# Tools for Integrating Large Scale Wind Power

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# Outline

- History of WPPT (Wind Power Prediction Tool)
- Methods used for predicting the wind power
- Modelling approach
- The WPPT implementation
- Case study
- Further possibilities
- Some references
- The ANEMOS consortium
- The CENER-ENFOR consortium

# WPPT in short

WPPT (Wind Power Prediction Tool) is one of the wind power forecasting solutions available with the longest historie of operational use.

- WPPT has been continously developed since 1993 – initially at DTU (Technical University of Denmark and since 2006 by ENFOR – in close co-operation with:
  - Energinet.dk,
  - Dong Energy),
  - The ANEMOS projects and consortium (since 2002)
  - DTU (since 2006).
- WPPT has been used operationally in utility control rooms for predicting wind power in Denmark since 1996.

Now in Denmark (DK1): Wind power covers on average about 27 pct of the system load (this is a world record).

# Prediction of wind power

In areas with high penetration of wind power 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 single wind farms.

For all major Danish power utilities with respect to wind power the required wind power predictions are provided by **WPPT**.

# 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 inputs

Depending on the configuration WPPT can take advantage of input from the following sources:

- Online measurements of wind power prod. (updated every 5min. – 1hr).
- Online measurements of the available production capacity.
- Online “measurements” of downregulated production.
- 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).
- Forecasted availability of the wind turbines.
- 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.

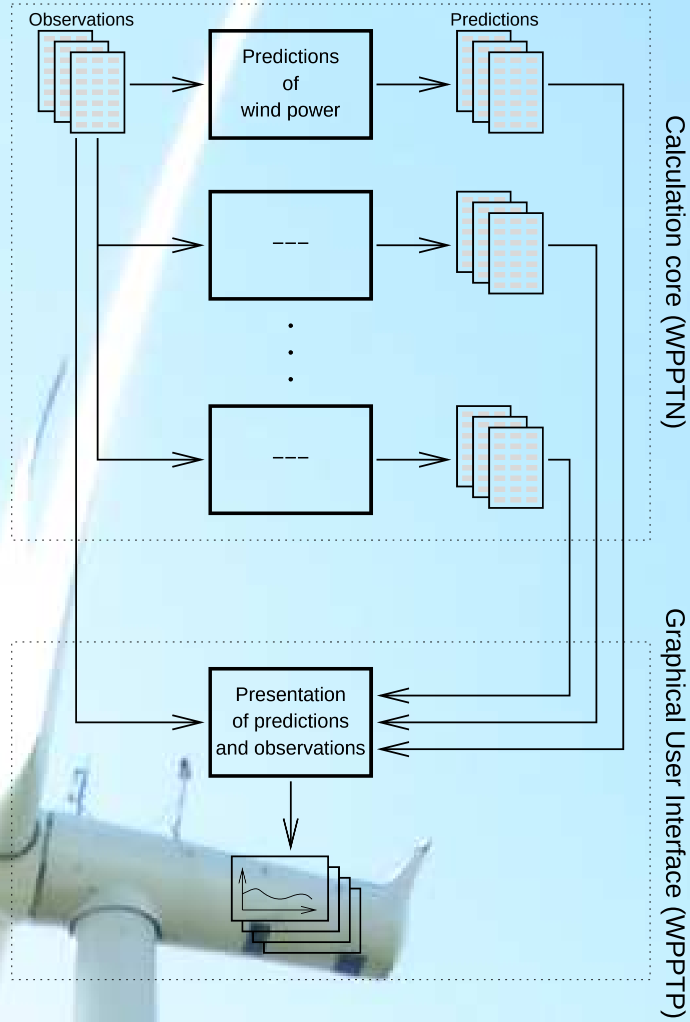
# The WPPT implementation

WPPT is implemented as a client–server setup with a graphical user interface (client) and a prediction model core (server). It runs on Windows, Linux and Unix.

The data interface for input to and output from the prediction model core is based on the internationally recognised DEPRI format.

The configuration of the prediction model core (WPPTN) and the graphical user interface (WPPTP) is done via a set of text files. These can be hand coded or automatically coded based on meta-data.

