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Integrated hydro- and wind power generation: a game changer towards environmental flow in the Sub-middle and Lower São Francisco River Basin?

Hagen Koch, [1]✉

Email hagen.koch@pik-potsdam.de

Ana Lígia Chaves Silva, [2]

Email analigiaifpb@hotmail.com

José Roberto Gonçalves de Azevedo, [2]

Email robdosport@hotmail.com

Werônica Meira de Souza, [3]

Email weronicameira@gmail.com

Johann Köppel, [4]

Email johann.koeppel@tu-berlin.de

Clecio Barbosa Souza Junior, [4]

Email junior@campus.tu-berlin.de

Alessandra Maciel de Lima Barros, [5]

Email alessandram@ons.org.br

Fred F. Hattermann, [1]

Email fred.hattermann@pik-potsdam.de

[1] Research Domain Climate Impacts and Vulnerabilities **AQ1** , Potsdam Institute for Climate Impact Research—PIK, P.O. Box. 601 203, 14412 Potsdam, Germany

[2] Departamento de Eng. Civil, Centro de Tecnologia e Geociências —CTG, Universidade Federal de Pernambuco—UFPE, Recife, Brazil

[3] Unidade Acadêmica de Garanhuns, Universidade Federal Rural de Pernambuco—UFRPE, Garanhuns, Brazil

[4] Berlin Institute of Technology, Environmental Assessment and Planning Research Group—TUB, Berlin, Germany

[5] Gerência de Hidrologia, Programação Energética e Consolidação da Carga dos Subsistemas Norte e Nordeste, Operador Nacional do Sistema Elétrico —ONS, Rua da Aurora, 1343, Recife, 50040-090 Brazil

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Abstract

Many renewable resources for the generation of electricity, such as hydropower and wind power, are dependent on climatic factors. Reservoirs have been created to overcome the stochastic nature of river flows and to make water supply more reliable. However, reservoirs are affecting the ecological status of river ecosystems, e.g., by modifying the flow regime, triggering discussions regarding the discharge of reservoirs. In Brazil's northeast region, the installed capacity for wind power generation has increased substantially in recent years. Setting up a modeling system for simulating wind power and hydropower generation in this study, it is analyzed whether wind power generation, peaking in the dry season, can help to achieve a more environmentally oriented flow regime in the Sub-middle and Lower São Francisco River Basin. Simulated higher discharges from reservoirs during the rainy season and lower discharges during the dry season, representing a more natural flow regime, will reduce hydropower generation in the dry season. Under recent conditions, the resulting gap in electricity generation can only be partially covered by wind power. A large share needs to be generated by thermal power plants or be imported from other regions in Brazil. The planned future increase in installed wind power capacity can change this picture; the demand for electricity generated by thermal power plants and imported will decrease. Adopting an integrated approach for hydropower and wind power generation, the flow regime in the Sub-middle and Lower São Francisco River Basin can be modified to improve the ecological status of the river system.

Keywords

São Francisco River basin
Electricity generation
Hydropower
Wind power
Environmental flow

Electronic supplementary material

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Introduction

AQ2

Due to the intermittent nature of the renewable electricity generation, systems using a single renewable energy source need to be highly oversized and have high operational and lifecycle costs (Bhandari et al. 2014). Two or more renewable energy resources can be combined to form a hybrid generating system that complements the drawbacks of each individual resource. In a grid connected system, the size of storage device can be relatively smaller because deficient electricity can be obtained from the grid (Bhandari et al. 2014).

Hydropower and wind power are renewable resources for the generation of electric energy. Both types of electricity generation are dependent on climatic factors. For instance, electricity generation by a hydropower plant is strongly connected to river discharge and hence to precipitation and evapotranspiration, while wind power generation makes direct use of wind and is therefore directly dependent on wind speed. Currently, there is no technology in use to reduce this direct dependence on wind. Reservoirs can balance, at least partially, the stochastic occurrence of precipitation and discharge and increase the reliability of water supply and hydropower generation. However, losses from reservoirs due to evaporation and seepage can reduce the volume of available water. Hydropower plants with a storage reservoir are highly dispatchable and electricity generation can be scheduled in less than an hour. For peak load generation, frequent startups and shutdowns can be executed without a significant damaging effect on the infrastructure. This makes hydropower plants, if storage volume is available, an excellent complement to other, intermittent, sources such as wind. Reservoirs are suitable to be used as energy storage facilities ("batteries"), storing water during high wind speed periods and releasing water for electricity generation when needed (Gebretsadik et al. 2016). The capacity to which hydropower generation is able to address the variability and unpredictability of wind power generation depends on factors such as infrastructural capacity, policy and physical constraints in water reservoir operation, electricity demand, and hydrological conditions. It is important to consider these factors in the planning phase as well as in the operational phase, as their contribution to overall effectiveness of the integrated operation is highly variable and often system specific (Gebretsadik et al. 2016).

Results of Ricostib and Sauer (2013) indicate that the total costs of wind power generation represent 57% of the total costs of thermal generation, showing its potential attractiveness. However, according to de Jong et al. (2016), there is also prejudice against wind power development, e.g., from lobby groups, local municipalities, landowners, or the media. In the literature, there exists a plentitude of studies analyzing the combined renewable electricity generation. A number of studies, e.g., Kaldellis et al. (2001) or Bueno and Carta (2006), have examined isolated combined wind- and hydropower systems for small islands.

Belanger and Gagnon (2002) analyze if wind power development requires the installation of additional backup capacity and increases the environmental impacts of hydropower facilities providing the backup when wind power generation is down. They show that wind power development requires backup capacity to compensate for wind fluctuations and that the output of the hydroelectric plant was significantly different when used exclusively to balance the output of a single wind plant and that this had a significant impact on river levels at different times of the year. Jaramillo et al. (2004) present a theoretical study combining wind power and hydropower electricity generation, where the hybrid plant could provide close to 20 MW of firm power to the electrical distribution system. Marinho and Aquino (2007) are using mean monthly observed inflows to Sobradinho Reservoir (years 1931 to 2004) in the São Francisco River Basin (Brazil) and mean monthly observed wind speed (years 2004 to 2006) to assess the effects of combined electricity generation. They conclude that the high wind speed can reduce the electricity demand for hydropower generation in the dry season. Dutra and Szklo (2008) use annual average wind velocities for Brazil's northeast region to make a first, rough estimation of the wind power generation potential. They conclude that additional studies are needed to precisely evaluate the complementarities between wind and hydraulic resources. Benitez et al. (2008) develop a nonlinear mathematical optimization program to investigate the economic and environmental implications of wind penetration in electrical grids and to assess if hydropower storage could be used to offset intermittence of wind power generation. Adding wind power generation to an electrical grid consisting of thermal and hydropower plants, it increases the system variability and results in a need for additional peak-load generation capacity, e.g., gas-fueled generators. When pumped hydrostorage is introduced in the system or the capacity of the existing water reservoirs is increased, these facilities could provide most of the peak load requirements. A stochastic optimization technique maximizing the joint profit of hydro and wind generators for a scheduling horizon of five periods, each being 1 h long, taking into account the uncertainty of wind power prediction, is presented by Angarita et al. (2009).

Castronuovo et al. (2014) develop an approach for optimal coordination of wind and pumped hydropower generation for the next day, running on hourly time step, that maximizes the market profit and apply this approach for a case study on the Iberian Peninsula, while Silva et al. (2015) develop a model for integrating hydropower and wind power generation using an optimization algorithm for a theoretical example. The model is run on hourly time step for 1 day and is intended for short-term management optimization, i.e., the next day. Martinez et al. (2015) propose a methodology to determine the optimal technology for an energy storage system and its sizing for power systems with high penetration of wind generation. Gebretsadik et al. (2016) develop a method optimizing daily operational considering hydropower operation constraints using an hourly time for step for a 1-year simulation period. de Jong et al. (2016) examine the feasibility of integrating large-scale wind power generation into the electricity grid of the northeastern Brazilian sub-system with a high proportion of existing hydroelectricity generation. They estimate the maximum achievable wind power penetration without exports to other Brazilian regions. The viable maximum penetration of wind power generation in the northeastern sub-system is estimated to be 65% of the average annual electricity demand, assuming that hydroelectric and gas generators have 100% scheduling flexibility. Above a wind energy penetration of 65%, increasing amounts of electricity would need to be curtailed or need to be exported to other Brazilian sub-systems. Theoretically, the surplus electricity from wind power generation could also be stored in pumped hydroreservoirs. However, none of the reservoirs in the northeastern region have been adapted to operate as pumped hydro plants up to now. In their study, de Jong et al. (2016) assume that even during drought periods the enormous amount of hydroelectric capacity can be fully utilized to balance variations in net load resulting from stochastic wind power generation.

