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Influence of the reliability of short-term electrical power forecasting for a wind farm on the generation cost per MWh. A case study in the Canary Islands

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Abstract

The generation cost of a wind farm has generally been studied on the basis of two factors: the initial investment cost and the operating and maintenance cost.
The problems caused in an electrical system by deviations between the actual electrical power generated by a wind farm and the electrical power estimated by prediction models need to be corrected. These deviations result in an additional economic cost.
This paper evaluates the deviation cost per unit of energy generated by wind farms and analyses the contribution of this cost to the total production cost. The study undertaken in this paper has been made specific to the Canary Islands (Spain).
It can be deduced from the results of the study that the deviation cost can amount to between 1.5% and 15.5% of the cost of producing electrical energy generated by a wind farm depending, amongst other parameters, on the error made in the prediction. Wind farms that are otherwise deemed profitable may not be considered so if the deviation cost is taken into account.

Keywords: short-term wind power prediction, wind energy cost, electric energy market

1. Introduction

The strategic objectives of the European Union in general and on an individual basis of Spain and the Canary Islands [1-3] concerning the contribution that wind energy should be making to electricity demand by the year 2020, will require a considerable increase in installed wind power within that time frame.

The processes involved in the sale and purchase of energy in electricity markets require knowledge of the scheduling of generation bids for future periods of up to 48 hours [4-8]. Such knowledge is vital in the framework of a liberalised electricity market, where the possession of accurate forecasts will allow favourable positioning of wind energy against other more conventional sources of electricity generation. This is even more true in weak electric systems, as may be considered the case of the Canary Archipelago (Spain) with its seven principal islands each of which has its own independent electricity system. For this reason, it is necessary to have very short-term (less than 48 hours) prediction models of the power output of wind farms.

A variety of errors in these models compromises their degree of reliability, resulting in many cases in the predicted values differing considerably from the actual measured values.

Various projects have been undertaken comparing different prediction tools presently in use with the aim of optimizing the results for short-term wind energy prediction. Two such projects which have been developed along these lines are ANEMOS [9-11] and Forecasting Exercise [12].
These projects attempt to take advantage of the potential of each of the prediction tools to create new improved tools. The different prediction tools were applied on an individual basis to each of the wind farms studied in the aforementioned projects.
For the purpose of comparing reliability in future electrical power forecasting, the authors of the ANEMOS and Forecasting Exercise projects used different metrics. For the study undertaken in this paper, the conclusions obtained from the Forecasting Exercise [12] for the metric which relates the forecast error with the actual measured power have been used. The Forecasting Exercise authors concluded that the mean value of the error, relative to actual production, for the case of individual wind farms was 55%, with 20% being the minimum error obtained by one of the forecast models.

To guarantee the supply and quality of the electricity, the system operator must be sure that the grids used to transport and distribute the energy are able to handle the amounts of this energy that are bought and sold in the market. The energy transactions of any particular day, D, are negotiated beforehand, generally on D-1. It is therefore extremely important that the negotiated energy bids are in fact available in the electricity system at the stipulated time. Any possible deviations that may occur in this sense will generate problems in that system. The system operator must act without delay to correct any power imbalances and guarantee the quality of the energy supply. These corrections to the electricity system entail an additional cost which is directly passed on to the electricity producers responsible for the imbalance [13-17]. In this paper, this cost has been called the deviation cost (Cd).

The cost structure of energy generation for a wind farm as considered to date in the scientific literature generally contemplates two factors: costs due to initial investment and operating and maintenance costs [18-21].

An evaluation is made in this paper of the mean deviation cost per unit of energy generated by a wind farm. An analysis will also be undertaken of the influence of the error committed in wind power prediction on the size of the deviation cost and on its contribution to the total production cost. After incorporating the deviation cost, the new production cost will be compared with the average energy sale prices in the electricity market.

The calculations made in this paper are specific to the electricity system and market of the Canary Archipelago, which are in turn regulated by the system and market operators of Spain.

2. Initial Data

A. Meteorological data

The weather data used in this study correspond to the mean hourly wind speed data from six weather stations (WS-1 to WS-6) (Figure 1) for the period 1999-2010. The data were recorded at a height of 10 m above ground level. The stations are located in six of the seven islands of the Canary Archipelago; Lanzarote, Fuerteventura, Gran Canaria, Tenerife, La Palma and El Hierro.

The data were supplied by the official authorised State Meteorological Agency (Spanish initials: AEMET), part of the Spanish Government Ministry of Agriculture, Food and Environment, which also acts as the authorised aeronautical meteorological agency [22].