Automatically coding is a very handy solution for large installations where frequent changes is required as the population of wind farms changes.



# The estimation model

The model for forecasting the power production in wind farms without on-line mesurements is given as

$$p_{t+k} \quad = \quad \sum_{i=1}^{N} a_i p_t^i + m + e_{t+k}$$

where $p_{t+k}$ is the future power production for the wind farm without on-line power production, $p_t^i$ is observed power production for “nearby” wind farm $i$ with on-line measurements and $N$ is the number of “nearby” wind farms with online measurements used in the estimation.

For wind farms **with** off-line measurements the parameters $a_i$ are estimated using adaptive RLS.

For wind farms **without** off-line measurements the parameters $a_i$ are fixed as a function of distance, nominal power and utilisation time.

# The power curve model

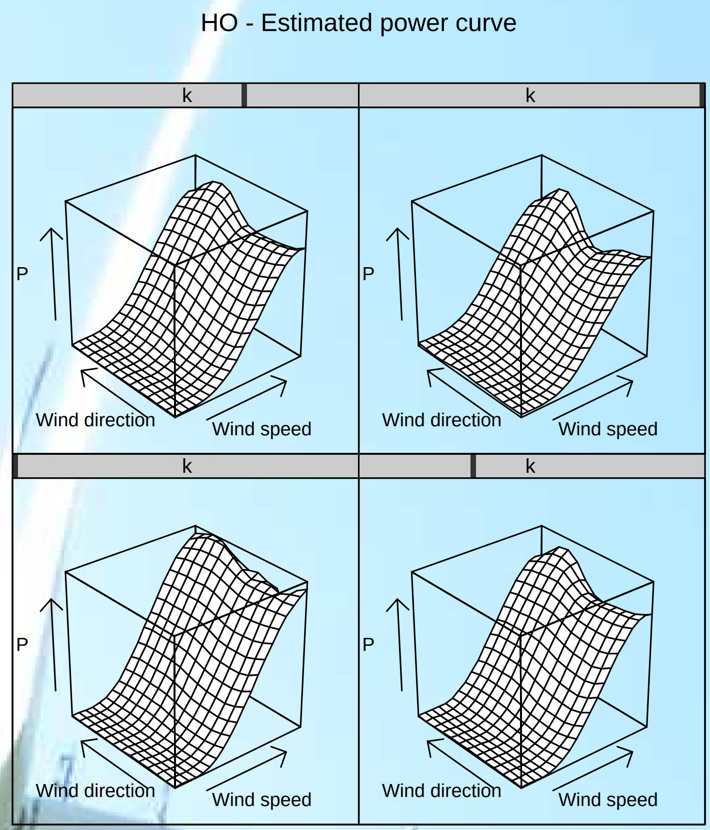
The wind turbine "power curve" model, $p^{tur} = f(w^{tur})$ is extended to a wind farm model, $p^{wf} = f(w^{wf}, \theta^{wf})$, by introducing wind direction dependency. By introducing a representative area wind speed and direction it can be further extended to cover all turbines in an entire region,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

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 dependendency 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).

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# The dynamical prediction model

The power curve models are used as input for an adaptively estimated dynamical model, which (as an example) leads to the following k-stop ahead forecasts:

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

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.

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# 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

