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Wind speed variability and portfolio effect – A case study in the Brazilian market

Gustavo S. Böhme [*], Eliane A. Fadigas , Dorel Soares , André L.V. Gimenes , Bruno C. Macedo

Department of Electrical Engineering, University of São Paulo, Av. Prof. Luciano Gualberto, Trav. 3,158, CEP 05508-970, São Paulo, SP, Brazil

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ABSTRACT

The profitability of a wind power project is evaluated during its development phase through a complete site assessment. At this stage, the LCoE (Levelized Cost of Energy) is determined considering many variables, such as wind turbine model, project layout, energy production, CAPEX (Capital Expenditure), OPEX (Operational Expenditure) and financial costs. However, in recent years, the seasonality and variability of the wind farms energy production have been gaining importance in this process in some markets, due to a migration of the new wind power projects from the regulated market to the free market. In the free market, the PPAs (Power Purchase Agreements) have short-term balance payments, different from the regulated market. In Brazil, payments in the regulated market are performed monthly based on the long-term AEP (Annual Energy Production) expected values, with annual and quadrennial balance payments. This paper focuses on an extensive case study of Brazil, where the energy spot prices vary constantly between 10 USD/MWh and 100 USD/MWh, exposing the wind farms owners to very relevant financial risk when trading energy based on long-term bilateral contracts. The assumed risks can become critical in cases of periods with extreme meteorological anomalies (wind speed variations below the respective long-term expected values), especially in situations where a simultaneous drought period occurs, eventually raising the market spot price to its ceiling value. A SPE (Specific Purpose Entity) account must be properly dimensioned and maintained, similar to a working capital, in order to the wind farm to be able to operate through these low wind speed periods without any capital call to the wind farm's controllers. This represents additional financial costs in the form of trapped cash. This study analyses the wind speed variability in NE-Brazil, where most of the wind farms in the country are concentrated, and analyses how the portfolio effect contributes to the reduction of this variability. This has been performed making use of the data provided by 4 met masts that surround the NE Brazilian territory (with distances between them ranging from 459 km to 724 km) and combining the obtained values to theoretical turbine power curves of different MW platforms (2, 3, 4 and 6 MW). The total period of available measurement sums more than 29 years of data. The results showed that the variability was higher in periods of lower average wind speed and that the analyzed location with the highest variability was the one close to the coast and with higher altitude. Additionally, the combinations that provided the best portfolio effect were those that included the location in the SW, furthest from the coast and with higher altitude. The different turbine platforms did not present a relevant difference in terms of resulting variability on the energy production nor portfolio effect, but when considering the cumulative impact of the meteorological anomalies (larger periods of wind speeds above or below the long-term expected values), the larger the wind turbine, the larger was the resulting exposure.

1. Introduction

This article highlights the increasing importance of the reported study to the energy sector, with emphasis to the case of Brazil. It then presents a comprehensive literature review on the evaluation

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[*] Corresponding author.
E-mail address: gustavo.bohme@gmail.com (G.S. Böhme).

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of the portfolio effect and proposes a new methodology to do so with a broader range of results. Finally, it presents the obtained results and the corresponding analysis, coming to interesting conclusions at the end. This study differs from most others found in the literature in many ways. It focuses in the most relevant Brazilian territory for the wind energy sector; It analyzes the variability and portfolio effect in different period sizes and not only in terms of wind speed, but also in terms of energy from different turbine platforms. Further, this work evaluates the cumulative impact of longer meteorological anomalies on a theoretical "energy account" that could be translated into a measure of exposure to energy spot price; Finally, it does not make use of mesoscale NWP models, avoiding additional uncertainties. It is important to realize that methodology and the reported findings of the case study could be applicable, with appropriate customization, to other markets, such as American and European.

The Brazilian energy sector has many different aspects that make it very important for wind farms developers to understand how the wind variability behaves compared to long-term expected values. It is also important for them to understand if a geographically disperse portfolio of wind farms contribute to the company's exposure to the spot prices variation, which ranges between 10 USD/MWh and 100 USD/MWh (see Fig. 1).

The Brazilian energy market is organized in two sectors: the Free Market, where the generating companies sell the produced energy directly to large consumers, and the Regulated Market, where the generating companies sell the generated energy to a pool of buyers (composed mainly by large distribution companies) via an energy auction, with well-defined rules of commercialization. These rules help the Brazilian wind power sector, due to how the balance of the energy is performed: the monthly payment is done based on the committed energy, and after 1 year of production, the total produced energy is compared to the period's committed energy value, and the difference is paid (bilaterally) based on that period's energy spot price. In the Free Market, the balance is performed as negotiated in the PPA, commonly defined in smaller periods (mostly monthly). This increases the exposure of the generating company to the spot price, due to the natural variability of the wind resource.

The wind power in Brazil is increasing rapidly in the last years (see Fig. 2), and the participation of wind farms in the Free Market has also grown representatively: in 2015 it was already 16.8% [1], and it increased by 14.6% in 2018 alone [2].

This study analyzed and combined the wind data of 4 different meteorological masts, covering the Brazilian NE tetragon territory, where more than 85% of all the country's wind power generation is concentrated [3]. This is important because most of the literature focuses on the portfolio effect present in Europe and USA. In total, more than 29 years of measurement data were used. The wind data was also combined to theoretical turbine power curves of different MW platforms (2, 3, 4 and 6 MW), to understand the exposure in terms of energy generation, and not only in terms wind speed. This further expands the study to evaluate how different turbine sizes impact on the portfolio effect. Finally, the cumulative impact of the meteorological anomalies was analyzed, allowing an understanding of the portfolio effect and different turbine sizes on the dimensioning of the SPE account. The study was conducted in different period sizes (1 month, 1, 2, 3, 4 and 5 years), meaning that the influence of large-scale meteorological anomalies in the portfolio effect has also been considered as subject of analysis. No data

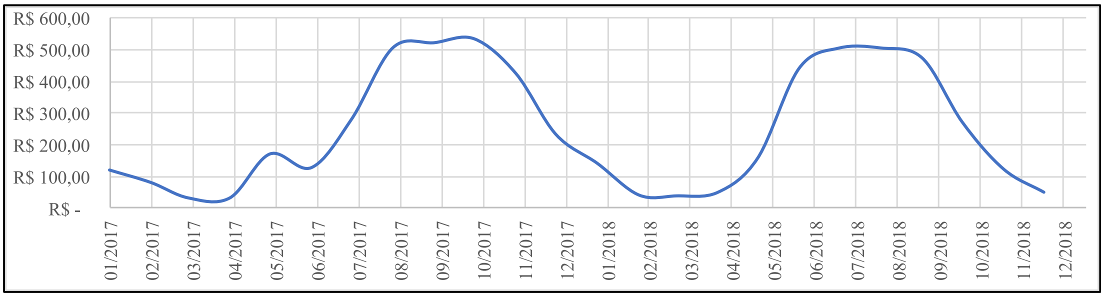

Fig. 1. Average energy spot price variation in Brazil (BRL) of a sample period in 2017–2018 [4].

