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Evaluation of greenhouse gas emissions avoided by wind generation in the Brazilian energetic matrix: A retroactive analysis and future potential

Danielle Rodrigues Raimundo, Ivan Felipe Silva dos Santos*, Geraldo Lúcio Tiago Filho, Regina Mambeli Barros

Natural Resources Institute, Federal University of Itajubá (UNIFEI - MG). GEER – Renewable Energy Group, Brazil

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ABSTRACT

In recent years, wind power generation has grown exponentially in Brazil. The Brazilian Ten-Year Plan for Energy Expansion predicts an installed wind capacity about of 22.4 GW by 2023. This study evaluates the potential of avoided carbon dioxide emissions due to wind power development in Brazil. First, the emissions avoided by using wind power until the year 2017 were analyzed retrospectively. The future growth projections of wind power in Brazil were then analyzed, using magnitude growth projection models, and the impact of avoided carbon dioxide emissions on the energy matrix was assessed, under various scenarios. The results show that the avoided emissions may correspond to 5.8% of the carbon dioxide emissions in 2030 for the entire Brazilian energy matrix.

1. Introduction

There is growing concern about global warming and what humanity will leave for future generations. This has inspired research on alternative methods of energy production and has encouraged thinking about sustainability and environmental conservation. In this context wind power becomes relevant, since it is a renewable and clean source of energy (Carvalho, 2017). A wind turbine operates within a range of wind speeds. Very low speeds are not enough to move the turbines. On the other hand, very high speeds above the nominal speed make the wind turbine operate in constant power-up mode until a cut-off limit, where the turbine stops operating in order to avoid structural damages (Raimundo and Santos, 2015). Fig. 1 shows an example of a working curve of a wind turbine.

Wind energy uses an inexhaustible natural resource, generates no waste during operation, and has very low levels of greenhouse gas emissions. Several authors have studied the life cycle emission factor of a wind farm in different locations obtaining values that vary from 7.1 to 34.1 gCO_2eq/kWh (Rajaei and Tinjum, 2013; Oebels and Pacca, 2013; Nugent and Sovacool, 2014). These values are well below the average values of other energy sources (obtained from IPCC, 2012), such as coal (1.001 gCO_2eq/kWh), natural gas (469 gCO_2eq/kWh) and Solar Photovoltaic (46 gCO_2eq/kWh). The differences between the emissions of wind power and other energy sources demonstrate the potential of this kind of energy in benefit of CO_2 emissions reduction. In 2016, wind power prevented more than 637 $MtCO_2$ emissions globally (Global Wind Energy Council - GWEC, 2017).

The energy balance of a wind turbine is also highly positive. Uddin and Kumar (2014) found that the time required for repayment of the energy consumed in the production (Energy Payback Time - EPBT) of turbines varies according to the wind speed, installed power, place of operation, among others. Tremeac and Meunier (2009) analyzed the EPBT of two wind turbines (250 W and 4.5 MW) in France. The authors obtained values equal respectively to 0.58 and 2.29 years for the 4.5 MW and the 250 W wind turbines. In Brazil, Carvalho (2017) obtained values of 0.33 years for 2 MW wind turbines. At all cases the EPBT values were less than the lifetime of the wind farm.

One of the major factors in the cost of electricity generated from wind is the capacity factor (CF). The CF of a wind park varies with the type of wind generator and with the distribution of the winds in the region throughout the year. The CF is defined as the ratio between energy production from wind turbines in a certain period of time and the energy that would be produced by the same if operated at maximum power during the same period (Khahro et al., 2014). As shown in Eq. (1) (Lima and Bezerra Filho, 2012), the production of electricity is directly proportional to the CF of the enterprise, which will directly impact its economic attractiveness (as shown by Liu et al., 2017). In Brazil, the annual average CF for wind farms has grown from approximately 25% in 2004 to 38% by 2015 (Brazilian Ministry of Mines and Energy - MME, 2015), although it varies significantly between months and

* Corresponding author.
E-mail addresses: daniellerraimundo@yahoo.com.br (D.R. Raimundo), ivanfelipedeice@hotmail.com (I.F.S.d. Santos), tiago_unifei@hotmail.com.br (G.L. Tiago Filho), mambeli@unifei.edu.br (R.M. Barros).

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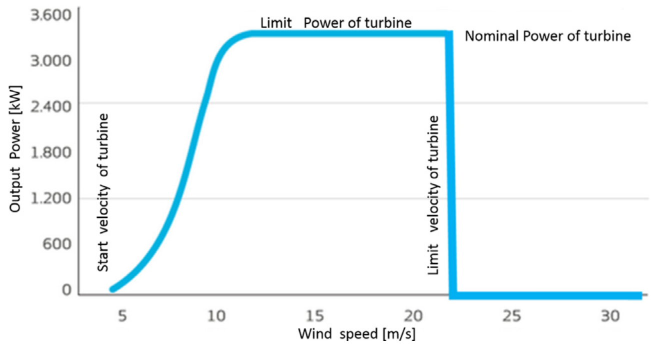

Fig. 1. Example of the working curve of a wind turbine. Power curve of the Vestas wind turbine, model V126, 3.3 MW.
Source: VESTAS (2015).

regions of the country.

$$E = P{\bullet}CF{\bullet}8{,}760 \tag{1}$$

Where: P is the power in kW, and 8760 is the number of hours in a year.

According to the GWEC (2016), the projected global wind energy installation capacity for 2021 is 800 GW. Fig. 2 shows the temporal evolution of the wind power installed around the world between 2001 and 2016. Wind energy has also gained importance in Brazil in recent years, as predicted by Filgueiras and Silva (2003). Currently, Brazil is the largest producer of wind energy in Latin America (Brazilian Communication Enterprise - EBC, 2017). The main region of wind energy production is Northeast Brazil (EBC, 2017). De Jong et al. (2017) estimates that by 2020, 57% of the energy consumed in Northeast Brazil will be produced by wind power generation.

Fig. 3 shows the percentage of participation of each country in the increase of wind power installed in 2014 around the world. This figure shows that 7% of the world's wind energy (17.6 GW) occurred in Brazil. Fig. 4 shows the evolution of Brazilian wind power capacity. There was a trend of exponential growth in wind power between the years 2005 and 2015 (as observed by Melo, 2013). In 2015, wind energy was responsible for 3.5% of all electricity in Brazil, totaling 21.6 TW h (Brazilian Energy Enterprise - EPE, 2016). Table 1 presents the variation of installed power in Brazil during 2014 and 2015. The data demonstrate the huge growth of wind energy in this period (56.2%), which is far greater than other sources' growth.

Despite the recent growth, there is still much wind potential to be developed in Brazil. The 10-year national plan for energy expansion includes 22.4 GW of wind power by 2023 (EPE, 2014). The total potential available in Brazil is estimated at 143.5 GW for wind turbines operating at a height of 50 m (Amarante et al., 2001a). There is still the offshore potential, virtually unexploited in the Brazil. Lima et al. (2015) studied the offshore wind potential of the state of Ceará, Brazil and obtained a potential of 720 W/m^2 and an average speed exceeding 8 m/s in all analyzed scenarios during the dry period.

In the Brazilian scenario, wind energy is advantageous for complementary usage with hydraulic power, a source with a higher rate of generation in the Brazilian matrix (EPE, 2016). Furthermore, such complementary generation could be established in different regions of the country (Amarante et al., 2001b; Silva et al., 2016). Due to this feature, studies have examined the possibility of installing wind turbines in reservoirs of large hydroelectric plants or even around small plants (Assireu et al., 2011; Leite et al., 2014). The wind power job generation potential in Brazil is 13.5 persons/y for each MW between the manufacturing of components and the first year of the plant. The total potential is 24.5 persons/y for each MW during the lifetime of the wind farm (Simas and Pacca, 2014).

The future development of renewable energy sources such as wind power is one of the key factors for the reduction of greenhouse gas emissions, which can assist in achieving targets assumed by the country in the Paris Agreement for the reduction of greenhouse gas emissions by 43%, with respect to the total emissions from 2005 by 2030 (MMA, 2016). Due to the importance of the theme, several models and scenarios, in an attempt to quantify and control CO_2 emissions, and to estimate avoided emissions due to the insertion of renewable sources or the implementation of energy management programs, have also been developed. These actions were encouraged by compliance with global targets as in the case of the Paris Agreement.

