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The complementary nature between wind and photovoltaic generation in Brazil and the role of energy storage in utility-scale hybrid power plants

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ABSTRACT

Solar and wind sources together provided more than half of the Brazilian Northeast electricity generation in 2019. This growing share of renewable energies in the Brazilian energy matrix increases the importance of portfolio optimization and the energy storage management. This paper assesses the complementary nature between wind and photovoltaic generation in the Brazilian Northeast, and how this complementarity, together with energy storage, can reduce the shortcomings that the corresponding natural resource intermittency imposes on these sources. The work consists of two main analyses: (i) analysis of the capability in supplying the Brazillian Northeast region power demand with a hybrid wind + solar + storage power plant; and (ii) contingency optimization analysis for hybrid wind + solar + storage power plants. The results show that wind and solar resources are consistently complementary in the region, with a daily Pearson's Correlation Coefficient of −0.51. Also, the load supply analysis shows that a renewable energy mix based on a 40% wind and 60% solar share would require the equivalent of only 6% of its annual generation in storage capacity. An energy curtailment analysis showed that the complementary nature of the wind and solar resources, together with energy storage, can lead to a reduction of up to 11% in transmission capacity demand.

1. Introduction

Renewable energy (RE) generation technologies accounted for 72% of the worldwide net generation capacity expansion (245 GW) in 2019, with solar and wind accounting for 90% of the 176 GW in newly added global RE generation capacity [1]. The intermittent and non-dispatchable nature of these two RE technologies can lead to variability issues in demand supply. Therefore, strategies to avoid or attenuate the effects of these resources' variability have become an important field of study. Brazil is a specific case due to its vast territory, with more than 8,500,000 km2 and latitudes ranging from 5°N to 33°S. With an installed generation capacity of over 170 GW, the Brazilian energy mix is very diverse in resources, with 62% of its energy being provided by hydroelectricity, 26% by thermoelectric plants (16% fossil fuel, 9% biomass, 1% nuclear), and around 12% by non-dispatchable RE sources (9% wind and 3% solar) [2]. Despite all the advantages provided by the major role of hydropower in the electricity mix, it also leads to a high dependency on the rainfall regime and water flow in the river basins. In recent years, river basins located in the Northeast have experienced intense water constraints, with water flow decreasing by up to 99% in some cases [3]. The impact of the drought period in the Northeast subsystem is being attenuated by the increasing penetration of RE in the region, which accounts for the highest solar and wind resource availability and installed capacity in the country [4,5]. The high availabilities of both resources create opportunities for wind + solar hybrid power plants, as shown by their geographical distribution shown in Fig. 1. Both wind and PV large-scale power plant projects are being installed in close proximity and, therefore, many projects share the same access point to the Brazilian Interconnected Transmission System (*Sistema Interligado Nacional - SIN* in Portuguese), and the high-voltage transmission lines. This increasing RE penetration and its concentration in the NE region start to demand solutions for issues such as the generation variability and curtailment losses due to transmission system congestion [6–8]. In this context, the present study aims to assess the temporal complementarity between the solar and wind resource availability and potential output generation, and how this complementarity,

Abbreviations: η_{ESS}, Energy storage system efficiency in %; ANEEL, Agência Nacional de Energia Elétrica (Brazilian Electricity Regulatory Agency); EPE, Empresa de Pesquisa Energética (Brazilian Energy Research Enterprise); GHI, Global horizontal irradiation; LOLP, Loss of Load Probability; MISO, Midcontinent Independent System Operator; N, North; NE, Northeast; ONS, Operador Nacional do Sistema (National Electricity System Operator); PCC, Pearson's Correlation Coefficient; PV, Photovoltaics; RE, Renewable Energy; S, South; SE/MW, Southeast/Midwest; SIN, Sistema Interligado Nacional (Brazilian Interconnected Electricity System

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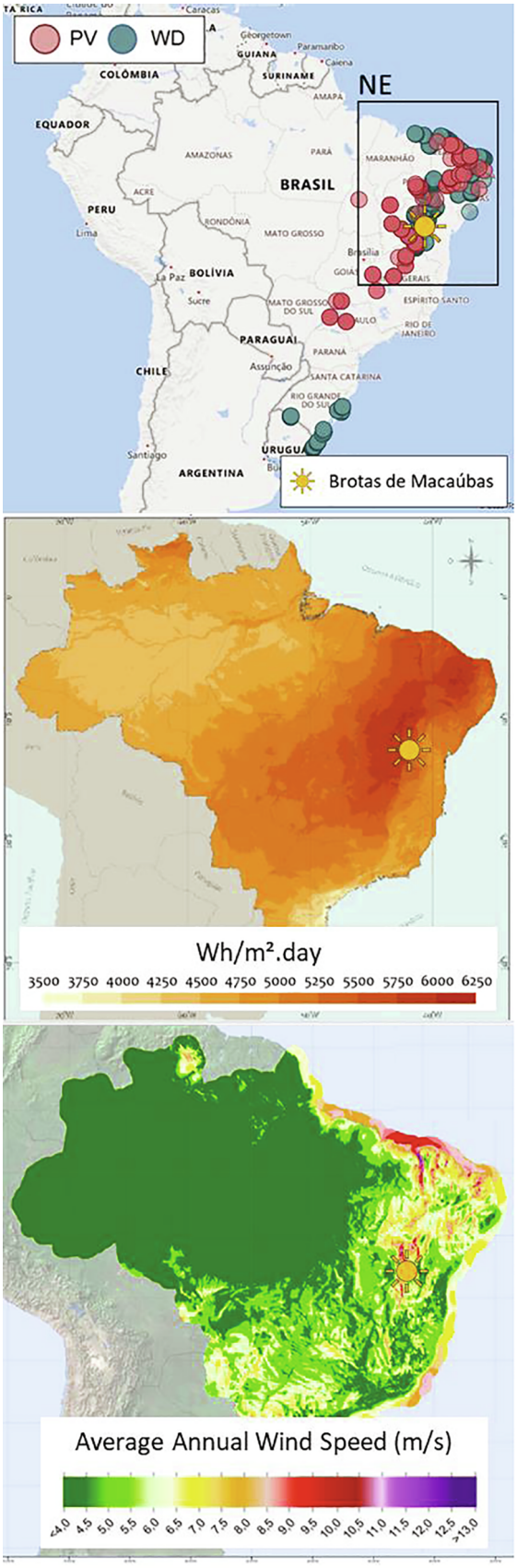


Fig. 1. Utility-scale wind and solar PV power plants installed until 2019 in the Brazilian Northeast [24], and location of the case study Brotas de Macaúbas hybrid wind/PV power plant in the State of Bahia (top); the case-study location highlighted in the global horizontal irradiance map from Atlas Brasileiro de Energia Solar [4] (middle); and in the average annual wind speed map from Atlas do Potêncial Eólico Brasileiro [5] (bottom).

together with short-term electrochemical energy storage, can be used to optimize a more widespread uptake of hybrid utility-scale wind + solar power plants.

