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Combing windpower and hydropower to decrease seasonal and inter-annual availability of renewable energy sources in Brazil

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Abstract – Short

A high share of Brazilian power production comes from hydropower sources. A further expansion of power generation is necessary due to high growth rates in electricity demand. As an alternative to carbon intensive thermal power production and the expansion of hydropower in the ecologically and socially sensitive North of Brazil, windpower production could help to cover increasing levels of demand. Variability of wind is however often considered a major obstacle for further expansion. We assess the variability of potential windpower production in the four most important windpower producing states Ceará (CE), Rio Grande do Norte (RN), Bahia (BA) and Rio Grande do Sul (RS). Instead of focusing on hourly or sub-hourly variability, we assess the seasonality and inter-annual variability. This is important as hydropower production shows strong seasonality in Brazil and as inter-annual variation of hydropower production is high. We generate and validate time series of windpower production from wind speeds derived from measurements and two global climate models (NCAR reanalysis and ECMWF reanalysis). Our results show that seasonal variability of windpower generation in the North-Eastern states is anticyclical to hydrological seasonality in the South-East, North-East, and North of Brazil. Inter-annual variability is lower for windpower production than for hydro inflows. No consistent inter-annual relationship between the two sources of renewable energy can be found with the exemption of the state of Ceará which shows low positive correlation with hydro inflows. This indicates that although integrating windpower into the system may cause electrical problems due to very short term variability, seasonal and inter-annual variability is considerably decreased if windpower expansion is favoured instead of hydropower. Our results also show that ECMWF data may be the best source of long-term wind timeseries as it is better able to reproduce ground measurements than NCAR.

Keywords: Windpower, Brazil, Seasonality, Inter-annual variability

1 INTRODUCTION

Electricity consumption in Brazil has risen by around 4% annually in the decade 2004-2013 and is projected to continue increasing rapidly by around 4.7% annually, driven by population and economic growth. An expansion of the Brazilian electricity generation capacity is therefore of importance, even when assuming that rigorous energy efficiency measures will take place [1]. Historically, Brazil relies on a very high share of hydropower production: in the decade 2004-2013 between 69% and 84% of electricity production came from hydropower sources [2]. Recently, windpower also entered the production matrix due to significant wind resources, principally in the North-East and South Region of the country. 20 GW of new hydropower capacity have been contracted and are partly under construction in the North of Brazil and a further expansion of 17 GW of hydropower is planned up to 2022. These projects are all placed in the region of the Amazon forest and may seriously affect local populations and also have negative impacts on the ecosystems in place [3], [4]. Relying on power generation from hydro production also increases operational complexity as seasonality of rainfall is very high in Brazil. The risk of loss of load or the need for the dispatch of very expensive backup thermal power production capacities due to hydrological variability would therefore increase – particularly as most new projects will not include storage opportunities [1]. Additionally, the expansion of hydropower in the Amazon may change the local climate in a way that the projected production levels are not attained, thus making the projects economically less viable [5]. For this reason, Brazil is planning to concurrently increase its thermal power production capacities by 5 GW, which will also increase Brazil's greenhouse gas emissions as expansion is based mainly on natural gas. From 2020 on the energy sector may therefore become the most important emitter of greenhouse gases in Brazil, replacing land use which shows decreasing emissions due to successful measures against deforestation. Brazil will show increasing trends in total emissions due to emission from energy by then [6].

An alternative to this expansion path is the much faster expansion of new, intermittent renewable sources, particular wind in the case of Brazil. Windpower production has seen high growth rates in recent years due to good wind resources in parts of the country, thus being able to economically compete with thermal power production [1]. Besides relative low costs, the advantages may be twofold: first, deployment of those technologies can occur close to the coast, thus reducing the impacts in the delicate ecosystem of the Amazon region[1]. And second, windpower may add a positive portfolio effect to the Brazilian renewable production portfolio, thus reducing the risks of long-term droughts in the current hydropower dominated power regime. However, intermittent production obviously has drawbacks as it cannot be dispatched on demand and there is, unlike to hydropower, no direct possibility of storage. The very short-term intermittency in terms of minutely or hourly ramping in production due to changes in wind speed is the focus of most of the research that deals with integration of renewables [8]–[12] as this kind of intermittency causes problems in the transmission grid and increases the need for quickly ramping backup capacities. Nevertheless, there are also longer-term issues that have to be regarded: wind regimes may have the same or a different seasonality than hydropower inflows. And inter-annual variation between the sources may be positively or negatively correlated. As the time-profile of production regimes may vary significantly from location to location for wind

[1] Wind resources are less concentrated than hydro power resources, simplifying finding non-conflictive locations. However, there are reports that windpower farms have been placed in ecologically and socially sensitive areas in the past in Brazil. This, however, may be prevented when deploying turbines at similar, less conflictive sites near by [7].

power in a large country as Brazil, this may allow choosing those sites where productivity of renewables is not only high but where it also best fits into the time profile of residual demand, i.e. electricity demand reduced by hydropower production [13].

Substantial research on this issue has been conducted in Brazil before, particularly on the seasonality of wind resources. Lopes and Borges [14] have shown that the electrical grid imposes significant restrictions on the amount of windpower that can be integrated into the system of the Southern Brazilian state of Rio Grande do Sul. Others, using simulated windpower production data, have shown that windpower and hydropower production are seasonally complementary, in particular between hydropower production in the North and Southeast regions and windpower production in the North East [15]–[17]: due to the climate regime in place, hydroinflows in these regions are higher in the first half of the year for most rivers while windpower production is higher in the second half of the year in the North East. However, there is only weak evidence on how windpower production may be correlated with hydropower inflows when removing seasonality and focusing on inter-annual variation. A low or even negative correlation would imply that expansion of windpower instead of hydropower could lower inter-annual variability of the availability of renewable resources. Chade Ricosti and Sauer [18] used modelled time series of windpower production derived from the NCEP/NCAR Reanalysis project [19] to assess long-term complementarity between North-Eastern wind and hydrological regimes. They show weak long-term complementarity between wind and hydropower production, i.e. windpower production seems to be higher in years of low precipitation in the relevant river basins. However, the authors do not apply thorough statistical tools for this purpose. Bezerra et al. [17] use the same dataset to investigate inter-annual complementarity. They find no evidence for a systematic relationship between hydro inflows and availability of wind. They do not use statistical testing in their analysis. Additionally, globally modeled data-sets may not contain a very good representation of some of the estimated parameters, in particular wind speeds and validation of the data set is therefore of high importance. Data quality issues, however, were not addressed by Chade Ricosti and Sauer [18], nor by Bezerra et al. [17].

