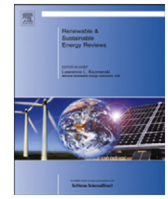
Renewable and Sustainable Energy Reviews 23 (2013) 526–535

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Solar and wind energy production in relation to the electricity load curve and hydroelectricity in the northeast region of Brazil

P. de Jong, A.S. Sánchez *, K. Esquerre, R.A. Kalid, E.A. Torres

Universidade Federal da Bahia, Escola Politécnica, Rua Aristides Novis, no. 2, 6 Andar—Federação, CEP 40.210-630 Salvador, BA, Brazil

A R T I C L E I N F O

Article history:
Received 10 April 2012
Received in revised form
23 January 2013
Accepted 26 January 2013
Available online 9 April 2013

Keywords:
Renewable energy
Load curve
Solar
Wind

A B S T R A C T

The objective of this research is to analyze the effectiveness of wind power and solar energy to supply electricity to the grid during peak demand periods in the Northeast of Brazil. To achieve this objective, a comparative analysis is performed between the electricity load curve for a typical year and a typical day and statistical data for wind speed and solar irradiation. The results obtained indicate that correlations exist and renewable energy can help support regional temporal demand in the existing electricity grid in an efficient and more environmentally friendly manner than fossil fuel power plants. Another interesting finding was the complementarity between hydroelectricity (the region's main energy resource) and wind and solar energy. That is, in the months of the dry season (when the cost of energy is more expensive) there is a greater availability of wind and solar energy. This makes investments in these two renewable sources more economically viable and also helps to diversify the electricity grid power supply, securing it against the effects of droughts.

Contents

1. Introduction

The Northeast (NE) region represents almost one fifth of Brazil's geographic area and is the homeland of 53.6 million people, as well as being the most arid part of the country. While Brazil overall has the world's largest water resources, this particular region suffers from occasional droughts, which can also affect the power supply, as the majority of the energy matrix is supplied by hydroelectricity. The region is privileged with huge solar and wind resources, while at the same time it imports a significant percentage of electricity from the North and Southeast regions [1], as shown in Fig. 1.

Forecasts for coming years, for the studied region, indicate an increase of around 4% in the Gross Domestic Product and an equivalent rise in the electricity demand [2,3]. This continuous rise of electricity demand is being addressed by increasing the capacity of existing fossil fuel power stations and by planning and constructing new ones [4]. The region's hydroelectric potential is almost saturated, and new tenders are only for small hydro plants. The main river of the region is the São Francisco River, which is responsible for 65% of the region's power supply [5]. With already five dams and several hydroelectric plants along its course, it is no longer possible to build big hydroelectric facilities as was done in the past. Additionally, there is a controversial project by the

* Corresponding author. Tel.: +55 71 32 839 800; fax: +55 71 32 839 801.
E-mail addresses: pieterj@ufba.br (P. de Jong), sanchezbahia@gmail.com, tevieneotekea@hotmail.com (A.S. Sánchez), karlaesquerre@ufba.br (K. Esquerre), kalid@ufba.br (R.A. Kalid), edniIdotorres@gmail.com (E.A. Torres).

1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2013.01.050

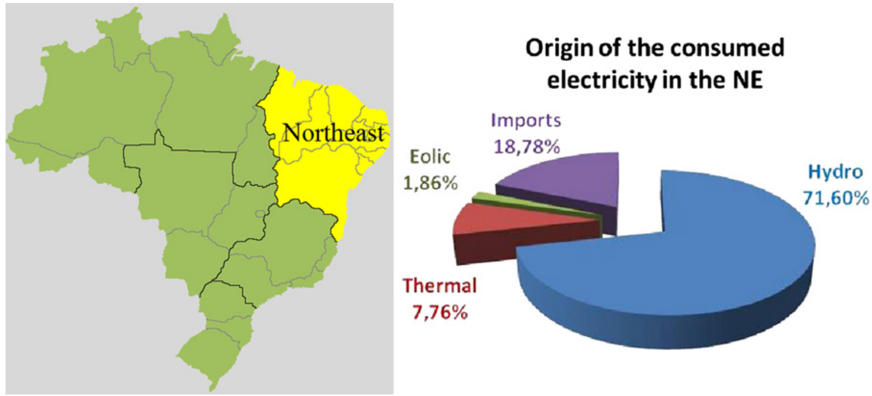


Fig. 1. Left: The Northeast (NE) region of Brazil. Right: Origin of the electricity consumed in the region, from Jan 2011 to Feb 2012. (Currently in the NE, "Thermal" electricity generation comes purely from fossil fuels. "Imports" consists mostly of hydro from other regions).

Brazilian government, already under construction, which aims to divert part of the river's water flow in order to irrigate arid territories. The completion of this project would further deteriorate the actual situation of hydroelectricity stagnation, resulting in a reduction of electricity production in the context of constantly rising electricity demand. The construction of the huge Belo Monte hydroelectric plant, in the northern state of Pará, once completed, will allow for an increase of imported electricity from the North region, but with significant amounts of energy loss due to the lengthy transmission lines. Additionally, large hydroelectric dams, such as Belo Monte, planned for the Amazon basin region have limited power output during the dry season and cause significant environmental conflicts.

In this context, the debate concerning the installation of nuclear power plants in the Northeast arises, fueled by the existence of uranium deposits in the region and by the government's wish to further develop the national nuclear industry. The "Plano Nacional de Energia- PNE 2030" (Brazilian National Energy Program) [6] which reflects the government strategy for expansion of the Brazilian electricity generation infrastructure, forecasts the need for an additional 4000 MW from nuclear power by 2025. This will mean the construction of two nuclear power plants in the Northeast and two more in the Southeast. According to this plan, the Brazilian Generation Matrix will see at least a 10% increase in the proportion of thermal electricity generation (including nuclear power) by 2030.

Whatever solution is adopted for electricity generation in the coming years, there is undoubtedly a need for planning, because the period of execution for large projects, such as a nuclear power plant or a big hydroelectric plant is in the order of 5–10 years. At the present moment Brazil is located at an interesting point in terms of energy planning, and current wind and solar technologies could play an important role in the near future. In this context, wind power has already taken off in the Northeast. In particularly the states of Bahia, Ceará and Rio Grande do Norte, have experienced a rapid growth in wind farm development due to their favorable conditions in terms of wind speed, frequency, distribution and turbulence.

By studying the correlation between the monthly variation of the load curve in a typical year and some characteristic parameters taken as representatives of renewable energy availability, this study aims to show the advantage of increasing the proportion of solar and wind power in the electrical grid in the Northeast. It will be shown that wind and solar power can support temporal demand variations in the electricity grid load curves (during a typical day and year) in a reasonably efficient manner.

Likewise, by studying the reverse correlation between the monthly availability of water in the São Francisco reservoirs and the availability of wind and solar power during a typical year, the benefits of solar and in particular wind power can be realized.

There have been a number of studies examining solar and wind resource complementarity and to what extent these resources correlate to peak load demand when connected to the electricity grid. Almeida [7] used a simple multivariable weather model for the simulation of a combined wind-solar-hydro power system in Portugal, using wind speed (m/s) at a height of 50 m, global radiation (kWh/m^2) and rainfall (l/m^2) data. The study calculated both simple and partial correlation coefficients between these three parameters.