The International Energy Agency (IEA, 2017), in its document entitled Energy Technology Perspectives (2017), presents three (3) scenarios, based on combinations of prognosis, trends and short-term analyzes that seek to address the future of the energy sector and assist in decision making. These scenarios consider different cases of global average temperature increase and economic growth until the years of 2060 and 2100. In addition to these scenarios, there are also methodologies that assist in the estimation of emissions from the energy sector. In 2006, the IPCC Guidelines for National Greenhouse

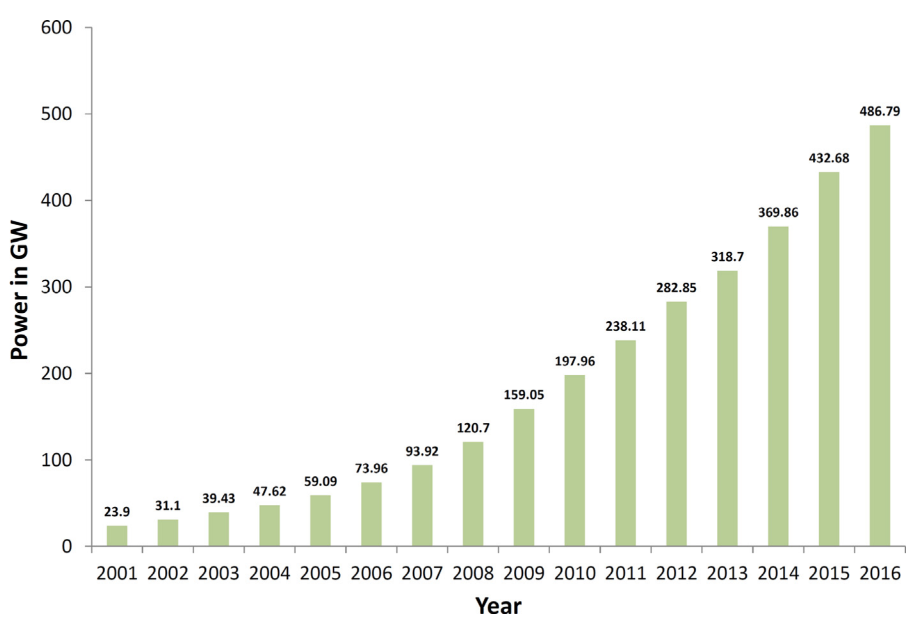

Fig. 2. Global growth of wind power in recent years. Source: GWEC (2016).

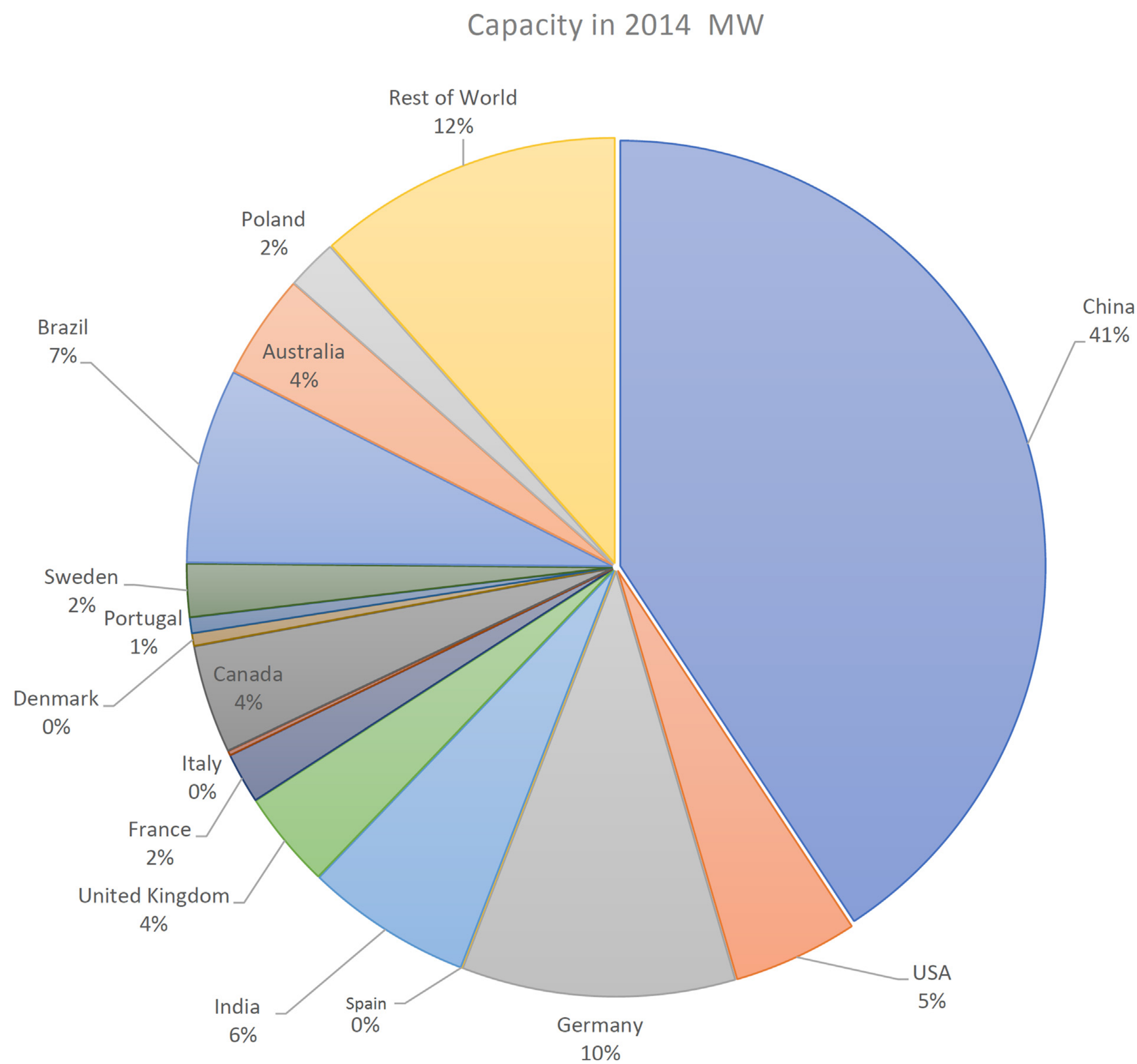

Fig. 3. New installed capacity of wind power in 2014. Source: World Wind Energy Association (WWEA, 2014).

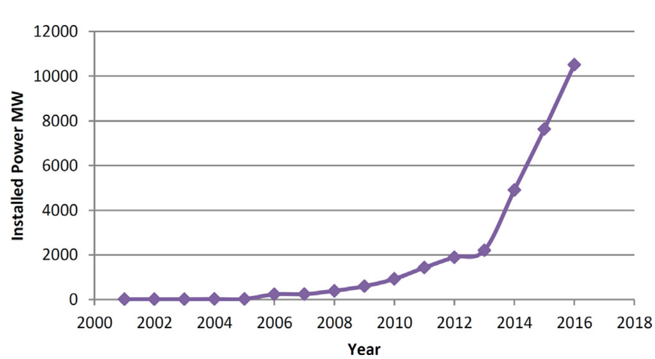

Fig. 4. Evolution of wind power capacity installed in Brazil. Source: Compiled by the authors based on Brazilian National Electric Energy Agency – ANEEL (2017), MME (2015) and CRESESB (2015).

Inventories established a standard global methodology for these estimates (IPCC, 2006), relating avoided emissions to energy savings, electricity consumption, and an average emission factor for the system (Vieira et al., 2018). This is the methodology of the online calculator of the International Renewable Energy Agency (IRENA, 2018), which can be used for initial estimates of avoided emissions due to penetration of renewables in a country. According to Goh and Ang (2018), another possible method is Equal Share (ES), a universal approach, regardless of the type of energy system, which estimates the reduction of emissions based on the change in the share of renewable energies in the electric matrix.

Table 1
Installed capacity in Brazil, in MW.
Source: EPE (2016).

Source	Installed Capacity in MW		
	2015	2014	Variation between 2014 and 2015
Hydroeletric	91,650	89,193	2.8 %
Thermal[a]	39,564	37,827	4.6 %
Nuclear	1,990	1,990	0.0 %
Wind	7,633	4,888	56.2%
Solar	21	15	42.3%
Total capacity in MW	140,858	133,914	5.2 %

[a] Includes biomass, oil gas and mineral coal.

