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Important Issues and Results When Considering the Stochastic Representation of Wind Power Plants in a Generation Optimization Model: An Application to the Large Brazilian Interconnected Power System

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Abstract

Wind power has an increasing share of the Brazilian energy market and may represent 11.6% of total capacity by 2024. For large hydro-thermal systems having high-storage capacity, a complementarity between hydro and wind production could have important effects. The current optimization models are applied to dispatch power plants to meet the market demand and optimize the generation dispatches considering only hydroelectric and thermal power plants. The remaining sources, including wind power, small-hydroelectric plants and biomass plants, are excluded from the optimization model and are included deterministically. This work introduces a general methodology to represent the stochastic behavior of wind production aimed at the planning and operation of large interconnected power systems. In fact, considering the generation of the wind power source stochastically could show the complementarity between the hydro and wind power production, reducing the energy price in the spot market with the reduction of thermal power dispatches. In addition to that, with a reduction in wind power and a simultaneous dry-season occurrence, this model, is able to show the need of thermal power plants dispatches as well as the reduction of the risk of energy shortages.

Keywords

Stochastic Optimization, Hydrothermal Systems Planning, Wind Power, Complementarity, Synthetic Series Generation

1. Introduction

The energy generation in Brazil is dominated by hydropower plants with large reservoirs which are arranged in cascades. It is forecasted to represent 11.6% of the Brazilian installed capacity by 2024 [1]. According to [2], the increase of wind power capacity worldwide in 2017 was 535 GW, reaching a total of 539 GW. China alone installed 19.7 GW in 2017, reaching 188 GW in total. Brazil was sixth in percentage increase in 2017 and is in the top ten countries in terms of total installed capacity.

In September 2016, the capacity factor registered by the state of Rio Grande do Norte was almost 57% and all states of the Northeast had capacity factor higher than 50% [3]. Wind power in the Northeast was able to meet 39% of the demand in this same month, when the reservoir levels were experiencing a shortage (**Figure 1**).

The Brazilian System Operator (ONS) dispatches the power plants to meet the demand. Cepel, the Brazilian Electric Energy Research Center, implemented the computational program Newave with the stochastic dual dynamic programming (SDDP) technique [4] to solve the large-scale long-term hydrothermal problems for the Brazilian system. The model aims to determine the optimal amount of hydro and thermal resources for operation planning and minimize the expected value of the operation cost [5]. In this study, we use the Newave model for the simulations.

The inflows are represented stochastically in the models as the future is unknown. Uncertainty is represented by a tree of scenarios where each branch of the tree is a hydrologic scenario. The Newave considers the variables' uncertainty through synthetic inflow scenarios to all subsystems [6]. GEVAZP, the synthetic inflow scenarios generation model, is connected to the Newave. It selects a stochastic time series PAR (p) algorithm to guarantee similarity between historical and synthetic series [7]. The PAR (p) is an auto regressive periodic function where p can vary from 1 - 6 (months), so each stochastic inflow can be dependent on the inflow that occurred in the same places up to 6 months before [8].

[9] shows wind and hydrologic generation scenarios with the same stochastic model PAR (p) for the operation planning and recommends the use of the wind series for the Brazilian planning hydrothermal operation. [10] developed a new methodology to build the scenario trees, removing non-linearity from the equations, which could make the future cost calculation in Newave an unfeasible task. Even though some studies recommend the stochastic model PAR (p), there are some limitations and questions remain whether this model is ideal for wind power series generation.

In [11] wind power generation is represented as a small hydro power generation and shows that the complementarity between wind power and hydropower results. Even though this study shows the same focus of our work, it does not detail the methodology for representing the stochastic series, how to consider the wind power plants as small hydro or even use the official model.

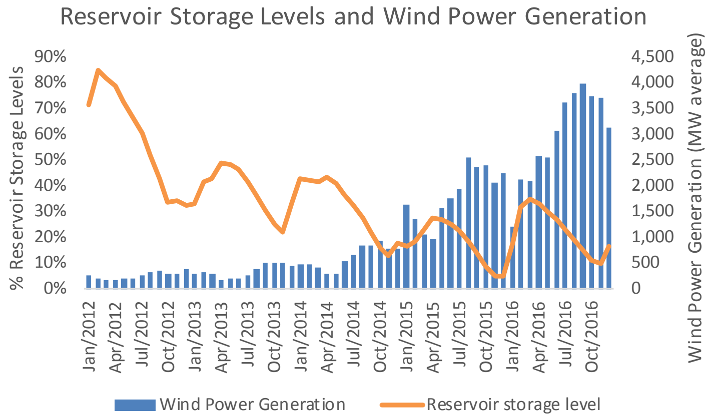

Figure 1. Reservoirs and wind power generation (Source: ONS, 2016-Juliana Mummey *et al.*).