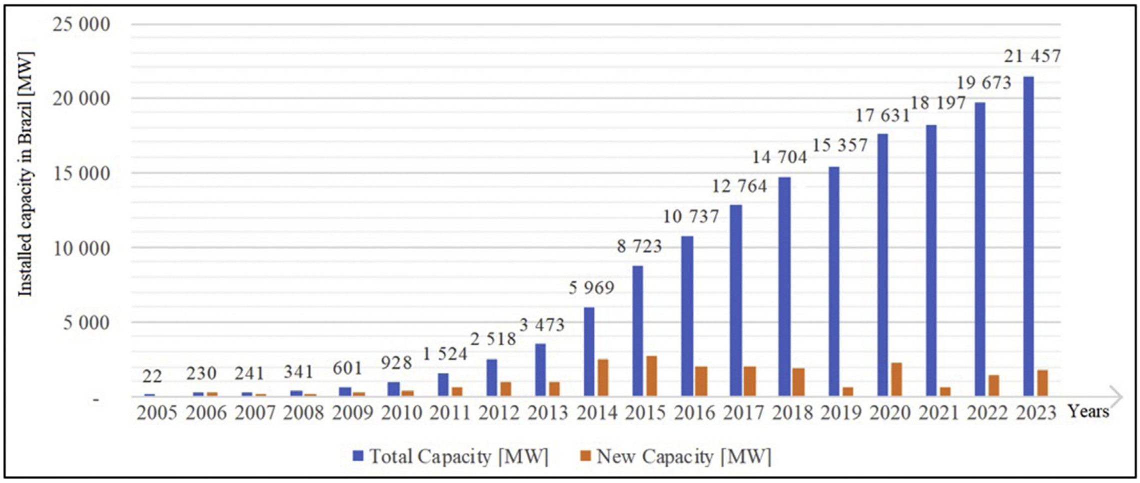

Fig. 2. Growth of wind power installed capacity in Brazil [3].

from mesoscale NWP (Numerical Weather Prediction) models were used in the study to avoid additional uncertainties, as most of the existing studies do [5].

Although the proposed methodology is applied to the Brazilian case, it is worthwhile to quote that the understanding of the variability and portfolio effect behavior is also important in more mature renewable energy markets, such as the American and European. This is due to the fact that the consolidation of renewable energy assets in large companies is a natural tendency through large portfolio acquisitions, that seek optimized combinations of risk and return [6].

2. Literature review

The matter involving wind farm variability and portfolio effect has been studied throughout the years. Kahn (1971) [7] suggested that a diversified sample of wind farms could be able to replace a conventional energy source at that time, due to the compensation for the resource's natural local variability.

Many years later, Factor and Milligan [8,9] analyzed how to optimize the wind farms distribution in Iowa (USA) to reduce the use of fuels cost of thermal power plants, based on hourly electric load data and wind measurement data.

De Carolis and Keith (2004) [10] stated that geographically disperse wind farms tend to achieve a lower energy production intermittency, obtaining optimal economical results in their study by combining these to gas turbines and energy storage solutions.

Holttinen (2005) [11] was able to prove with a study based on Scandinavian wind farms that by spreading the wind farms, reduced variability, increased predictability and a decrease in the occasions with near zero or peak output could be achieved.

Sinden (2005) [12] has analyzed the wind power production in UK. He stated that the variability of the wind is not a fixed property, as different locations experience different wind conditions in concurrent periods. He also identified that in the analyzed sample, the correlation between the wind power patterns decreases with increased distances.

Archer (2007) [13] concluded, based on a study with 19 wind power plants in the USA, that interconnected wind farms can be considered as a reliable baseload electric power when considering 33%–47% of a yearly averaged production.

Giebel (2007) [14] stated that the energy generation of dispersed wind farms is less variable than that of a single region. His study was based on 1 year of data obtained from 60 meteorological stations distributed across Europe. The data was extrapolated to 50 m height above ground making use of a logarithmic wind profile and sector-dependent roughness obtained from a WAsP analysis, published in Landberg (1994) [15].

Drake and Hubacek (2007) [16] analyzed the portfolio effect of 4 wind farms in UK, comparing the used methodology to the portfolio theory used within financial markets. The study presents a method to define what is the ideal allocation of wind power capacity in each location to minimize aggregated wind power variability per unit of power generation.

Katzenstein et al. (2010) [17] analyzed the variability of 20 wind farms in Texas, USA. His study showed that, for the used sample, the hourly-based variability can be reduced by 87% when combining 4 wind farms, and all additional 16 wind farms contribute only to another 8% reduction.

Dunlop (2004) [18], Roques et al. (2010) [19] and Chaves-Schwinteck (2013) [20] analyzed the impact of the application of the modern portfolio theory (also known as mean-variance portfolio theory) on wind farms. Their analysis tried to minimize the overall risks of wind farms owners and to maximize their returns. All authors concluded that the modern portfolio theory requires adaptations to be applied to wind farms, due to additional elements that influence the decision on the choice of a specific wind farm (such as site availability, access do integrated grid, environmental restrictions, offtake conditions, and other factors).

Reichenberg (2014) [21] presented a method to optimize the geographic allocation of wind farms in European Nordic countries and in Germany, in a way to achieve relevant reductions in the standard deviation values of the analyzed sample. In the presented results, a sample's value of 91% was reduced to 54%.

Quiao et al. (2014) [22] proposed a model to optimize a company's energy trading based on the geographical diversity of wind farms by making use of PCA (Principal Component Analysis) to manage correlated wind speeds.

