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The vulnerability of wind power to climate change in Brazil

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ABSTRACT

The availability and reliability of wind power depend a great deal on current and future climate conditions, which may vary in light of possible global climate change (GCC). Long-term energy planning, however, does not normally take possible future GCC into consideration, which may turn out to be a risky exercise. In the case of Brazil, the untapped wind power potential is known to be impressive, provided that climate conditions remain the same over time. The focus of this study is to analyze some possible impacts of GCC on the wind power potential of Brazil, by simulating wind conditions associated with the IPCC A2 and B2 Scenarios. Results based on the HadCM3 general circulation model and the analysis of the country's wind database indicate that the wind power potential in Brazil would not be jeopardized in the future due to possible new climate conditions. On the contrary, improved wind conditions are expected, particularly in the Northeast coast of the country. Therefore, investments in wind power generation can be an interesting way to expand renewable energy production in Brazil. However, given the large uncertainties associated with GCC models and scenarios, the findings of this paper should be viewed as a possibility rather than as a projection.

1. Introduction

The Brazilian energy sector relies heavily on renewable energy sources. Some 45% of all energy produced in the country comes from renewable energy sources. In the power sector, this reliance is even higher. Hydroelectric power plants accounted for 80% of Brazil's electric power generation in 2008 [1]. Bioenergy has also become increasingly important in the Brazilian energy sector, both for electricity generation (e.g. sugarcane bagasse) and liquid biofuels production (e.g. sugarcane ethanol).

Although not fully exploited,[1] the wind power potential in Brazil is quite impressive in certain regions of the country, such as in the Northeast coastal region and parts of the South and the Southeast [2]. Expansion of wind power generation is a possibility to increase the country's supply of electricity using renewable energy sources. Indeed, the Brazilian natural endowment has very interesting complementarities between wind and hydraulic resources in some regions of the country [3,4], which would help optimizing the operation of the National Interconnected Power System (*Sistema Interligado Nacional*–SIN).

Given the predominance of hydropower in the Brazilian power system, stabilizing the seasonal fluctuations in power supply using alternative renewable sources such as wind power may be an interesting way of minimizing the risk of shortages during critical dry periods. In fact, as stressed in [4], a promising advantage of wind power in Brazil is the hydro-wind power seasonal complementarities, which are stronger in the Northeast region. Along the coast line of the state of Ceará, [6,7] show that using wind power generation in the Northeast would optimize the regional power system, especially with respect to the hydro power plants of Sobradinho, Itaparica, and Paulo Afonso I, II, III and IV. For an achievable potential estimated as 37.9 GW (96.9 TWh/year) [4], the average levelised cost for using the whole Northeastern wind power potential would correspond to 79.37 US$/MWh.[2]

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[1] As of today, Brazil's total wind power installed capacity equals 24.7 MW [5], which is equivalent to 0.17% of the country's total estimated wind power potential of 143.5 GW [2].

[2] This value represents the average value for the best sites in the Northeast region, considering a 1500 US$/kW capital cost [4], a 14 US$/MWh operation and maintenance cost, a 10% discount rate and a 25 year life span [8]. For comparison purposes, the levelised costs of other power generating options that could supply Brazil's power grid are [9]: nuclear–113 US$/MWh; natural gas–79 US$/MWh; coal–134 US$/MWh; sugarcane bagasse–74 US$/MWh; large and medium hydropower in the Northern region–46 US$/MWh.

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The availability and reliability of renewable power sources, however, greatly depend on current and future climate conditions, which may vary in light of global climate change (GCC) related to the past, current and future emission of greenhouse gases [10]. Long-term energy planning in Brazil has not yet analyzed or assessed the possible impacts of GCC scenarios on the vulnerability of the Brazilian energy system. Therefore, the focus of this study is to analyze the impacts of GCC on wind power generation in Brazil. Parallel studies which aim at other renewable energy sources, such as hydropower generation and biomass production, have also been conducted [11] under the aegis of a broader project, which aimed at investigating the vulnerabilities of the whole Brazilian energy system to GCG [12].

The scientific literature on GCC and energy is very much focused on the role of energy consumption as a source of greenhouse gases emissions. Work on the impacts of GCC on energy production and consumption, however, is very incipient and a formal knowledge base is limited [13]. Nevertheless, few studies have attempted to cover such issue. In the case of wind power, a case study for Brazil was conducted by [12], which is revised in this paper. Other studies on impacts of GCC on wind power production include [14] and [15]. Finally, Pryor and Barthelmie [16] made a review on climate impacts assessments on wind energy.

The impacts of GCC on wind power are assessed by simulating future scenarios for the country's gross wind power potential, taking into account climate projections based on the A2 and B2 emission scenarios of the IPCC Special Report on Emission Scenarios [17–19]. In order to accomplish this objective, this paper is organized as follows: the next section discusses the database used; Section 3 presents the methodology deployed; Section 4 shows the results obtained; and, finally, Section 5 concludes the paper.

2. Database

The climate projections used in this study are based on the emission and concentration levels of two IPCC scenario (A2, high emissions, and B2, low emissions). They are two of four qualitative storylines characterized by different economic and energy development paths. They describe divergent futures in an attempt to cover a significant portion of the underlying uncertainties in the key driving forces for the emission of greenhouse gases [17].

