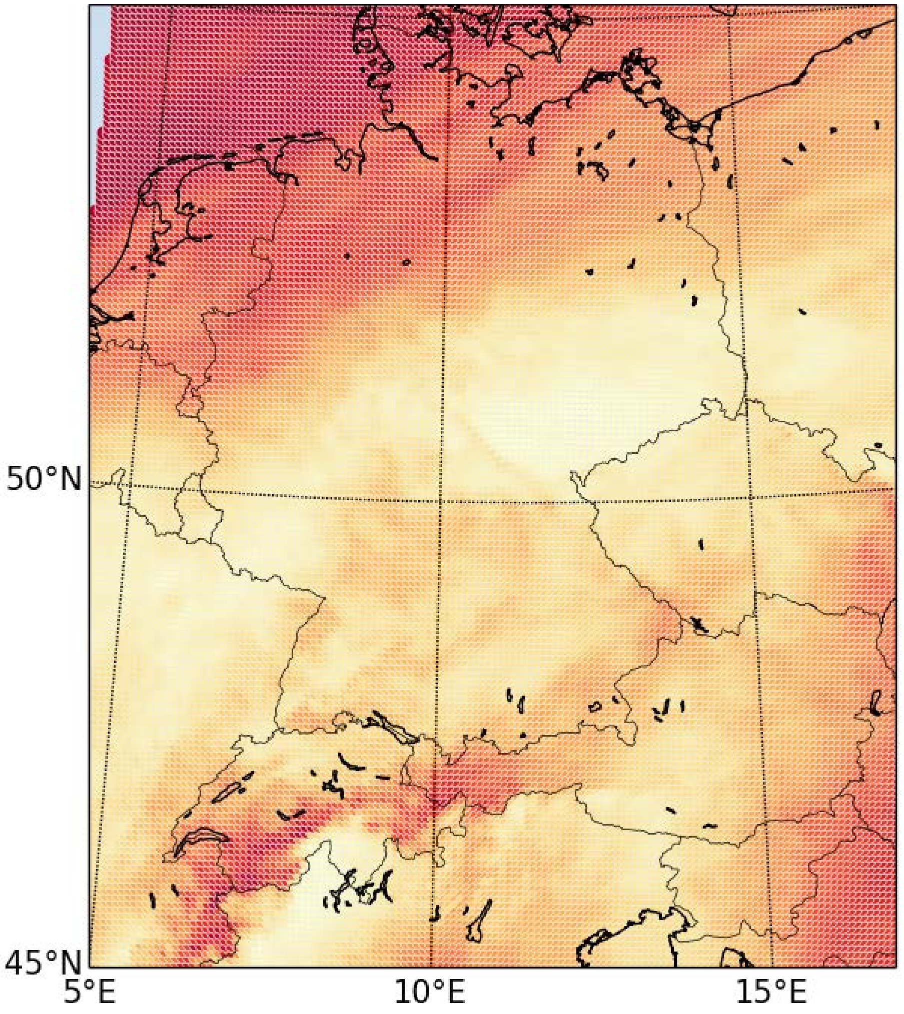


forecast horizon hours days

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)

COSMO EU, dir. irradiance
2104-05-02, 12:00



Numerical weather predictions

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Post processing:

- bias correction and combination with linear regression

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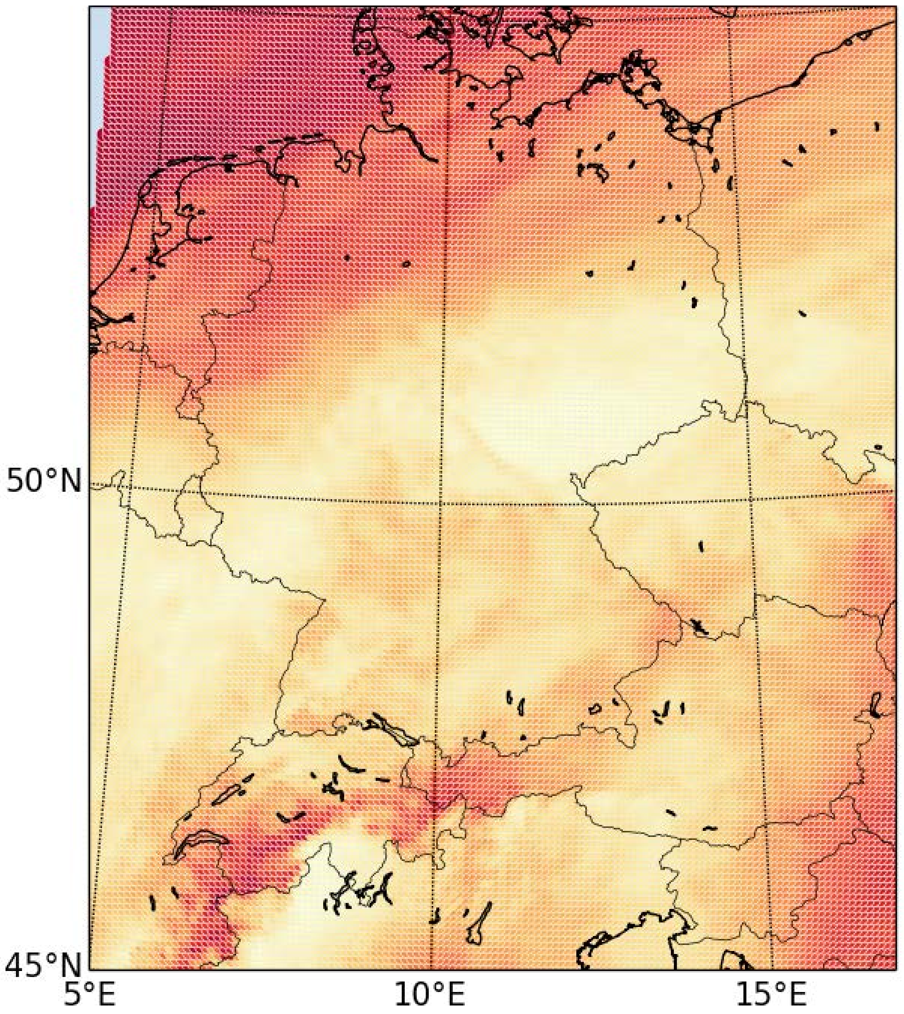
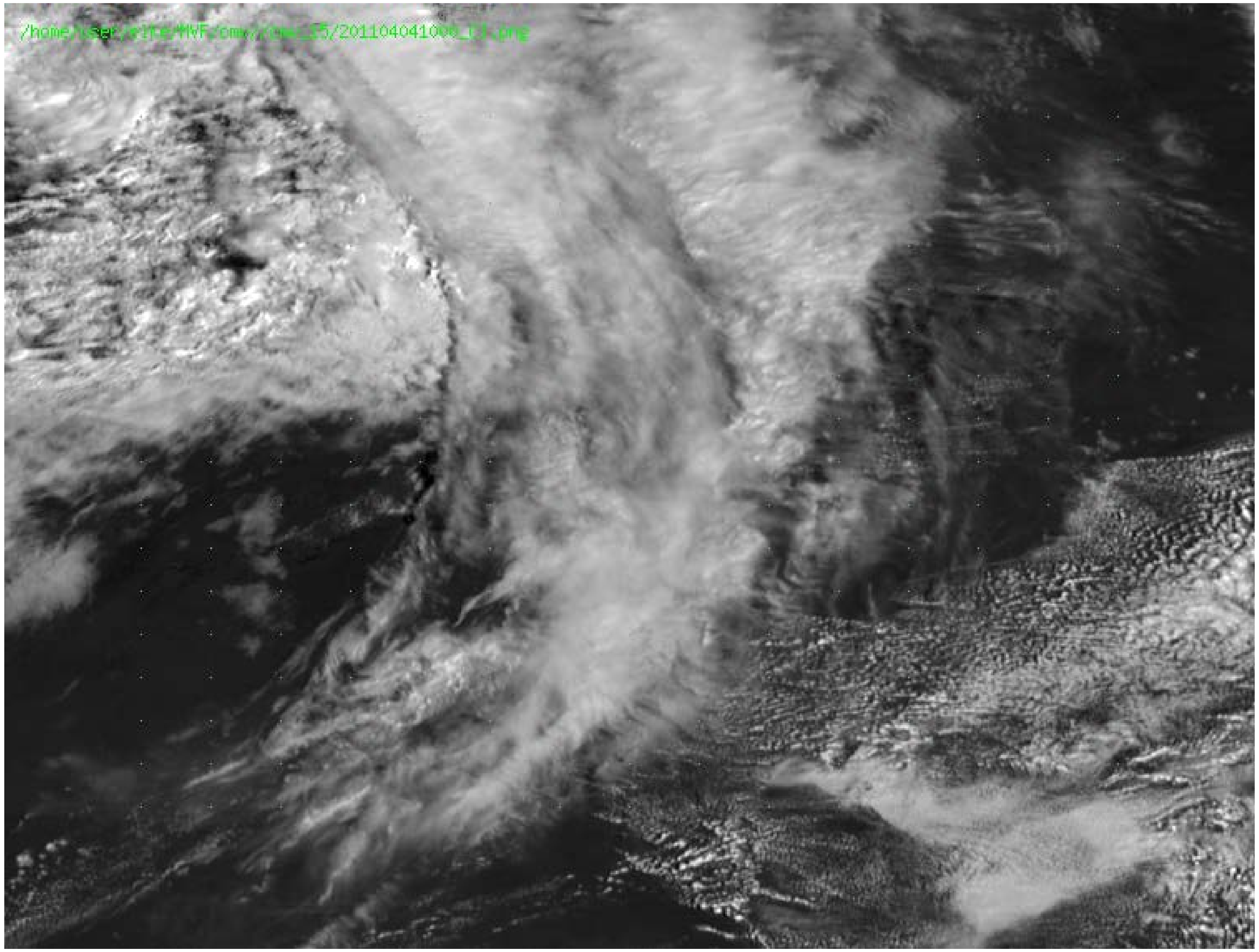


Irradiance prediction based on satellite data

- cloud index from Meteosat images with Heliosat method*

  resolution in Germany
  - 1.2km x 2.2 km
  - 15 minutes

Meteosat Second Generation (high resolution visible range)



*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

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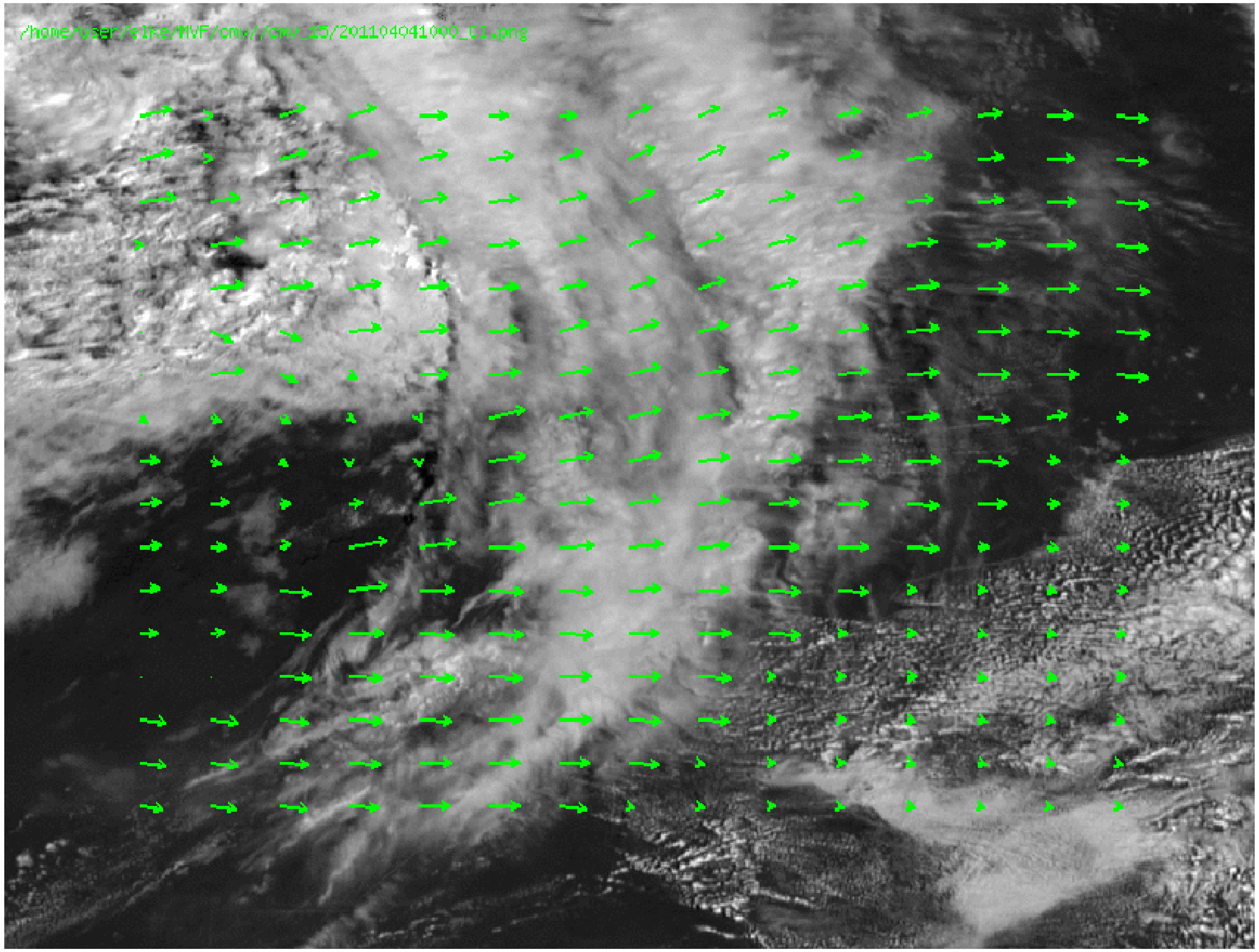
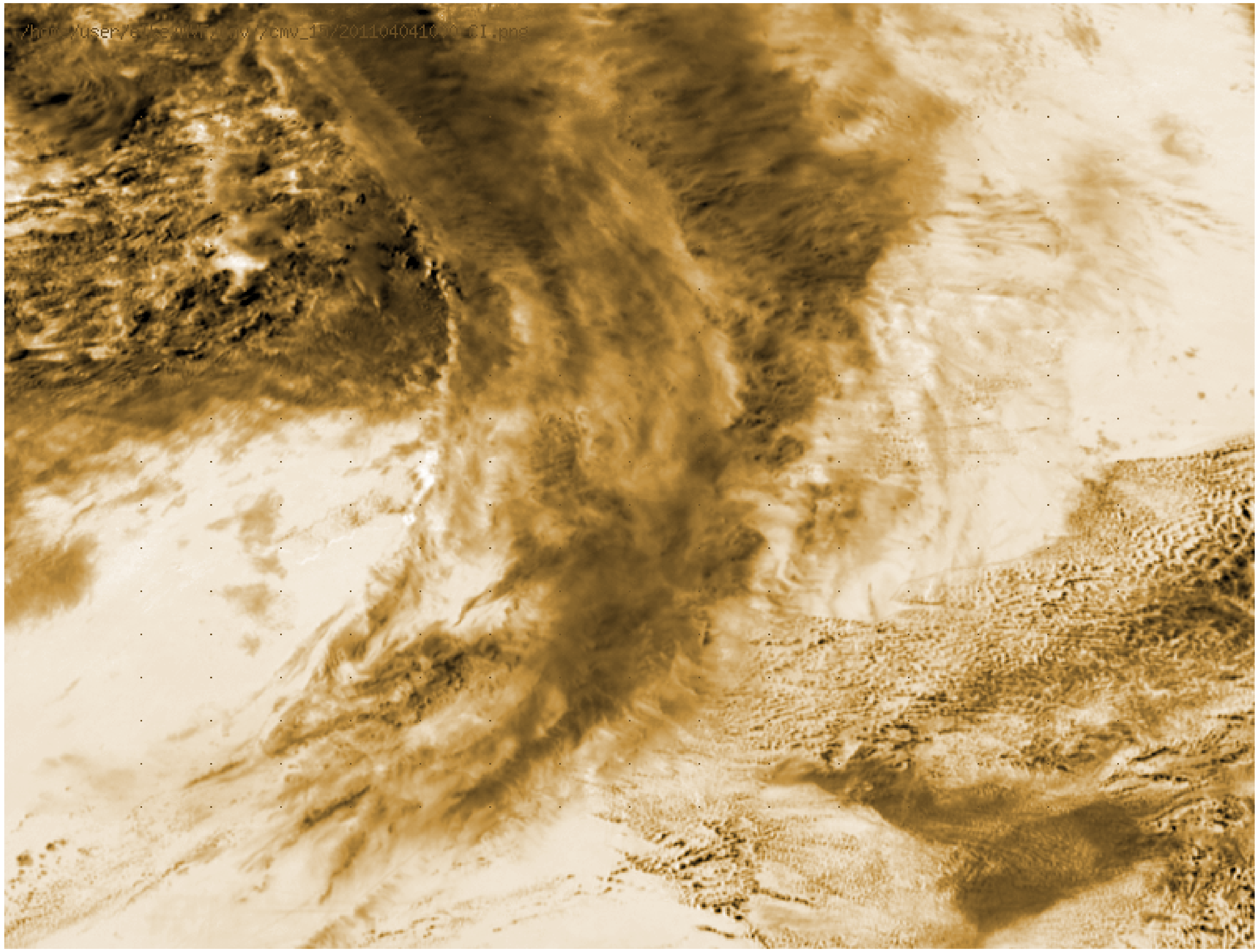


