DELIVERABLE REPORT D-1.10:
Communication of Wind Power Forecast Uncertainty: Towards a Standard

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Abstract:

The present document describes the current possibilities for communicating uncertainty in wind power predictions, and tends towards the definition of a common standard. Information on forecast uncertainty will then be used as input to methods developed in WP3, and which are related to optimal decision-making.

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Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released	x	R0	General public	x		Private web site	x	
S1	Reviewed		R1	Restricted to project members			Public web site	x	
S2	Pending for review		R2	Restricted to European. Commission			Paper copy		
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PL: *Project leader*   **WPL:** *Work package leader*   **TL:** *Task leader*

Background

Today, most of the existing wind power prediction methods provide end-users with point forecasts. The parameters of the models involved are commonly obtained with minimum least square estimation. If denoting by p_{t+k} the measured power value at time $t+k$, p_{t+k} can be seen as a realization of the random variable P_{t+k}. In parallel, write $\hat{p}_{t+k|t}$ a point forecast issued at time t for lead time $t+k$, based on a model M, its parameters ϕ_t, and the information set Ω_t gathering the available information on the process up to time t. Estimating the model parameters with minimum least squares makes that $\hat{p}_{t+k|t}$ corresponds to the conditional expectation of P_{t+k}, given M, Ω_t and ϕ_t:

$$\hat{p}_{t+k|t} = \mathbb{E}[P_{t+k}|\mathbf{M}, \phi_t, \Omega_t] \tag{1}$$

Owing to their highly variable level of accuracy, a large part of the recent research works has focused on associating uncertainty estimates to these point forecasts. They may take the form of risk indices or probabilistic forecasts [1], or finally of scenarios of short-term wind power production. The latter ones are the most common and utilized in practice today, even though risk indices are shown to be a promising alternative (and maybe complementary) approach [2]. In parallel, scenarios of wind generation may prove to be essential for some decision-making problems for which temporal and/or spatial interdependence structure of prediction errors must be accounted for. A brief description of these 3 alternative ways of communicating forecast uncertainty is given below.

Probabilistic forecasts

Probabilistic predictions can be either derived from meteorological ensembles [3], based on physical considerations [4], or finally produced from one of the numerous statistical methods that have appeared in the literature, see [5, 6, 7, 8, 9] among others. If appropriately incorporated in decision-making methods, they permit to significantly increase the value of wind generation. Recent developments in that direction concentrate on e.g. dynamic reserve quantification [10], optimal operation of combined wind-hydro power plants [11] or on the design of optimal trading strategies [12].

Nonparametric probabilistic predictions may take the form of quantile, interval or density forecasts. Let f_{t+k} be the probability density function of P_{t+k}, and let F_{t+k} be the related cumulative distribution function. Provided that F_{t+k} is a strictly increasing function, the quantile $q_{t+k}^{(\alpha)}$ with proportion $\alpha \in [0,1]$ of the random variable P_{t+k} is uniquely defined as the value x such that

$$\mathrm{P}(P_{t+k} < x) = \alpha, \quad \text{or} \quad q_{t+k}^{(\alpha)} = F_{t+k}^{-1}(\alpha) \tag{2}$$

A quantile forecast $\hat{q}_{t+k|t}^{(\alpha)}$ with nominal proportion α is an estimate of $q_{t+k}^{(\alpha)}$ produced at time t for lead time $t+k$, given the information set Ω_t at time t.

For most decision-making processes, such as power system operation, a single quantile forecast is not sufficient for making an optimal decision. Instead, it is necessary to have the whole information about the random variable P_{t+k} for horizons ranging from few hours to several days ahead, see e.g. [12]. If no assumption is made about the shape of the target distributions, a nonparametric forecast $\hat{f}_{t+k|t}$ of the density function of the variable of interest at lead time $t+k$ can be produced by gathering a set of m quantile forecasts

$$\hat{f}_{t+k|t} = \{\hat{q}_{t+k|t}^{(\alpha_i)} \mid 0 \leq \alpha_1 < \ldots < \alpha_i < \ldots < \alpha_m \leq 1\} \tag{3}$$

that is, with chosen nominal proportions spread on the unit interval. These types of probabilistic forecasts are hereafter referred to as predictive distributions. $\hat{F}_{t+k|t}$ denotes the cumulative distribution function related to $\hat{f}_{t+k|t}$. Note that interval forecasts correspond to the specific case for which only two quantiles are quoted, and whose nominal proportions are chosen to be symmet-