Many interesting case studies have been published in the scientific literature, evaluating different strategies to compensate the drawbacks derived from the intermittency of RE sources [9–14], showing that energy storage system additions and portfolio sizing optimization can mitigate RE generation curtailment and increase these sources dispatchability [15–18]. Tang et al. [19] presented a hybrid hydro-wind-PV size optimization for a hydropower station in the Yalong River Basin, China and showed that the hybrid power plant guarantees the quantity and quality of the generated energy. Ma T. and Javed M.S. [20] have developed a cost-optimal autonomous hybrid renewable energy system to mitigate the disharmony between RE generation and supply in Jiuduansha, a remote island near Shangai-China, and have obtained an optimal wind/solar share of about 30% to 10%. Celik [21] carried out an optimization and techno-economic analysis of a wind/photovoltaic hybrid energy system in comparison to single wind and photovoltaic power plants, and concluded that an optimum combination of the hybrid wind/PV energy system provides higher system performance than either of the single systems for the same system cost for every battery storage capacity analyzed. Wang et al. [22] have proposed an approach that minimizes the fluctuation in the combined power output of a hydro, wind and photovoltaic portfolio and maximizes their combined power generation while adhering to the target reservoir's water levels in the reservoir refilling period. Gan et al. [23] developed a sizing tool focused on optimal sizing of diesel generator and battery storage systems in hybrid wind/PV systems.

2. Case study

A case study is presented here, based on the power generation of a utility-scale 95 MW wind power plant and two R&D-scale 2 kWp photovoltaic plants (one at fixed tilt = local latitude, and one single-axis tracking, both shown in Fig. 2.), located in Brotas de Macaúbas – Bahia (12.31°S, 42.34°W), highlighted in the maps shown in Fig. 1. The diagram shown in Fig. 2. also illustrates the hybrid generator with the existing wind and photovoltaic plants, as well as the simulated energy storage system. The wind distribution regime in the region drops during the day, when solar resource peaks, which makes the region one of the most suitable locations for wind and solar complementarity in the country [25,26]. The typical Global Horizontal Irradiance (GHI) and wind speed annual average day profiles are presented in Fig. 3. The case study technical specifications are summarized in Table 1.

Wind speed, fixed tilt (12°), and tracking solar irradiance values, together with power generation of the three generators were used to assess the complementarity between the wind and solar resources, and power plant output generation figures. These data were used to optimize the wind/solar mix in order to maximize the load supply. This study is comprised of two main analyses: (i) load supply, and (ii) wind/solar power curtailment optimization.

2.1. Load supply

The load supply analysis aims at assessing how the wind/solar mix can shape the energy storage needs to achieve a hybrid system designed to feed 100% of the energy supply demands of the NE Brazilian region with wind + solar. The data used in the analysis were the power

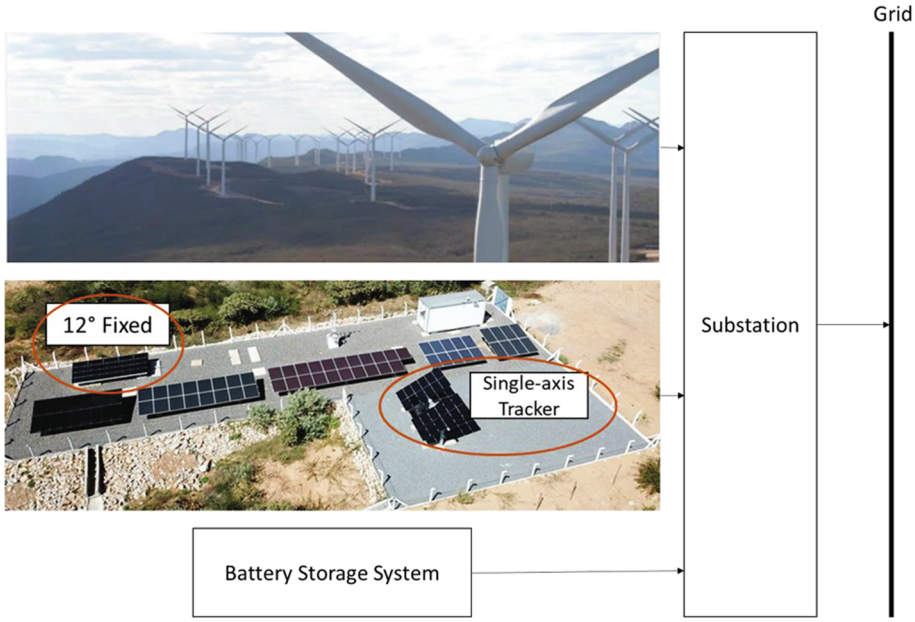


Fig. 2. Block diagram showing the 95 MW wind power plant, the R&D solar PV + wind and solar measurement station used as case study in Brotas de Macaúbas – Bahia + a simulated electrochemical storage system. The image shows a number of different PV technologies, including the two (circled) PV systems evaluated in this paper (12° fixed tilt and single-axis tracker).

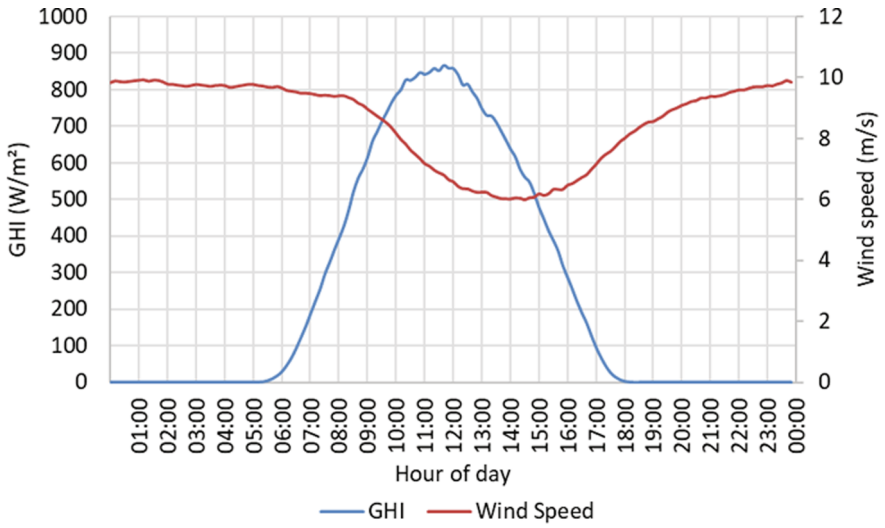


Fig. 3. Global Horizontal Irradiance (GHI, in W/m^2) and wind speed (m/s) annual averages in Brotas de Macaúbas, Bahia.

Table 1
Case study specifications.

Latitude		12.31° S
Longitude		42.34° W
Wind plant nominal power		95 MW
Photovoltaic plant nominal power	Tracker	2.2 kWp
	Fixed Tilt – 12°	2.2 kWp
Substation nominal power	–	100 MVA

Table 2
Composition of the simulated wind + solar generation scenarios in the load supply analysis.