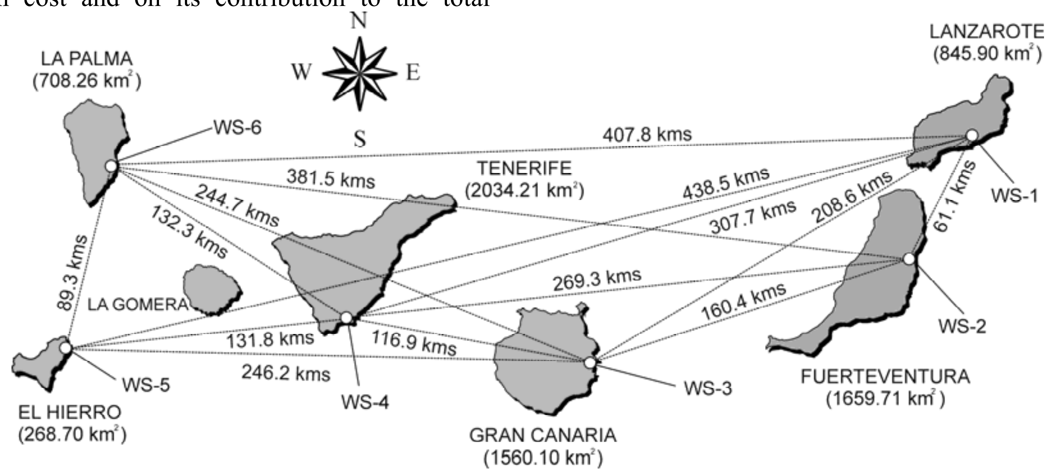

Fig. 1. Location of the weather stations used.

B. Wind turbine data

An Enercon E-70 wind turbine with rated power of 2300 kW was chosen for the wind-sourced electrical energy generation calculations.

Wind turbine manufacturers usually provide the power curves of their wind turbines in a discrete form with M nodes (Pwt_j, V_j; where j=1…M) [23].

3. Methodology

In the particular case of Spain's electricity systems, the deviation cost is determined for each hour of the year. Spain's transmission system operator (Spanish initials: REE), publishes the charge per unit of deviated energy (€/MWh) on its website [24].

The present analysis uses the mean values of the deviation charges, available for each hour of the year during the period from 2007 to 2011. The mean hourly deviation charges were calculated for each month of this five year period, Eq. (1).

$$\overline{Cd_{h,m}} = \frac{1}{N_y \times N_d} \sum_{d=1}^{N_d} \sum_{y=1}^{N_y} Cd_{h,m,d,y} \qquad (1)$$

where:

$\overline{Cd_{h,m}}$; is the mean deviation charge for hour "h" of month "m" in the study period 2007-2011 (in Euros/$MWh_{deviated}$)

Cd $_{h,m,d,y}$; is the deviation charge for hour "h" of day "d", relative to month "m" and year "y"

N_y; is the number of years of the study period

N_d; is the number of days of the month under consideration

Using the available mean hourly wind speeds from the different weather stations (Fig. 1) and the power curve of the chosen wind turbine, it is possible to estimate the mean hourly electrical power for each of the weather stations, $Pwt_{h,m,d,y}$..

where:

$Pwt_{h,m,d,y}$; is the electrical power of the wind turbine in hour "h" of day "d", relative to month "m" and year "y" (in kW)

Gran Canaria and Tenerife are the most populated islands and account for 80% of the total installed power. It is expected that most of the Archipelago's future wind farms will be installed on these two islands. For this reason, when estimating the hourly distribution per month of the electrical power of the wind turbine, this was weighted depending on the island where the reference weather station is located. This weighted power distribution was calculated to enable estimation of the weighted mean deviation costs.

As described for the deviation charges, using the hourly data of electrical power for the 12 years for which wind data were available (1999-2010), the mean electrical power for each hour of each month of the year, $\overline{Pwt_{h,m}}$, was estimated.

