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G-2015-119

November 2015

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La publication de ces rapports de recherche est rendue possible grâce au soutien de HEC Montréal, Polytechnique Montréal, Université McGill, Université du Québec à Montréal, ainsi que du Fonds de recherche du Québec – Nature et technologies.

Dépôt légal – Bibliothèque et Archives nationales du Québec, 2015.

The authors are exclusively responsible for the content of their research papers published in the series *Les Cahiers du GERAD*.

The publication of these research reports is made possible thanks to the support of HEC Montréal, Polytechnique Montréal, McGill University, Université du Québec à Montréal, as well as the Fonds de recherche du Québec – Nature et technologies.

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A methodology for ensemble wind power scenarios generation from numerical weather predictions

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November 2015

**Les Cahiers du GERAD
G-2015-119**

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Abstract: Electric utilities have been using wind power to an increasing extent in order to provide clean energy. However, this resource depends on the intermittency of wind, and this makes balancing supply and demand challenging for the system operator. In this paper we propose a downscaling approach yielding daily probabilistic wind speed scenarios for the turbine hub height, thus making them useful for generating possible wind power scenarios that could be used to maintain the network balance in light of these possible outcomes.

Acknowledgments: This work was funded by an ECO Energy Innovation Initiative grant from Natural Resources Canada.

1 Introduction

Wind power is an emerging source of renewable energy with more than 51 GW installed during 2014, taking its global total capacity to almost 370 GW. This increase is not only because of environmental considerations, but also because of its speed of deployment and cost stability [1]. Utilities managing electric grids with large-scale wind power operation have to take into account its intermittency to be able to balance supply and demand. An accurate forecast of possible wind power scenarios is important for applications like unit commitment or demand side management by system operators and profit maximization by electricity traders [2-4].

Three approaches are used for short-term prediction: 1) The physical approach based on numerical weather prediction (NWP) uses meteorological conditions to forecast the wind speed, 2) the statistical approach based on applying learning algorithms (i.e. regression, neural networks, etc.) to historical data without considering meteorological conditions, 3) a hybrid approach that mixes both approaches [4,5].

Because a deterministic forecast is sensitive to initial forecast conditions that can affect significantly its final outcome, decisions that rely on a single deterministic forecast could result in misleading strategies [6]. Therefore we are interested in this paper in generating scenarios of wind power based on wind speed ensemble forecast, where each member of the ensemble differs in its initial conditions and/or atmosphere modeling. Such an ensemble gives the decision maker a better idea about the wind power uncertainty and results in a more robust strategies. The available NWPs for wind speed are calculated at 10m above ground level (a.g.l.), yet the hub height is at a higher altitudes. Extrapolating wind speed at 10m to a higher altitude is a common approach in meteorology, where physical models parameterized mainly by roughness length and atmospheric stability measured via the Monin-Obukhov length are used [7]. The approach presented in this paper is a hybrid one, as it downscales the NWP wind speed forecast calculated at low altitudes to hub height by training a linear regression model using both NWP data and deterministic forecasts at 100m, which we assume to be a good approximation to the hub height. Those adjusted wind speed scenarios are then converted to ensemble power production scenarios using wind turbine power curves.

2 Wind speed scenarios

Environment Canada (EC) provides several sets of NWP forecasts at 10m a.g.l. of excellent resolution, especially for Québec. The NWP database includes outputs of the ensemble solution, describing various possible outcomes of weather evolution anywhere in the world, with an average resolution of 100 km. Those data are generated according to the Global Environmental Model (GEM), an integrated forecasting and data assimilation system developed by the Canadian Meteorological Centre. The wind speed is calculated twice a day (at $T = 0h$ and $T = 12h$), over a horizon of 144 hours with temporal resolution of 6 hours. We denote by $V_{T+t,d}^F$ the wind speed forecast at time $T + t$ and at d meters of height. Multiple scenarios of wind speed forecast are generated according to perturbed initial states, as well as the different models used for variant atmospheric parameters (i.e., deep convection, precipitation, turbulence, roughness length, etc.) [8]. We call those scenarios Global Ensemble Prediction (GEP). We only consider the forecast for $12 \leq t \leq 144$, which is assumed to be reliable, so the value at $T + 6$ is omitted.