[12] analyses the impact of considering the uncertainty of wind power generation scenarios using the model SDDP. The results show an increase of the costs and point out that by changing the future cost methodology the impact could be reduced.

Given the wind power generation variability and considering the increase in the share of wind power in the Brazilian electricity matrix, this paper aims to present a study about the stochastic representation of wind power generation in the Brazilian official models. The impacts on the other source's generation and when wind power plants are represented as run-of-river power plants, will be discussed ahead.

The current study differs from the existing literature because it uses an optimization simulation model (Newave) to represent the wind and hydro generation stochasticity, while previous work doesn't represent explicitly the wind and hydro production variability. In fact, the correlation between the power generation of these two sources is obtained from the historical registered behavior of the water flows at the main Brazilian river basins and series of wind speed, which were reconstructed based on data obtained from meso-scale meteorological models [13]. In addition to that, this study shows the production complementarity between wind and hydro generation as a result of the simulation model when using the stochastic formulation for both kind of sources. It is worthwhile to point out that currently the Brazilian System Operator model considers the wind power deterministically and therefore it does not represent the variability of the wind power source.

This introduction describes the problem focused in this work, a brief survey of the state of the art of wind power in Brazil, expansion perspectives and studies about wind power series. Section 2 shows the methodology involved such as: 1) wind speed database and wind power generation, and 2) wind power representation in the Brazilian system. Section 3 shows the results of the simulations: 1) the rebuilt historic of wind power generation (considering the occurrence of hydraulic and wind power production varying simultaneously) and comparison to the official historical simulation (average monthly historical values, each month is the same every year); 2) based on "1" and a hypothetic scenario of an increase of wind power capacity and an increase of the Northeast and South demands; and 3) same as "1" but considering synthetic series. Section 4 concludes this article.

2. Methodology

This work uses two sources of wind speed data representing 16 sites in the Northeast and the South of Brazil. We plotted the Weibull distribution to fit the wind speed distribution. Then, a power curve of each site is used to calculate the wind power generation. All this data represents an input to the optimization model Newave in order to run the program. Figure 2 represents the schematic diagram of the methodology.

2.1. Wind Speed and Wind Power Generation

The methodology of wind speed historical data reconstruction and its power generation was based on [13]. Two databases were considered: Vortex (Mesoscale atmospheric model on-line that estimates wind speed for places without measurements) and NOAA (numerical model from National Oceanic and Atmospheric Administration).

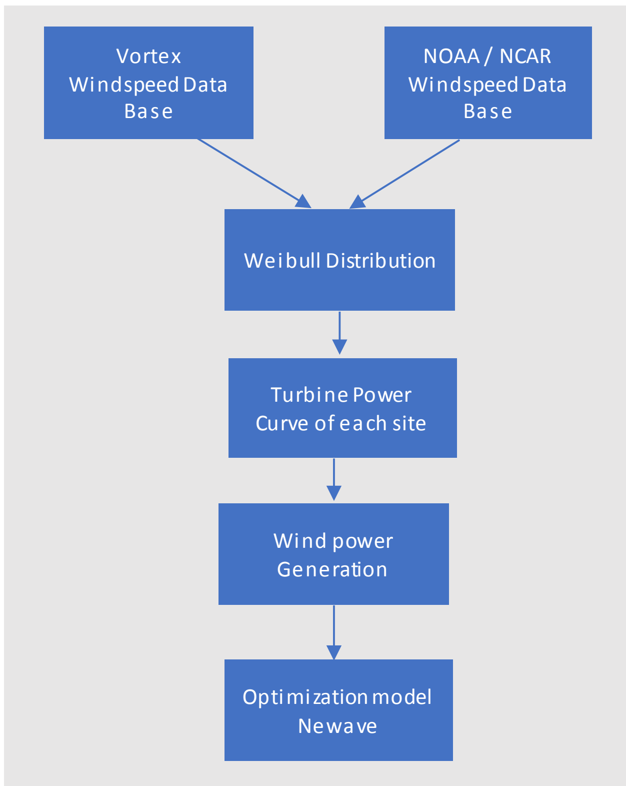

Figure 2. Schematic diagram of the methodology.