François et al. (2017) apply a hydrothermal optimization and simulation model for Norway aiming at minimizing the overall system costs using weekly climate input to assess the effect of the development of additional wind farms and of the development of a new transmission line on the energy balance of mid-Norway. Barbosa et al. (2017) are using an energy system model for the year 2030 to assess the possibility of 100% renewable energy supply for South and Central America. The model is based on linear optimization considering constraints and is composed of a set of power generation and storage technologies. The region is subdivided into 15 sub-regions, and existing hydropower dams are used as batteries for solar and wind electricity storage. According to their results, renewable energy technologies can generate enough energy to cover all electricity demand in the region. Oliveira and Maria (2017) present an optimization approach for the planning of renewable generation in energy distribution systems considering generation based on wind turbines and photovoltaic panels. Their objective is to determine the optimal placement of the generation by minimizing the investment and operational costs. They use probability distribution functions for the estimation of solar radiation and wind speed. To simplify the optimization, they use linear relationship between climate input, i.e., the probability distribution functions and electricity generation. For the estimation of the load factor of wind generation, they use a linear relationship between wind speed and electricity generation.

AQ3

In most studies, combining wind power and hydropower generation, longer time scale effects of wind variability on reservoir storage are not considered. In order to accommodate for seasonal variability reservoir rule, curves need to be adjusted to take the intermittency of wind power generation, longer time scale variability, and variability in electricity demand into consideration

(Gebretsadik et al. 2016). Furthermore, hydropower reservoirs often serve multiple functions, including human and agricultural irrigation water supply, flood control, fish habitat, and recreation, which can constrain their use for purely system balancing (de Jong et al. 2016).

In many studies, probability distribution functions are used for the assessment of wind power (and solar power) generation. This allows for including uncertainties in electricity generation of wind power (and solar power) plants. However, using probability distribution functions for wind power (and solar power) generation, the relationship to other climate variables, e.g., precipitation or air temperature, important for runoff generation and hydropower generation, is lost. Furthermore, the listed studies only discuss and apply approaches to estimate wind power generation, but no comparison between observed and simulated wind power generation is given, showing that the approach and data used are able to present the analyzed system.

With the construction and operation of dams built to overcome the stochastic nature of river flows and to make water supply more reliable, a discussion has emerged regarding the benefits as compared to the environmental and social costs (Scudder 2005; Bergkamp et al. 2000). Impacts of large dams include altered flow regimes, alteration of sediment transport, change of aquatic biodiversity, flooding or falling dry of native vegetation, greenhouse gas emissions, reallocation of water by evaporation and infiltration, resettlement of human populations, and loss of fertile soils (Anderson et al. 2006; Fearnside 2002). In recent decades, there has been a discussion surrounding a more ecologically or environmentally oriented flow regime for river basins (Porse et al. 2015; Yin et al. 2011). The discussion usually focuses on how to manage reservoirs in a way that provides environmental flows for sustaining ecosystem services while considering societal demands (provision of potable or irrigation water) and the generation of electricity by hydropower plants (e.g., Porse et al. 2015; Richter and Thomas 2007). For the determination of environmental flows, there exist worldwide more than 200 methods that are generally grouped into four categories: (i) hydrological rules, (ii) hydraulic rating methods, (iii) habitat simulation methods, and (iv) holistic methodologies. For an in-depth discussion of these methods, the reader can refer to King et al. (2008) or Arthington et al. (2006).

Study area

The study area is the Sub-middle and Lower São Francisco River Basin. The

São Francisco River Basin (see Fig. S1 in the Supplementary Material) has an area of approximately 640,000 km^2, and it is the largest river basin that is located entirely in Brazil, occupying 8% of Brazilian territory. While the headwaters receive high annual precipitation sums (up to 2000 mm/a) with an annual potential evaporation of 1000 mm/a, the middle and lower sections are characterized by much lower annual precipitation sums, being as low as 350 mm/a, and annual potential evaporation higher 1500 mm/a in some areas (CBHSF 2004). The mean discharge at the mouth of the São Francisco river is 2846 m^3/s (ANA/MMA 2013). Due to the high intra- and inter-annual variation of precipitation and resulting river flows in the São Francisco River Basin, reservoirs with large storage capacities to compensate for these variations have been build (see Fig. S1). The largest dams are Três Marias in the Upper São Francisco River Basin with a total capacity of 19,528 hm^3 (live capacity of 15,278 hm^3, installed hydropower generation capacity 396 MW), Sobradinho (total capacity of 34,117 hm^3, live capacity of 28,669 hm^3, 1050 MW), and Itaparica (total capacity of 10,782 hm^3, live capacity of 3549 hm^3, 1500 MW). The main uses of these reservoirs are flood protection and hydropower generation, but they also deliver water for agricultural irrigation and to municipalities, and are used to augment streamflow for navigation. Downstream of Itaparica Reservoir, there are a number of large hydropower plants, including Apolônio Sales (installed capacity 400 MW), Paulo Afonso 1 (180 MW), Paulo Afonso 2 (445 MW), Paulo Afonso 3 (800 MW), Paulo Afonso 4 (2460 MW), and Xingó (3000 MW) (ANA/GEF /PNUMA/OEA 2004). While the huge Sobradinho Reservoir, the uppermost reservoir of the hydropower cascade in the Sub-middle and Lower São Francisco River Basin, is used for balancing inter-annual variations, the smaller capacity of the Itaparica Reservoir is used for balancing intra-annual variations. The hydropower plants in the Sub-middle and Lower São Francisco River Basin are operated by *Companhia Hidro Elétrica do São Francisco* (CHESF).

The hydropower plants in the São Francisco River Basin are the most important resources for electricity generation of Brazil's northeast region (Dutra and Szklo 2008) and are part of the large, continental size power plant and electricity transmission system of Brazil. The power plants of the Brazilian system are dispatched by an governmental agency, the system operator *Operador Nacional do Sistema Elétrico* (ONS), based on the operational costs, calculated to minimize the total operational costs on the basis of a model of the Brazilian electricity generation and transmission system (Calabria et al. 2014). The operational costs include the variable costs of the thermal generation and the opportunity cost of water storage of hydropower generation. This centralized dispatch is performed on an annual, monthly, weekly, and intraday load level basis. The system operator ONS decides about the actual electricity generated, not the individual companies responsible for the operation.

Due to the huge volumes of the reservoirs and their operation, the discharge at the main river has changed dramatically. The natural flow regime with wet and dry seasons no longer exists (Medeiros et al. 2013). Recently, environmental hydrograms were developed within the project "*Avaliação dos Impactos Hidrológicos da Implantação do Hidrograma Ambiental*, *do baixo trecho do rio São Francisco*—AIHA." This project provided monthly target values for river discharges for the Sub-middle and Lower São Francisco River Basin. Both local populations and water authorities were involved in the discussion and the development. The environmental hydrograms were developed primarily to consider the river in-stream requirements and water uses along the respective river stretch and were derived for normal and dry years using the Building Block Methodology (see Ferreira 2014; Medeiros et al. 2013). In Brazil's northeast region, the austral winter half year is the dry season in the São Francisco River Basin and the wind speed is high, while the austral summer is the rainy season with low wind speeds (see Melo et al. 2013), resulting in complementarities between wind and hydraulic resources (Dutra and Szklo 2008). Wind power in Brazil's northeast region is currently undergoing rapid development and installed capacity is expected to exceed 16,400 MW by 2020. According to Jong et al. (2016), annual average wind power generation will grow to more than 6700 MW. Energy storage provided by reservoirs will be ideal for integrating intermittent wind power generation. Currently, the transmission limits for electricity exports from the northeastern sub-system to the southeast and north regions are 4000 and 4400 MW, respectively. As wind power capacity increases across different locations in the region, it is expected that the variability and extreme instances of highs and lows of wind power generation will be further reduced. It is estimated that the average electricity demand for the entire northeastern sub-system will reach 12,250 MW by 2020 (Jong et al. 2016).

The research topic of this paper is to analyze if wind power generation can help to achieve a more environmentally oriented flow regime in the Sub-middle and Lower São Francisco River Basin with higher discharges during the rainy season and lower discharges during the dry season, leading to reduced hydropower generation in the latter. Considered is the system as of the year 2015 and for a year 2020 scenario. We use wind speed data (3-h time intervals) for wind power generation and other climate variables and river discharge on a daily time step for hydropower generation to simulate the integrated electricity northeastern sub-system.

