Forecasting of Wind Power

Henrik Madsen

hm@imm.dtu.dk

Informatics and Mathematical Modelling, Technical University of Denmark

Offshore Center Denmark, March 2006

Outline

- Department of IMM at DTU
- System characteristics
- Configuration examples
- Reliable uncertainty intervals
- Value of forecasting
- Final remarks

Informatics and Mathematical Modelling

Informatics and Mathematical Modelling at DTU consists of the following sections:

- Informatics
  - Computer Science
  - Computer Engineering
- Mathematical Modelling
  - Geoinformatics
  - Image Processing and Computer Graphics
  - Signal Processing
  - Mathematical Physics
  - Numerical Analysis
  - Operations Research
  - Mathematical Statistics

The main participants in research activities related to wind power prediction are the from the **Section of Mathematical Statistics**.

Prediction of wind power

In areas such as the Western part of Denmark and the Northern part of Germany, reliable wind power predictions are needed in order to ensure safe and economic operation of the power system.

Accurate wind power predictions are needed with different prediction horizons in order to ensure

- (a few hours) efficient and safe use of regulation power (spinning reserve) and the transmission system,
- (12 to 36 hours) efficient trading on the Nordic power exchange, NordPool,
- (days) optimal operation of eg. large CHP plants.

Predictions of wind power are needed both for the total supply area as well as on a regional scale and for a single wind farm.

For all major Danish power utilities with respect to wind power the required wind power predictions are provided by a prediction tool – **Wind Power Prediction Tool (WPPT)** – developed at IMM/DTU.

DTU

Modelling approach – the grouping

WPPT can be used to predict the power production for individual wind farms (offshore or onshore), or for wind turbines distributed over a larger area. The wind turbines in the region may be grouped according to:

- Geographical distribution ideally following the weather regions.
- Legislation governing the connection (in Denmark the wind turbines in each sub-area have been grouped in prioritized production and non-prioritized production).
- Other relevant criterias.

Modelling approach – the input

Depending on the configuration WPPT requires input from the following sources:

- Online measurements of wind farm prod. (updated every 5min. – 1hr).
- Aggregated high resolution energy readings from all wind turbines in the groups defined above (updated with a delay of 3-5 weeks).
- Forecasts of wind speed and wind direction covering wind farms and sub-areas (horizon 0–48(120)hrs updated 2–4 times a day).
- Other measurements/predictions (local wind speed, stability, etc. can be used)

System characteristics

The total system consisting of wind farms measured online, wind turbines not measured online and meteorological forecasts will inevitably change over time as:

- the population of wind turbines changes,
- changes in unmodelled or insufficiently modelled characteristics (important examples: roughness and dirty blades),
- changes in the NWP models.

A wind power prediction system must be able to handle these time-variations in model and system. WPPT employes adaptive and recursive model estimation to handle this issue.

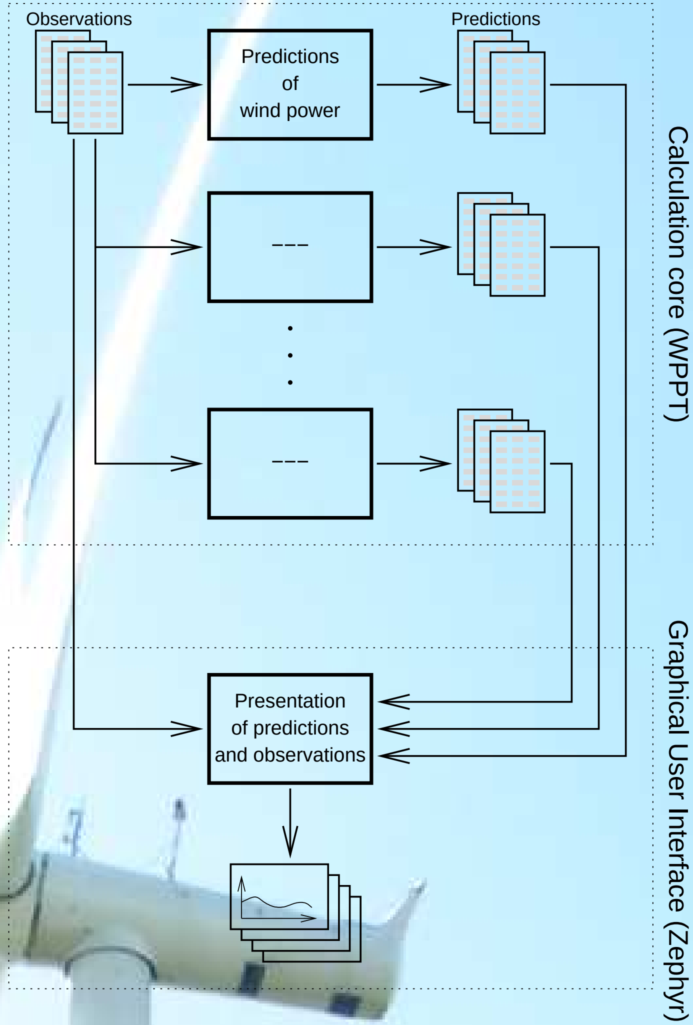
Following the initial installation WPPT will automatically calibrate the models to the actual situation.

