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Madsen, Henrik; Zugno, Marco; Pinson, Pierre; Aalborg Nielsen, Henrik Aalborg Nielsen; Skov Nielsen, Torben

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#### Wind Power Forecasting with a Focus on Risk and Uncertainties

Henrik Madsen<sup>1</sup>, Marco Zugno<sup>1</sup>, Pierre Pinson<sup>1</sup>, Henrik Aalborg Nielsen<sup>2</sup>, Torben Skov Nielsen<sup>2</sup>

hm@imm.dtu.dk

(1) Department for Mathematics and Computer Science
DTU Compute, DTU, Lyngby
www.imm.dtu.dk/~hm
(2) ENFOR A/S
Lyngsø Allé 3
DK-2970 Hørsholm
www.enfor.dk



## Outline

- Wind power forecasting
- Use of several providers of MET forecasts
- Uncertainty and confidence intervals
- Scenario forecasting
- Value of wind power forecasts
- Optimal bidding for a wind farm owner
- Electricity price forecasting
- Impact of wind power on EU cross-border power flows



# **Wind Power Forecasting - History**

Our methods for probabilistic wind power forecasting have been implemented in the **Anemos Wind Power Prediction System** and **WPPT** 

- The methods have been continuously developed since 1993 in collaboration with
  - Energinet.dk,
  - Dong Energy,
  - Vattenfall,
  - Risø
  - The ANEMOS projects partners/consortium (since 2002)
  - ENFOR
- The methods have been used operationally for predicting wind power in Denmark since 1996.
- Anemos/WPPT is now used all over Europe, Australia, and North America.

#### **Sources for uncertainty - Need for adaptivity**

Errors in MET forecasts and measurements will end up in errors in wind power forecasts.

A need for automatic adaptation of the prediction models is due to

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

An adequate forecasting system must use **adaptive and recursive model estimation** to handle these issues.

We started (some 20 years ago) assuming Gaussianity; but this is a very serious (wrong) assumption (still assumed by many forecasting providers)!

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

# **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 3 power forecasts.



Typically an improvement on 10-15 pct in accuracy of the point prediction is seen by including more than one MET provider. Two or more MET providers imply information about uncertainty

# **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.

We consider the following methods for estimating the uncertainty of the forecasted wind power production:

- Resampling techniques.
- Ensemble based but corrected quantiles.
- Quantile regression.
- Stochastic differential equations (new approach).

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.



# **Quantile regression - An example**

#### Effect of variables:



- Forecasted power has a large influence.
- The effect of horizon is of less importance.
- Some increased uncertainty for westerly winds.



#### **Example: Probabilistic forecasts**



Notice how the confidence intervals varies ...

But the correlation in forecasts errors is not described so far.



## **Correlation structure of forecast errors**

It is important to model the **interdependence structure** of the prediction errors.

An example of interdependence correlation matrix:





#### **Correct (top) and naive (bottom) scenarios**





# **Use of Stochastic Diff. Equations**

The state equation describes the future wind power production

$$dx_t = -\theta(\boldsymbol{u_t}) \cdot (x_t - \hat{p}_{t|0})dt +$$

$$2\sqrt{\theta(\boldsymbol{u_t})\alpha(\boldsymbol{u_t})\hat{p}_{t|0}(1-\hat{p}_{t|0})x_t\cdot(1-x_t)dw_t},$$

with  $\alpha(\boldsymbol{u_t}) \in (0, 1)$ , and the observation equation

$$y_h = x_{t_h|0} + e_h,$$

where  $h \in \{1, 2, ..., 48\}, t_h = k, e_h \sim N(0, s^2), x_0 = "observed power at t=0", and$ 

- $\hat{p}_{t|0}$  point forecast by **WPPT** (Wind Power Prediction Tool)
  - $\boldsymbol{u_t}$  input vector (here t and  $\hat{p}_{t|0}$ )

# **SDE** approach – Correlation structures



Use of SDEs provides a possibility to model eg. time varying and wind power dependent correlation structures.

SDEs provide a perfect framework for **combined wind and solar power forecasting**. Today both the **Anemos Prediction Platform** and **WPPT** provide operations forecasts of both wind and solar power production.