We aim at assessing the seasonality of windpower and the correlation of deseasonalized windpower simulations with hydropower production to allow an assessment of multi-annual effects of adding larger shares of windpower to the Brazilian power system in comparison to expanding hydropower. We focus on assessing potential windpower production in the four most important windpower producing states in Brazil, i.e. Bahia (BA), Ceará (CE), Rio Grande do Norte (RN), and Rio Grande do Sul (RS). While long-term time series of hydro inflows into hydropower plants are available since 1931, production time series from windpower plants are only available since 2006. For the first time, we therefore combine different data sets from ground measurements, and globally modelled time series from two climate reanalysis projects – the NCAR/RCEP reanalysis [19] and the ECMWF interim reanalysis [20] - to come up with simulated time series of windpower production. The data sets are cross-validated and estimates of the long-term variability of windpower production and of its correlation with hydropower production are derived.

In the following section, we present which data sets were used for the simulation of windpower production, how they were cross-validated, and how they were used to assess the effect on long-term variability of joint output of hydropower and windpower system. Results, including the validation process, are presented in section 3. We compare our results to other publications, discuss the limitations of our study in section 4, and finally conclude indicating policy recommendations in the very last section of the paper.

2 DATA & METHODOLOGY

We model monthly time series of windpower production for a multi-annual period to be able to calculate seasonality and inter-annual variability of hydropower and windpower sources. We focus on monthly data as hydropower inflows are only available publicly at that frequency. The simulation of synthetic time series is necessary as long-term data from real production sites is not available – annual production surpassed 100 GWh as recently as 2006 [2]. Also, windpower production data is publicly only published in an aggregated way since 2006. Our methodology can additionally be used to simulate synthetic windpower time series for sites where currently no turbines are installed. Nevertheless we limit our assessment to existing locations. All data sets we use are publicly available for download on the internet and comprise either measured or modelled wind speeds.

An overview of the used data sources is given in Table 1. INMET, NCAR, and ECMWF data are used to simulate long-term windpower production. INMET data is provided by the national meteorological office and comprises of wind speed measurements at a height of 10 meters above ground. NCAR and ECMWF data are outputs of global meteorological models. Besides wind speeds, these models deliver other meteorological parameters as well at different atmospheric pressure levels. While outputs for several reanalysis projects by these organizations are available, we have chosen those datasets because they provide the highest frequency of data and because they are continuously updated. AMA data is collected by measuring wind speeds at hub height of wind turbines at real production locations. However, the data is made available only in an aggregated form for the four most important states of windpower production – Bahia, Ceará, Rio Grande do Norte, and Rio Grande do Sul – and only monthly mean wind speeds for each hour of a day are downloadable for the years 2012-2013. This data is therefore not used for simulation of windpower time series, but for the selection of measurement stations that are used subsequently for simulation. The temporal resolution is different between INMET (3 measurements a day) and NCAR and ECMWF that comprise of 4 simulations a day. As this may affect results we have also run the whole analysis removing one measurement per day from the NCAR and ECMWF time-series. Results were not changed significantly by this procedure, though. They are available upon request.

The modeling and validation process includes three steps, which are outlined in detail in the subsequent sections:

(1) We select those locations from the set of available long-term time series which best reproduce AMA wind speed data.
(2) Using those time series, we simulate daily windpower production time series for the period 1979-2013 and aggregate the data to monthly production.
(3) We cross-validate the three resulting time-series.
(4) Finally, we assess seasonality and non-seasonal components of the time-series and the correlation with hydropower production.

Table 1: Data sources for simulation of windpower production

Data source	Period	Spatial Resolution	Temporal Resolution	Type
INMET [21]	1962-present (long periods of missing data)	602 stations for the whole of Brazil	3 observations / day (00:00, 12:00, 18:00)	Measurement from meteorological stations at 10m height
AMA [22]	2012-present (no missing data)	One dataset for Bahia, Ceará, Rio Grande do Norte, Rio Grande do Sul	Monthly mean wind speed for each hour of day	Measurement at hub height of wind turbines
NCAR Reanalysis [19]	1948-present (no missing data)	2.5 x 2.5 Degree Grid, globally	4 model outputs / day (00:00, 06:00, 12:00, 18:00)	Modelled wind speeds at different atmospheric pressure levels
ECMWF Interim Reanalysis [20]	1979-present (no missing data)	0.75 x 0.75 Degree Grid, globally	4 model outputs / day (00:00, 06:00, 12:00, 18:00)	Modelled wind speeds at different atmospheric pressure levels

2.1 Site selection

We focus on the four federal states for which reference measurements at the hub height of wind turbines are available in the AMA database: Bahia, Ceará, Rio Grande do Norte, and Rio Grande do Sul. Those states are also the ones which most recently significantly increased their production capacities. We select locations from the three data sources INMET, NCAR, and ECMWF within the border of these states. While the NCAR and ECMWF data is complete and no further treatment of data is necessary, we select a subset of INMET data which has a sufficiently high number of data available for the comparison period 2012-2013.