We need to have wind speeds at the hub height to generate the appropriate corresponding wind power scenarios, but the data provided by EC is for wind speed at 10m of height. Figure 3 gives an example of how significant the difference can be between the mean scenario of the EC forecast at 10m and the deterministic forecast, whence the need to correct those scenarios.

The deterministic forecast upon which the ensemble of 10m forecasts are adjusted, is an interpolation of the GEM NWP of EC with a temporal resolution of 15 minutes. This interpolation is provided by WPred, a service company of Montréal. Table 1 depicts some error measures of the WPred deterministic forecast of wind speed, where ME, MAE and RMSE are the mean error, mean absolute error and root-mean-square error respectively. The results shows a small error standard deviation that increases with time with a maximum value of 2.79 for five days ahead. In this section we show how we used both wind speed forecasts of GEP and WPred to extrapolate wind speed scenarios at the hub height using regression analysis, by applying the

Table 1: Error measures of wind speed deterministic forecast [m/s]

Time	Error Measures	Value
Day+1	ME	-0.49
	MAE	2.03
	RMSE	2.60
Day+2	ME	-0.49
	MAE	2.011
	RMSE	2.56
Day+3	ME	-0.48
	MAE	2.06
	RMSE	2.64
Day+4	ME	-0.46
	MAE	2.08
	RMSE	2.66
Day+5	ME	-0.44
	MAE	2.16
	RMSE	2.79

following expression:

$$V_{T+t,100}^F = a * V_{T+t,10}^F. \quad (1)$$

The offset of the linear equation in (1) has been omitted because of its insignificant improvement, and to avoid having negative values for wind speed which is absurd [9].

We collected GEP and WPred data for both Montreal and Quebec City from mid-July 2015 until October 2015. $V_{i,T+t,10}^{arch}$ denotes the i^{th} scenario of the archived GEP wind speed forecast at time $T + t$ and 10m height, where $i \in \mathcal{I} = \{1, 2, \dots, I\}$. $V_{T+t,100}^{arch}$ denotes the archived deterministic forecast for wind speed at time $T + t$ and 100m of height.

We compute the optimal value of the coefficient a that minimizes the least squared error between the GEP mean wind speed scenario $\bar{V}_{T+t,10}^{arch}$ and $V_{T+t,100}^{arch}$. With $\mathcal{T} = \{12, 18, 24, \dots, \mathcal{T}\}$, we have

$$a^* = \underset{a}{\operatorname{argmin}} E(a) := \left\{ \sum_{t \in \mathcal{T}} (V_{T+t,100}^{arch} - a * \bar{V}_{T+t,10}^{arch})^2 \right\}, \quad (2)$$

where

$$\bar{V}_{T+t,10}^{arch} = \frac{1}{I} \sum_{i=0}^I V_{i,T+t,10}^{arch}. \quad (3)$$

The optimization program (2) is a convex quadratic unconstrained problem and thus easy to solve.

3 Wind power predictions

We are able to generate wind speed scenarios at the hub height based on the EC forecast with a step-size of 6 hours via Eq. (1). We then apply a cubic spline interpolation to get hourly wind speed scenarios. To generate the wind power production scenarios, we use the power curve of wind turbines in Figure 1, adjusted for air density as in the International Electrotechnical Commission standard of wind turbines [IEC 61400-12].

Solving the optimization problem (2) gives the linear approximation of the relation between the mean scenario wind speed at 10m and the corresponding wind speed at 100m of the deterministic forecast shown in Figure 2. Applying this linear correction to the EC forecast gives wind speed scenarios as illustrated in Figure 4. Although the mean scenario of the corrected ensemble doesn't follow the deterministic forecast, the scenarios do cover the range of all possible values that the deterministic forecast predicts. In addition