The Vortex database provides the hourly wind speed from 1982 to 2014 for every 10 meters of height, starting at 50 meters up to 150 meters. The NOAA database presents daily values of wind speed at 42 meters since 1947. There were 16 sites considered and **Figure 3** shows the seasonality of hourly wind speed data of the site at Paracuru, as an example. It can be observed that there is a trend of higher wind speeds and shorter variability in the second six months of the year.

We transformed both series (NOAA and Vortex) into the same period to be comparable, using the same years from 1982 to 2010 and daily wind speeds. We also considered all series with cross-correlation greater than 0.8 and then a vertical extrapolation to transform the NOAA data from 10 meters to 120 meters high with the logarithmic curve with the Vortex data available. We calculated monthly standard deviation with the Vortex data and based on the daily average wind speed we plotted the Weibull distribution (the Weibull probability density function was used to fit the wind speed distribution) for each month. Then we calculated the energy generated with the power curve of each site and the Weibull distribution fit to the historical data. Based on the daily wind power generation, we added all days of the month to transform into monthly wind power generation from 1948 to 2014.

2.2. Wind Power Representation

The model Newave has four main subsystems and nine regions: Paraná, Itaipu, Madeira, Teles Pires and Southeast (five regions in the Southeast subsystem); North and Belo Monte (two regions in the North subsystem); Northeast subsystem (one region) and South subsystem (one region). The maximum capacity of regions for the model is 15, so we included four regions in the Northeast: CE (Ceará), BA (Bahia), PI + PE (Piauí + Pernambuco) and RN (Rio Grande do Norte), and two regions in the South region: SC (Santa Catarina) and RS (Rio Grande do Sul), as **Figure 4**. These new regions are wind basins and represent areas of the system with high concentration of sites and a correlated wind regime.

Each region has the wind power installed capacity of the state and the respective expansion according to the Monitoring Department of Electric System (DMSE). Each wind power site was included in the program as if it was a run-of-river power plant. As there are many sites, with different seasonalities inside the same state, we put the values of the closest sites and their expansion according to where they are in the Abeeólica (Wind Power Association) data [14].

3. Results

There are three simulations with the Newave model for this study: 1) considering the re-constructed wind power historical generation and a comparison with the official historical case of August 2016; 2) based on "1" but considering an increase of the wind power capacity and also an increase of the Northeast and South demands; and 3) based on "1" but considering synthetic series. With these

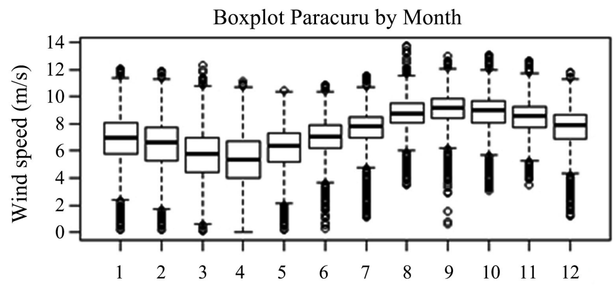

Figure 3. Wind speed seasonality.

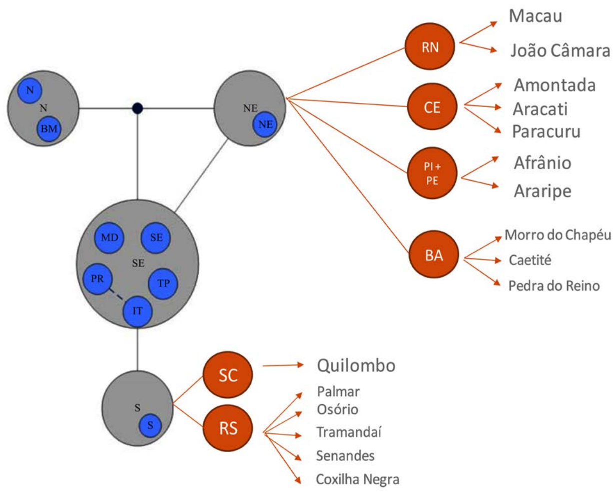

Figure 4. Representation of regions.

cases, we analyze the complementarity of wind power generation with hydropower, verifying in dry seasons a) if the wind power can generate more; b) if with more wind power capacity, what is the role of wind power generation to meet the demand; and c) if the behavior with synthetic series is compatible with the observed one when using historical series.