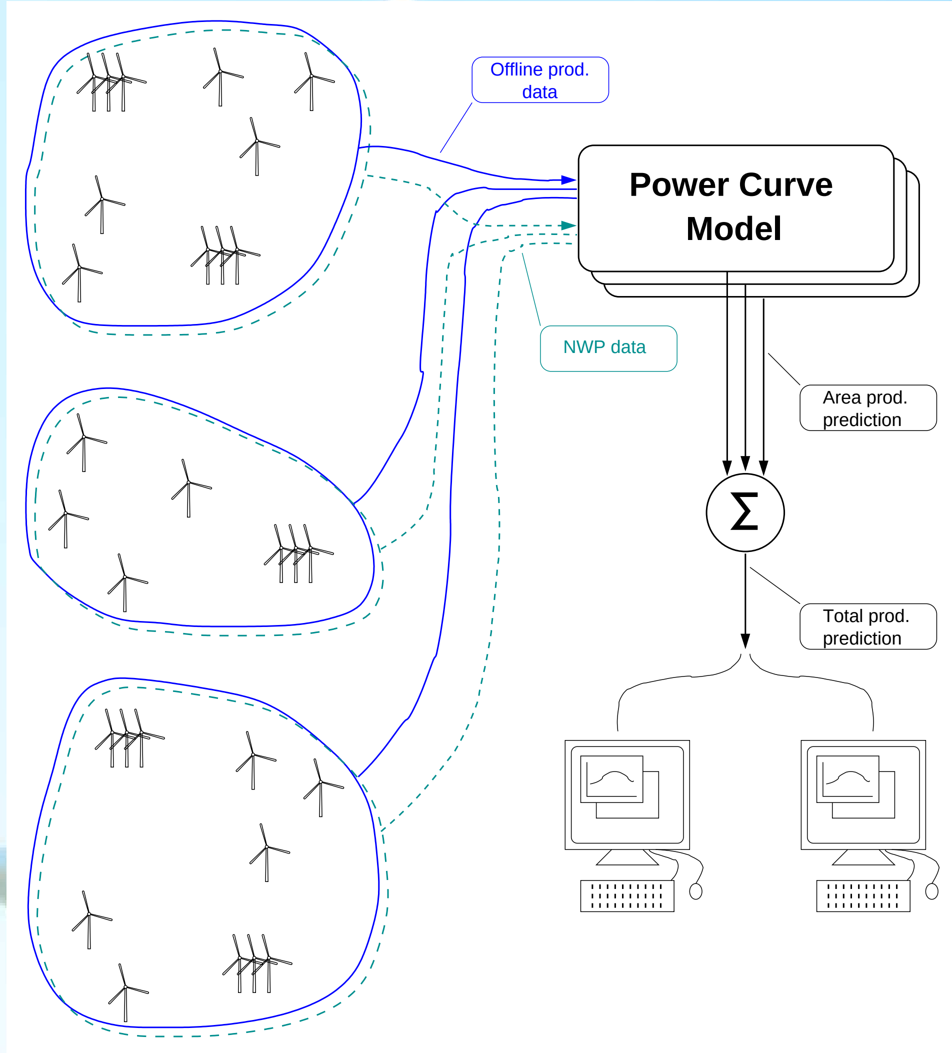
$\bar{\theta}^{ar}_{t+k|t}$ is forecasted regional wind direction.

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 Energinet.dk (the TSO of Denmark). The following characterizes the installation:

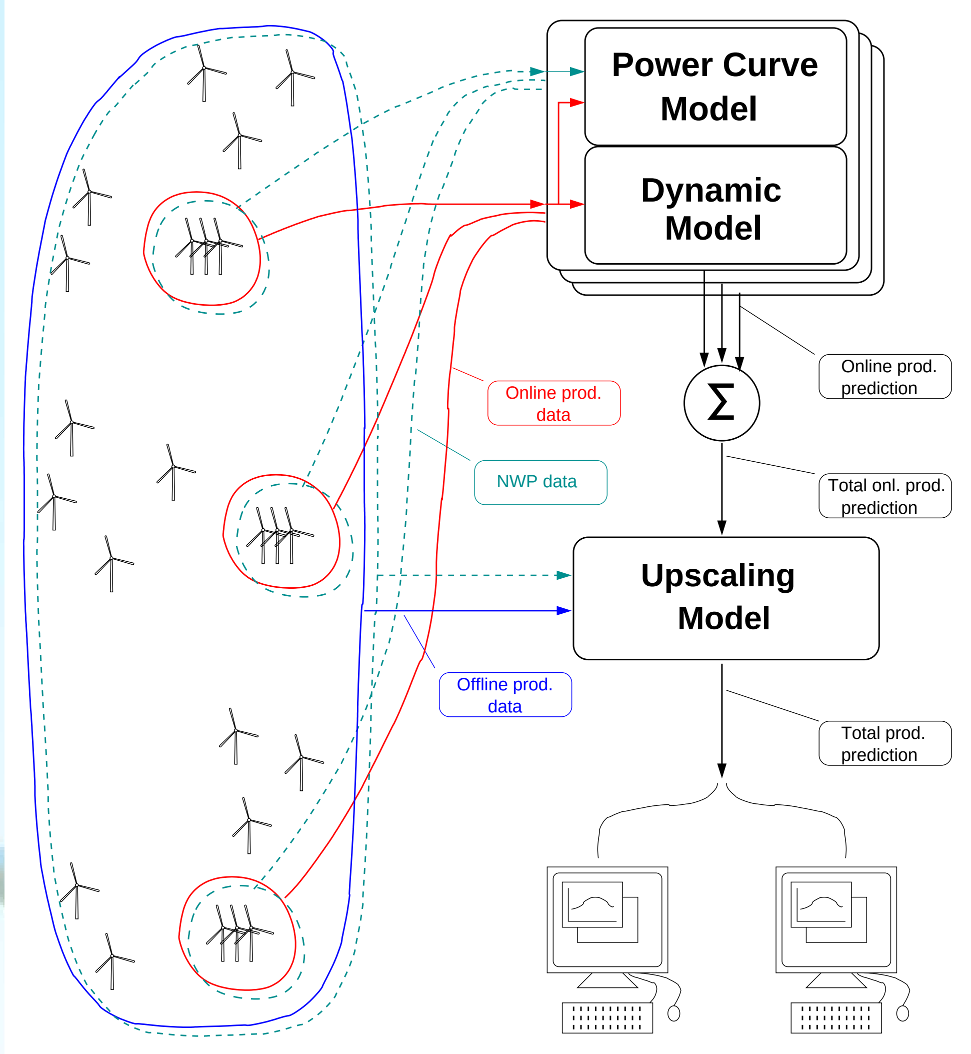
- A large number of wind farms and stand-alone wind turbines.
- Frequent changes in the wind turbine population as old wind turbines are decommissioned and replaced by new and larger machines.
- Offline production data with a resolution of 15 min. is available for more than 99% of the wind turbines in 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:

- 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.

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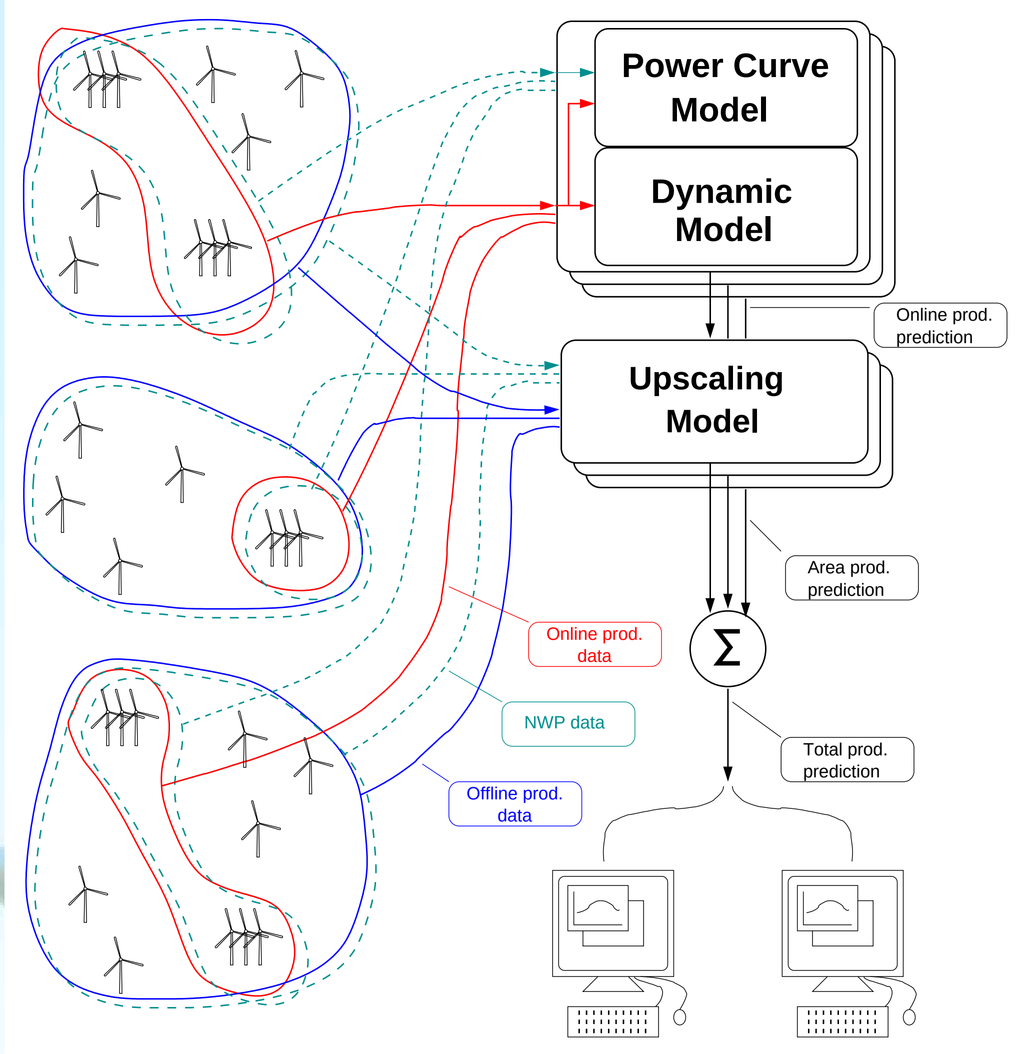
# Configuration Example No. 3