From the results obtained for the mean hourly deviation charges per month, $\overline{Cd_{h,m}}$; and the mean hourly electrical power per month, $\overline{Pwt_{h,m}}$, the values of the weighted mean monthly deviation cost are obtained, Eq. (2).

$$\overline{Cd_m} = \frac{1}{\sum_{h=1}^{24} \overline{Pwt_{h,m}}} \sum_{h=1}^{24} \overline{Cd_{h,m}} \times \overline{Pwt_{h,m}} \tag{2}$$

where:

$\overline{Cd_m}$; is the weighted mean deviation cost for month "m" (in Euros/$MWh_{deviated}$)

Once the mean hourly electrical power per month has been obtained, it is possible to calculate the electrical energy for each month of the year, Eq. (3).

$$Ewt_m = \left(\frac{1}{24} \sum_{h=1}^{24} Pwt_{h,m} \right) \times N_{h,m} \tag{3}$$

where:

Ewt_m; is the electrical energy generated by the wind turbine in month "m" (in kWh)

$N_{h,m}$; is the number of hours in month "m"

Bearing in mind that the wind resource varies not only depending on the hour of the day but also over the different months of the year, the weighted mean deviation cost in the year is calculated as shown in Eq. (4).

$$\overline{Cd} = \frac{1}{\sum_{h=1}^{12} E_m} \sum_{h=1}^{12} \overline{Cd_m} \times E_m \tag{4}$$

where:

$\overline{Cd}$; is the mean deviation cost in a year (in Euros/$MWh_{deviated}$)

To calculate the effect of this deviation cost on the total electrical power production cost of the wind farm, the value of the error which is committed in the forecast must be taken into account.

The metric used in this study relates the error with the actual measured production, Eqs. (5) and (6) [12].

$$MARE = \frac{1}{N} \sum_{i=1}^{N} EMAP_i \tag{5}$$

where:

MARE ; is the Mean Absolute Relative Error

N; is the number of predicted time periods

EMAP; is the error relative to the actual measured power for the prediction period "i" of size "m", Eq. (6).

$$EMAP = \frac{\sum_{h=1}^{m} \left| P_f(t+h) - P_m(t+h) \right|}{\sum_{h=1}^{m} P_m(t+h)} \times 100 \tag{6}$$

where:

P_f (t+h); is the predicted power at instant "t" for hour "t+h"

P_m (t+h); is the measured power at instant "t+h"

m; is the size of the forecast period. This can vary between 1 and 48 hours

With the results obtained from Eq. (4) and Eq. (5), it is possible to calculate the deviation cost per unit of generated energy, Eq. (7).

$$Cd_e = \overline{Cd} \times \frac{MARE}{100} \tag{7}$$

where:

Cd_e; is the specific deviation cost or the mean deviation cost per unit of energy generated by the wind farm (in Euros/$MWh_{generated}$)

As can be observed in Eq. (7), the specific deviation cost is a function of the error committed in the prediction of the electrical power generated by the wind farm. In this paper, an analysis is made of the effect of the deviation cost, as a function of the forecast error, on the total production costs of wind-sourced electrical energy. A comparison will also be made of the specific deviation cost, Cd_e, in relation to the sale price of the electrical energy.

Incorporation of the specific deviation cost, Cd_e, as a new factor in the production cost will affect the economic profitability of wind farms. The degree of this effect will depend on the error in the forecast and on the energy performance (EP) of the wind farm, Eq. (8). It is for this reason that the results have been made specific to this energy performance.

$$EP = \frac{\text{Electrical energy generated over a year by a wind farm}}{\text{Rated capacity of the wind farm}} \quad (8)$$

where:

EP; is the energy performance of a wind farm located in a particular area (in MWh/MW).

4. Analysis of results

If, in addition to the standard production cost structure used in the scientific literature [18-21], the cost factor analysed in this paper is also incorporated, then the total cost of the electrical energy produced by a wind farm can be calculated through Eq. (9)

$$C_T = C_I + C_{O\&M} + C_d \quad (9)$$

where:

C_T; is the total cost of the electrical energy generated by a wind farm divided by the rated capacity of that farm in MW (in Euros/MW)

C_I; is the initial investment cost divided by the rated capacity of the wind farm in MW (in Euros/MW)

$C_{O\&M}$; is the operating and maintenance cost divided by the rated capacity of the wind farm in MW (in Euros/MW)

C_d; is the total cost due to deviations between predicted and measured electrical power divided by the rated capacity of the wind farm in MW (in Euros/$MW_{deviated}$).

For the purposes of this paper, a simplified calculation model of the specific cost of energy (COE) was chosen, Eq. (10). This method, similar to the EPRI TAG method [18-19] estimates the cost as the ratio between the total costs and the annual electrical energy produced by the wind farm.