The A2 scenario (pessimistic, high emission) describes a heterogeneous world, where regional oriented economic development is emphasized. In this scenario, there is less emphasis on economic, social, and cultural interactions between regions, which become more self-reliant and tend to preserve the local identities. Also, per capita economic growth and technological change are uneven and slow, which do not help to narrow down the gap between non-industrialized and developing parts of the world. Final energy intensities in the A2 scenario decline with a pace of 0.5–0.7% per year over time [17].

In the B2 scenario (optimistic, low emission), there is an increased concern for environmental and social sustainability at the national and local levels. This scenario presents a world with continuously increasing global population at a rate lower than that of A2, intermediate levels of economic development and also more regionally heterogeneous technological innovations. The final energy intensity of the B2 scenario declines at about 1% per year, in line with the average historical experience since 1800 [17].

The A2 and B2 IPCC emission scenarios were used because they were dynamically downscaled into regional climate projections for Brazil by a team of Brazilian climate specialists from CPTEC/INPE, using the PRECIS (Providing Regional Climates for Impacts Studies) model. This is a regional climate model developed by the Hadley Centre, which downscales the results of the HadCM3 general circulation model (GCM).[3]

Two time slices are used in this study. One for the present climate conditions (1961–1990), denominated *Baseline*, and one for the 2071–2100 period, for both the A2 and B2 scenarios. The *Baseline* is a simulation of the current climate using the Regional Climate Model, not necessarily being equivalent to the historical data,[4] and it is used as the climate model's reference for the current climate conditions. The scenario projections (A2 and B2) were compared to the *Baseline* in an attempt to eliminate possible climate model biases.

The future technical wind potential[5] simulation is then based on the estimated figures of the PRECIS model [18,19], which provides the average annual wind velocity in squares of 50 km $\times$ 50 km for the time slices considered. The available data do not include the roughness or the shape and scale parameters of the Weibull distribution,[6] which would be necessary for a more precise analysis. Nor is the annual standard deviation of the wind velocities provided by the climate simulations, which is an important factor for estimating the wind power generation of a given installed capacity.

Climate models are representations of very complex systems. The level of uncertainty about the impacts of the concentration of greenhouse gases on the global climate (GCM), and on the Brazilian climate in particular (regional climate model) becomes evident when comparing the results of different GCMs [21]. The estimated impacts of global climate change on the Brazilian wind power potential presented in this paper are intrinsically dependent on the climate projections adopted. Besides the uncertainties of the emission scenarios, there are uncertainties related to the global climate model and to the downscaling of its results to the regional climate model. In such a long-term scenario analysis, the trends and directions should be emphasized, rather than precise results, given the cumulative uncertainties in such a study. Nevertheless, this study is an important contribution as to what are the likely vulnerabilities, and uncertainties, to which the Brazilian energy system can be exposed in a long-term global climate change scenario.

3. Methodology

In this study, a simple approach called the "delta method" [28,29] was used. It consists of applying the variation between the simulated GCM results for current and future climate conditions to the historical values of a certain climatic variable. Although this approach has been widely used in GCC impact studies [30–33] due to its simplicity it is limited for not considering variations in the relationship between climate variables at the large and small scale. On the other hand, this approach has the benefit of minimizing

[3] The lateral boundary conditions for the PRECIS model is given by the global atmosphere general circulation model HadAM3P, which constitutes the atmospheric component of the ocean-atmosphere global climate model HadCM3, forced with sea surface temperature anomalies [20]. For more detailed information on the methodological aspects of the PRECIS model, see [20,21,22].

[4] It is crucial to adjust the Baseline data to current climate conditions so as to minimize the model's error. In a previous study [12], the comparison of the global climate scenarios to historical data led to results distinct from the ones obtained here.

[5] Technical potential refers to total wind resources and their exploitation assuming a set of technological premises. Other variables, such as area restrictions and competition with other land uses, impact the share of this potential that may actually be exploited.

[6] The Weibull distribution is a widely used statistical distribution to analyze the behavior of wind velocities [23–27].

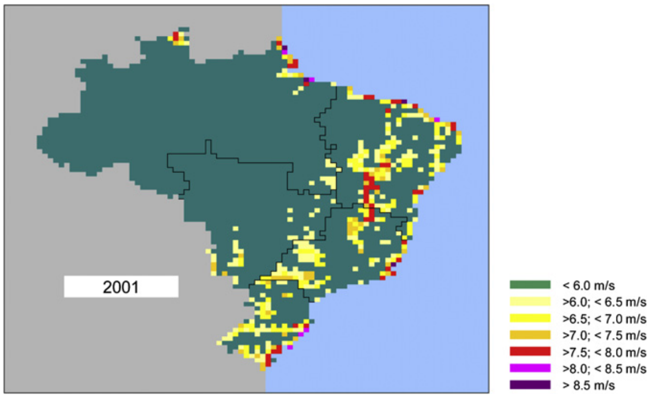

Fig. 1. Average Annual Wind Velocity: 2001 (elaboration from [2]).

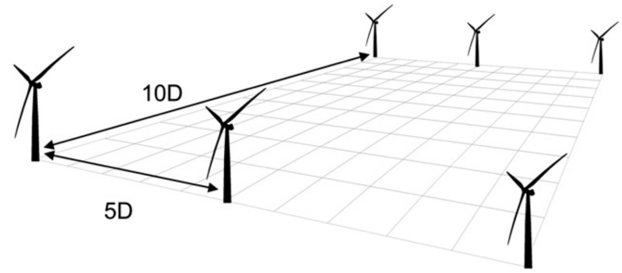

Fig. 2. Configuration "5D × 10D"–Wind Turbine Arrangement.

some of the GCM errors, assuming that the GCM bias for future and current climate conditions is the same.