The current WPPT implementation

WPPT/Zephyr is implemented as a client–server setup with a graphical user interface (client) and a prediction model core (server).

The prediction model core is implemented in two versions:

- **Prediktor/Zephyr:** An implementation of Prediktor model from Risø for cases with no use of on-line measurement data.
- **WPPT/Zephyr:** An implemetation of the model set developed at IMM which also considers on-line data.



The power curve model

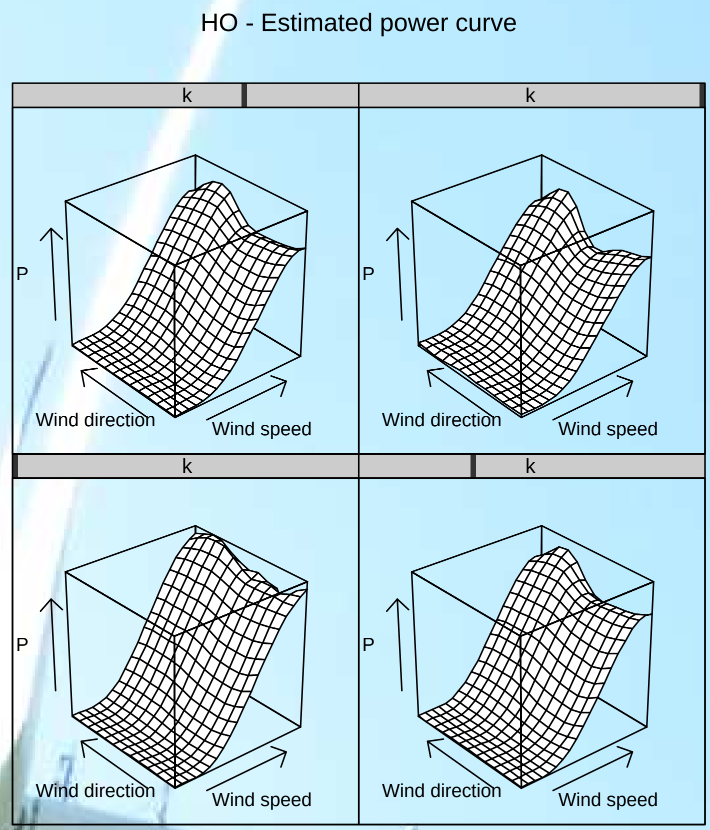
The wind turbine "power curve" model, $p^{tur} = f(w^{tur})$ is extended to a wind farm model, $p^{wf} = f(w^{wf}, \theta^{wf})$, by introducing wind direction dependency. By introducing a representative area wind speed and direction it can be further extended to cover all turbines in an entire region, $p^{ar} = f(\bar{w}^{ar}, \bar{\theta}^{ar})$.

The power curve model is defined as:

$$\hat{p}_{t+k|t} = f(\ \bar{w}_{t+k|t},\ \bar{\theta}_{t+k|t},\ k\ )$$

where
$\bar{w}_{t+k|t}$ is forecasted wind speed, and
$\bar{\theta}_{t+k|t}$ is forecasted wind direction.

The characteristics of the NWP change with the prediction horizon. Hence the dependency of prediction horizon *k* in the model.



Plots of the estimated power curve for the Hollandsbjerg wind farm (k = 0, 12, 24 and 36 hours).