Martin et al. (2015) [23] analyzed the portfolio effect of wind farms in different spatial and time scales. The study stated that the correlation of the wind between wind farms decreases as the separation between the wind farms increases. It also analyzed how far the wind farms need to be to reduce the overall variability effectively. The results varied depending on the filters applied on the data sample a depending on the analyzed regions.

Dowds et al. (2015) [5] performed a review of 12 previous large-scale wind integration studies. It pointed out that most of the studies make use of mesoscale NWP models, that have substantially less power spectral energy than the empirical data obtained from measurement masts and wind farms. The review also indicated that many of the existing studies explicitly or implicitly assume that wind power step-change follow exponential probability distributions (such as Gaussian), and that this significantly underestimates the frequency of large changes in wind power.

Handschy et al. (2017) [24] analyzed the effect of a geographically disperse set of wind farms in the USA by comparing the systematic dependence of periods of low-power (below 5% of total capacity) with the theory of Large Deviations. The study showed that by aggregating disperse wind farms, the decrease in low-power events is more relevant than the respective decrease in the variation around the mean power values, described by its standard deviation.

Susteras et al. (2011) [25] focus on the fact that wind generators in the British electricity market have historically operated without trading in the open market. These low levels of trading activities are mostly due to the combination of uncertainties in wind generation output levels, which are intermittent in nature, and the relatively small size of wind farm operators who lack large portfolios to hedge for such uncertainties. The paper illustrates the potential benefit of the introduction of an energy reallocation mechanism - ERM, aiming at to circumvent the individual risks, providing a risk sharing between all participants, similar to that existent in Brazil for hydro generators. Therefore, the ERM incentivize the wind farm owners to increase their trading activities, reaching a more efficient market position and improving the liquidity of the wholesale electricity market.

3. Methodology

The 4 selected met masts that were used in this study cover the northeastern tetragon territory in Brazil (see in yellow in Fig. 3), where most of the wind power installed capacity is in the country (due to the higher wind speed resource present in the region). The distance between each mast ranges from 459 km to 724 km, and they are all relatively close to the intertropical convergence zone, inside the southern Hadley cell. Their main characteristics are described in Table 1.

Even though the available measurement data of some met masts go all the way back to 2011, only the concurrent data of all 4 met masts were used in this study to allow comparisons to be made.

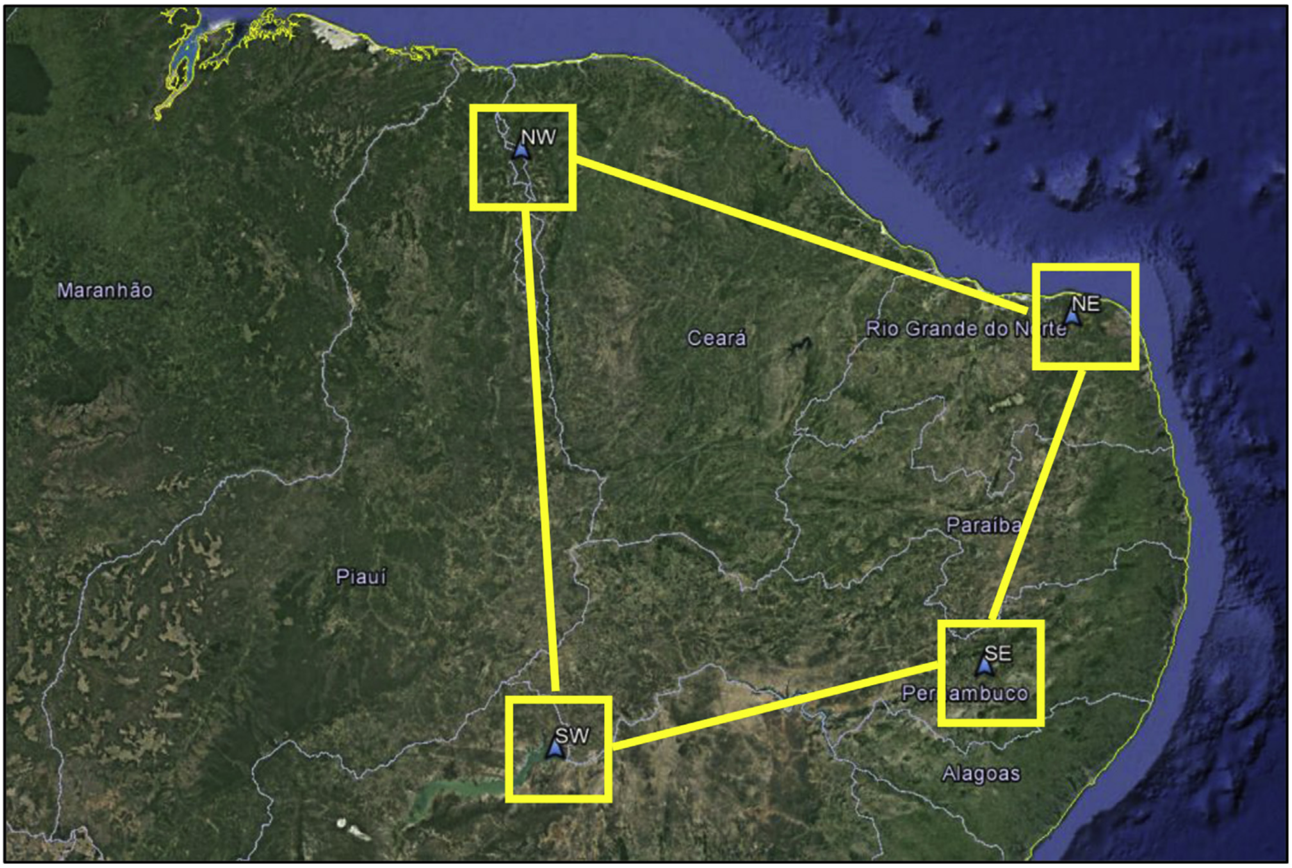

Fig. 3. Met masts location in Brazilian NE territory (Google Earth).

Table 1
Met masts main characteristics.