Scenario	Wind fraction	Solar fraction
# 01	0%	100%
# 02	10%	90%
# 03	20%	80%
# 04	30%	70%
# 05	40%	60%
# 06	50%	50%
# 07	60%	40%
# 08	70%	30%
# 09	80%	20%
# 10	90%	10%
# 11	100%	0%

generation measurements from the wind and PV systems (proportionally upscaled from the wind and solar power plants real output data), and the publicly-available NE region load data, which were obtained from the Brazilian Electrical System Operator (*Operador Nacional do Sistema Elétrico – ONS* in Portuguese) website. Both datasets correspond to real measured values for the year 2018.

2.2. Curtailment optimization

The clustered distribution of the growing number of utility-scale wind and solar PV power plants shown in Fig. 1 can lead to curtailment losses due to limitations of the load or transmission system congestion [27,28]. On the other hand, new investments in transmission lines designed to accommodate generation flows from RE power plants could make these new lines idle when solar and wind resources dwindle.

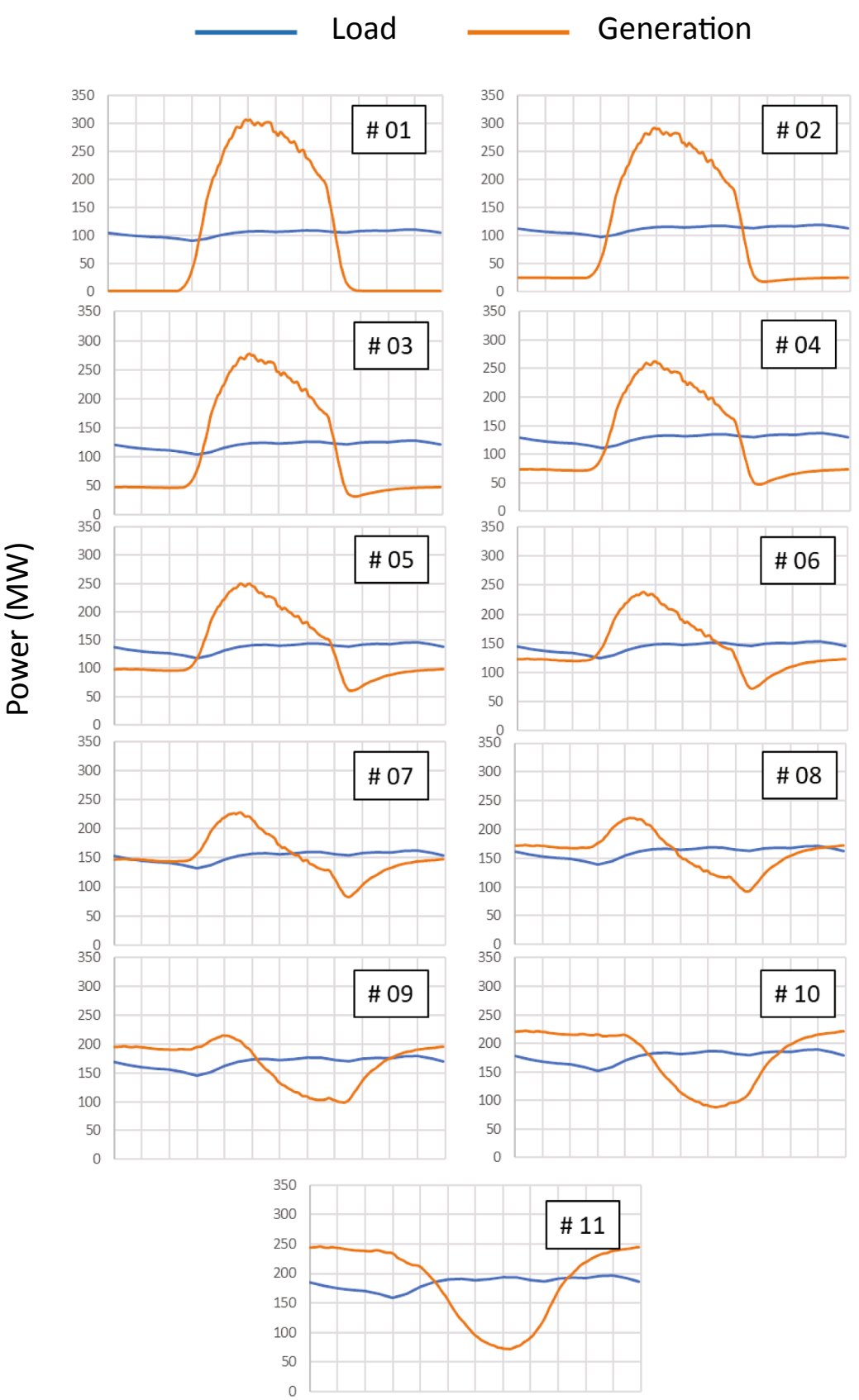


Fig. 4. Average daily profile of hybrid wind + solar generation, and normalized load curve for each of the 11 scenarios.

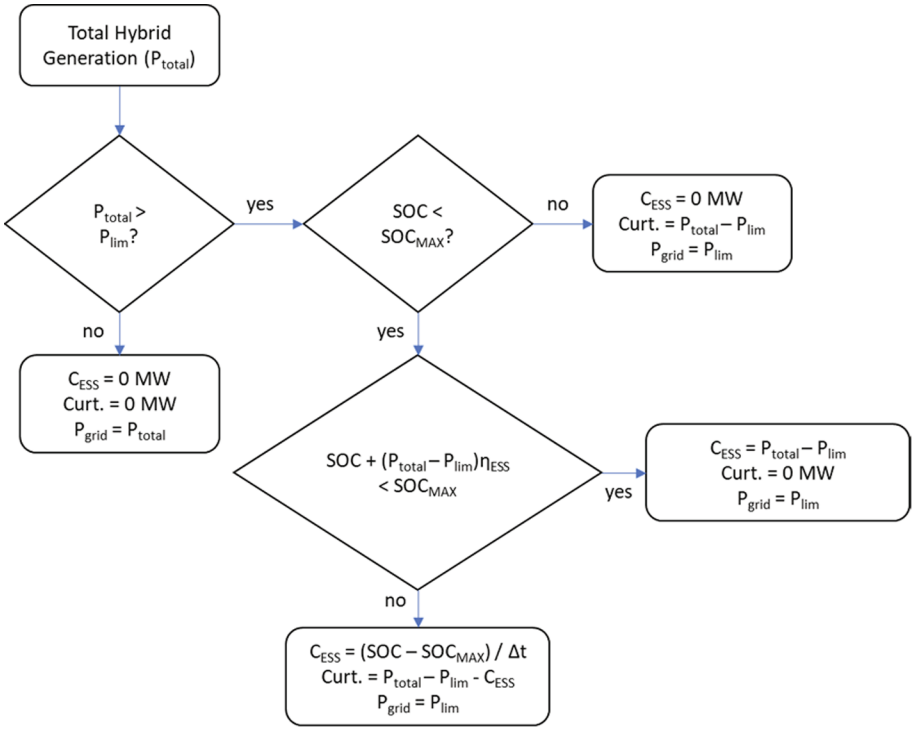


Fig. 5. Flow diagram of the energy storage system charging/discharging dispatch strategy.

Table 3
Modeling characteristics of the battery energy storage system.