Irradiance prediction based on satellite data

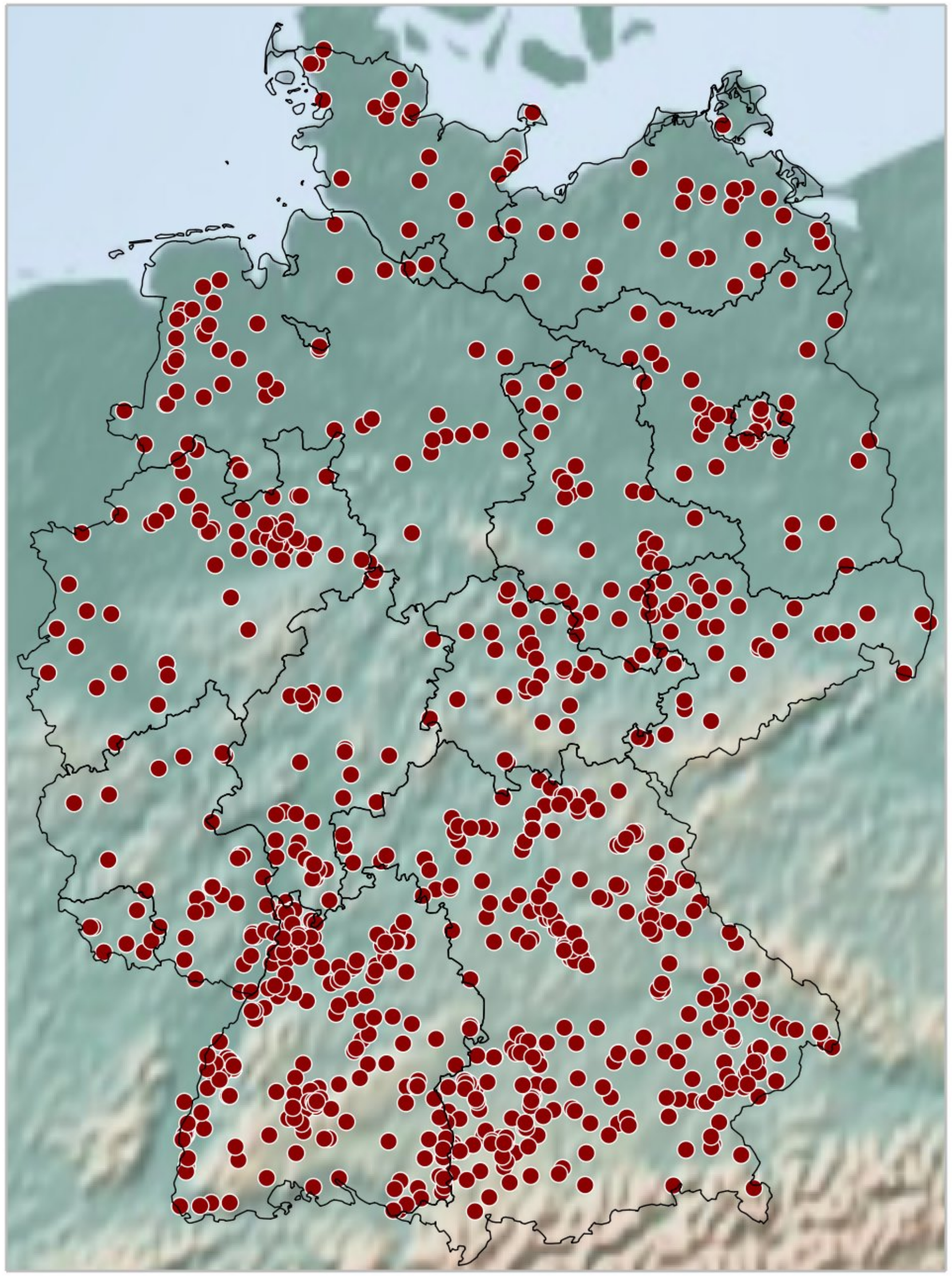
- cloud index from Meteosat images with Heliosat method
- cloud motion vectors by identification of matching cloud structures in consecutive images
- extrapolation of cloud motion to predict future cloud index
- irradiance from predicted cloud index images with Heliosat method

satellite derived irradiance maps



Measurement data

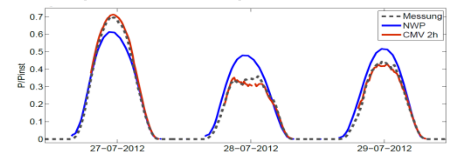
- March- November 2013
- 15 minute values
- 921 PV systems[1)] in Germany
- information on PV system tilt and orientation



[1)]Monitoring data base of Meteocontrol GmbH

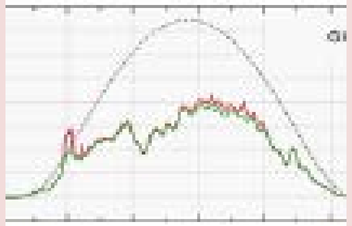
Overview of forecasting scheme

PV power predictions



PV power forecasting: PV simulation and statistical models

PV power measurement



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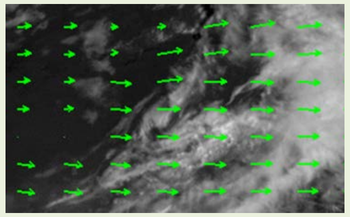

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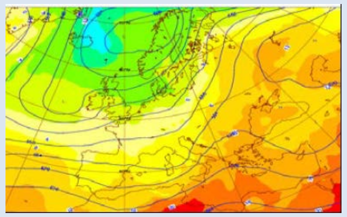


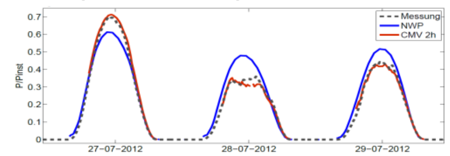
forecast horizon hours → days

Overview of forecasting scheme

persistence:
constant ratio of measured PV power P_{meas} to clear sky PV power P_{clear}

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

PV power predictions



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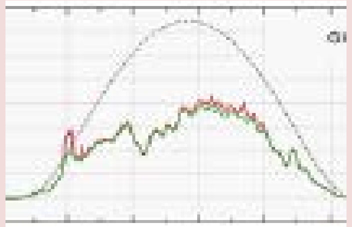

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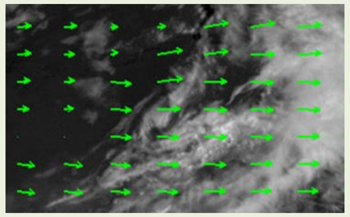

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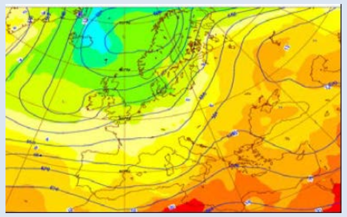
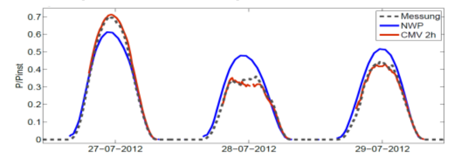


forecast horizon hours days

Different input data and models

PV power predictions

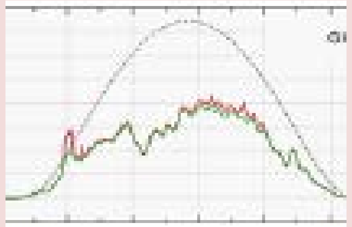


persistence

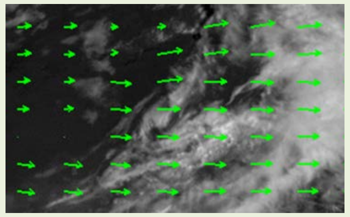
PV simulation:

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

PV power measurement



satellite cloud motion forecast CMV



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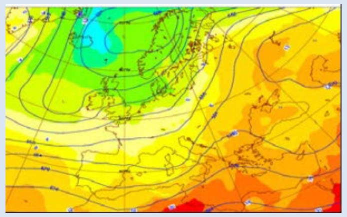

forecast horizon hours days

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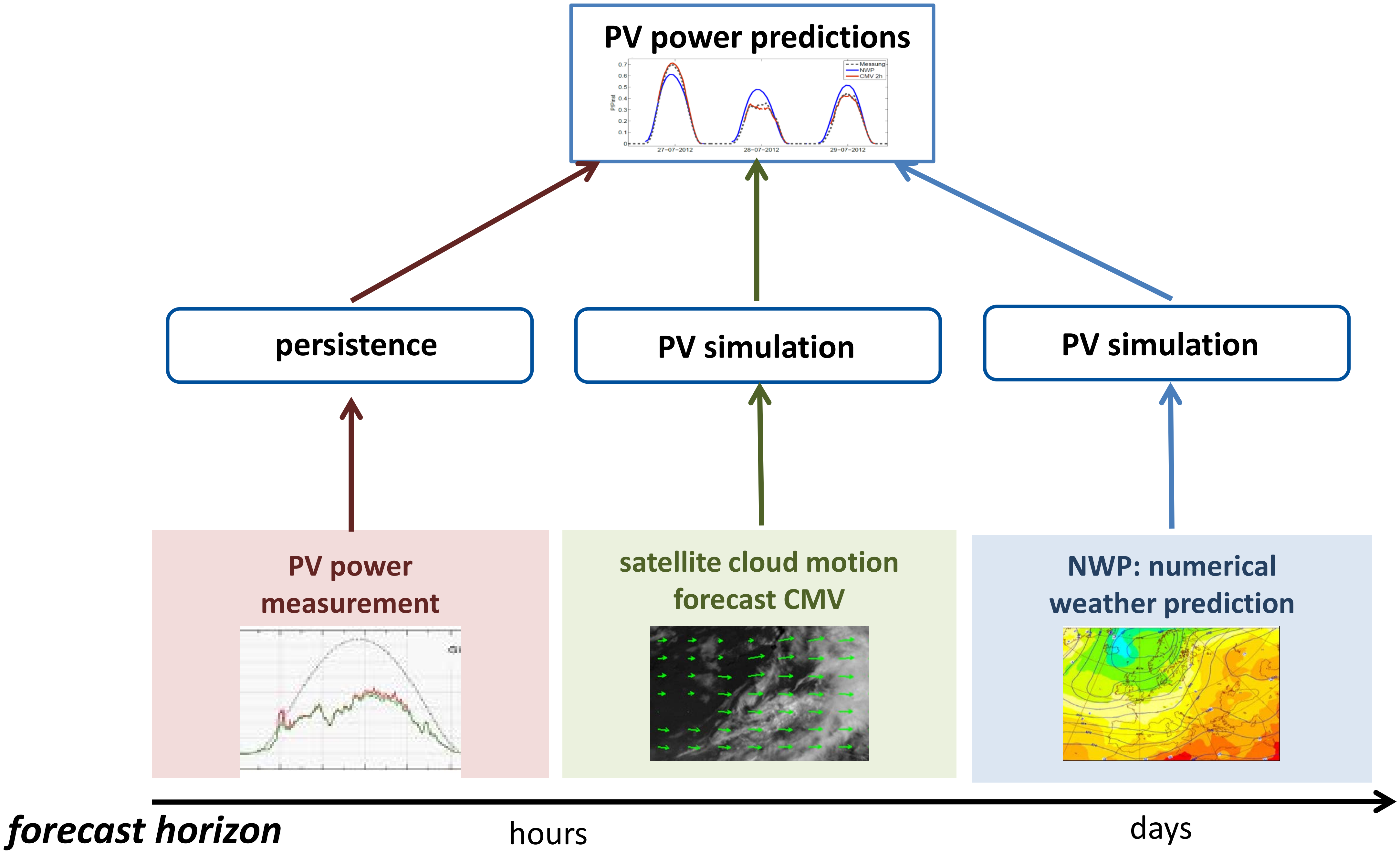
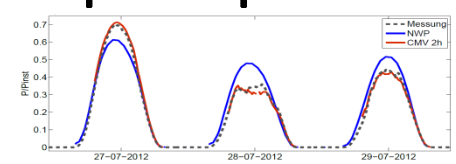


Different input data and models

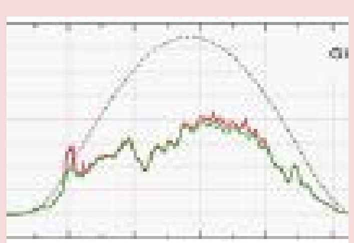
PV power predictions



Evaluation:
here forecast horizons
15 min to 5 hours ahead

persistence | **PV simulation** | **PV simulation**

PV power measurement



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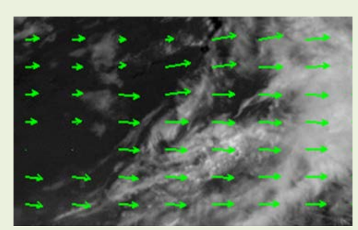

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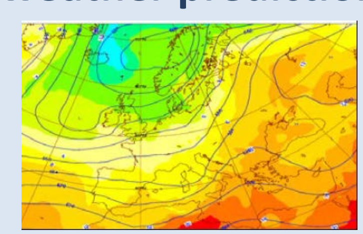
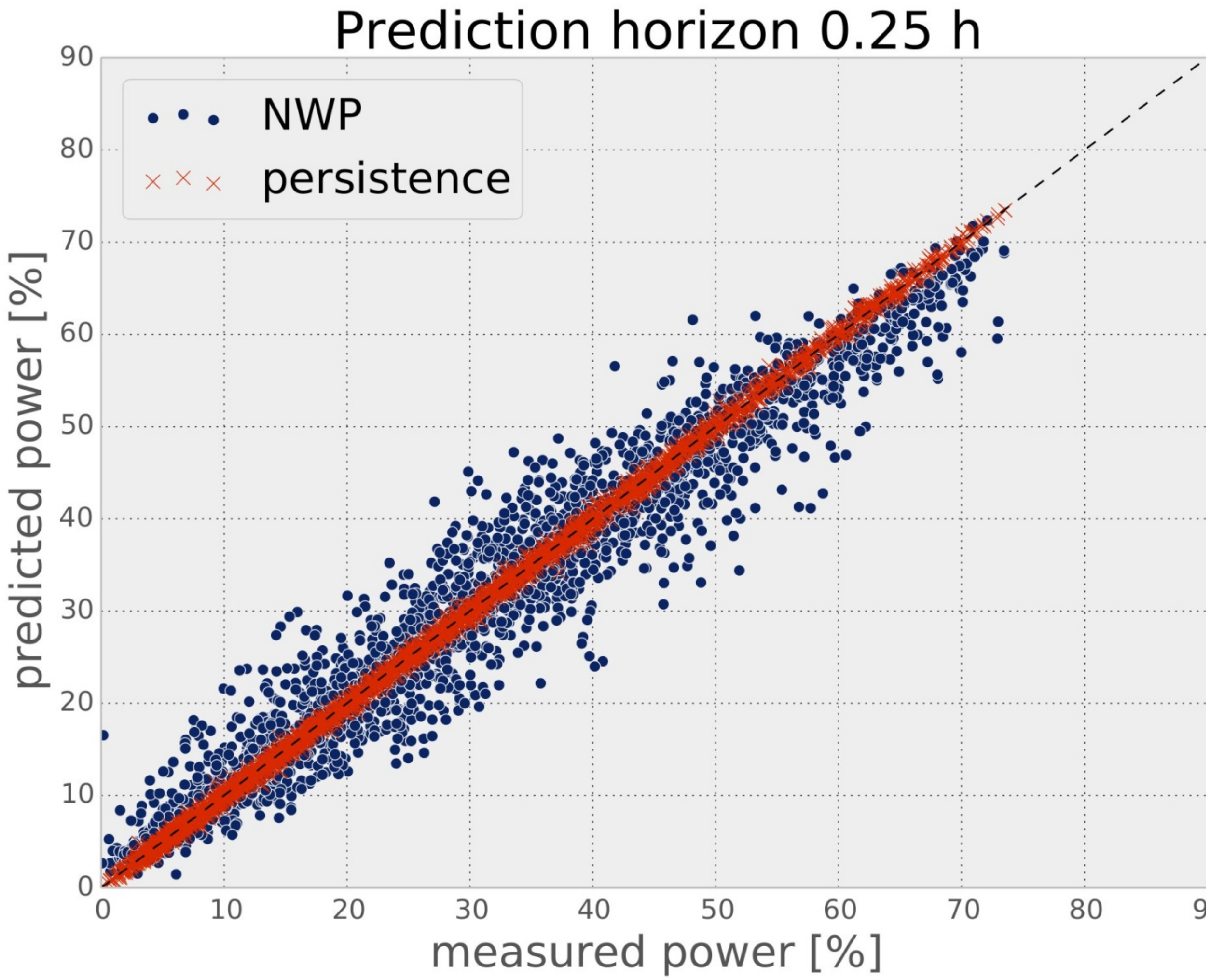
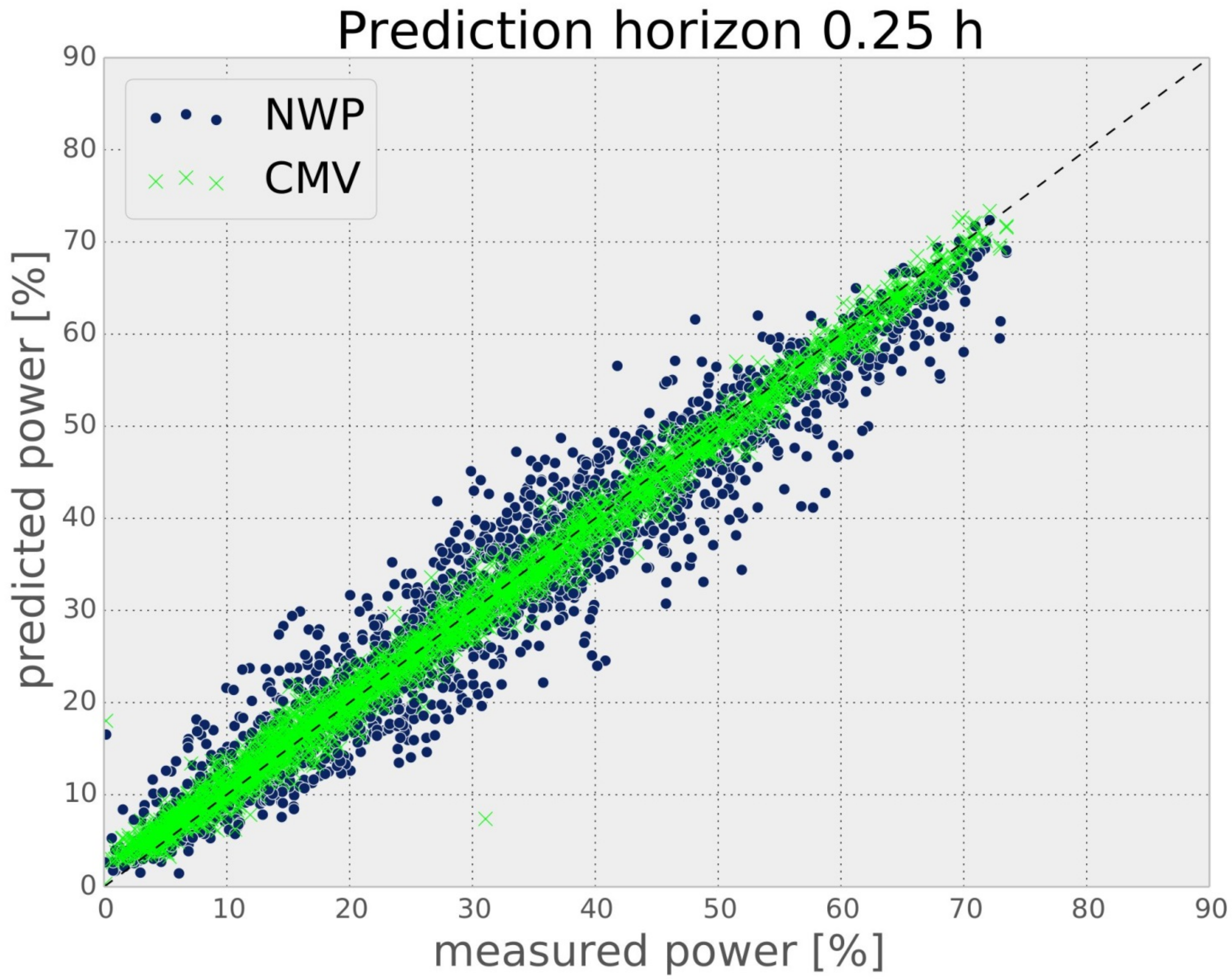


