How wind energy is contributing to the achievement of Brazilian commitments to the Paris Agreement

Como a energia eólica está contribuindo para o Brasil atingir os compromissos assumidos no Acordo de Paris

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ABSTRACT

The Paris Agreement was signed to reduce greenhouse gas emissions, and Brazil is committed to increasing renewable energy participation in the electrical matrix. This study aims to evaluate how wind energy fulfils the goals determined in the agreement. Through a systematic literature review, 10 relevant studies were identified and together with the analysis of data available in the National Energy Balance report from the Energy Research Company. Comparing the data obtained in the period with the established targets was possible. The success of policies for the sector in reaching the goals above was also evaluated. The results show that wind energy is the renewable source that most benefited from tax incentives and, thus, contributed to the expansion of the share of renewable energy in the Brazilian electrical matrix.

Keywords: Paris agreement. Electrical sector. Renewable energy. Wind energy. Electrical efficiency.

RESUMO

O Acordo de Paris foi assinado com o intuito de reduzir as emissões de gases de efeito estufa. O Brasil se comprometeu a aumentar a participação de energias renováveis na matriz elétrica. O objetivo *deste estudo é avaliar como a energia eólica está contribuindo para o cumprimento das metas assumidas no Acordo. Por meio de uma revisão sistemática da literatura, foram identificados dez estudos pertinentes e, juntamente com uma análise dos dados disponíveis no Relatório de Balanço Energético Nacional, da Empresa de Pesquisa Energética (EPE), foi possível comparar os dados obtidos no período com as metas estabelecidas e avaliar o sucesso das políticas para o setor no atingimento dos objetivos mencionados. Os resultados demostram que a energia eólica é a fonte renovável que mais se beneficiou dos incentivos fiscais e, assim, contribuiu para a expansão da participação da energia renovável na matriz elétrica brasileira.*

Palavras-chave: Acordo de Paris. Setor elétrico. Energia renovável. Energia eólica. Eficiência elétrica.

1 INTRODUCTION

The objective of the Paris agreement is to strengthen the global response to the threat of climate change by ensuring that the global average temperature increase is less than 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to up to 1.5°C above pre-industrial levels (UNFCCC, 2016). To reach this objective, governments constructed their own commitments based on the so-called Intended Nationally Determined Contributions (INDC). Each nation presented its contribution to reducing greenhouse gas emissions by the INDCs, following what each government considered feasible based on the local social and economic scenarios (MMA, 2016). Brazil has committed to reducing greenhouse gas emissions by 37% below 2005 levels by 2025, with a subsequent commitment to reduce greenhouse gas emissions by 43% below 2005 levels by 2030 (BRASIL, 2016). After the 2001 energy crisis, Brazil has been developing public policies to increase renewable electric energy in the National Electric System. Examples include the Emergency Wind Energy Program (Proeólica – Brazilian acronym) and the Incentive Program for Alternative Sources of Electric Energy (Proinfa – Brazilian acronym).

Following the Paris Agreement, the United Nations adopted, in 2015, the Sustainable Development Goals (SDGs) as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity. Goal 7 sets the challenge of affordable and clean energy for all (UNDP, 2022). Access to transparency and quality of public data are critical elements for good information governance to support decision-making and policy formulation. The Brazilian Institute of Geography and Statistics (IBGE – Brazilian acronym) has been advancing in nationalizing the SDG indicators (LINDOSO *et al.*, 2021). Of the seven corresponding global indicators, Brazil has already adapted the estimation methodology for six of them, whereas for one of them data is unavailable at a national scale (IBGE, 2022). Wind energy, a type of clean energy, which is widely distributed, pollution-free, and free of greenhouse gas emissions during operation (ZHANG, 2020), can benefit the country, ensuring universal, reliable, modern, and affordable access to electricity services. To make this happen, eliminating incentives to expand the exploration and use of fossil fuels (oil, gas, and coal) is essential, as well as reallocating investment resources from these sectors to expand the generation and use of renewable sources (GRUPO DE TRABALHO DA SOCIEDADE CIVIL, 2022).

The Energy Research Company (EPE – Brazilian acronym) predicts that the total energy consumption in Brazil will grow 3.5% per year until 2031, an average annual increase of 19.7 TWh. Residential consumption grows as the number of residential consumers increases. The evolution of consumption in the industrial sector stands out regarding the use of the installed capacity, and consumption in the commercial sector should grow mainly due to the pandemic (EPE, 2022). Meeting the increasing demand for energy while decreasing greenhouse gas and air pollutant emissions requires decarbonizing the electricity sector and providing electrical energy to at least parts of the transportation and industrial sectors (MORRISON *et al.*, 2015; ROCKSTRÖM *et al.*, 2017). However, large industries worldwide continue to rely on fossil fuels as an energy source

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(GOMAA *et al.*, 2019). Although decarbonizing energy systems requires substantial infrastructure investments, it also yields large decreases in climate and health costs (JACOBSON *et al.*, 2018).