Therefore, the Brazilian Wind Power Potential Map, developed by CEPEL [2],[7] was revised in light of the variations in the average wind velocities projected for the A2 and B2 GCC scenarios in relation to the *Baseline* simulations. Firstly, then, the Brazilian Wind Power Potential Map had to be brought to the same spatial scale of the climate projections (Fig. 1). This was done by taking average values for each 50 km × 50 km area in [2], which provided the reference values onto which the variations in wind velocities between the *Baseline* and the two climate change scenarios were applied.

The wind velocities projected by the climate model refer to the velocity at a 10 m height, which is below that of a typical commercial wind turbine. The relationship between height and wind velocity can be approximated by a logarithmic rule [7], in which roughness is one of the key parameters. Since roughness depends greatly on the vegetation cover, which is also susceptible to climatic impacts [34], the distribution of wind velocities according to height can also be affected by GCC. In this study, the projected average wind velocities variations were applied to those of the current wind power potential map [2]. This means that it is assumed here that no changes in vegetation cover occur during the period of time examined in this study when extrapolating the wind velocity to a hub height of 50 m [2] using the logarithmic rule.

Moreover, since the projected variations in average wind velocities due to GCC were applied to the estimated historical velocities, all the premises used in translating those estimates into power generation potential by [2] were also kept the same in this study. Generally speaking, the wind power potential results from the integration of the useful areas in a Geographical Information System (GIS) model. This model basically crosses georeferenced wind velocity information with restrictions–such as wind cut-off speed, existence of natural reserves or rivers, lakes and sea–to select the areas suitable for wind power generation (occurrences). This first estimate is the technical wind power potential. Restrictions related to more precise information about each area[8] cannot be fully inserted in the simulation. Therefore, it is assumed, as in [2], that only a share of 20% of the gross wind power potential can be commercially explored.

Following the premises of [2], the power that can be installed in each occurrence was estimated using a "5D × 10D" arrangement for wind turbines (Fig. 2), where "D" is the diameter of the rotor area of the turbine. In this arrangement, the rate of occupation of the adopted standard turbines of 500 kW[9] is 2 MW/km^2. Therefore, in each occurrence (50 km × 50 km = 2500 km^2), assuming the 20% exploitable share, the power installed is equal to: 2 MW/km^2 × 2500 km^2 × 0.2 = 1 GW. So, the total national wind power potential[10] is calculated by multiplying this value by the number of occurrences.

The amount of electricity generated by this potential is, in turn, a function of: the power curve of the wind turbine, which depicts the wind turbine power generation as a function of the wind speed; and the wind shear or the wind velocity distributions, which are usually estimated using the Weibull probability distribution function. Although the first is a turbine's technical parameter, which can be easily obtained, the second is a stochastic parameter, for which climate projections do not have information about. In fact, only the wind velocities are available from climate projections used in this study, which deeply limited the analysis. Therefore, it was necessary to assume that the amount of electricity produced by wind turbines, given an average wind velocity at each occurrence, is the same throughout time. Hence, the only parameter altered in the probability density function was the average wind velocity, so that the capacity factor[11] estimated in [2] for a given wind velocity range and region is the same throughout the analysis. Although this is a strong assumption, it was necessary given the lack of more detailed data from the climate projections.

4. Results

Fig. 1 presented a map of the historical average wind velocities estimated for 2001 by [2] at the same scale as the climate projections (50 km × 50 km). Figs. 3 and 4 show the variation in wind

[7] The Electric Power Research Center (CEPEL) pursued the elaboration of the Atlas of Brazil's Wind Power Potential, contracting different enterprises and using the so-called MesoMap System [4]. This system is a set of integrated models for simulating atmospheric conditions, applying data on meteorology and geography. It is suitable for large continental areas without fine and reliable data of wind profiles coming from anemometric sensors (this is the case of Mid-west and North regions of Brazil). It models meteorological phenomena, including: orographic waves, convective wind, sea or lake breeze, thermal breezes from mountains etc. According to the Brazilian Wind Potential Atlas [2], Brazil's wind power technical potential reaches the figure of 143,470 MW. In this report, it is assumed that the potential wind power capacity covers only areas with average annual wind speeds above 7.0 m/s, with turbines installed on towers fifty meters high, a land occupancy rate of 2 MW/km^2 and does not include any offshore potential.

[8] Other variables, such as different land uses, can affect the share of the gross potential that can be actually exploited.

[9] As of today, Brazil already uses larger turbines (in the range of 2 MW). Although the future exploitation of the Brazilian wind power potential should be based on more advanced technologies, this parameter was kept constant for the purpose of conducting a *ceteris paribus* analysis.

[10] Defined as the total maximum wind generation capacity that could be installed in the country for the adopted premises.

[11] Capacity factor refers to the ratio of the energy actually produced to the total energy that would be produced if the turbine generate at full power the whole time.

