Calculation of the capacity value for wind generation in Uruguay

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Abstract—**Traditionally the Uruguayan electric system has been composed of thermal and hydroelectric generation. In the last decade a huge amount of wind and solar generation has been added into the system. This has lead in practice to a reduction of the amount of the thermal back up capacity required. In fact, several MW of thermal generation has recently been decommissioned. However, current regulation in Uruguay do not consider the contribution of wind or solar generation to firm capacity. The aim of this work is to establish an adequate methodology to estimate the contribution of the wind farms in Uruguay to the firm power capacity of the system. Finally, simulations with real data were made in R software in order to evaluate the amount of this constribution.**

I. INTRODUCTION

The Uruguayan electric wholesale market regulation (RM-MEE) [1], [2] establishes the basis for the operation of the electricity market in Uruguay. This regulation was published in 2002, when the generation fleet only consisted of thermal and hydroelectric power. So the calculation criteria for firm power were established only for these two types of generation sources. In the last decade, the energy matrix has changed, adding non-conventional renewable energies (NCRE) such as wind, photovoltaics and biomass. For the case of biomass, the calculation of the firm power is analogous to the thermal source. However, the other two sources (of intermittent nature) are not considered in the same regulation, despite their important participation in the electricity supply. In the case of wind generation, it exceeded 1500 MW installed at the end of 2017, or about one half the installed capacity value of the thermal and hydroelectric power installed. The forecast for the next 30 years maintains a trend of growth of wind and solar generation resources above other sources. In this context, it is essential to be able to evaluate the contribution of intermittent NCRE, to adequately estimate the reliability of the system in terms of security of supply, and achieve a better planning of the generation and the grid expansion. The literature discusses the study of firm power through the concept of capacity value or credits [3]. This paper aims to provide a consistent calculation method for the capacity value of NCRE, in order to meet security of supply/supply adequacy standards, and it is organized as follows. In Section 2 the calculation methods found in the bibliography are presented and discussed. In Section 3, the procedure used to perform simulations based on the definition of Effective Load Carrying Capability (ELCC) [9] is detailed. In Section IV the results obtained in the simulations are presented. These results are obtained from simulations implemented in the programming language R. The data comes from the hourly demand data and total wind generation of the Uruguayan electricity system in 2016. Finally, Section V is for the conclusions of our work.

II. METHODOLOGY

A. Statistical methods

Statistical methods are based on [4], [5], [6] historical records of power or energy consumption at peak hours and/or during greatest demand periods of the year. The capacity factor for a given year is calculated as the ratio between the average power (energy) delivered in the period of interest and the installed power (energy that could be supplied based on the installed power). Generally this factor is averaged with the data of n previous years according to the criteria used. This model is usually applied in markets which objective is to grant credit-payment's capacity to wind generators, but the method does not seem to be a useful tool for estimating the systems reliability since the value of the demand is not taken into account.

B. Analytical methods - Voorspools and D'haeseleer's formula

Voorspools and D'haeseleer develop their equations in [4] and [7] based on the observations made by Van Wijk on the behavior of wind power as a function of the penetration percentage. The proposed formulas consider the participation of wind generated power, the capacity factor of the wind projects and the reliability of the conventional system.

$$CC = \alpha \frac{CF_w}{R_s}(1 + \beta).\ if\, x < 1\%$$

$$CC = \alpha \frac{CF_w}{R_s}(1 + \beta.e^{-b(x-1)}).\ if\, x > 1\%$$

Where:

- CC: Capacity credit as a percentage of installed capacity.

- x: Wind penetration level in relation to the maximum load.
- CF_w: Project capacity factor.
- R_s: System reliability.
- α: 37.6
- β: 1,843
- b: 0.094

The above formulas indicate that for very low percentages of wind penetration (less than 1 %), the capacity credit is constant and as installed wind power increases (above 1 % of penetration) the value of the capacity credit decreases exponentially towards a constant value.