# **Type of forecasts required**

- **Point forecasts (normal forecasts)**; a single value for each time point in the future. Sometimes with simple error bands.
- **Probabilistic or quantile forecasts**; the full conditional distribution for each time point in the future.
- **Scenarios**; probabilistic correct scenarios of the future wind power production.





#### Wind power – asymmetrical penalties

The revenue from trading a specific hour on NordPool can be expressed as

$$P_{S} \times \text{Bid} + \begin{cases} P_{D} \times (\text{Actual} - \text{Bid}) & \text{if} \quad \text{Actual} > \text{Bid} \\ P_{U} \times (\text{Actual} - \text{Bid}) & \text{if} \quad \text{Actual} < \text{Bid} \end{cases}$$

 $P_S$  is the spot price and  $P_D/P_U$  is the down/up reg. price. The bid maximising the expected revenue is the following **quantile** 

 $\frac{E[P_S] - E[P_D]}{E[P_U] - E[P_D]}$ 

in the conditional distribution of the future wind power production.

# Wind power – asymmetrical penalties

- It is difficult to know the regulation prices at the day ahead level research into forecasting is ongoing.
- The expression for the quantile is concerned with expected values of the prices just getting these somewhat right will increase the revenue.
- A simple tracking of  $C_D$  and  $C_U$  is a starting point.
- The bids maximizing the revenue during the period September 2009 to March 2010:





#### **Sizing of energy storage**



Illustrative example based on 50 day ahead scenarios as in the situation considered before. Used for calculating the risk for a storage to be too small.



#### **Risk calculations – Examples**

- Imbalance ramp forecasting; probabilities of ramp events
- Calculation of required storage as a function of horison (possibly obtained by varying hydro power production). Also show is the probability that this storage will be sufficient.



#### **Forecasting the electricity prices**



- Lower price for higher predicted production/penetration
- Daily peaks flatten out with higher predicted production/penetration
- Prices vary through out the year in accordance with water level in reservoirs

# **Using forecasted penetration of wind power**

A better model for price forecasting is obtained ...



... by using forecasted penetration instead of forecasted production. In conclusion: The forecasted penetration (forecasted wind power / forecasted load) is an important explanatory variable.



#### **Effect of wind power forecasts**

Forecasted Wind power penetration also affects the distribution of prices





# **Prices related to up/down regulation**

Consider the **up regulation** as an example.

Here Quantile Regression is used to obtain quantiles for the prices related to up regulation (given the event 'up regulation').



Higher prices for up regulation is more likely during day time. (Similar plot exists for down regulation)



# Wind and EU cross-border power flows



Map of impact and sensitivity of EU cross-border power flows to predicted wind power penetration in Germany... here if within 10-15% of installed capacity

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# Conclusions

- The forecasting models must be **adaptive** (in order to taken changes of dust on blades, changes roughness, etc., into account).
- Reliable estimates of the **forecast accuracy** is very important (check the reliability by eg. reliability diagrams).
- Reliable probabilistic forecasts are important to gain the **full economical value**.
- Use more than a single MET provider for delivering the input to the prediction tool this improves the accuracy of wind power forecasts with 10-15 pct.
- Estimates of the **correlation in forecasts errors** important.
- Forecasts of '**cross dependencies**' between load, prices, wind and solar power are important.
- Probabilistic forecasts are very important for asymmetric cost functions.
- Probabilistic forecasts can provide **risk related answers** for questions like
  - What is the **risk** that this storage is not large enough for the next 5 hours?
  - What is the **risk** for an increase in wind power production of more that 50 pct over the next two hours?
  - What is the **risk** for a cut-off due to high wind speeds the next couple of hours.