forecast horizon hours → days

Regional forecasts:
persistence, CMV and NWP based forecasts





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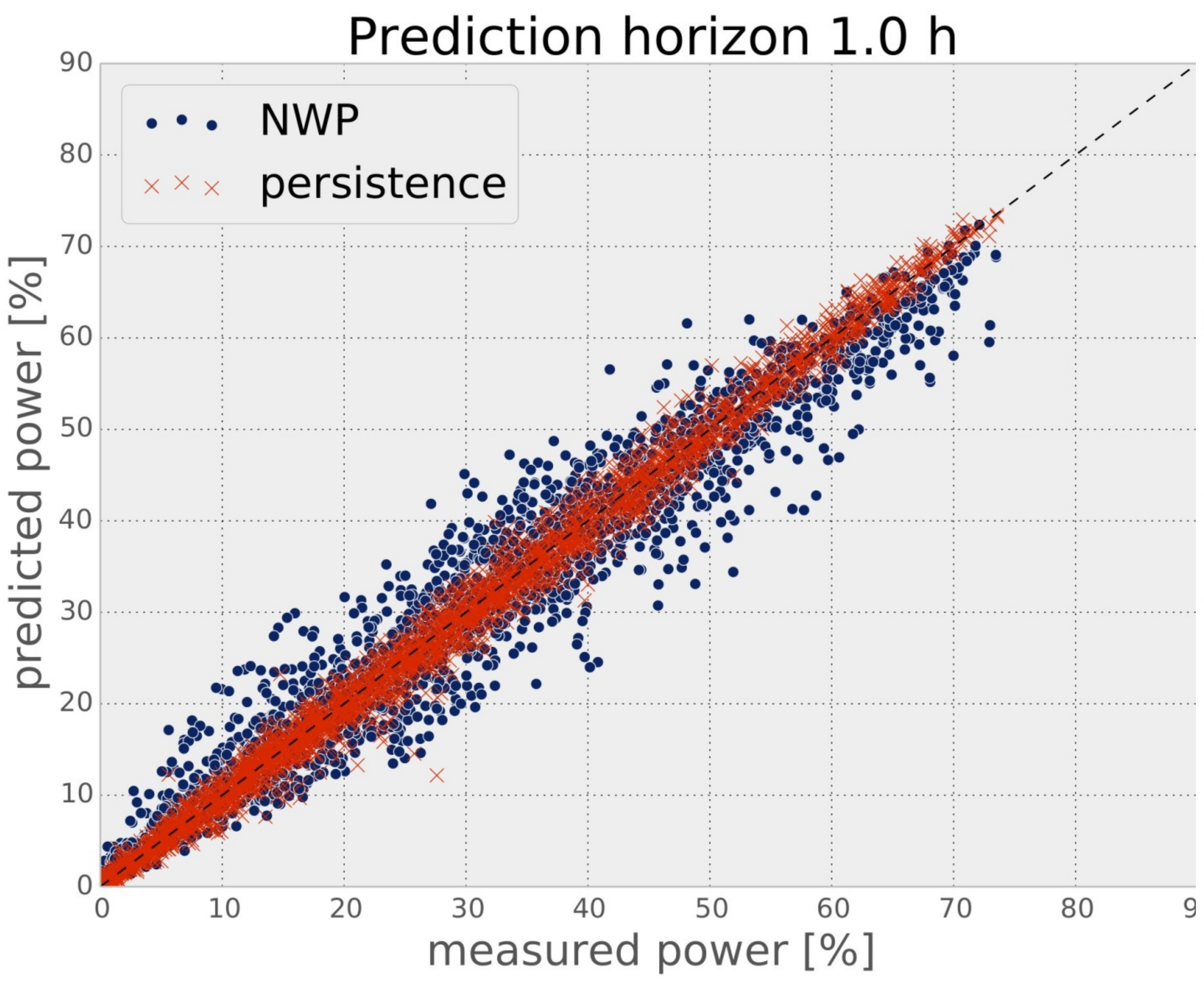

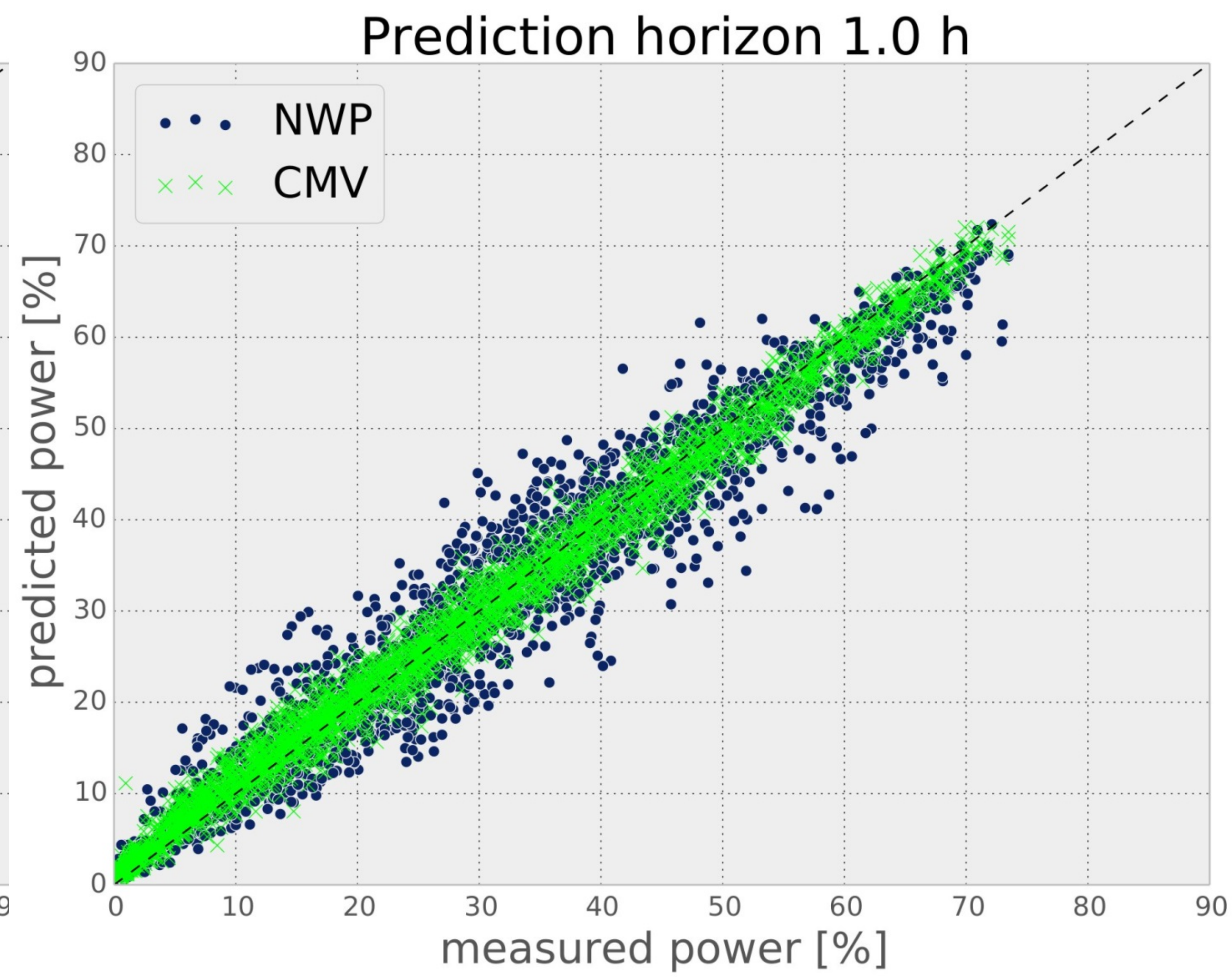

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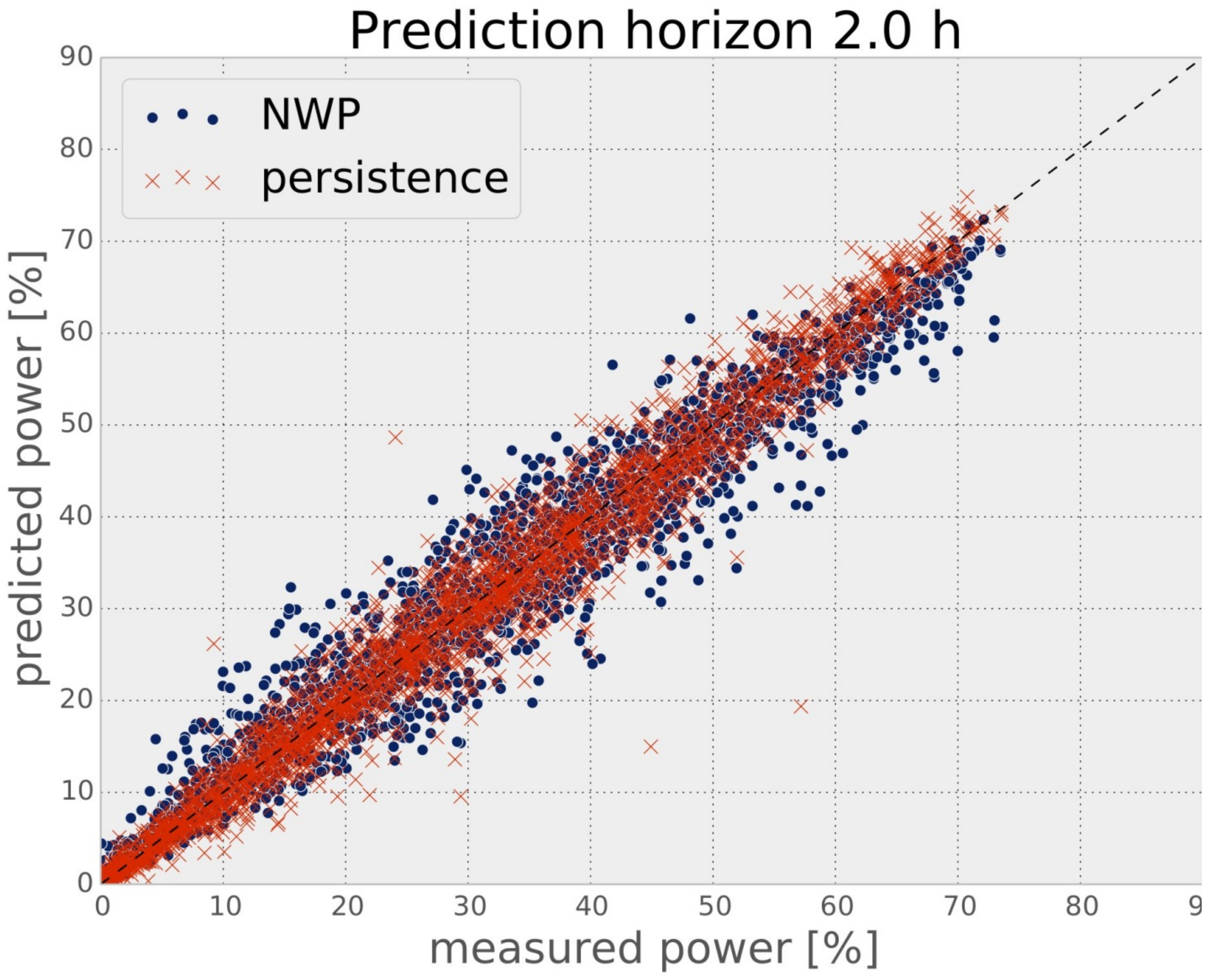