Moura [8] in the article entitled "Multi-objective optimization of a mixed renewable system with demand-side management" studied the correlation between wind, solar and hydro resources in Portugal by presenting the yearly variation curves of their capacity factors.

A study by Hoicka and Rowlands [9] found that combining renewable energy sources such as wind and solar power in Ontario, Canada, smoothed out power production in terms of reducing instances of high and low values. Additionally, increasing the number of locations geographically of both wind and solar resources further smoothed out power generation and produced less variability. The study did not consider the correlation of wind and solar resources data with variations in the region's electricity load.

Li et al. [10] examines the correlation of wind and solar resources data against the electricity load curve in NSW, Australia for an entire year. The normalized results showed a strong complementarity between the combined resources of wind and solar source, which also cross correlated to the electricity demand.

Mai et al. [11] simulated hourly production of electricity in the USA for 2050 with nearly 80% of electricity from renewable resources, including nearly 50% from variable renewable generation. The simulations predicted that there would be no hours of unserved load during peak load hours in summer (July) or during any other hour of the year.

Similarly, Elliston et al. [12] demonstrated simulations for a 100% renewable energy systems to meet actual hourly demand in the Australian National Electricity Market (NEM) in 2010. They found that various renewable configuration were technically feasible and could meet the NEM supply-demand reliability standard. Technologies included in the simulations were concentrated solar thermal (CST) power with storage, wind, PV, existing hydro and biogas turbines.

Sayeef et al. [13] examined various international studies on the intermittency of wind and solar energy and their correlation with hourly load profiles. Similarly, Burger [14] shows daily weekly, monthly and annual graphs of planned versus actual production of photovoltaic, wind and conventional energies in Germany.

Fig. 2. Automatic station for environmental data collection.
Courtesy: SINDA.

In Brazil, though wind and solar resource data exists, very little research has been done on the complementarity of these renewable resources combined with existing hydroelectric plants and how they will impact on the electricity grid and the load curve.

A study on integrating wind energy generated in the NE of Brazil into the region's power system by Borba et al. [15] found that by 2030 there would be approximately 6.5% of surplus wind energy between midnight and 6am during the seasons of summer and autumn. The authors propose that this excess energy during the first six months of the year could be used to charge a fleet of plug-in hybrid electric vehicles. However the study does not take into consideration the water savings that could be made by controlling hydroelectricity production during these periods of surplus wind generation. A simple graph of seasonal variations between wind power, hydroelectricity output availability and the NE load curve demonstrates the complementary nature of wind power to large hydroelectricity availability, but the authors do not consider the advantages of this complementarity.

2. Methodology

The research is based on a statistical study of variables that define wind and solar resources, and their correlation with the load curve and the hydroelectric reservoir levels. The parameters chosen to characterize the availability of renewable energies are global solar irradiation on a horizontal surface (MJ/m^2) and wind speed at 10 m height (m/s). Extensive sampled data of these parameters were consulted in detail for the studied region. The specific location chosen for the meteorological data was the Metropolitan Region of Salvador (MRS) in the state of Bahia, however the parameters are extrapolated to represent the Northeast coastal areas, and therefore load curves and reservoir level data from the whole Northeast region were considered. Fig. 2.

With a population of 3.9 million, the Metropolitan Region of Salvador is the largest population center in the NE and includes a very active industrial area within its limits. It is worth noting that MRS is not one of the most privileged areas in terms of wind resources, but has a wind pattern similar in seasonal variation to the Metropolitan Region of Recife (MRR), which is the second largest metropolitan area in the Northeast. Altogether, these two metropolitan areas represent 40% of the total electricity consumption of the Northeast region and their demand behavior is quite similar to the overall load profile considered in the statistical study [16, 17].

The wind speed data represents a particular geographical area and depends on several factors (roughness of surface, relief, microregions with particular wind patterns). The representative area is smaller than in the case of solar, and is restricted to the surroundings of the data collection weather-station. The wind maps consulted in this research ("Atlas de Potencial Eólico da Bahia" [18] and "Atlas de Potencial Eólico do Brasil" [19]) show a wide area of homogeneous values for average wind speed that stretches up from the MRS along a large portion of the coast.

The global solar radiation offers a much bigger representative area. The yearly variation of this parameter for the MRS is similar to the whole of the Northeast (radiation isolines are shown in Fig. 3). However the MRS has one of the highest annual rainfall totals in the Northeast, and dryer locations away from the coast would be more suitable for solar facilities. Studies on the spatial variability of solar resources in phytogeographic homogeneous regions show that daily global radiation and monthly averages can be extrapolated up to 200 km away with errors of the order of 15% with a confidence level of 90% (Gallegos and Lopardo, 1998) [20].

For solar radiation data, measurements from SINDA—Sistema Nacional de Dados Ambientais—were used. SINDA is a Brazilian network of automatic weather-stations for environmental data collection [21]. The automatic weather station located in Salvador (Bahia) measures solar radiation (sun plus sky radiation) every minute with a LiCor pyranometer, logs the data, calculates the mean value every three hours and then transmits it to a satellite. The sensor accuracy is $\pm 5\%$ if properly calibrated against an Eppley Precision Spectral Pyranometer (PSP) and recalibrated every two years. For this research, the arithmetic mean value for solar radiation was calculated for each month, from September 1998 to May 2009.

Other solar radiation databases for the chosen location were consulted during the preparation of this research. The "Atlas Solarimétrico do Brasil" (Brazilian Solarimetric Atlas) [22] uses a set of Campbell–Stokes-type heliographs for direct solar radiation measurement, while the NASA Surface Meteorology and Solar Energy Dataset [23] use satellite measurement.

Even though the difference between the measurements of these three databases does not exceed 5% of the measured values, the SINDA Database was considered more accurate and its data was chosen for the monthly mean calculation, because of the quality of the measurement equipment, the regularity of periodic calibrations and because the SINDA Database had the longest measurement log.