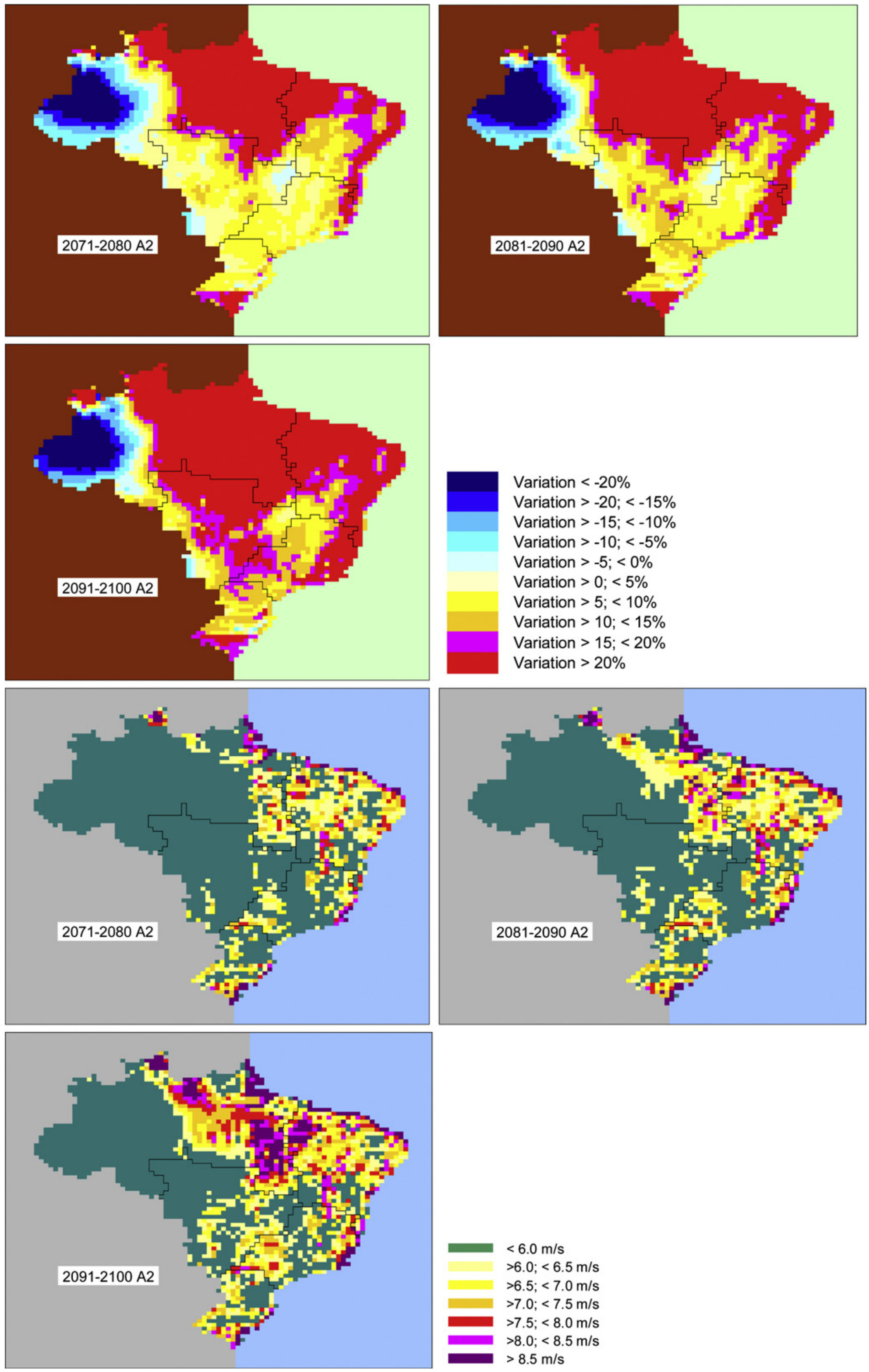

Fig. 3. Variation in average wind velocities in relation to *Baseline* and new projected average wind velocities: Scenario A2.

velocities between the *Baseline* and the A2 and B2 climate scenarios, respectively, as well as the results of the application of those variations on the current wind velocities presented in Fig. 1. Tables 1 and 2 present the total estimated power, capacity factor and amount of energy generated per region for each scenario.

According to these results, the climate projections show that the average wind velocities would increase considerably in the coastal regions in general and in the north/northeast regions of the country in particular. In the coastal regions, the exploitation of the wind power potential becomes very attractive not only because of high