The dynamical prediction model

The dynamical prediction model for power production in wind farms and regions is given as

$$p_{t+k|t} = a_1 p_t + a_2 p_{t-1} + b\,\hat{p}^{pc}_{t+k|t} + \sum_{i=1}^{3} [c_i^c \cos \frac{2i\pi h^{24}_{t+k}}{24} + c_i^s \sin \frac{2i\pi h^{24}_{t+k}}{24}] + m + e_{t+k}$$

where p_t is observed power production, $k \in [1; 48]$ (hours) is prediction horizon, $\hat{p}^{pc}_{t+k|t}$ is power curve prediction and h^{24}_{t+k} is time of day.

Model features include

- multi-step prediction model to handle non-linearities and unmodelled effects,
- the number of terms in the model depends on the prediction horizon,
- non-stationarity are handled by adaptive estimation of the model parameters,
- the deviation between observed and forecasted diurnal variation is model by a Fourier expansion.

A model for upscaling

The dynamic upscaling model for a region is defined as:

$$\hat{p}^{reg}_{t+k|t} = f(\ \bar{w}^{ar}_{t+k|t},\ \bar{\theta}^{ar}_{t+k|t},\ k\ )\ \hat{p}^{loc}_{t+k|t}$$

where

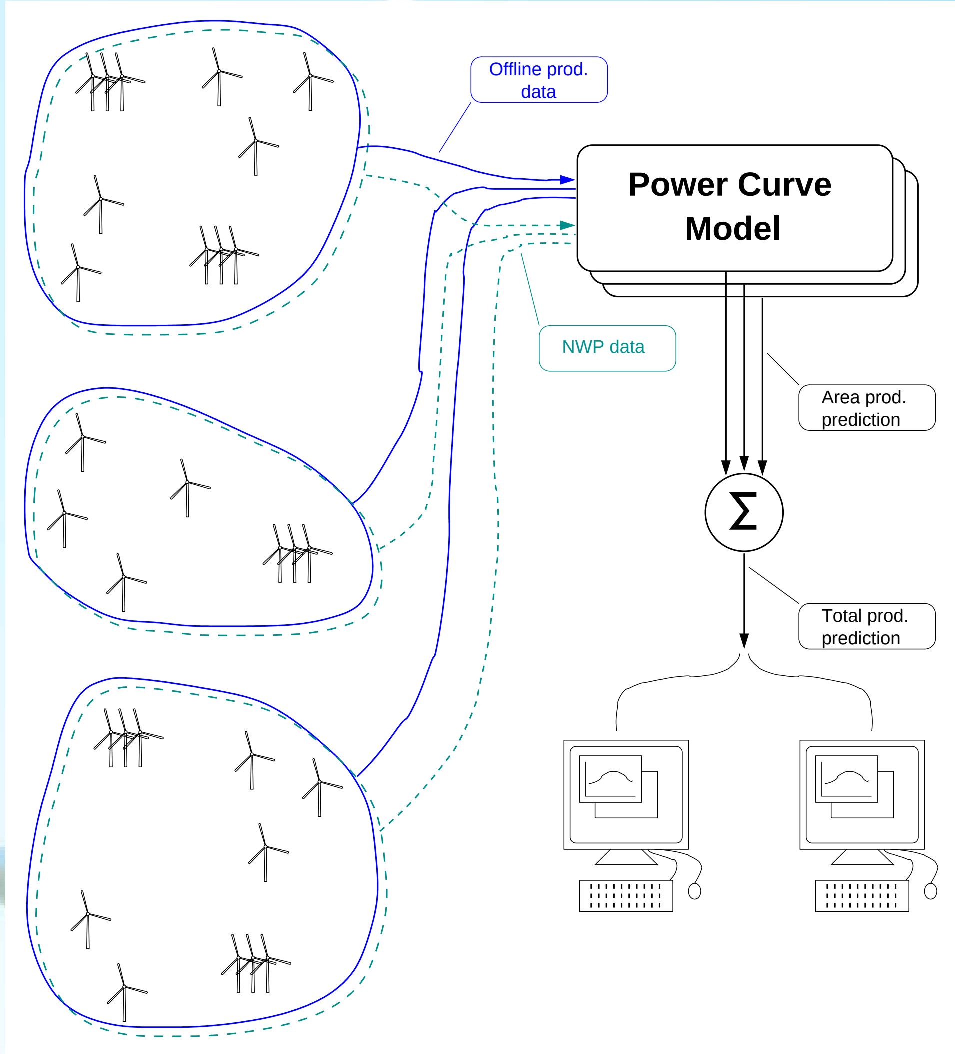
$\hat{p}^{loc}_{t+k|t}$ is a local (dynamic) power prediction within the region,
$\bar{w}^{ar}_{t+k|t}$ is forecasted regional wind speed, and
$\bar{\theta}^{ar}_{t+k|t}$ is forecasted regional wind direction.