This configuration of WPPT is used by Energinet.dk. Characteristics for the installation:

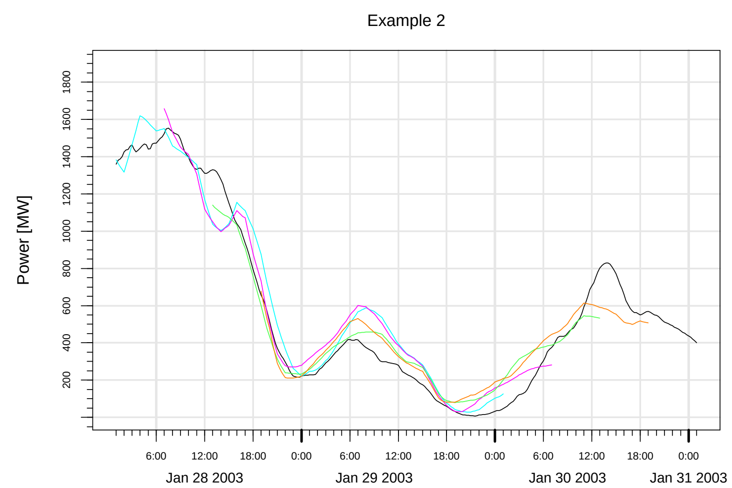
- A large number of wind farms and stand-alone wind turbines.
- Frequent changes in the wind turbine population.
- Offline production data with a resolution of 15 min. is available for more than 99% of the wind turbines in the area.
- Online data for a large number of wind farms are available. The number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

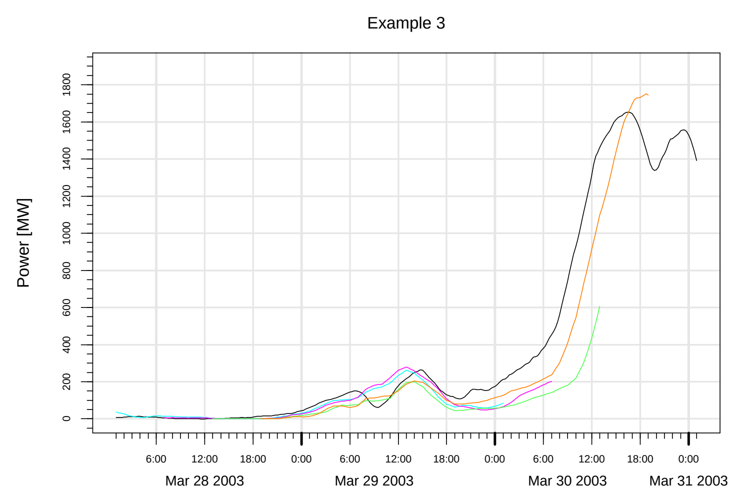


# Results and examples for a case study

The case study covers the western part of Denmark (DK1) and corresponds to a configuration is used by Energinet.dk:

- **Period:** From November 2006 to October 2007 (both included).
- **Power data freq:** 15 minutes.
- **NWP data:** Gridded values of 10m wind speed and wind direction for DK1.
- **Area wind speed/direction:** Calculated as the geographical mean of the gridded NWP values.
- For **this** test case the day-a-head performance of WPPT is:
    - RMSE=7.0% of installed capacity.
    - MAE=5.3% of installed capacity.
    - BIAS=0.03% of installed capacity.

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# Further possibilities

WPPT is a very flexible system for wind power forecasting and a number of further possibilities are available:

- Providing forecasts on the ultra-short horizon from e.g. 5 minutes to 2 hours in steps of 5 minutes (ultra short-term forecasting).
- Using NWP data from more than one provider (model combination).
- Providing estimates of expected uncertainty (probabilistic forecasts) of the power predictions using quantile regression (no additional inputs needed) or ensemble forecasts (ensemble forecasts of wind speed and wind direction needed).

# Ultra short-term forecasting

Model aiming specifically at providing short-term forecasts with high time resolution. A typical setup will be with a forecast horizon up to 2 hours a head in time with a time resolution of 5 minutes. The forecasts will be updated every 5 minutes. The following conditions are taken into account by the model:

- Current (last) measured production.
- Current “variability” of the measured production.
- Forecasted wind speed.
- Non-linear relationsships in data.
- Horizontal dependencies (every horizon is modelled individually).

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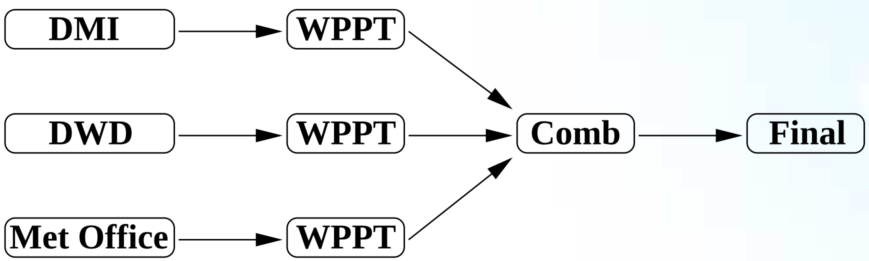
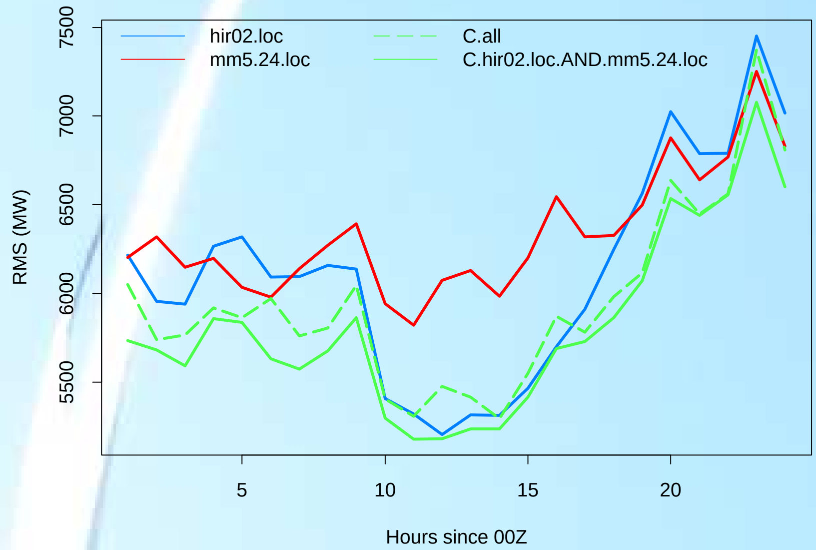
# Combined forecasting

- A number of power forecasts are weighted together to form a new improved power forecast.
- These could come from parallel configurations of WPPT using NWP inputs from **different MET providers** or they could come from other power prediction providers.
- In addition to the improved performance also the robustness of the system is increased.