We chose two historical critical (dry years) periods to analyze the data. The first one refers to the years 1951 to 1955 (the horizon of Newave is 5 years). These years presented low inflow in the Northeast and re-constructed wind power generation with some months below the average. The second period refers to 2010 to 2014. These years presented low inflow in the Northeast and re-constructed wind power generation above average. Considering the synthetic series, the data are analyzed through the average values.

3.1. Simulation Considering the Wind Power in Regions

The marginal costs of the simulation, when representing variability with wind power in regions and with scenarios coming from the historical series, tend to be lower than the official case, see Table 1. Considering the period of 1951 to 1955, as it is a dry period, there is a need to dispatch more thermal power plants to save more water in the reservoirs for the future, which is why there is an increase of the costs in both the official case and in the simulation. However, the costs of

Table 1. Marginal costs and generation.

August of the 4th year	Official Average	Official 1951-1955	Official 2010-2014	Simulation Average	Simulation 1951-1955	Simulation 2010-2014
CMO Southeast (R$/MWh)	28	152	6	9	47	2
CMO South (R$/MWh)	27	152	6	8	47	2
CMO Northeast (R$/MWh)	21	85	6	1	0	0
CMO North (R$/MWh)	24	114	6	7	44	1
Hydropower Generation SE (GW average)	25.96	23.09	27.89	25.80	28.76	21.86
Hydropower Generation S	11.71	11.37	13.74	10.30	6.66	13.63
Hydropower Generation NE	4.88	5.67	3.79	4.48	4.41	4.37
Hydropower Generation N	5.89	5.73	3.29	6.67	7.10	7.10
Hydropower Generation System	**48.44**	**45.86**	**48.71**	**47.25**	**46.93**	**46.96**
Thermal Power Generation SE (GW average)	2.87	3.83	2.71	2.73	2.88	2.71
Thermal Power Generation S	0.81	0.98	0.78	0.78	0.78	0.78
Thermal Power Generation NE	0.58	0.71	0.57	0.57	0.57	0.57
Thermal Power Generation N	1.26	2.59	1.21	1.21	1.21	1.21
Thermal Power Generation System	**5.52**	**8.11**	**5.27**	**5.29**	**5.44**	**5.27**
Wind Power Generation S (GW average)	0.87	0.87	0.87	1.05	1.05	1.15
Wind Power Generation NE	8.26	8.26	8.26	9.49	9.67	9.71
Wind Power Generation System	**9.13**	**9.13**	**9.13**	**10.54**	**10.72**	**10.86**

the simulation are lower than in the official case. This happens because, as in the official case, the wind power generation is deterministic and, hence, there is no change of this generation if it is a dry season or not. Considering the simulation, in February of 1955, for example, even though there is a low hydraulic inflow in the Northeast and the re-constructed wind power is also low, there is a higher wind power generation, with less need of thermal power generation, reducing the marginal costs of operation, see Figure 5. It shows the complementarity of the hydro with the wind power in the Northeast in the simulation. Considering the period of 2010 to 2014, as the re-constructed wind power was higher than in 1951 to 1955, wind power generation could complement even more with the hydropower generation, see Table 1.

As an example, the last February of the period (Table 2), we can see that despite the wind power generation in the average simulation being lower than the official deterministic case as February is a month with low wind power generation, the marginal costs of the simulation are still lower than the official case. This happens because there was more hydropower generation with the increase of wind power generation in previous months, allowing more water in the reservoirs. Considering the hydrologic scenarios corresponding to the historical years of 1951-1955 and 2010-2014, which represent the dry seasons, there is an increase in the wind power generation in the simulation, complementing the hydropower generation and reducing the marginal costs, even in a month with low wind power generation.