Characteristic	Value	Description
$SOC_{initial}$	1	State of charge initial value
SOC_{min}	0.2	Minimum state of charge
SOC_{max}	1	Maximum state of charge
DOD_{max}	0.8	Maximum depth of discharge
C_{max}	1C	Maximum C factor of charge or discharge
η_{ESS}	90%	Mean efficiency in both charge and discharge processes

These issues can be avoided or attenuated by an optimal mix of wind/solar and energy storage [7,27,29,30]. The curtailment optimization analysis tries to evaluate how energy storage can avoid curtailment losses against new investments in expanding transmission capacity.

3. Methodology

3.1. Data and statistical description

As mentioned before, we used one year of wind speed, fixed tilt and single-axis tracking solar irradiances, wind generation, and photovoltaic generation measured data with a timestep of 10 min. We have made a general statistical description to evaluate the temporal complementarity between the resources (wind speeds and irradiances) and between the generations (wind and solar PV).

To quantify the temporal complementarity between the time series, we used the Pearson Correlation Coefficient (PCC) [26,31–33].

The PCC was calculated for each day of the year and then a monthly average was obtained. The same strategy was used to calculate the PCC for the solar and wind resource data and for the output power generation data. The PCCs between wind and solar resources and output power generation were calculated using four dataset combinations: (i) wind speed and fixed tilt irradiance; (ii) wind generation and fixed tilt PV generation; (iii) wind speed and single-axis tracking irradiance; and (iv) wind generation and single-axis tracking PV generation. This allowed us to assess if the difference between the fixed and single-axis tracker solar irradiance profiles leads to relevant differences in PCC values.

It is known that a large solar irradiance resource measurement temporal resolution can significantly modify the irradiance characteristics, with important consequences especially in PV system design, like the PV Inverter Loading Ratio – ILR [34–36]. Therefore, in order to evaluate the influence of the data timestep on the PCC values, the original 10-min timestep dataset were grouped into a one-hour timestep dataset and then this new dataset was used to calculate new PCC values.

3.2. Load supply

To assess the capacity of a hybrid wind/solar generation portfolio to supply the Brazilian NE load, we defined 11 wind/solar scenarios to evaluate how these different scenarios could minimize the need for an energy storage system. The 11 scenarios are presented in Table 2. For each scenario, we normalized the load curve so that the total energy generated by the hybrid wind + solar power plant in the scenario is equal to the total energy consumed. The wind and solar ratios presented in Table 2 refer to the nominal installed power and not to the total energy generated. Therefore, scenarios with solar predominance result in a smaller amount of energy generation, since the wind power plant capacity factor is typically and intrinsically higher than the solar PV power plant capacity factor.

Fig. 4 shows the normalized load and the hybrid generation profiles for each scenario in Table 2, averaged over the whole year.

To quantify the system's ability to fully supply the load, we used the Loss of Load Probability (LOLP) concept, defined by Eq. (1) [37–41].

$$LOLP = \frac{\sum_{i=1}^{n} P_i^{Def}}{\sum_{i=1}^{n} P_i^{CG}} \quad (1)$$

The LOLP was calculated for each day, and the LOLP monthly value is the average of the daily values. For each scenario we simulated the application of an energy storage system with a storage capacity from 0 to 190,000 MWh. We have also analyzed the correlation between the generation of each case and the original load curve through the PCC, to

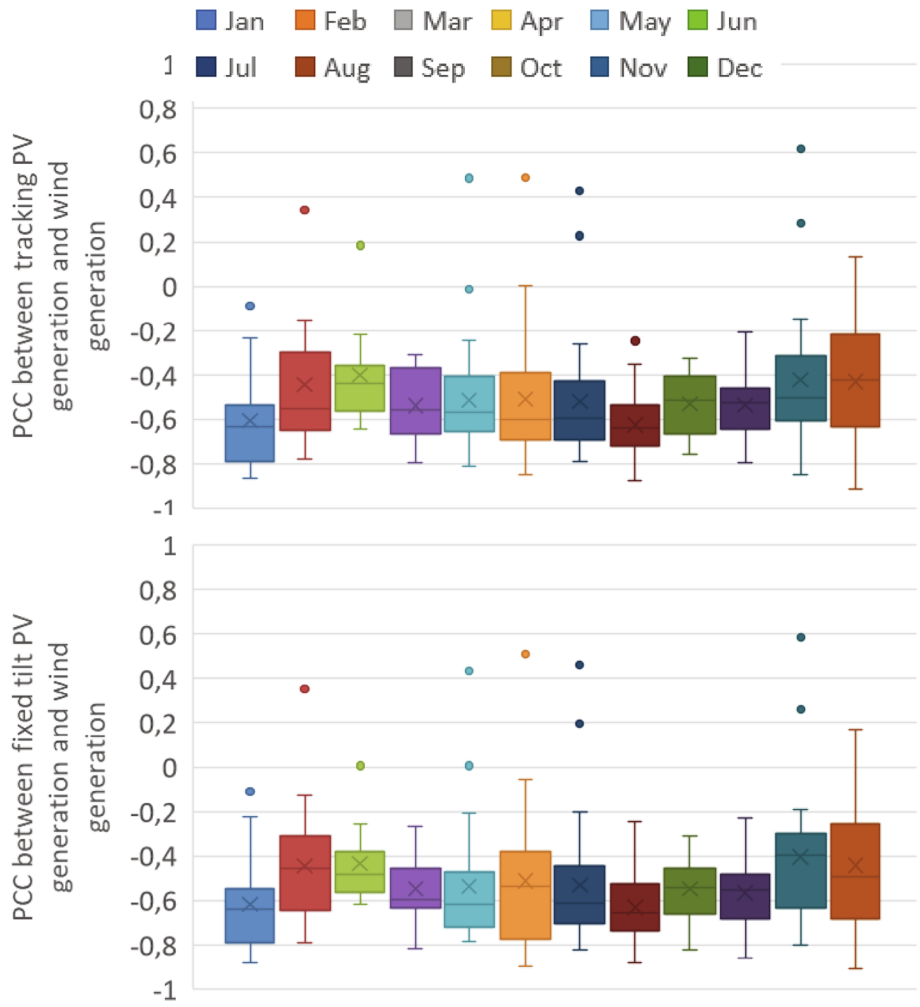


Fig. 6. Correlation boxplot (Pearson Correlation Coefficient - PCC) between wind generation and PV generation (fixed latitude tilt and single-axis tracking) profiles in Brotas de Macaúbas-BA.

Table 4
Means and standard deviations between wind generation and PV generation (fixed latitude tilt and single-axis tracking) profiles in Brotas de Macaúbas-BA.

Month	Mean Tracking	Std. Dev. Tracking	Mean Fixed Tilt	Std. Dev. Fixed Tilt
Jan	−0.61	34%	−0.62	33%
Feb	−0.44	65%	−0.45	60%
Mar	−0.40	59%	−0.43	44%
Apr	−0.54	29%	−0.55	28%
May	−0.51	51%	−0.54	50%
Jun	−0.51	59%	−0.51	61%
Jul	−0.52	53%	−0.53	54%
Aug	−0.63	22%	−0.63	24%
Sep	−0.53	24%	−0.55	25%
Oct	−0.53	27%	−0.57	26%
Nov	−0.42	78%	−0.40	78%
Dec	−0.43	63%	−0.44	68%
Annual average	**−0.51**	**47%**	**−0.52**	**45%**

evaluate which case presents the generation profile closest to the load profile.