The example show results achieved for the Tunø Knob wind farms using combinations of up to 9 power forecasts.




If too many highly correlated forecasts are combined the performance may decrease compared to using fewer and less correlated forecasts. Typically an improvement on 10-15 pct is seen by including more than one MET provider.

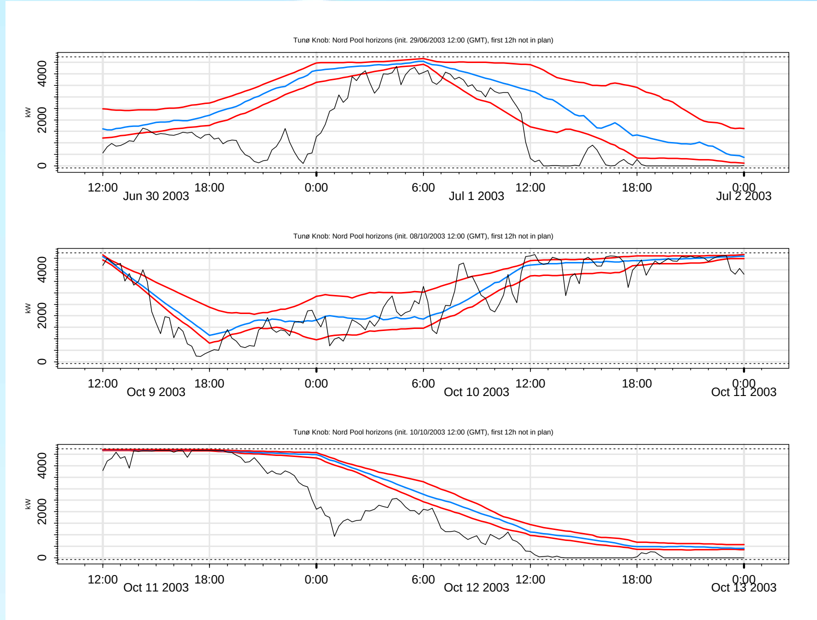
# Uncertainty estimation

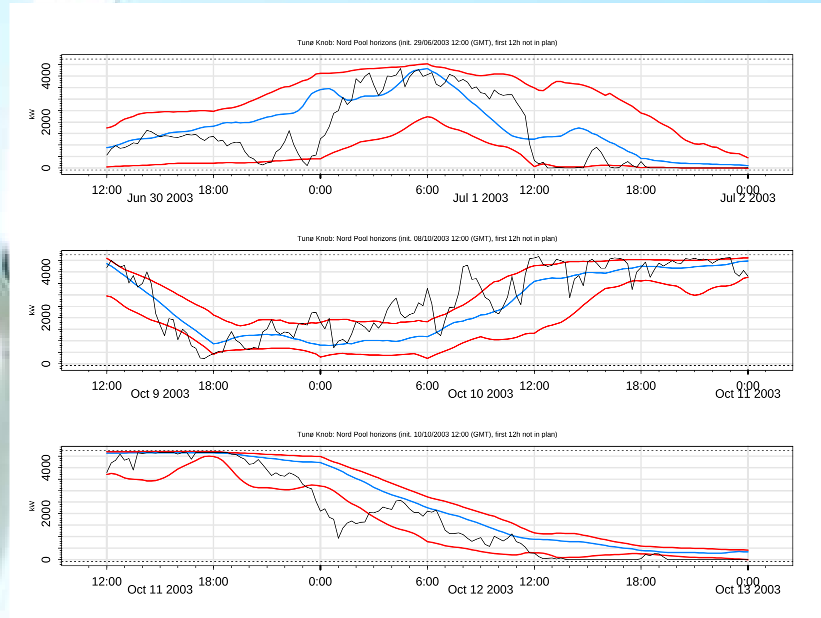
In many applications it is crucial that a prediction tool delivers reliable estimates (probabilistc forecasts) of the expected uncertainty of the wind power prediction.