In a first step, we select INMET data which have an almost complete set of data available for the period 2012-2013 – the period for which AMA data is available. The maximum number of missing data points is set to 100, i.e. 5% of the total time series. Missing data is interpolated between the two neighboring data points, allowing a maximum gap of 9 consecutive data points (i.e. 3 days of measurements). The total number of data locations per state and the number of stations containing sufficiently few data omissions for the INMET data are shown in Table 2.

To select the stations that best reproduce wind speeds at real production locations in the respective states, we calculated measures of fit between INMET, NCAR, and ECMWF data and reference data from AMA. INMET, NCAR and ECMWF data is not available on an hourly basis. We therefore calculate the average monthly wind speed for all data sources. However, INMET, NCAR, and ECMWF data are, depending on the chosen pressure level, not necessarily observations at the same height above ground compared to AMA which measures at hub height. We therefore calculate calibration factors that are the simple proportion of the mean of the complete time-series of the AMA data and the mean of the other three data sources. We do so for different pressure levels to test the influence of height on reproduction quality.

Table 2: Number of NCAR and ECMWF modeled locations and INMET stations for the four states.

	NCAR	**ECMWF**	**INMET**	
	Total number of model locations		*Total number of measurement stations*	*Stations with less than 100 missing values in period 2012-2013*
Bahia	13	87	8	5
Ceará	3	22	6	5
Rio Grande do Norte	3*	8	5	5
Rio Grande do Sul	8	43	15	7

**There are no NCAR points within Rio Grande do Norte. We therefore chose the closest neighboring points in Pernambuco and Ceará.*

For the selection of data locations which best represent AMA data, we calculate the Mean Squared Error (NSE) and the Pearson Correlation coefficient (COR) between INMET, NCAR, ECMWF and AMA data. We do so for the mean wind speeds of all possible sets of locations for each region and choose the set of measurement locations that minimize MSE. We also test correlations for significance, applying both tests for Spearman Correlation based on algorithm AS 89 [23] and standard tests for Pearson Correlation [24]. We report for most results in the paper Spearman test results as well, as for some of the involved distributions normality was rejected by the Shapiro-Wilk test and Spearman correlation does not rely on the assumption of normality.

2.2 Derivation of windpower time-series

When generating windpower time series for the period 1979-2013, we first have to address missing data in the INMET timeseries. For that purpose, we linearly interpolate up to one month of unavailable data and subsequently only use completed years for further analysis. We have tested interpolation with different period lengths (between 10 to 100 days) and results did not change significantly, we therefore assume that interpolation does not change results by much.

Windpower production for each of the selected data points for each of the three data sources INMET, NCAR, and ECMWF is calculated by assuming a standard power curve for a typical Brazilian 2 MW wind turbine (Melo 2012). The measurement and modelled values for wind speeds are used as input to the power curve. As observation frequency differs between the different data sources, we assume that the respective observation is representative for the production of the subsequent period, i.e. an ECMWF wind speed at 00:00 is assumed to be representative for the subsequent 6 hours, the windpower production derived from the wind speed is therefore multiplied by 6 to estimate the production for the whole period. Subsequently, we aggregate the production from all data points within a certain state and aggregate the monthly data to come up with total state production of windpower.

2.3 Cross validation

The three datasets used to simulate windpower production comprise of ground measurements from INMET and of global climate models. We first calibrate the mean production of NCAR and ECMWF to INMET data and then cross-validate our modelled windpower production, comparing climate model based data with INMET measurements. For that purpose, we first deseasonalize the data using dummies in a linear regressions and compare them for the three datasets to assess how seasonality is affected by the choice of a particular dataset[2]. Afterwards, we calculate the

[2] We have also calculated regressions including a linear trend to test for trends in climate. There was no consistent pattern for the trend, i.e. some datasets showed for some

correlation between the residuals of the respective time-series to assess how deviation from seasonality is captured by the three data sources. Wherever we report correlations between timeseries, we have also calculated MSE and linear regressions. As all indicators point into the same direction, we omit them in the results section. The respective results are available on request.

2.4 Comparison with hydropower data

We use historical values for hydro inflows into hydropower plants available for the period 1931-2013 [25] instead of hydropower production timeseries. Hydropower production is heavily influenced by storage while inflows are a good indicator for natural availability of hydrological resources, thus better enabling us to assess natural variability in total resource availability. We use those measurements from the dataset which are associated with currently operating power plants to best cover the hydropower system currently in operation. We deseasonalize the hydropower data too and compare the seasonality of windpower production with hydropower production. Finally, we assess if non-seasonal variability in the dataset is correlated with windpower production.

2.5 Variance reducing effect

Finally, we show how seasonality and annual variability of the availability of renewables is affected if either hydropower in the North or windpower is added to the system. For that purpose, we use timeseries of hydropower inflows and of simulated windpower production, normalized by dividing by the mean of the respective timeseries. We assume that shares of wind and hydropower are added, linearly scaling the timeseries. Thus, we can show the effect on seasonality and on annual variability by adding different shares of renewable sources to the system. The complete analysis was conducted using the statistical software R, version 3.10 [26].

3 RESULTS

3.1 Site selection

Table 3 shows the results of the site selection procedure. Results indicate that the ECMWF model best reproduces AMA measurements, i.e. it has the highest correlation and the lowest MSE for all states – besides RS, where INMET data fits slightly better. The difference between ground level modelled wind speeds and speeds at 100 m is minor for ECMWF data – obviously, the calibration factor decreases with increasing height. NCAR reproduces the data worse than the other two sources – and in this case, a significant difference between ground level and level 2 measurements (i.e. pressure level above ground) can be observed. For NCAR, data on level 2 much better reproduces AMA measurements than the ground level data. The capability of INMET data of reproducing AMA data lies somewhere in between ECMWF and NCAR data. As an example, Figure 1 shows how the ECMWF time series fits to AMA data. While the time-series in BA is almost perfectly reproduced after calibration, the data set shows larger deviations for RS.