3.3. Curtailment optimization

The curtailment optimization analysis is focused on assessing how energy storage can reduce transmission capacity needs and curtailment losses, and assist the system in keeping a constant energy generation profile. In our case study, this analysis is based on a 395 MWp plant, composed by a 300 MWp PV plant (based on the two 2kWp R&D generators scaled up to 300 MWp) and the 95 MW existing wind plant. The 300 MWp capacity was defined in order to simulate an expected project to be installed at the site.

The existing 95 MW wind plant has a 100 MVA substation that is used as the base case of this analysis. We simulated cases varying the storage capacity, similarly to the previous analysis, and changing the substation size up to the total combined solar + wind capacity of 395 MVA.

3.4. Energy storage model

In all analyses, the storage system charging and discharging process was the same. At times when the power generated by the hybrid wind + solar power plant is higher than a previously set power limit, which in the load supply analysis is the demand value and in the contingency analysis is the substation rated capacity – the energy that would be curtailed is stored in the energy storage system. If the energy to be stored exceeds the total capacity of the storage system, the energy is stored until the system reaches its maximum capacity and the rest is lost (curtailed). If the system is fully charged, all further generation is discarded.

The discharge will take place when there is a need to feed energy into the grid; that is, in the load supply analysis, when the power of the hybrid solar + wind power plant does not meet the system demand and, in the curtailment or contingency analysis, when the hybrid

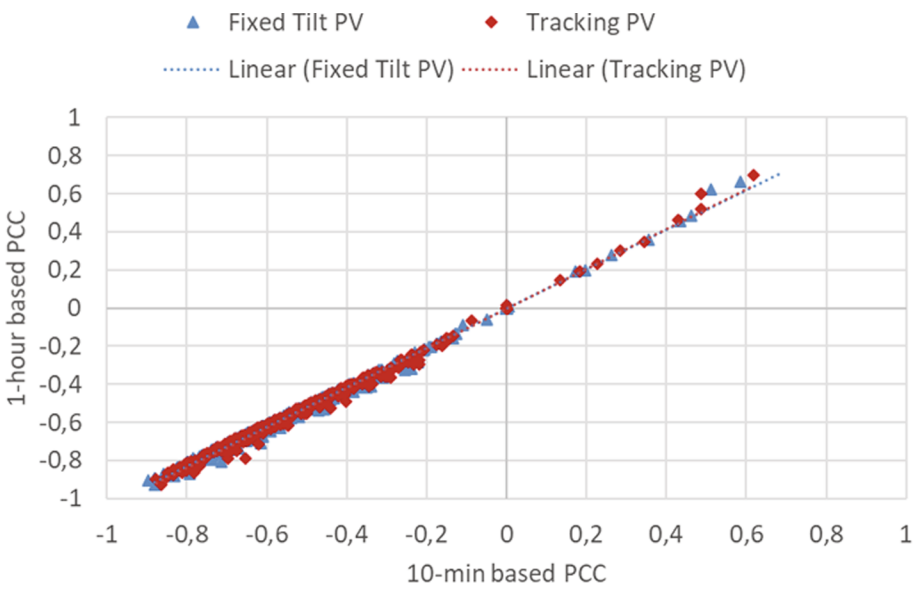


Fig. 7. Correlation between 10-min and 1-hour wind generation and PV generation (fixed latitude tilt and single-axis tracking) profiles (Pearson Correlation Coefficient – PCC) for the Brotas de Macaúbas site.

Table 5
Means of the 10-min and 1-hour wind generation and PV generation (fixed latitude tilt and single-axis tracking) profiles (Pearson Correlation Coefficient – PCC) for the Brotas de Macaúbas site.

Data temporal resolution	Tracking PV	Fixed Tilt PV
10 min	−0.52	−0.52
1 h	−0.54	−0.54

solar + wind power plant generation is below the substation rated capacity. Fig. 5 summarizes the energy storage system charge and discharge process. This process is carried out every timestep of each simulation for each scenario evaluated.

The energy storage system model simulated is based on a lithium ion battery technology, due to its flexibility and high efficiency [12,42–45], which makes this type of battery suitable for the needs of a RE grid. The main characteristics of the model are shown in Table 3. At this point, it is important to note that this model does not include capacity degradation; however, as the expected annual number of cycles is 365, that is, one cycle per day, and with a maximum discharge rate of 1C, the expected degradation is negligible for the analyzed period [45].

Table 6
Means of the wind and solar generation output and wind and solar resource availabilities PCCs.

Correlation type	Tracking PV	Fixed Tilt PV
Generation	−0.44	−0.51
Resources	−0.52	−0.52

4. Results and discussion

4.1. Statistical description

The PCC 10-min daily values distribution for fixed latitude tilt and

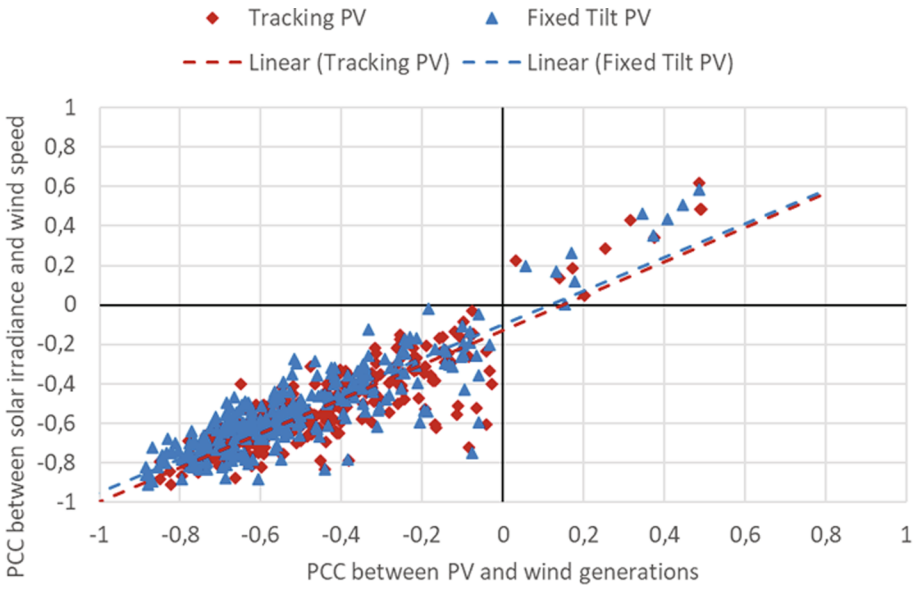


Fig. 8. Correlation between the wind and solar generation output and the wind and the solar resource availabilities PCCs.