According to Keith et al. (2003), the avoided emission calculation methods are generally based on the following methodologies: (i)

Displaced emissions analysis and time-specific marginal emission rates: This approach is based on an hour-by-hour analysis of plant or system dispatch. Electric system dispatch models, which provide a dynamic representation of the regional electric system, can be used to assess net emissions impacts; (ii) Plant addition/retirement emission factors: displaced emission rates can be developed based on the emission rates of the new plants projected to be added to the system and the old plants projected to be retired; and (iii) System average emission factors: These rates are calculated by dividing total system emissions by its generation, yielding a system average emission rate in terms of pollution mass per unit of energy. This emission factor is then applied to the output of specific resources to estimate net changes in emissions.

The future development of renewable energy sources such as wind power is one of the key factors for the reduction of greenhouse gas emissions, which can assist in achieving targets for the reduction of greenhouse gas emissions by 43% in relation to the total emissions of the year 2005, by 2030 (EBC, 2015). The GHG emissions reduction has great social, economic and environmental relevance for Brazil (and for any country), as this minimization combat climate change impacts. According to Salati et al. (2008), climate change can have a great impact on water resources in Brazil by altering evapotranspiration rates and water balance, which have been presenting alarming results for some river basins, especially in the North East region, where the rivers discharges can suffer huge reductions by 2100. Regarding agriculture, climatic changes and temperature variations can have a severe impact on crops such as soybeans, coffee, and corn, which could reduce soybean planting area by up to 41% until 2070 (Pinto et al., 2009).

Schaeffer et al. (2009) as cited by Marcovitch (2011) also studied the impacts that climate change can have on the Brazilian energy sector by 2035. Climate change can affect the hydroelectric generation reliability, reducing by up to 30% the firm energy that can be generated in North and Northeast regions. Furthermore, climate change can raise energy demand due to the increase of air conditioning use in the country by up to 6% in the residential sector. Finally, it may concentrate the crops to produce biofuels (such as sugarcane) in the Southeast due to water deficit predicted for the North and Northeast regions. Hdidouan and Staffel (2017) further point out that climate change can alter wind discharges affecting future wind potential or increasing wind power costs. According to Huback et al. (2016), the most worrisome issue is that generally the public and private agents of the electricity sector do not incorporate the effects of future climate changes in planning, operation, and investments. In this context, studies that seek to study avoided emissions and their related aspects of renewable sources based on future energy planning gain economic and social importance.

In addition, Marcovitch (2011) highlighted that climate change can have an impact on areas such as land use patterns, the Brazilian coastal zone, and Amazonian biodiversity. In view of these climate change impacts, it is imperative to increase emissions avoided in the country to prevent them, in addition to the diagnosis of avoided emissions from energy sources which growth is already in national planning, such as wind energy. Likewise, Marcovitch (2011) highlighted that climate change can have an impact on areas such as land use patterns, the Brazilian coastal zone, and Amazonian biodiversity. In view of these climate change impacts, it is imperative to increase emissions avoided in the country to prevent them.

One of the pioneer studies of avoided emissions calculations in Brazil was carried out by La Rovere and Americano (2002), which evaluated the emissions savings of the energy efficiency sector. Researches as those developed by de Calili et al. (2014) (on the national energy efficiency plan) and Barros and Tiago Filho (2012) (on generation in Small Hydroelectric Plants, SHP), evaluated the potential of reducing CO_2 emissions in Brazil by means of similar methodologies. Both studied the Brazilian electric sector and its average emission factors to estimate mitigation effects. The present study follows methodology similar to these (see Section 2 of methodology). Another study that evaluated GHG avoided emissions due to renewable energy growth was Zhai et al. (2012). The authors studied the solar photovoltaic penetration in the energy matrix of 10 states in the USA. For a penetration level of 10%, they obtained an avoided CO_2 emission potential of 1500 g/W

Due to the importance of the issue of avoided emissions and climate change, studies are required to assess the potential of renewable energy sources to clean the energy matrix. In this context, the present study aims to estimate the CO_2 emissions avoided as a result of the growth in wind farms in Brazil by analyzing the historical growth between 2001 and 2016 and the projected growth until 2030. The novelty of this work is to measure the positive impact of wind energy growth in Brazil, since this study had not yet been carried out in the country. The calculations performed in this work can be used to verify the efficiency of wind energy to clean the energy matrix, besides serving as a planning tool for the Brazilian energetic system. The methodology applied in this work can also be applied to other energy sources and other countries.

2. Methodology

The CO_2 avoided emissions can be defined, in the present study, as the difference between the CO_2 emissions regarding the same amount of electric energy produced by the contribution of various sources and those produced by the wind power. The avoided CO_2 emissions were first estimated for the historical growth of wind energy between 2001 and 2016. Next, the CO_2 emissions that would be avoided by 2030 due to projected wind power development were estimated.

2.1. Retrospective analysis of avoided emissions by installed wind capacity

Historical data were collected on greenhouse gas emissions, wind energy capacity factor and installed wind capacity in Brazil from 2001 to 2016 (see Fig. 3 and Table 2). The data were used to calculate the avoided emissions in each year by multiplying the energy generated in each year by the emission factor of the Brazilian electric matrix (Eq. (2)– based on Barros and Tiago Filho, 2012). The avoided greenhouse gas emissions obtained for one year was added to the avoided emissions of the previous year to estimate the accumulated emissions in each year (Eq. (3)). At the end of the calculations, the accumulated avoided emissions for the entire period could be determined. The calculated avoided emissions refers to the replacement of the power from the grid by energy produced from wind, thus, the average emission factor of the Brazilian national interconnected system was used.

$$E_{AVi} = (F_{Ei} - F_W)\ .\ E_i \tag{2}$$

$$E_{AAV} = \sum_{i=1}^{n} E_{AVi} \tag{3}$$

Where E_{AVi} is the avoided greenhouse gas emissions in year *i* in tCO_2/year; F_W is the wind power life-cycle emission factor in tCO_{2eq}/MWh, adopted as 0.0341, e.g., average value of projects obtained by Nugent and Sovacool (2014). This factor refers to the entire implementation phase and operation of the wind farm and includes emissions during the manufacturing phase of the park's equipment and its deployment; F_{Ei} is the Brazilian emission factor of the combined margin in tCO_2/MWh at year I; E_i is the annual energy production in MWh/year (calculated by Eq. (1)); E_{AAV} is the total accumulated avoided emissions in tCO_2/year; i is the present year; and n is the number of years in the period analyzed.

The CO_2 emission factor FE_i was determined by combining the operation and construction margin of the Brazilian energy matrix (Eq. (4)), as suggested by the United Nations Framework Convention on Climate Change (UNFCCC, 2013).

$$F_E = E_{FO} \bullet w_O + E_{FC} \bullet w_B \tag{4}$$

Where: F_E is the CO_2 emission factor for the Brazilian electric matrix (in

Table 2

Emission factors and wind energy capacity factor in Brazil from 2001 to 2016. Elaborated by authors using data of MCT (2017), Vieira et al. (2017), MME (2015) and MME (2017).

Year	Construction margin emission Factor (E_{FC} in tCO_2/MWh)[a]	Operation Margin Emission Factor (E_{FO} in tCO_2/MWh)[b]	Combined Margin Emission Factor (F_E in tCO_2/MWh)[c]	Capacity Factor (CF) of wind energy in Brazil[d]
2001	0.096	0.376	0.306	0.193
2002	0.096	0.322	0.266	0.241
2003	0.096	0.274	0.230	0.248
2004	0.096	0.350	0.287	0.252
2005	0.096	0.323	0.266	0.262
2006	0.081	0.323	0.263	0.345
2007	0.078	0.291	0.238	0.324
2008	0.146	0.477	0.394	0.338
2009	0.079	0.248	0.206	0.334
2010	0.140	0.479	0.394	0.331
2011	0.106	0.292	0.245	0.324
2012	0.201	0.518	0.438	0.345
2013	0.271	0.593	0.513	0.359
2014	0.296	0.584	0.512	0.365
2015	0.255	0.558	0.482	0.379
2016	0.274	0.623	0.536	0.416

[a] The E_{FC} values of 2006–2016 were obtained in Brazilian Ministry Of Science and Technology (MCT, 2017). The construction margin emission factors of 2001–2005 were not available in Brazilian official systems and were adopted as the average emission factor of the years 2006–2009 since the standard deviation of EFC data in these years was very low (0.028 tCO_2/MWh).

[b] The E_{FO} values of 2006 to 2016 were obtained in Brazilian Ministry Of Science and Technology (MCT, 2017). The values from 2001 to 2006 were obtained in Vieira et al. (2016).

[c] F_E values were calculated by Eq. (4).