The future development of renewable energy sources, such as wind power, is one of the key factors for reducing greenhouse gas emissions (RAIMUNDO *et al.*, 2018). According to Abeeólica (2021), Brazilian-installed wind capacity increased more than two and a half times from 2014 to 2020, going from 5,974 MW to 17,747 MW, representing a significant average growth rate of 20% per year. Despite the significant growth of wind generation and other renewable sources besides hydro for electricity generation in recent years in Brazil, there was the risk of a new blackout in 2021, when the country faced its greatest water shortage since 1930 (MME, 2021). The water scarcity situation highlighted how the different uses of water affect the management of reservoirs (EPE, 2022).

This study aims to assess how wind energy contributes to Brazil's achievement of the commitments for the energy sector in the Paris Agreement. The available data from the Energy Research Office (EPE) from 2014 to 2020 and the relevant literature were analyzed.

This paper is organized into four sections: besides this Introduction, Section 2 describes the Materials and Methods used, Section 3 discusses the Results and Discussion, and Section 4 presents the Conclusions.

2 MATERIALS AND METHODS

The study was conducted via a systematic review of the literature and the analysis of data available in the National Energy Balance Report of the EPE, the Annual Bulletin of Wind Generation of the Brazilian Wind Energy Association (Abeeólica), and the Global Wind Energy Report published by the Global Wind Energy Council (Gwec). The period selected for analysis was from 2014 (before the Paris Agreement was signed) to 2020.

The databases used for the systematic review searches were Science Direct and Google Scholar. The descriptors used were: "Paris Agreement," "Wind Energy," and "Brazil." The inclusion criteria for the search of publications were: the relevance of content to the theme addressed in this study (assessed by the authors) and papers written in English and Portuguese. All papers published outside the defined period and languages, as well as theses and dissertations, were excluded.

After conducting the search, it was possible to find 181 studies related to the theme. Of these, 50 relevant studies were pre-selected. After reading the titles and abstracts, 10 studies were selected as relevant to compose this systematic review.

The expansion of domestic use of non-fossil energy sources by increasing the share of renewable energy (other than hydropower) was also studied. The current goal is to increase participation in the electricity supply to at least 23% by 2030. Consequently, the percentage contribution of these sources to the Brazilian electricity matrix from 2014 to 2020 was assessed. These include wind, biomass, and solar energy.

As for achieving 10% efficiency gains in the electricity sector, the losses from the difference between internal electricity supply (supply) and final consumption (demand) per year were estimated. The efficiency gain was evaluated by reducing losses during the generation, transmission, and distribution of electric energy in the period. The target was to reduce losses by 10% of the value of losses in 2014.

3 RESULTS AND DISCUSSION

This section is organized into five subsections: Subsection 1 focuses on the Paris Agreement; Subsection 2 focuses on the world and Brazilian electricity matrix; Subsection 3 shows the participation of renewable and non-renewable energies in the Brazilian electricity matrix; Subsection 4 addresses Efficiency in the Electricity Sector; Subsection 5 assesses the results of public policies for the expansion of wind power in Brazil.

3.1 THE PARIS AGREEMENT

The Paris Agreement is a global treaty that aims to reduce greenhouse gas emissions in the context of sustainable development. The agreement was negotiated during the 21st Conference of the Parties of the United Nations (COP21) in Paris and approved by the 195 countries of the United Nations Framework Convention on Climate Change on December 12, 2015.

Over the last decade, the use of wind power as a renewable energy source in the electricity sector has been growing faster than other available sources in Brazil and worldwide. For Arantegui and Jänger-Waldau (2018), wind energy is one of the leading technological options for shifting towards a decarbonized energy supply.

In 2015, around 27.3 GW of new power generation capacity was connected in the European Union. Renewable energy sources accounted for 20.6 GW or 75.6% of all new generation capacity. Wind energy contributed 12.2 GW, or 44.6% of the newly installed capacity, as reported by Arantegui and Jänger-Waldau (2018).

