# Planning the distribution of wind farms in Uruguay in order to optimize the operability of large amounts of wind power.

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## 1. Abstract

The electric power generation system of Uruguay will face significant changes in the near future. The main change is due to the incorporation of a large amount of wind power. The objective is to reach 1200 MW of installed capacity by 2015. The expected electricity demand for that year is 1400 MW on average with a peak of 2000 MW, so wind power penetration would be 60% and 33% of power and energy respectively.

Wind resource has been analyzed, focusing on its spatial-temporal behavior, and different wind farm distributions all over the country have been studied, modeling the operation of the power generation system in each case.

According to the simulations of the electrical system (time step of 1 hour), the supply cost is almost not affected by the wind power allocation. We conclude that any non-centralized wind power distribution would manage to reduce high frequency variations, thereby reducing reserve capacity requirements.

## 2. Objectives

The aim of this work is to propose a preliminary distribution of wind farms, taking into account the power capacity to be installed in the next years. Based on the characteristics of wind climate and its spatial-temporal distribution over the territory, this proposal seeks to reduce the effects of temporal variability of the wind speed at different scales on the supply of electricity.

To accomplish that goal, 14 time series of 10 minutes average wind speed and direction from June 2009 to May 2011, covering most of the territory, have been normalized to 80m, taking into account the measured wind profile, and analyzed. Figure 1 shows the location of each of the meteorological stations used.

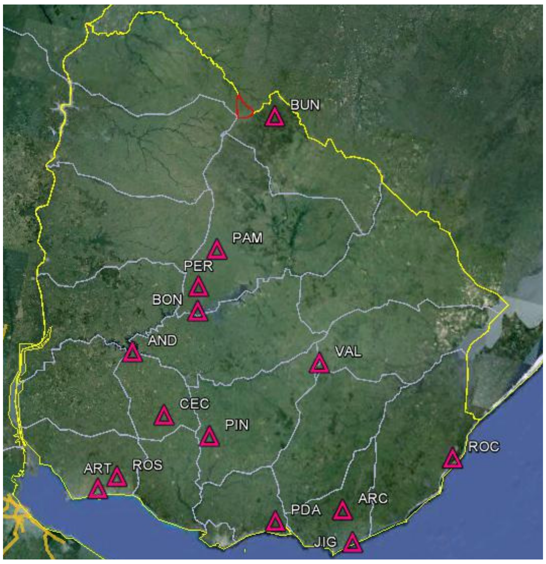


**Fig. 1.** Uruguay map with the location of the meteorological stations.

## 3. Methods

A comprehensive statistical analysis of the time series behavior has been performed. Principal component (EOF) Analysis has been used to reduce the number of variables. The three most significant principal components (PCs) have been selected to represent the spatial-temporal behavior of the wind resource over the territory.

Wind speed time series have been transformed into power production through two power curves belonging to different wind turbines, depending on the IEC class of the site, and modeling the effects of the wakes. A Cluster Analysis has been done to separate data in groups according to the daily cycle of the mean power production in each site.

Different wind farms distributions have been analyzed with the model presented in [1]. Those distributions were obtained from configurations calculated to accomplish the following goals:

- minimize hourly power variability (D1), as defined in [2]
- minimize hourly difference in the mean power production between each hour (D2)
- maximize wind energy (D3)

Distribution D2 was modified to obtain a more realistic configuration, taking into account the Cluster Analysis.

The results obtained have been used in simulations of the electrical system planned to 2015, with the electricity system simulation platform - SimSEE [3].

## 4. Results

### 4.1. Statistical analysis

*EOF analysis*

Results obtained from the EOF technique show certain homogeneity of the wind field throughout the territory. The first three PCs represent 87% of the total variation (PC1 = 49%, PC2 = 33%, PC3 = 5%).

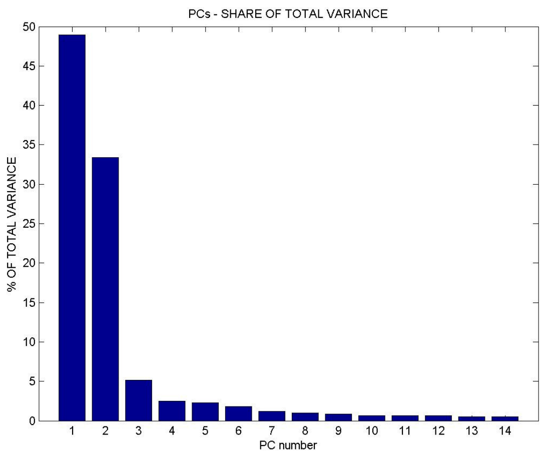


**Fig. 2.** Fraction of variability represented by each PC

This result was expected due to the topography and size of the country, and also because of the strong influence of the South Atlantic anticyclone over the region. This synoptic phenomenon is primarily responsible for the first two PCs found. The third PC represents the sea breeze, whose influence can be observed throughout the analyzed territory with different weight at each site.