[d] Values of 2001–2015 Were obtained in MME (2015). Value of 2016 was obtained in MME (2017).

tCO_2/MWh); w_O and w_B are the weights of the operation and construction phases, which are equal to 0.75 and 0.25 for wind power according to the UNFCCC (2013); and E_{FO} and E_{FC} are the emission factor for the construction and operation margins of the Brazilian electric matrix in each year (presented in Table 2). Table 2 shows the growth of both the Brazilian matrix emission factor and the wind power capacity factor in the last years. These factors contribute to an increase of avoided emissions due to wind power generation because they represent a greater wind power penetration into an electrical matrix, which has become less clear in the recent years.

2.2. Future analysis of the installed wind capacity growth and emissions avoided

Future projections were carried out using the historical growth of the installed wind power capacity in Brazil from 2001 to 2016 (Fig. 2). The aim was to project the future growth of this energy source using different models between the years of 2017 to 2030. The projected power values were used to calculate the avoided greenhouse gas emissions according to Eqs. (2) and (3). By observing the Eq. (2) it can be verified that the authors considered in the calculations the emission factors from the Brazilian energy matrix. The growth of wind power not only replace an energy source of high emissions index, such as those powered thermal by fossil fuel but the energy of the interconnected system grid, a derived energy from various sources defined by the mix of the Brazilian energy matrix. With this consideration, the authors assume that the growth of wind generation will penalize not only thermal sources but that renewable sources also compete for greater penetration in the Brazilian energy mix.

Different projection models were applied using a generic parameter *Y*, which can represent any variable for which historical growth data is available (in this case, installed wind power P). This method was also used in previous studies for energy analysis purposes, as in Purohit and

Table 3

Projection models used in this work.

Model	Description	Equation[a]
Model of decreasing rate of growth	This model involves forecasting the *Y* parameter (Eq. (5)) using three years of historical data Y_0, Y_1, and Y_2 (related to the years t_0, t_1, and t_2). It assumes that the growth has a saturation point or a limit denominated as K_s (Eq. (5)). The value of K_s is reached after continuous growth. The coefficient K_d in Eq. (6) is a proportionality constant and can be found using Eq. (7). Y(t) is the analyzed parameter in each year, and t is the current year (Qasim, 1999).	$Ks = \frac{2Y_0 . Y_1 . Y_2 - {Y_1}^2 . (Y_0 + Y_2)}{Y_0 . Y_2 - {Y_1}^2}$ (5) $Y(t) = Y_2 + (K_s - Y_2). [1 - e^{-K_d(t-t_2)}]$ (6) $K_d = \frac{\ln[(K_s - Y_2)/(K_s - Y_1)]}{t_2 - t_1}$ (7) Where: Y_0, Y_1, and Y_2 = historical data of the analyzed parameter; t_0, t_1, and t_2 = years of the historical data; K_s = Saturation point; K_d = proportionality constant and Y(t) is the analyzed parameter in each year.
Logistic model	The logistic model assumes that the growth of *Y* follows a logistic math relation and forms a curve *S*. The same restrictions and saturation value (K_s) of the decreasing growth model are applied to this model, which was initially presented by Verhust and later in studies by Qasim (1999) and Barros and Tiago Filho (2012), among others. The growth of *Y* can be predicted using Eq. (8) and the constants *a* and *c* inherent to the model (Eqs. (9) and (10)).	$Y(t) = \frac{K_s}{1 + ce^{a(t-t0)}}$ (8) $a = \frac{1}{t_2 - t_1} . ln\left[\frac{Y_0(K_s - Y_1)}{Y_1(K_s - Y_0)}\right]$ (9) $c = \frac{K_s - Y_0}{Y_0}$ (10) Where: Y_0, Y_1, and Y_2 = historical data of the analyzed parameter; t_0, t_1, and t_2 = years of the historical data; K_s = Saturation point; *a* and *c* are constants of the model and Y(t) is the analyzed parameter in each year.
Logistic model assigning a saturation value (K_s)	This model was presented by Purohit and Kandpal (2005), as shown in Eq. (11), and it uses the constants *a* and *b* and an arbitrary saturation point. The constants *a* and *b* are adjusted by the least squares method (Eq. (8)), which can be done using the solver® feature in Microsoft Excel® to minimize the deviation D. The difference in this model from a traditional logistic model is the attribution of the saturation value K_s and the assigning of a curve that applies this arbitrary saturation value to historical data. *Y* is predicted using Eq. (12).	$MinD^2,\ D = \sum_{i=1}^{n}\left\{\ln\left[\left(\frac{Y(t)}{K_s}\right).\left(\frac{K_s - Y(t)}{K_s}\right)^{-1}\right] - (a + bt)\right\}$ (11) $Y(t) = K_s . \left[\frac{e^{a+bt}}{1 + e^{a+bt}}\right]$ (12) Where: D = deviation minimized by the least squares method; K_s = Saturation point; *a* and *b* are constants of the model and Y(t) is the analyzed parameter in each year.

[a] These models are normally applied to population projections. But in this work they were applied to installed power (Y(t) = P(t)), as done by Barros and Tiago Filho (2012). Nevertheless, no adaptions were needed in the mathematical equations in relation to original references.

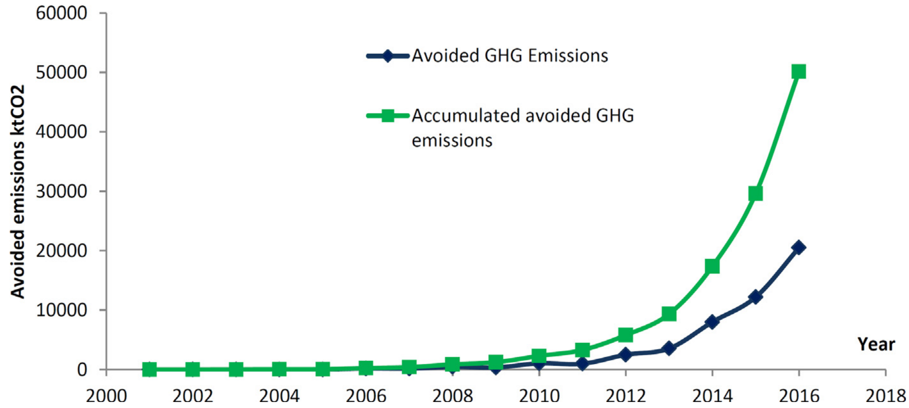

Fig. 5. Avoided greenhouse gas emissions by using wind power in Brazil (2001–2016).

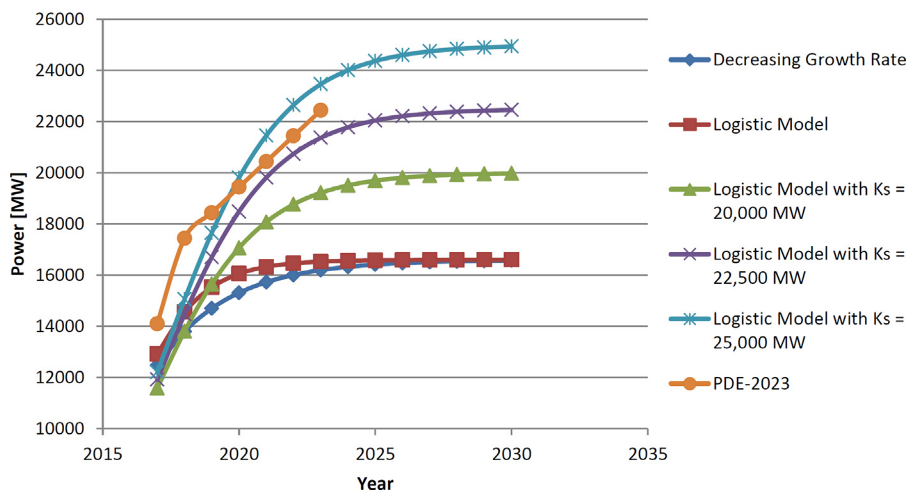

Fig. 6. Wind power projection.

Kandpal (2005) and Barros and Tiago Filho (2012). These models are presented in Table 3.

The logistic growth model was applied to three values of saturation power K_s: 20, 22.5, and 25 GW. These values were chosen based on the values presented by the Ten-Year National Expansion Plan (in Portuguese, *Plano Decenal de Expansão Nacional,* PDE-2023) established by the Brazilian Energy Enterprise (EPE, 2014). This plan predicts an installed wind capacity about of 22.4 GW by 2023. Therefore, projection values were chosen to be less than that expected by the PDE (conservative value – 20 GW), near the expected value (22.5 GW), and higher than the value (optimistic value – 25 GW). The choice of a pessimistic scenario looks for emission values avoided in a scenario in which the country cannot achieve the growth targets of the PDE (2023), which may occur due to economic factors, energy planning changes in the country over the next years, among others. The choice of the optimistic scenario considers that the goals of wind energy growth in the country will be exceeded by 2.6 GW.