Data and methods

General

Data used in this study are daily electricity demand for the northeastern Brazilian electricity sub-system, observed wind speed data for 3-h time intervals for selected stations in the region and further climate variables, e.g., air temperature and relative humidity to calculate potential evaporation from the reservoirs and river discharge on a daily time step to simulate hydropower generation at the Sobradinho and Itaparica reservoirs and the hydropower plants downstream. We are using observed climate data from 2001 to 2014 to include a wide range of climate variations, i.e., dry, normal, and wet years. To include variations in electricity demand, we use observed data from 2013 to 2015, representing a recent state, and a year 2020 scenario with increased electricity demand and higher installed wind power capacity.

In our approach, we assume a certain electricity demand to be covered by wind power and hydropower plants. Because there is no technology to reduce the direct dependence of wind power generation on wind speed, but reservoirs can be used to store and release water, i.e., generate electricity when needed, first wind power generation is simulated. In the second step, depending on electricity demand, hydropower generation is simulated to fill the gap between electricity demand to be covered by wind power and hydropower generation. In the operation of the reservoir, the restrictions described below, e.g., for minimum flows or maximum discharge variation between two following days, are included.

The simulated daily electricity generation of wind power and hydropower plants is compared to the electricity demand, and resulting discharges are compared to environmental hydrograms on a monthly basis. Besides comparing the resulting discharges with the environmental hydrograms, we use the Pardé coefficient and Indicators of Hydrological Alterations (IHA—Richter et al. 1996) to assess results for the different operation strategies with the natural flow regime of the pre-dam period. The IHA are a set of 32 biologically relevant flow indicators that can be used to assess the degree of flow modification by comparing the pre- and post-impact periods. From the 32 flow indicators of the IHA, we select the volume and occurrence (Julian day) for the annual maximum 7-day mean flow and the annual minimum 7-day mean flow.

Model for wind power generation

In estimating wind power generation, annual and daily variations must be considered. Furthermore, wind power generation power curves and an extrapolation to the hub-height of the wind mills are necessary. In the calculations of wind power generation, a power curve as described by Koch et al. (2015) or Akdag and Güler (2011) is applied: a horizontal axis wind turbine with a hub-height of 100 m and blades of 50 m in length. The wind turbine does not produce if the wind speed is below 4 m/s. Above this threshold, the utilization increases up to a wind speed of 15 m/s and is utilized at 100% for wind speeds below 30 m/s. The wind turbine is shut down if the wind speed threshold of 30 m/s is surpassed. The wind speed data were extrapolated to hub-height of 100 m aboveground using a logarithmic wind profile (Hoogwijk et al. 2004):

$$\mathrm{VH} = \mathrm{VM}\ \left(\ln(H/\mathrm{z0})/\ln(M/\mathrm{z0})\right) \quad 1$$

- where *VH* is the wind speed at hub-height (m/s), *VM* is the wind speed at anemometer height (m/s), *H* is the hub-height (m), *M* is the anemometer height, and z0 is the roughness length of the surface (m). No thermal effects on wind speed are included in this function.

Model for hydropower generation

To simulate hydropower generation, information on the following characteristics of the hydropower plant is needed: maximum head, maximum turbine flow capacity, and the efficiency of the turbines. Knowing the water level (head) and reservoir outflow, the daily hydropower generation can be calculated:

$$\mathrm{KW} = \min\left(Q, Q\ \mathrm{max}\right) \times \mathrm{g} \times \eta \times \mathrm{h} \times \rho \quad 2$$

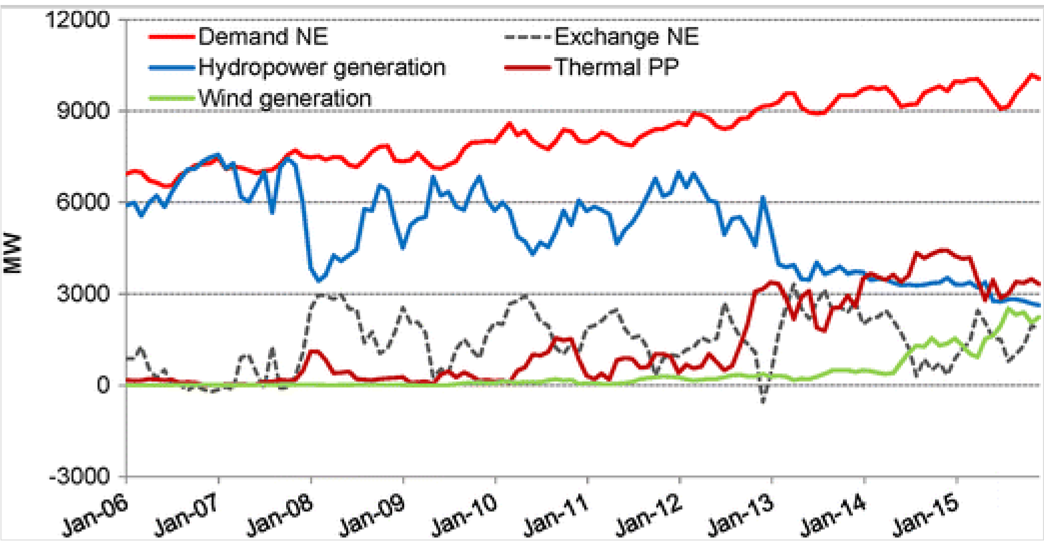
- where *Q*(max) is actual (maximum) flow (m^3/s), *g* is the acceleration due to gravity (m/s), η is turbine efficiency (−), h is head (m), and ρ is density of water (kg/m^3).

Electricity generation in Brazil's northeast region and in the São Francisco River basin

Data on electricity demand, electricity generation by hydropower and thermal power plants, wind power plants, and electricity imported to and exported from Brazil's northeast region are available from ONS (2016a). The developments between 2006 and 2015 are shown in Fig. 1, with positive values for electricity exchange meaning import from and negative values meaning export to other regions of Brazil. From 2006 to 2015, the mean annual electricity demand has increased by approximately 42%.

Fig. 1

Development of mean monthly electricity demand, electricity generation by hydropower plants, thermal power plants and wind power plants, and electricity exchange (positive is import from, negative is export to other regions of Brazil) for Brazil's northeast region (ONS 2016a)



Since 2012, with declining hydropower generation in the São Francisco River Basin due to an ongoing drought, the generation by thermal power plants has increased sharply (see Fig. 1). Additionally, increased wind power generation, due to the higher installed wind generation capacity, is also notable. The amount of electricity imported to Brazil's northeast region shows high fluctuations depending on the demand and generation in the region, and the electricity generation in other regions of Brazil.

Simulation of wind power generation for Brazil's northeast region

Data from climate observation stations Petrolina/PE (PCD 32475; May 2001 to December 2015), Irecê/BA (PCD 32546; January 2001 to December 2015), Floresta/PE (PCD 32026; May 2002 to December 2014), and Belém de São Francisco/PE (PCD 31935; August 2005 to December 2015) were used in this study (3-h mean wind speed at a height of 10 m; data from INPE 2016). Overall, the daily cycle of wind speeds shows a similar behavior for all stations, with the maximum values observed in the afternoon (12:00–18:00 h) and minimum in the early morning hours (3:00–9:00 h) (see also Melo et al. 2013). The observation records of the four listed stations contain gaps, with Petrolina/PE (PCD 32475) and Irecê/BA (PCD 32546) having data for 76.5 and 98.5%, respectively, for the time period from 2001 to 2014. The gaps were filled with data from Floresta/PE (PCD 32026) and Belém de São Francisco/PE (PCD 31935) depending on the availability. In cases where none of the station had data for a certain time interval, data from preceding days were used.

In Fig. S1, the mean annual wind speed at a height of 50 m for greater north-eastern Brazil (based on data from CEPEL 2005) and the cities of Petrolina and Irecê are shown. The wind speed for the grid cells including the cities of Petrolina (mean annual wind speed 5.4 m/s) and Irecê (mean annual wind speed 5.9 m/s) is in the class 5.01 to 6.00 m/s. In the surroundings, there are cells with mean annual wind speed of 8.01 to 9.00 m/s and cells with mean annual wind speed of 4.01 to 5.00 m/s. However, the majority of cells are in the same class as Petrolina and Irecê and in the class 6.01 to 7.00 m/s. Therefore, the wind speed measured at the Petrolina/PE (PCD 32475) and Irecê/BA (PCD 32546) climate observation stations can be seen as representatives of wind speed in this region.

Depending on land use and vegetation in the surroundings, for Eq. (1) roughness lengths of the surface (z0) of 0.02 and 0.15 were used for Petrolina/PE (PCD 32475) and Irecê/BA (PCD 32546), respectively. The anemometer height for both stations is 10 m.