The characteristics of the NWP and $\hat{p}^{loc}$ change with the prediction horizon. Hence the dependendency of prediction horizon k in the model.

Configuration Example No. 1

This configuration of WPPT is used by a TSO in Denmark. The following characterizes the installation:

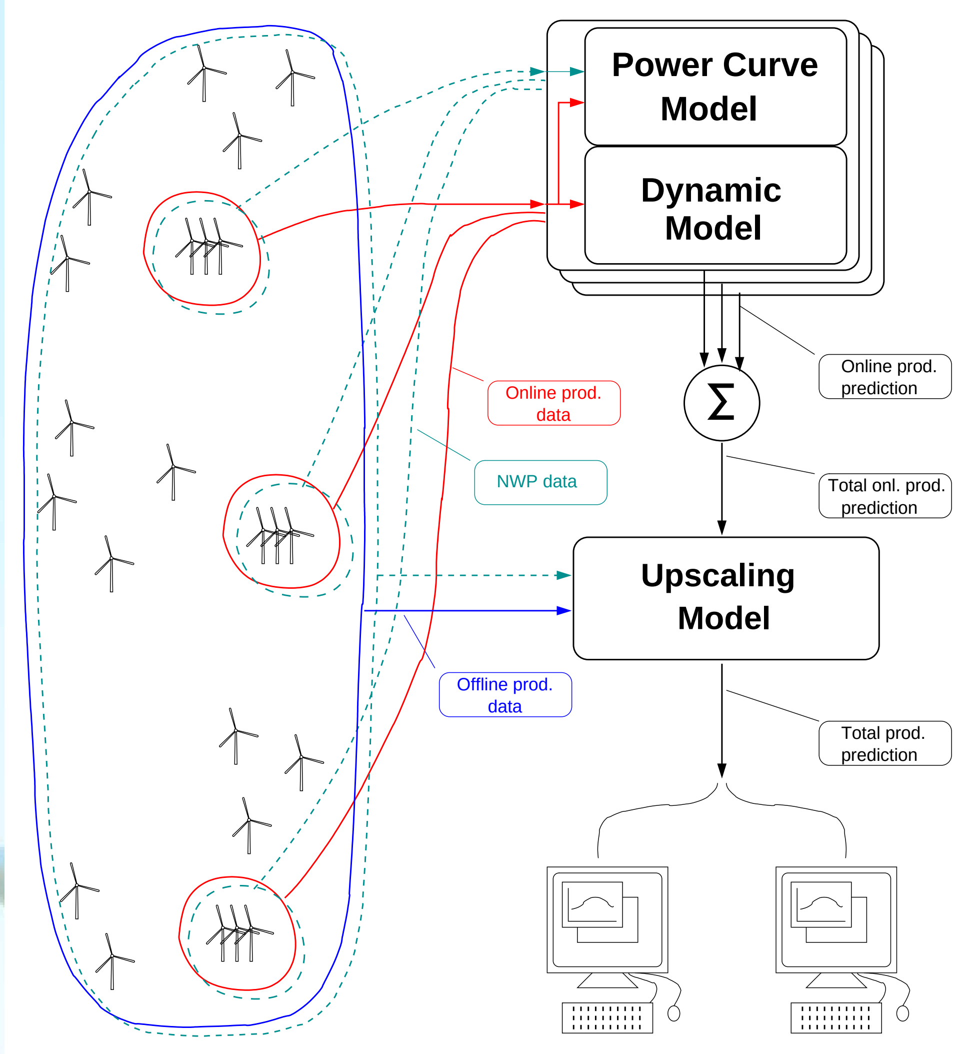
- A large number of wind farms and stand-alone wind turbines.
- Frequent changes in the wind turbine population as old wind turbines are decommissioned and replaced by new and larger machines.
- Offline production data with a resolution of 15 min. is available for more than 99% of the wind turbines in the area. The data is released with a delay of 3-5 weeks.
- No online data enters the models.