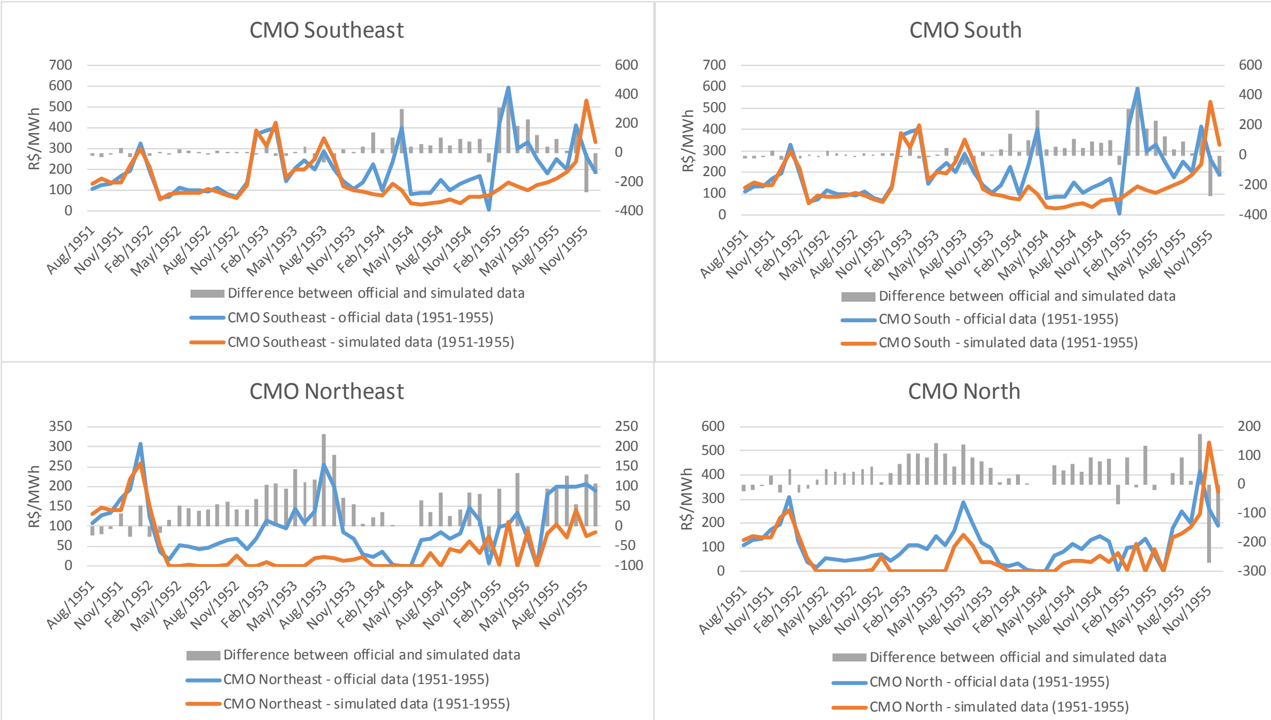

Figure 5. Marginal costs of the simulation vs. official case.

Table 2. Marginal costs and generation.

February of the 5th year	Official Average	Official 1951-1955	Official 2010-2014	Simulation Average	Simulation 1951-1955	Simulation 2010-2014
CMO Southeast (R$/MWh)	24	416	65	9	105	22
CMO South (R$/MWh)	24	416	65	9	105	22
CMO Northeast (R$/MWh)	8	99	0	2	4	0
CMO North (R$/MWh)	8	99	0	2	4	0
Hydropower Generation SE (GW average)	44.13	31.60	29.94	43.49	35.51	38.14
Hydropower Generation S	6.39	7.52	13.46	7.06	6.76	5.05
Hydropower Generation NE	6.15	3.77	3.85	7.69	4.16	4.16
Hydropower Generation N	7.31	15.47	16.60	6.88	15.47	13.83
Hydropower Generation System	**63.98**	**58.36**	**63.85**	**65.12**	**61.90**	**61.18**
Thermal Power Generation SE (GW average)	2.88	7.19	2.95	2.75	3.84	2.84
Thermal Power Generation S	1.07	1.24	1.20	1.05	1.23	1.04
Thermal Power Generation NE	0.59	0.71	0.57	0.57	0.57	0.57
Thermal Power Generation N	1.27	2.27	1.21	1.22	1.22	1.21
Thermal Power Generation System	**5.81**	**11.41**	**5.93**	**5.59**	**6.86**	**5.66**
Wind Power Generation S (GW average)	0.53	0.53	0.53	0.81	0.73	1.00
Wind Power Generation NE	5.17	5.17	5.17	3.95	6.00	7.63
Wind Power Generation System	**5.70**	**5.70**	**5.70**	**4.76**	**6.73**	**8.63**