In Fig. S2, the observed mean monthly utilization of wind power plants for Brazil's northeast region is shown for the years 2010 to 2014 (data for 2010 and 2011 from MME 2012; data for 2012 to 2014 from ONS 2016b). Also shown is the simulated mean monthly utilization using the observed wind speed data for Petrolina/PE (PCD 32475) and Irecê/BA (PCD 32546), being representative of wind speeds in this region. As only data from these two stations were available for the time period used in this study, the power curve described above was modified: the wind turbine does not produce as long as the wind speed is below 3 m/s. The wind turbine is shut down if the wind speed threshold of 35 m/s is surpassed. These modifications were necessary because in case the wind speed is below 4 m/s at the Petrolina/PE (PCD 32475) and Irecê/BA (PCD 32546) stations, in some parts of the greater north-eastern Brazil, wind speed will be higher than 4 m/s. In case wind speeds are higher 30 m/s at the considered stations, in some parts of the greater north-eastern Brazil, wind speed will be lower than 30 m/s.

Although there are deviations between observation and simulation, the annual cycle, i.e., lower utilization in the austral summer and higher utilization in the austral winter, can be reproduced. According to ANEEL (2016), the installed capacity for wind power in July 2016 was 7400 MW. In this study, an operational capacity of 7000 MW for wind power is assumed for Brazil's northeast region, i.e., it is assumed that a small share of the installed capacity due to maintenance is out of operation or is not connected to the electricity transmission grid. Wind power plants with a generation capacity of 3084 MW are under construction in Brazil's northeast region currently, while 5180 MW is in the planning phase (ANEEL 2016).

Simulation of hydropower generation for the São Francisco River Basin

Daily inflow and outflow time series, as well as volumes for the Sobradinho and Itaparica reservoirs, were available from ONS up to the year 2014. A reservoir module developed by Koch et al. (2013) for the eco-hydrological model SWIM (Krysanova et al. 1998) was used in this study. The reservoir module is a conceptual representation of storage-release processes based on three management options, to which the reservoirs are assigned according to their operation policy:

i. Objective is the minimum discharge downstream considering the minimum and maximum volumes of the given reservoir for each month.

ii. Daily release based on hydropower generation demand considering the minimum and maximum volumes of the given reservoir for each month; other restrictions can be included by introducing for example daily minimum or maximum discharges.

iii. Daily release based on the water level of the reservoir.

In order to exclude deviations between observed and simulated discharges upstream of the Sobradinho Reservoir, the reservoir module was applied outside of SWIM, i.e., the observed daily inflow time series were used as input for the reservoir module. Daily climate data were available from the WATCH-project up to 2014 (http://www.eu-watch.org /; Weedon et al. 2011). These data were used to calculate the potential evaporation using the TURC-IVANOV methodology (see Wendling and Schellin 1986). Using the observed inflow time series, with precipitation and the potential evaporation rates calculated, the reservoir module was used to simulate the operation of the Sobradinho and Itaparica reservoirs and the electricity generation by these reservoirs and the hydropower plants downstream. In this study, management option (ii) is used to simulate the reservoir operation of the Sobradinho and Itaparica reservoirs. Depending on the electricity demand (see below) and wind power generation for each day, the demand on hydropower generation is calculated. Depending on the water level (head of the hydropower plant depending on the actual volume), the discharge to be released is calculated considering further restrictions (see below). The data characterizing each hydropower plant (see Eq. (2)) are taken from ONS (2016c). The hydropower plants included in this study, i.e., all hydropower plants listed in the "Introduction" section except Três Marias reservoir located in the Upper São Francisco River Basin, have an installed capacity of 9780 MW.

Electricity demand

In the years 2013, 2014, and 2015, the mean electricity demand for Brazil's northeast region was 9284, 9569, and 9803 MW, respectively. In 2013, the minimum and maximum daily values were 7567 and 10,426 MW; in 2014, the minimum and maximum daily values were 8032 and 10,506 MW; and in 2015, the values rose to 8044 and 10,958 MW. The electricity demand for the years from 2013 to 2015 can be seen as a variation of the present state and is therefore used in this study.

According to data of ONS (2016a), the long-term utilization of the hydropower plants in the São Francisco River Basin is 46% (years 2010 to 2015). Due to the drought during the years 2013 to 2015, the mean utilization was 35% only. The long-term utilization of the thermal plants for Brazil's northeast region was approximately 50% (years 2010 to 2015) with a mean utilization of 76% for the years 2013 to 2015 (ONS 2016a). According to data of MME (2012) and ONS (2016b), the mean utilization of wind power plants for Brazil's northeast region is 40% (years 2010 to 2015). As can be seen in

Fig. S2, the mean monthly values can be as low as 11%.

An installed capacity of 4400 MW for thermal power plants and a long-term utilization of 55% (mean generation of 2420 MW) is assumed. In the long term, a utilization of 50% for hydropower plants (mean generation of 4890 MW) and of 25% for wind power plants (mean generation of 1720 MW) is assumed. According to these assumptions, in the long term, 73% of the electricity generation in Brazil's northeast region should be covered by wind power and hydropower generation. For thermal power plants, we choose a somewhat higher utilization compared to the years 2010 to 2015, as the electricity demand in the first years of this time period was lower (see Fig. 1). Also, for hydropower plants, we choose a somewhat higher utilization because the last years showed extreme low values due to the strong drought. For wind power, we choose a rather low value compared to the long-term utilization. This is due to the fact that this type of generation is highly variable and choosing high utilization targets would impose extreme demands on hydropower generation.

Reservoirs can be used to store and release water, i.e., generate electricity when needed. Therefore, first wind power generation is simulated, and in the second step, depending on electricity demand, hydropower generation is simulated to fill the gap between electricity demand and generation. Further restrictions are set for the discharges from the Sobradinho and Itaparica reservoirs: according to ONS (2016d, 2016e), the maximum discharge variation between two following days is 1000 m^3/s. The gap not covered by hydropower generation then needs to be covered by thermal power plants and/or imported electricity. Due to a minimum discharge of 1300 m^3/s, the hydropower plants have a base generation. Therefore, on days with high wind power generation, the combined hydropower wind power generation can be higher than the electricity demand to be covered by wind power and hydropower. In this case, thermal power plant generation and/or electricity imports can be reduced.

Climate data are needed for the simulation of wind power and hydropower generation. Wind speed data were available for the period from 2001 to 2015. Because precipitation data and climate data needed for the calculation of potential evaporation were only available up to 2014, the time period from 2001 to 2014 was used for this study. As the electricity demand during this time period was much lower than the demand in recent years, scenarios with electricity demands representing the present state (years 2013 to 2015) were applied. In scenario “demand 1” the observed electricity demand from 2013 is used for the years 2001, 2004, 2007, 2010, and 2013, the observed demand from 2014 is used for the years 2002, 2005, 2008, etc. Scenario “demand 2” uses the observed demand from 2014 for the years 2001, 2004, 2007, 2010, and 2013, the observed demand from 2015 for the years 2002, 2005, 2008, etc. In this way, three scenarios for the present electricity demand are created to account for the uncertainty surrounding electricity demand and climatic variation.

According to ANEEL (2016), the installed capacity for wind power generation in Brazil’s northeast region will increase to approximately 15,670 MW by 2020. For this “2020” scenario, an operational wind power capacity of 15,000 MW is assumed in the simulations for Brazil’s northeast region, i.e., it is assumed that a small share of the installed capacity due to maintenance is out of operation or is not connected to the transmission grid. For hydropower generation and thermal power generation, a negligible future change is given in ANEEL (2016) including an increase in installed hydropower generation of 33 MW.