Due to the difficulty to predict the future behavior of the emission factor of the Brazilian electricity matrix (because this variable depends of the electricity matrix composition which varies in function of economic and political factors), for each one of these three values of K_S were performed by the calculations of the avoided emissions in three scenarios. The scenarios were constructed considering variations in electrical matrix over the years (which reflects the emission factor used in the calculations - FE) and the average capacity factor of wind power generation in the country (which tends to be reduced over the years, as the best sites of wind energy are being used). These scenarios are presented as following:

1) **Scenario 1 (SC1)**: scenario which considers that there will be a strong decline (linear) of the factor of wind power capacity in the country and that Brazil will not be able to fulfill the goals of the Paris Agreement of 43% reduction of emissions until 2030 (EBC, 2015). In this scenario, the Brazilian electricity matrix shall maintain, in 2030, a standard next to the current, possessing emission factor equal to the average of the years 2013 to 2016 (0.511 tCO_2/MWh) and the capacity factor of wind generation will be reduced to 0.32 in 2030. The definition of this scenario is to consider that the participation of heat in the electric matrix will remain high in 2030, as in recent years (over 16% - EPE, 2016), which may occur due to economic factors, political changes of energy planning, among others. This scenario is considering further reduce the wind load factor, and therefore the worst case scenario from an environmental point of view.
2) **Scenario 2 (SC2)**: scenario which considers that the reduction targets of the Paris Agreement will force a greater diffusion of renewable energy in the electricity matrix, causing a reduction of 40% in the emission factor of the electricity grid until 2030 (reduction to 0.38 tCO_2/MWh). A slight decline in the capacity factor until 2030 to 38% is considered (the same value as of the year 2015). Considerations of this scenario imply a strong decrease in the share of thermal energy in the national electricity matrix and in the use of thermal technologies with lower GHG emissions (such as natural gas and combined cycles). This scenario is considering a smaller reduction of the wind load factor. Therefore, it is the best scenario from an environmental point of view.
3) **Scenario 3 (SC3)**: Intermediate scenario. In this scenario, an intermediate diffusion of renewable energy to SC1 and SC2 is

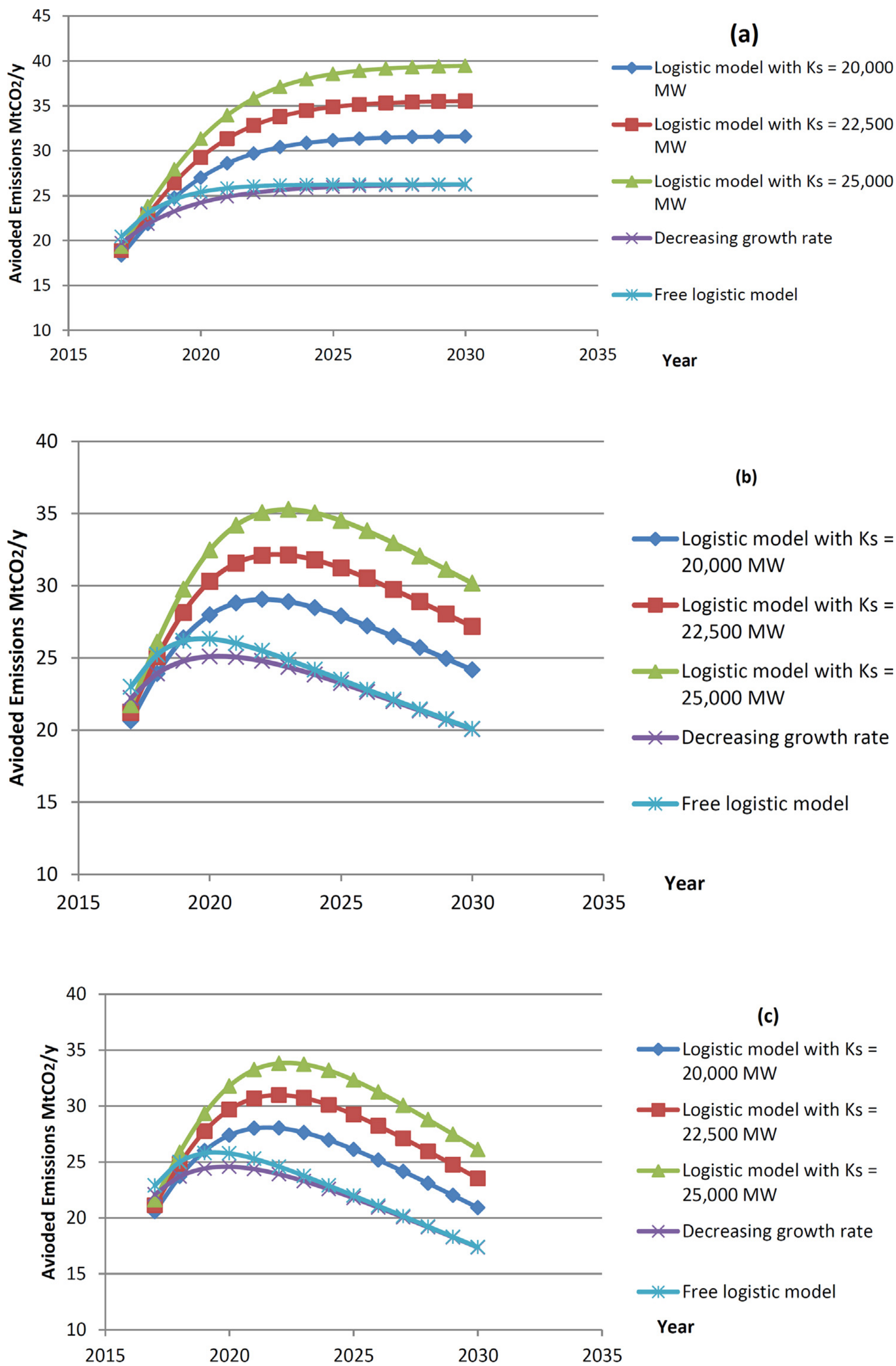

Fig. 7. Annual avoided greenhouse gas emissions by using wind development in Brazil. (a) SC1; (b) SC3 and (c) SC2.

considered, causing a reduction of 20% in the emission factor to 0.428 tCO_2/MWh, from the electricity grid until 2030. The capacity factor was linearly reduced up to 35% in 2030, decreasing to a value equal to the average of those defined in scenarios 1 and 2. This scenario considers an improvement in the share of renewables in the country's electricity matrix. However, it considers a decrease in the average capacity factor of the national wind generation. Therefore, it is an intermediate scenario from the environmental point of view.

3. Results

3.1. Retrospective analysis

The emissions avoided between 2001 and 2016 are shown in Fig. 5. Until 2016, approximately 50 $MtCO_2$ of emissions had been avoided due to the development of wind energy in Brazil. Approximately 95% of these avoided emissions occurred between 2010 and 2016, when the wind generation capacity had reached 927 MW and started to become relevant in the Brazilian energy matrix. In 2015, the anthropogenic CO_2