The vector representation of the first three PCs (figure 3) shows that the direction of PC1 is northeast, while the direction of PC2 is southeast. On the other hand, PC3 looks like a vortex, whose centre is located at the central-southwest region of the territory (close to stations Pin and CeC).

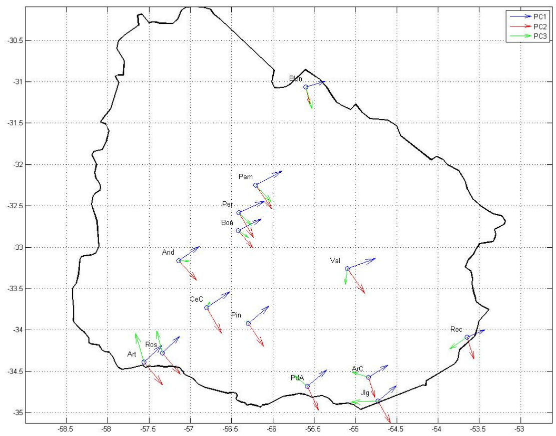


**Fig. 3.** Uruguay map with the eigenvectors of the first 3 PCs.

The main characteristic period found for each of the three PCs selected is 24 hours. This is explained by the strong influence of atmospheric stability on wind climate. Frequently, the atmospheric boundary layer during the evening is stably stratified almost all over the territory. PC1 and PC2 have also another characteristic period, around 8 - 10 days. These components are thought to be representing the South Atlantic anticyclone phenomenon, which affects Uruguay with direction NE or SE depending on its location. In addition to this, this synoptic phenomenon has a characteristic period around 10 days, which is similar to the above period found for PC1 and PC2. On the other hand, no other period of similar importance has been found taking into account PC3. This component is thought to be representing the sea breeze phenomenon.

*Seasonality*

Seasonal variation is low throughout the territory. The lowest wind energy months are those from autumn and the beginning of winter, while the peak month is September. Monthly average wind speed of the former is about 90% of the annual average, whereas the latter is about 110%.

*Hourly and daily variation*

Hourly and daily variation is strong, with more energy during midnight and early morning almost all over the country. Wind speed average behavior in stations near the coast is different from that in stations located within the territory. The former usually has higher ratios between hourly average wind speed and daily mean value than the latter in those hours. Figure 4 depicts the hourly average wind speed for each station located in the south and north region of the country.