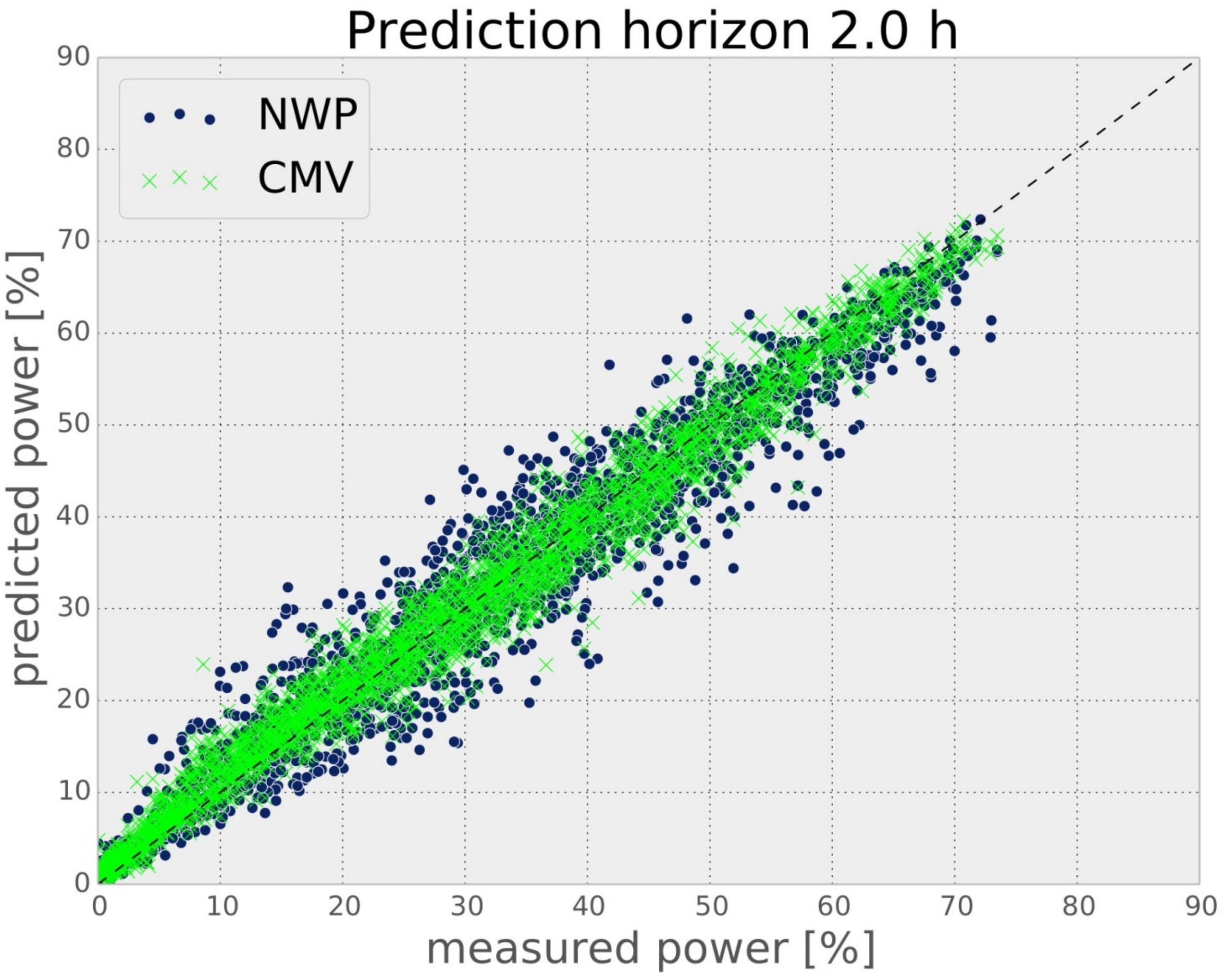

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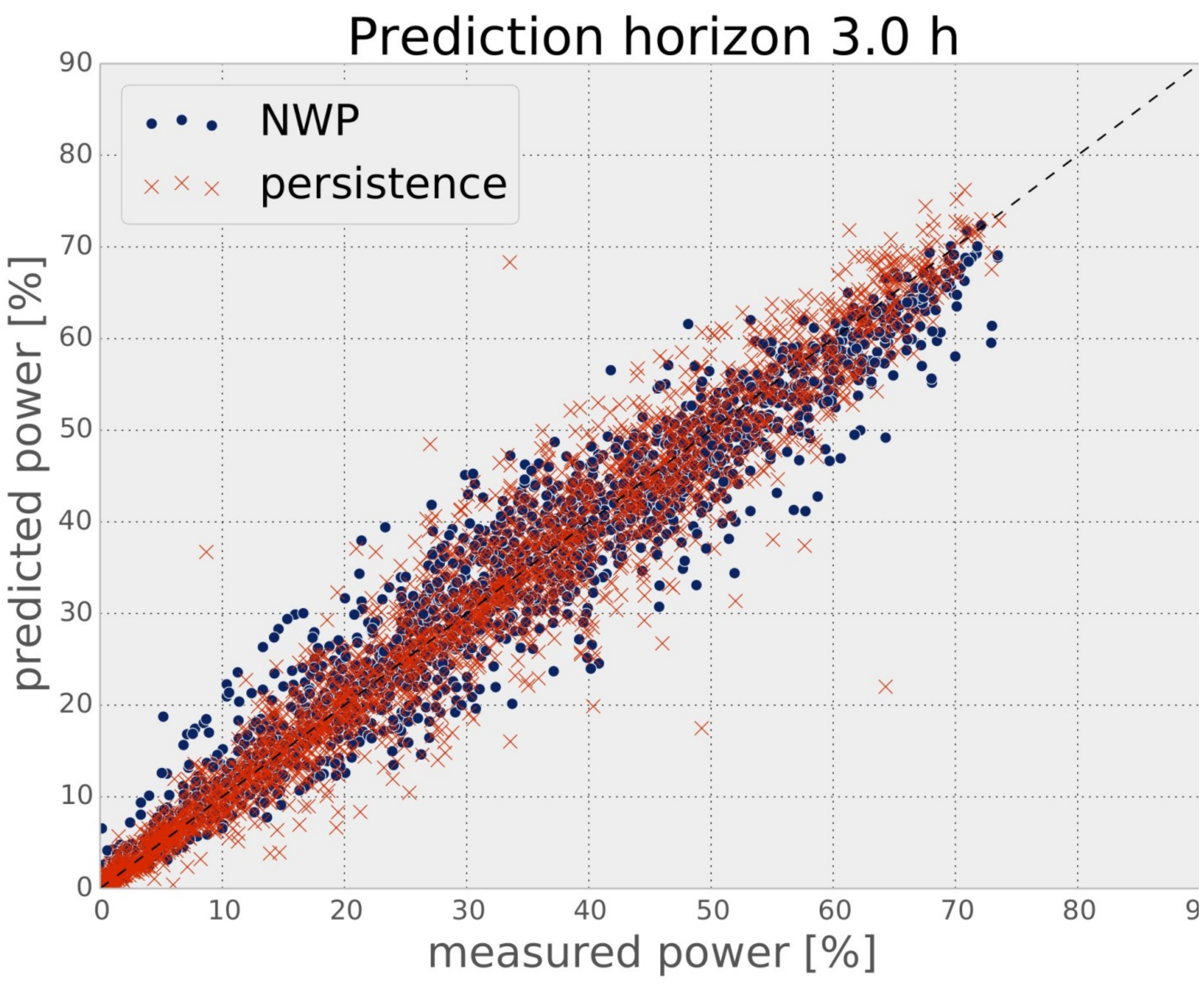

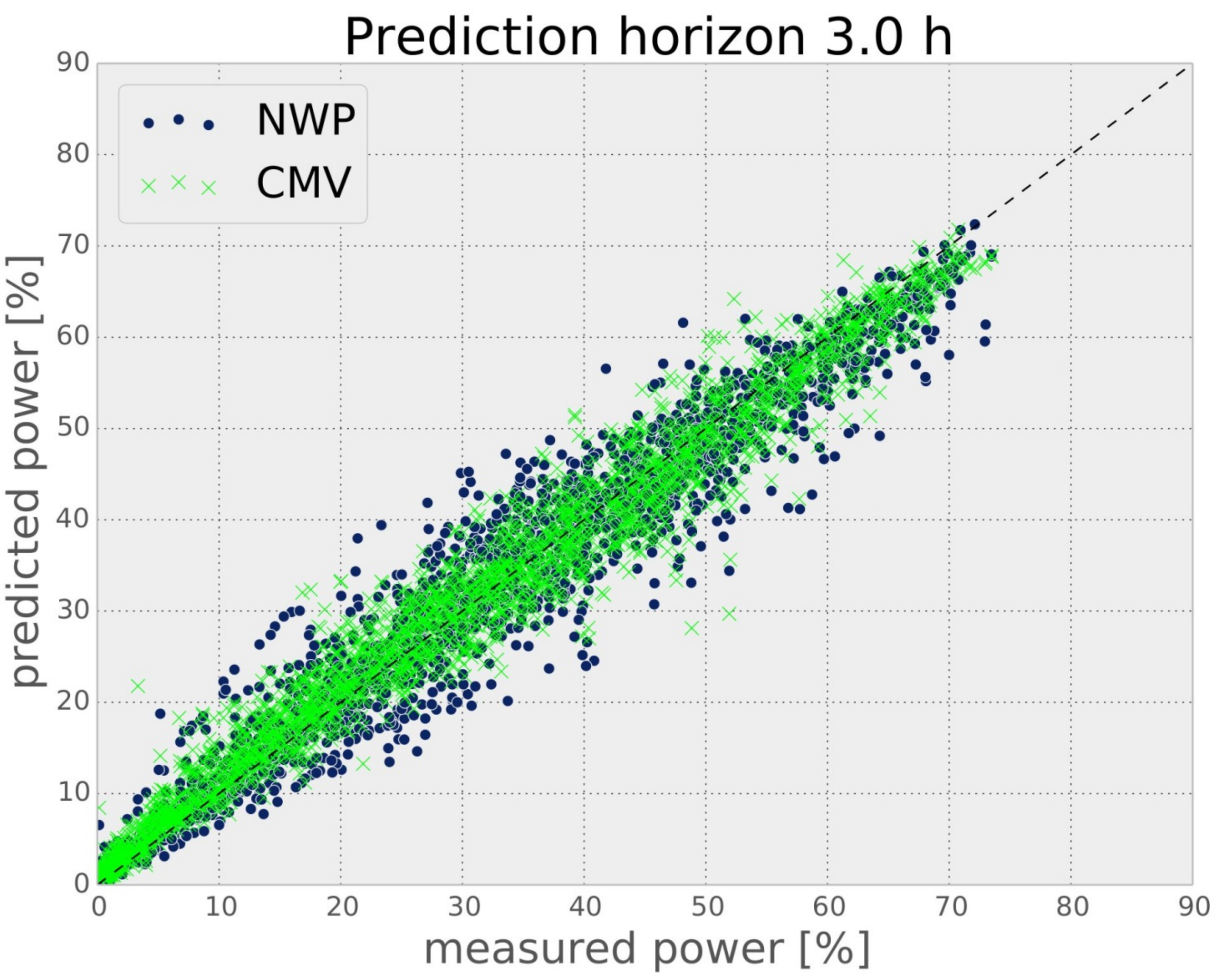

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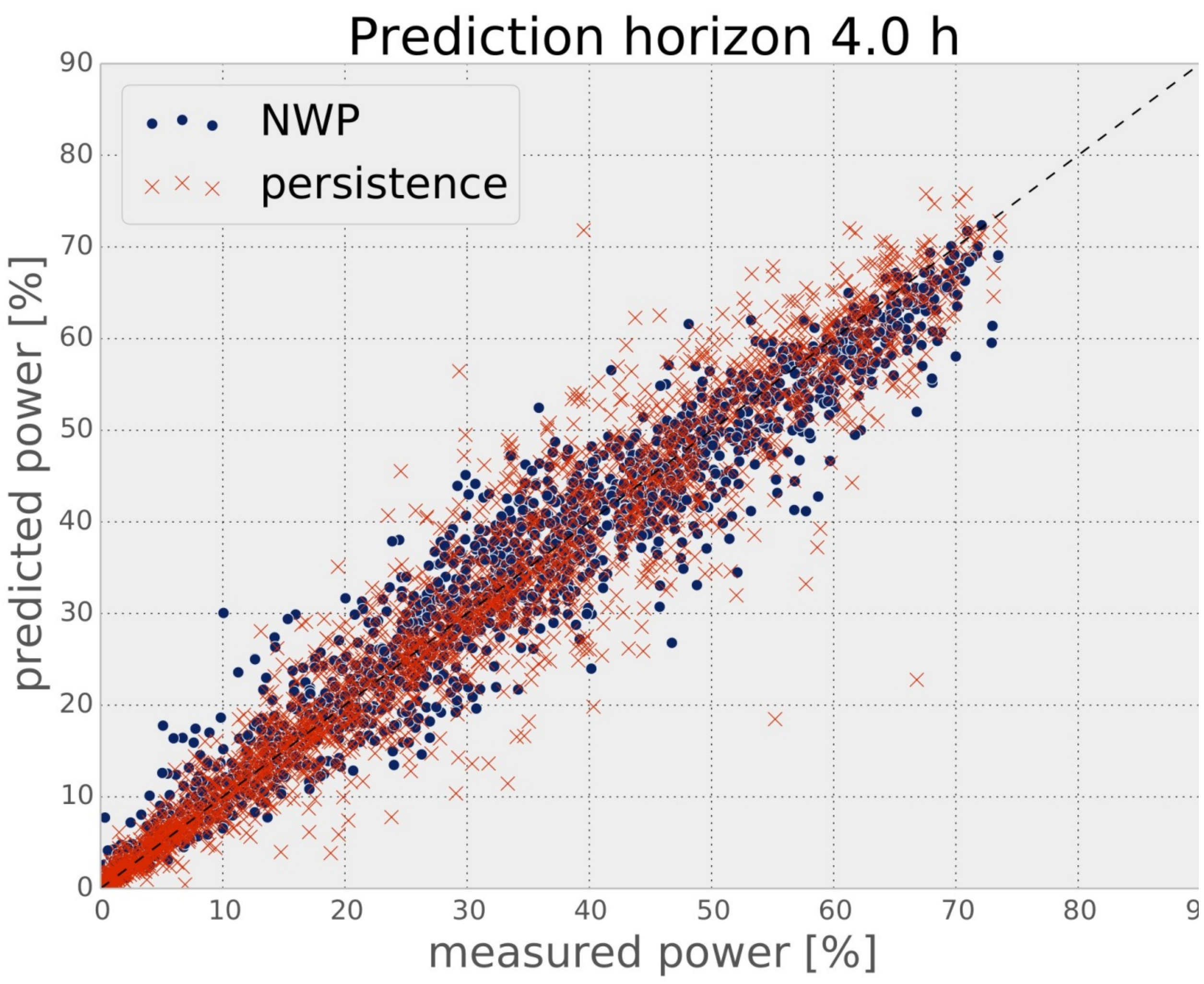
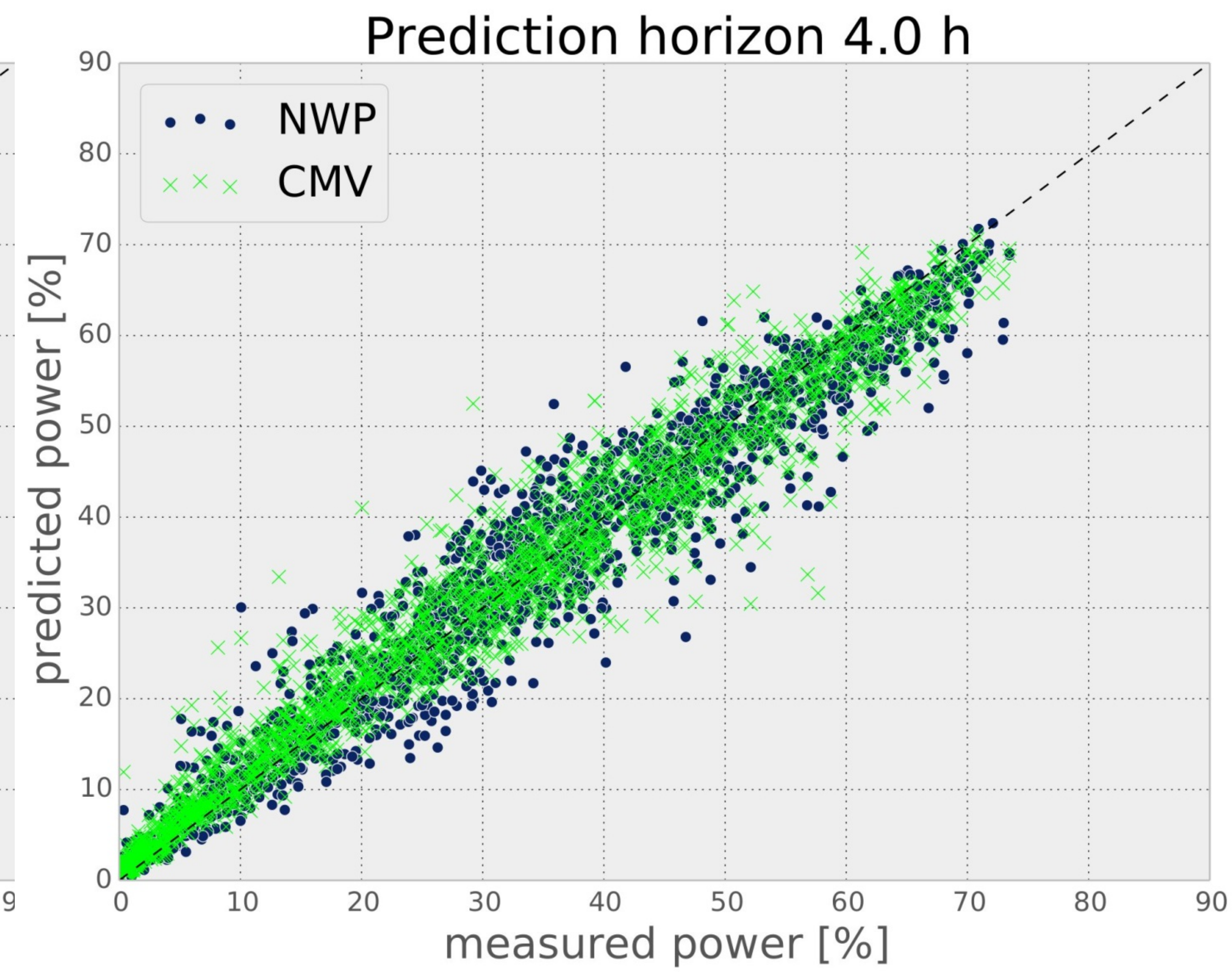
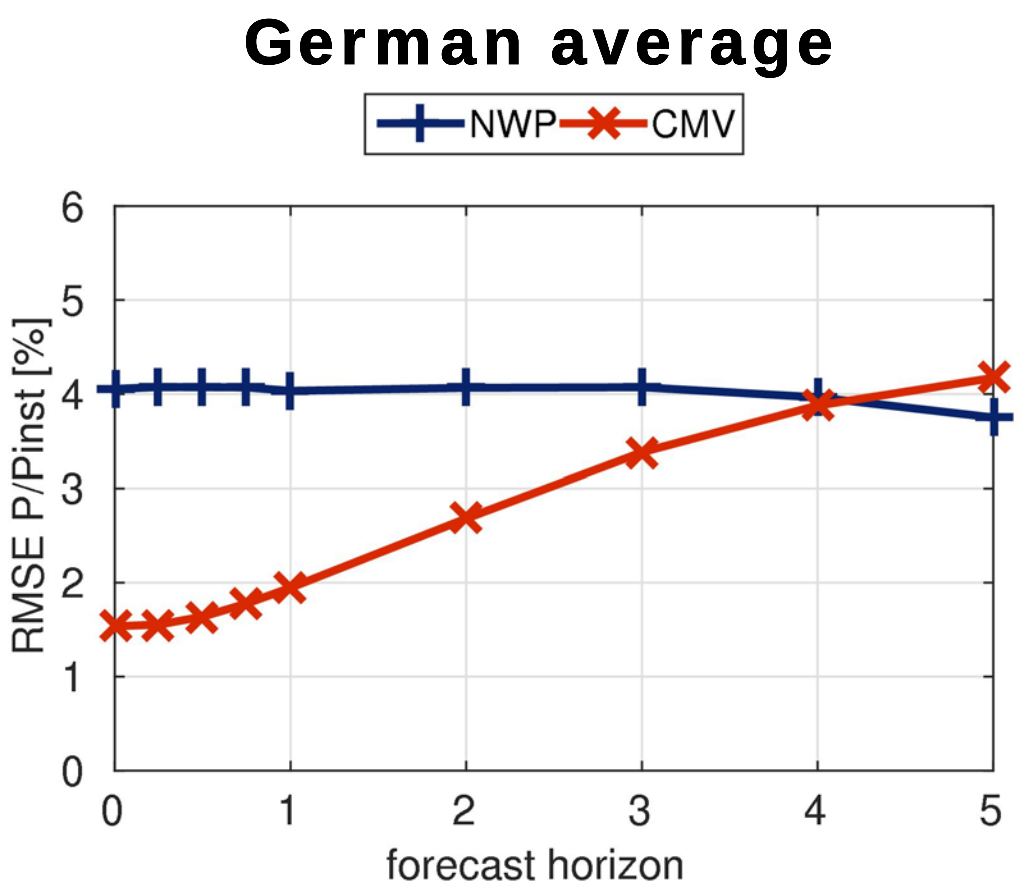