Wind speed data at a height of 10 m was collected by a measurement tower at the Millennium Inorganic Chemicals industrial facilities located in Camaçari, MRS. The measurement instrument was an anemometer (wind tunnel-calibrated anemometer with $\pm 1.5\%$ accuracy) and a series of measurements (one every 15 min) were considered during the whole year of 2001. In order to assure that the wind pattern during that year had a similar behavior to other years, other databases were consulted including

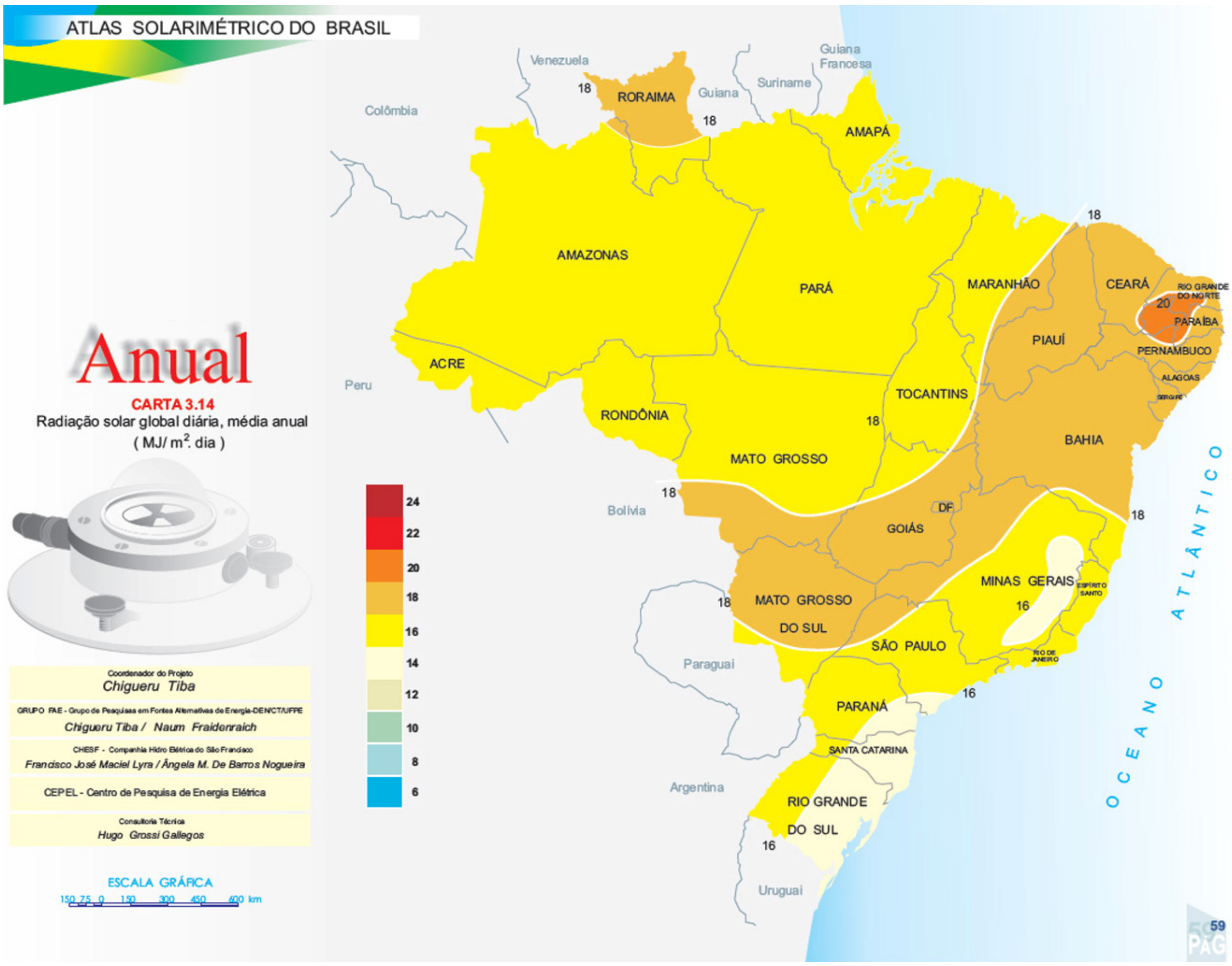


Fig. 3. Isolines for daily global solar radiation annual average.
Courtesy: Brazilian Solarimetric Atlas.

the “Atlas do Potencial Eólico da Bahia”, “Atlas do Potencial Eólico do Brasil” and also measurements from the same tower in the Millennium facilities for the years 1999, 2000 and 2002 [24]. More recent data at the same location was not available. Wind speed data for 2001 was the most complete dataset and had the least anomalies compared to the other years of available data. The SINDA database also has wind speed data at 10 m height for the same year and location (mean values every 3 h), so all data records were compared with the purpose of replacing outliers and missing values.

The load profile, which is the curve that shows the variation of the electrical power demand over periods of time, is available for the considered region, for periods of 24 h and 12 months. This load curve is calculated by the ONS—Brazil's Electrical Grid Operator—which has records of load curves for the last several years. The 12 month load curve profile was calculated as the mean from the last 13 years of load curves, using monthly mean values of electrical power demand measured by the ONS. The accuracy of the power demand measurement is approximately $\pm 0.8\%$ (according to the ONS' four-monthly revisions of demand projections) [25].

The ONS also maintains a historical record of reservoir water levels for each region in Brazil, due to the importance of hydroelectricity in the national energy matrix. Based on the measurements of the last 13 years, the mean curve that shows the annual variation of the water level in the NE region's reservoirs was calculated. But the time period of the research can be extended by considering the years before the big hydroelectric complexes were built. By focusing only on the São Francisco River, it is possible to calculate the mean values of its monthly flow rate for the entire period from 1931 to 2010, as there are complete flow records for these years at the locations where the main dams were built [26].

Once a reliable data base of electricity demand and renewable energy parameters was collected, a statistical study was carried out. Correlation coefficients between the data sets were calculated.

By comparing two sets of data at a time (Solar vs. Demand, Wind vs. Demand, Solar+Wind vs. Demand; Solar+Wind vs. Reservoir water levels and water flow rate, separately and together) a study of the relationship between the average monthly values of these parameters that characterize solar, wind, hydroelectric resources and electric demand during a typical year, can be carried out. The renewable energy system (Solar+Wind) that considers the combination of solar and wind resources assumes 50% solar and 50%wind power by calculating the mean value between the normalized solar and normalized wind average monthly values during a typical year.

The Pearson product-moment correlation coefficient (hereafter Pearson correlation coefficient) ranges from −1 to 1. When comparing two sets of data (X and Y), a value of 1 implies that a linear equation describes the relationship between X and Y perfectly, with all data points lying on a line for which Y increases as X increases. A value of −1 implies that all data points lie on a line for which Y decreases as X increases. A value of 0 implies that there is no linear correlation between the variables.

The Pearson correlation coefficient indicates the strength of a linear relationship between two variables (which may exist even if one is a nonlinear function of the other), but its value generally does not completely characterize their relationship. A visual examination of the data sets also proves to be useful, so graphs demonstrating the variations of the parameters during a typical year are shown with the aim of complementing the statistical calculation of Pearson correlation coefficients.

3. Variation of solar resources in the region during a typical year

The NE region is located between the Equator and the Tropic of Capricorn, and receives the highest annual average solar radiation in the country (see Fig. 3) which is due to the low precipitation rate. This enormous potential for electricity generation remains largely unexplored, with the exception of a few small photovoltaic systems in some isolated rural communities and the recently completed 1 MW PV Solar Plant in Tauá, Ceará, which is connected to the grid [27].