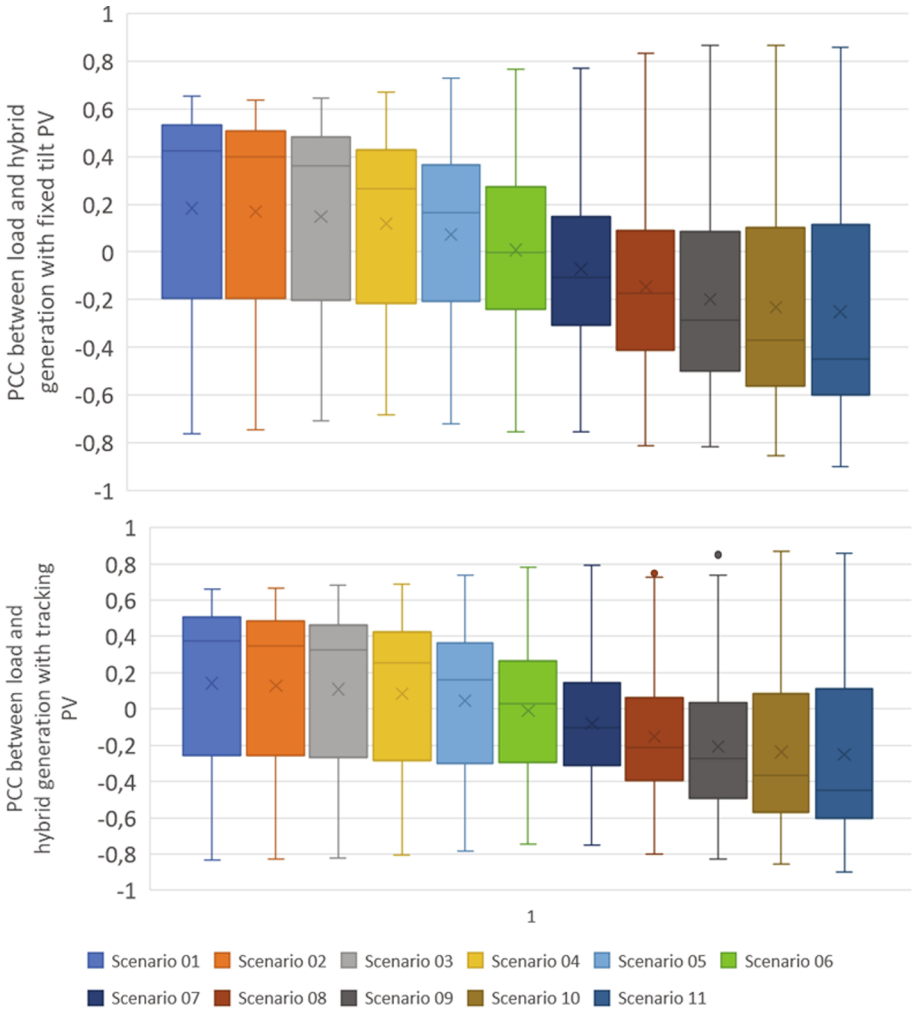


Fig. 9. Daily correlation (PCCs) boxplot between hybrid wind + solar generation and load for the 11 hybrid wind + solar scenarios for fixed latitude tilt PV (upper plot) and single-axis tracking PV (lower plot) generators.

single-axis tracker PV systems output generation in relation to the wind park output generation are presented in Fig. 6, and Table 4 presents the monthly PCC values and its standard deviation. The average complementarity for each month remains constant throughout the year, and that of the winter and summer months is more dispersed. An average PCC of −0.51 was obtained for both PV topologies, a value similar to the presented in [26] for the same region.

These values indicate that there is a good complementarity between the wind and solar generation profiles in Brotas de Macaúbas, and that there is not much difference in this aspect when comparing the fixed and the single-axis tracking PV technology. In addition, the distributions also indicate that the average complementarity between generation profiles remains practically constant throughout the year, and that there is no clear seasonal pattern in the variability of this indicator over the months. It should be noted that these analyses are valid to demonstrate the proposed evaluation methodology, and were carried out for a single year (2018) to show a trend; for more definitive conclusions on the distribution pattern throughout the year, however, more years of data should be evaluated.

4.1.1. Data temporal resolution influence

The comparison between the daily PCC values from 10-min datasets and 1-hour datasets is presented in Fig. 7. Table 5 presents the average values for each PCC. These results indicate that an hourly overestimate analysis has a complementarity index of about 4%. Considering that the PCC is just an indicator, this 4% difference does not lead to a different overall conclusion. Therefore, simulations carried out with hourly timesteps are satisfactory and do not lead to significant losses in information about the complementarity index.

4.1.2. Generation PCC vs resources PCC

The analyses presented here mainly highlight the correlations (PCCs) between the wind power plants generation profiles. However, in the project design and certification phase, only local wind and solar resources data are available. While the power of a photovoltaic plant is linearly proportional to the irradiance on the plane of the modules, the same is not true for the relation between wind speed and wind generation; the power of a wind turbine is proportional to the cube of the wind speed. Thus, variations in different resources have a different impact on the corresponding generation outputs. Therefore, the complementarity between the resources is not necessarily reflected in the complementarity between the generation profiles of each technology. A correlation analysis was carried out between the PCCs of wind and solar generation output and the PCCs between the wind and solar resources. Fig. 8 and Table 6 show these correlations and it can be noted that while the PCCs values are not perfectly correlated, the annual means are close. This means that a complementary index based on the wind and solar resources would lead to the same conclusion as if it were calculated with the generation data.