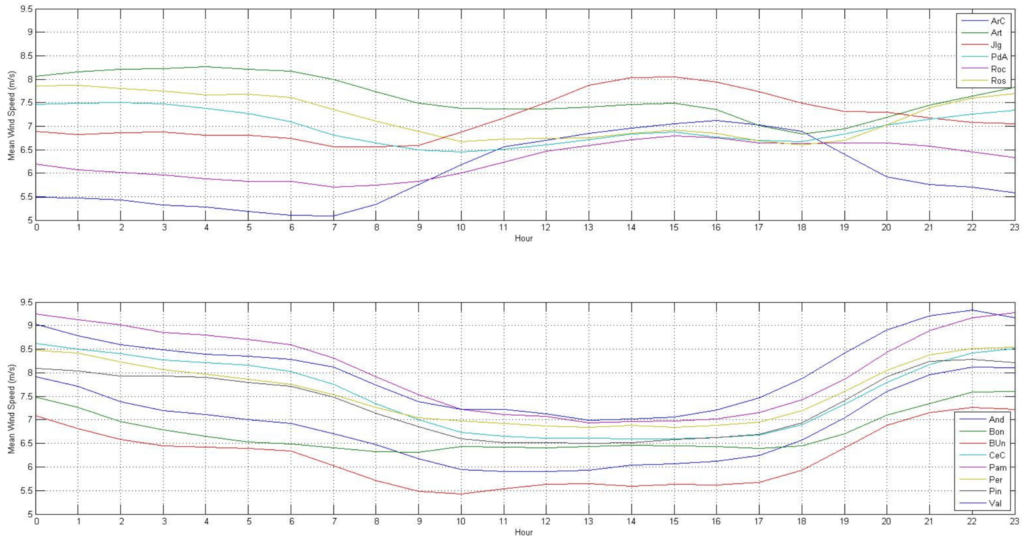


**Fig. 4.** Daily cycle of the wind speed (top: South region, bottom: North region).

*High-frequency variability*

High-frequency variability (10 minutes - 1 hour) is particularly observed during daytime. Neither seasonal nor regional differences in high-frequency variability have been found through the analysis. In addition to this, high-frequency variability is uncorrelated among the stations, even taking into account stations close to each other. Therefore, this variability tends to cancel out as more stations are considered.

*Cluster analysis*

Cluster Analysis has been performed, grouping the stations with similar wind power daily behavior. As a result, three clusters have been identified, representing the continental region (Cluster 1), the southeast region at the Atlantic coast (Cluster 2) and the southwest region at the Uruguay river coast (Cluster 3). Figure 5 depicts the dendrogram obtained through this analysis.

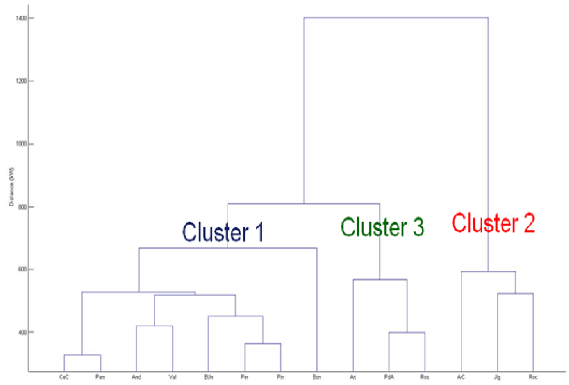


**Fig. 5.** Dendrogram – Cluster Analysis.

4.2. Wind power output

The conversion from wind speed data to wind power for each time series was done through a power curve corresponding to a wind turbine IEC class II or class III, depending on the average wind speed. Also, wake effect was considered by applying a factor to each wind speed, according to the wind direction sector, to obtain a loss around 7%. This was accomplished through decreasing the wind speed depending on the wind direction sector and taking into account the wind energy rose, to represent more faithfully a wind farm. Nonetheless, as explained above the focus of this research is to evaluate the spatial-temporal behavior of the wind resource and not to model exactly the wind power output of a wind farm.

4.3. Power distributions

High-frequency variability causes additional costs for the operation of the electrical system due to reserve capacities requirements. In order to reduce this additional cost the distribution D1 was calculated to minimize hourly power variability. Hourly power variability is represented as follows:

$$\Delta P_{\text{var}} = \sqrt{\sum_i \left( \sum_{k=1}^{k=14} \alpha_k \left( P_{i+1}^{(k)} - P_i^{(k)} \right) \right)^2} \tag{1}$$

where $\alpha_k$ is the proportion of the total wind power to be installed in location *k* and $P_i^{(k)}$ is the wind power generation of location *k* and hour *i*.

Another aim would be to minimize hourly difference in the mean power production between each hour (equation 2 represents this difference for hours *h* and *j*). It is desirable to concentrate the generated power mostly in daytime because those are the peak hours. It is desirable to concentrate the generated power mostly in daytime because those are the peak hours. Different daily cycles, found in the above three clusters, were considered in order to balance the power generation during a day. Additionally, the stations on the south region are characterized by lower average wind speed. Distribution D2 was calculated to accomplish this goal.

$$\Delta P_{h,j} = \sum_{i,\, hour\ h} \left( \sum_{k=1}^{k=14} \alpha_k P_i^{(k)} \right) - \sum_{i,\, hour\ j} \left( \sum_{k=1}^{k=14} \alpha_k P_i^{(k)} \right) \tag{2}$$

Next, distribution D2 was modified to obtain a more realistic configuration, keeping the total energy production and taking into account the Cluster Analysis and the wind power already installed. Finally, distribution D3 aims to maximize wind power generation by allocating all the capacity in the appropriate site. Figure 6 depicts the above distributions D1 and D2, representing each cluster.