Mast	Distance to mast [km]				Measurement period			Concurrent period		
	NW	NE	SE	SW	Start	End	Years	Start	End	Years
NW	–	605	724	623	May 15, 2013	December 01, 2019	6.6	June 01, 2013	June 01, 2019	6.0
NE	605	–	677	465	April 30, 2011	December 02, 2019	8.6	June 01, 2013	June 01, 2019	6.0
SE	724	677	–	459	May 28, 2013	December 01, 2019	6.5	June 01, 2013	June 01, 2019	6.0
SW	623	465	459	–	June 28, 2012	December 04, 2019	7.4	June 01, 2013	June 01, 2019	6.0

This reduced the available period from 8.6 available measurement years (mast NE) to 6 concurrent measurement years.

All measurement was performed at 80 m height and made use of equipment indicated by IEC-Measnet standards. They were performed in a 10-min basis, and the average recovery rate for the anemometers used in the study is over 98%.

At first glance, the time series of the monthly average wind speed of all met masts (see Fig. 4) do now show a clear compensation (when one or more met masts have lower wind speed, the other(s) do not have a higher wind speed and vice versa). However, this was analyzed in detail, in order to identify the portfolio effect.

The wind speed monthly profile, obtained from the concurrent 6 years of data, and the respective monthly standard deviation are presented in Fig. 5. Months with lower average wind speed

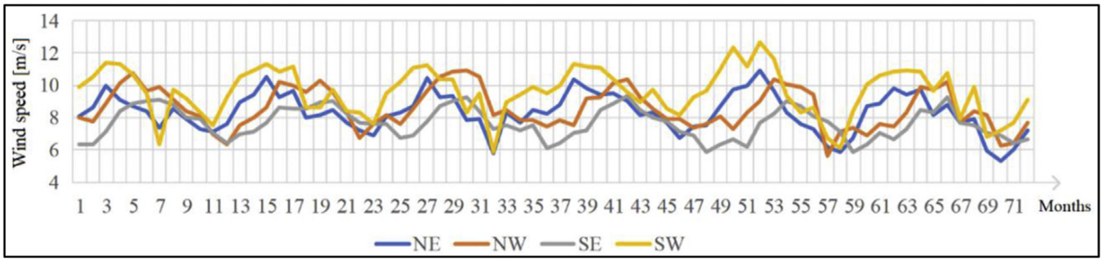

Fig. 4. Time series of monthly average wind speed of all met masts [months x wind speed].

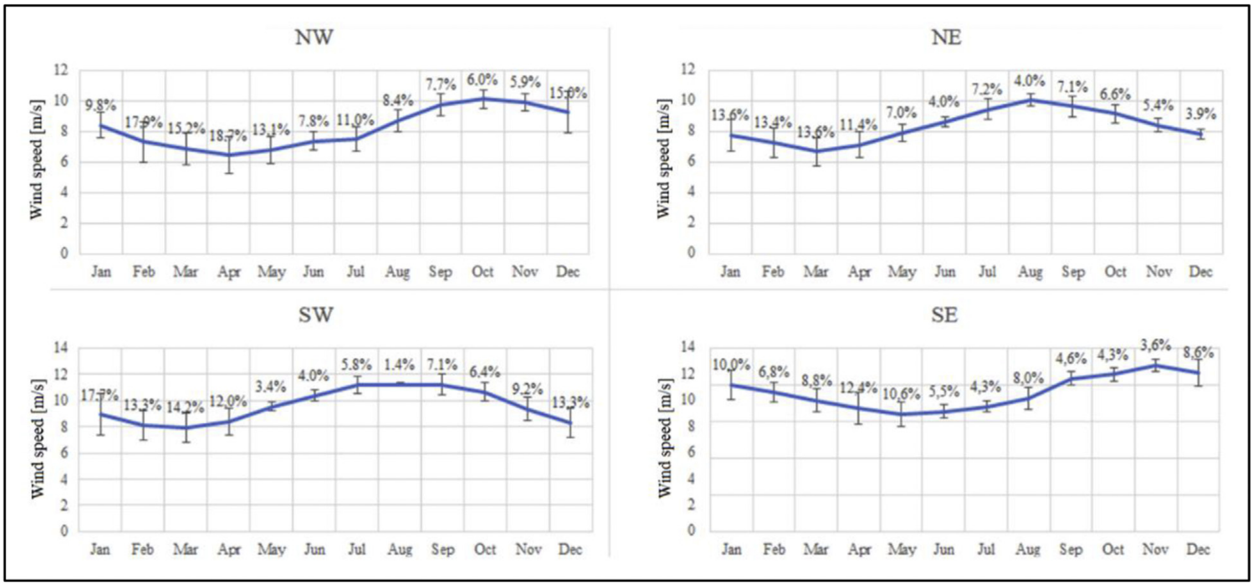

Fig. 5. Wind speed monthly profile and SD for concurrent 6 years of data [months x wind speed].

presented higher standard deviation, similar to the microscale turbulence behavior.

According to international studies, conducted by AWST [26], regions close to the intertropical convergence zone have a higher interannual variability, approaching or exceeding 10%. This is much higher than the average values suggested by more generic studies, of 6% [27,28]. The met masts studied here have an average interannual variability of 7.8% (NW), 3.6% (SE), 2.0% (NE) and 1.3% (SW).

To define the monthly energy production time series of different models of wind turbine, the monthly wind speed values of A and k constants (adjusted Weibull distribution) were calculated for each month, based on the 10-min data, and the resulting frequency distribution was combined to the wind turbines respective power curves (see Fig. 6). The 4 used power curves are set for standard air density (1.225 kg/m^3) and for average turbulence intensity.

The main purpose of calculating the energy-based time series is to understand how the different turbine platforms contribute to the wind farm's exposure to the resource's variability and to the different portfolio effects. It is worth mentioning that in the ramp-up section of the power curves (between 3 and 9 m/s in most turbine models), any variation on the wind speed is expected to have a cubic variation on the power, making the resource variability even more relevant in terms of the exposure to spot prices.