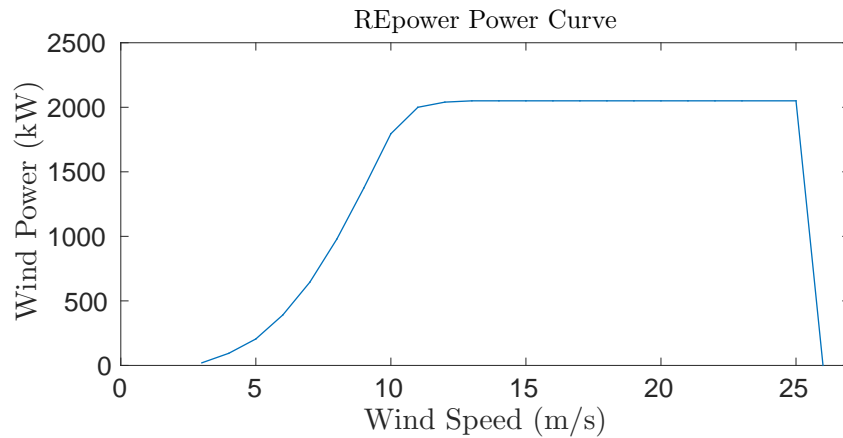


Figure 1: Power curves

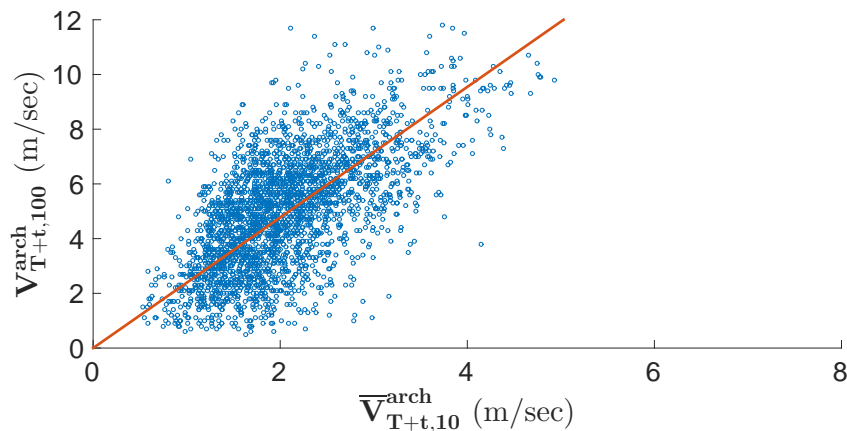


Figure 2: Linear regression

to the linear regression model presented so far, we also studied quadratic and cubic regression by solving (4)–(5) respectively to check if we can improve the correction. Figure 5 illustrates the estimate values of the standard deviation of the error in predicting a future observation for the three approximations and the results show that the linear one has the least max standard deviation error as indicated in Table 2, while the mean estimate of the standard deviation of the error in predicting are almost the same for the three models.

Using the approach above, we used historical sets of wind speed forecasts for the regions of Montréal and Quebec City, and we generated the corresponding total wind power scenarios for four farms: Montérégie and De l'Érable near Montréal, Massif du Sud and Seigneurie de Beaupré near Quebec City. The former have turbines of type Rpower and Enercon. Figure 6 gives an example of such ensemble wind power scenarios.

$$b^* = \operatorname{argmin}_{b \in \mathbb{R}^2} E(b) := \left\{ \sum_{t \in \mathfrak{T}} \left[V_{T+t,100}^{arch} - (b_1 * (\overline{V}_{T+t,10}^{arch})^2 + b_2 * \overline{V}_{T+t,10}^{arch}) \right]^2 \right\} \quad (4)$$

$$c^* = \operatorname{argmin}_{c \in \mathbb{R}^3} E(c) := \left\{ \sum_{t \in \mathfrak{T}} \left[V_{T+t,100}^{arch} - (c_1 * (\overline{V}_{T+t,10}^{arch})^3 + c_2 * (\overline{V}_{T+t,10}^{arch})^2 + c_3 * \overline{V}_{T+t,10}^{arch}) \right]^2 \right\} \quad (5)$$

4 Evaluation of the uncertainty estimation

The objective of the proposed approach is to represent the short-term wind power in a form of ensemble wind power scenarios that can be used by decision-makers in order to take actions according to these possible sets