#### **Some references**

- H. Madsen: *Time Series Analysis*, Chapman and Hall, 392 pp, 2008.
- H. Madsen and P. Thyregod: *Introduction to General and Generalized Linear Models*, Chapman and Hall, 320 pp., 2011.
- P. Pinson and H. Madsen: *Forecasting Wind Power Generation: From Statistical Framework to Practical Aspects*. New book in progress will be available 2012.
- T.S. Nielsen, A. Joensen, H. Madsen, L. Landberg, G. Giebel: *A New Reference for Predicting Wind Power*, Wind Energy, Vol. 1, pp. 29-34, 1999.
- H.Aa. Nielsen, H. Madsen: *A generalization of some classical time series tools*, Computational Statistics and Data Analysis, Vol. 37, pp. 13-31, 2001.
- H. Madsen, P. Pinson, G. Kariniotakis, H.Aa. Nielsen, T.S. Nilsen: *Standardizing the performance evaluation of short-term wind prediction models*, Wind Engineering, Vol. 29, pp. 475-489, 2005.
- H.A. Nielsen, T.S. Nielsen, H. Madsen, S.I. Pindado, M. Jesus, M. Ignacio: *Optimal Combination of Wind Power Forecasts*, Wind Energy, Vol. 10, pp. 471-482, 2007.
- A. Costa, A. Crespo, J. Navarro, G. Lizcano, H. Madsen, F. Feitosa, *A review on the young history of the wind power short-term prediction*, Renew. Sustain. Energy Rev., Vol. 12, pp. 1725-1744, 2008.



# **Some references (Cont.)**

- P. Bacher, H. Madsen, H.Aa. Nielsen: *Online Short-term Solar Power Forecasting*, Solar Energy, Vol. 83(10), pp. 1772-1783, 2009.
- P. Pinson, H. Madsen: *Ensemble-based probabilistic forecasting at Horns Rev.* Wind Energy, Vol. 12(2), pp. 137-155 (special issue on Offshore Wind Energy), 2009.
- P. Pinson, H. Madsen: Adaptive modeling and forecasting of wind power fluctuations with Markov-switching autoregressive models. Journal of Forecasting, 2010.
- C.L. Vincent, G. Giebel, P. Pinson, H. Madsen: *Resolving non-stationary spectral signals in wind speed time-series using the Hilbert-Huang transform.* Journal of Applied Meteorology and Climatology, Vol. 49(2), pp. 253-267, 2010.
- P. Pinson, P. McSharry, H. Madsen. *Reliability diagrams for nonparametric density forecasts of continuous variables: accounting for serial correlation*. Quarterly Journal of the Royal Meteorological Society, Vol. 136(646), pp. 77-90, 2010.
- G. Reikard, P. Pinson, J. Bidlot (2011). *Forecasting ocean waves A comparison of ECMWF wave model with time-series methods*. Ocean Engineering in press.
- C. Gallego, P. Pinson, H. Madsen, A. Costa, A. Cuerva (2011). *Influence of local wind speed and direction on wind power dynamics Application to offshore very short-term forecasting*. Applied Energy, in press



# **Some references (Cont.)**

- C.L. Vincent, P. Pinson, G. Giebel (2011). *Wind fluctuations over the North Sea*. International Journal of Climatology, available online
- J. Tastu, P. Pinson, E. Kotwa, H.Aa. Nielsen, H. Madsen (2011). *Spatio-temporal analysis and modeling of wind power forecast errors*. Wind Energy 14(1), pp. 43-60
- F. Thordarson, H.Aa. Nielsen, H. Madsen, P. Pinson (2010). *Conditional weighted combination of wind power forecasts*. Wind Energy 13(8), pp. 751-763
- P. Pinson, G. Kariniotakis (2010). Conditional prediction intervals of wind power generation. IEEE Transactions on Power Systems 25(4), pp. 1845-1856
- P. Pinson, H.Aa. Nielsen, H. Madsen, G. Kariniotakis (2009). Skill forecasting from ensemble predictions of wind power. Applied Energy 86(7-8), pp. 1326-1334.
- P. Pinson, H.Aa. Nielsen, J.K. Moeller, H. Madsen, G. Kariniotakis (2007). *Nonparametric probabilistic forecasts of wind power: required properties and evaluation*. Wind Energy 10(6), pp. 497-516.
- T. Jónsson, P. Pinson (2010). *On the market impact of wind energy forecasts*. Energy Economics, Vol. 32(2), pp. 313-320.
- T. Jónsson, M. Zugno, H. Madsen, P. Pinson (2010). On the Market Impact of Wind Power (Forecasts) - An Overview of the Effects of Large-scale Integration of Wind Power on the Electricity Market. IAEE International Conference, Rio de Janeiro, Brazil.