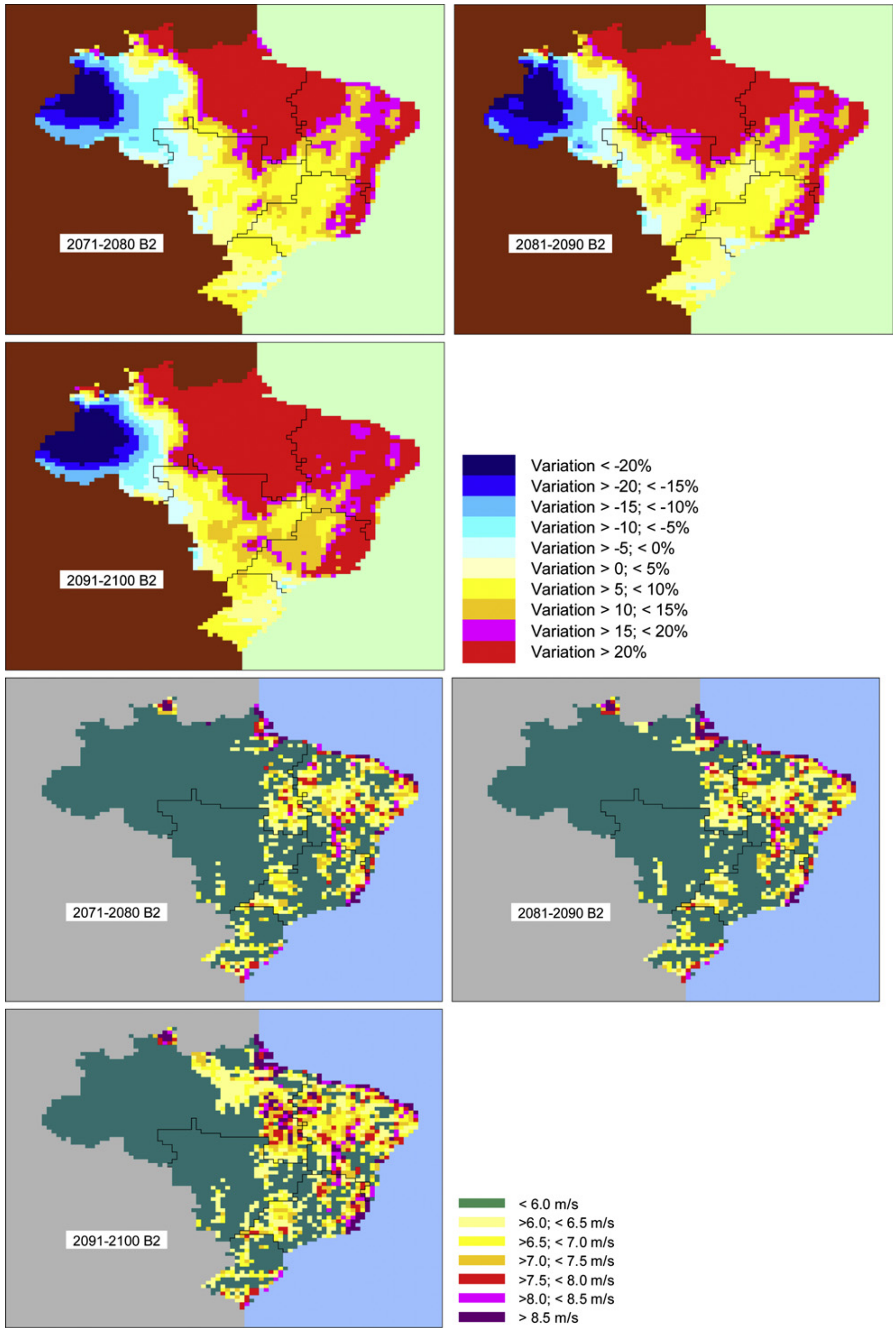

Fig. 4. Variation in average wind velocities in relation to *Baseline* and new projected average wind velocities: Scenario B2.

wind speeds, but also because of the proximity to large consumer centres, thus entailing in lower transmission costs and losses.[12] In this sense, there is also room for offshore wind power generation, although this option is still more costly, which should be further investigated in future studies. As a matter of fact, in the coastal areas the climate projections show a higher number of occurrences of high wind velocities (above 8.5 m/s), raising the possibility of including different turbine designs that can generate more power at higher wind velocities in future analyses.

Given the greater occurrence of high average wind velocities, the aggregated capacity factor for each region and for the country as a whole increase, according to the results of the climate models. This means that, for a given installed capacity, a greater amount of energy could be generated. The results based on the climate projections show that the Brazilian wind power generation potential could have a threefold increase in the B2 scenario and

[12] There are, also, logistical advantages in exploiting the Brazilian coastal wind potential, since the poor quality of the roads and the absence of other means of transportation make the transportation of high capacity turbines across the country very costly [4].

Table 1
Brazilian wind potential: scenario A2.