Voorspools and D'haeseleer [7], [8] incorporate the spatial dispersion factor of wind turbines into the previous equations, resulting in the following:

$$CC = \left(\frac{U}{V+\delta}\right)\left(\frac{CF_w}{R_s}\right)(1+W).\ if\ x < 1\%$$

$$CC = \left(\frac{U}{V+\delta}\right)\left(\frac{CF_w}{R_s}\right)(1+W.e^{-Y(V+\delta)(x-1)}).\ if\ x > 1\%$$

Where:

- δ: Scattering coefficient
- U:32.8
- V:0.306
- W:3.26
- Y:0.1077

C. Probabilistic methods

The probabilistic methods for capacity credit calculation are based on the concept of loss of load probability (LOLP). Although they have slight differences in their definition, the idea is to determine the amount of load that can be added to the demand of the system due to the incorporation of a new generator keeping the same degree of reliability.This idea allows us to think about the growth of the system, which makes it suitable for planning purposes.In the particular case of Uruguay regulation, future security of supply is achieved by a percentage requirement of contracted firm power capacity. If none capacity credits are recognized for wind and solar, then overinvestment in thermal generation may occur.

- Equivalent Load Carrying Capability - ELCC If adding X MW of generation produces that the demand can be increased by Y MW keeping the previous value of the LOLP (i.e. the value without the additional X MW), then the capacity credit of the generator is Y MW.

- Equivalent Firm Capacity- EFC If adding X MW of generation decreases the LOLP as a 100 % reliable generator of Y MW, then the capacity credit of the X MW generator is Y MW.

- Equivalent Conventional Capacity- ECC If adding X MW of generation decreases the LOLP as a reliable generator not 100 % available in Y MW, then the capacity credit of the generator X MW, is Y MW.

D. Theoretical calculation of LOLP

In an electrical system that has a generation fleet composed of N generators with an installed power C_T , the Loss of Load Probability is defined as the probability that the energy demand (including losses) is greater than the available generation [9] Mathematically the probability of loss of load of a system can be expressed as:

$$LOLP = P\left(D_e^0 > G_d\right) \tag{1}$$

Where:
D_e^0 is the characteristic demand of the system
G_d is the system's available generation.

The available generation results from the subtraction between the installed generation C_T and the sum of the power of all the generators that are not available (outages). $\sum_{j=1}^{N} O_j$,

$$G_d = C_T - \sum_{j=1}^{N} O_j \tag{2}$$

The first term C_T in the equation 2 is deterministic, while $\sum_{j=1}^{N} O_j$ is a random variable. Based on the above, the equation 1 can be written as:

$$\begin{aligned} LOLP &= P\left(D_e^0 > C_T - \sum_{j=1}^{N} O_j\right) \\ &= P\left(D_e^0 + \sum_{j=1}^{N} O_j > C_T\right) \end{aligned} \tag{3}$$

For [9]:

$$\begin{aligned} P\left(\sum_{j=1}^{k} O_j > x\right) &= p_k.P\left(\sum_{j=1}^{k-1} O_j > x\right) \\ &+ q_k.P\left(\sum_{j=1}^{k-1} O_j > x\right) \end{aligned} \tag{4}$$

Since p_k is the probability that the kth generator will operate, $q_k = 1 - p_k$ and C_k the installed power of the kth generator. If the equation 4 takes $x = C_T - D_0$ (system reservation) it results:

$$\begin{aligned} P\left(\sum_{j=1}^{k} O_j > C_T - D_0\right) &= p_k.P\left(\sum_{j=1}^{k-1} O_j > C_T - D_0\right) \\ &+ q_k.P\left(\sum_{j=1}^{k-1} O_j > C_T - D_0\right) \end{aligned} \tag{5}$$

Applying equation 3:

$$P\left(D_0 + \sum_{j=1}^{k} O_j > C_T\right) = p_k.P\left(D_0 + \sum_{j=1}^{k-1} O_j > C_T\right) + q_k.P\left(D_0 + \sum_{j=1}^{k-1} O_j > C_T\right) \quad (6)$$