3.1. Variability of the wind speed and energy production

The variability of each time series (wind speed and all 4 different energy production) with increased sizes of measurement period (1, 2, 3, 4 and 5 years) was analyzed to identify how the average values behave around the ones considered to be long-term values (6 years in this study). This provided a measure of the uncertainty regarding the measurement long-term representativeness. No LTC (Long-Term Correction) was performed on the measurement data based on NWP models, because of the very low correlation factor obtained for mast NW and SE, when combined to sources such as MERRA-2 and ERA-5. If the LTC was performed, the uncertainty on the study would increase according to Equation (1), below, resulting in a higher σ value than the marginal variation of additional years of measurement.

$$\sigma = VAR\sqrt{\left(\frac{R2^2}{PER_{LT}} + \frac{1 - R2^2}{PER_{CON}}\right)} \qquad \text{(Equation 1)}$$

where:

VAR Wind speed variation (SD) of the period
R2 Correlation of concurrent period

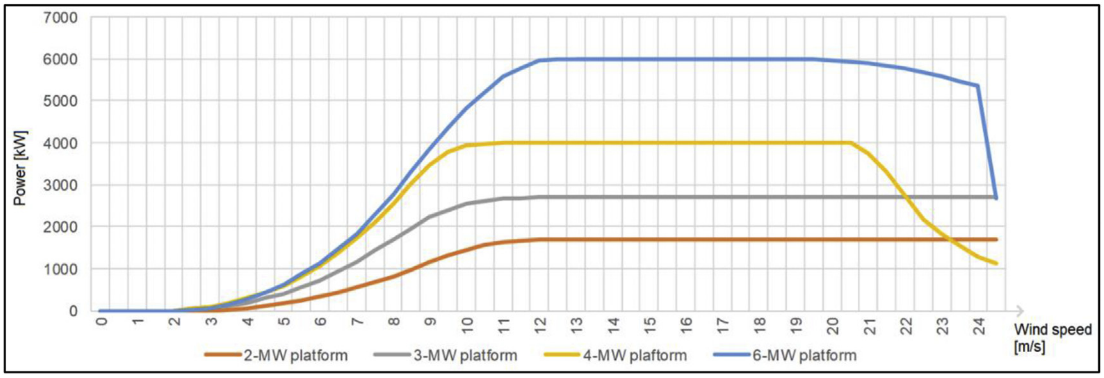

Fig. 6. Theoretical power curve of wind turbine platforms analyzed [wind speed x power].

PER_{LT} Size of the LTC reference period
PER_{CON} Size of the LTC target period

The variability of a specific period was obtained by calculating the Average Deviation (AD) of the respective period, as indicated in Equation (2).

$$AD = \frac{1}{N}\sum |x - x_{LT}| \qquad \text{(Equation 2)}$$

where:

N Number of events
x Wind speed or energy generation average of respective period
x_{LT} LT value of wind speed or energy generation (6-years average)

Most bibliographic studies present the variability as a measure of the standard deviation of the wind speed. Another way the variability is presented in the bibliography is in terms of the frequency of low-power events identified in the available time series.

To calculate the combined variability, the different time series were summed in their concurrent time steps and averaged to generate the combined time series. The variability of this combined time series is then calculated as mentioned above.

3.2. *Portfolio effect*

The portfolio effect is obtained by the difference between the combined time series variability and the average of each independent respective variability.

Most bibliographic references present the portfolio effect as the reduction on the respective variabilities (defined by the standard deviation) or as a measure on the reduction of the P90 when combining different sources of energy production assets, compared to the sum of their respective individual P90 values. P90 is the value with 90% probability of exceedance of the expected AEP (Annual Energy Production) calculated for each wind farm.

Each variability and portfolio effects were calculated with the 4 independent masts, and then combining both northern masts (N–N), both southern masts (S–S), both eastern masts (E-E), both western masts (W–W) and finally all 4 masts (360°). This was performed in different time scales, to see if the portfolio effect changed when considering a monthly basis, 1-year basis, 2-year basis, 3-year basis, 4-year basis and 5-year basis.

Independent variables and negative-related variables tend to have a higher portfolio effect than those with a positive correlation [6]. Most bibliographic references also suggest that the correlation between the different masts decreases with increasing distances, thus increasing the portfolio effect.

3.3. *Meteorological anomaly cumulative impact*

An analysis was performed to identify the worst-case scenario of cumulative negative meteorological anomalies in terms of energy balance. This was done to evaluate the relative amount of necessary trapped cash for each region when treated individually and when combined under the impacts of portfolio effect. The adopted approach is based on the definition of a time-varying energy account, that increases when the respective month has a positive meteorological anomaly (energy generation is above that month's long-term expected value) and decreases when the respective month has a negative meteorological anomaly (energy generation is below that month's long-term expected value).

4. Results

4.1. *Variability of the wind speed and energy production*

The initial results obtained for the NW region presented a much higher variability than all other regions. To better understand this, an in-depth study was performed to see if external elements were influencing the results, and the presence of a wind farm in the wind upstream direction was found (1 km away). The procedures to eliminate the wake impacts described in the bibliography were performed [29], and relevant changes in the wind speed were found (difference between original time series and revised time series presented in Fig. 7).

The same analysis was then extrapolated to the other regions, and a similar situation was identified in the SE. The presence of a wind farm in the wind upstream direction was found at a larger distance (4.5 km away), but still, the revision presented relevant differences to the original scenario before the removal of the wake impact (see Fig. 8). Due to the larger distance to the turbines in the

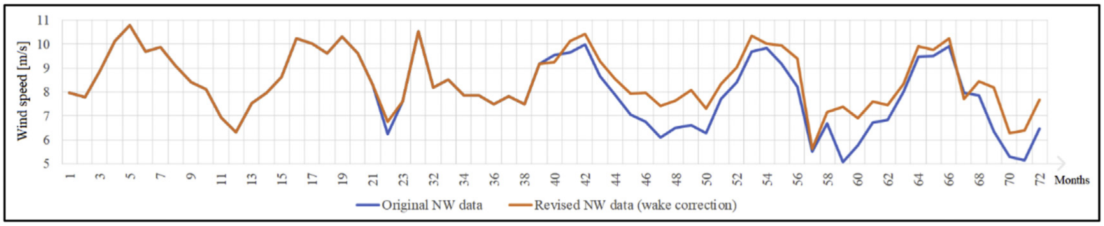

Fig. 7. NW MCP period of original and revised wind speed time series [month x wind speed].