Region	Average velocity m/s	2001 [2]				A2-2071–2080				A2 – 2081–2090				A2 – 2091–2100			
		Number of occurrences	Capacity factor	Power (GW)	Energy (TWh)	Number of occurrences	Capacity Factor	Power (GW)	Energy (TWh)	Number of occurrences	Capacity factor	Powe (GW)r	Energy (TWh)	Number of occurrences	Capacity Factor	Power (GW)	Energy (TWh)
North	<6.0	1216	–	–	–	1050	–	–	–	908	–	–	–	706	–	–	–
North	6.0–6.5	19	13.0%	19	21.6	90	13.0%	90	102.5	121	13.0%	121	137.8	88	13.0%	88	100.2
North	6.5–7.0	5	17.0%	5	7.4	41	17.0%	41	61.1	100	17.0%	100	148.9	97	17.0%	97	144.5
North	7.0–7.5	7	20.0%	7	12.3	21	20.0%	21	36.8	42	20.0%	42	73.6	108	20.0%	108	189.2
North	7.5–8.0	7	25.0%	7	15.3	20	25.0%	20	43.8	18	25.0%	18	39.4	86	25.0%	86	188.3
North	8.0–8.5	2	30.0%	2	5.3	13	30.0%	13	34.2	26	30.0%	26	68.3	55	30.0%	55	144.5
North	>8.5	2	35.0%	2	6.1	23	35.0%	23	70.5	43	35.0%	43	131.8	118	35.0%	118	361.8
North – total	>6.0	42	18.5%	42	68.1	208	19.1%	208	348.8	350	19.6%	350	599.9	552	23.3%	552	1128.6
Northeast	<6.0	356	–	–	–	156	–	–	–	112	–	–	–	87	–	–	–
Northeast	6.0–6.5	57	13.0%	57	64.9	126	13.0%	126	143.5	118	13.0%	118	134.4	66	13.0%	66	75.2
Northeast	6.5–7.0	54	17.0%	54	80.4	89	17.0%	89	132.5	98	17.0%	98	145.9	127	17.0%	127	189.1
Northeast	7.0–7.5	17	20.0%	17	29.8	59	20.0%	59	103.4	68	20.0%	68	119.1	75	20.0%	75	131.4
Northeast	7.5–8.0	23	25.0%	23	50.4	46	25.0%	46	100.7	54	25.0%	54	118.3	58	25.0%	58	127.0
Northeast	8.0–8.5	1	30.0%	1	2.6	15	30.0%	15	39.4	31	30.0%	31	81.5	48	30.0%	48	126.1
Northeast	>8.5	1	35.0%	1	3.1	18	35.0%	18	55.2	28	35.0%	28	85.8	48	35.0%	48	147.2
Northeast – total	>6.0	153	17.2%	153	231.2	353	18.6%	353	574.7	397	19.7%	397	685.0	422	21.5%	422	796.0
Center-West	<6.0	503	–	–	–	503	–	–	–	472	–	–	–	380	–	–	–
Center-West	6.0–6.5	26	13.0%	26	29.6	20	13.0%	20	22.8	47	13.0%	47	53.5	92	13.0%	92	104.8
Center-West	6.5–7.0	2	17.0%	2	3.0	11	17.0%	11	16.4	15	17.0%	15	22.3	45	17.0%	45	67.0
Center-West	7.0–7.5	4	20.0%	4	7.0	1	20.0%	1	1.8	1	20.0%	1	1.8	13	20.0%	13	22.8
Center-West	7.5–8.0	0	25.0%	0	0.0	0	25.0%	0	0.0	0	25.0%	0	0.0	4	25.0%	4	8.8
Center-West	8.0–8.5	0	30.0%	0	0.0	0	30.0%	0	0.0	0	30.0%	0	0.0	1	30.0%	1	2.6
Center-West	>8.5	0	35.0%	0	0.0	0	35.0%	0	0.0	0	35.0%	0	0.0	0	35.0%	0	0.0
Center-West – total	>6.0	32	14.1%	32	39.6	32	14.6%	32	40.9	63	14.1%	63	77.6	155	15.2%	155	205.9
Southeast	<6.0	219	–	–	–	193	–	–	–	166	–	–	–	118	–	–	–
Southeast	6.0–6.5	44	13.0%	44	50.1	52	13.0%	52	59.2	52	13.0%	52	59.2	62	13.0%	62	70.6
Southeast	6.5–7.0	33	17.0%	33	49.1	41	17.0%	41	61.1	41	17.0%	41	61.1	55	17.0%	55	81.9
Southeast	7.0–7.5	18	20.0%	18	31.5	19	20.0%	19	33.3	36	20.0%	36	63.1	44	20.0%	44	77.1
Southeast	7.5–8.0	9	25.0%	9	19.7	8	25.0%	8	17.5	12	25.0%	12	26.3	23	25.0%	23	50.4
Southeast	8.0–8.5	0	30.0%	0	0.0	7	30.0%	7	18.4	8	30.0%	8	21.0	8	30.0%	8	21.0
Southeast	>8.5	1	35.0%	1	3.1	4	35.0%	4	12.3	9	35.0%	9	27.6	14	35.0%	14	42.9
southeast – total	>6.0	105	16.7%	105	153.6	131	17.6%	131	201.7	158	18.7%	158	258.2	206	19.1%	206	343.9
South	<6.0	119	–	–	–	99	–	–	–	88	–	–	–	75	–	–	–
South	6.0–6.5	32	13.0%	32	36.4	28	13.0%	28	31.9	33	13.0%	33	37.6	38	13.0%	38	43.3
South	6.5–7.0	29	17.0%	29	43.2	34	17.0%	34	50.6	32	17.0%	32	47.7	37	17.0%	37	55.1
South	7.0–7.5	11	20.0%	11	19.3	19	20.0%	19	33.3	25	20.0%	25	43.8	25	20.0%	25	43.8
South	7.5–8.0	8	25.0%	8	17.5	7	25.0%	7	15.3	9	25.0%	9	19.7	10	25.0%	10	21.9
South	8.0–8.5	3	30.0%	3	7.9	2	30.0%	2	5.3	2	30.0%	2	5.3	7	30.0%	7	18.4
South	>8.5	0	35.0%	0	0.0	13	35.0%	13	39.9	13	35.0%	13	39.9	10	35.0%	10	30.7
South – total	>6.0	83	17.1%	83	124.3	103	19.5%	103	176.3	114	19.4%	114	193.9	127	19.2%	127	213.1
Brazil – total		415.0	17.0%	415.0	616.7	827.0	18.5%	827.0	1342.5	1082.0	19.1%	1082.0	1814.6	1462.0	21.0%	1462.0	2687.6

Note: Wind velocity at hub height (50 m [2])

Table 2
Brazilian wind potential: scenario B2.