Configuration Example No. 2

This configuration of WPPT is used by a large wind farm owner in Denmark. Characteristics for the installation:

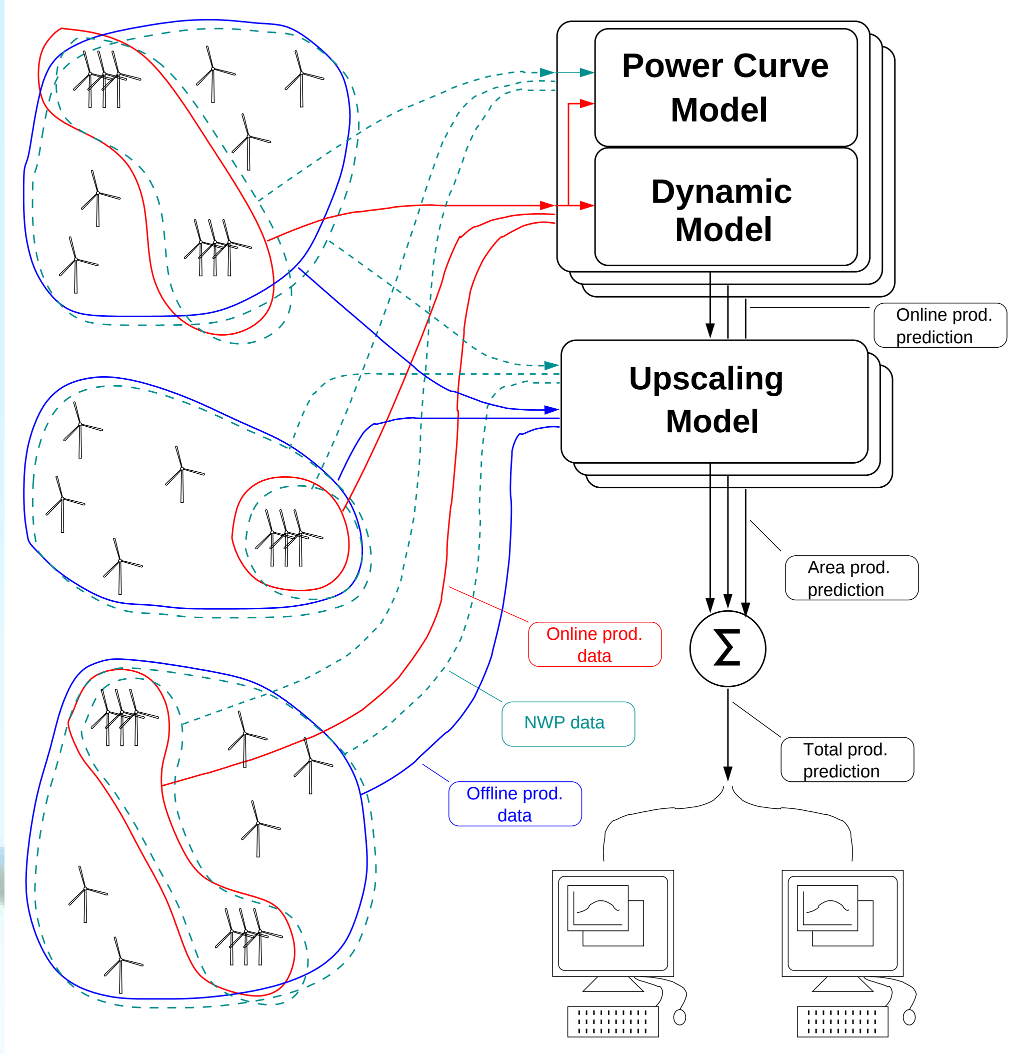
- A reasonable (< 20) number of wind farms.
- Infrequent changes in configuration for the wind farms. The number of online wind farms is not expected to change much.
- Online data for all wind farms of the owner are available.
- Offline production data with a resolution of 15 min. is available for more than 99% of the wind turbines in the area as a grand total. The data is released with a delay of 3-5 weeks.