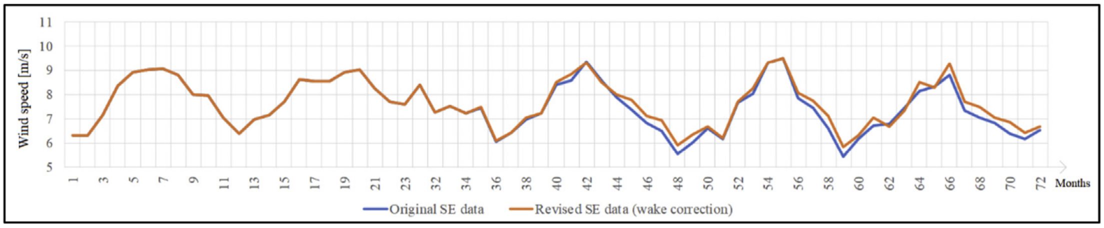

Fig. 8. SE MCP period of original and revised wind speed time series [month x wind speed].

Table 2
Rev. Variability of the wind speed for all regions, their combinations and for analyzed periods.

Variability [%]:	V_ave				
Per Region	12-mt	24-mt	36-mt	48-mt	60-mt
NE	1.86%	0.91%	0.52%	0.51%	0.35%
NW	2.45%	2.13%	1.41%	0.62%	0.43%
SE	2.69%	2.51%	1.67%	0.81%	0.41%
SW	1.87%	1.17%	0.63%	0.30%	0.15%
Combinations					
N—N	1.82%	1.34%	0.90%	0.56%	0.36%
S—S	1.39%	0.70%	0.60%	0.46%	0.24%
E-E	1.73%	1.27%	0.98%	0.63%	0.36%
W—W	1.59%	0.91%	0.57%	0.41%	0.24%
360	1.51%	1.01%	0.76%	0.51%	0.29%

upstream direction when compared to NW region, the difference in the revised time series was accordingly smaller.

The revised values for all regions and respective combinations are presented below, in Tables 2—4.

4.2. *Portfolio effect*

The portfolio effects obtained for each combination and period are presented in Tables 5—7.

4.3. *Meteorological anomaly cumulative impact*

The monthly variation around the long-term expected energy production generates a surplus or deficit value that will accumulate in time. This allows a comparative analysis on the necessary trapped cash to operate each wind farm when independent and when combined to wind farms in other regions. The results are presented in Table 8.

If the starting point of the complete period is the one with the largest accumulated negative anomaly pointed in the sample, the variable will never be negative. The same is valid for the opposite scenario: if the starting point of the complete period is the one with the largest accumulated positive anomaly, the variable will never be positive. The first case mentioned above is illustrated in the example of Fig. 9, where the results for the NW region with 6-MW platform turbines cumulative result is always positive. Due to this, the best metric to evaluate the cumulative impact of the energy production variability is the total range described by the lowest deficit and the highest surplus (see Table 8).

5. Analysis

5.1. *Variability of the wind speed and energy production*

The values presented in Tables 2—4 allows a large number of direct readings from the results.

The first is that the variability of the wind resource and consequent energy production in all different turbine platforms decreases as the period of analysis increases (the more years are included in the sample, the closer the average results will be of the long-term values). This is in line with the reduction of the LTC uncertainty formula presented in Equation (1).

Second, is that the variability of the energy production is larger than the variability of the wind speed, due to the cubic relation between these variables (as explained in Item 2).

Third, is that SE region has a higher variability in wind speed, followed by NE, NW and lastly by SW.

There was no clear indication that the variability of the energy increases with the turbine platform. An additional variable that contributes to the energy production is the rotor size, that also change between each platform. The diameters range from 82.5 m to 155 m and contribute differently in terms of increased power output for each bin of wind speed, as indicated in Fig. 6.

5.2. *Portfolio effect*

The results, presented in Tables 5—7, showed that there is a relevant reduction in the wind variability of the portfolio for all analyzed combination of regions, ranging from 0.34% to 0.88% (the original individual region's variability ranges from 1.86% to 2.69%, as presented in Tables 2—4).

The large majority of portfolio effect cases decreased with the increase of the period's size and practically stabilized after 48 months' period (see Table 5).

The region that seems to have contributed the most to the remaining regions variability decrease in wind speed is SW (S—S, and W—W combinations where it is present have the highest portfolio effect when compared to the other 2-regions combinations, for all period sizes). One of the facts that could explain this is this region's geographical location, furthest from the Atlantic Ocean than all other analyzed regions (see Table 9).

This same conclusion is not valid for most of the energy-based analysis on the periods containing 12, 24 and 48 months. This could be explained by the different average wind speed values of each analyzed region and by the impact of the wind frequency distributions when combined to each turbine power curve. The two combinations that benefit the most from the portfolio effect are in this case the S—S (first) and 360 (second).

Something important to notice is that the 360 scenario, that

Table 3
Rev. Variability of the energy production for regions, their combinations and analyzed periods.

Variability [%]:	2-MW platform					3-MW platform				
Per Region	12-mt	24-mt	36-mt	48-mt	60-mt	12-mt	24-mt	36-mt	48-mt	60-mt
NE	3.50%	1.80%	1.08%	0.98%	0.63%	3.11%	1.70%	1.10%	0.95%	0.61%
NW	3.43%	2.69%	1.85%	0.83%	0.61%	2.82%	2.07%	1.42%	0.64%	0.48%
SE	5.25%	4.79%	3.19%	1.59%	0.77%	4.03%	3.60%	2.39%	1.20%	0.58%
SW	2.29%	1.27%	0.78%	0.43%	0.23%	2.09%	1.02%	0.70%	0.40%	0.20%
Combinations										
N—N	2.99%	2.08%	1.30%	0.89%	0.56%	2.60%	1.79%	1.14%	0.78%	0.52%
S—S	2.42%	1.50%	1.24%	0.85%	0.40%	2.10%	1.29%	1.05%	0.71%	0.32%
E-E	3.44%	2.47%	1.90%	1.22%	0.66%	2.96%	2.09%	1.60%	1.05%	0.58%
W—W	2.44%	1.39%	0.86%	0.59%	0.33%	2.17%	1.23%	0.76%	0.50%	0.28%
360	2.59%	1.76%	1.31%	0.86%	0.48%	2.25%	1.52%	1.13%	0.74%	0.42%

Table 4
Rev. Variability of the energy production for regions, their combinations and analyzed periods.

