SPATIALLY SEAMLESS FORECASTING OF WIND POWER GENERATION WITH GENERALIZED POWER CURVES

C. Waimann\textsuperscript{1}, P. Pinson\textsuperscript{3} and C. Saulo\textsuperscript{1,2}

cwaimann@cima.fcen.uba.ar

1) Centro de Investigaciones del Mar y la Atmosfera, UMI-IFAECI/CNRS, Buenos Aires, Argentina
2) Universidad de Buenos Aires, Departamento de Ciencias de la atmósfera y los océanos, Buenos Aires, Argentina.
3) Technical University of Denmark, Center for Electric Power and Energy, Kgs. Lyngby, Denmark
Some background about wind power in Denmark

• Denmark has the world largest wind power capacity in proportion to the size of the electricity consumption and in 2013 covered 33.2% of its electricity demand by wind power.

• On December 2013, wind power reached a level corresponding to more than half of the electricity consumption (54.8%).

Source: www.energinet.dk

• It has a long tradition in wind industry, including the development of wind power forecasting tools for optimal power system operations.

Eg: WPPT, ZEPHYR
I. To build **computationally-efficient** and **high-quality** forecasting methodologies for a large number of sites based on a combination of numerical weather predictions (NWP) and local observations, for lead times up to 60 hours ahead.

II. To examine different multi varying linear models for wind power prediction, describing their characteristics and testing their performance.

III. To propose a **spatial generalization** of wind power prediction models, suitable for forecasting wind power generation at a large number of sites using a single model.

IV. To test the performance of **Ordinary Kriging**, considering it as an appealing methodology to obtain the coefficients of the multi linear models and the power curves at any new location where a new wind farm could be settled.
Wind power measurements

- 3 years (2008 to 2010)
- More than 400 electrical substations on Western Denmark.
- Time resolution of wind power data: 15 minutes.
- Normalization of data using the maximum value of each wind farm.

Geographical distribution of the electrical substations.
The Danish Meteorological Institute (DMI) provided information of hourly wind speed forecasts at 10m and 100m above ground level up to 60 hours ahead.

High Resolution Limited Area Model (HIRLAM), with 0.15° horizontal grid spacing.

Four forecast cycles (00, 06, 12, and 18 UTC) were available. For simplicity, this analysis is focused on the 12-UTC cycle.

DMI-HIRLAM domains. Figure taken from Petersen et al (2005).
I. Estimation of the power curves: Locally Weighted Linear Regression

- Each power curve was estimated for every prediction horizon and, in case a) for every electrical substation.
II. Mix models

Three models built as a linear combination between power output observations and forecasts based on NWP models are proposed. The predictions models for the jth wind farm are given as:

\[ M_1: \hat{P}_{j,1}(t + k|t) = c_{01}(j, t + k) + c_{11}(j, t + k) \cdot P_j(t) + c_{21}(j, t + k) \cdot \hat{P}_{j,10m}^{NWP}(t + k|t) \]

\[ M_2: \hat{P}_{j,2}(t + k|t) = c_{02}(j, t + k) + c_{12}(j, t + k) \cdot P_j(t) + c_{22}(j, t + k) \cdot \hat{P}_{j,100m}^{NWP}(t + k|t) \]

\[ M_3: \hat{P}_{j,3}(t + k|t) = c_{03}(j, t + k) + c_{13}(j, t + k) \cdot P_j(t) + c_{23}(j, t + k) \cdot \hat{P}_{j,10m,1PC}^{NWP}(t + k|t) \]

- We followed a classical approach of the problem where models parameters are estimated in the ‘training period’ (2008 and 2009) and remain constant over the evaluation period (2010).
III. Spatial interpolation of coefficients \{c_{mn}\} and power curves: Ordinary Kriging (OK)

- Kriging is a spatial interpolation technique to predict the value on a target unsampled location via known values at other observations in the neighbourhood of the point of interest and was applied through the implementation of a robust method in order to objectively assess the magnitude of the errors that OK introduces, and their spatial and temporal distribution.

- Two models were built based on interpolated \{c_{mn}\} coefficients and power curves.

**M4:**

\[ \hat{P}_{j,4}(t + k|t) = ok_{c_{03}}(j, t + k) + ok_{c_{13}}(j, t + k) \cdot P_j(t) + ok_{c_{23}}(j, t + k) \cdot \hat{P}_{j,10m,1PC}^{NW}(t + k|t) \]

**M5:**

\[ \hat{P}_{j,5}(t + k|t) = ok_{c_{01}}(j, t + k) + ok_{c_{11}}(j, t + k) \cdot P_j(t) + ok_{c_{21}}(j, t + k) \cdot ok_{\hat{P}_{j,10m}^{NW}}(t + k|t) \]
Some highlights: Normalized Mean Absolute Error (NMAE)

On average, model $M_1$, which makes use of wind speed forecasts at 10m and a power curve fitted for each wind farm, yields more accurate results than the other models.

<table>
<thead>
<tr>
<th></th>
<th>12 hr</th>
<th>24 hr</th>
<th>36 hr</th>
<th>48 hr</th>
<th>60 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_1$</td>
<td>8.85%</td>
<td>12.28%</td>
<td>10.21%</td>
<td>15.53%</td>
<td>12.08%</td>
</tr>
<tr>
<td>$M_2$</td>
<td>10.73%</td>
<td>14.06%</td>
<td>12.07%</td>
<td>16.82%</td>
<td>13.41%</td>
</tr>
<tr>
<td>$M_3$</td>
<td>9.13%</td>
<td>12.53%</td>
<td>10.49%</td>
<td>15.77%</td>
<td>12.24%</td>
</tr>
<tr>
<td>$M_4$</td>
<td>9.60%</td>
<td>12.63%</td>
<td>10.88%</td>
<td>15.84%</td>
<td>12.56%</td>
</tr>
<tr>
<td>$M_5$</td>
<td>9.45%</td>
<td>12.45%</td>
<td>10.72%</td>
<td>15.65%</td>
<td>12.49%</td>
</tr>
</tbody>
</table>

Table.1: NMAE values of $M_1$ to $M_5$ for some prediction horizons

The magnitude of these errors is comparable to those found in Kariniotakis et.al (2004) for flat terrains.
RESULTS

Model intercomparison

M1

M2

M3

M4

M5

(a) NMAE [%] vs Hours

(b) NMAE [%] vs Hours

(c) NMAE [%] vs Hours

(d) NMAE [%] vs Hours

(e) NMAE [%] vs Hours
RESULTS

Spatial distribution of NMAE values of $M_1$
Analysis of OK errors: Comparison between $M_4$ and $M_5$

(-) $M_5$ BT $M_4$

(+) $M_4$ BT $M_5$
Analysis of OK errors: Comparison between M1 and M5

- Better performance is obtained with M1, and depicts errors comparable to those found for flat terrains.
- Using wind speed forecasts at 100m introduces considerable errors and should be avoided.
- M3 which makes use of wind speed M3 (wind speed forecasts at 10m and a single average power curve for the entire Jutland) has a similar performance to M1.
- OK appears as an appealing methodology to start forecasting wind power for any new wind farm that could be settled inland. Errors due to estimations using OK are smaller than 10%.
- M4 (single average power curve and interpolated multi-linear coefficients) works better inland with respect to M5 which outperforms in the majority of the region, particularly in coastal areas.
• WWOSC 2014 organizers for letting me participate in this interesting conference, and for the financial support.
• Energinet and DMI for providing data of all electrical power substations and wind forecasts.