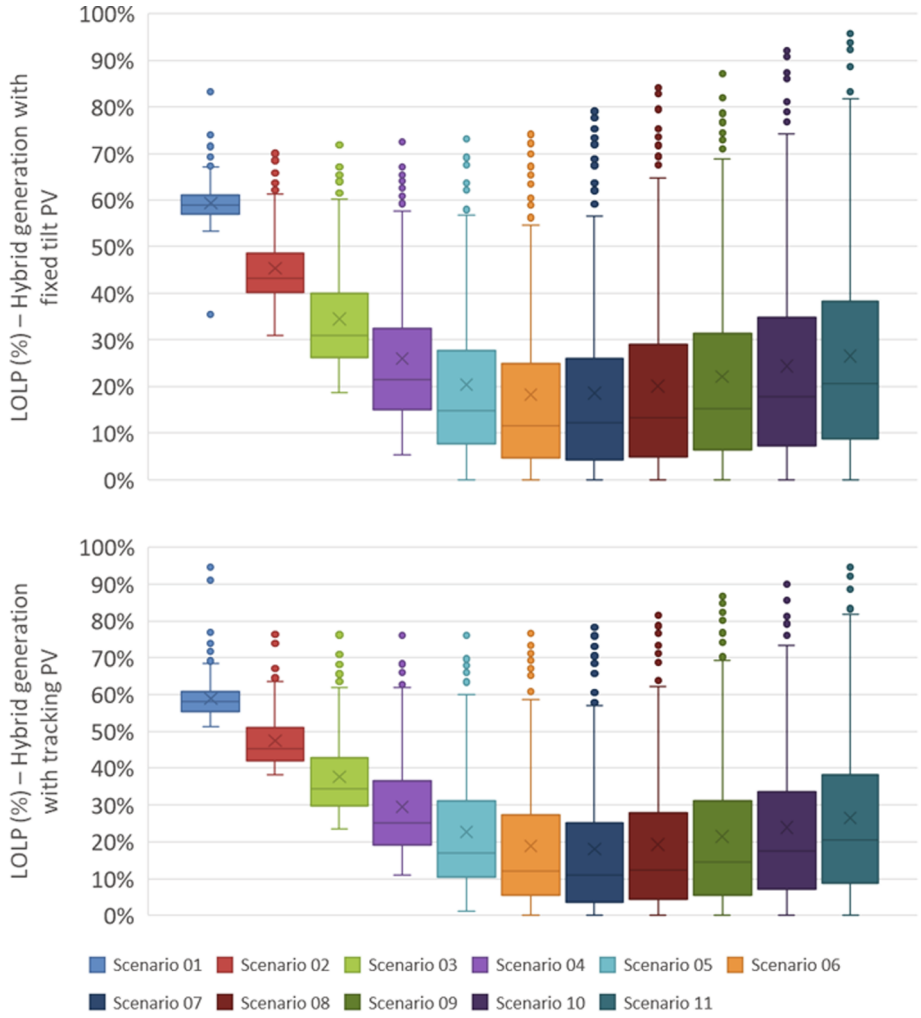


Fig. 10. Daily LOLP boxplot between hybrid wind + solar generation and load for the 11 hybrid wind + solar scenarios for fixed latitude tilt PV (upper plot) and single-axis tracking PV (lower plot) generators.

Table 7
LOLP for all the 11 hybrid wind + solar (fixed latitude tilt PV) power plants and storage scenarios.

		LOLP (%)										
		Scenario 01	Scenario 02	Scenario 03	Scenario 04	Scenario 05	Scenario 06	Scenario 07	Scenario 08	Scenario 09	Scenario 10	Scenario 11
Storage Capacity (MWh)	2500	12%	10%	9%	9%	9%	10%	11%	12%	13%	14%	15%
	5000	11%	8%	8%	8%	8%	9%	10%	11%	11%	12%	13%
	7500	11%	8%	7%	7%	8%	8%	9%	10%	11%	11%	12%
	10000	10%	8%	7%	7%	7%	7%	8%	9%	10%	11%	12%
	20000	10%	7%	6%	6%	6%	6%	7%	8%	8%	9%	9%
	30000	9%	6%	4%	4%	5%	5%	6%	7%	7%	8%	9%
	40000	8%	5%	4%	3%	4%	4%	5%	6%	7%	7%	8%
	50000	7%	5%	3%	2%	2%	3%	4%	5%	6%	6%	7%
	60000	6%	4%	2%	1%	1%	2%	3%	4%	5%	6%	6%
	70000	5%	3%	2%	0%	0%	1%	2%	3%	4%	5%	6%
	80000	4%	2%	1%	0%	0%	1%	1%	2%	3%	4%	5%
	90000	3%	2%	0%	0%	0%	0%	1%	1%	2%	3%	4%
	100000	2%	1%	0%	0%	0%	0%	0%	1%	2%	2%	3%
	110000	1%	0%	0%	0%	0%	0%	0%	1%	1%	2%	3%
	120000	1%	0%	0%	0%	0%	0%	0%	0%	1%	1%	2%
	130000	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	2%
	140000	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%
	150000	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
	160000	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
	170000	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	180000	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	190000	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 8
LOLP for all the 11 hybrid wind + solar (single-axis tracking PV) power plants and storage scenarios.

Storage Capacity (MWh)	LOLP (%)										
	Scenario 01	Scenario 02	Scenario 03	Scenario 04	Scenario 05	Scenario 06	Scenario 07	Scenario 08	Scenario 09	Scenario 10	Scenario 11
2500	15%	11%	10%	10%	9%	10%	10%	12%	13%	14%	15%
5000	12%	10%	8%	8%	8%	9%	9%	10%	11%	12%	13%
7500	11%	9%	8%	7%	7%	8%	8%	9%	10%	11%	12%
10000	11%	9%	7%	7%	7%	7%	8%	9%	10%	11%	12%
20000	10%	8%	6%	6%	6%	6%	7%	7%	8%	9%	9%
30000	9%	7%	5%	5%	5%	5%	6%	6%	7%	8%	9%
40000	9%	7%	5%	4%	4%	4%	5%	5%	6%	7%	8%
50000	8%	6%	4%	3%	3%	3%	4%	5%	5%	6%	7%
60000	7%	5%	4%	2%	2%	2%	3%	4%	5%	6%	6%
70000	6%	4%	3%	2%	1%	1%	2%	3%	4%	5%	6%
80000	6%	4%	2%	1%	0%	1%	1%	2%	3%	4%	5%
90000	5%	3%	2%	0%	0%	0%	1%	1%	2%	3%	4%
100000	4%	2%	1%	0%	0%	0%	0%	1%	1%	2%	3%
110000	3%	2%	0%	0%	0%	0%	0%	0%	1%	2%	3%
120000	3%	1%	0%	0%	0%	0%	0%	0%	1%	1%	2%
130000	2%	1%	0%	0%	0%	0%	0%	0%	0%	1%	2%
140000	1%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%
150000	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
160000	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
170000	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
180000	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
190000	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 9
Energy produced in each scenario and the corresponding storage capacity for LOLP = 0 with fixed latitude tilt PV system.

Scenario	Generated Energy (MWh)	Storage capacity for LOLP = 0 (% of generated energy)
# 01	794,934	16%
# 02	898,638	12%
# 03	1,002,343	9%
# 04	1,106,047	6%
# 05	1,209,751	6%
# 06	1,313,456	7%
# 07	1,417,160	7%
# 08	1,520,865	8%
# 09	1,624,569	8%
# 10	1,728,274	9%
# 11	1,831,978	9%

Table 10
Energy produced in each scenario and the corresponding storage capacity for LOLP = 0 with single-axis tracking PV system.

Scenario	Generated Energy (MWh)	Storage capacity for LOLP = 0 (% of generated energy)
# 01	1,000,286	16%
# 02	1,083,455	13%
# 03	1,166,624	9%
# 04	1,249,794	7%
# 05	1,332,963	6%
# 06	1,416,132	7%
# 07	1,499,301	7%
# 08	1,582,470	7%
# 09	1,665,640	8%
# 10	1,748,809	9%
# 11	1,831,978	9%

4.2. Load supply

A load supply analysis was carried out for the 11 scenarios shown in Table 2; Fig. 9 shows the boxplots of the correlations between the normalized demand curve and the hybrid wind + solar generation profile of each scenario. The LOLP distributions are presented in Fig. 10.

For both the fixed latitude tilt and single-axis tracking PV systems, results indicate that solar generation has a higher correlation with the load curve than wind generation, which peaks at night in the Brazilian NE region. However, analyzing the results of the LOLP, it is noted that the scenarios with a higher solar fraction tend to have an average LOLP of 60%, the worst value in all scenarios. As the share of wind grows, the LOLP tends to decrease and reaches its minimum, for fixed latitude tilt PV systems, in scenario #6 (50% for each source), with an average LOLP of 18% and, for single-axis tracking PV systems, in scenario #7 (40% PV and 60% wind), with an average LOLP also of 18%. These results show that, although the correlation index is indicative of optimization, the PCC alone cannot be considered as a definitive factor for the optimization of hybrid wind + solar power plants.