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states significant positive or negative trends. For none of the datasets, the adjusted R^2 increased by more than 0.02 when including the trend variable. Results of validation and of correlation of data with residuals from de-trended timeseries did not change any of the conclusions drawn from the ones estimated without trend. Those results are available on request. The same applies to the time-series of hydrological inflows.

For the further calculations in this paper, we use the stations from the INMET data set, the NCAR level 2 grid points, and the ECMWF ground level grid points that best reproduce AMA data. The respective measurement sites chosen are shown in Figure 2. Observe that the selected sites are more inland in BA and more on the coast in CE and RN – this supports our approach as windpower production is located inland in BA and on the coast in the other two states. RS has a mix of the two types of locations.

Table 3: Comparison of performance indicators for comparing AMA data with INMET, NCAR and ECMWF data sets

		Bahia	Ceará	Rio Grande do Norte	Rio Grande do Sul
INMET	*Correlation*	0.84***(***)	0.95*** (***)	0.88***(***)	0.92***(***)
	MSE	0.62	0.15	0.38	0.14
	Number of stations	2	2	2	2
	Calibration factor	3.73	2.90	2.19	2.04
NCAR/ NCEP Ground level	*Pearson*	0.57**(**)	0.25	0.63**(**)	0.61**(**)
	MSE	2.91	2.00	2.14	0.86
	Number of stations	1	3	2	1
	Calibration factor	2.06	10.08	7.97	1.71
NCAR/ NCEP level 2	*Pearson*	0.83***(***)	0.58**(**)	0.89***(***)	0.66***(***)
	MSE	1.31	1.38	0.22	0.57
	Number of stations	1	1	1	1
	Calibration factor	1.37	0.99	0.87	0.99
ECMWF ground level	*Pearson*	0.99***(***)	0.96***(***)	0.98***(***)	0.88***(***)
	MSE	0.03	0.14	0.05	0.18
	Number of stations	3	3	1	3
	Calibration factor	1.94	1.94	1.45	1.95
ECMWF 100m	*Pearson*	0.99***(***)	0.96***(***)	0.97***(***)	0.81***(***)
	MSE	0.03	0.12	0.05	0.29
	Number of stations	4	2	1	1
	Calibration factor	1.31	1.31	1.01	1.23

,,***Significance level of 0.05, 0.01,0.001 of Pearson Correlation and, in parentheses, of Spearman Correlation calculated using AS 89 [23].*

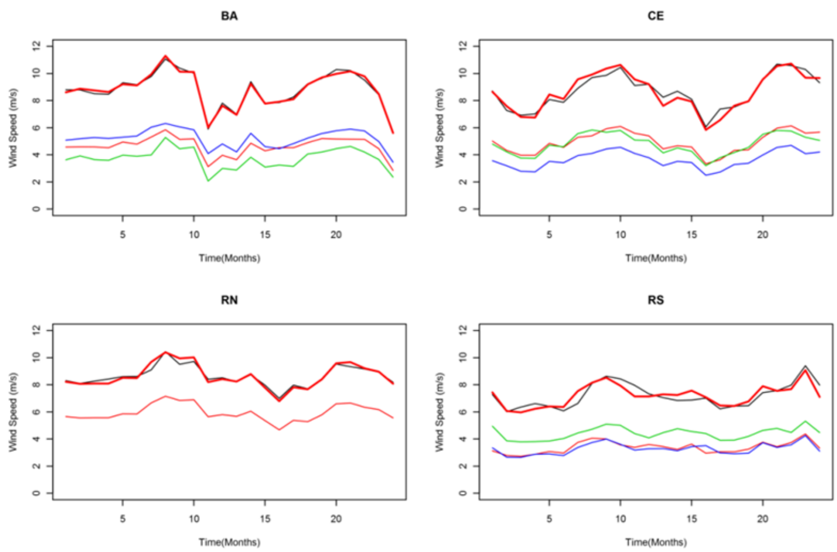

Figure 1: Example of comparing average monthly wind speeds from ECMWF (ground level) and AMA data sets for the years 2012 and 2013. The data from ECMWF modeling points that best reproduce AMA data are shown. Note: the fat red line shows the mean of data from the different ECMWF stations, multiplied by the calibration factor, the black line is measurement data from AMA. The colored thin lines correspond to data from individual ECMWF modeling points without calibration.

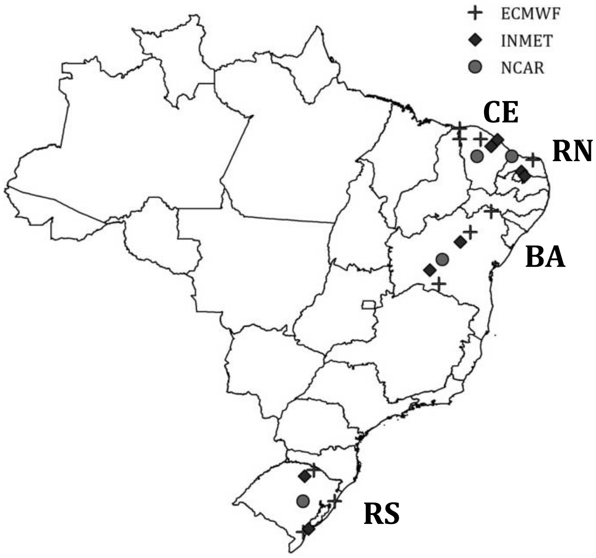

Figure 2: Measurement locations for the three data sets in the four states BA, CE, RN, and RS.