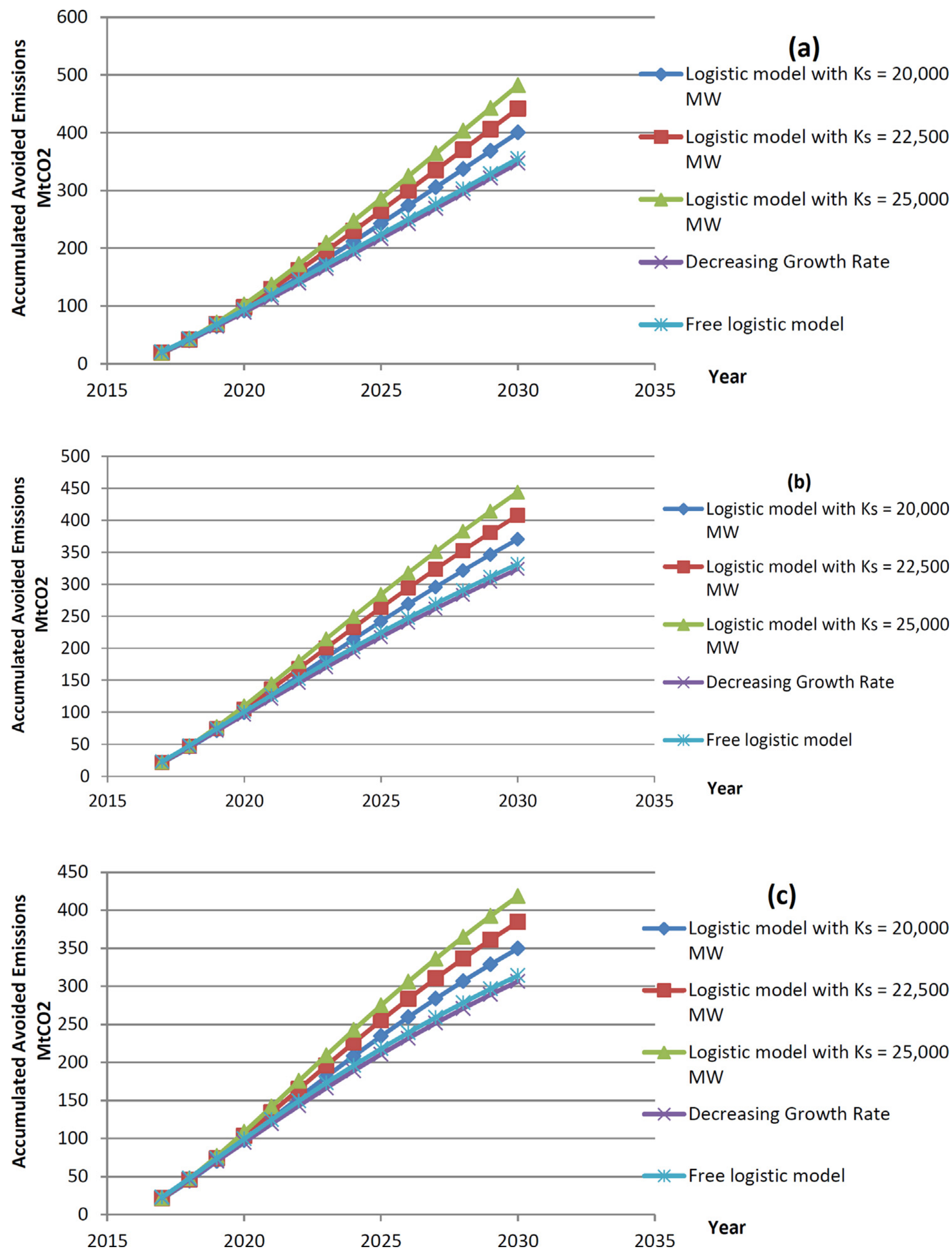

Fig. 8. Accumulated avoided greenhouse gas emissions by using wind development in Brazil. (a) SC1; (b) SC3 and (c) SC2.

emissions associated with the national energy matrix were 462.34 $MtCO_2$ (EPE, 2016). Therefore, all wind generation registered in Brazil between 2001 and 2016 was not enough to reduce 12% of the Brazilian energy matrix emissions.

By dividing all wind energy emissions by the energy produced during 2001–2016, the average avoided emissions factor was obtained due to national wind development as 0.485 tCO_2 per MWh generated. Vieira et al. (2018) estimated the avoided emissions due to programs for the Energy conservation and efficiency in Brazil, obtaining a factor of avoided emissions of 0.332 tCO_2/MWh. Therefore, the factor of avoided emissions due to the development of wind power is superior to those due to the energy efficiency programs in the country.

3.2. Prospective analysis

The historical power data in Fig. 4 were used to predict the growth of wind power in Brazil with the models presented in section 2.2. As mentioned, the logistic growth model was applied using three values of saturation power K_s. Fig. 6 shows the results and their comparison with the PDE-2023 projections (EPE, 2014).

Fig. 6 shows that the logistic model without K_s attribution and the decreasing rate of growth model predict a limited growth. Both results are far from the values expected by PDE-2023 (EPE, 2014). The saturation value Ks in these models was of 16.6 GW. Both models allow a free growth of power values, without imposing stabilization, depending on the history of these values. Thus, to ensure that the predicted values for the PDE-2023 will be achieved, the growth in wind country should not follow a downward trend of growth, which implies a need for government action on the energy market, so that the growth expected by PDE-2023 is achieved.

The results of Fig. 6 were used to calculate the avoided greenhouse gas emissions annually and overall in Scenarios 1, 2 and 3 (Figs. 7 and 8). The conservative values of K_s (20 GW) resulted in a total of 400.18 $MtCO_2$ (average of 30.78 $MtCO_2$/y - SC1), 370.44 $MtCO_2$ (average of

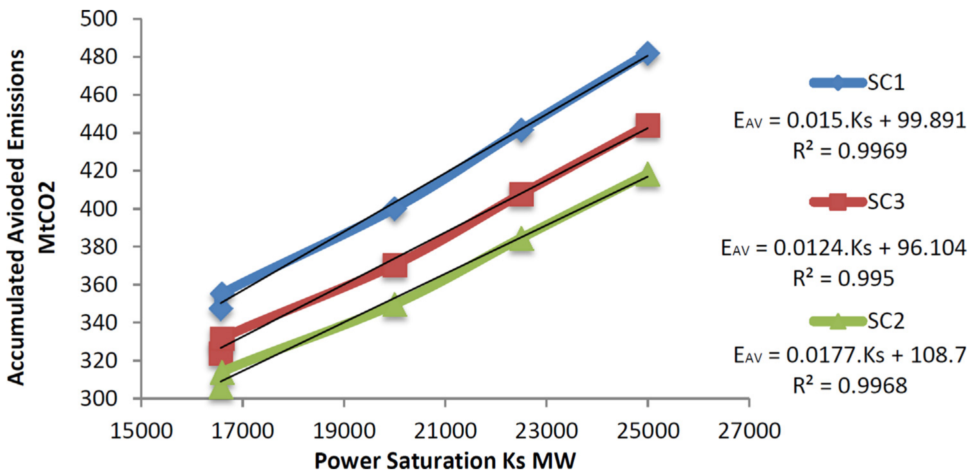

Fig. 9. Correlation of saturation power K_s and the accumulated avoided emissions between 2017 and 2030.

Table 4
Projected emissions and avoided emissions due to wind energy generation in Brazil.

Year		2020	2025	2030
Projected emissions in Brazil by energy generation in $MtCO_2$		562.1	666.45	770.8
Ks = 20 GW				
Avoided CO_2 emissions $MtCO_2$	SC1	27.00	31.16	31.60
	SC2	27.39	26.12	20.92
	SC3	27.96	27.89	24.16
Percentual of the Brazilian electric generation CO_2 projected emissions	SC1	4.80	4.68	4.10
	SC2	4.87	3.92	2.71
	SC3	4.97	4.18	3.13
Ks = 22.5 GW				
Avoided CO_2 emissions $MtCO_2$	SC1	29.25	34.88	35.53
	SC2	29.67	29.23	23.52
	SC3	30.29	31.22	27.16
Percentual of the Brazilian electric generation CO_2 projected emissions	SC1	5.20	5.23	4.61
	SC2	5.28	4.39	3.05
	SC3	5.39	4.68	3.52
Ks = 25 GW				
Avoided CO_2 emissions $MtCO_2$	SC1	31.34	38.56	39.46
	SC2	31.79	32.31	26.12
	SC3	32.46	34.51	30.16
Percentual of the Brazilian electric generation CO_2 projected emissions	SC1	5.58	5.79	5.12
	SC2	5.66	4.85	3.39
	SC3	5.77	5.18	3.91

28.5 $MtCO_2$/y - SC2) and 349.66 $MtCO_2$ (average of 26.9 $MtCO_2$/y – SC3), whereas the optimistic value of K_s (25 GW) indicated 482.1 $MtCO_2$ (average of 37.1 $MtCO_2$/y - SC1), 444.1 $MtCO_2$ (average of 34.2 $MtCO_2$/y – SC2) and 418.5 $MtCO_2$ (average of 32.2 $MtCO_2$/y – SC3). Comparing these scenarios, it is noted that the scenario SC1 can increase by up to 15% of the values of avoided emissions in scenario SC2, because this scenario considers an array supply less clean than others scenarios. The decreasing growth rate model and the logistic model without K_s attribution, reached a maximum of 355.2 MtCO2, with an annual average of 27.3 $MtCO_2$/y.

Fig. 7 presents curves in a format close to a parabola in the SC2 and SC3 scenarios. They show a peak in the avoided emission values, which then begins to decrease. Such behavior can be explained by the fact that these are the most optimistic scenarios from the environmental point of view. This behavior is because they consider a greater decrease in the emission factors of the electric matrix each year (higher rate of penetration of renewables). The wind energy into an electrical insertion increasingly cleaner array will have less impact than in a matrix with greater GHG emissions index. Over the years, and the installed capacity approaching of saturation points, wind generation reduces annual growth while the emission factor decreases. As a result of this combination, the avoided emissions begin to decline.