3.2. Simulation Considering Wind Power in Regions and an Increase of the Wind Power Capacity

This hypothetical case adds 10 times the wind power capacity to the system proportionally to both the Northeast and South subsystems. We used this increase as the wind power capacity today represents a tenth of the hydroelectric plants in Brazil and we wanted to understand the impact that the same proportion of both sources would represent. It also increases the demand of both subsystems, otherwise the model would be optimistic. Considering the second six months of the years, the wind power generation can be the main source to attend the demand because in this part of the year there are higher wind speeds and greater wind power generation. However, considering the first six months, wind power generation could not be enough to meet the demand and there could be a need to increase hydro and thermal power generation, increasing the marginal cost of the Northeast, once it becomes the region with the most increase of the demand. In the example of February, in **Table 3**, even though it is February and the wind speeds are not high, considering the dry season of 1951-1955, the wind power generation was greater than the average. Considering the years of 2010-2014, the wind power generation is much greater, showing the complementarity of the case.

Table 3. Marginal costs and generation.

February of the 5th year	Simulation Average	Simulation 1951-1955	Simulation 2010-2014
CMO Southeast (R$/MWh)	3	101	0
CMO South (R$/MWh)	3	101	0
CMO Northeast (R$/MWh)	469	101	0
CMO North (R$/MWh)	2	101	0
Hydropower Generation SE (GW average)	44.33	41.34	32.54
Hydropower Generation S	7.03	5.43	10.03
Hydropower Generation NE	7.56	8.33	3.85
Hydropower Generation N	8.70	12.88	11.63
Hydropower Generation System	**67.61**	**67.98**	**58.06**
Thermal Power Generation SE (GW average)	2.72	3.59	2.69
Thermal Power Generation S	1.05	1.23	1.04
Thermal Power Generation NE	1.90	0.74	0.57
Thermal Power Generation N	1.23	2.01	1.21
Thermal Power Generation System	**6.89**	**7.57**	**5.51**
Wind Power Generation S (GW average)	7.41	5.69	7.91
Wind Power Generation NE	36.57	37.24	47.00
Wind Power Generation System	**43.98**	**42.93**	**54.91**

3.3. Simulation Considering Wind Power in Regions and Synthetic Series

In the case of synthetic series, the marginal costs of the simulation also present reductions in almost all months for all subsystems compared to the official case, see Figure 6. However, considering February of the last year, which in this case is February of 2020, wind power generation was lower than in the official case with synthetic series in the Northeast and higher in the South, see Table 4.

Even with the lower wind power generation in this specific month, the marginal cost was lower than the official case with synthetic series. This is because as there is more wind power generation in the previous months, the reservoir storage levels are higher and consequently there is more availability of hydropower to generate energy and reduce the costs.

Figure 7 shows that there is more wind power generation in almost all months in the simulation compared to the official case in the Northeast and in the South. However, in the wet season (period between December and April) of the years, wind power in the Northeast showed lower values, emphasizing the seasonality. There is a decrease of marginal costs in the simulation because of the higher hydropower generation. This happens because the storage level of the reservoirs is higher than the official case, with the higher wind power in previous months.

Figure 8 shows the complementarity of the wind power generation with the hydropower generation in the Northeast comparing the official case and the simulations and considering synthetic series. As the official case is deterministic, wind power generation considers the same seasonality during those years.

Table 4. Marginal costs and generation.

February of the 5th year	Official Average	Simulation Average
CMO Southeast (R$/MWh)	23	10
CMO South (R$/MWh)	25	10
CMO Northeast (R$/MWh)	8	3
CMO North (R$/MWh)	9	3
Hydropower Generation SE (GW average)	43.68	43.14
Hydropower Generation S	6.02	6.82
Hydropower Generation NE	6.14	7.39
Hydropower Generation N	8.24	7.53
Hydropower Generation System	**64.08**	**64.87**
Thermal Power Generation SE (GW average)	2.87	2.74
Thermal Power Generation S	1.07	1.06
Thermal Power Generation NE	0.59	0.57
Thermal Power Generation N	1.26	1.22
Thermal Power Generation System	**5.79**	**5.59**
Wind Power Generation S (GW average)	0.53	0.87
Wind Power Generation NE	5.17	3.94
Wind Power Generation System	**5.70**	**4.81**