3.2 Cross-Validation

Using the time series of wind speeds from the datasets chosen as described above, we modelled monthly time series of windpower production for the period 1997-2013. For this period, all three data sets provide data (although with significant amounts of missing data for the case of INMET). The factors for calibrating the mean production of NCAR and ECMWF data to INMET data are shown in Table 4. For BA, NCAR shows a much higher calibration factor than ECMWF. Windspeeds in CE are estimated to be 20% lower by both modelled datasets. The other two states reproduce the INMET mean quite well. The monthly mean production as measured by monthly dummy variables in the regression model is shown in Figure 3. There are strong deviations of the models from the measured values in BA: models show much stronger seasonality than measured INMET data. However, the results of the site-selection in the previous section showed a better match of ECMWF data with measurements at actual windparks while NCAR and INMET showed a similar match for the case of BA. For the case of CE, NCAR strongly deviates from the other two timeseries – the fit between AMA measurements and NCAR is also low. This may be an indication that NCAR does not reproduce well windspeeds in CE. INMET data produces lower differences between the seasons than ECMWF data. For RN, all datasets produce similar seasonality. For RS, NCAR also shows stronger deviation from the other two datasets. RS has lower variability within the year than winds in the North-East.

Table 4: Calibration factors for calibration NCAR and ECMWF data to INMET. The number shows the mean of INMET production divided by the mean of the respective dataset.

	NCAR	ECMWF
BA	1.23	1.03
CE	0.80	0.79
RN	1.01	0.96
RS	1.07	1.04

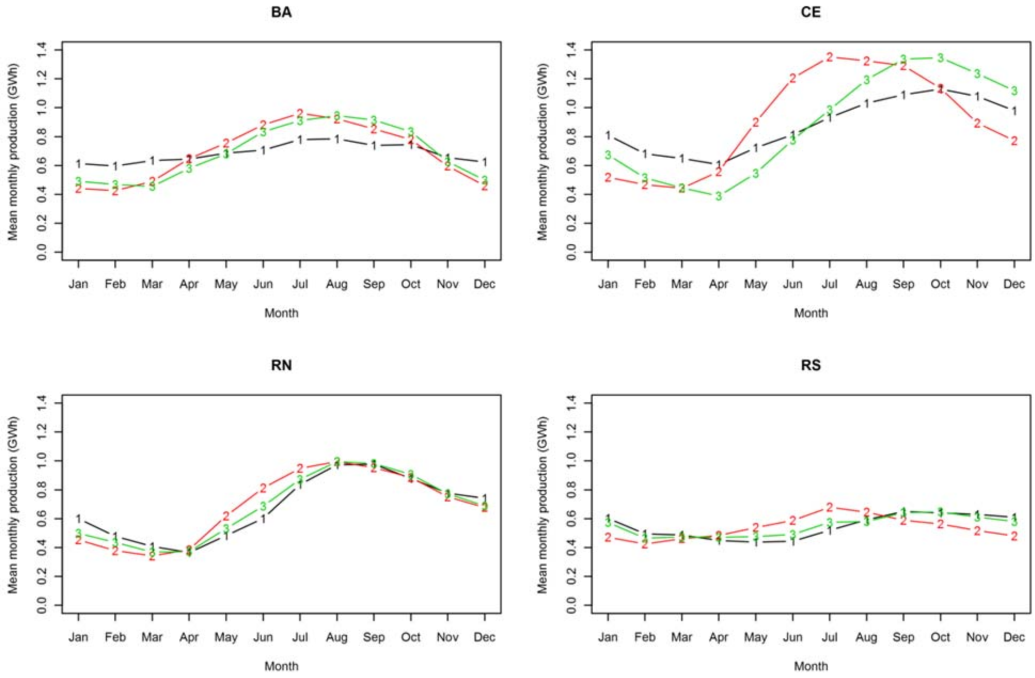

Figure 3: Dummy variables of regression models for the period 1979-2013 and the four states. The curves show the average production per month. Note: Black (1) shows INMET data, red (2) NCAR data, green (3) ECMWF data.

Results of correlating the residuals of the regression model using INMET data with the residualts of the regressions using the other two data sets are shown in Table 5. First, it can be observed that consistently, for all period and all states, ECMWF data is higher correlated with INMET data than the NCAR dataset. Second, correlation increases over time with the exception of the state of CE that shows a higher correlation for the first than the second period. This indicates that data and/or model quality is increasing over time. The state where seasonal production of the three data sources matches best, i.e. RN, also shows the highest correlation between the datasets with exception of the first period. With the exception of the second period and the ECMWF data set, BA is the state with the lowest correlation. Figure 4 shows plots of the timeseries of the residuals. The figure confirms that the best match is achieved in the state of RN, and indicates that inter-annual variability is lower for BA. There is no agreement of data sources on the variance for the other states, though. The seasonality shown above indicates that correlation between North-Eastern states is high – we also report correlation between monthly residuals in Table 6. Correlation is consistently highest between CE and RN for all states - the two states are neighbours, high correlations therefore have to be expected. BA is slightly less correlated with RN and CE consistently for all datasets. The datasets do not agree on direction and the significance level of correlation with RS. In some cases, relatively low correlations are found, in others not. RS is very distant from the other states, lower correlation has to be therefore expected.

Table 5: Correlation between residuals of regression of INMET and NCAR / ECMWF data

	NCAR	ECMWF	n
Complete period: 1997-2013			
BA	0.18***(***)	0.43***(***)	322
CE	0.35***(***)	0.51***(***)	258
RN	0.54***(***)	0.62***(***)	300
RS	0.4***(***)	0.46***(***)	326
First period: 1979-1996			
BA	0.21*(**)	0.27**(***)	106
CE	0.6***(***)	0.66***(***)	85
RN	0.59***(***)	0.61***(***)	99
RS	0.36***(***)	0.45***(***)	118
Second period: 1997-2013			
BA	0.3***(***)	0.6***(***)	216
CE	0.37***(***)	0.54***(***)	173
RN	0.56***(***)	0.78***(***)	201
RS	0.44***(***)	0.54***(***)	208

,,***Significance level of 0.05, 0.01,0.001 of Pearson Correlation and, in parentheses, of Spearman Correlation calculated using AS 89 [23].*