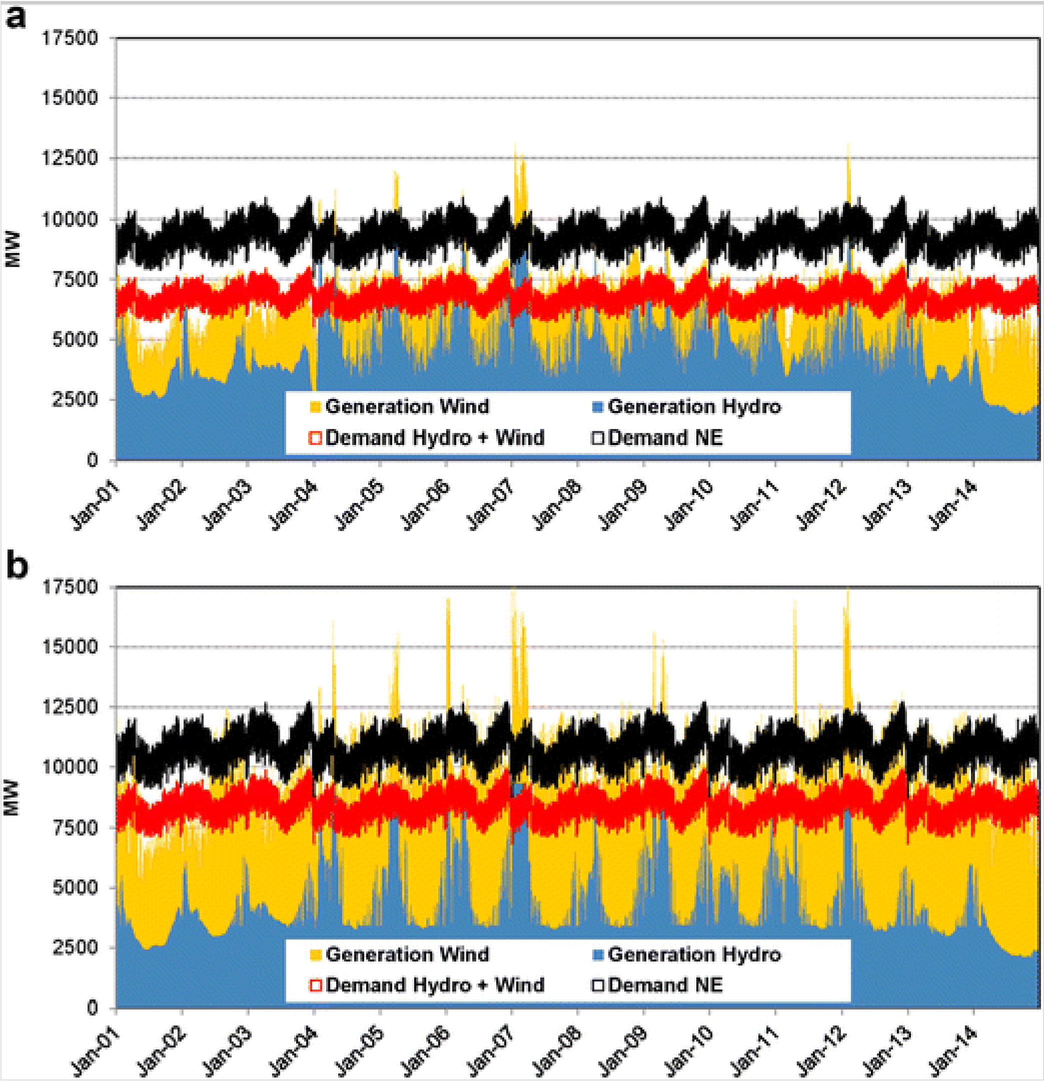
In the past, due to fast economic growth in Brazil, in the planning for Brazil’s northeast region, high growth rates for electricity demand of 5.0 to 5.4% per year were assumed (e.g., MME 2009). Due to the economic crisis in the last years, in the planning for 2014 to 2019, growth rates in electricity demand of 3.2% per year (MME 2015a) or of 3.7% per year for 2016 to 2020 (MME 2015b) were applied. According to ONS (2016a), the observed growth between 2014 and 2015 was 2.6%, while the observed growth between 2015 and 2016 was 2.4%. Therefore, in the second set of scenarios, labeled 2020, simulations are carried out assuming an increase in electricity demand of 3% per year until 2020, being somewhat lower than the values used by MME (2015a, b), but somewhat higher than the increase observed between 2014 and 2016. Using a growth rate of 3% per year, the mean electricity demand will increase from approximately 9530 MW (mean 2013 to 2015) to approximately 11,060 MW in 2020. A long-term utilization of 55% (mean generation of 2420 MW) for thermal power plants and of 50% for hydropower plants (mean generation of 4890 MW) is assumed. For wind power plants, a long-term utilization of 25% (mean generation of 3750 MW) is assumed. According to these assumptions, in the long-term, 78% of the electricity generation in Brazil’s northeast region should be covered by wind power and hydropower generation. The approach used in the simulation is the same as described above. First, wind power generation is simulated, and in the second step, depending on electricity demand, hydropower generation is simulated to fill the gap between electricity demand and generation. The restrictions for reservoir management, a maximum discharge variation between days of 1000 m^3/s and minimum discharge of 1300 m^3/s, remain unchanged. The remaining gap not covered by hydropower generation needs to be covered by thermal power plants and/or imported electricity.

Results

The simulated wind and hydropower generation, the demand on wind and hydropower generation, and the total electricity demand for Brazil's northeast region for scenario demand 1 are shown in Fig. 2a exemplary. For the very dry years 2001, 2002, and 2014, power generation by wind and hydropower plants is almost always lower than the demand on wind and hydropower generation, i.e., generation by thermal power plants and/or electricity import need to be increased in order to compensate. In the rather wet years 2004 to 2010, the generation of wind and hydropower plants is almost always higher than the demand on wind and hydropower generation, i.e., generation by thermal power plants and/or electricity import can be reduced. Sometimes the generation of wind and hydropower plants is even higher than the total demand, i.e., electricity can be exported. As can also be seen in Fig. 2a, during long drought periods, hydropower generation is not able to respond to changes in electricity demand. The variation in generation between days is very small, as only the minimum discharge is released. Daily variations in electricity generation can be very high in wet periods. The long-term mean utilization simulated for wind power generation is 35% (2456 MW), with a daily maximum and minimum of 81% (5671 MW) and 5% (372 MW), respectively. For hydropower generation, the long-term mean utilization simulated is approximately 45% (4380 MW), with a daily maximum and minimum of 100% (9780 MW) and 19% (1815 MW), respectively. The minimum hydropower generation for all three demand scenarios is simulated at the end of September and beginning of October 2014, where discharges from Sobradinho and Itaparica reservoirs are below the minimum discharge of 1300 m^3/s.

Fig. 2

Simulated wind and hydropower generation, demand on wind and hydropower generation, and total electricity demand for Brazil's northeast region **a** for scenario "demand 1" and **b** for scenario "demand 1 (2020)"