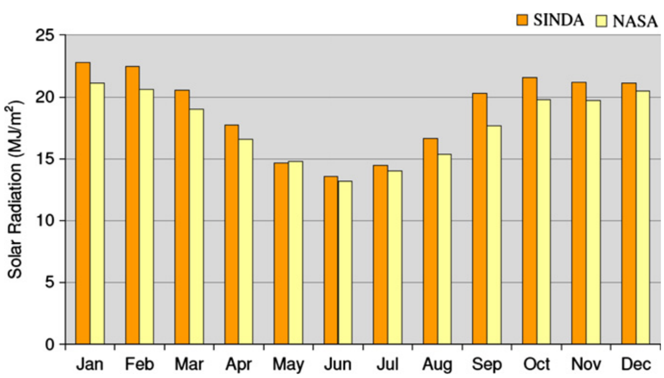


Fig. 4. Variation of annual average solar radiation for each month from 1998 to 2009 in the MRS.

The bar graph in Fig. 4, which shows the monthly variations of average daily solar radiation in the MRS during 12 months, is largely representative for most of the Northeast region as is demonstrated by the isolines in Fig. 3. There are relatively high values of solar energy even during the winter minimum month of June and the deviation does not exceed 28% from the annual average of 18.91 MJ/m^2.

4. Variation of wind resources in the region during a typical year

As well as the Northeast having the largest solar energy availability in the country (as seen above in Fig. 3), the Northeast region is also by far the most privileged in terms of wind power potential (Fig. 5).

According to the Empresa de Pesquisa Energtica EPE (Energy Research Company) the NE region has the potential to generate 75 GW of electric power from wind sources. If only 10% of this wind power potential was implemented, this would easily account for the electricity deficit in the NE that currently is imported from other regions. The best winds occur along the coastal areas of the states of Ceará and Rio Grande do Norte and in the interior of the state of Bahia (in the Chapada Diamantina region). In recent years, particularly in these three areas of the NE region, wind power production has taken off and reached a peak of 3% of the total energy generated in the NE in November 2011 [28]. Figs. 7 and 8 show the average wind power generated per month during 2011 in Ceará and Rio Grande do Norte where several wind farms already exist. As a result of the auctions held by ANEEL from 2009 to 2011, in Bahia alone, 57 wind farms with a capacity of 1418 MW are contracted to be installed in the next few years, and recently the state licensed locations for an additional 133 wind farms with a total capacity of 3200 MW [29,30]. The region's potential has also attracted the attention and business of international manufacturers of wind

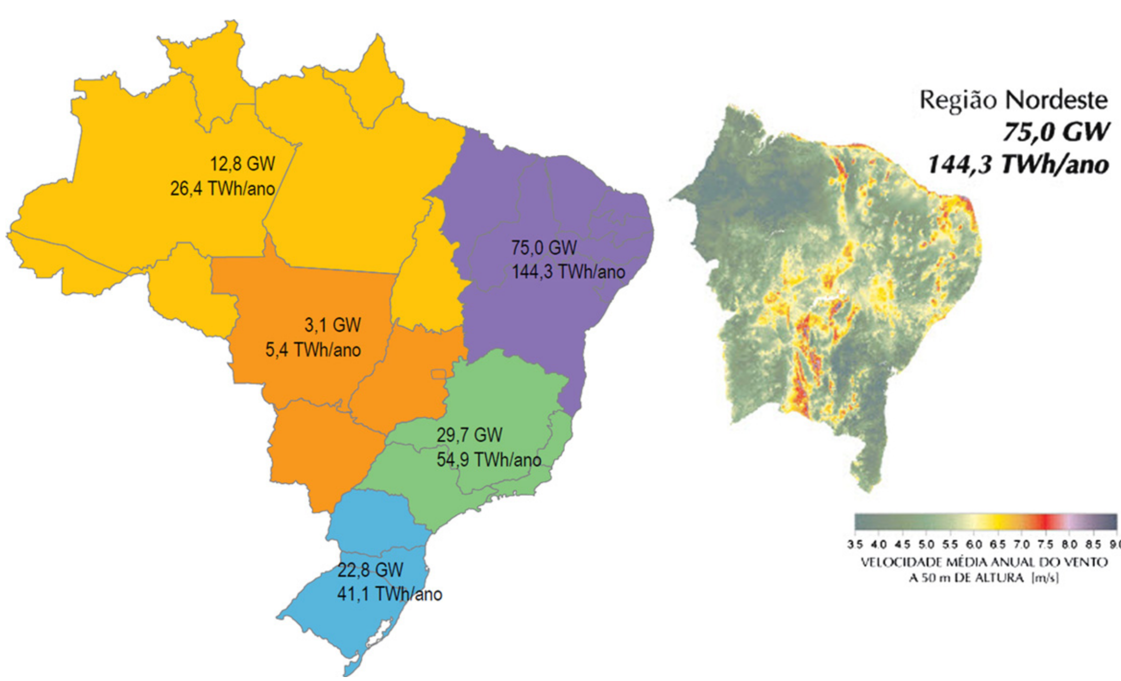


Fig. 5. Left: potential of energy generation from wind sources in the five regions of Brazil, courtesy of EPE. Right: map of available wind power for the NE region, courtesy of "Atlas de Potencial Eólico do Brasil".

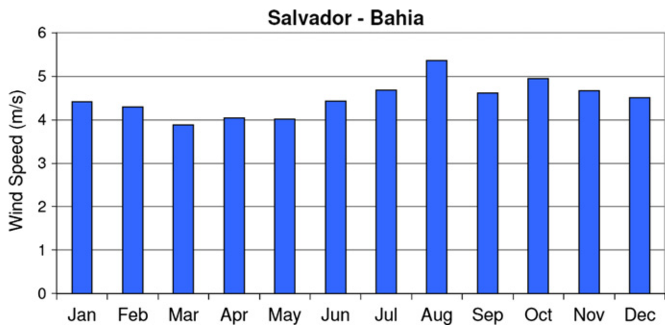


Fig. 6. Average wind speed (at a height of 10 m) for each month of 2001 in Salvador (NE State of Bahia).

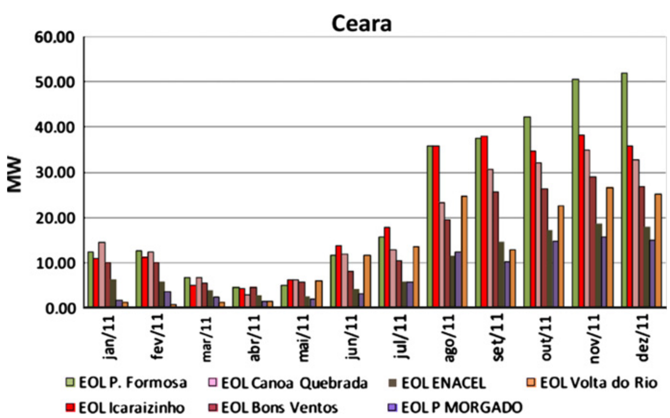


Fig. 7. Average power generated by wind farms in the NE State of Ceará (Jan 2011 to Dec 2011).
Courtesy: ONS.

turbines and blades (in 2011 both ALSTOM and Gamesa opened wind turbine factories in the Metropolitan Region of Salvador).