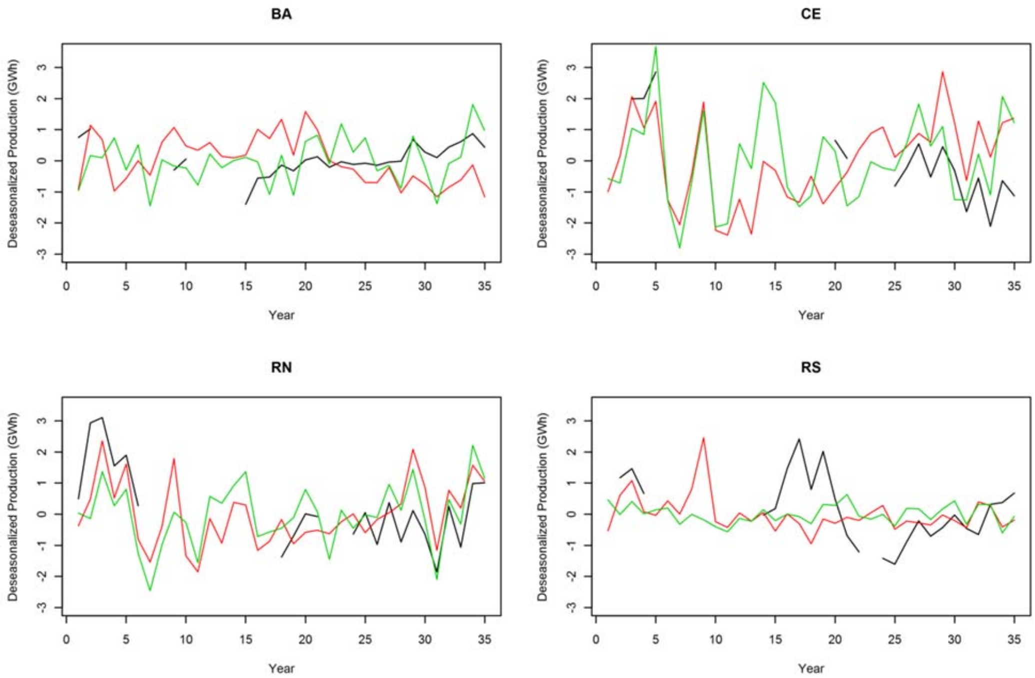

Figure 4: Annually aggregated residuals of the regression analysis for the period 1979-2013. Note: Black (1) shows INMET data, red (2) NCAR data, green (3) ECMWF data. Missing data causes the holes in the INMET timeseries.

Table 6: Correlation between deseasonalized timeseries of windpower production in the four states for the period 1979-2013.

		CE	RN	RS
BA	INMET	0.16*(**)	0.4***(***)	-0.03()
	NCAR	0.15**(*)	0.21***(***)	0.21***(***)
	ECMWF	0.36***(***)	0.63***(***)	-0.06()
CE	INMET		0.58***(***)	0.23***(**)
	NCAR		0.91***(***)	0.19***(*)
	ECMWF		0.69***(***)	0.04()
RN	INMET			0.15*(**)
	NCAR			0.25***(***)
	ECWMF			0.03()

,,***Significance level of 0.05, 0.01,0.001 of Pearson Correlation and, in parentheses, of Spearman Correlation calculated using AS 89 [23].*

3.3 Comparison with hydropower data

First, we discuss relations between hydropower production in the current system. Figure 5 shows seasonality of hydropower inflows in the four Brazilian subsystems – please observe that those are not coincident with the four states we use for aggregating windpower timeseries. The most important subsystem is the South-East where 57% of total inflows occur. Seasonality is highest for Northern hydropower production and lowest for Southern, where an increase in inflows can be observed in the second half of the year. Adding more hydropower from the North of Brazil to the system therefore obviously increases seasonality further. Table 7 shows confidence intervals of correlations of deseasonalized timeseries between the zones – we show confidence intervals to be able to compare to correlations of windpower production with hydropower inflows later. Correlation of inflows are high between the North-East, South, and North regions. The South is negatively correlated with the South-East and the North-East.

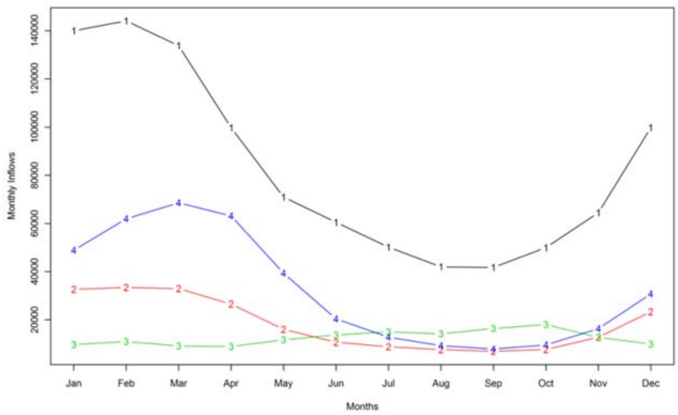

Figure 5: Dummy variables of regression models for the period 1931-2013 and the four Brazilian subsystems. The curves represent the monthly average inflows. Note: Black (1) shows inflows in the South-East, red (2) North-East, green (3) South, blue (4) North.

Table 7: Confidence interval of correlation between deseasonalized monthly hydropower inflows in the four states for the period 1979-2013 (n=420). Confidence level=0.999 for Pearson correlation.