The equivalent load duration curve of the system for the kth power generator can be expressed as:

$$D_k = D_0 + \sum_{j=1}^{k} O_j \quad (7)$$

Calling $F_{D_e^k}(x) = P(D_e^k > x)$, then $1 - F_{D_e^k}(x)$ is the cumulative demand distribution function (FDA) and applying this equality in the equation 6 results:

$$F_{D_e^k}(x) = p_k.F_{D_e^{k-1}}(x) + q_k.F_{D_e^{k-1}}(x - C_k) \quad (8)$$

$$LOLP = F_{D_e^k}(C_T) \quad (9)$$

The equations 8 and 9 will be used to perform the simulations for the calculation of firm power.

III. SIMULATIONS

A. Calculation procedure

For the simulations, demand data and wind generation recorded in 2016 were used. The calculations were made monthly to differentiate the variability of the wind resource throughout the year and because the installed power is not constant for all the months as a result of the entrance of new wind farms during the year.

We observe here that the results may underestimate the true availability of the resource, due to certain operative constraints occuring in Uruguay that sometimes force the generators to dispatch lower power than the available. The procedure developed to calculate the capacity credit was carried out by applying the previous definition of the ELCC, following the three steps detailed below. Calculations were implemented in the programming language R, and the input data used were: The hourly data of the demand and the hourly data of the subtraction between demand and the wind generation ordered by date. The data of the conventional generators indicated in table I .

- The hourly data of the demand and the hourly data of the subtraction between the demand and the wind generation ordered by date.
- The data of the conventional generators indicated in the table.

TABLE I

Termal and hydro power plants [2]

Power plant	Merit order	Installed Power (MW)	Availability p
Salto Grande-base	1	70	0.99
Biomasa	2	146.3	0.85
CBO Motores	3	80	0.8
CBO Sexta	4	120	0.35
PTA	5	300	0.8
APR	6	50	0.9
CTR La Tablada	7	200	0.75
Rincon del Bonete	8	152	0.99
Baygorria	9	108	0.99
Palmar	10	333	0.99
Salto Grande Flexible	11	876	0.99

Step 1 - Consists in calculating the LOLP of the system assuming that the generation is only given by conventional generation plants.

The implemented code takes the hourly data of the demand, it orders them counting the number of hours in which a certain value of demand is exceeded, generating the probability function of the demand characteristic for the system $F_{D_e^0}(x)$. Then the equation 8 is applied iteratively, starting from a single installed generator and adding a new generator in each step.

$$F_{D_e^1}(x) = p_1.F_{D_e^0}(x) + q_1.F_{D_e^0}(x - C_1)$$

$$F_{D_e^{11}}(x) = p_{11}.F_{D_e^{10}}(x) + q_{11}.F_{D_e^{10}}(x - C_{11})$$

Then the equation 9 is applied, obtaining the LOLP for step 1: $LOLP = F_{D_e^{11}}(C_T)$.

Step 2 - The procedure is analogous to step 1, with the exception that the data which is read to generate the cumulative distribution function of the demand consists on the subtraction between the demand and the wind generation over the calculation period. This is mathematically valid and can easily be derived from the equations for calculating the LOLP seen in the previous section. The LOLP (LOLP2) that is obtained is less than LOLP1.

Step 3 - A constant demand value (hour to hour) is added to the characteristic demand curve used in step 2 and the LOLP (LOLP3) is calculated until it matches LOLP1. This calculation is done conditionally, adding to the difference ”Demand - Wind Generation” a demand value that increases in each step until the difference between LOLP1 and LOLP3 is less than a defined chosen value.

The demand value that leads to LOLP1 equal LOLP3, represents the capacity credit (ELCC). To express this value in percentage form, the previous obtained result should be divided by the installed wind power of the considered month.