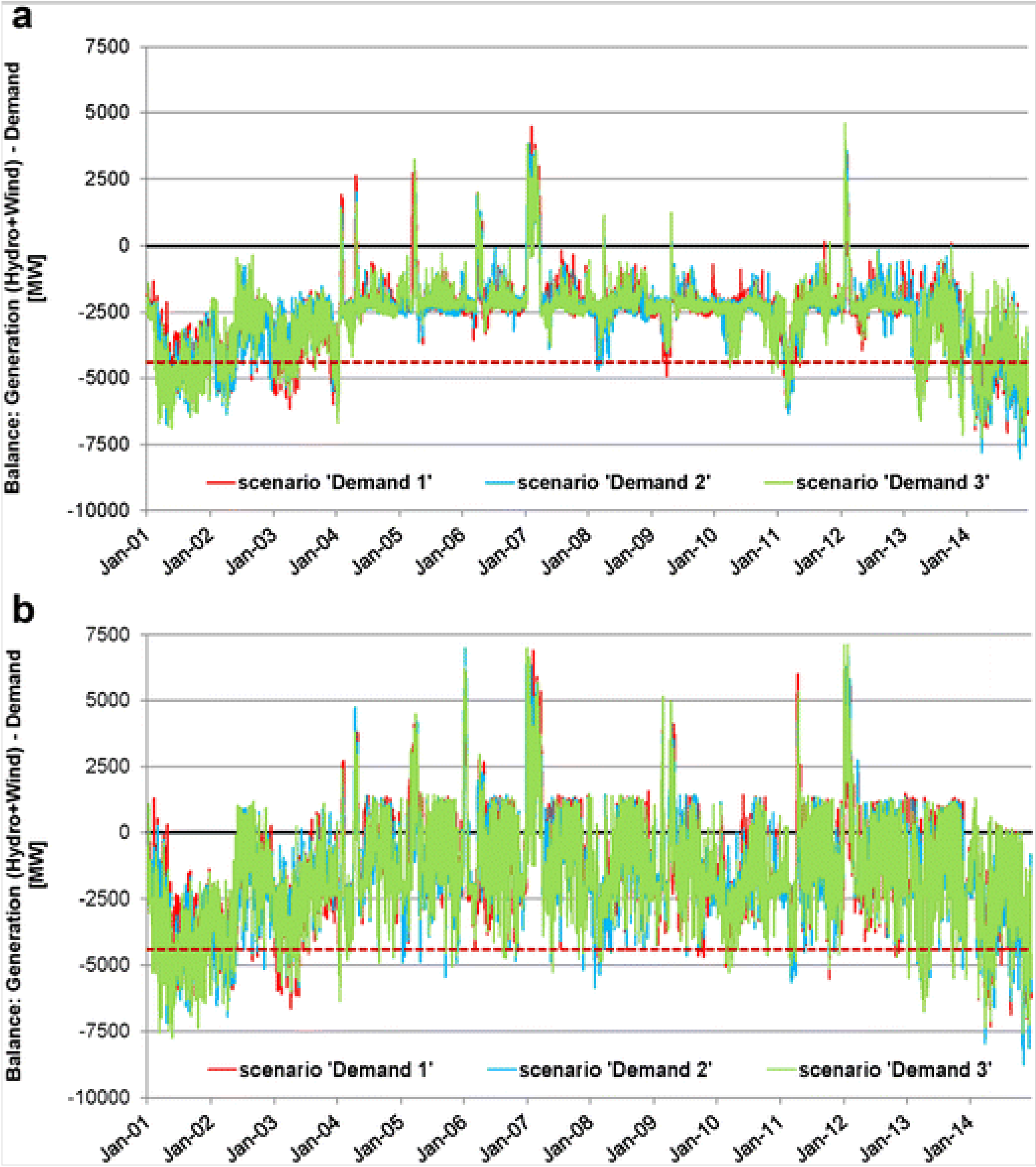


The simulated wind and hydropower generation, the demand on wind and hydropower generation, and the total electricity demand for Brazil's northeast region for scenario "demand 1 (2020)" are shown in Fig. 2b exemplary. In the year 2001 and the beginning of 2002, the generation of wind and hydropower plants sometimes is lower than the demand on wind and hydropower generation, i.e., generation by thermal power plants and/or electricity import is necessary. In the years from 2004 to 2013, the generation of wind and hydropower plants is almost always higher than the demand on wind and hydropower generation, thus generation by thermal power plants and/or electricity imports can be reduced. Sometimes the generation of wind and hydropower plants is higher than the total demand allowing for electricity to be exported. During the rather wet years from 2004 to 2012, a base hydropower generation of approximately 3200 MW is visible. Although wind power can provide most of the demanded electricity, the reservoirs need to release a minimum discharge of 1300 m^3/s and therefore are generating more electricity than is demanded. As the same wind speed data as for the present state (“2015”) are used, the utilization simulated for wind power generation is 35% (mean), 81% (maximum), and 5% (minimum). Due to the increased installed capacity, the mean generation is 5263 MW, with a daily maximum and minimum of 12,151 and 797 MW, respectively. For hydropower generation, the simulated long-term mean utilization is approximately 43% (4210 MW), with a daily maximum and minimum of 100% (9780 MW) and 21% (2060 MW), respectively. The minimum hydropower generation for all three demand scenarios is simulated for October and November 2014, where discharges from Sobradinho and Itaparica reservoirs are below the minimum discharge of 1300 m^3/s.

The balance between simulated wind and hydropower generation, and the demand on wind and hydropower generation, is shown in Fig. 3a for all three scenarios representing the present state. Also shown is the installed capacity of 4400 MW for thermal power plants. The balance between simulated wind and hydropower generation, and the demand on wind and hydropower generation is shown in Fig. 3b for the 2020 scenarios.

Fig. 3

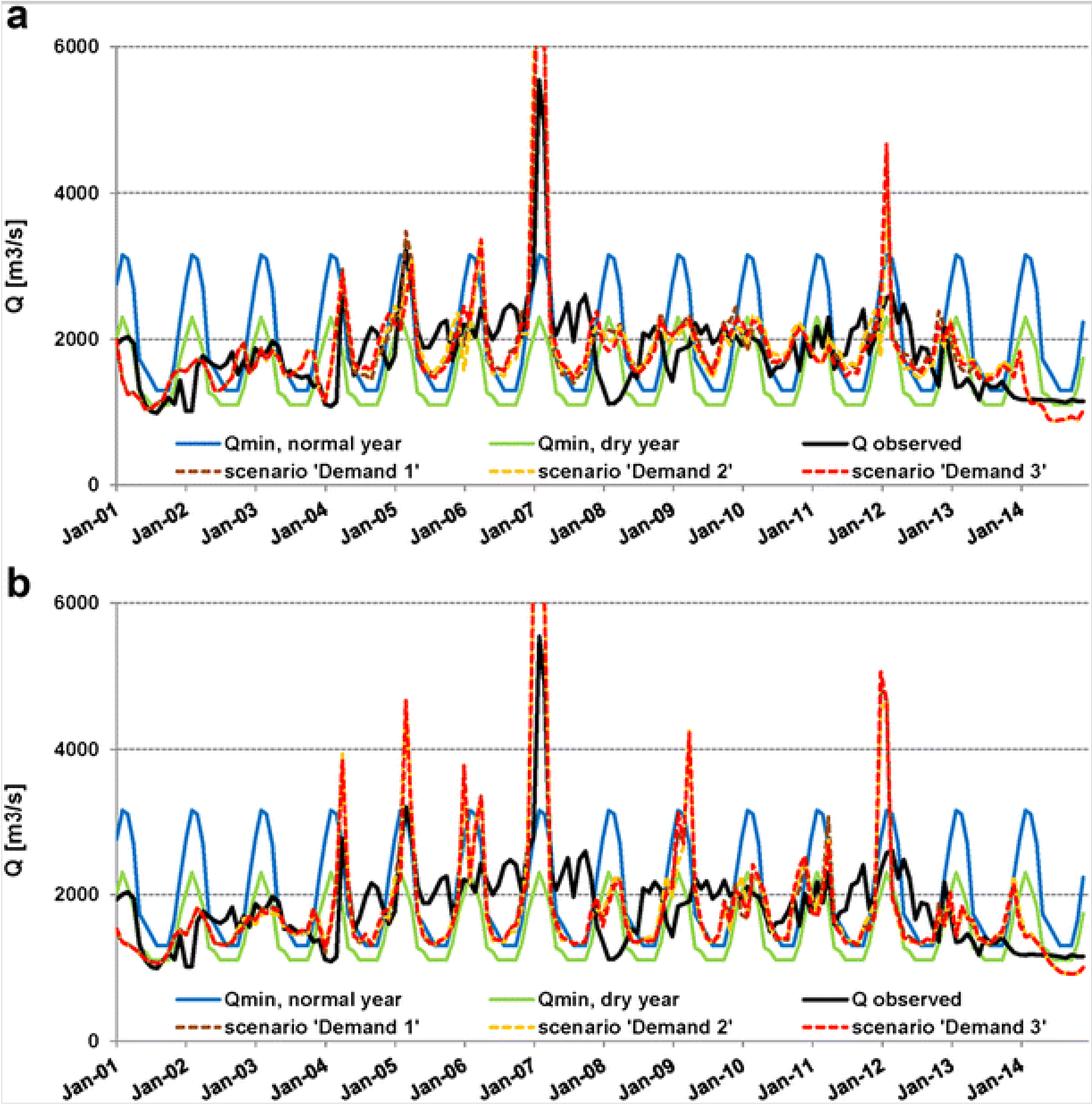
Balance between simulated wind and hydropower generation and demand on wind and hydropower generation **a** for the present state and **b** for “2020” scenarios, dotted brownish line: installed capacity of 4400 MW for thermal power plants



The mean monthly discharges from the Sobradinho Reservoir, observed from 2001 to 2014 and simulated for all scenarios, are shown in Fig. 4. Also shown are the environmental hydrograms for normal and dry years.

Fig. 4

Observed and simulated mean monthly discharge for Sobradinho Reservoir **a** for the present state and **b** for “2020” scenarios and environmental hydrograms for normal and dry years (Qmin)



The dimensionless Pardé coefficients (PC) relating the mean monthly discharge of a given month ($Q(mon)$) to the mean annual discharge ($Q(a)$):

- $$PC = \frac{Q(mon)}{\mathrm{Q}(a)} \quad 3$$

are shown in Fig. S3. To present the natural flow regime, observed flows from the 14-year period before the building of the first large dam, i.e., Três Marias Reservoir, are provided (the length of this period was chosen as all simulation runs also have a length of 14 years). The annual cycle existent before the building of the dams, i.e., the period from 1947 to 1960, shows the strongest variation, while the observed flows for the period from 2001 to 2014 shows the weakest variation, i.e., the Pardé coefficient is close to unity throughout the year. The variation for the environmental hydrograms is stronger than for the observed flows for the period from 2001 to 2014, but weaker than for 1947–1960, as water users and uses were considered in the creation of the environmental hydrograms.

For a further assessment of the flows, the volume and occurrence (Julian day) of the annual maximum 7-day mean flow and the annual minimum 7-day mean flow were selected from the IHA flow indicators. Other IHA indicators were analyzed too. It was found that for instance the annual minimum 1-day mean flow is not a good indicator for the flow regime of the Sub-middle and Lower São Francisco River Basin, as almost all years show at least 1 day with only the minimum discharge of 1300 m^3/s released by the reservoirs. This is true for the observations from 2001 to 2014, as well as for the scenario simulations.