	North-East	South	North
South-East	[0.38,0.62]	[0.03,0.34]	[0.24,0.51]
North-East		[-0.27,0.05]	[0.58,0.77]
South			[-0.35,-0.04]

When comparing Figure 3 and Figure 5, a strong seasonal complementarity can be observed between North-Eastern wind (i.e. BA, CE, RN) and hydropower inflows in the South-East, North-East, and North. As hydropower inflows in the South are low in comparison to the rest of the system, adding windpower to the system therefore stabilizes seasonal availability of renewable energies. Beyond seasonality, windpower production may also contribute to the system by stabilizing inter-annual variability of hydropower inflows. We assess this effect by calculating correlations of the sum of all deseasonalized hydropower inflows with deseasonalized windpower production for the four states (see Table 8). For the states of BA, RN, and RS results are mixed, depending on the dataset and no consistent pattern of positive or negative correlation can be derived. However, there is one exception: All datasets reject the null hypothesis of no correlation between CE and the sum of hydro inflows. When comparing correlations of windpower production with the correlation of hydropower production in the North with the rest of the country (see Table 7), it can be observed that the confidence intervals overlap for the states of CE and RN. This indicates that adding windpower from BA and RS will cause lower increases in total variance of the availability of renewable power sources than adding hydropower production from the North. We also show the correlations between the four subsystems and the four states in the Appendix. These results indicate that correlations between hydro inflows the South-Eastern and North-Eastern subsystem are strongest with CE, followed by RN. Windpower production in BA and in RS is less correlated. The correlations between annual availability of hydroinflows and windpower production are also shown in Table 8. Due to the low number of observations, the confidence intervals are wide – and they do not allow rejecting the hypothesis of no correlation between the power sources.

Table 8: Confidence intervals of Pearson correlation of deseasonalized residuals and of annual sums of INMET, NCAR, and ECMWF data and hydropower inflows for the period 1979-2013. Confidence level=0.999. Hint: we show in parentheses the number of observations

	INMET	NCAR	ECMWF	INMET	NCAR	ECMWF
	Correlation of deseasonalized residuals			Correlation of annual sums		
BA	[-0.15,0.21] (324)	[-0.25,0.07] (420)	[-0.14,0.18] (420)	[-0.14, 0.75] (25)	[-0.65,0.37] (35)	[-0.74,-0.2] (35)
CE	[0,0.39] (252)	[0.05,0.36] (420)	[0.11,0.41] (420)	[-0.09,0.92] (18)	[-0.48,0.57] (35)	[-0.23,0.73] (35)
RN	[-0.07,0.3] (300)	[0.06,0.36] (420)	[0.02,0.33] (420)	[-0.3,-0.83] (22)	[-0.41,-0.62] (35)	[-0.53,-0.52] (35)
RS	[-0.08,0.28] (324)	[-0.15,0.17] (420)	[-0.12,0.2] (420)	[-0.35,0.79] (24)	[-0.5,0.55] (35)	[-0.35,0.77] (35)

3.4 Variance reduction through windpower

Figure 6 shows the impact on the seasonal availability of renewable resources when adding different renewable resources to the system. Observe that INMET data is not shown due to the missing data, which would make comparison between data sources complicated. It can clearly be observed that adding more hydropower from the North increases seasonality substantially, while adding windpower actually flattens the seasonal profile, thus contributing to a more stable annual output. NCAR data flattens the output less than ECWMF. The biggest difference between the datasets can be observed for CE. RS seems to be the state that less contributes to smoothening seasonal output in the two datasets. Inter-annual variance is also lower when adding windpower instead of hydropower as indicated by Table 9. Adding wind from BA even decreases inter-annual variance when using the ECMWF dataset for windpower simulation. The states CE and RN are the states that most increase inter-annual variance.

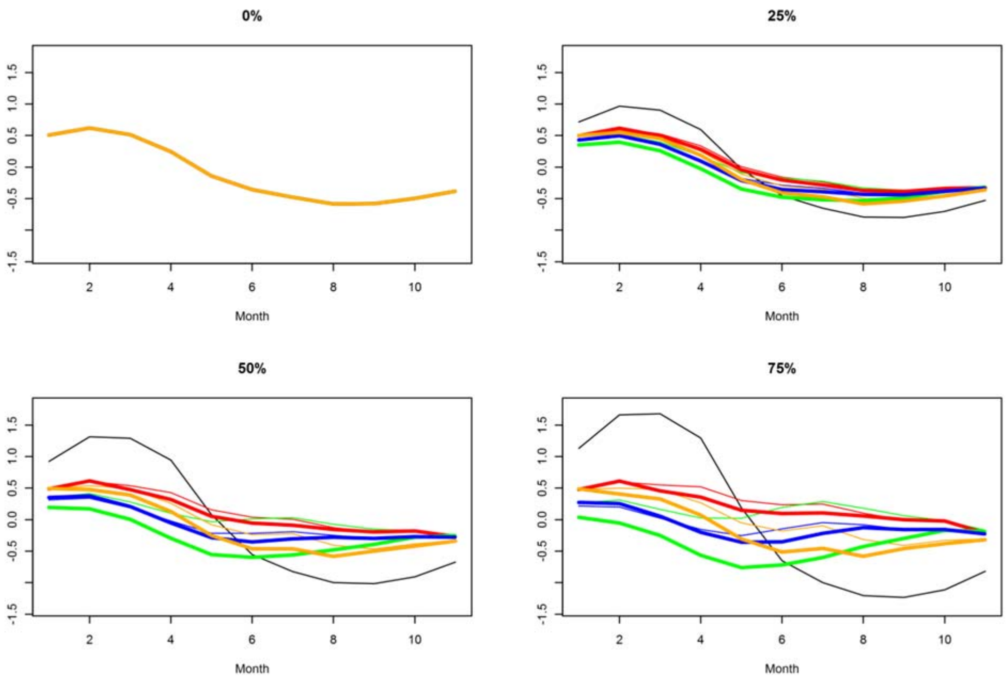

Figure 6: Seasonal availability of renewable electricity for different amounts of windpower and hydropower production from the North. The %shares indicate the amount of wind and hydropower, respectively, added to the system in relation to current total hydro inflows. Note: Black: hydropower, red: BA, green: CE, blue: RN, orange: RS. Fat line: NCAR-wind, thin line: ECMWF – wind.