IV. RESULTS

In several studies where the contribution of the wind generation has been addressed as [3] and [10] it is indicated that some of the influential factors to improve the percentage of the capacity credit are:

- Good level of interconnection of wind energy.
- Consider large areas for taking measurements.
- High correlation between wind speed and demand peaks.

Some of these characteristics are present in the Uruguayan electric system. In the case of the interconnection of the network, Uruguay has a strong link both with Argentina (2000 MW) and Brazil (570 MW). The wind generation data were taken over a large area within the national territory, since the wind generation farms are installed in practically all regions of the country; however this consideration should be weighed by the fact that the country area is small and the behavior of the wind is similar throughout all over it. The correlation between demand and wind generation is shown in figures 1, 2, 3.

The calculations were made without considering constraints in conventional plants such as droughts, floods or problems in the supply of fuel. The results of the capacity credits are shown in the second column of the table II; these values are discriminated for each month of the year 2016. The third column of the table shows the installed power of wind source; these data were generated from information published on AUDEE (Uruguayan Wind Energy Association) web page.

TABLE II
ELCC AND INDICATORS OF WIND GENERATION

Month	ELCC (%)	Intalled wind power (MW)	Average wind power (MW)	Normalized average wind generation (MW)	Wind generation wind power (%)
January	29.7	859	380	380	27.4
February	19.3	859	311	311	21.5
March	25.7	859	354	354	27.7
April	35.7	909	377	356	26.5
May	22.6	909	323	305	19.3
June	21.2	969	330	292	17.2
July	24.8	969	363	322	19.4
August	24.8	969	367	326	21.5
September	29.8	1190	431	311	21.1
October	31.5	1190	533	385	29.1
November	22.3	1210	416	295	22.9
December	21.9	1210	390	277	21.1

The fourth column shows the average wind generation at peak hours, the fifth column is analogous to the previous one but normalized to the installed power in January, that is, how much would be the average generation for each month if all the months had the same installed power, say the one of January. Although these values show the contribution that the wind source has for each month, we see the importance in considering the correlation with the demand, which has different scaffolding in the different seasons of the year.

The sixth column shows the percentage of the wind generation that satisfies the monthly demand by month, that is, the ratio between the wind generation indicated in the fifth column and the average demand in the peak hours of the monthly day. The idea of showing these data is to have a reference on the calculated ELCC values, but being aware that they are conceptually different.

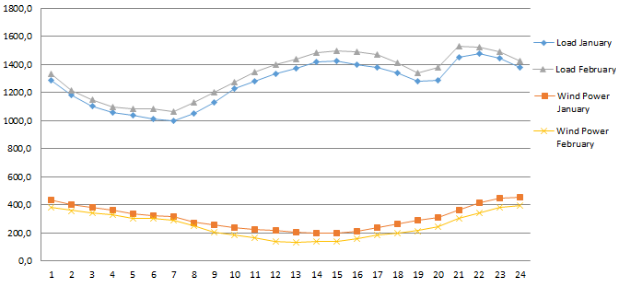

Fig. 1. Comparison demand and wind generation in the months of January and February.

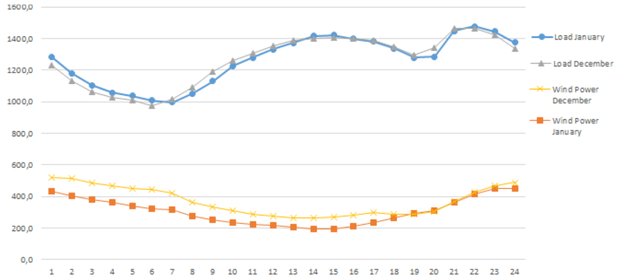

Fig. 2. Wind demand and generation comparison in the months of January and December.

If the months of January and February are compared (see Figure 1), it is noted that the trend of the wind generation and demand curves is similar, but with lower demand values and higher values of wind generation in January compared to February. This generates, as seen in Table II, a large difference in the calculated ELCC.