Region	Average Velocity m/s	2001 [2]				B2 – 2071–2080				B2 – 2081–2090				B2 – 2091–2100			
		Number of occurrences	Capacity factor	Power (GW)	Energy (TWh)	Number of occurrences	Capacity factor	Power (GW)	Energy (TWh)	Number of occurrences	Capacity factor	Power (GW)	Energy (TWh)	Number of occurrences	Capacity factor	Power (GW)	Energy (TWh)
North	< 6.0	1216	–	–	–	1095	–	–	–	1059	–	–	–	907	–	–	–
North	6.0–6.5	19	13.0%	19	21.6	56	13.0%	56	63.8	91	13.0%	91	103.6	127	13.0%	127	144.6
North	6.5–7.0	5	17.0%	5	7.4	45	17.0%	45	67.0	36	17.0%	36	53.6	72	17.0%	72	107.2
North	7.0–7.5	7	20.0%	7	12.3	18	20.0%	18	31.5	18	20.0%	18	31.5	56	20.0%	56	98.1
North	7.5–8.0	7	25.0%	7	15.3	17	25.0%	17	37.2	19	25.0%	19	41.6	31	25.0%	31	67.9
North	8.0–8.5	2	30.0%	2	5.3	7	30.0%	7	18.4	5	30.0%	5	13.1	14	30.0%	14	36.8
North	> 8.5	2	35.0%	2	6.1	20	35.0%	20	61.3	30	35.0%	30	92.0	51	35.0%	51	156.4
North – total	>6.0	42	18.5%	42	68.1	163	19.6%	163	279.3	199	19.2%	199	335.5	351	19.9%	351	611.0
Northeast	< 6.0	356	–	–	–	176	–	–	–	162	–	–	–	99	–	–	–
Northeast	6.0–6.5	57	13.0%	57	64.9	110	13.0%	110	125.3	115	13.0%	115	131.0	93	13.0%	93	105.9
Northeast	6.5–7.0	54	17.0%	54	80.4	88	17.0%	88	131.0	91	17.0%	91	135.5	121	17.0%	121	180.2
Northeast	7.0–7.5	17	20.0%	17	29.8	55	20.0%	55	96.4	57	20.0%	57	99.9	78	20.0%	78	136.7
Northeast	7.5–8.0	23	25.0%	23	50.4	41	25.0%	41	89.8	46	25.0%	46	100.7	49	25.0%	49	107.3
Northeast	8.0–8.5	1	30.0%	1	2.6	24	30.0%	24	63.1	20	30.0%	20	52.6	33	30.0%	33	86.7
Northeast	> 8.5	1	35.0%	1	3.1	15	35.0%	15	46.0	18	35.0%	18	55.2	36	35.0%	36	110.4
Northeast – total	>6.0	153	17.2%	153	231.2	333	18.9%	333	551.5	347	18.9%	347	574.8	410	20.2%	410	727.2
Center-West	< 6.0	503	–	–	–	493	–	–	–	494	–	–	–	456	–	–	–
Center-West	6.0–6.5	26	13.0%	26	29.6	29	13.0%	29	33.0	30	13.0%	30	34.2	58	13.0%	58	66.1
Center-West	6.5–7.0	2	17.0%	2	3.0	12	17.0%	12	17.9	10	17.0%	10	14.9	16	17.0%	16	23.8
Center-West	7.0–7.5	4	20.0%	4	7.0	1	20.0%	1	1.8	1	20.0%	1	1.8	5	20.0%	5	8.8
Center-West	7.5–8.0	0	25.0%	0	0.0	0	25.0%	0	0.0	0	25.0%	0	0.0	0	25.0%	0	0.0
Center-West	8.0–8.5	0	30.0%	0	0.0	0	30.0%	0	0.0	0	30.0%	0	0.0	0	30.0%	0	0.0
Center-West	> 8.5	0	35.0%	0	0.0	0	35.0%	0	0.0	0	35.0%	0	0.0	0	35.0%	0	0.0
Center-West – total	>6.0	32	14.1%	32	39.6	42	14.3%	42	52.6	41	14.1%	41	50.8	79	14.3%	79	98.6
Southeast	< 6.0	219	–	–	–	180	–	–	–	182	–	–	–	122	–	–	–
Southeast	6.0–6.5	44	13.0%	44	50.1	47	13.0%	47	53.5	55	13.0%	55	62.6	73	13.0%	73	83.1
Southeast	6.5–7.0	33	17.0%	33	49.1	46	17.0%	46	68.5	40	17.0%	40	59.6	45	17.0%	45	67.0
Southeast	7.0–7.5	18	20.0%	18	31.5	30	20.0%	30	52.6	26	20.0%	26	45.6	39	20.0%	39	68.3
Southeast	7.5–8.0	9	25.0%	9	19.7	7	25.0%	7	15.3	8	25.0%	8	17.5	18	25.0%	18	39.4
Southeast	8.0–8.5	0	30.0%	0	0.0	6	30.0%	6	15.8	4	30.0%	4	10.5	10	30.0%	10	26.3
Southeast	> 8.5	1	35.0%	1	3.1	8	35.0%	8	24.5	9	35.0%	9	27.6	17	35.0%	17	52.1
Southeast – total	>6.0	105	16.7%	105	153.6	144	18.3%	144	230.2	142	18.0%	142	223.4	202	19.0%	202	336.3
South	<6.0	119	–	–	–	115	–	–	–	119	–	–	–	111	111	–	–
South	6.0–6.5	32	13.0%	32	36.4	34	13.0%	34	38.7	33	13.0%	33	37.6	36	13.0%	36	41.0
South	6.5–7.0	29	17.0%	29	43.2	30	17.0%	30	44.7	28	17.0%	28	41.7	29	17.0%	29	43.2
South	7.0–7.5	11	20.0%	11	19.3	9	20.0%	9	15.8	8	20.0%	8	14.0	10	20.0%	10	17.5
South	7.5–8.0	8	25.0%	8	17.5	8	25.0%	8	17.5	9	25.0%	9	19.7	11	25.0%	11	24.1
South	8.0–8.5	3	30.0%	3	7.9	6	30.0%	6	15.8	5	30.0%	5	13.1	5	30.0%	5	13.1
South	>8.5	0	35.0%	0	0.0	0	35.0%	0	0.0	0	35.0%	0	0.0	0	35.0%	0	0.0
South – total	>6.0	83	17.1%	83	124.3	87	17.4%	87	132.5	83	17.3%	83	126.1	91	17.4%	91	138.9
Brazil – total		415.0	17.0%	415.0	616.7	769.0	18.5%	769.0	1246.1	812.0	18.4%	812.0	1310.7	1133.0	19.3%	1133.0	1912.0