ric around the median. Prediction intervals are then symmetric in terms of probabilities, but not in terms of distance to the median. This is owing to the fact that distributions of potential wind power production are not symmetric themselves. For a more detailed description of probabilistic forecasts of wind generation, as well as a discussion on their required and desirable properties, we refer to [13]. An example of a 43-hour ahead wind power forecasts along with nonparametric probabilistic forecasts is given in Figure 1.
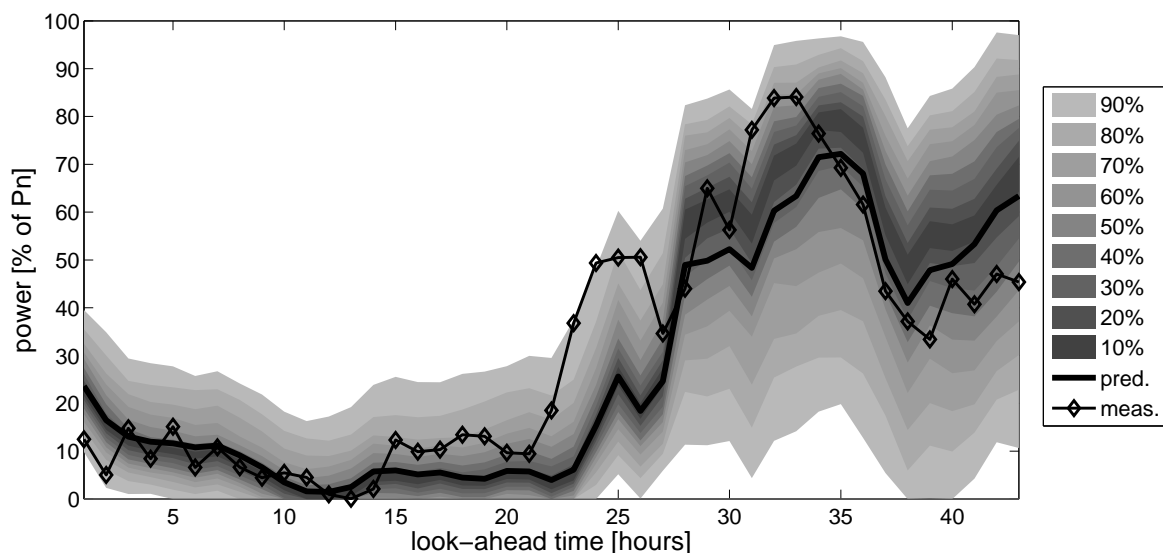
FIGURE 1: *Example of probabilistic predictions of wind generation in the form of nonparametric predictive distributions. Point predictions are obtained from wind forecasts and historical measurements of power production, with the WPPT method. They are then accompanied with interval forecasts produced with adaptive quantile regression. The nominal coverage rates of the prediction intervals are set to 10, 20, ..., and 90%.*
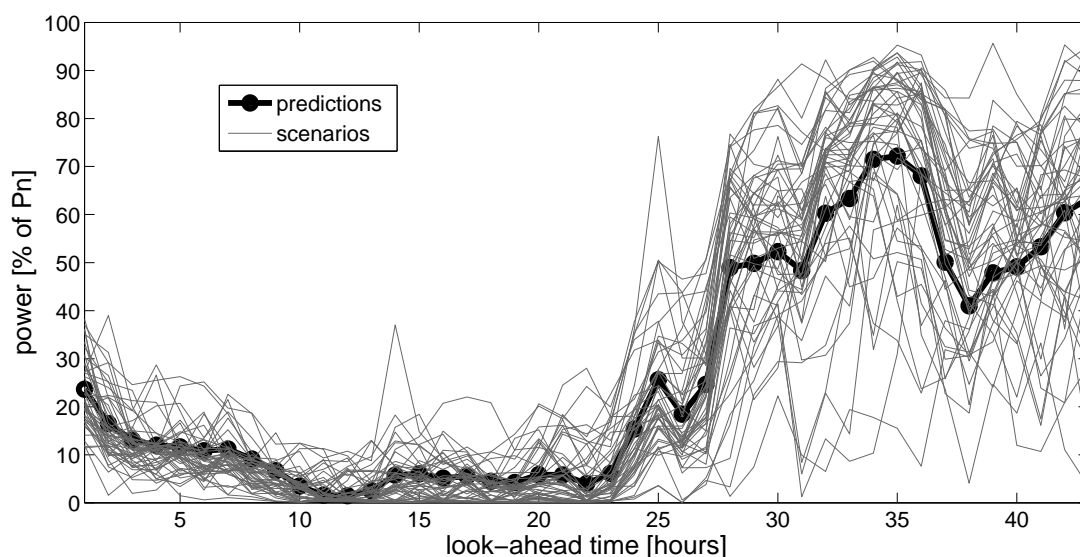
FIGURE 2: *Example of wind power point predictions with 50 alternative scenarios produced from the method described in the paper (for the same period as in Fig. 1). The point prediction series correspond to the most likely scenario while the others reflect the prediction uncertainty and the interdependence structure of predictions errors.*

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Prediction risk indices

It appears that low quality forecasts of wind generation are partly due to the power prediction model, and partly to the Numerical Weather Prediction (NWP) systems. Indeed, during some periods weather dynamics can be relatively more predictable, while at some other point in time they may prove to be unpredictable, and this regardless of the forecasting method employed. Since power predictions are derived from nonlinear transformations of wind forecasts, the level of uncertainty in meteorological predictions may be amplified or dampened through this transformation. Providing forecast users with an *a priori* warning on expected level of prediction uncertainty may allow them to develop alternative (and more or less risk averse) strategies. In an operational context, a skill forecast associated to a given point prediction may be more easily understood than probabilistic forecasts. Also, skill forecasts are not directly related to a given prediction method since they relate to an assessment of the inherent predictability of weather dynamics.