In Figure 2 it can be seen that the demand curves for December and January are similar and the wind generation values are higher in the month of December except for the peak hours of the night, however, the ELCC is higher for January since it is calculated as a percentage and the installed wind power in December is considerably higher than in January.

Finally, the months of February and April are compared, as these are the ones in which the extreme values of ELCC are given. The figure 3 shows the average demand per hour and the wind generation data for both months and figure 4 shows the respective equivalent load duration curve with and without wind contribution.

In February the behavior of the demand shows two peaks: one in the early afternoon and the other about 21 hrs, both of similar magnitudes. The peak of the afternoon coincides with the minimum values of contribution of the wind resource, this causes that the amount of hours accumulated with high values of demand is significantly higher than in April since in this

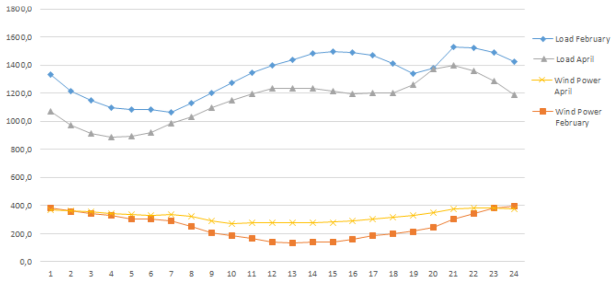

Fig. 3. Wind demand and generation comparison in the months of February and April.

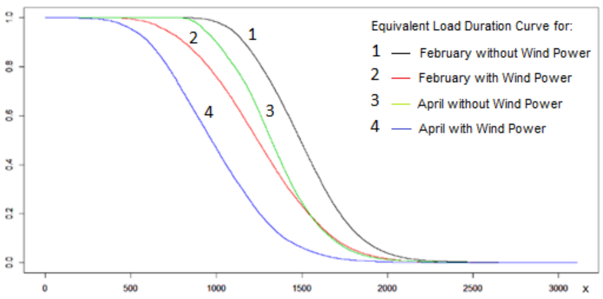

Fig. 4. Equivalent load duration curve with and without wind for the months of February and April.

month changes the course of the demand curve, disappearing the peak of the afternoon and substantially decreasing the demand with respect to February.

Therefore, the LOLP in February is high and in turn the contribution of the wind resource is not significant, resulting in a low value of ELCC.

If we observe the separation between the curves of the figure 4, for the months studied, due to the incorporation of wind, it is clear that the effect is greater in April and therefore also the ”extra” demand that has to be add to the system to get the initial LOLP.

V. CONCLUSIONS

The best-known methods of calculating capacity credits according to the revision of international experiences were presented [10] and [11], and the calculation of the ELCC was described in detail. This method was used to carry out simulations based on the data from the Uruguayan electrical system of 2016.

The principal contribution of this work was the development of a method that could be implemented quickly, with adaptability, and which does not require a large amount of historical data records (in this case one year).

The simulations were splited by month; if they are averaged for one year the capacity credit is approximately 25%, displacing mainly thermal generation (because it is the most expensive). The regulation of generation in the electrical system of Uruguay is carried out mainly with hydroelectric dams and although the wind resource is intermittent, it allows to preserve the water of the dams, which results in an indirect energy storage that allows to better plan the supply of the demand in the medium and long term. In the particular case of Uruguay regulation, future security of supply is achieved by a percentage requirement of contracted firm power capacity. If none capacity credits are recognized for wind and solar, then overinvestment in thermal generation may occur.

Results obtained must be understood as a reference. However, to go in depth, it should be considered hypotheses such as droughts, floods, etc., and perform simulations using several years' data. It would also be interesting to replicate the calculations for photovoltaic generation [12], which has a notoriously different behavior compared to wind.

Finally, we concluded that it is necessary to update the electricity market regulations in Uruguay, including a firm power calculation methodology for non-conventional renewable energies.

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