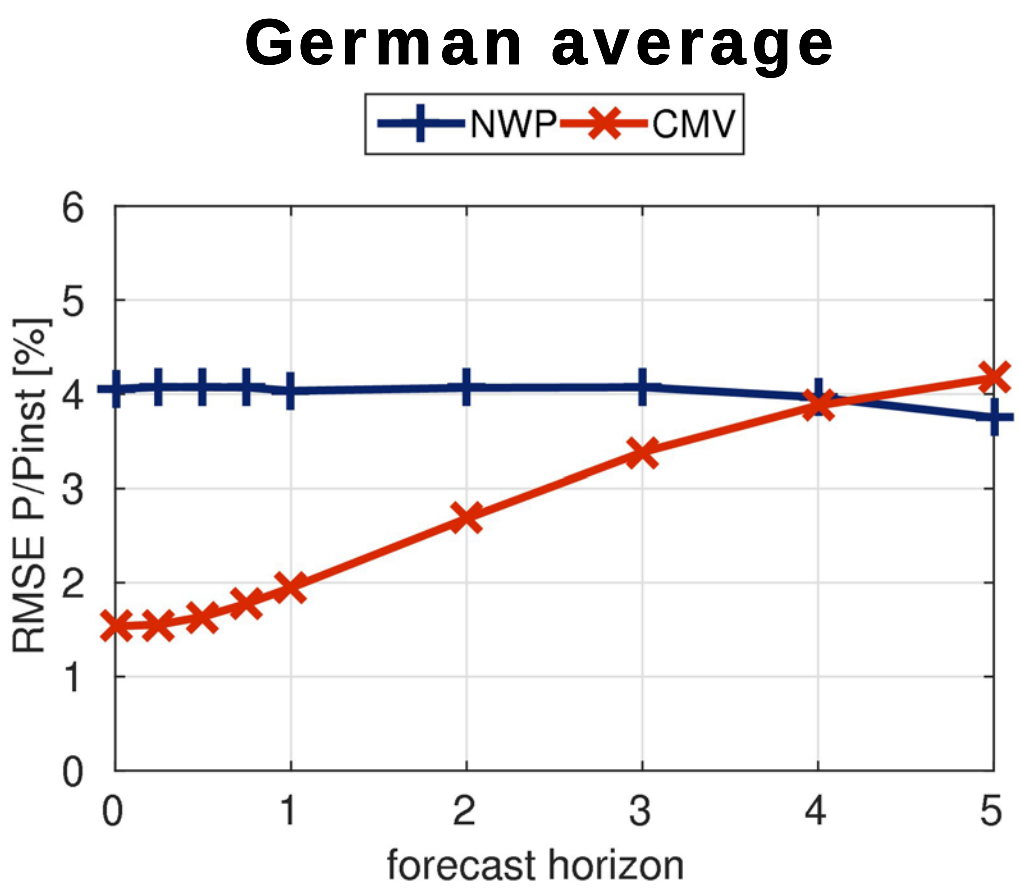
Rmse in dependence of forecast horizon



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

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



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

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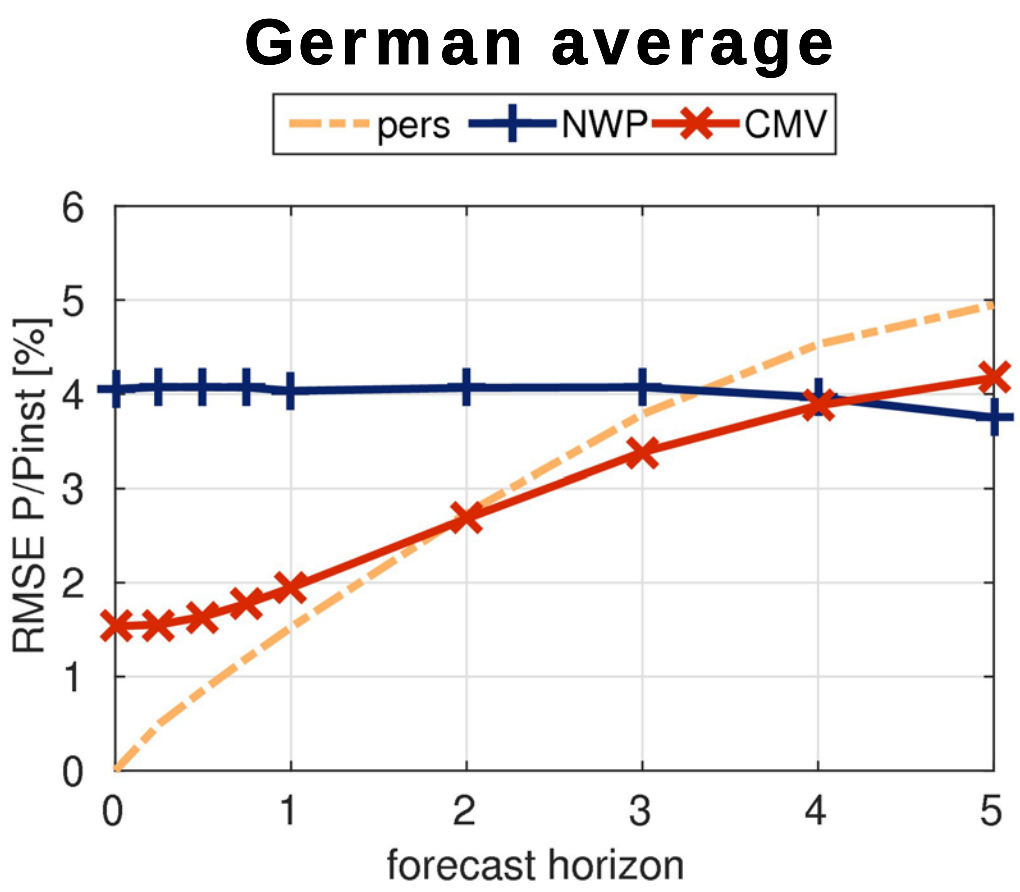
Rmse in dependence of forecast horizon



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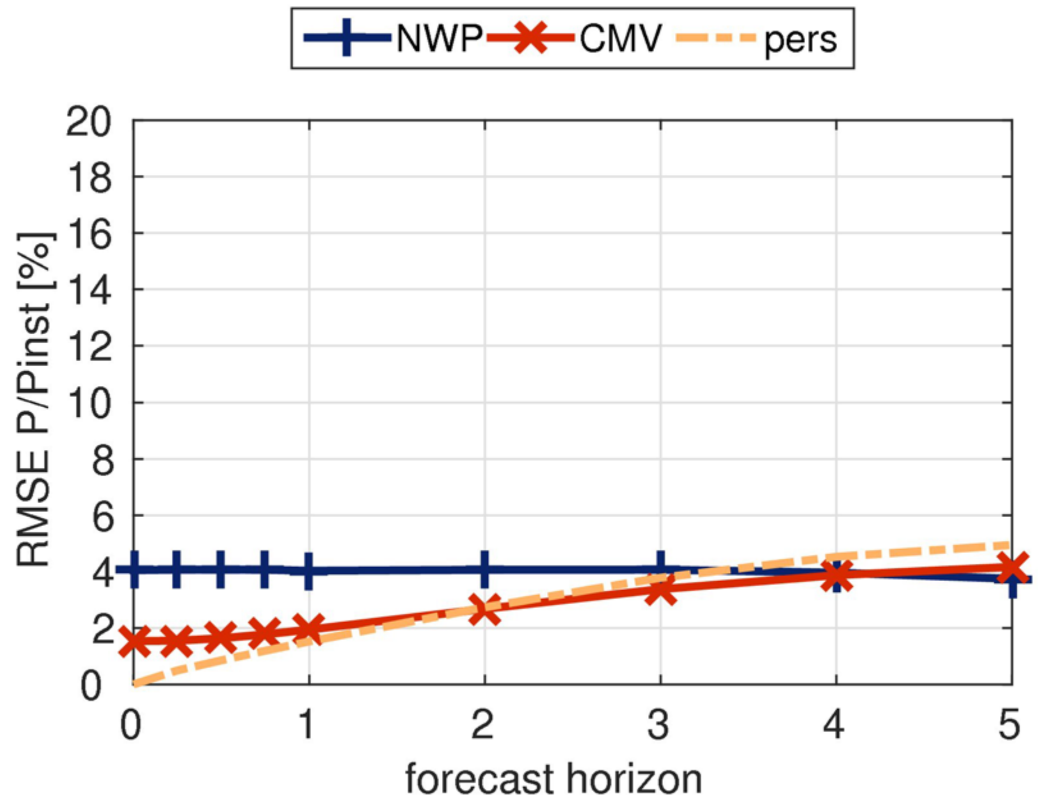
- CMV forecasts better than NWP based forecast up to 4 hours ahead
- persistence better than CMV forecasts up to 1.5 hour ahead

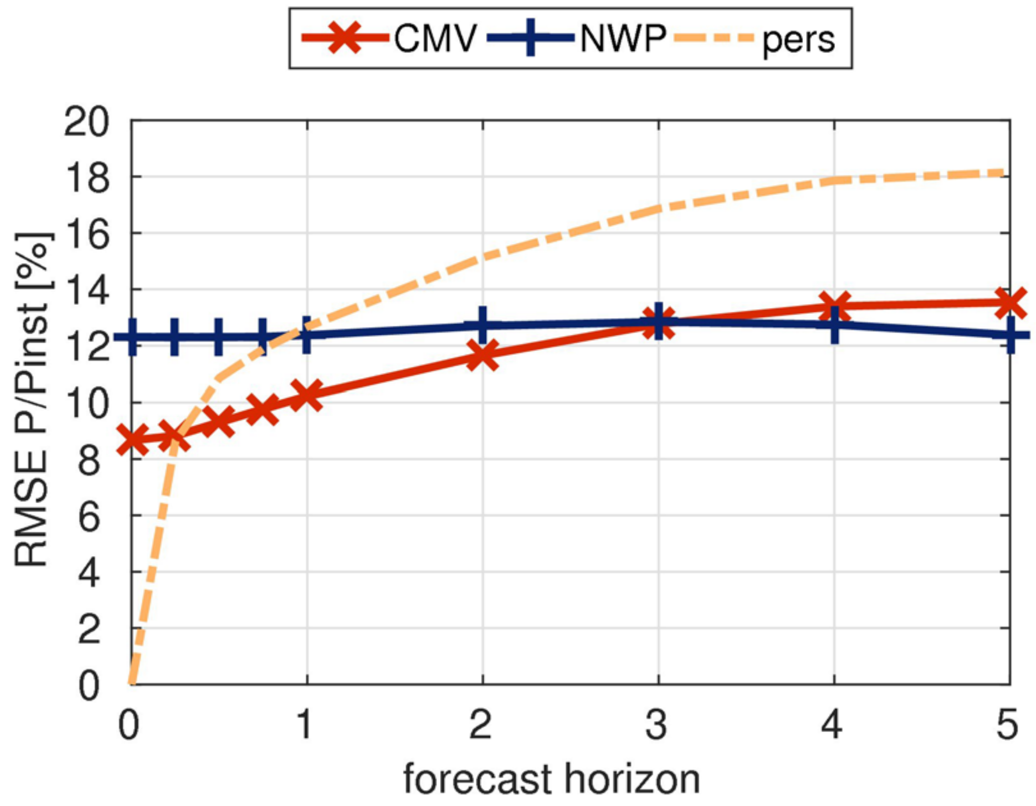
15 minute values
normalization to installed power P_{inst}
only daylight values, calculation time of CMV: sunel > 10°
only hours with all models available included in dependence of forecast horizon

Rmse in dependence of forecast horizon

German average



single sites

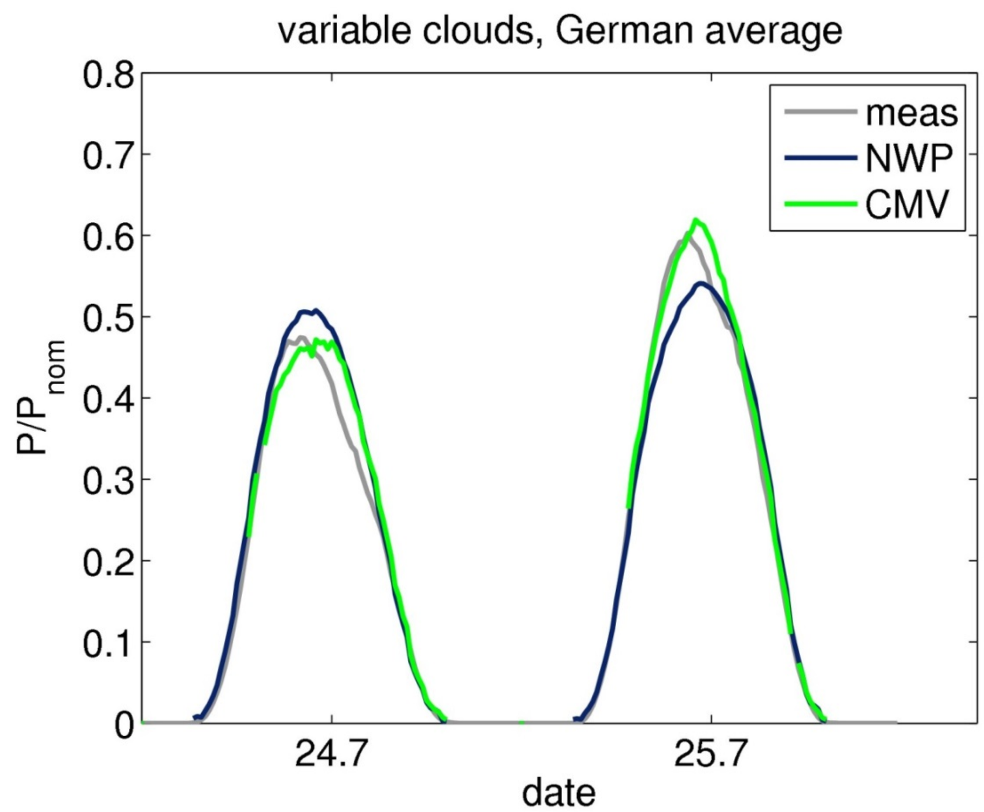


comparison of German average and single site forecasts:

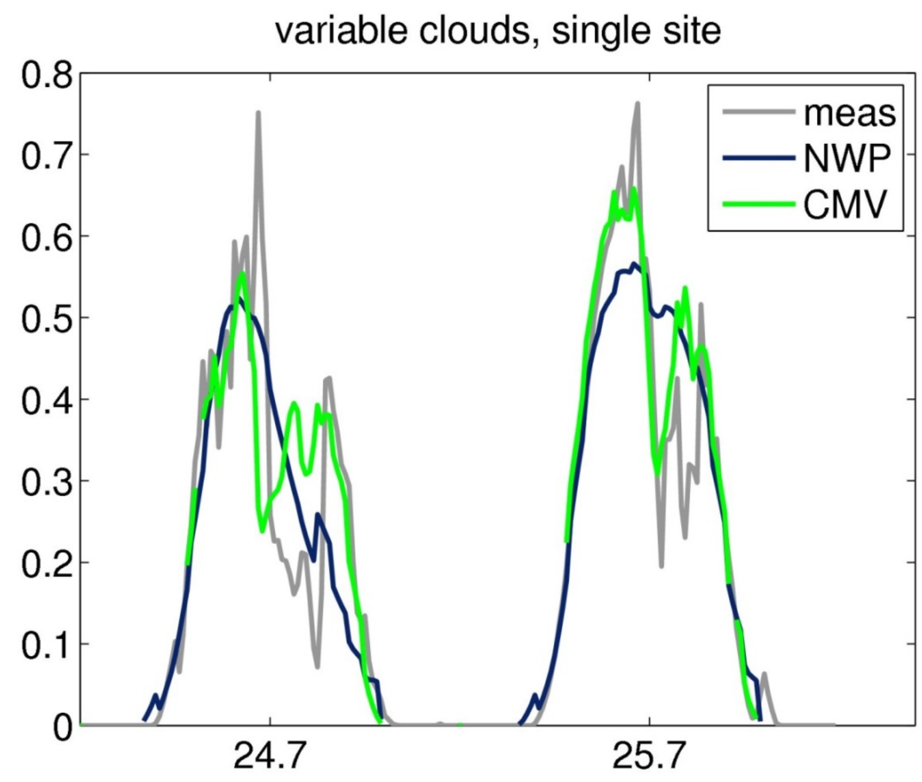
- German average RMSE about 1/3 of single site RMSE for NWP forecasts