For deriving skill forecasts, ensemble forecasts are commonly used as input. An alternative to their use relate to the works of Lange and Focken [4] towards the definition of weather dynamics indicators. More precisely, they utilize methods from synoptic climatology to classify the local weather conditions based on measurements of wind speed and direction, as well as pressure, and consequently relate them to different levels of forecast uncertainty. Ensemble forecasts consist of a set of alternative forecast scenarios for the coming period, obtained by stochastic perturbation of the initial conditions of NWP models and possibly stochastic parameterization of these models [14]. Different types of meteorological ensemble predictions may be considered, provided either by the European Centre for Medium-range Weather Forecasts (ECMWF), by the National Centre for Environmental Prediction (NCEP), or alternatively by Météo-France. In a general manner, a skill forecast consists of a single numerical value that informs on the confidence one may have in the provided point predictions. To each index value can be associated information on the potential magnitude of prediction errors, possibly with quantiles of such distributions. For a thorough discussion on various aspects of skill forecasting for the wind power application, see [2].

Scenarios of short-term wind power production

Probabilistic forecasts are generated on a per look-ahead time basis. They do not inform on the development of the prediction errors through prediction series, since they neglect their interdependence structure. However, this information is of particular importance for many time-dependent and multi-stage decision-making processes e.g. the economic operation of conventional generation in combination to wind power output. In order to satisfy this additional requirement, it is proposed here to generate scenarios of short-term wind power production. These scenarios should respect the (nonparametric) predictive densities for the coming period, and additionally reflect the interdependence structure (at the temporal and/or spatial levels) of the prediction errors. The importance of such tools has been highlighted on the definition of recent complete power system management methodologies, either for optimal integration of wind power into energy systems [15] or for optimal planning in presence of distributed storage devices [16]. Such scenarios of short-term wind power production can be generated with appropriate statistical methods [17] or by recalibration of ensemble forecasts of wind power, see e.g. [18]. Each of them represent has the same probability of occuring. For the same period as in Figure 1, Figure 2 gives associated scenarios of short-term wind power production, which, in addition to respecting the nonparametric probabilistic forecasts for the coming period, also rely on the a model of the interdependence structure of predictions errors among the set of look-ahead times.

Communication format and operational aspects

Probabilistic forecasts

In practice, as formulated in (3), predictive densities for each look-ahead time would be given by a set of quantiles with different nominal proportions spanning the $[0, 1]$ interval. Typically, the chosen incremental step in nominal proportion is 0.05, thus leading to a set of 21 quantiles. Information on a given predictive densities for each look-ahead time could then be summarized as it is done in Table 1, when given along with classical point forecasts of wind power.

TABLE 1: *Summarizing predictive densities with a set of quantile forecasts with various nominal proportions.*

hor. [h]	point preds. $[\% \, P_n]$	quant. 0	quant. 0.05	...	quant. 0.90	quant. 0.95	quant. 1
0	45	0	4	...	61	82	100
1	32	0	2	...	58	67	100
2	33	0	8	...	54	19	100
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
47	46	0	7	...	72	79	100
48	27	0	3	...	78	81	100

Prediction risk indices

For the case of skill forecasts one can imagine that the value of the risk index is given along with the corresponding point prediction, as illustrated in Table 2. Note that in the case for which skill forecasts are derived from ensemble predictions, these ensemble predictions may also be communicated in complement to the risk index value, following the format detailed in the next Paragraph below.

TABLE 2: *Communicating prediction risk indices along with point forecasts of wind generation. Here the confidence one should have in the provided point forecasts is ranked on a {1,2,...,5} ladder (1 corresponding to the highest confidence level).*

hor. [h]	point preds. $[\% \, P_n]$	risk index
0	45	1
1	32	1
2	33	2
⋮	⋮	⋮
47	46	4
48	27	4

Scenarios of short-term wind power production

Communicating scenarios of short-term wind power production is quite straightforward, as each generated scenario resembles the traditionally provided point forecasts of wind power. Therefore, one may imagine that scenarios would be provided in parallel with such point forecasts, as shown in Table 3.

TABLE 3: *Traditionally point forecast series, and related N scenarios of short-term wind power production.*

hor. [h]	point preds. [$\% P_n$]	scen. 1 [$\% P_n$]	...	scen. N [$\% P_n$]
0	41	38	...	43
1	2	1	...	6
2	3	14	...	12
⋮	⋮	⋮	⋮	⋮
47	46	57	...	72
48	42	61	...	59

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