This parabolic (or inverted U) behavior is not verified in Fig. 7A since scenario SC1 considers that the high indices of the emission factors will be maintained by 2030. However, even in Fig. 7A, a stabilization of the values of emissions avoided over the years is observed. This is caused by the approximation of the installed power to the saturation limit and by the linear decrease of the capacity factor adopted in this scenario. These results demonstrate that the GHG emissions avoided due to the penetration of a renewable source in the electric matrix do not grow indefinitely and have no linear relation with a percentage of generation from this source.

The values of saturation power K_s of each model were correlated with the accumulated emissions avoided in the projected period in all analyzed scenarios. The results are presented in Fig. 9, which shows linearity between the growth limit imposed on wind energy and the accumulated greenhouse gas emissions avoided by wind energy development. The best fit equation of curves in Fig. 9 can be used to predict the CO_2 emissions avoided for any goal of wind power growth.

The magnitude of the predicted emissions avoided in Figs. 7 and 8 were evaluated using national projected energy matrix emissions from 2020, 2025, and 2030 (MME, 2007), as shown in Table 4. According to the data from Table 4, the avoided greenhouse gas emissions in the optimistic K_s value (25 GW) can reach 5.77% of the total Brazilian Energy Matrix emissions in 2030. This value is highly expressive since we are considering only one source of renewable energy. For the years of 2025 and 2030, the avoided emissions stabilize, and their percentages in relation to the energy matrix emissions decrease. This may be explained by the steady growth of greenhouse gas emissions in Brazil during these years.

As previously discussed, Brazil is a participant in the Paris Agreement of 2016, with a commitment to reduce CO_2 emissions by 43% by 2030 (MMA, 2016) regarding total emissions for the year 2005. If considered the Brazilian data from 2014 as a basis for predicting the reduction in total CO_2 emissions (1285 $MtCO_{2eq}$ - MCTIC, 2016), the emissions avoided due to the development of wind power in 2030 may represent (depending on the scenario analyzed) a 1.6 to 3.1% reduction of Brazilian total emissions of 2014, which will help to achieve national targets for reducing emissions.

4. Conclusions

Wind has become an important energy source in Brazil, since it is the second largest renewable source in the Brazilian energy matrix. In recent years, exponential growth has been observed. The growth of this source is extremely important for building a diversified, clean, and renewable energetic matrix. The present study assessed the impact of

CO_2 emissions avoided due to this growth.

The projected avoided emissions (2017–2030) were much greater than the historical emissions avoided (2001–2017), since the total installed wind power in Brazil only began to become significant in 2011, when it exceeded 1 GW. The emissions avoided due to wind power generation were projected while considering that the future emission factor would follow the same trend as in previous years. Thus, the emissions avoided were estimated as 40 $MtCO_2$ for 2030 in the most optimistic scenarios.

This estimation represents up to 5.7% of the greenhouse gas emissions in the national system. These values are significant as Brazil already has a clean energetic matrix. It was also estimated that the CO_2 avoided due to the projected wind growth can represent up to 3.1% of the total emissions of Brazil in 2014. Thus, wind growth could help to achieve targets in emission reduction assumed by the Brazilian government in the Paris Agreement of 2016.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2018.06.020.

References

Amarante, O.A.C., Zack, M.B.J., Leite de Sá, A., 2001a. Atlas of Brazilian Wind Potential. Electrical Energy Research Center (Cepel), Brasília, Brasil (In Portuguese).

Amarante, O.A.C., Schultz, D.J., Bittencourt, R.M., Rocha, N.A., 2001b. Wind/Hydro complementary seasonal regimes in Brazil. DEWI Mag. 19, 79–86 (In Portuguese).

ANEEL.National Electric Energy Agency, 2017. Management Information Bulletin (BIG). Avaiable at:. Accessed: 24 May 2017. (In Portuguese). http://www.aneel.gov.br/informacoes-gerenciais.

Assireu, A.T., Pimenta, F.M., Souza, V., 2011. Assessment of the Wind Power Potential of Hydroelectric Reservoirs. Energy Resources: Development, Distribution, and Exploitation. Nova Science Publishers, Inc, New York, NY.

Barros, R., Tiago Filho, G.L., 2012. Small hydropower and carbon credits revenue for an SHP project in national isolated and interconnected systems in Brazil. Renew. Energy 48, 27–34.

Calili, R.F., Souza, R.C., Galli, A., Armstrong, M., Marcato, A.L.M., 2014. Estimating the cost savings and avoided CO2 emissions in Brazil by implementing energy efficient policies. Energy Policy 67, 4–15.

Carvalho, B.P.A., 2017. Evaluation of the environmental useful life of wind turbines according to the regions of production and operation. Final Graduation Work in Environmental Engineering. Federal University of Itajubá, Itajubá (Brazil) November, 2017 (In Portuguese).

CRESESB, 2015. Reference Center for Solar and Wind Energy Sérgio Brito. Avaiable at:. Accessed: 24 May 2017. (In Portuguese). http://www.cresesb.cepel.br/index.php?section=atlas_eolico.

de Jong, P., Dargaville, R., Silver, J., Utembe, S., Kiperstok, A., Torres, E.A., 2017. Forecasting high proportions of wind energy supplying the Brazilian Northeast electricity grid. Appl. Energy 195, 538–555.

EBC, 2017. Brazilian Company of communication. Note on National Infrastructure: Brazil is the Largest Generator of Wind Energy in Latin America. Avaiable at: http://www.brasil.gov.br/infraestrutura/2017/03/brasil-e-o-maior-gerador-de-energia-eolica-da-america-latina Accessed: 09 May 2017. (In Portuguese).

EPE. Energy Research Company, 2014. Decennial energy expansion plan PDE-2023. Ministry of Mines and Energy. Available at: http://www.epe.gov.br/Estudos/Documents/Relat%C3%B3rio%20Final%20do%20PDE%202023.pdf Accessed: 18 May 2017. (In Portuguese).

EPE. Energy Research Company, 2016. National energy balance (BEN). Summary Report - Base Year 2015. Available at: https://ben.epe.gov.br/downloads/S%C3%ADntese%20do%20Relat%C3%B3rio%20Final_2016_Web.pdf Accessed: 09 May 2017. (In Portuguese).

Filgueiras, A., Silva, T.M.V., 2003. Wind energy in Brazil-present and future. Renew. Sustain. Energy Rev. 7, 439–451.

Goh, T., Ang, B.W., 2018. Quantifying CO_2 emission reductions from renewables and nuclear energy – some paradoxes. Energy Policy 113, 651–662.

GWEC. Global Wind Energy Council, 2016. Global Wind Statistics. Available at:. Accessed 10 May 2017. http://www.gwec.net/global-figures/graphs/.

GWEC. Global Wind Energy Council, 2017. Wind in Numbers. Available at:. Accessed 11/05/2017. http://www.gwec.net/global-figures/wind-in-numbers/.

Hdidouan, D., Staffel, I., 2017. The impact of climate change on the levelised cost of wind energy. Renew. Energy 101, 575–592.

Huback, V.B.S., Castro, N.J., Dantas, G.A., Silva, P.P., Rosental, R., Magalhães, M.A., 2016. Climate Change and Impacts on the Electric Power Sector: A Review of the Literature. Available at. Brazilian Congress of Energy Planning, Gramado (RS) Accessed: 27 March 2018. http://www.gesel.ie.ufrj.br/app/webroot/files/publications/07_xcbpe0244.pdf.

IEA. International Energy Agency, 2017. Energy technology perspectives 2017. Catalysing Energy Technology Transformations. OECD/IEA.

IPCC. Intergovernmental Panel on Climate Change, 2006. Guidelines for National Greenhouse Gas Inventories Energy. Institute for Global Environmental Strategies (IGES) p. 2.

IPCC. Intergovernmental Panel on Climate Change, 2012. Renewable Energy Sources and Climate Change Mitigation. Summary for Policymakers and Technical Summary. Available at. Accessed 16 November 2017. https://www.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf.

IRENA. International Renewable Energy Agency, 2018. Avoided Emissions Calculator. Available at. Accessed: 31 March 2018.. http://www.irena.org/climatechange/Avoided-Emissions-Calculator.