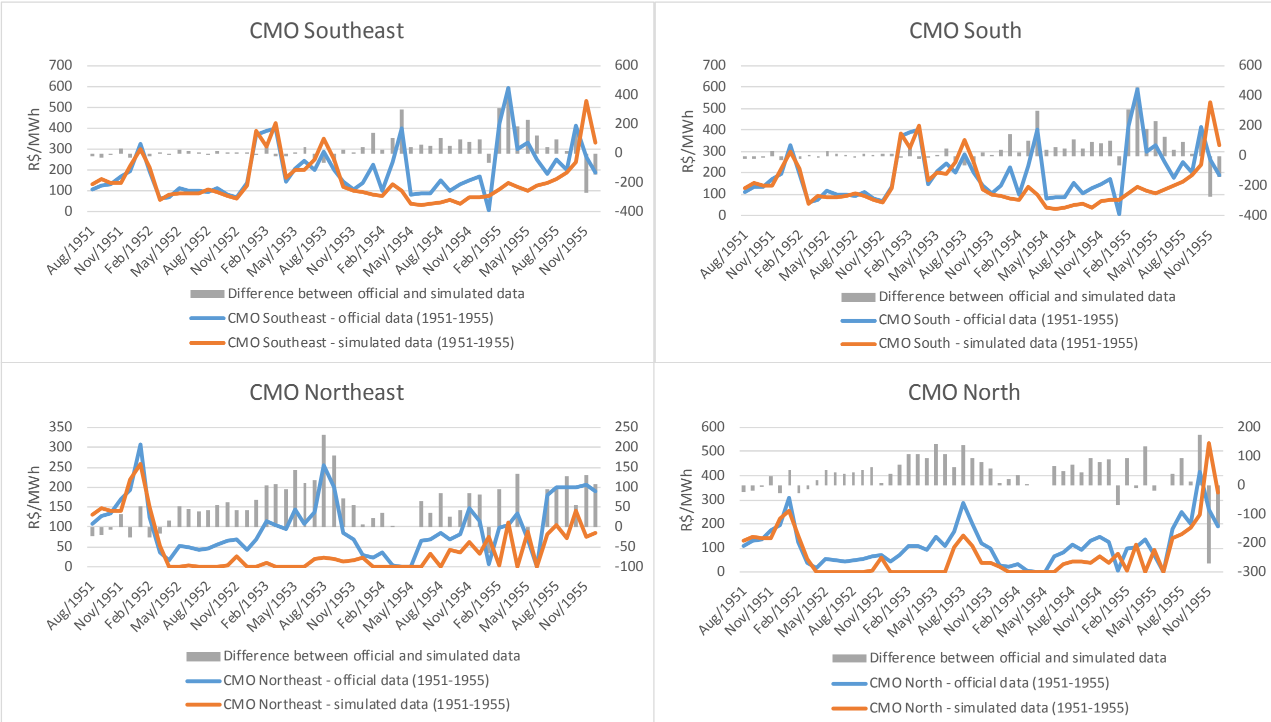

Figure 6. Marginal costs of the simulation vs. Official case with synthetic series.