In Fig. 5a, a concentration of high flows for the annual maximum 7-day mean flow for Itaparica Reservoir between Julian days 9 and 114 in the observations from 1947 to 1960 is shown. The observations from 2001 to 2014 show high flows between Julian days 278 and 131. The scenarios with present electricity demand (2015) show high flows between Julian days 311 and 126, while the scenarios 2020 show high flows between Julian days 338 and 97. The observations from 1947 to 1960 show annual minimum 7-day mean flow for Itaparica Reservoir between Julian days 271 and 337; the observations for the years 2001 to 2014 show a spread all over the year (Fig. 5b). In the scenario 2015, the minimum flows are still spread all over the year, concentrating between Julian days 170 and 260. The scenario 2020 shows minimum flows between Julian days 175 and 273.The mean monthly volumes for the Sobradinho Reservoir, observed from 2001 to 2014 and simulated for the scenarios representing the present state and the 2020 scenarios, are shown in Fig. 6a, b, respectively. In the long term, the storage variation is reduced in both scenarios compared to observations. In the short term (day to day) operation, discharge variations from the reservoirs are restricted to 1000 m^3/s between two following days. This can lead to restrictions in hydropower generation, e.g., a day with high wind power and low hydropower generation is followed by a day of low wind power generation and potentially high demand on hydropower generation, resulting in failures to meet the demand on wind and hydropower generation (see Figs. 2 and 3).

Fig. 5

Observed and simulated discharge and occurrence (Julian day) for Itaparica Reservoir. **a** Annual maximum 7-day mean flow. **b** Annual minimum 7-day mean flow

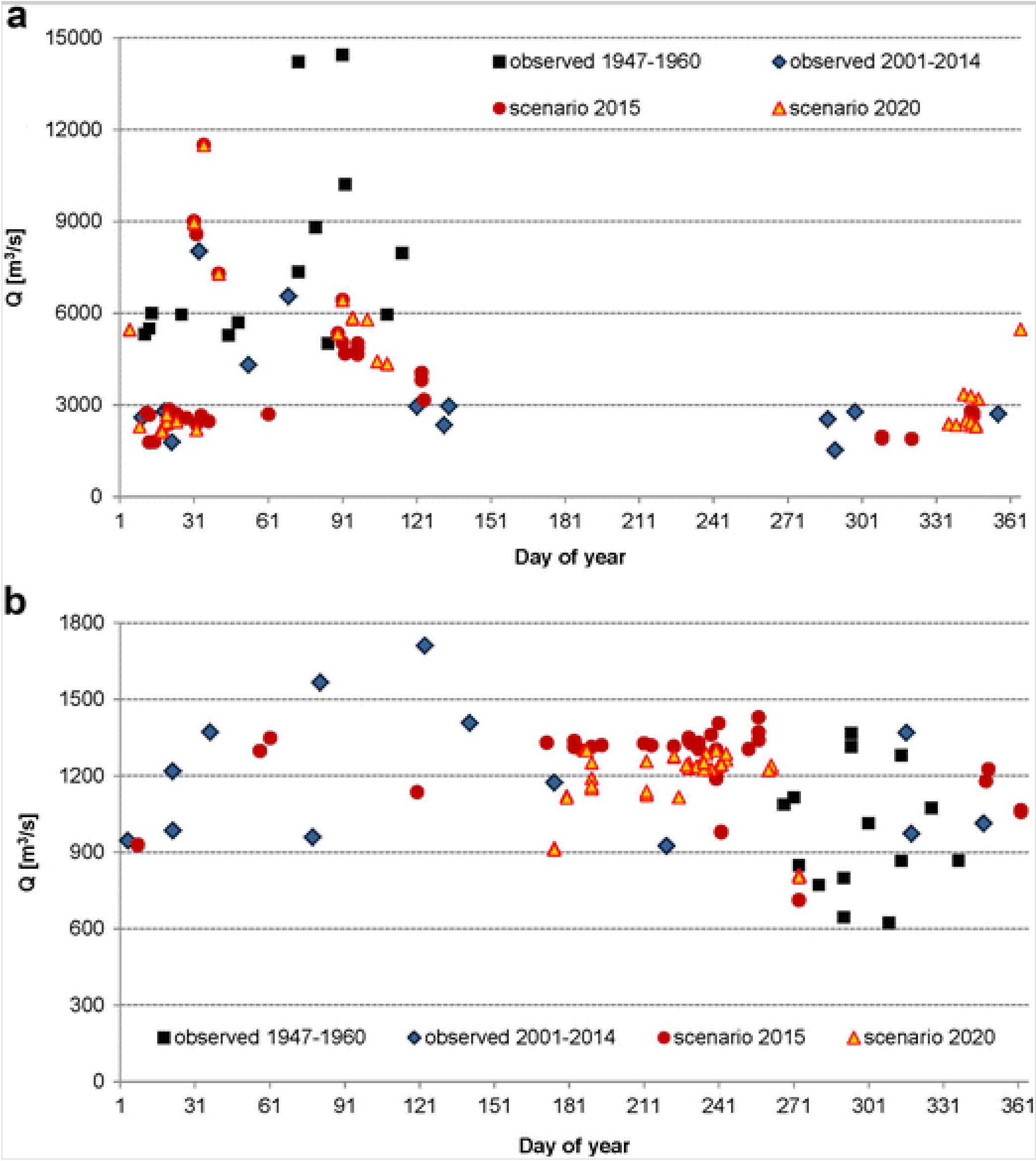
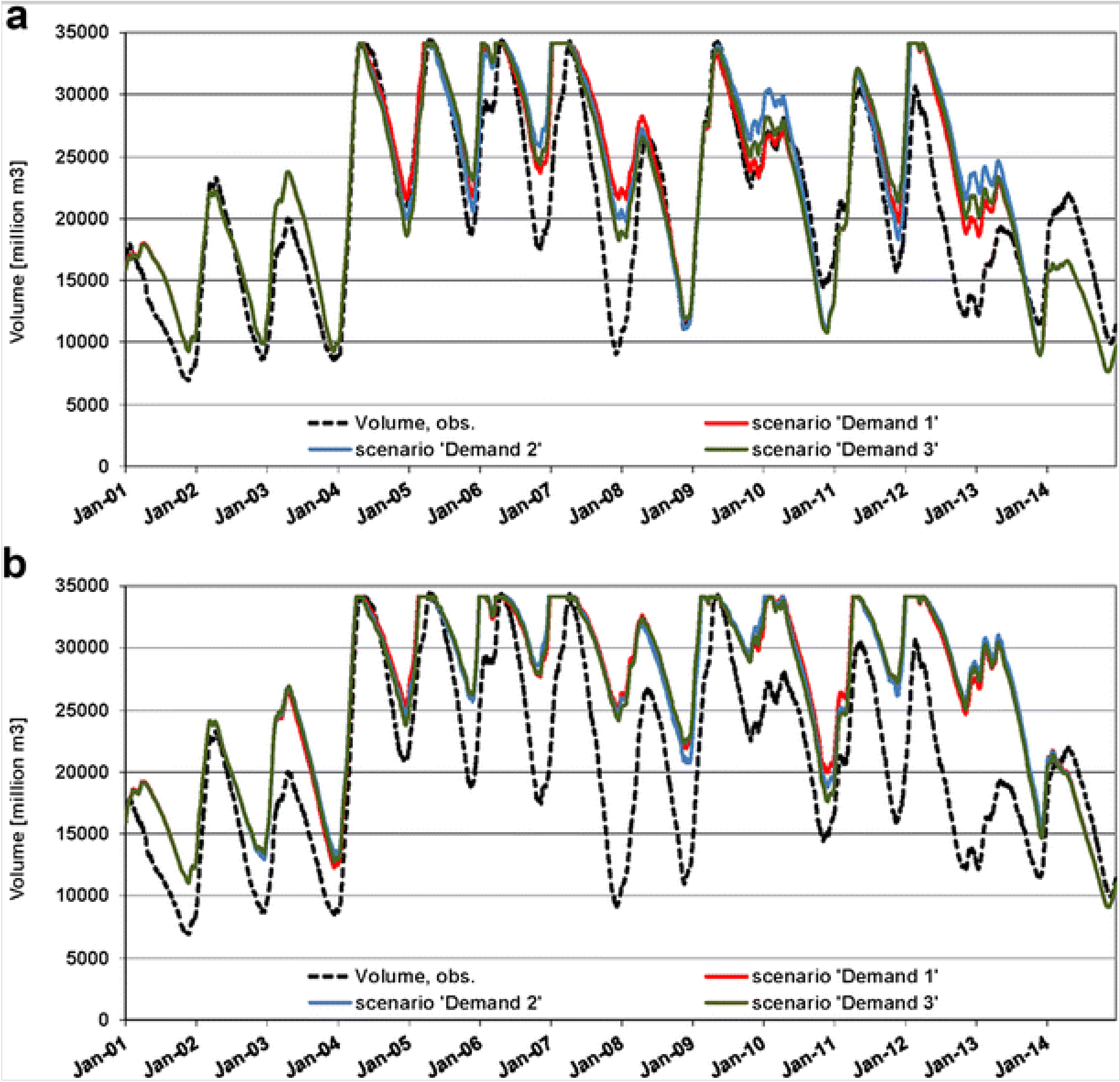