Based on these results, energy storage systems were gradually added until total demand was met (LOLP = 0%) for each scenario. Tables 7 and 8 show the annual LOLP for each case, representing the impact of energy storage on the capacity of hybrid wind + solar power plants to supply the load. Tables 9 and 10 present the storage needs for each scenario as a percentage of the total energy consumed in that scenario for the fixed latitude tilt and single-axis tracking PV systems, respectively. The results presented in Table 9 show that a 40% wind and 60% solar share minimizes the storage capacity needs. In this scenario, approximately 70 GWh of storage would be necessary to fully meet the demand, which represents 6% of all energy consumed by the normalized demand. According to a recent report [46], it is expected that in 2024 the global total of first life battery systems connected to the grid will be approximately 41 GWh; and, according to [47], the electric vehicle market is expected to deploy 400 GWh of lithium-ion batteries, which can later be used in second life stationary applications such as the ones presented here [48,49]. Therefore, a total wind + solar + storage electricity mix scenario is not yet realistic. However, it is worth remembering that the PV market (cumulative installed PV capacity > 600 GWp in early 2020, and 2019 installed capacity > 120 GWp) only reached the first 1 GW of cumulative installed capacity in 2000.

4.3. Curtailment optimization

The curtailment losses resulting from each combination of storage capacity and substation size are presented in Table 11 (fixed latitude tilt PV) and Table 12 (single-axis tracking PV) for the 395 MWp (95 MW wind + 300 MWp PV) hybrid wind + solar generator.

In the single-axis tracking PV system case, the current 100 MVA substation is unable to dispatch the annual generation of the system and, therefore, even adding storage, there is a stagnation of curtailment

Table 11
Energy curtailment losses for hybrid wind + solar (fixed latitude tilt) power plant.

		Curtailment losses (%)										
		Storage Capacity (MWh)										
		0	**200**	**400**	**600**	**800**	**1000**	**1200**	**1400**	**1600**	**1800**	**2000**
Substation (MVA)	**100**	35.3%	28.5%	22.3%	17.6%	15.1%	13.9%	13.3%	12.9%	12.6%	12.3%	12.0%
	150	21.7%	14.8%	9.3%	4.9%	1.9%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%
	200	11.2%	5.1%	1.8%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	250	4.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	300	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	350	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	400	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 12
Energy curtailment losses for hybrid wind + solar (single-axis tracking) power plant.

		Curtailment losses (%)										
		Storage Capacity (MWh)										
		0	**200**	**400**	**600**	**800**	**1000**	**1200**	**1400**	**1600**	**1800**	**2000**
Substation (MVA)	**100**	42.1%	36.0%	30.4%	26.4%	24.0%	22.7%	22.0%	21.5%	21.2%	21.0%	21.7%
	150	28.6%	22.1%	16.9%	12.2%	8.2%	5.0%	2.7%	1.3%	0.8%	0.5%	0.4%
	200	17.1%	10.8%	6.6%	3.6%	1.7%	0.6%	0.1%	0.0%	0.0%	0.0%	0.0%
	250	7.7%	2.9%	1.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	300	2.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	350	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	400	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

losses at about 20%. However, the expansion of that substation's capacity by just 50 MVA resulted in about 14% curtailment losses reduction, and in this case, a storage capacity to avoid curtailment losses of around 3.4 GWh. In the fixed latitude tilt PV case, the curtailment losses profile as a function of the storage capacity and substation size is similar to the one of the single-axis tracking PV case, with a change in magnitude due to the higher capacity factor of the single-axis tracking PV system.

It is worth to note that, in all cases, the expansion of the substation had a much greater impact than the adoption of storage. However, it was not necessary to expand the substation up to the project's nominal power (395 MW), so that the energy curtailment was practically negligible, which makes it evident that the temporal complementarity of the two sources led to an optimization of the entire transmission infrastructure. It is also important to highlight that, although the expansion of the transmission infrastructure results in a larger reduction in energy curtailment, the use of energy storage systems brings other benefits to the security and operation of the grid, such as the temporal match between generation and consumption, black start, ramp smoothing and tariff arbitrage [50–52]. The results presented here show that there is room for discussion and improvements in the regulation of hybrid systems in Brazil, which currently treats hybrid projects as if the two or more complementary sources were totally independent generators and without any synergy or mutual effect. This approach generally leads to transmission system over-contracting and, consequently, to a higher energy tariff.

5. Conclusions

For the case study in in Brotas de Macaúbas - Bahia, there is a relevant temporal complementarity between the wind and solar resources and the corresponding generation profiles, with an average annual Pearson's Correlation Coefficient of −0.51, indicating that this site is highly suitable for hybrid wind + solar power plants, as also concluded in [26].

The results also showed that the combination of 40% wind and 60% solar is the optimal portfolio mix to meet the load of the Brazilian NE region. This combination is the result of two particular characteristics of the region: the increase in demand in the daytime, coinciding with the solar PV generation, which resulted in a correlation of 0.18 and 0.14 between the generation of the fixed latitude tilt PV and single-axis tracking PV systems, respectively, and the demand curve; and the predominance of wind generation in the evening and throughout the night. These results contrast with those obtained by [20] for a small off-grid island hybrid wind + solar + storage system, in which the LOLP also increases as the solar participation increases, but it decreases with the increasing wind participation, while in our results for a much larger and complex GT&D system, the optimal point is in the midway between the extreme cases.

Despite this optimization, it would still be necessary/advantageous to use energy storage systems for the temporal matching of energy generation and consumption. The optimal scenario based on minimal storage need has a 40% wind and 60% solar share, and would require only 6% of its annual generation in storage capacity. Comparing this result with others presented in the literature, this 40% wind and 60% solar share has a higher solar participation than the one obtained by Midcontinent Independent System Operator MISO region in North America, as presented in [53], which can be ascribed to the excellent match between the solar resource availability and the transmission load curve in the region.

The curtailment optimization showed that the temporal complementary nature between the resources reduces up to 11% in the hired transmission capacity and that the transmission capacity expansion has a higher impact on the curtailment compared with the addition of energy storage capacity. Therefore, there is room for discussion and improvements in the regulation of hybrid systems in Brazil, which currently treats hybrid projects as if the two or more complementary sources were totally independent generators and without any synergy or mutual effect.

In the light of the current moment of transformation of the electricity sector in Brazil and elsewhere, with a growing uptake of utility-scale wind and solar power plants, this work shows that the temporal complementary of wind and solar resources in the Brazilian Northeast is consistent and it can have a major role in the optimal portfolio design. This is not only in the load supply context, but also in the planning of the integration and expansion of the transmission system. Moreover, this works indicates that while energy storage can have a key role in the temporal matching between non-dispatchable generation and the load

supply, the transmission capacity has the main role in reducing curtailment.

CRediT authorship contribution statement

Rafael Antunes Campos: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Lucas Rafael do Nascimento:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Ricardo Rüther:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing - original draft, 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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