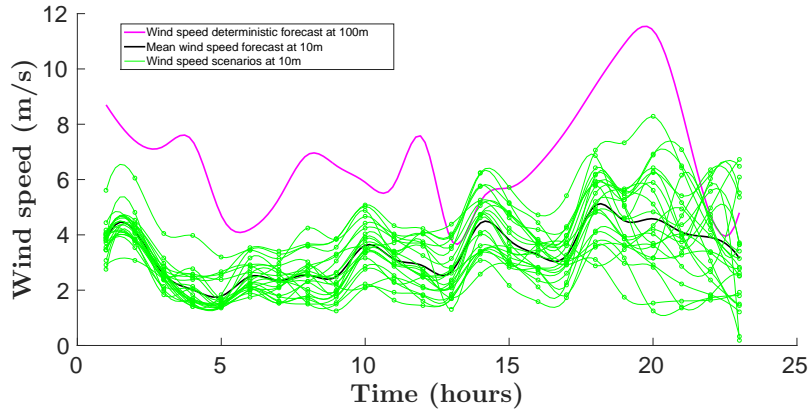


Figure 3: Set scenarios

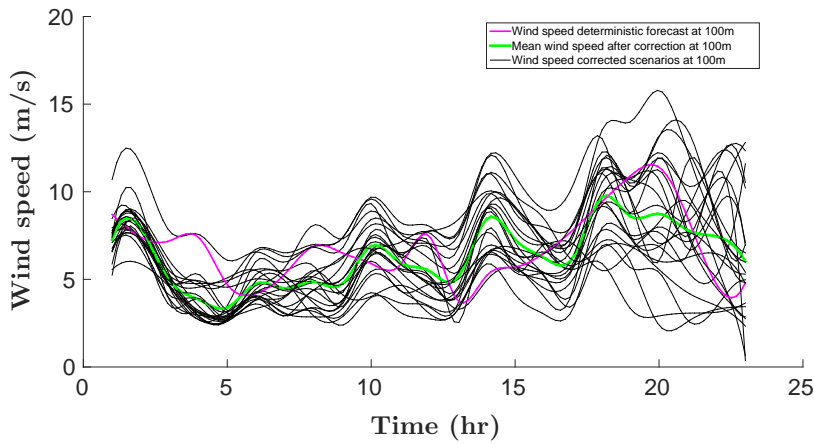


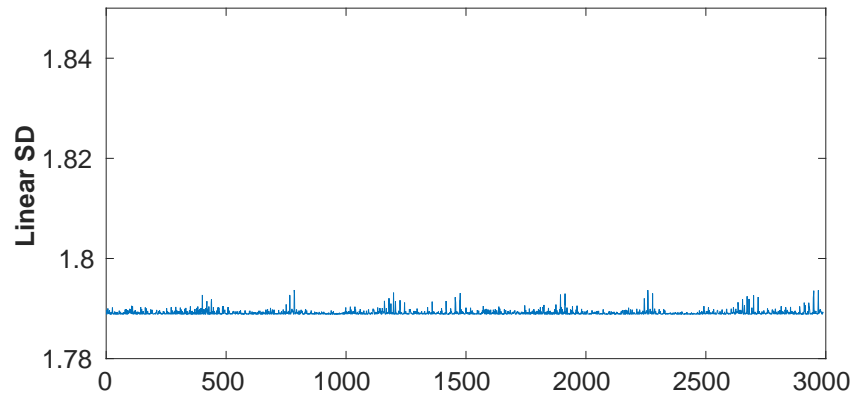
Figure 4: Corrected scenarios

Table 2: Comparison between different regression models

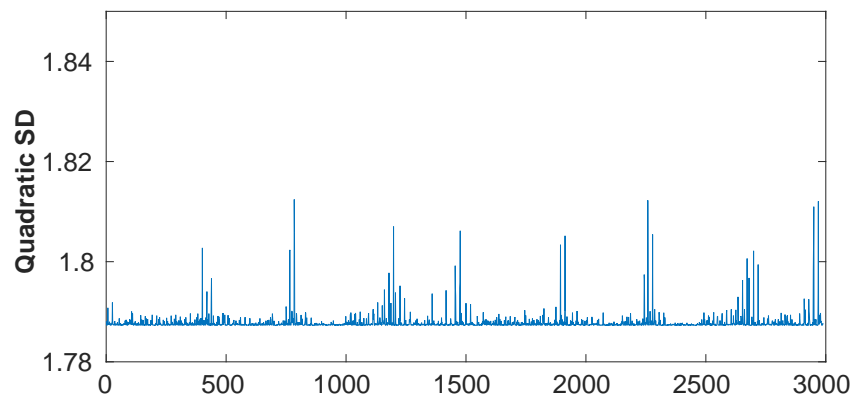
	Linear Model	Quadratic Model	Cubic Model
Max std of error	1.7937	1.8124	1.843
Mean std of error	1.7892	1.7878	1.787

of possible power outcomes. Thus, the evaluation of the approach's quality is not about how accurately it predicts the future intermittent wind power, but rather how well it represents the wind power's uncertainty. This quality measure is illustrated in [6] by evaluating how the scenarios spread changes with the prediction uncertainty. The ensemble spread of an instance $n \in \mathfrak{N} = \{1, 2, \dots, N\}$ at time t is quantified by the standard deviation of ensemble members $\sigma_f^n(t)$, and the level of prediction uncertainty is given by the forecast error $e^n(t)$ between the ensemble forecast mean, denoted by \bar{V}_{T+t}^n and the real realization of wind speed V_{T+t}^n for instance n (6). Note that because we don't have access to real wind power production data, we conducted this quality evaluation test over wind speed scenarios and used the available real wind speed data for different regions in Canada on the EC website.

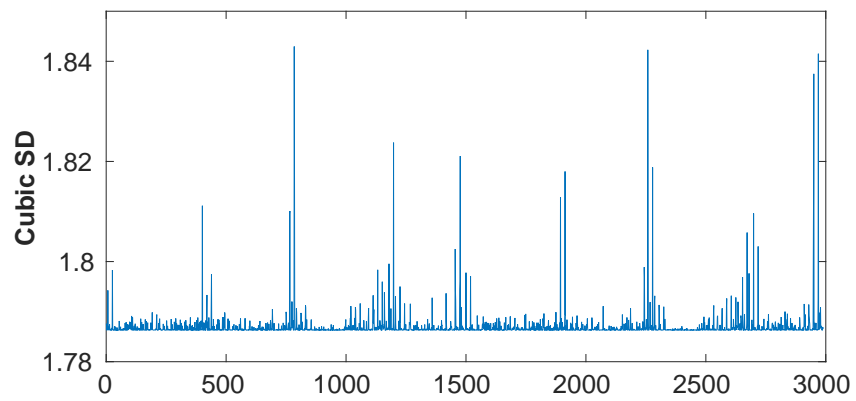
Figure 7 depicts in a form of a box plot the ratio $e^n(t)/\sigma_f^n(t)$, where the ideal case is when the median, represented by the red line within each box, equals 1 as this is the case where the ensemble spread better reflects the prediction error. The uncertainty is overestimated when the median is less than 1, and vice versa. The results show that predictions over the first 5 hours reflect relatively well the wind speed uncertainty, however starting from the 6th hour, wind forecast spread is most of the time underestimated. This less