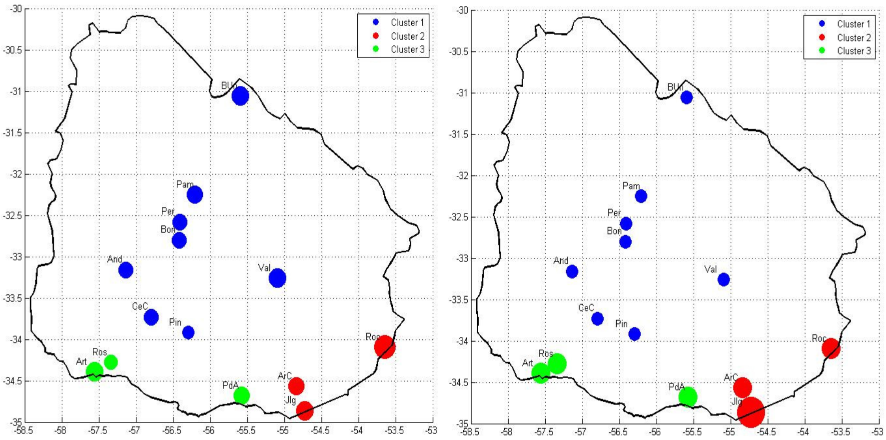


**Fig. 6.** Wind power distributions D1 (left) and D2 (right).

*Assessment of the proposed distributions*

Power production from distribution D1 is quite similar to that from D2, both corresponding to an approximate capacity factor of 41%. On the other hand, D3, which maximizes the power production, has a capacity factor of about 49%.

High-frequency variability is minimized with distribution D1. Nonetheless, high-frequency variability of D2 is not much higher, whereas it is maximum for D3. Figure 7 shows the probability of having a wind power generation difference between consecutive hours equal or less than a certain value, considering distribution D1, D2 and D3.

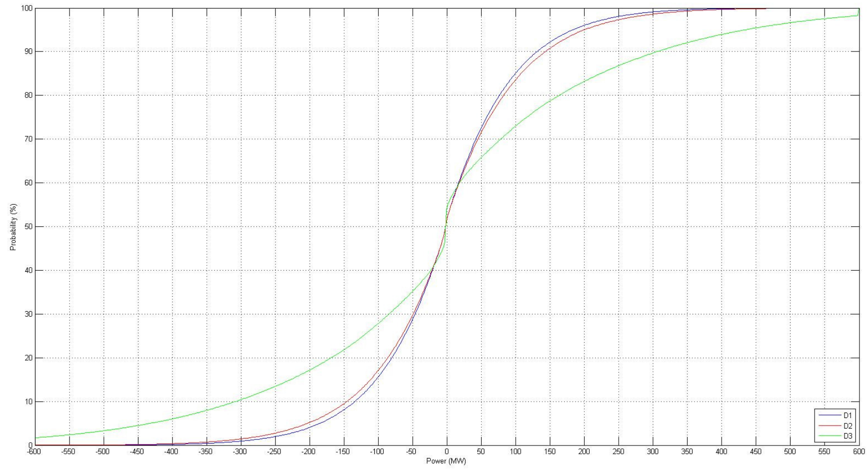


**Fig. 7.** Probability of hourly wind power variations (D1, D2 and D3).

It is observed that wind power variations between consecutive hours, with a 90% probability, are, in absolute value, less than or equal to 182 MW (15% of nominal power), 200 MW (17% of nominal power) and 435 MW (36% of nominal power) for distributions D1, D2 and D3 respectively. The effect of this variability on the operation of the electrical system planned to 2015 has been calculated through its simulation with the electricity system simulation platform SimSEE [3].

Most of the variability is controlled by the hydroelectric power stations. Uruguay has 1500 MW of installed hydroelectricity, being Salto Grande, shared with Argentina, its largest hydroelectricity plant. Nowadays, Uruguay does not perform secondary regulation, which is done through the interconnection with Argentina, whose capacity is 2000 MW. Secondary regulation of the Argentine system is done by Salto Grande almost 20% of the time. Analyzing historical data of these events and considering them as an indirect representation of the regulation capacity, it was found that the additional regulation capacity requirements would be low (figure 8). For instance, it was observed that the probability of having hourly variations of more than 200 MW increases 7% (D1), 8.5% (D2) and 18% (D3), with respect to the current hydroelectric system's regulation capacity (when it operates for Argentine system).