Note: Wind velocity at hub height (50 m [2]) a four-fold increase in the A2 scenario as compared to the reference situation of today. However, these results are not determinative, given the uncertainties in the climate projections and in the assumptions made in this study. Instead, it shows that the set of climate projections used in this study (the HadCM3 results) indicates that wind power generation in Brazil should not be jeopardized by GCC.

Previous studies [12] for Brazil arrived at distinct results, since they did not adjust the *Baseline* to the historical data. This is specifically relevant for the case of the São Francisco River Basin, where there were significant discrepancies between the historical data and the *Baseline* simulation. This, once more, call the attention for the uncertainties associated with studies based on long-term climate projections. In this sense, comparing the climate projections to the *Baseline* and applying that over a more solid set of data based on historical values, as given by [2], was a way to isolate some possible GCM biases.

The above results were calculated using the current vegetation cover of the Brazilian surface. Changes in the vegetation cover may cause significant impacts on wind velocities, as they are affected by the friction against the surface of the earth. Indeed, the wind shear at different heights is very much influenced by the roughness of the terrain [4]. Alterations in the vegetation cover may affect wind velocities at lower and higher heights, such as those of the wind turbine's tower. GCC may, indeed, have a significant impact on ecosystems, which may not be able to adapt completely to a new climate condition. Additionally, human interference by deforestation and changes in land use may contribute to an even faster alteration of these ecosystems [34].

Projections of the potential biomes for the 2070–2099 period using the results of different global climate models[13] [34] show a substitution of more humid biomes (such as tropical forests) towards those adapted to a lower availability of water, such as savannahs, deserts and semi-deserts. Basically, higher temperatures would cause alterations in the water cycle by increasing the evapotranspiration, which would, in turn, reduce the quantity of water available to plants.

The potential vegetation projections of [34], however, are based on the same climate projections used in this study. The impacts that changes in vegetation might have on the climate projections (especially wind velocity) do not feedback the climate model used here.[14] In other words, the wind speed with the new vegetation cover may differ from the initial climate projections.

In this sense, the results for the Brazilian wind power generation potential are limited by not including any possible changes in the vegetation cover. These changes should have been previously accounted for in the projections if they were to be used in an analysis like this one. However, since this is not the case, it is important that, in the future, this variable be included in the analysis.

5. Final remarks

The climate projections for the IPCC GCC scenarios of the HadCM3 model used in this study [18,19] indicate that the wind power generation potential in Brazil will probably not be negatively impacted by GCC. On the contrary, the results show an increase in the wind potential in Brazil over time as a consequence of GCC.

Therefore, although wind power can be vulnerable to GCC, results from this study give evidence that the exploration of the Brazilian wind power potential may be a good alternative for expanding renewable energy production in the country. In this sense, the exploration of the wind power potential in the coastal regions, particularly in the Northeast, seems to be the best alternative not only because of the model's results, but also because of its current economic attractiveness.

Moreover, given higher wind velocities in the north-northeast coast of Brazil in the future climate change scenarios, the exploitation of the offshore wind power generation potential may be a valuable opportunity for the Brazilian power sector. Although offshore wind power technologies have higher transport, installation and maintenance costs [4], they may become a viable option as on-shore potential becomes more scarce as a result of environmental restrictions and competition with other land uses. This is an interesting topic for future analysis.

Besides the uncertainties related to climate modelling, there are limitations of the quantitative results of this study related to the assumptions made to overcome the absence of more detailed data and to some technological assumptions made here. Therefore, this study endeavoured to make a *ceteris paribus* analysis, on which trends and directions should be more emphasized rather than precise results.

It should also be noted that the results of this paper depend fundamentally on the quality of the climate projections on which it is based, further raising the need for caution in interpreting the results portrayed here. Improvements could be made, given the lack of consensus on the results of different GCMs, through a more thorough analysis, including wind projections from different global and regional models. This could help coping with some of the uncertainties related to studies such as this one, and add useful information about the vulnerability of renewable energy production to GCC.

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