The initial investment cost can be estimated at 1200000€/MW [26-27] and the operating and maintenance cost at 45000€/MW [26]. Taking into account these values, the expression for EP, Eq. (8), and the expression for specific deviation cost, Eq. (7), the specific cost of the electrical energy generated by a wind farm can be expressed by Eq. (10).

$$COE = \frac{C_I \times FCR}{EP} + \frac{C_{O\delta M}}{EP} + Cd_e \quad (10)$$

where:

COE; is the specific cost of the electrical energy generated by a wind farm (in Euros/MWh)

FCR; is the fixed charge rate per year, Eq. (11).

$$FCR = \frac{r}{(1+r)^{lt} - 1} + r \quad (11)$$

where:

r ; is the discount rate. Taking as reference the cost of long-term Spanish debt a value has been assumed for the discount rate equal to 0.048 (4.8%)

lt; is the useful life of the wind turbine. For this study, a useful life of 20 years has been assumed which corresponds to the warranty period given by the manufacturers

Table 1 shows the results obtained for mean monthly electrical power, $\overline{Pwt_m}$. It can be seen that the mean power varies depending on the season of the year.

To evaluate the energy contribution of each month to the total production over the year, the relative values were calculated using Eq. (12). Table 1 shows the results obtained. These are the results which represent the conditions of wind-sourced electrical energy exploitation in the Canary Archipelago.

$$Ewt_m(\%) = \frac{\overline{Pwt_m} \times N_{h,m}}{\sum_{m=1}^{12} \overline{Pwt_m} \times N_{h,m}} \times 100 \quad (12)$$

where:

$Ewt_m(\%)$; is the relative value of the electrical energy generated by the wind turbine in month "m" with respect to the total for the year.

$N_{h,m}$; is the number of hours in month "m"

$\overline{Pwt_m}$; is the mean electrical power of the wind turbine in month "m".

Table 1 Initial results

Month	$\overline{Pwt_m}$	$Ewt_m(\%)$	$\overline{Cd_m}$
Jan	286.5	4.34%	15.24
Feb	413.8	5.67%	13.70
Mar	504.9	7.65%	12.91
Apr	617.9	9.07%	10.94
May	646.8	9.81%	10.01
Jun	791.0	11.61%	9.51
Jul	1085.4	16.46%	9.80
Aug	865.8	13.13%	9.84
Sep	482.4	7.08%	12.11
Oct	340.3	5.16%	13.66
Nov	328.3	4.82%	13.72
Dec	344.0	5.22%	15.97

From the information published by the Spanish electricity system operator related to deviation charges [24] and by applying Eqs. (1) y (2), an estimation was made of the mean monthly deviation cost, $\overline{Cd_m}$. The results are shown in Table 1.

From the results obtained for the relative exploitation of the electrical energy, $Ewt_m(\%)$, and the mean monthly deviation cost, $\overline{Cd_m}$, calculation was made of the mean annual value of the deviation cost for each unit of deviated energy. This cost for the period under consideration amounts to 11.47 €/MWh$_{deviated}$.

To calculate the mean electrical energy price we used the hourly data published on the Spanish Electricity Market Operator web site [25]. The hourly data for the year 2011 were used for the purpose of the particular analysis undertaken in this paper.

Following a procedure similar to that considered for calculation of the deviation cost, the result obtained for the specific mean sale price of the electrical energy (Pr_e) is 59.89€/MWh.

The specific production cost of electrical energy by a wind farm is a function of its energy performance, Eq. (8). From Eq. (8), it can be deduced that the higher the EP, the lower the cost due to initial investment and operating and maintenance. For this reason, the results have been made specific to the energy performance of the wind farm.

In Spain as a whole, the mean energy performance for the years 2007-2011 ranged between 2000 and 2200 MWh/MW. In the particular case of the Canary Islands, the corresponding values are between 2200 and 2600 MWh/MW [28]. For the year 2011, the mean EP of wind farms in the Canary Islands was 2425 MWh/MW [29].

For this reason, the results were analysed for an energy performance range equal to: $1800 \leq EP \leq 2800$.

The specific deviation cost, Cd_e, has been included in the production cost structure of the electrical energy generated by a wind farm (Eq. 10). This cost factor is a function of the error committed in short-term prediction, Eq. (7). Taking into consideration the mean results obtained for the error in studies carried out using different wind farms and different predictors [12], the results have been analysed in this paper on the basis of a range of mean forecast errors of 0% to 80%. In this way, the results that are obtained can be applicable to a wide variety of cases with wind farms of different characteristics and with different types of electrical power predictors.