The monthly average wind speed for the MRS over a 12 month period, at a height of 10 m, is shown in Fig. 6. The average wind speed ranges from a maximum in August to a minimum in March. The curve shows little variability, with a maximum deviation of 19.5% around the mean value for the year of 4.5 m/s. Wind speed increases proportionally with height (see Eq. 1) and it can be observed that for the same location, at a height of 50 m (the typical height of modern commercial wind turbines) the average annual wind speed would be approximately 6 m/s, according to “Atlas do Potencial Eólico da Bahia”. By measuring wind speed data at a different height there is only a change in magnitude, but it does not change the average monthly or daily wind profile curve. The other data sources consulted provided similar average wind speed profiles at height of 30 m, 50 m and 70 m.

$$V_2 = V_1 (H_2/H_1)^{\alpha} \quad (1)$$

where:

V_1 is the wind speed at the height of the measurement, V_2 is the estimated new wind speed at a new height, H_1 and H_2 are the respective heights, α is the friction index, which is dependent on the location (Li et al.) [10].

It should be noted that wind regimes in different regions of the NE can vary from one another. Figs. 7 and 8 show the annual profile of wind power generation for Ceará and Rio Grande de Norte. Though not identical to the MRS profile, it can be seen that the minimum wind speeds also occurred in March and April.

5. Variation of hydropower availability in the region during a typical year

The interior of Brazil's Northeast region is known as the Drought Polygon. With 950.000 km^2, it is an irregular shaped region where people live under the recurring threat of water scarcity (the most recent drought occurring in 2012).

The semi-arid regions of NE receive an average of less than 800 mm of rain annually, most of which falls in a period of three to five months of the year (Dec–Apr). Occasionally there is much less rainfall than the average in consecutive years, which results in long periods of drought. This phenomenon is not anthropogenic, with the worst droughts recorded in 1777–78, 1877–79 and 1915 [31]. However, regional changes in rainfall patterns due to Global Warming may threaten the production of hydroelectricity to an even larger degree. Forecasts for the NE region show a marked decline in rainfall, resulting in a reduction of up to 60–90% of water flow rates in rivers in the NE by 2070 [32].

Fig. 9 shows curves of the monthly variation of the volume of water in the Northeast region's main reservoirs. Based on measurements over the last 13 years the mean curve for the volume of water in the NE reservoirs was calculated and is shown in Fig. 10. In Fig. 9 it is easy to visualize the drought of 2001, which caused interruptions and outages to the electricity supply in the region and also nationally, due to the reliance on hydroelectric generation.

An extension of the drought that began in 1998 caused by the “El Niño” phenomenon, the drought of 2001 was particularly severe compared to earlier ones: at the time, not only the Northeast, but the whole of Brazil was in an energy crisis scenario,

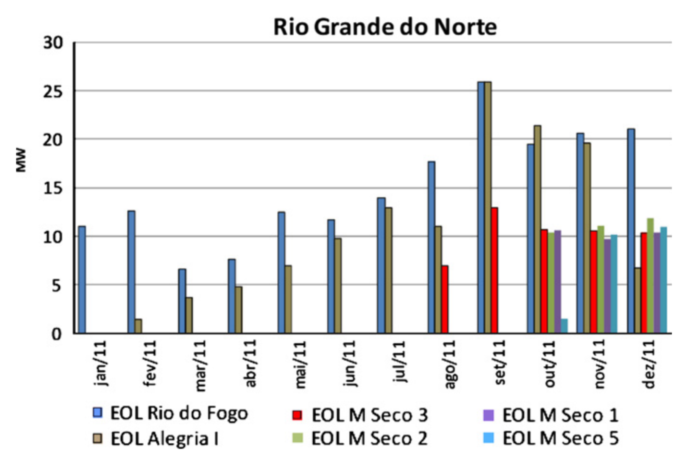


Fig. 8. Average power generated by wind farms in the NE State of Rio Grande do Norte (Jan 2011 to Dec 2011).
Courtesy: ONS.

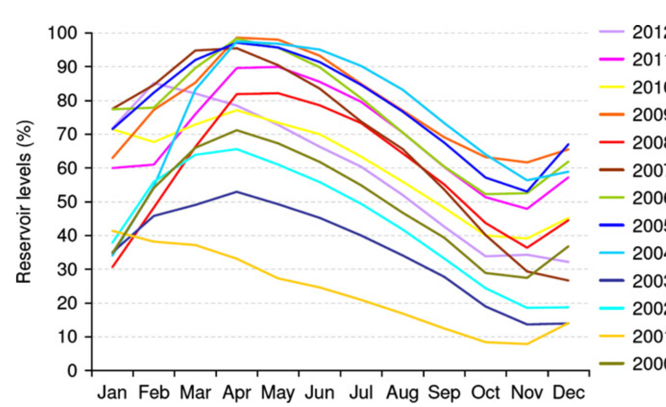


Fig. 9. NE reservoir volumes (as a percentage of the total capacity) from 2000 to 2012.

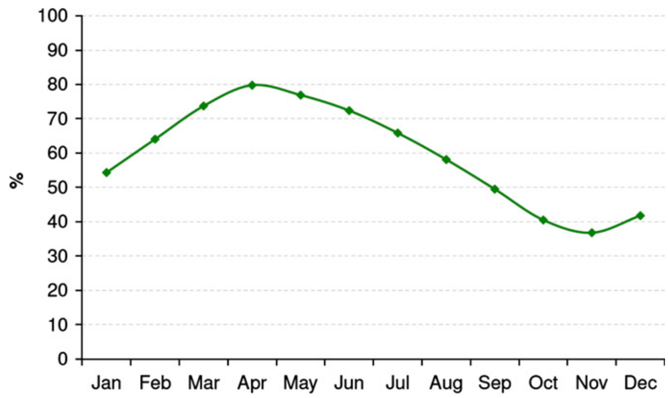


Fig. 10. Average reservoir level (2000–2012).

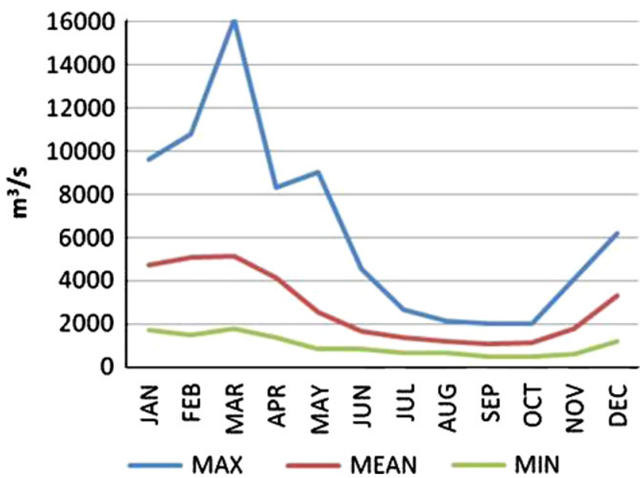


Fig. 11. Flow rate of the São Francisco River: curves with the maximum, mean and minimum recorded flow for each month. Average values from 1931 to 2010.

which was caused by lack of investments in the energy sector and the lack of rain. This was unprecedented in the country's history.

The government, caught by surprise, was forced to urgently cut 20% of electricity consumption in almost the entire country. After the drought broke in 2002, the application of these cuts—that caused severe losses in the Brazilian economy—was eased thanks to the positive results of a voluntary electricity-rationing campaign. One of the consequences of this crisis was the impetus given to electricity generation from fossil fuels in the following years.