Table 9: Annual variance of combined wind-hydro output when adding different shares of windpower from different states or hydropower from the North.

	Hydroinflows North	BA	CE	RN	RS	BA	CE	RN	RS
		NCAR				ECMWF			
0%	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90
25%	8.01	4.72	5.30	5.48	5.08	4.46	6.01	5.12	5.10
50%	12.52	4.81	6.23	6.59	5.50	4.28	7.73	5.84	5.36
75%	18.41	5.18	7.69	8.22	6.18	4.34	10.06	7.06	5.69

4 DISCUSSION

Our analysis confirms seasonal complementarity of North-Eastern wind and hydrological resources as has been shown before. Bezerra et al. [17] also conclude that RS has the weakest and CE strongest seasonality. Correlations between states in the NCAR dataset are similar to Bezerra et al. [17]. Dutra and Szlko [15] only show results for windpower in CE and they show, similar to our results, lowest production in April and highest in September/October. The monthly values of production compare very well to ECMWF data.

Inter-annual complementarity has been assessed before by Chade Ricosti and Sauer [18] for the North-East of Brazil. They used the NCAR data-set for this purpose. Our analysis shows that this data-set does not reproduce well ground measurements of wind speeds. Also, the conclusion that there is some kind of multi-annual complementarity between hydro and windresources is based on an analysis without testing for statistical significance. Our analysis does not indicate that the hypothesis of no correlation between the non-seasonal components of hydro- and windpower can be rejected – comparable to Bezerra et al. [17]. However, there is strong evidence that correlation of simulated windpower production with the current hydropower inflows is significantly below the correlation of hydropower resources in the North, at least with the exemption of CE.

Although we suggest that including windpower into the power grid may decrease variability of renewable resources on the longer term, we did not at all assess if the residual electricity system is able to cope with the intermittency of windpower on a much shorter period of time, i.e. minutes and hours. Integrating large amounts of windpower into the power grid may cause serious challenges for the grid and for the dispatch of thermal and hydropower plants. There is therefore a trade-off between reducing monthly and multi-annual variability and short-term variability which is going to be increased when integrating wind into the system. Still, if monthly and inter-annual variability is reduced, existing hydropower reservoirs can be increasingly used to balance short term fluctuations in the availability of intermittent renewables.

We use monthly average wind speed measurements from AMA to select reference measurement locations for simulating windpower production in the four most important wind producing states in Brazil. As windpower production is a non-linear function of wind speeds, comparing our simulations to a very short time-series of average wind speeds may distort results significantly – however, more detailed data is not published. The very high fit of ECMWF data to AMA data for three of the four states, however, suggests that the underlying process is modelled reasonably well.

The lower fit of INMET and NCAR data to AMA data may be partly explained by the low spatial resolution of measurements available – there are between 5 to 10 times more measurement points available for ECMWF data than for INMET and NCAR data. If the distance to the measurement locations of AMA grows, agreement between the different sources naturally decreases. Unfortunately, information on the exact location of measurement locations by AMA is not publically available.

When analysing the variance reducing effect of wind, we did not in detail analyse inflows into hydropower plants at different rivers, i.e. we assumed that adding new hydropower capacity in the North will scale hydropower inflows according to the inflows observed at existing locations. This would imply a perfect correlation between new hydropower plants and existing capacities in the North, obviously too strong of an assumption. As the same assumption is used for scaling windpower production, we however overestimate variance of both sources.

5 CONCLUSIONS

For the integration of windpower into the Brazilian electrical system, the following conclusions can be drawn: if seasonal variability should be reduced, integration of North-Eastern wind is to be preferred over wind from the South due to a higher complementarity with hydropower resources. Integrating wind from any state will decrease inter-annual variability in the combined hydro – windpower system in comparison to an expansion with hydropower from the North. Windpower production from BA and RS contribute most to low inter-annual variance.

From a modelling perspective, we can conclude that publicly available globally modelled data sets of wind speeds are to a certain extent able to reproduce ground measurements. Seasonality and inter-annual variability of wind speeds seems to be captured reasonably well by those data sets, particularly for later periods of measurements. We conclude that ECMWF data better reproduces AMA as well as INMET data in comparison to NCAR. If long-term windpower production is to be simulated in the four states examined, we therefore recommend using ECMWF data.

Future work includes modelling of winds at other locations than existing windpower locations. This will allow a further examination of complementarity between wind sources and between wind and hydropower production. Also, integrating the produced windpower time series into dispatch models may allow estimating the economic value of reduced monthly and inter-annual variability to the system. A detailed analysis of correlation with inflows in different river systems and in particular with potential hydropower production at planned hydropower sites is another important line of research.

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APPENDIX

CORRELATIONS OF DESEASONALIZED TIMESERIES OF HYDRO INFLOWS AND WINDPOWER PRODUCTION

		BA	CE	RN	RS
SE	INMET	0()	0.21***(**)	0.11()	0.07()
	NCAR	-0.1*()	0.2***(**)	0.22***(***)	-0.02()
	ECMWF	0.02()	0.27***(***)	0.17***(**)	0.01()
NE	INMET	0.06()	0.13*(*)	0.06()	0.05()
	NCAR	-0.18***(**)	0.1*(*)	0.13**(*)	0.02()
	ECMWF	-0.02()	0.15**(*)	0.14**(*)	0.04()
S	INMET	-0.01()	0.03()	0.11()	0.1()
	NCAR	0.14**(**)	0.09()	0.07()	0.02()
	ECMWF	0.04()	0.17***(**)	0.02()	0.09(**)
N	INMET	0.06()	0.09()	0.02()	0.07()
	NCAR	-0.08()	0.13*(**)	0.12*(*)	0.04()
	ECMWF	0.01()	0.07()	0.11*()	0.01()

,,***Significance level of 0.05, 0.01,0.001 of Pearson Correlation and, in parentheses, of Spearman Correlation calculated using AS 89 [23].*

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