Fig. 6

Observed and simulated monthly volume for Sobradinho Reservoir **a** for the present state and **b** for “2020” scenarios



Discussion

In this paper, an approach to integrate electricity generation by wind power plants, hydropower plants, and thermal power plants is presented. In the scenarios analyzed, the high electricity demand in Brazil's northeast region cannot be fully covered by wind power and hydropower plants all the time. Under present conditions, a large share needs to be generated by thermal power plants or to be imported. Due to the strong increase in installed wind power generation capacity underway and planned for upcoming years, the share to be generated by thermal power plants or to be imported can be reduced. Compared to the present state, in the long term, less electricity needs to be generated by thermal power plants or to be imported. The simulations interconnecting wind power and hydropower generation lead to stronger variations in the demand on hydropower generation. With higher overall electricity demand and higher demand on wind power generation in the 2020 scenarios, due to the high variability in wind power generation, also the variability in the electricity balance (exchange with other regions) is increasing compared to the present state. In the three scenarios representing the present state, the long-term balance is − 2706, − 2745, and − 2722. In the three 2020 scenarios, the long-term balances are − 1639, − 1679, and − 1664 MW, respectively. That means, although electricity demand is increasing, due to higher installed wind power capacity, the electricity imports can be reduced.

While Jong et al. (2016) give an average electricity demand for the northeastern sub-system of 12,250 MW in 2020, we use an average electricity demand of 11,060 MW. One reason for the higher value given in Jong et al. (2016) is that due to the fast economic growth in Brazil in the decade 2001 to 2010, growth rates for electricity demand higher 5% per year were used in the past, while due to the economic crisis during the last years, we use a growth rate of 3% per year. According to Jong et al. (2016), wind power in Brazil's northeast region is currently undergoing rapid development and installed capacity is expected to exceed 16,400 MW by 2020 and that annual average wind power generation will grow to more than 6700 MW while according to ANEEL (2016), the installed capacity for wind power generation in Brazil's northeast region will increase to approximately 15,670 MW by 2020. In this study for the year 2020, an operational wind power capacity of 15,000 MW is assumed, a value also somewhat lower than given by Jong et al. (2016).

The question whether wind power generation can help to achieve a more environmentally oriented flow regime can be answered positively. The interconnection of wind power and hydropower generation enables a more dynamic flow regime in the Sub-middle and Lower São Francisco River Basin, i.e., higher discharges in the rainy season and lower discharges in the dry season compared to the observed values. During long drought periods, e.g., from 2001 to 2003 and from 2013 to 2014, the attempt to release higher discharges at the beginning of the rainy season leads to low discharges later on with discharges clearly below the minimum discharge. The same conclusions can be drawn for the 2020 scenarios (see Fig. 4b). Overall, for all scenarios simulated, the Pardé coefficients are very close to those of the environmental hydrograms, for the 2020 scenarios even closer than for the present state. The simulated flows for the annual maximum 7-day mean flow for the present state (2015) and the scenarios 2020 (Fig. 5a) show a certain shift for the day of occurrence, being closer to the pre-dam period (1947–1960) than the observed discharges (2001–2014). While the simulated flows for the annual minimum 7-day mean flow for the present state (2015) already show a concentration between Julian days 170 and 260, low flows can occur in any month. In the scenario 2020, minimum flows are between Julian days 175 and 273, while the observed minimum flows for the years 1947 to 1960 are between Julian days 271 and 337. Anyway, from these results, it can be concluded that especially in the scenarios 2020, the flow regime is much closer to the natural state than under the present operation, i.e., observed discharges from 2001 to 2014.

With regard to reservoir volumes, differences between the three demand scenarios are found in more wet years at the end of the dry and begin of the wet season (see Fig. 6). In more dry years, e.g., 2001 to 2003 or 2014, the differences between the three demand scenarios are very small, as the low reservoir volumes and restrictions in the reservoir operation reduce the ability to operate the reservoir according to the electricity demand and only the minimum discharge is be released from the reservoir. Side effects of the changed reservoir operation like reduced water availability for water users are included in the simulations by including minimum discharges from the reservoirs. During longer drought periods (years 2001, 2014), the simulated discharges are below the minimum discharge of 1300 m^3/s, but this is also found in the observed discharges under the present operation. The results for wind power and hydropower generation as well as for reservoir volumes point to the necessity to include longer time periods in this kind of study. Applying a shorter time period, e.g., years 2004 to 2010, the result would be that the electricity demand on wind power and hydropower generation can be supplied by these by 100%. Only including the drought periods at the start, years 2001 to 2003, and at the end, years 2013 and 2014, of the simulation period used in this study, periods of clear electricity deficits with the need to increase thermal generation and/or electricity imports are detected.

The values assumed for the long-term utilization of thermal power (55%), hydropower (50%), and wind power plants (25%) are open to discussion, as higher respectively lower values can change the results of this simulation study. The long-term mean utilization simulated for wind power generation is 35%, with a daily maximum and minimum of 81 and 5%, respectively. For the present state, the simulated long-term hydropower utilization is approximately 45%, with a minimum utilization of 19%, while for 2020, the long-term mean utilization is approximately 43% and the daily minimum is 21%. The increased installed wind power capacity in the 2020 scenarios reduces the long-term demand on hydropower generation (lower mean utilization), leading to higher volumes (see Fig. 6) and higher generation during drought periods (higher minimum utilization). In our simulations, a utilization of 25% for wind power plants is reached on approximately 75% of all days. From our perspective, this is a reasonable value for long-term planning as it indicates that during 75% of all days, hydropower utilization, assumed to be 50% in the long term, can be reduced and water can be stored for 25% of all days, where wind power generation is lower than the long-term planning value.

According to the results of this simulation study, by adopting an integrated approach for electricity generation, the flow regime in the Sub-middle and Lower São Francisco River Basin can be changed to achieve a better ecological status. It is important to recognize that at the same time other water demands, e.g., for irrigated agriculture or industrial use, may counteract the outlined approach in order to maintain the current flow regime. This does not stand against a relevant discourse to achieve a more environmentally oriented flow regime, but it is safe to say that a sound dissemination and cooperative discussion of such an integrated hydro-/wind power approach is crucial.

Furthermore, the ecosystems of reservoirs themselves are not considered here. For example, strong water level variations lead to the displacement of shorelines which affect the aquatic ecosystem in various ways (Hirsch et al. 2014; Hofmann et al. 2008; Wantzen et al. 2008; Coops et al. 2003). Large areas are getting inundated as a result of rising water levels and desiccated with declining water levels. Aquatic and riparian organisms are physically stressed during strong short-term water level variations (Hofman et al. 2008). It should also be recognized that wind power generation can come along with unintended side effects for ecosystem functions and services as well as social implications and thus need to be sensitively developed as well (Gartman et al. 2017). Inter alia, these side effects can involve implications for wildlife, likewise displacement of their habitats, collision with rotor blades and relevant cumulative effects (Köppel 2017; Gartman et al. 2016a, b; Bulling and Köppel 2016; Schuster et al. 2015; Gartman et al. 2014; Köppel et al. 2012). Manifold societal responses to the siting of wind farms have been voiced as well, for example, effects on real estate values, human health concerns like noise and infrasound discourse, visual impacts on landscapes of cultural and tourism relevance, and implications for indigenous people (e.g., Huesca-Pérez et al. 2016). On the other hand, according to de Sena et al. (2016), the social acceptance of wind and solar power generation in northeast Brazil seems strong.

In future studies, the generation by solar power should be included. According to ANEEL (2016), the installed capacity for solar power generation in Brazil's northeast region is 15 MW only. By 2020, the installed capacity will increase to approximately 1900 MW, i.e., 12% of the wind power generation capacity. Also, long-term effects of climate change on hydropower and wind power generation should be included in future studies. According to Hattermann et al. (2018, this SI), climate change could reduce hydropower generation markedly. However, recently available climate scenario runs of different climate models give no clear trend for future precipitation, i.e., some models show a wetter while others show a drier future for Brazil's northeast region (see also Silveira et al. 2016).

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