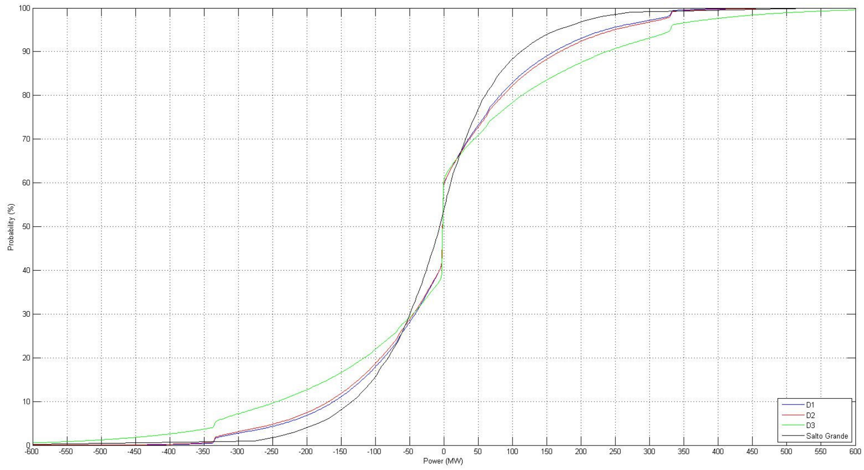


**Fig. 8.** Probability of hourly wind power variations (D1, D2 and D3) and hourly power variations of the hydroelectric power stations performing secondary regulation (historical data).

In order to meet the extra regulation capacity requirements, the system would have the other hydroelectricity plants and also 1000 MW of thermal power plants capable of making a fast adjustment in power output in response to system demand. Considering the above mentioned characteristics of high-frequency variability of each distribution, it is noted that there is a large difference between D1 / D2, which distribute wind power more or less uniformly throughout the territory, and D3 that maximizes energy production placing all wind farms in one site. The difference among D1 and D2 is much less marked, while D1 has been designed in order to minimize this variability and consequently the regulation capacity costs.

Through simulations with SimSEE, the expected supplying cost of the electrical system has been calculated for each distribution. These costs do not include those of spinning reserve for secondary regulation. In the simulations it was assumed that the price of exported energy is negligible and the system can not import energy under no circumstances, despite that the interconnection with Argentina is 2000 MW and the interconnection with Brazil is going to be 500 MW in the near future. The objective is to calculate the Uruguayan system requirements for the incorporation of the planned wind power regardless of the international exchanges.

The daily cycle of wind power production of distribution D2 shows a broader uniformity than the others. This distribution has been designed in order to increase wind power generation during peak hours and to decrease it the rest of the time, avoiding export surpluses. Distribution D3, that maximizes wind energy production, does not manage to increase significantly the generation during peak hours. Furthermore, it generates large amounts during the evening when the electrical demand is lower.

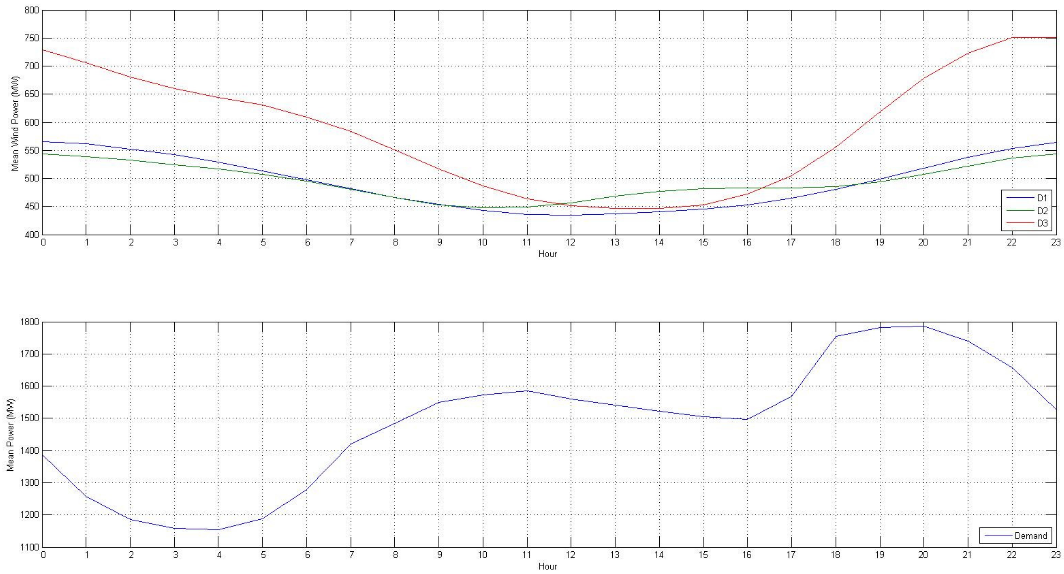


**Fig. 9.** Daily cycle of the wind power and energy demand (top and bottom respectively).

The expected value of the system supply cost of distributions D1 and D2 is almost the same, while distribution D3 presents a higher cost (+5%). Taking into account the hourly average cost, it seems that the higher cost of D3 is mainly due to the large amounts of exported energy surplus during midnight and the early morning. It also responds to the need to operate thermal power plants (slow-start units) around peak hours during nighttime in order to avoid power deficit.