Research on an even longer time frame can be done on the hydroelectric resources of the NE region, by also focusing on the monthly variations of the São Francisco River's water flow, as the ONS has flow data for the past 80 years. To calculate the Pearson correlation coefficients, the river's mean flow rate for each month of a calendar year was considered as shown in Fig. 11.

6. Variation of the NE's electricity demand (load curve) during a typical year

In 2011 the average electricity demand in the NE region was approximately 8500 MW with instantaneous peaks of 10,000 MW [33]. The three major metropolitan areas in the NE (Salvador, Recife and Fortaleza) account for an average demand of 2100, 1100 and 1500 MW respectively.

A correlation between energy demand and daily temperatures has been established by many electrical utilities as there is a causal

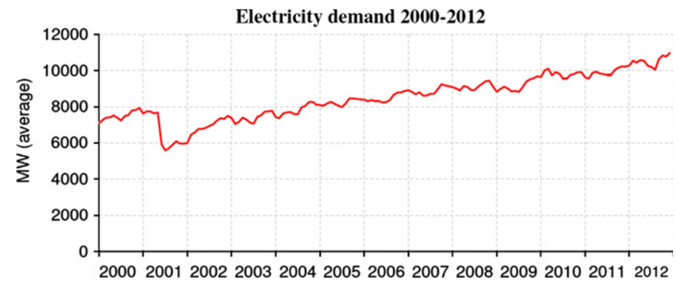


Fig. 12. Growth in electricity demand in the NE region since 2000.

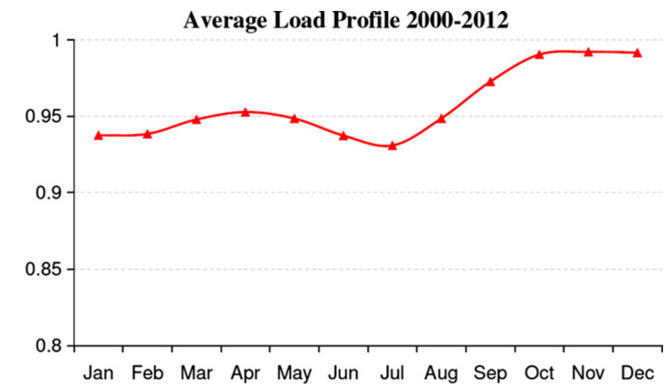


Fig. 13. Normalized average electricity load profile in the NE region during the last 13 years. (Vertical scale only shows the upper 20% part or the curve). Data from 2001 and 2002 were disregarded, because they were atypical years due to a severe drought which resulted in electricity-rationing in 2001 and the removal of rationing in 2002.

Table 1
Pearson correlation coefficients for the studied parameters.

	Solar	Wind	Combined Solar + Wind
Demand (yearly load curve)	0.464	0.286	0.546
Hydro availability (reservoir level)	−0.595	−0.611	−0.815
São Francisco river flow rate	0.459	−0.703	0.075

relationship: electrical consumption tends to drop on temperate days due to lower demand for air conditioning (or heating in the case of colder climate countries). According to the ONS, the occurrence of milder temperatures during 2011 was one of the reasons the electricity demand did not rise significantly in the NE region compared with other years [33]. In the NE region there is a large influence on electricity demand from air conditioning use. That is, there is increased electricity demand during the austral summer (from November to March) when the highest temperatures typically occur and there is less electricity demand in the cooler months from May to August.

The resulting Load Profile for the NE region, considering data from the last 13 years (as shown in Fig. 12), is influenced by seasonal consumption patterns as explained above and by the annual growth in demand. Therefore average demand in the last months of the year tends to be higher than in the initial months of the same year, as shown in Fig. 13.

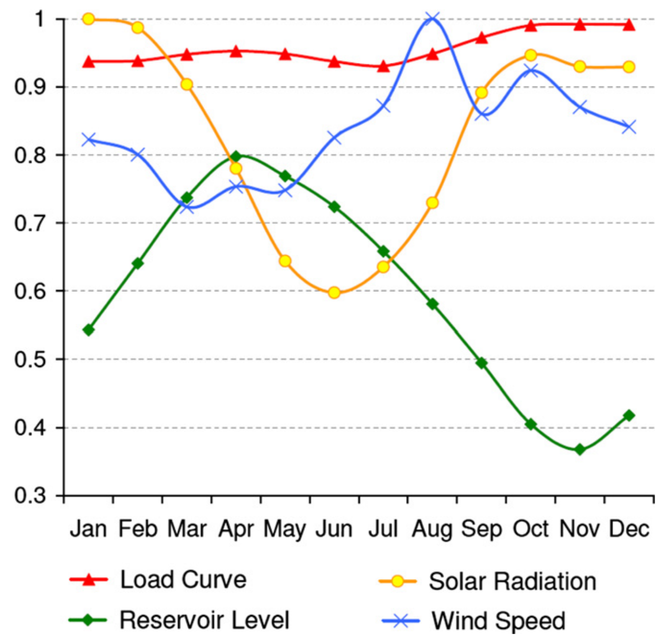


Fig. 14. Monthly variation of the parameters normalized to their maximum value.

7. Correlations and results found

The calculated Pearson correlation coefficients are shown in Table 1. There is a significant positive correlation between the individual renewable energy sources (wind and solar) and the yearly load curve. The negative correlation between the renewable energy sources (Wind + Solar combined) and the NE's hydroelectric capacity (reservoir levels) has a much larger magnitude (0.815). Importantly this demonstrates that during the months when hydroelectric capacity is reduced, the average output from the renewable energy sources (wind and solar) is greater and vice versa.

Although the values of the coefficients indicate a medium-strong level of correlation between the parameters, the correlations are better illustrated graphically in Fig. 14, which shows the variations of all the parameters during a typical year.

Solar radiation has a variation of 40% between its minimum and maximum annual values. For wind, the variation for the studied years was around 27%. These resources complement each other very well: lower wind speeds tend to occur during the austral summer (from November to March) when solar radiation is at its maximum. During austral winter, from May to September, solar radiation is at its lowest levels, while wind speeds tend to be stronger and more consistent.

The variations of solar and wind resources, considered aggregately, have the potential to complement greatly the drop in hydroelectric availability that occurs typically between June and November. Higher and more consistent wind speeds typically occur in the dry season, when the São Francisco's flow is at its minimum (in the months when there is more scarcity of water).

In the last few months of each calendar year (October–December), the electricity demand increases to its maximum and at the same time hydroelectric reservoirs reach their lowest levels (approximately 40% of their maximum in November). Fortunately in these critical months of high energy consumption and low hydroelectric availability, wind and particularly solar resources are high compared to their annual maximums (average wind speeds are approximately 85% of their maximum and solar radiation is approximately 95% of its annual maximum).

Additionally in these same critical months (October–December) the average power output from existing wind farms in Ceará reach their annual peak and wind power outputs are also high in Rio Grande do Norte as shown in Figs. 7 and 8.