Configuration Example No. 3

This configuration of WPPT is used by a TSO in Denmark. Characteristics for the installation:

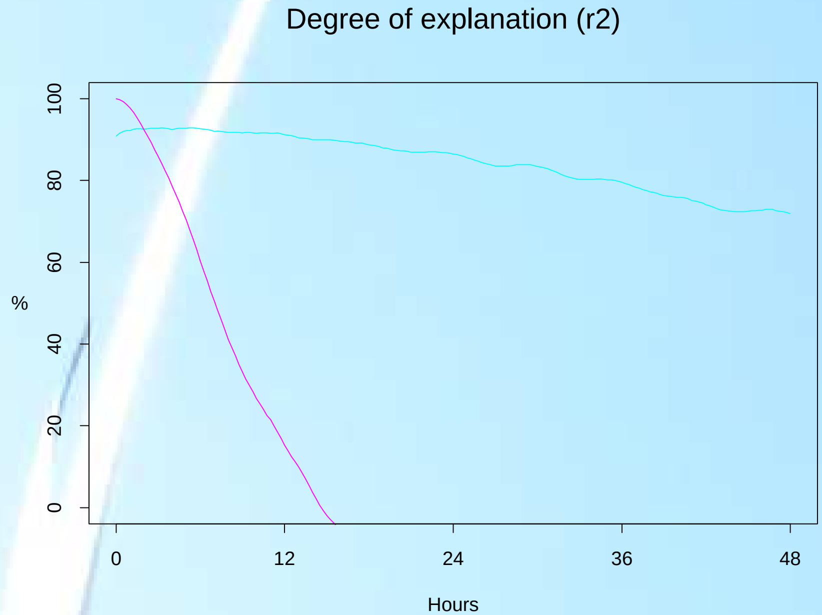
- A large number of wind farms and stand-alone wind turbines.
- Frequent changes in the wind turbine population.
- Offline production data with a resolution of 15 min. is available for more than 99% of the wind turbines in the area.
- Online data for a large number of wind farms are available. The number of online wind farms increases quite frequently.



Results and examples for a case study

The case study corresponds to the first configuration example. This configuration is used by Eltra (TSO in the western part of Denmark):

- **Period:** From June 2002 to May 2003 (both included) following a 2 month initialization period.
- **Power data freq:** 15 minutes.
- **NWP data:** Gridded values of 10m wind speed and wind direction covering the Eltra area updated 4 times a day. The predictions range from 0 to 48hours ahead with a 1hour resolution.
- **Area wind speed/direction:** Calculated as the geographical mean of the gridded NWP values.