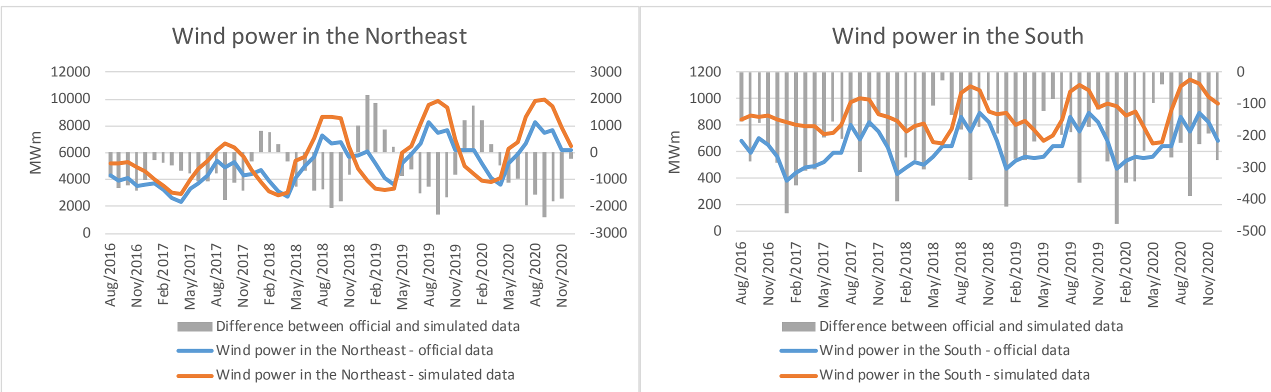

Figure 7. Wind power generation vs. official case with synthetic series.

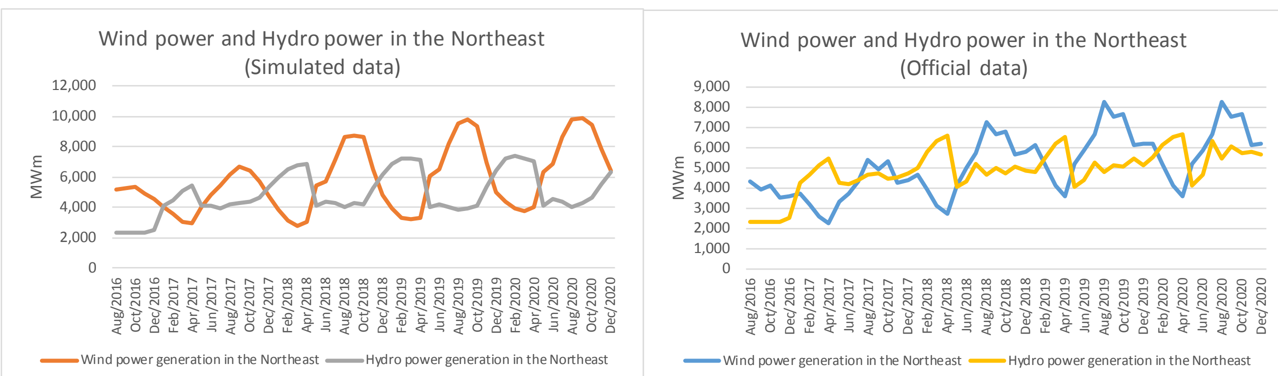

Figure 8. Complementarity of hydropower and wind power generation.

4. Final Remarks and Conclusions

The aim of this work was to present a study to stochastically represent wind power generation in the optimization model (Newave) of the Brazilian electricity system, also, to evaluate how the complementarity of wind power with hydropower can influence the hydro and thermal power dispatches considering variability of the wind power source, as well as the consequences for the short-term marginal prices and spot market prices.

There were three simulations comparing the official case with the wind power represented in regions with historical and synthetic series. The results presented were similar from the conceptual and qualitative point of view. In most of these cases, there is a reduction in the marginal costs of operation with the simulation and less variability in the costs. It happened because there is more complementarity in these cases, reducing the need of thermal dispatch to meet the demand. In a deterministic simulation, as nowadays state of the art, the huge variability of the wind power production is not considered and, as a consequence, the complementarity effect between hydro and wind generation is not taken into account as an important benefit to the System.

When wind power capacity was increased, it was used as the main source to meet the demand. In the second six months, there were no problems for supplying the demand, because the wind power generation is high in these periods. However, considering the first six months, the simulation showed that the wind power was not enough to attend the demand, lessening the system reliability. These scenarios of different seasons are not represented in the deterministic models, which show the relevance of considering such scenarios.

Considering synthetic series there is also an increase of wind power generation in most of the scenarios, reducing the marginal costs of operation. However, we observe that in some wet periods of the years, wind power generation was lower than the official case, showing the complementarity and seasonality of the source, highlighted even more with the stochastic representation of wind power.

This is a case study specific for the Brazilian system but presents methodology that can be replicated to problems of the same nature in any part of the world. To conduct a more detailed analysis we recommend 1) the use of a database with wind speed measurements with anemometers together with a re-analysis database; and 2) the use of a higher number of sites, covering greater parts of the regions.

Finally, it is important to emphasize that this work does not intend to forecast wind power generation, but rather to show that the deterministic methodology considered in the optimization models of the Brazilian system needs to be reevaluated.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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