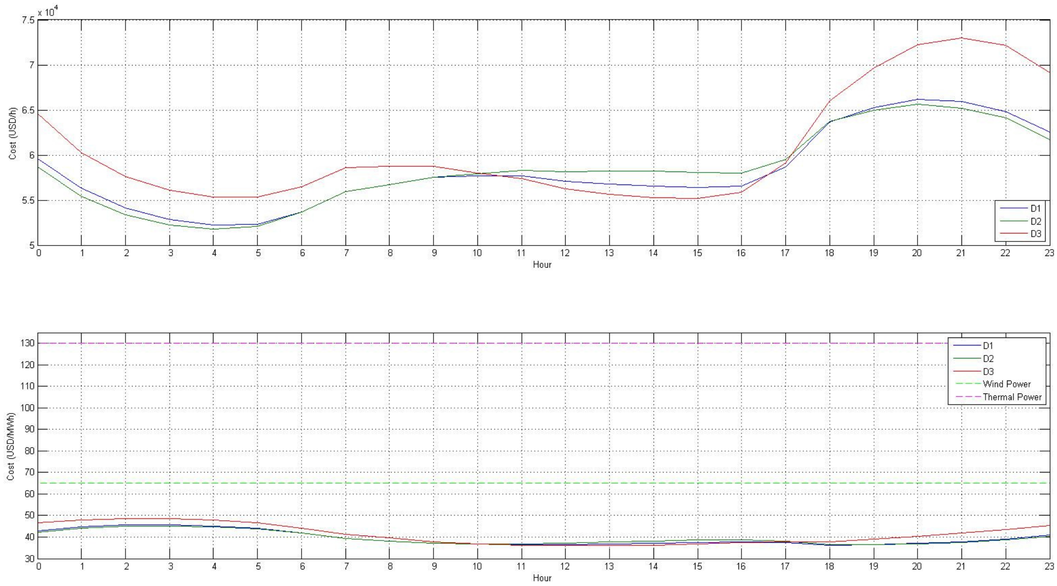


**Fig. 10.** Mean hourly cost (top: USD/h, bottom: USD/MWh).

Due to the important share of hydroelectricity in the electric market, the expected value of the system supply cost (USD/MWh) is much lower than the wind power costs and thermal power costs. Despite the system supply costs resulting from distributions D1 and D2 are quite similar, it should be emphasized, as mentioned above, that the costs of secondary regulation are not included, so D2 would increase its cost respect to D1.

## 5. Conclusions

Wind resource has been analyzed through 14 time series, focusing on its spatial-temporal behavior. Principal component (EOF) Analysis has been used and three principal components have been identified and selected as they represent most of the total variation. In addition to this, a Cluster Analysis has been performed considering the daily cycle (hourly average wind speed), finding three groups representing different regions of the territory. Taking into account the above mentioned and the results obtained, we conclude that the wind field is influenced by the same phenomenon and it is fairly uniform throughout the territory of Uruguay.

Three different distributions of the total wind power planned to be installed in 2015 have been proposed, which have been obtained to accomplish different goals: minimize hourly power variability (D1), minimize hourly difference in the mean power production between each hour (D2) and maximize wind energy (D3).

High frequency variability (10 minutes - 1 hour) is uncorrelated among the 14 sites and it is minimal when wind power is distributed according to D1, which is very close to distributing wind power uniformly among them. Nonetheless, high frequency variability could be reduced considerably with any decentralized distribution of wind power. Hourly average wind power obtained with D2 manages to be higher in peak hours and lower in hours of less electrical demand.

Simulations of the electrical system (time step of 1 hour, wind power distribution: D1, D2 or D3) have been performed with SimSEE. According to these simulations, the supply cost is almost not affected by wind power allocation. We conclude that any non-centralized wind power distribution would manage to reduce high frequency variations, thereby reducing reserve capacity requirements.

## 6. References

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