Rmse in dependence of forecast horizon

German average



single sites



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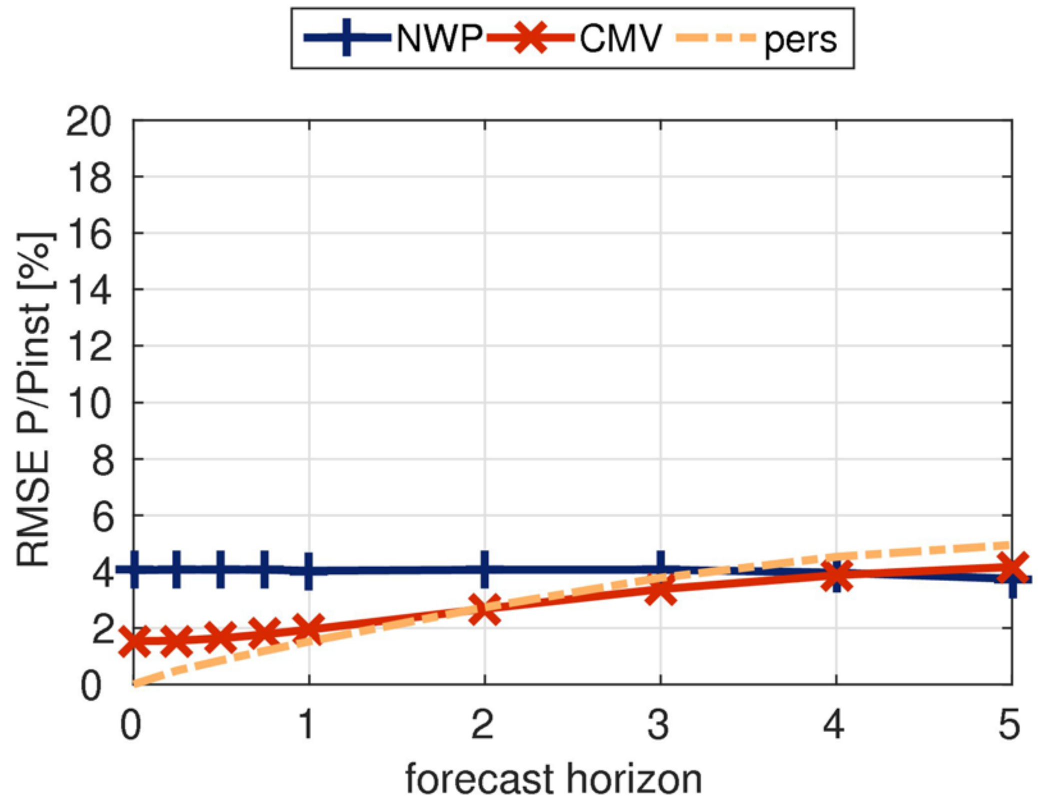
Rmse in dependence of forecast horizon

German average



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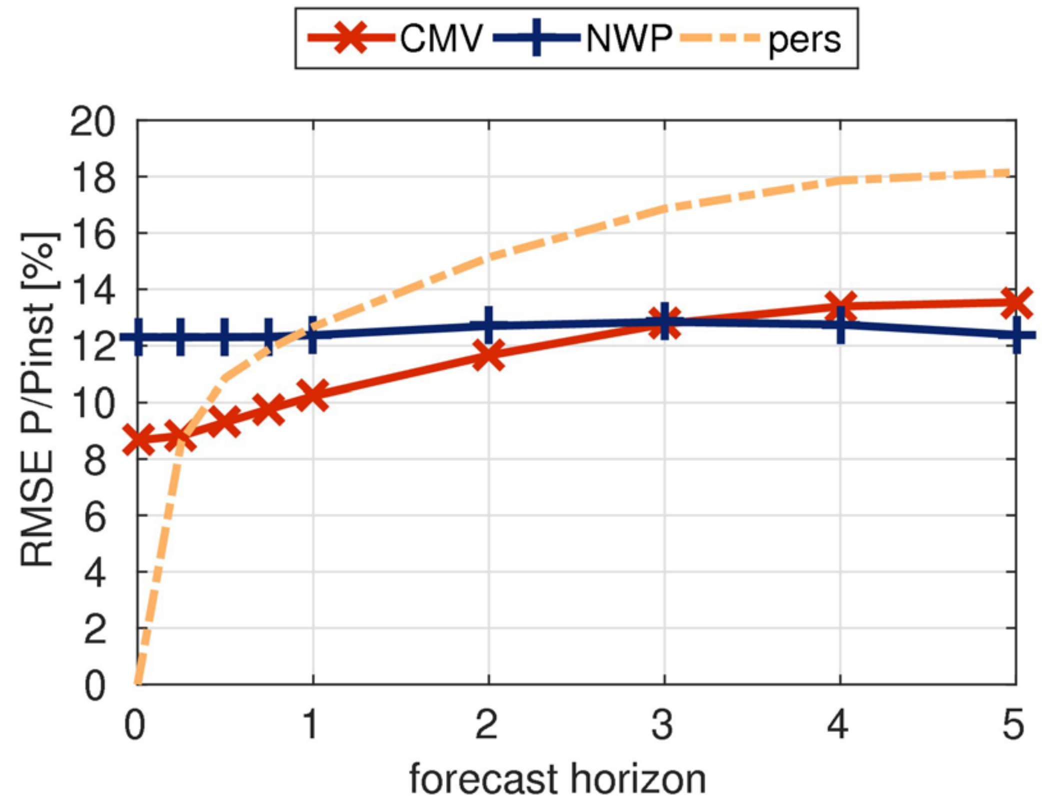

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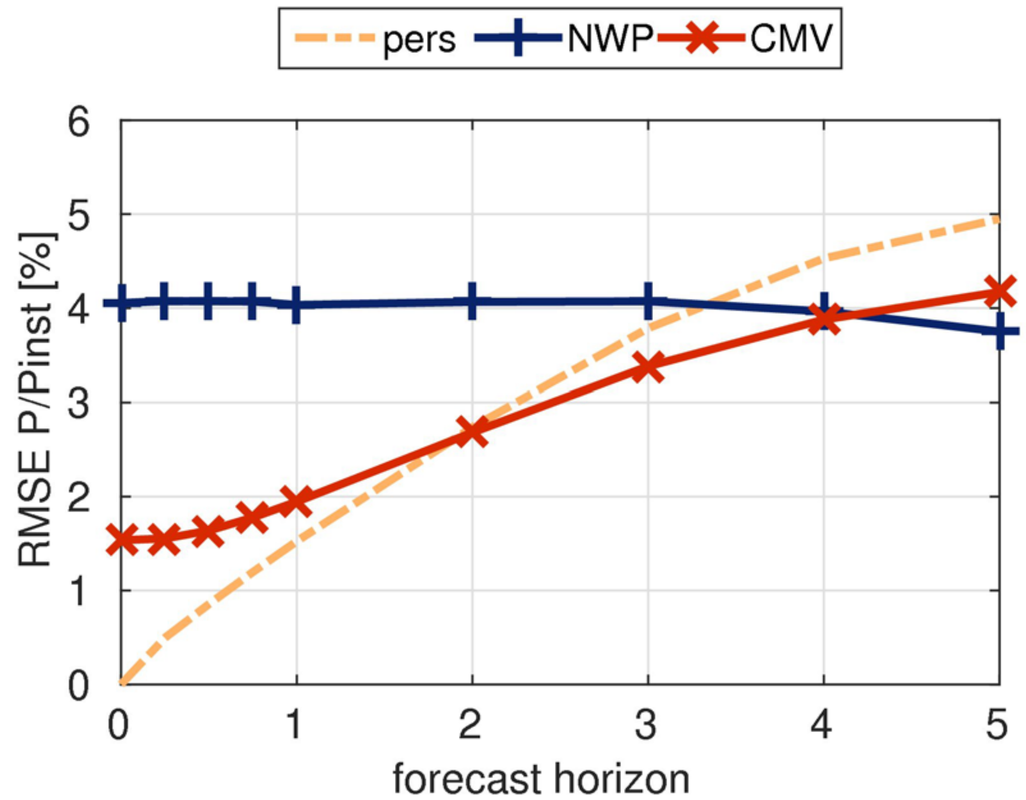
Rmse in dependence of forecast horizon

German average



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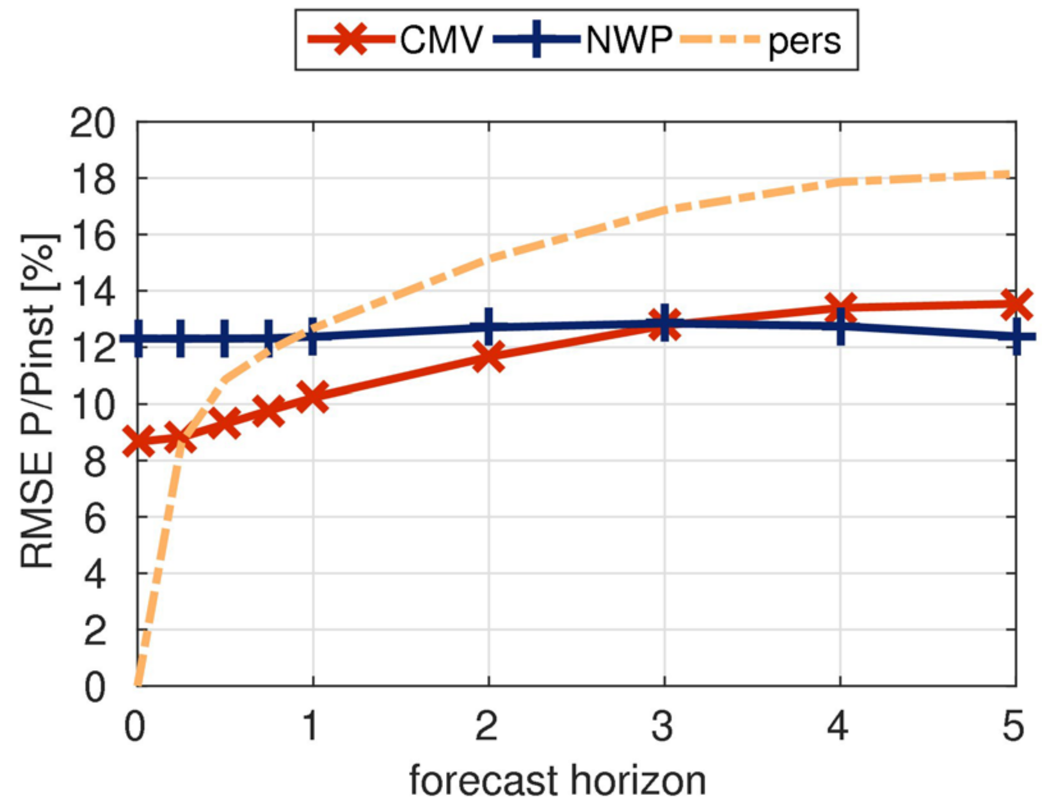
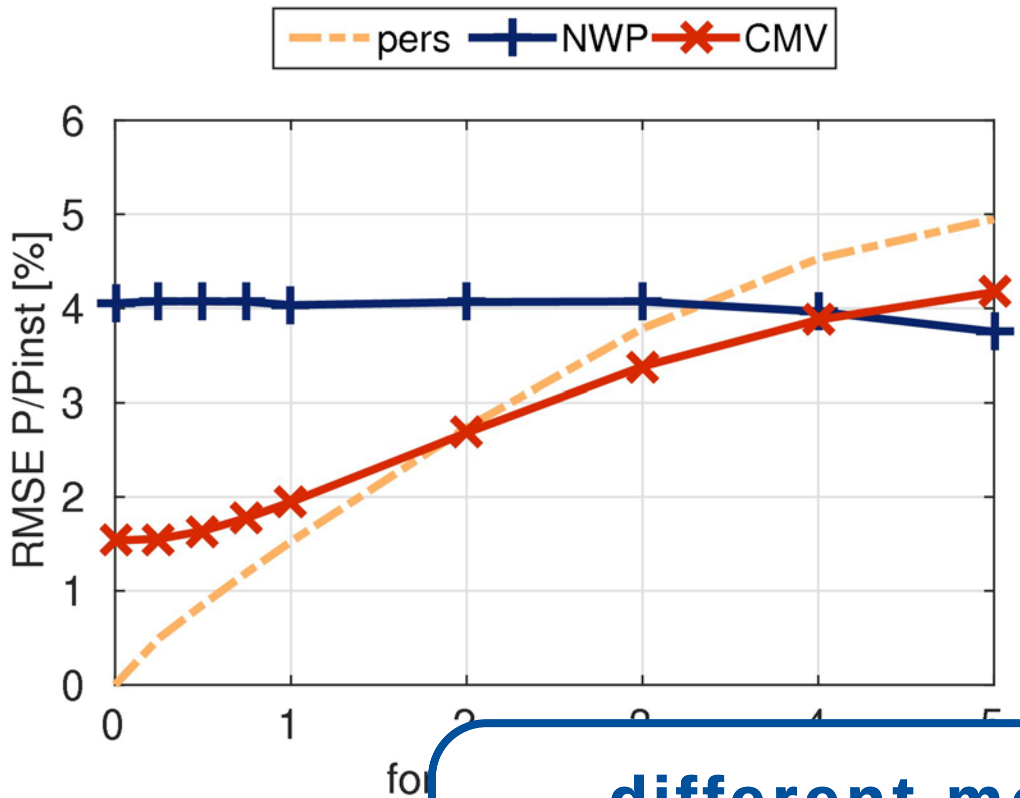


comparison of German average and single site forecasts:

- 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



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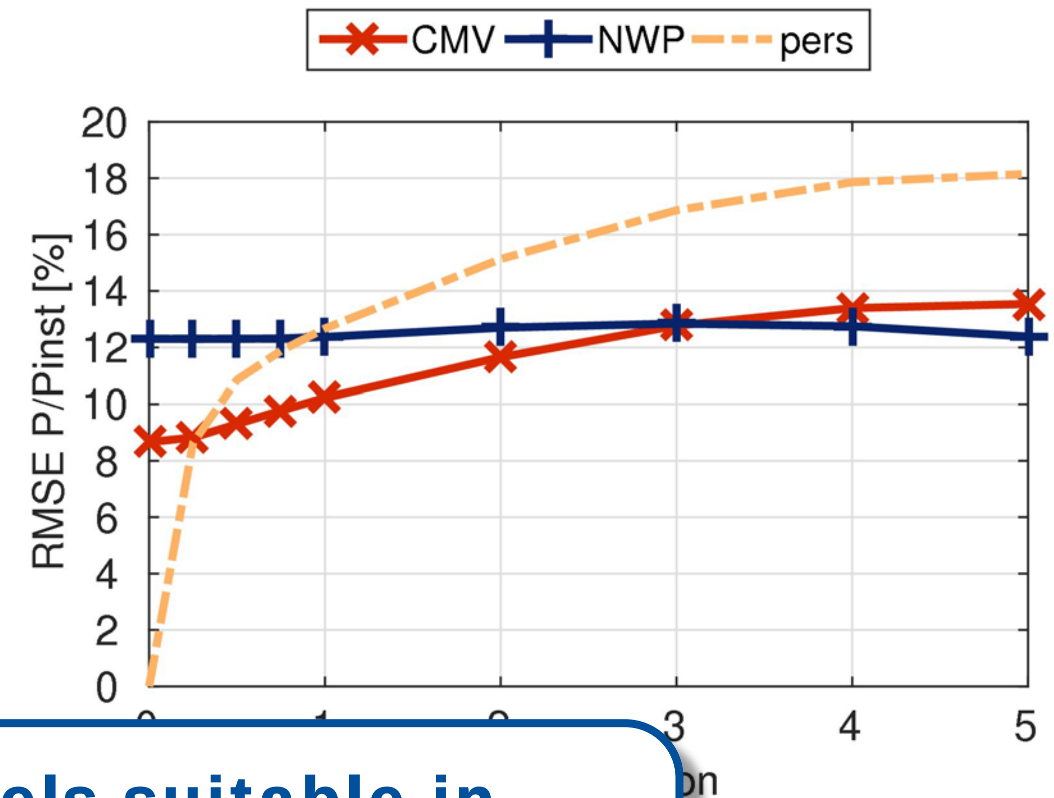
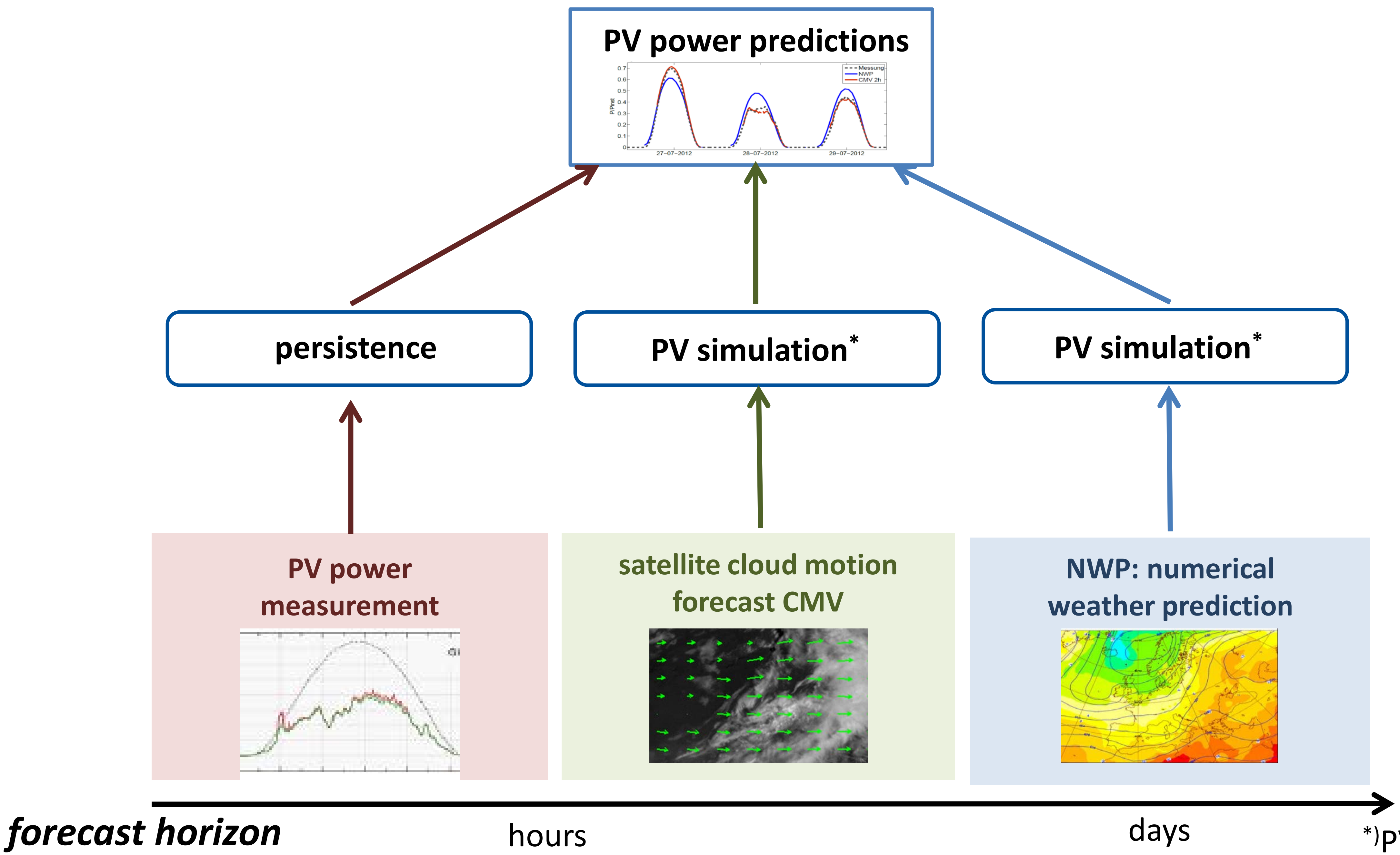


different models suitable in dependence of forecast horizon and spatial scale

comparis forecasts:

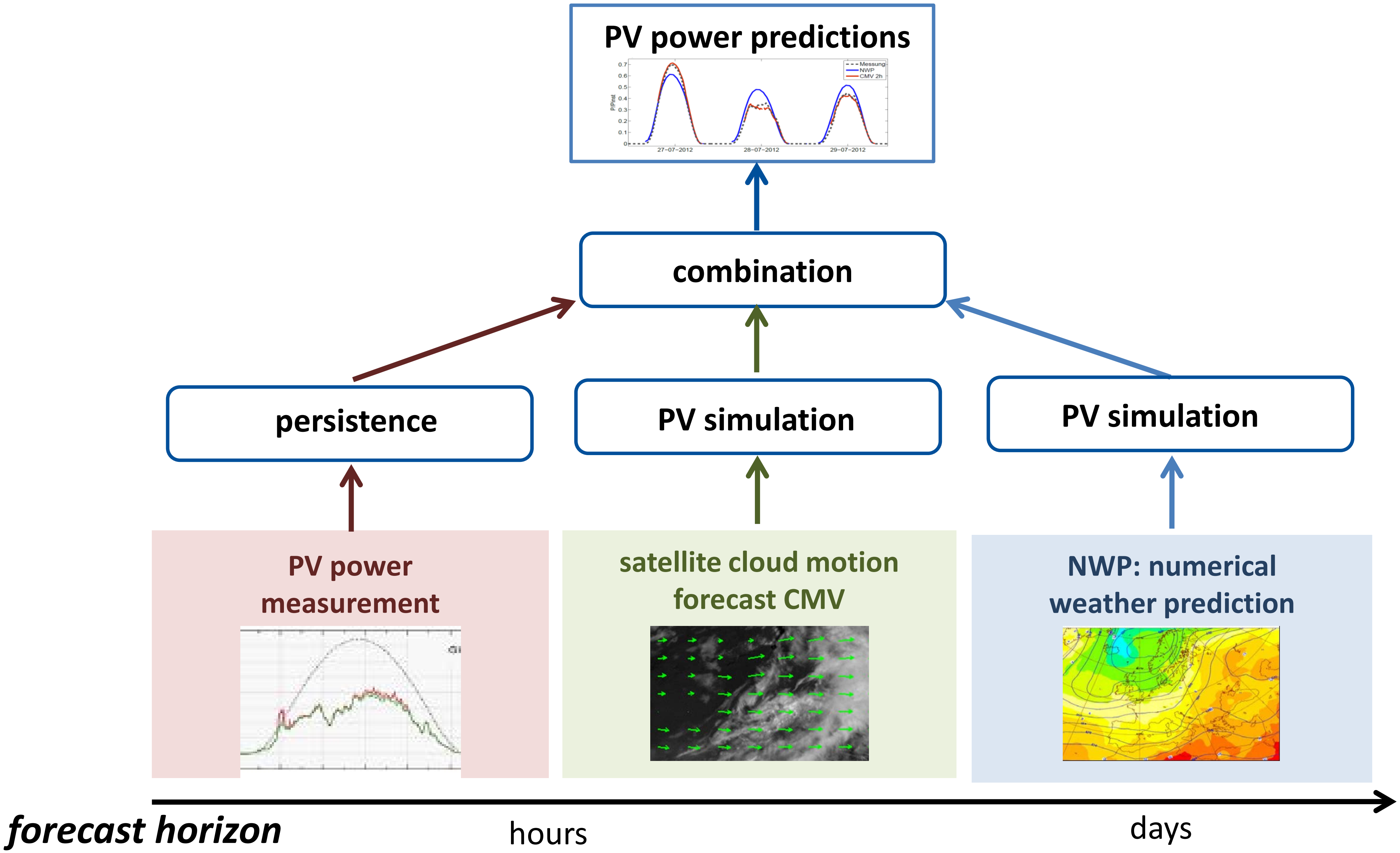
- German average RMSE about 1/3 of single sites RMSE for NWP forecasts
- improvements with persistence and CMV larger for regional forecasts

Different input data and models



*) PV simulation with bias correction

Combination of different models



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

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- forecast horizon
- hour of the day

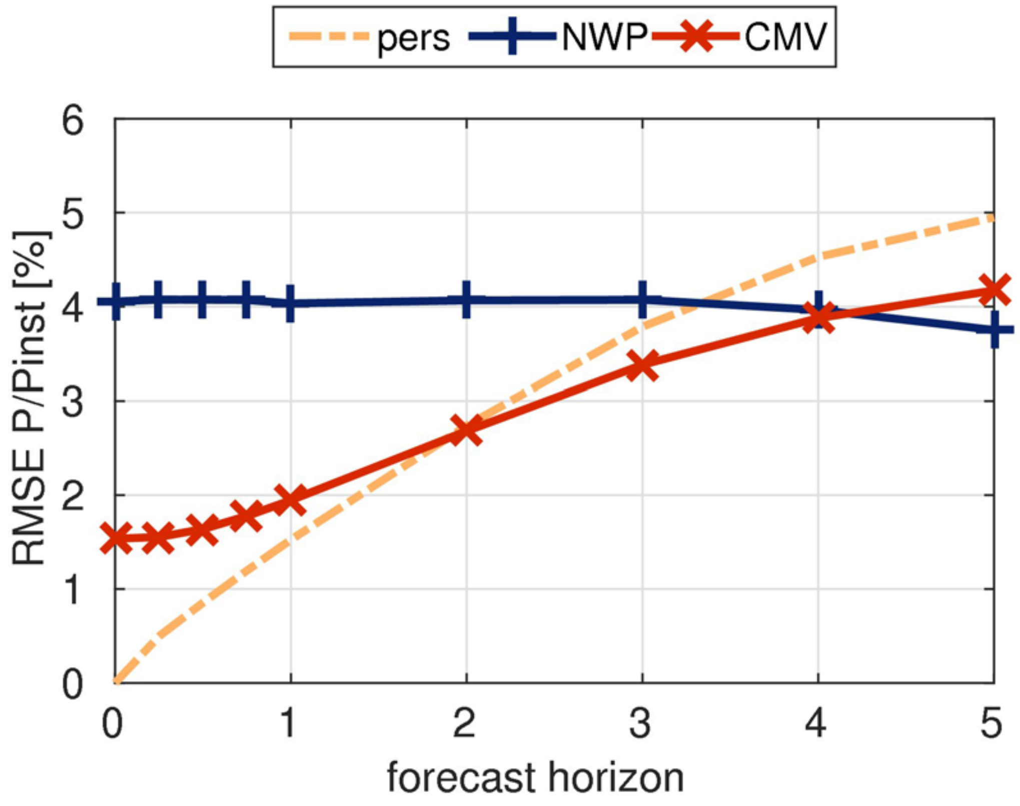
training data:

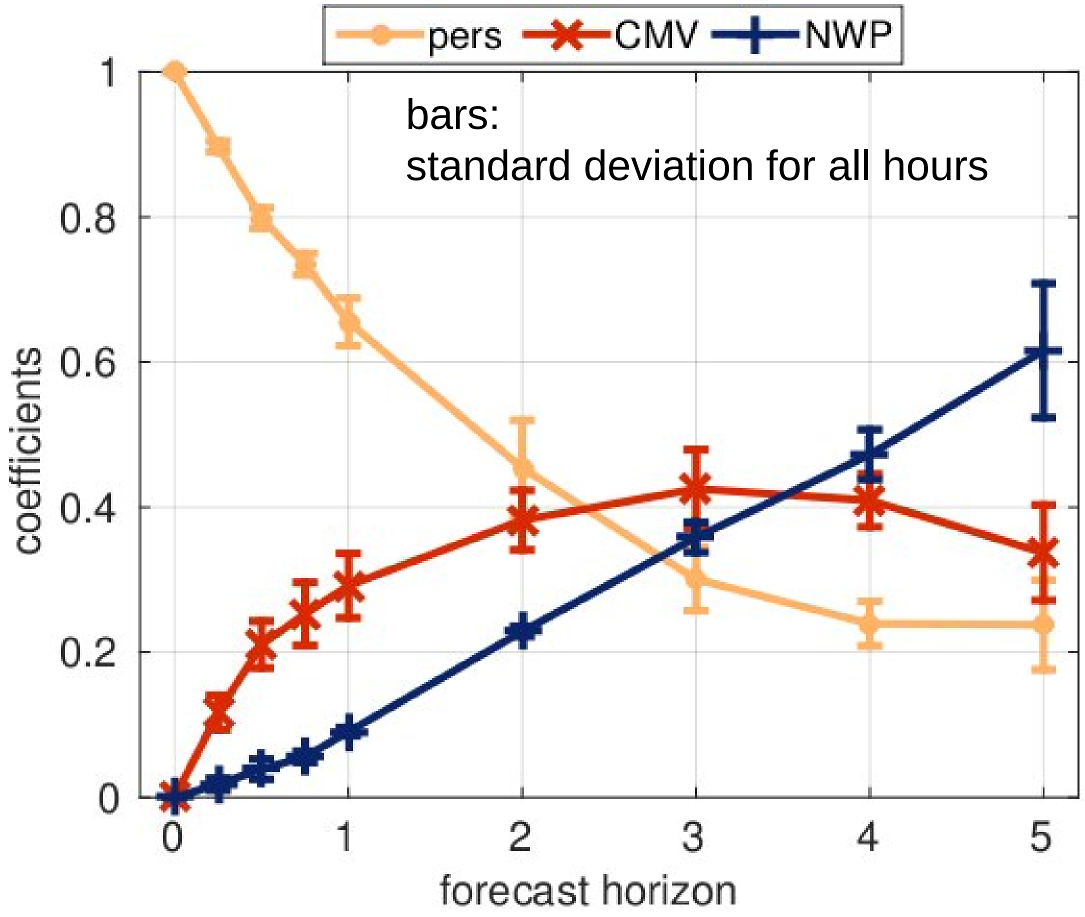
daily update with measurements of last 30 days

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

Regional forecasts

regression coefficients in dependence of **forecast horizon**

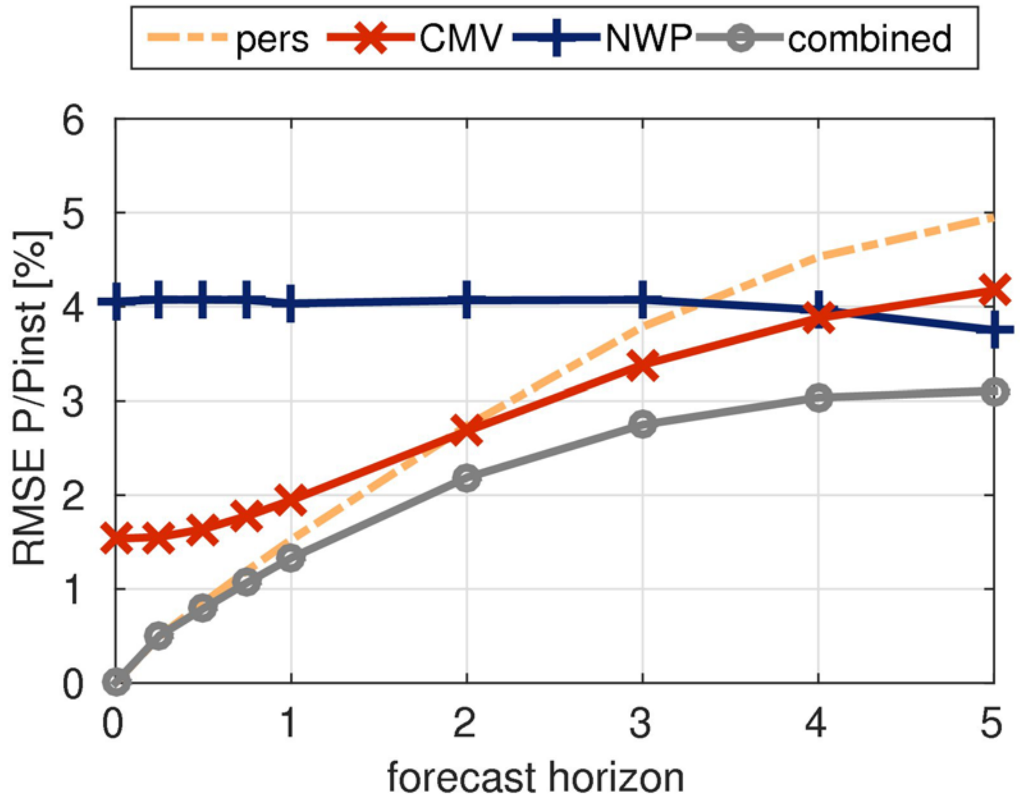




regression coefficients (weights) reflect horizon dependent forecast performance of different models