From November the São Francisco flow rate usually begins to increase and the reservoirs begin filling again. However, if there is a lack of rainfall and a long drought occurs, reservoir levels would further drop and without alternative electricity supply sources, such as wind power, shortages in electricity supply could occur as happened in 2001.

The tariff structure of Brazilian electricity utilities could play an important role in the implementation of wind farms and solar plants in the region. In the RMS as well as in many other locations in the NE, the hourly-seasonal pricing structure reflects the reliance on hydroelectricity. The rate per megawatt differentiates between both peak and off-peak periods and between the dry season (May–Nov) and the wet season (Dec–April), during which the reservoirs fill to their highest levels [34].

It can be argued that there is a clear correlation between the months of greater wind and solar energy resource availability and the months of water stress, when high (dry period) energy tariffs are in place. This coincidence is a factor in making investments in the renewable energy sector more economically viable.

8. Renewable energy sources compared to the electricity load curve during a typical 24 h

A more detailed investigation focusing on the hourly variations of wind, solar resources and the electricity demand profile during a typical 24 h day can be done using the consulted meteorological databases together with ONS load curve profile.

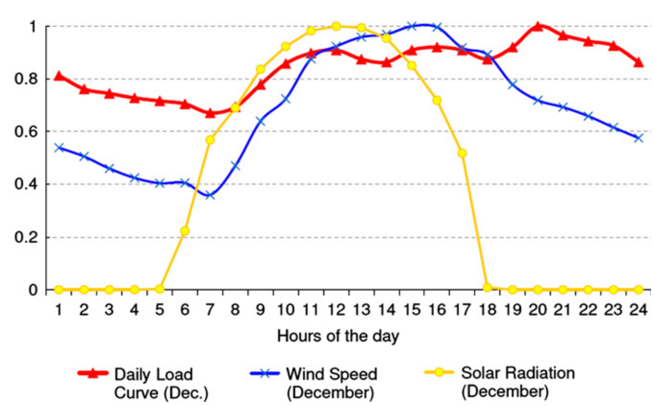


Fig. 15. Summer hourly variation of the parameters normalized to their maximum value.

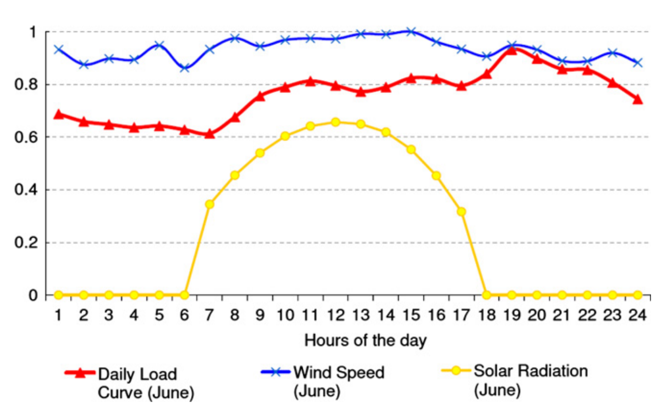


Fig. 16. Winter hourly variation of the parameters normalized to their maximum value.

In Fig. 15, the hourly load curve profile for the NE region [17] during a typical December (summer) weekday is plotted together with the hourly December average wind speeds and average solar radiation. The plotted values for respective parameters were calculated by taking the mean of all measurements of each particular hour in the entire month. Then the mean values for each respective parameter were normalized as a fraction of their maximum value (which occurred in either December or June).

The curves in Fig. 16 were calculated by the same method, but show the results for a typical June (winter) weekday.

The electrical load for a typical 24 h weekday in the Northeast drops down to a minimum between 3:00 h and 7:00 h, and features its highest peaks between 19:00 and 20:00 h. As a result of electricity consumption patterns, there are specific peaks at 11:00, 15:00, 19:00 and 22:00 h.

Electricity distributors such as COELBA (the Electric Company of Bahia) raise energy tariffs during three consecutive hours chosen by the consumer between 17:00 h to 21:00 h and between 19:00 h to 22:00 h during daylight saving (summer time) [29,12].

Wind and solar energy resources correlate reasonably well to the load curve during daylight hours and have the potential to help satisfying electricity demand during the morning and early afternoon peaks.

Solar energy could be a good choice to support the daily rise of electricity demand that occurs in the morning from 7:00 h until the second peak in demand at 15:00 h, however PV solar power would not support the main peak in demand at 19:00 h (in winter) and 20:00 h (in summer). In order to support the demand after the second peak, various technologies of thermal energy storage could be employed. Concentrated solar thermal plants in operation today (in Italy, Spain and the USA) are already storing energy in the form of thermal oil and pressurized molten salts to extend the daily operational period of the plants. Solana, the largest solar plant in the world (in Arizona, USA) was designed with a capacity of six hours of energy storage to cover the local demand peak, according to Abengoa Solar and the Department of Energy of the United States [35].

In the summer months the 24 h wind speed curve varies with an oscillating behavior, with a pronounced maximum at about 15:00 h and minimum at about 6:00 h. Wind speeds during the winter months have much less variation and are more consistent throughout the day and night. The greater daily oscillation in summer, compared to winter, is due to sunlight heating air and land masses in the central hours of the day, which in summer causes a greater variability in the average wind speed profile during a 24 h day. This meteorological effect is in keeping with various studies that found that wind and solar power combined are often complementary during a 24 h day and their combined output is generally smoother with fewer severe troughs and peaks [9].

In Fig. 15 it can be observed that the average daily minimum wind speed in summer coincides with the minimum in electrical demand and then from 7:00 h accompanies the rise in electricity demand in the morning. Additionally the average wind speed remains relatively high until about 18 h and therefore wind power could support all the daylight peaks in demand (at 11:00 and 15:00 h). In summer, even though the average wind speed steadily declines from about 18:00 h to midnight, wind power could still significantly support the evening peaks in consumption which occur at 19:00 and 22:00 h.

However there is still concern about the reliability and security of electricity generated from wind and solar power, due to the uncertainty and intermittent nature of wind and sunlight. Neither wind nor PV solar power can be relied upon 100% of the time, due to their sporadic nature, without some kind of energy storage or hybrid system. But in Brazil the existing hydroelectric network could also easily serve as a hybrid system. Unlike coal fired power stations, the power output from hydroelectric plants can be adjusted rapidly to increase or decrease supply as required.

9. Conclusion and future work

This study has shown that renewable energy sources in the NE region of Brazil (particularly when used in combination with each other) have a correlation with the electricity load curve during a typical 24 h day. Both wind and solar power have the potential to assist with energy production during the morning and early afternoon peak electricity demand, while wind power could also partly support the evening peak demand.

Wind power resources are more abundant in the dry season months (May–November) when water flow into the São Francisco reservoirs is at its lowest level and solar power is more abundant when hydroelectric reservoirs are at their lowest levels. This is important as the NE, compared to the other regions of Brazil, is particularly vulnerable to water shortages either as a result of drought or from the effects of global warming and this will significantly impact on the NE's ability to reliably supply energy from hydroelectricity. Therefore renewable energy production will help to save water during the dry season and improve energy security in the NE region. The coincidence that wind resources are greater during most of the dry season when electricity costs are higher, significantly contributes to the viability of renewable energy plants such as wind farms.