Variability [%]:	4-MW platform					6-MW platform				
Per Region	12-mt	24-mt	36-mt	48-mt	60-mt	12-mt	24-mt	36-mt	48-mt	60-mt
NE	3.16%	1.76%	1.14%	0.98%	0.62%	3.53%	1.04%	1.04%	0.96%	0.62%
NW	2.79%	2.01%	1.37%	0.62%	0.47%	3.54%	1.95%	1.95%	0.87%	0.63%
SE	4.02%	3.57%	2.37%	1.20%	0.57%	5.41%	3.30%	3.30%	1.65%	0.80%
SW	2.09%	0.99%	0.70%	0.41%	0.19%	2.36%	0.81%	0.81%	0.43%	0.23%
Combinations										
N–N	2.61%	1.80%	1.14%	0.79%	0.52%	3.04%	1.32%	1.32%	0.90%	0.57%
S–S	2.11%	1.32%	1.07%	0.71%	0.32%	2.43%	1.24%	1.24%	0.86%	0.41%
E-E	2.99%	2.12%	1.62%	1.06%	0.59%	3.46%	1.92%	1.92%	1.23%	0.66%
W–W	2.18%	1.23%	0.76%	0.50%	0.27%	2.46%	0.86%	0.86%	0.61%	0.35%
360	2.27%	1.53%	1.14%	0.75%	0.42%	2.62%	1.32%	1.32%	0.87%	0.49%

Table 5
Portfolio effect calculated for combined wind speed values for analyzed periods.

Portfolio effect	V_ave				
	12-mt	24-mt	36-mt	48-mt	60-mt
N–N	0.34%	0.18%	0.06%	0.01%	0.04%
S–S	0.88%	1.14%	0.55%	0.09%	0.05%
E-E	0.54%	0.44%	0.12%	0.03%	0.02%
W–W	0.57%	0.74%	0.45%	0.05%	0.06%
360	0.71%	0.67%	0.30%	0.05%	0.04%

contains all 4 regions combined, does not always present the largest impact in terms of portfolio effect. There are other combinations that have better results if one should consider having wind farms in only 2 regions.

A higher portfolio effect was expected in both W–W and E-E scenarios (that combines a norther region to a southern region), due to the different predominance of the effects from the SE-Trade Winds (southern regions) and NE-Trade Winds (northern regions). However, this has proven to not be the case. This could indicate that

Table 6
Portfolio effect calculated for combined energy production values for analyzed periods.

Portfolio effect	2-MW platform					3-MW platform				
	12-mt	24-mt	36-mt	48-mt	60-mt	12-mt	24-mt	36-mt	48-mt	60-mt
N–N	0.47%	0.16%	0.16%	0.01%	0.06%	0.36%	0.10%	0.12%	0.01%	0.03%
S–S	1.36%	1.53%	0.74%	0.16%	0.10%	0.96%	1.01%	0.49%	0.10%	0.07%
E-E	0.94%	0.83%	0.23%	0.07%	0.04%	0.62%	0.56%	0.14%	0.03%	0.01%
W–W	0.42%	0.59%	0.46%	0.04%	0.08%	0.28%	0.31%	0.30%	0.02%	0.06%
360	1.02%	0.87%	0.41%	0.10%	0.08%	0.76%	0.58%	0.27%	0.06%	0.05%

Table 7
Portfolio effect calculated for combined energy production values for analyzed periods.

Portfolio effect	4-MW platform					6-MW platform				
	12-mt	24-mt	36-mt	48-mt	60-mt	12-mt	24-mt	36-mt	48-mt	60-mt
N–N	0.37%	0.09%	0.11%	0.01%	0.03%	0.50%	0.17%	0.17%	0.01%	0.06%
S–S	0.94%	0.96%	0.47%	0.09%	0.06%	1.45%	0.82%	0.82%	0.18%	0.11%
E-E	0.60%	0.54%	0.13%	0.03%	0.01%	1.01%	0.25%	0.25%	0.07%	0.05%
W–W	0.26%	0.27%	0.27%	0.01%	0.06%	0.49%	0.52%	0.52%	0.05%	0.09%
360	0.75%	0.55%	0.25%	0.05%	0.05%	1.09%	0.45%	0.45%	0.11%	0.09%

Table 8
Surplus and deficit of cumulative energy production anomalies.

[MWh/WTG]	2-MW platform			3-MW platform			4-MW platform			6-MW platform		
	MAX surplus	MIN deficit	MAX range	MAX surplus	MIN deficit	MAX range	MAX surplus	MIN deficit	MAX range	MAX surplus	MIN deficit	MAX range
Per Region												
NE	44.7	−17.6	62.4	77.1	−23.8	101.0	118.8	−35.4	154.2	151.6	−62.7	214.3
NW	41.0	−1.8	42.8	60.1	−5.2	65.4	89.8	−8.9	98.7	146.8	−5.7	152.5
SE	45.4	−5.0	50.4	63.2	−9.7	72.9	94.5	−15.3	109.8	161.8	−16.5	178.3
SW	31.5	−21.2	52.7	50.0	−29.4	79.4	75.6	−42.5	118.1	109.4	−78.2	187.6
Combinations												
N–N	39.7	−7.4	47.1	64.0	−10.3	74.3	97.2	−15.4	112.6	137.5	−25.9	163.4
S–S	28.5	−7.0	35.5	44.1	−12.2	56.3	67.6	−18.5	86.0	99.5	−24.2	123.7
E-E	39.4	−9.8	49.2	64.4	−14.9	79.3	98.9	−22.6	121.5	134.7	−33.8	168.5
W–W	34.8	−4.8	39.6	53.2	−8.5	61.7	79.9	−13.0	92.9	122.2	−16.3	138.5
360	34.0	−7.2	41.2	53.3	−11.3	64.6	80.8	−17.0	97.8	118.3	−25.0	143.4