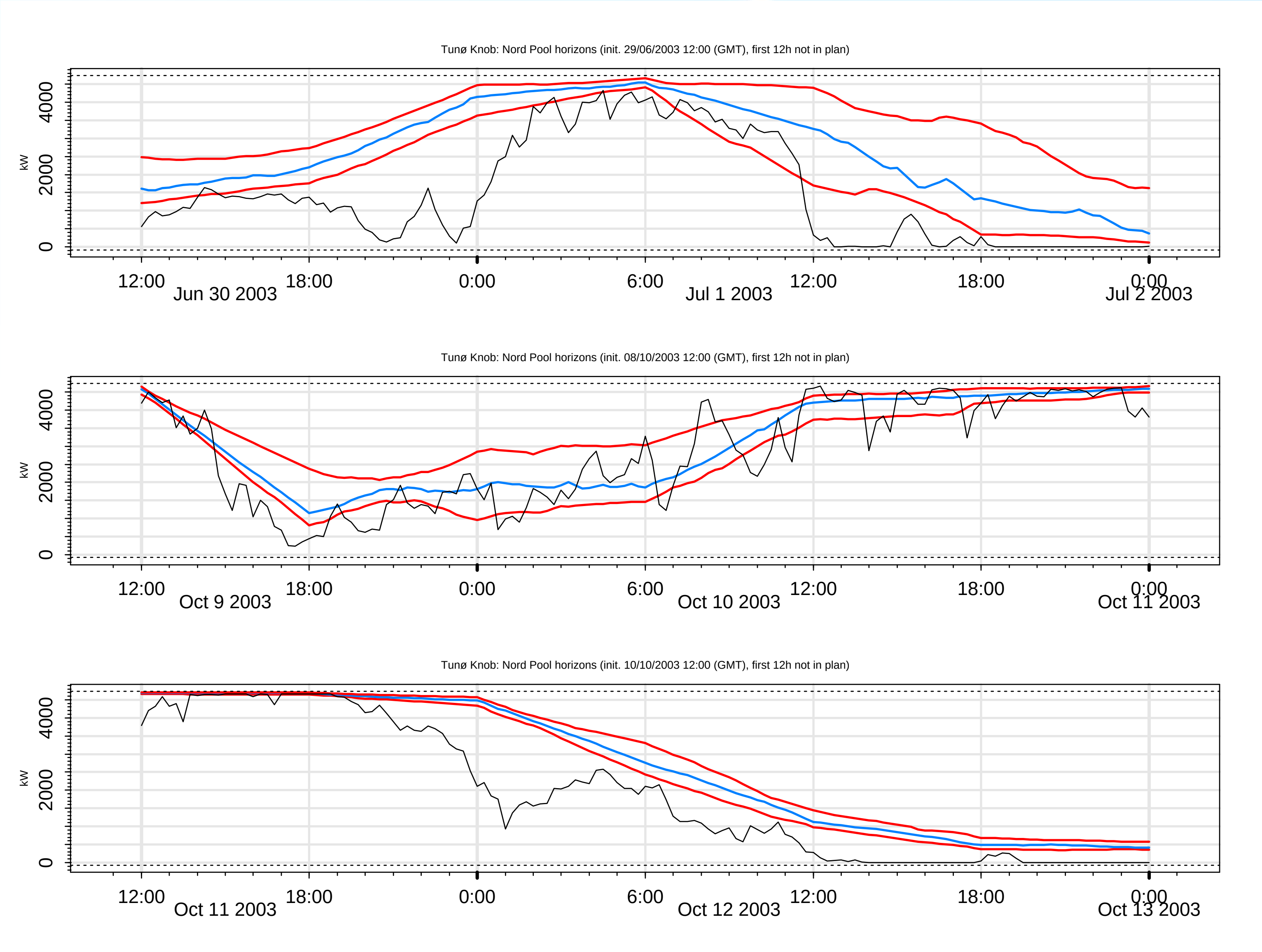
Performance of WPPT/Zephyr (blue line) compared to the performance of the naive predictor (red line). Degree of explanation is defined as $r_k^2 = \frac{V\{p\} - V\{\tilde{p}_k\}}{V\{p\}}$.

Uncertainty estimation

- It is crucial that a prediction tool delivers reliable estimates of the uncertainty of the wind power prediction.
- We consider three methods for estimating the uncertainty of the forecasted wind power production:
  - Adaptive variance estimation.
  - Ensemble based - but corrected - quantiles.
  - Quantile regression.