Solar energy is strongest in summer months (October–March), which coincides exactly with the months of highest demand and thus could support electricity production during daytime peak demands caused by air conditioning.

Other studies could be performed considering the correlation of demand with the uncertainties of renewable energy sources. Further study could include an analysis of the stability of energy produced from an operational wind farm in the NE and measured real-time energy output from other types of renewable energy installations over consecutive 24 h periods.

Acknowledgment

We would like to thank the Coordination for the Improvement of Higher Education Personnel - CAPES and the Ministry of Science and Technology of Brazil for its financial support for this research.

References

[1] ONS—Operador Nacional do Sistema Elétrico. Planejamento da Operação Elétrica de Médio Prazo. PEL—2012–2013; 2011.
[2] ETENE—Escritório Técnico de Estudos Económicos do Nordeste. Cenário Macroeconómico. 2012. Tech. rep.; 2011.
[3] MME—Ministry of Mines and Energy (Brazil) and EPE—Empresa de Pesquisa Energética. Projeção da Demanda de Energia Elétrica para os anos 2011-2020. Nota Técnica DEA 03/11; 2011.
[4] MME—Ministry of Mines and Energy (Brazil) and EPE—Empresa de Pesquisa Energética. Balanço Energético Nacional; 2011.
[5] ONS—Operador Nacional do Sistema Elétrico. Plano Anual da Operação. vol. I; 2011.
[6] MME—Ministry of Mines and Energy (Brazil) and EPE—Empresa de Pesquisa Energética. Brazilian National Energy Program/Plano Nacional de Energia. PNE 2030; 2006.
[7] Almeida AT de, Martins A, Jesus H, Clímaco J. Source reliability in a combined wind-solar-hydro system. IEEE Transactions on Power Apparatus and Systems 1983;6:1515–20 PAS—102.
[8] Moura PS, Almeida AT de. Multi-objective optimization of a mixed renewable system with demand-side management. Renewable and Sustainable Energy Reviews 2010;14:1461–8.
[9] Hoicka CE, Rowlands IH. Solar and wind resource complementarity: Advancing options for renewable electricity integration in Ontario, Canada. Renewable Energy 2011;36:97–107.

[10] Li Y, Agelidis VG, Shrivastava Y. Wind-solar resource complementarity and its combined correlation with electricity load demand. ICIEA: 4th IEEE conference on industrial electronics and applications, p. 3623–8; 2009.
[11] Mai T, Wiser R, Sandor D, Brinkman G, Heath G, Denholm P et al., Exploration of high-penetration renewable electricity futures. Vol. 1 of renewable electricity futures study 2012—Golden. CO: National Renewable Energy Laboratory.
[12] Elliston B, Diesendorf M, MacGill I. Simulations of scenarios with 100% renewable electricity in the Australian national electricity market. Energy Policy 2012;45:606–13.
[13] Sayeef S, Heslop S, Cornforth D, Moore T, Percy S, Ward JK, et al. Solar intermittency: Australia's clean energy challenge—characterising the effect of high penetration solar intermittency on Australian electricity networks. Australian Solar Institute—ASI, 2012, p. 195.
[14] Burger B. Electricity production from solar and wind in Germany in 2012. Fraunhofer Institute for Solar Energy Systems—ISE, 2012, p. 260.
[15] Borba BC, Szklo A, Schaeffer R. Plug-in hybrid electric vehicles as a way to maximize the integration of variable renewable energy in power systems: the case of wind generation in northeastern Brazil. Energy 2012;37:469–81.
[16] Godoy MV de. Modelagem do consumo de energia elétrica residencial na cidade de Recife: o processo de tomada de decisão para políticas de eficientização de energia elétrica; 2006.
[17] ONS—Operador Nacional do Sistema Elétrico. RE-3-128-2008 PEL 2009–2010; 2008.
[18] COELBA—Companhia Elétrica da Bahia and ANEEL—Agência Nacional de Energia Elétrica/Brazilian Electricity Regulatory Agency. Atlas do Potencial Eólico do Estado da Bahia; 2003.
[19] Brower M, sá AL de, Zack J. Atlas do Potencial Eólico Brasileiro. CRESESB; 2000, p. 42.
[20] Grossi Gallegos HG, Lopardo R. Spatial variability of the global solar radiation obtained by the Solarimetric Network in the Argentine Pampa Humeda. Solar Energy 1998;40(5):397–404.
[21] INPE—Instituto Nacional de Pesquisas Espaciais/National Institute for Space Research in Brazil and CPTEC—Centro de Previsão do Tempo e Estudos Climáticos/Center for Weather Forecast and Climatic Studies. Sistema Nacional de Dados Ambientais—SINDA Database; 2012.
[22] Tiba C, Fraidenraich N, Moszkowicz M, Gallegos HG, Lyra FM. Atlas Solarimétrico do Brasil/Solarimetric Atlas of Brazil, CRESESB; 2000.
[23] RETScreen Climate Database, based in NASA satellite measures and software RETScreen4, RETScreen International; 2011.
[24] Millennium Inorganic Chemicals Inc. Meteorological database; 2002.
[25] ONS—Operador Nacional do Sistema Elétrico. 2ª Revisão quadrimestral das projeções da demanda de energia elétrica do Sistema Interligado Nacional; 2010.
[26] MPX Ltd., Workshop sobre inovação para o estabelecimento do setor de energia solar fotovoltaica no Brasil; 2011.
[27] ONS—Operador Nacional do Sistema Elétrico. Acompanhamento mensal de geração de energia das usinas eolielétricas com programação e despacho centralizados pelo ONS; November 2011.
[28] ANEEL—Agência Nacional da Energia Elétrica/Brazilian Electricity Regulatory Agency. Banco de Dados de Geração; 2012.
[29] SECOM—Secretaria de Comunicação Social do Governo da Bahia/Government of Bahia, Mais 133 projetos para energia eólica são licenciados na Bahia; 2012.
[30] Alves J. Historia das Secas (Século XVII a XIX); 1982.
[31] Tanajura CAS, Genz F, Araujo H. Mudanças climáticas e recursos hídricos na Bahia: validação da simulação do clima presente do HadRM3P e comparação com os cenários A2 e B2 para 2070–2100. Revista Brasileira de Meteorologia ed. online; 2010. vol. 3. p. 345–58.
[32] ONS—Operador Nacional do Sistema Elétrico. RE-3/262/2011. Atualização de Séries Históricas de Vazões. Período 1931 a 2010; 2011.
[33] ONS—Operador Nacional do Sistema Elétrico. 2011 Annual Load Report/Boletim de Carga Anual 2011; 2012.
[34] COELBA—Companhia Elétrica da Bahia. Electricity Tariffs—Tabelas de tarifas e preços finais de energia elétrica/Resolução 1.142 de 19.04.2011; 2011.
[35] D. O. E.—U.S. Department of Energy. Final environmental assessment for Department of Energy loan guarantee to Abengoa Solar Inc. for the Solana Thermal Electric Power Project. DOE/EA—1683; May 2010.