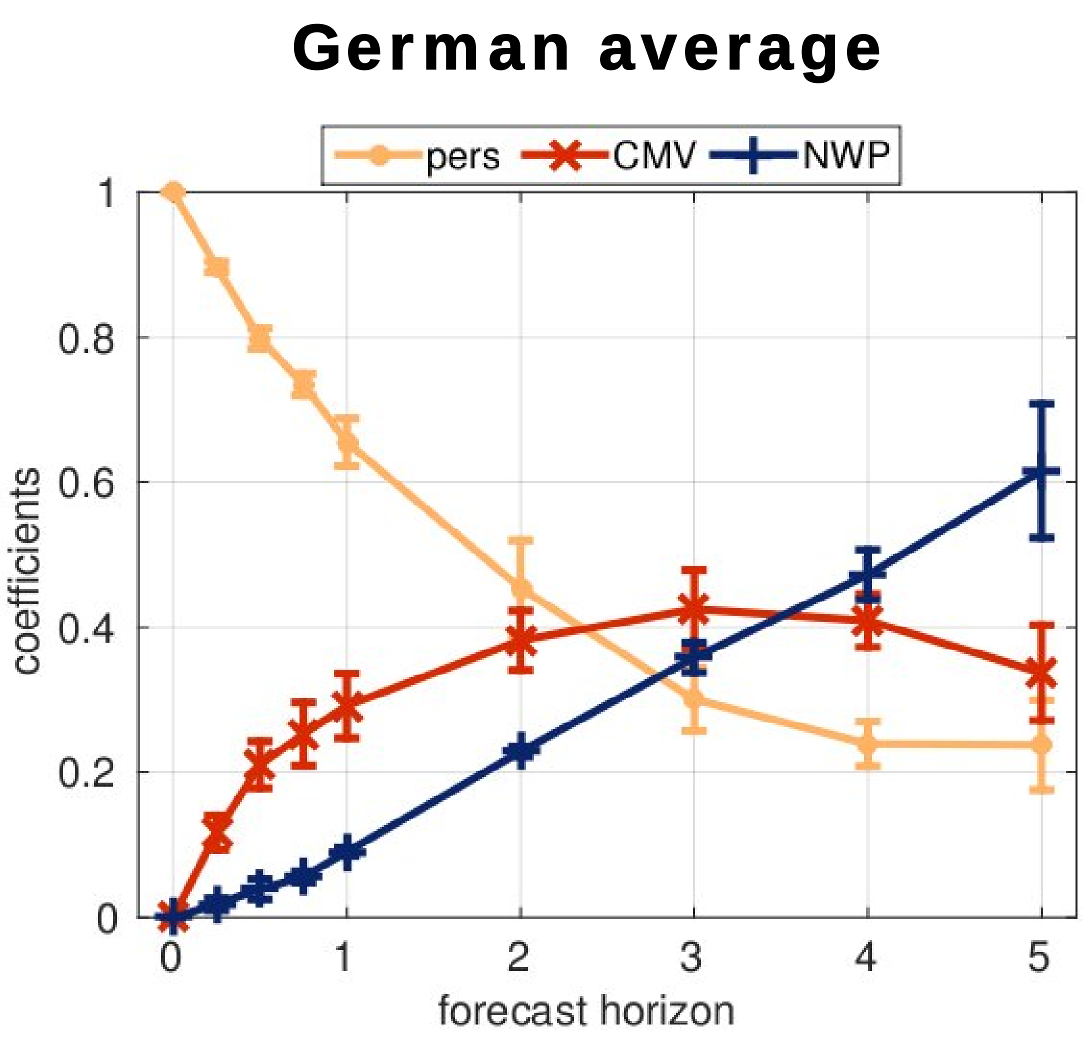
Regional forecasts

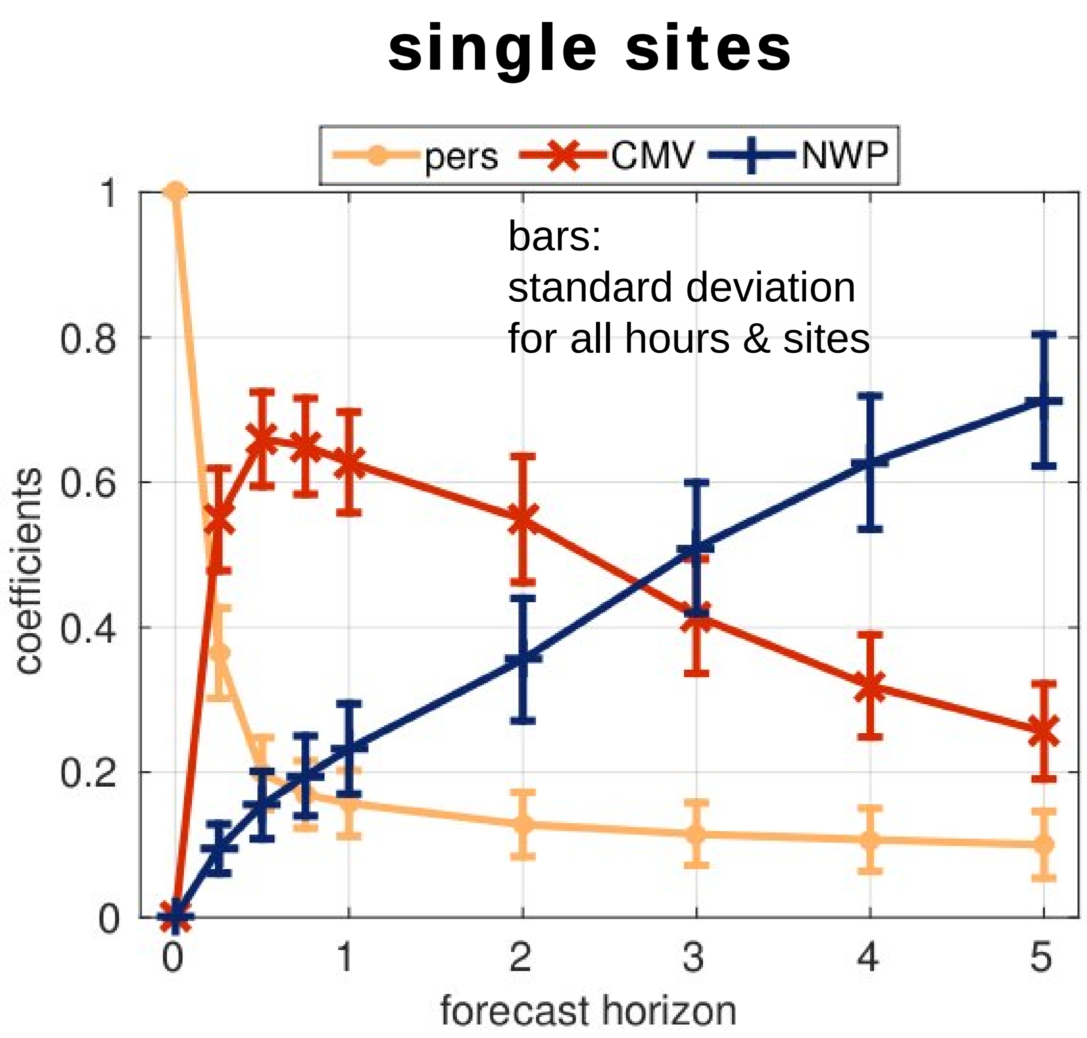
Rmse in dependence of forecast horizons



Considerable improvement with combined model over single model forecasts

Regression coefficients

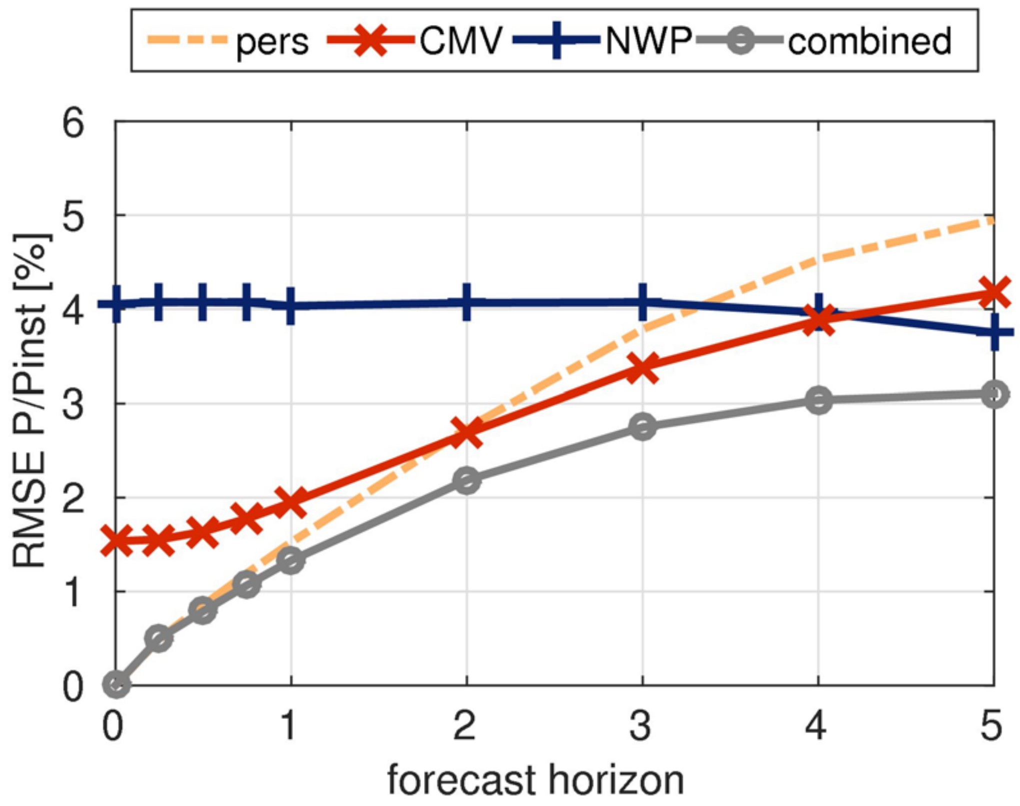




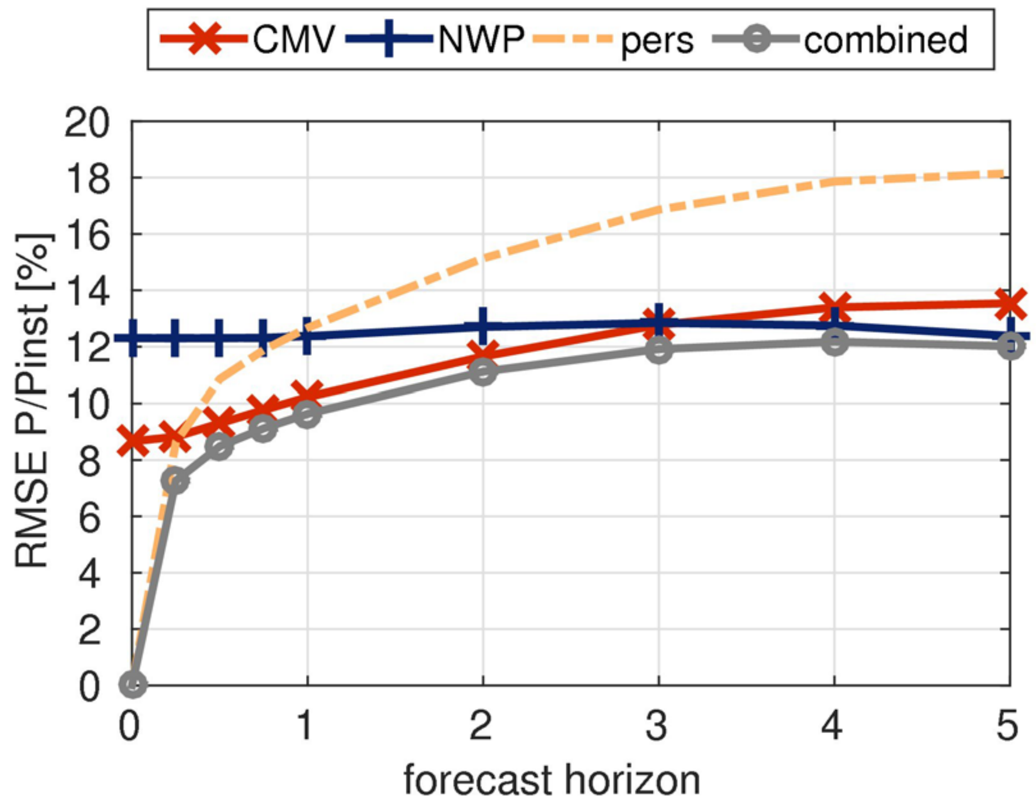
horizon dependent regression coefficients **different** for regional and single site forecasts

Rmse in dependence of forecast horizon

German average



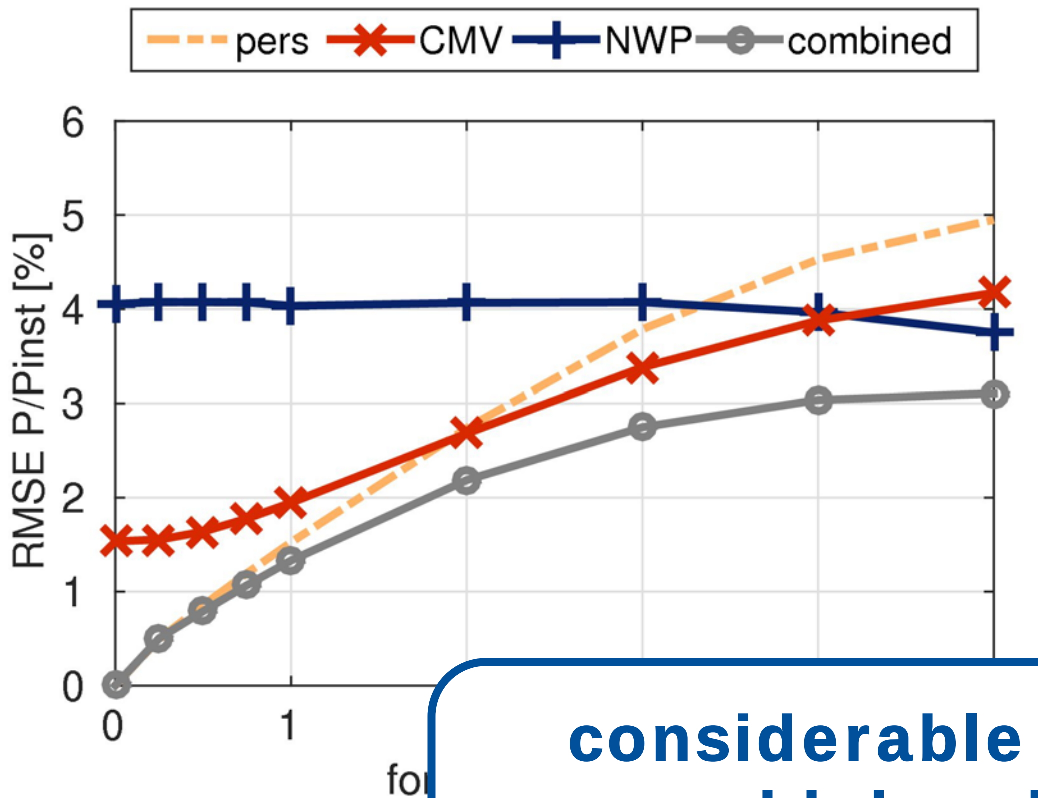
single sites



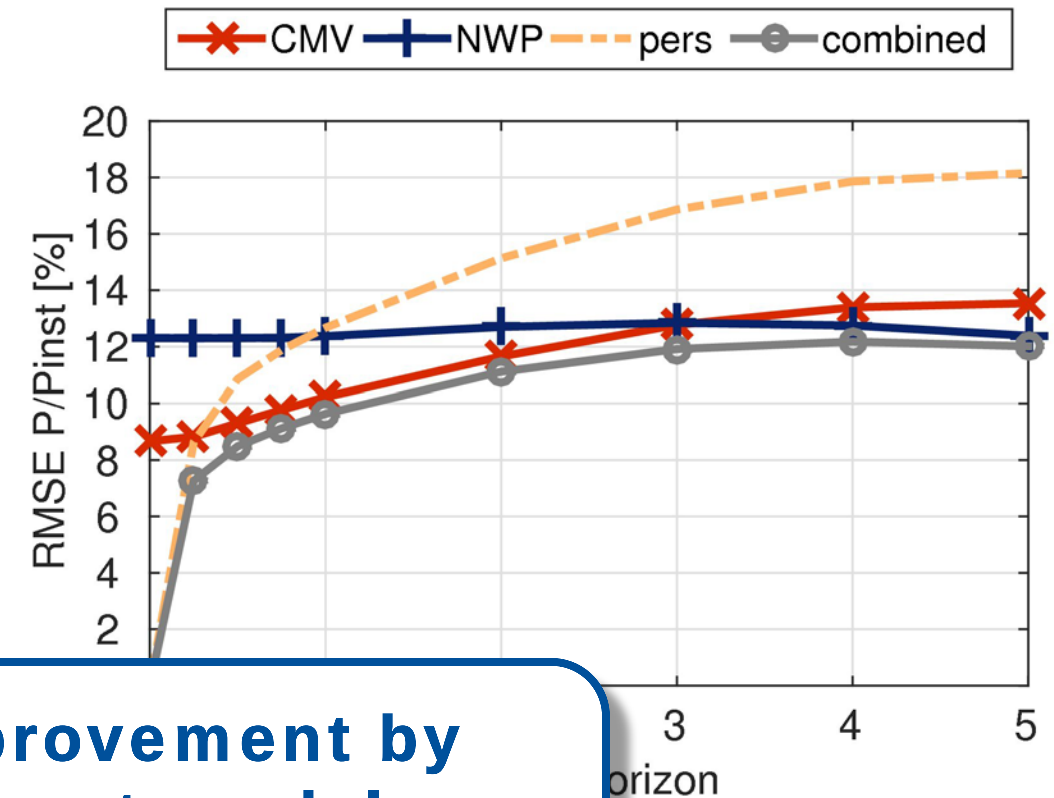
- forecast combination outperforms single model forecasts for all horizons
- improvements with combination larger for regional forecasts

Rmse in dependence of forecast horizon

German average



single sites



considerable improvement by combining different models with statistical learning

- forecast … del forecasts for all ho…
- improvements with combination larger for regional forecasts

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_{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

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Thank you for your attention!

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