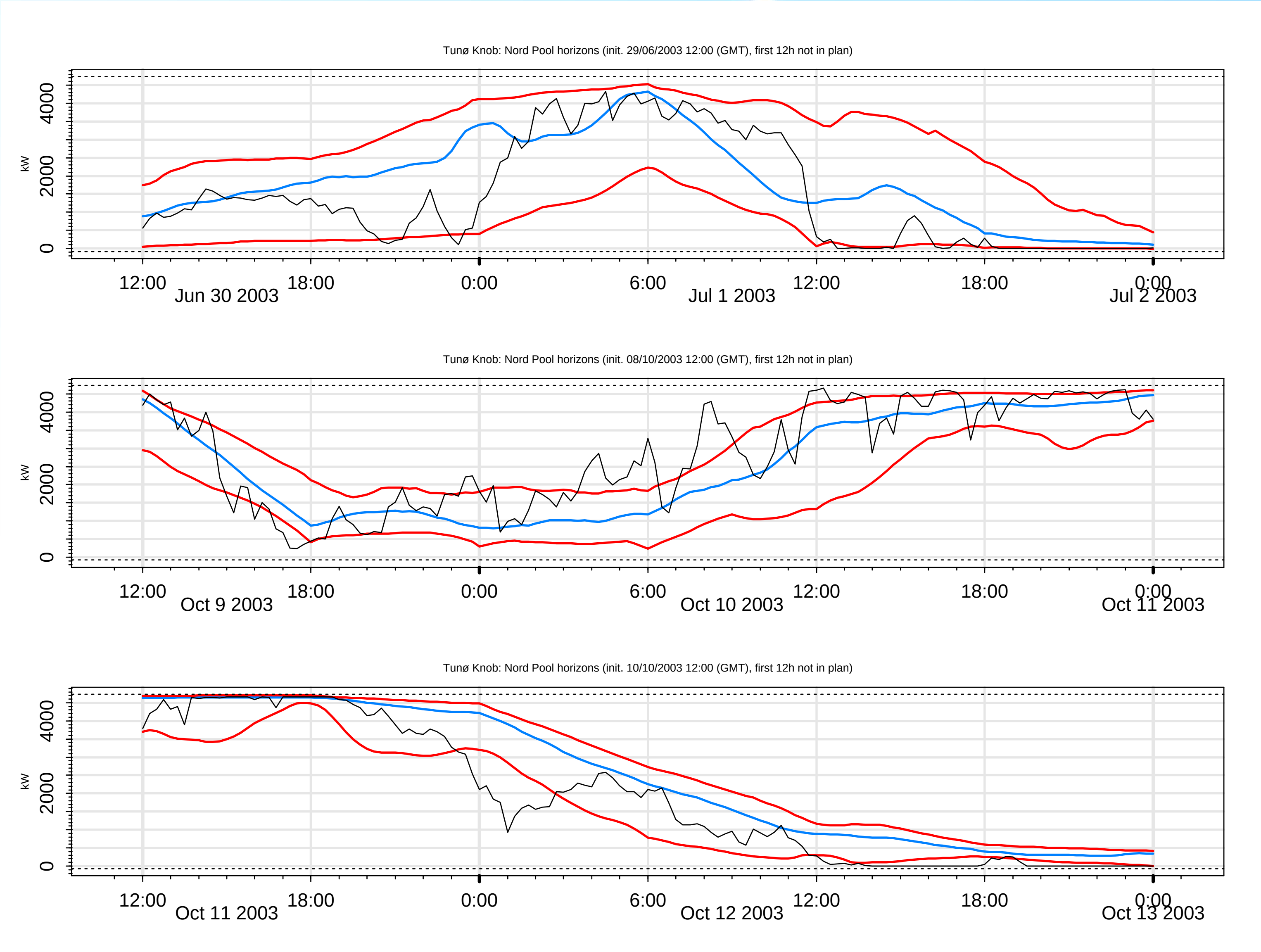
Raw quantiles – directly by MET ensembles

ECMEF, Tunø (offshore park), 29/6, 8/10, 10/10 (2003). 25%, 50%, 75%, quantiles.



Quantiles – corrected by stat. model

Tunø (offshore park), 29/6, 8/10, 10/10 (2003). 25%, 50%, 75%, quantiles.



Some references

- WPPT (Wind Power Prediction Tool) is installed at the following Danish utilities:
  - Eltra / Energinet.dk – TSO for the western part of Denmark (*www.eltra.dk*)
  - Elsam – CHP and wind farm owner in the western part of Denmark (*www.elsam.com*).
  - Elkraft – TSO for the eastern part of Denmark (*www.elkraft.dk*).
  - E2 – CHP and wind farm owner in the eastern part of Denmark (*www.e2.dk*).
- It is installed – or going to be installed in the near future – at the following utilities outside Denmark:
  - Nuon (Holland)
  - Hydro Tasmania (Australia)
  - ESB (Ireland)
  - Sotavento (Spain)
  - EWE (Germany)
  - PPC (Greece)

Value of forecasts

- Case study: A 15 MW wind farm in the Dutch electricity market, prices and measurements from the entire year 2002.
- From a phd thesis by Pierre Pinson (2006)
- The costs are due to the imbalance penalties on the regulation market.
- Value of an advanced method for point forecasting: **The regulation costs are diminished by nearly 38 pct.** compared to the costs of using the persistance forecasts.
- Added value of reliable uncertainties: **A further decrease of regulation costs – up to 39 pct.**

For further information please send an email to:

hm@imm.dtu.dk or hm@enfor.dk

enfor a/s:

Forecasting and Optimization for the Energy Sector