(a) Linear model



(b) Quadratic model



(c) Cubic model

Figure 5: Estimate of the standard deviation

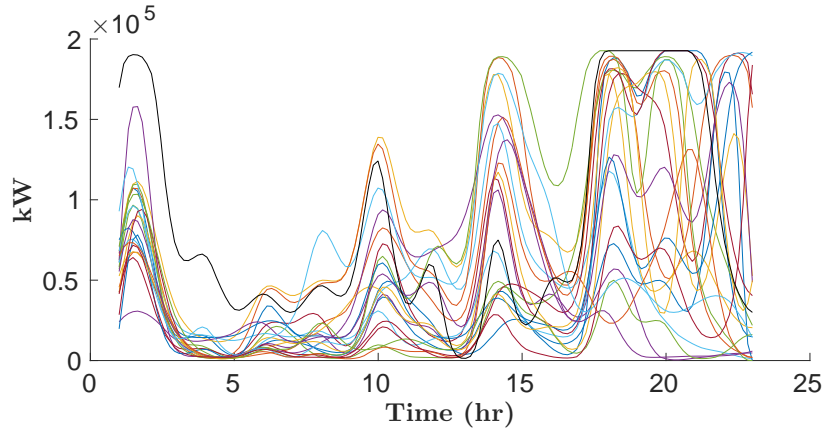


Figure 6: Wind power scenarios

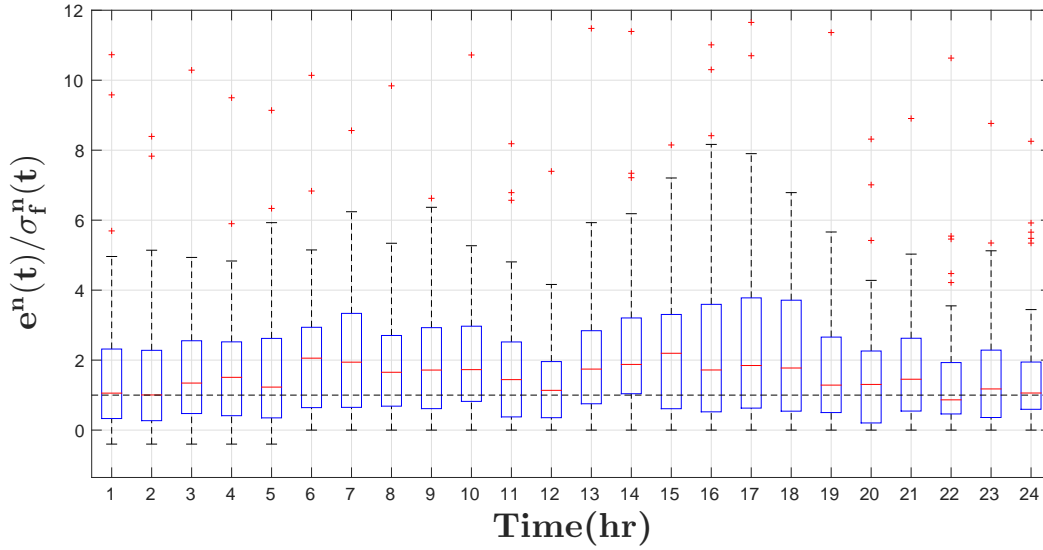


Figure 7: Uncertainty representation of wind speed

accurate representation of uncertainty over long horizons is maybe due to the lack of efficient NWP historical data, still the uncertainty over the first 5 hours is well represented. This can help decision-makers to make robust decisions over short periods, and correct those decisions over time by updating the generated scenarios when new information is available, as is done in stochastic optimization with recourse.

$$e^n(t) = |V_{T+t}^n - \bar{V}_{T+t}^n| \quad \forall n \in \mathfrak{N}, \forall t \in \mathfrak{T} \quad (6a)$$

$$\sigma_f^n(t) = \left[\frac{1}{I} \sum_{i=1}^I (V_{i,T+t}^n - \bar{V}_{T+t}^n)^2 \right]^{\frac{1}{2}} \quad \forall n \in \mathfrak{N}, \forall t \in \mathfrak{T} \quad (6b)$$

$$\bar{V}_{T+t}^n = \frac{1}{I} \sum_{i=1}^I V_{i,T+t}^n \quad \forall n \in \mathfrak{N}, \forall t \in \mathfrak{T} \quad (6c)$$

5 Conclusion and future work

In this paper we proposed an approach that generates ensemble wind power scenarios based on the NWP wind speed forecast. The approach uses a linear model, based on regression analysis, that downscales the NWP scenarios at 10m to a higher altitude using a deterministic forecast calculated at 100m a.g.l. The wind speed scenarios show a good ability in reflecting the wind uncertainty within a few hours, whereas this uncertainty reflection becomes less representative while going forward in time. The next step is to collect real power production data of certain wind farms and apply our approach to see how well it will reflect the power intermittency.

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