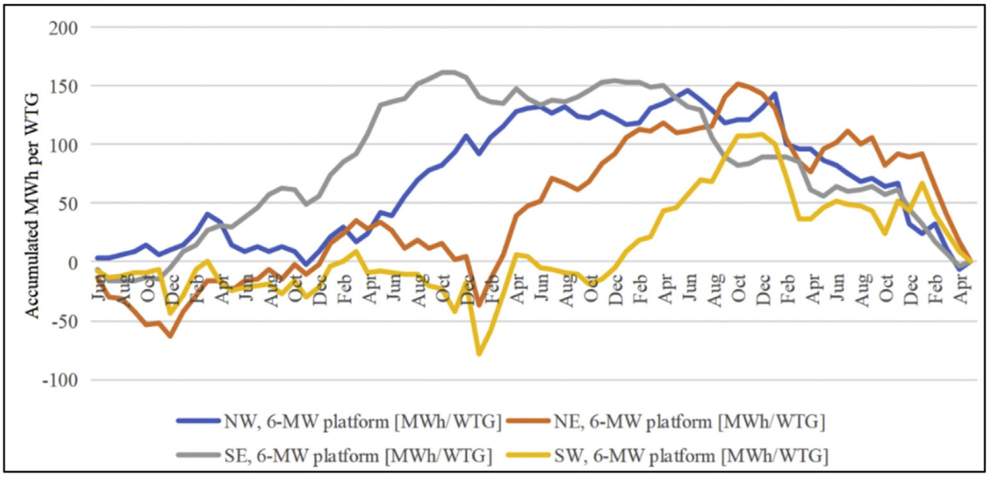

Fig. 9. Cumulative energy production anomalies for 6-MW platform [months x MWh/WTG].

Table 9
Approximate distance of each region to coast and met mast altitude.

Region:	Approximate distance to coast [km]	Altitude [m]	V_ave [m/s]
NE	40	213	8.3
NW	105	673	8.6
SE	160	769	7.7
SW	440	658	9.6

the continentality (climatic effects due to the different thermal capacity of the land and the ocean), combined to the effects of the thermohaline circulation (ocean currents) has a higher impact on the large-scale wind speeds (geostrophic wind) that influence the meteorological anomalies. The different altitudes of each mast location do not explain this behavior (see Table 9).

5.3. *Meteorological anomaly cumulative impact*

Even if the portfolio effect is not present in concurrent periods, it may be identified through the cumulative impact of the meteorological anomalies.

Something that can be identified in Fig. 9 is how the pairs NE + SW and NW + SE have noticeable more similar behaviors (with different scales). This explains in part why the S—S and S—W combinations had more relevant portfolio effects when compared to the other combinations.

Additionally, the quantitative analysis of the cumulative impact showed to be very sensitive when the start of the period is. Therefore, the suggested reference in this article for the comparison between each combination of regions is the MAX range (MAX minus MIN value of cumulative impact). When this is done, several conclusions can be drawn for the analyzed sample:

- The NW location has the lowest cumulative impact on the analysis considering a single region, followed by SE, SW and lastly by NE.
- The S—S combination has the lowest cumulative impact on the analysis considering combined regions, followed by W—W, 360, N—N and lastly by E-E.
- The 360 scenario is again not the most beneficial combination of windfarms for a reduced impact on the reduction of the exposition to meteorological anomalies.

The results also show that the larger the turbine platform, the greater the cumulative impact is, as expected. The values show a high correlated behavior (R2 of 0.985) which is also influenced by the rotor size on each platform, that ranges between 82.5 m and 155 m.

This type of analysis can help the companies dimension the necessary trapped cash required as working capital to operate wind farms in the free market. The maximum range can be combined to other critical scenarios, such as a large downtime due to events in the substation (i.e. due to a main transformer failure), to check which is the critical path that defines the value that should be considered in the operation of the wind farms.

6. Conclusion

The migration of a large volume of wind power projects to the free market in Brazil requires a better understanding on the possible exposure of each wind farm due to meteorological anomalies. The analysis presented in this article studied 4 different regions in NE-Brazilian territory, where most of the competitive wind resource is present in the country. It verified how the variability of each region behaves locally and with increased periods of analysis. It also combined different regions to analyze how the portfolio effect contributed to a reduced exposition to the wind variability. These analyses were performed with 4 different turbine platforms (2, 3, 4 and 6 MW), in order to verify the consequent impact in terms of energy production and cumulative impact during long periods of meteorological anomalies. Last, but not least, it is important to realize that although this paper's Case Study is focused on the Brazilian Energy System, the methodology and the reported findings could be applicable, with appropriate customization, to other markets, such as American and European.

The analysis on the wind resource variability of each individual region showed that the monthly standard deviation was higher in the periods with lower wind speed average, following a relation similar to that of microscale turbulence. This indicates that a time-varying trapped cash planning is possible for all wind farms, provided an in-depth analysis of the exposure due to the cumulative impact of meteorological anomalies and due to catastrophic events is performed.

The obtained results for the wind resource variability of each individual region also provided information on which are the locations with higher variability, which has proven to be in the SE, relatively close to the coast and with the highest altitude. However, when the cumulative energy exposure due to meteorological anomalies is considered, the region that presented the largest exposure is in the NW. This indicates that even though this is not the region with higher variability, it is the region that will require the largest amount of trapped cash in order to operate wind farms in the free market.

The analysis on combined regions provided information on the portfolio effect on the different options. The 360 scenario, even though it has the largest number of regions combined, is not the option with the lowest resulting variability nor cumulative energy exposure due to meteorological anomalies. The combinations that had the best portfolio effect results in terms of wind speed were those that combined the SW region (furthest from the coast) to a region close to the coast (thus, S—S combination and W—W combination). In terms of energy production, the combinations that had the best portfolio effect results were S—S (first) and 360 (second).

The obtained results on the impact on the energy variability followed a relation close to the theoretical cubic relation, when compared to the wind variability results.

The variability of the energy production showed no relevant difference between the analyzed turbine platforms, but when the cumulative impact is considered, the larger the platform, the larger the impact becomes.

This study allows agents to evaluate which are the best combinations in terms of NE Brazilian regions to reduce the exposure to the variability of the wind resource in the country. It also presents methodologies to help companies dimension the trapped cash required to operate in the free market in both wind farm level and holding level. The results for each different turbine platform could also contribute to the decision on which turbine is best for a specific project when analyzing the different options of TSA (Turbine Supply Agreement).

Further studies considering hourly data should be performed in the close future, due to imminent regulatory changes in the Brazilian energy sector that are being evaluated by the different related agencies. The energy spot price will become hourly-based, instead of weekly as it is today. Additionally, data from different wind farms in each region should be analyzed to identify if microscale effects play a relevant role in the variability of each region.

CRediT authorship contribution statement

Gustavo S. Böhme: Writing - review & editing. **Eliane A. Fadigas:** Writing - review & editing. **Dorel Soares:** Writing - review & editing. **André L.V. Gimenes:** Writing - review & editing. **Bruno C. Macedo:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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