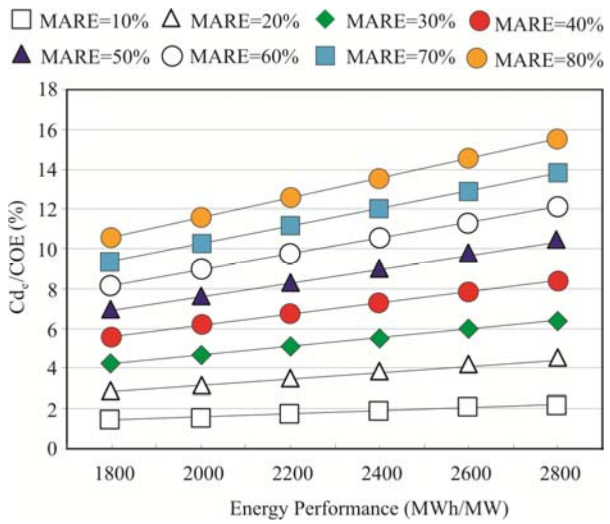

Fig. 2. Contribution of the deviation cost to the production cost of electrical energy by a wind farm.

Figure 2 shows the results of the contribution of the deviation cost to the total production cost of electrical energy generated by a wind farm as a function of the forecast error (MARE). It can be seen that the contribution of the deviation cost rises with the forecast error. For the specific case of an EP of 2800 MWh/MW, the contribution of the deviation cost to the total cost can vary from 2.1% to 15.54% for MARE values of 10% to 80%, respectively.

Figure 3 compares the total production costs (COE) with the sale price of electrical energy (Pr_e).

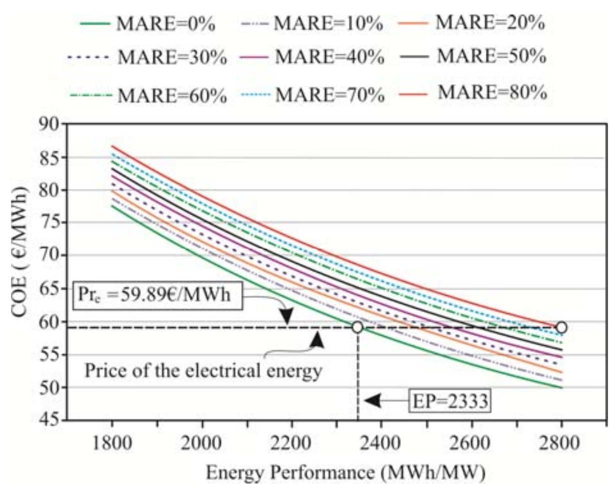

Fig. 3. Total production cost of the electrical energy generated by a wind farm (COE).

It can be observed in Figure 3 that, for the specific case in which there are no errors in the prediction, MARE=0%, in order for the total production cost to be lower than the sale price of the energy, Pr_e, the energy performance of a site has to be higher than 2333 MWh/MWh. However, if the prediction error is equal to 80%, in order for the total production cost to be lower than the sale price of the energy, Pr_e, the energy performance should be higher than 2800MWh/MW. So, the energy performance which is required of a site in order for the production cost not to be higher than the sale price of the energy has to rise as the forecast error increases. For the specific case of a wind farm with an EP equal to 2425 MWh/MW, equivalent to the mean value obtained for the Canary Islands in 2011 [29], the maximum possible mean relative error (MARE) in order for the COE to be lower than the Pr_e is approximately 10%, as can be deduced from Figure 3.

5. Conclusions

Deviations between the predicted and measured electrical energy production values for an established energy demand will give rise to alterations to the electrical system. Resolving these alterations will entail an additional economic cost which is proportionally passed on to the generation sources which have caused the deviation.

The authors of this paper propose that the specific deviation cost (Cd_e) should be considered as an additional factor in the cost structure of a wind farm's electrical energy production, Eq. (10). As shown in Figure 2, its contribution to the total cost depends on the forecast error. In an economic analysis of a wind farm project it is a necessary condition that the total production cost of the electrical energy (COE) is lower than the specific sale price of the energy (Pr_e) or, in other words, than the income per unit of energy. The energy performance that is required of a wind farm located in a specific area so that the production cost will be lower than the sale price depends on the power forecast error.

For prediction errors of 0%, the energy performance has to be greater than 2333 MWh/MW. When the error rises to 80%, it has to be higher than 2800 MWh/MW.

In general, the economic cost associated with deviations between predicted and measured electrical energy production will lower the economic profitability of wind farms.

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