Keith, G., Henn, P., Breceda, M., 2003. Estimating the Emission Reduction Benefits of Renewable Electricity and Energy Efficiency in North America: Experience and Methods. Available at. Accessed: 03 March 2018. http://www.synapse-energy.com/sites/default/files/Synapse%20Report.2003-09.CEC_.Emission-Reduction-Benefits-Renewables-and-EEEstimates.03-18.pdf.

Khahro, S.F., Tabbassum, K., Soomro, A.M., Liao, X., Alvi, M.B., Dong, L., Manzoor, M.F., 2014. Techno-economical evaluation of wind energy potential and analysis of power generation from wind at gharo, Sindh Pakistan. Renew. Sustain. Energy Rev. 35, 460–474.

La Rovere, E.L., Americano, B.B., 2002. Domestic actions contributing to the mitigation of GHG emissions from power generation in Brazil. Climate Policy 2, 247–254.

Leite, M.D.P., Santos, I.F.S., Barros, R.M., Tiago Filho, G.L., 2014. The combined use of small hydroelectric power plants and wind farms. Braz. J. Energy 20, 103–116 (In Portuguese).

Lima, L.A., Bezerra Filho, C.R., 2012. Wind resource evaluation in são joão do cariri (SJC) – paraiba, Brazil. Renew. Sustain. Energy Rev. 16, 474–480.

Lima, D.K.S., Leão, R.P.S., Santos, A.C.S., Melo, F.D.C., Couto, V.M., Noronha, A.W.T., Oliveira Jr, D.S., 2015. Estimating the offshore wind resources of the State of ceara in Brazil. Renew. Energ. 83, 203–221.

Liu, C., Wang, Y., Zhu, R., 2017. Assessment of the economic potential of China's onshore wind electricity. Resour. Conserv. Recycl. 121, 33–39.

Marcovitch, J. The economics of climate change in Brazil: costs and opportunities. Technical coordinators: Margulis, S. and Dubeux, C. B. S. General coordinator: Marcovitch, J. São Paulo: FEA/USP, 2011. 84 p. Available at http://www.usp.br/mudarfuturo/PDF/Estudo_do_Clima-Ingles-14-04-2011.pdf. Accessed: 27 March 2018.

MCT. Ministry of Science Technology and Innovation, 2017. CO_2 Emission Factors. Available at:. Accessed: 19 January 2017 (In Portuguese). http://www.mct.gov.br/index.php/content/view/74689.html.

MCTIC. Ministry of Science, Technology, Innovation and Communications, 2016. Annual Estimates of Greenhouse Gas Emissions in Brazil. Available at:. 3a ed. Accessed: 23 May 2017. (In Portuguese). http://sirene.mcti.gov.br/documents/1686653/1706227/LIVRO_MCTIC_EstimativaDeGases_Publica%C3%A7%C3%A3o_210x297mm_FINAL_WEB.pdf/61e78a4d-5ebe-49cd-bd16-4ebca30ad6cd.

Melo, E. Wind power source: aspects of insertion, technology and competitiveness. Advanced Studies. 2013 27, 77, São Paulo, (In Portuguese).

MMA. Ministry of Environment, 2016. Information Note on the Paris Agreement. Available at:. Accessed: 23 May 2017. (In Portuguese). http://www.mma.gov.br/clima/convencao-das-nacoes-unidas/acordo-de-paris.

MME. Ministry of Mines and Energy, 2007. National Energy Matrix-2030. Brasília. Available at:. Accessed: 11 May 2017. (In Portuguese). http://www.mme.gov.br/documents/1138787/1732860/Matriz+Energ%C3%A9tica+Nacional+2030/39d39feb-1307-4f4f-9658-039b86b94bbd;jsessionid=663523DDBACC54787760CDC404F8C998.srv155.

MME. Ministry of Mines and Energy, 2015. Wind Energy in Brazil and the World. Available at:. Accessed: 11 May 2017. (In Portuguese). http://www.mme.gov.br/documents/10584/3894319/Energia+E%C3%B3lica+-+ano+ref++2015+(3).pdf/f5ca897d-bc63-400c-9389-582cd4f00ea2.

MME. Ministry of Mines and Energy, 2017. Brazil Reaches the 7th Place in the Ranking of the World'S Wind Generation. Available at. Accessed: 16/11/ November 2017. (In Portuguese). http://www.mme.gov.br/web/guest/pagina-inicial/outras-noticas/-/asset_publisher/32hLrOzMKwWb/content/brasil-chega-ao-7-lugar-no-ranking-da-geracao-eolica-mundial.

Nugent, D., Sovacool, B.K., 2014. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: a critical meta-survey. Energy Policy 65, 229–244.

Oebels, K.B., Pacca, S., 2013. Life cycle assessment of an onshore wind farm located at the northeastern coast of Brazil. Renew. Energ. 53, 60–70.

Pinto, H.S., Assad, E., Pellegrino, G., 2009. Impacts of Climate Change on Agricultural Production. Cepagri/ Unicamp Embrapa Agropecuária.
Purohit, P., Kandpal, T.C., 2005. Renewable energy technologies for irrigation water pumping in India: projected levels of dissemination, energy delivery and investment requirements using available diffusion models. Renew. Sustain. Energy Rev. 9, 592–607.
Qasim, S.R., 1999. Wastewater Treatment Plants – Planninng Design and Operation, 2nd ed. Technomic Publishing Company, Lancaster, Pennsylvania, USA 1107 p.
Raimundo, D.R., Santos, I.F.S., 2015. Study of a wind power project in Brazil: Economic feasibility and avoided emissions. Braz. Renew. Energy J. 4 (4).
Rajaei, M., Tinjum, J.M., 2013. Life cycle assessment of energy balance and emissions of a wind energy plant. Geotech. Geol. Eng. 31, 1663–1670.
Salati, E., Schindler, W., Victoria, D.C., Salati, E., Souza, J.C.S., Nova, N.A.V., 2008. Projected Supply of Water Resources in Brazil Under Future Climate Scenarios (2015 – 2100). Brazilian Foundation for Sustainable Development. Available at. Accessed: 27 March 2018. (In Portuguese). http://fas-amazonas.org/versao/2012/wordpress/wp-content/uploads/2013/07/Oferta-de-%C3%A1gua-no-BR-2015-2100.pdf.
Schaeffer, R., Szklo, A., Lucena, A.F.P., Souza, R., Borba, B., Costa, I.V.L., Pereira Jr., A.O., Cunha, S.H., 2009. Impacts on Demand and Reliability in the Energy Sector. Report of PPE/ COPPE/UFRJ. (In Portuguese).
Silva, A.R., Pimenta, F.M., Assireu, A.T., Spyrides, M.H.C., 2016. Complementarity of Brazil's hydro and offshore wind power. Renew. Sustain. Energy Rev. 56, 413–427.
Simas, M., Pacca, S., 2014. Assessing employment in renewable energy technologies: a case study for wind power in Brazil. Renew. Sustain. Energy Rev. 31, 83–90.
Tremeac, B., Meunier, F., 2009. Life cycle analysis of 4.5 MW and 250 W wind turbines. Renew. Sustain. Energy Rev. 13, 2104–2110.
Uddin, S.M., Kumar, S., 2014. Energy, emissions and environmental impact analysis of wind turbine using life cycle assessment technique. J. Clean. Prod. 69, 153–164.
UNFCC. United Nations Framework Convention on Climate Change, 2013. Tool to Calculate the Emission Factor for an Electricity System. Accessed: 05 January 2017. https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-07-v5.0.pdf.
VESTAS, 2015. Products and Services. Model Wind Turbine Power Curve V126. Avaiable at:. Accessed: 08 June 2015. (In Portuguese). http://www.vestas.com/en/products_and_services/turbines/v126-3_3_mw#.
Vieira, N.B.D., Santos, I.F.S., Haddad, J., Nogueira, L.A.H., 2017. Proposal of a correlation model between the emission factors of the national interconnected system (SIN) and the thermoelectric generation in Brazil between 2000 and 2015. Braz. J. Energy 23, 77 (In Portuguese).
Vieira, N.B.D., Nogueira, L.A.H., Haddad, J., 2018. An assessment of CO2 emissions avoided by energy-efficiency programs: a general methodology and a case study in Brazil. Energy 14, 702–715.
WWEA. World Wind Energy Association, 2014. Half-Year Report. 2014. Avaiable at:. Accessed: 17 August 2017. http://www.wwindea.org/webimages/WWEA_half_year_report_2014.pdf.
Zhai, P., Larsen, P., Millstein, D., Menon, S., Masanet, E., 2012. The potential for avoided emissions from photovoltaic electricity in the United States. Energy 47, 443–450.