WPPT provides three methods for estimating the uncertainty of the forecasted wind power production:

- Adaptive variance estimation.
- Ensemble based - but corrected - quantiles.
- Quantile regression.

The plots show raw (top) and corrected (bottom) uncertainty intervales based on ECMEF ensembles for Tunø Knob (offshore park), 29/6, 8/10, 10/10 (2003). Shown are the 25%, 50%, 75%, quantiles.

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# Value of wind power 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.**

# Lessons learned

The lessons learned during more that 15 years of wind power forecasting:

- The forecasting models must be adaptive (in order to taken changes of dust on blades, changes roughness, etc. into account).
- Should be implemented using a robust software solution.
- Reliable estimates of the forecast accuracy is very important.
- Use more than a single MET provider for delivering the input to the wind power prediction tool – this improves the accuracy.
- The tool must be easy to calibrate to new wind farms, etc.
- It is advantegous if the same tool can be used for forecasting for a single wind farm, a collection of wind farms, a state/region, and the entire country.
- The running costs must be low.
- Coarse grid resolution did not give better results - a better and cheaper way is to use a combination of statistical and physical methods.

# Some references

- WPPT (Wind Power Prediction Tool) is installed – or going to be installed in the near future – at the following Danish utilities:
  - Energinet.dk – The TSO of Denmark (*www.energinet.dk*)
  - DONG Energy – CHP and wind farm owner in Denmark and abroad. (*www.dongenergy.dk*).
  - Vattenfall – CHP and wind farm owner in Denmark and abroad (*www.vattenfall.com*).
  - NEAS – Major energy manager/trader in Denmark (*www.neas.dk*).
- It is installed – or going to be installed in the near future – at the following utilities outside Denmark:
  - Nuon (Holland)
  - E.ON (Sweden)
  - NEMMCO (Australia)
  - Soni (Nortern Ireland)
  - Hydro Quebec (Canada)
  - EirGrid (Ireland)
  - PPC (Greece)

# Services offered by ENFOR

- The WPPT software for Wind Power Prediction.
- The SOLARFOR software for Solar Power Prediction.
- LOADFOR – for forecasting the power load.
- PRESS – for forecasting the heating load in district heating system, and for optimizing the temperatures in the district heating net.
- PRICEFOR – for forecasting the energy prices.
- GASFOR – for forecating the consumption of gas.
- Other services related to optimization of system with a large share of renewable energy.

For more information – see www.enfor.eu.

# The CENER-ENFOR Consortium

The leading company in Spain for Wind Power Forecasting and Resource estimation, CENER, and ENFOR has established a consortium. This consortium offers the following services:

- Wind Power forecasting. By using LocalPred by CENER or WPPT – or both.
- Solar Power forecasting. By using software form either CENER or ENFOR.
- High resolution MET forecasts (s input eg. for LocalPred or WPPT).
- Resource estimation.
- Selection and evaluation of potential sites for wind farms.
- CDF analysis of wind farms with a high resolution.
- Support in the planning phase of wind energy at regional or national scale.
- Analysis of the power grid at local or national scale in order to study the penetratin limits.
- Tools for integrating large amount of wind power in power systems (stability of power systems).
- Tools for optimize the participation of wind energy in the market.

# ANEMOS consortium

Since the start-up of the series of ANEMOS projects in 2002, some of the members have founded a consortium for integration of large scale wind power. A homogenous user interface to a rather large number of European tools for wind power prediction is developed. The prediction tools embedded in the ANEMOS software today is:

- AWPPS (from Ecole des Mines de Paris)
- LocalPred (from CENER)
- WPPT (from ENFOR)
- Prediktor (from Risø)
- Previento (from EMSYS)
- Sipreolico (from UC3M)
- Vamemos (from RAL)

The consortium and the series of ANEMOS projects are succesfully headed by Georges Kariniotakis, Ecole des Mines de Paris.