After approval by the National Congress, Brazil ratified the Paris Agreement. On September 2nd, the instrument was delivered to the United Nations. Thus, Brazilian targets have become official commitments. Regarding nationally determined contribution (NDC), Brazil has committed to reducing greenhouse gas emissions by 37% below 2005 levels in 2025, with a subsequent commitment to reduce greenhouse gas emissions by 43% below 2005 levels in 2030. For that, the country has committed to increasing the share of sustainable bioenergy in its energy matrix to approximately 18% by 2030, restoring and reforesting 12 million hectares of forests, as well as achieving an estimated 45% share of renewable energy in the composition of the energy matrix in 2030 (MMA, 2016).

For the electricity sector, the targets were (BRASIL, 2016):

I. Expand domestic use of non-fossil energy sources by increasing the share of renewable sources (other than hydropower) in electricity supply to at least 23% by 2030, including expanding the shares of wind, biomass, and solar sources.

II. Achieve 10% efficiency gains in the electricity sector by 2030.

As the CEBDS (2017) described, the goals set by the NDC are interdependent, so the challenge is to achieve them harmoniously and cooperatively. The objective is to maintain a high proportion of renewable energy in a matrix, with greater inclusion of renewable sources other than hydro, in an uncertain context of energy consumption growth by 2030, and with the additional target of increasing energy efficiency by 10%.

3.2 WORLD AND BRAZILIAN ELECTRICITY MATRIX

Figure 1 shows the use of renewable and non-renewable sources for electricity generation in Brazil and the world in 2019 (IEA, 2021).

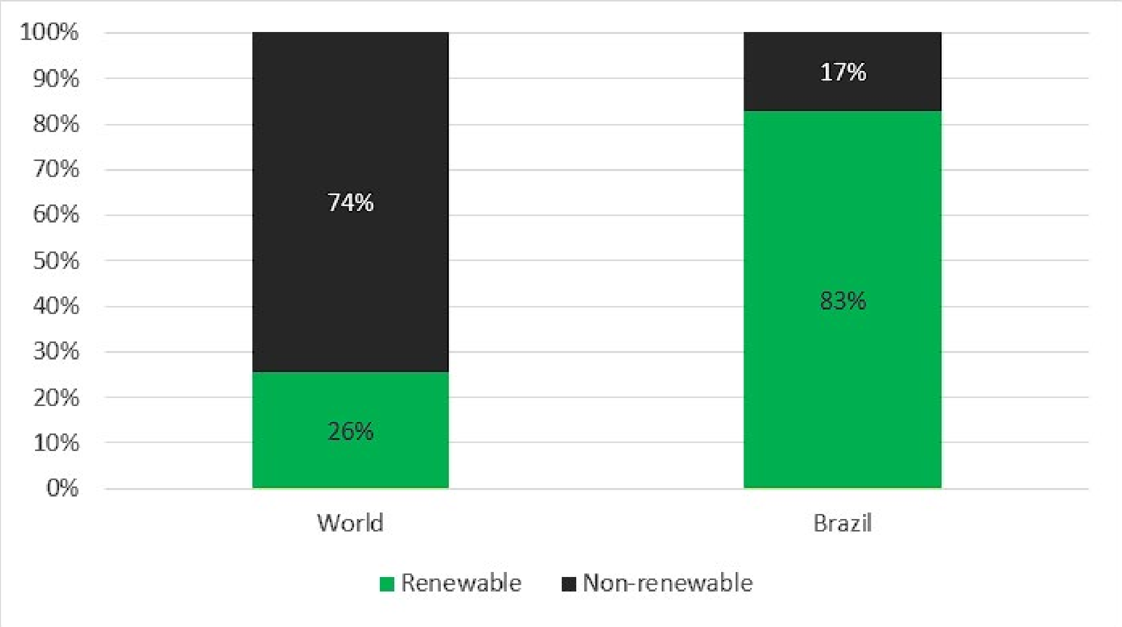

Figure 1 | Participation of renewable and non-renewable energy in the Brazilian and World Electricity Matrix in 2019

Source: IEA (2021).

The world's electricity matrix is composed mainly of non-renewable energy sources (74%), especially coal and natural gas, which account for 60% of the world's electricity matrix. On the other hand, the Brazilian electricity matrix is more renewable. Adding hydraulic, wind, biomass, solar, and other renewable sources, 83% of the Brazilian electric matrix is composed of renewable energy sources.

3.3 PARTICIPATION OF NON-RENEWABLE AND RENEWABLE ENERGY IN THE BRAZILIAN ELECTRICITY MATRIX

Table 1 shows data on domestic electricity supply by source from 2014 (before the Paris Agreement) to 2020.

Table 1 | Data of the Internal Electricity Supply

	2014 (GWh)	*2015 (GWh)*	*2016 (GWh)*	*2017 (GWh)*	*2018 (GWh)*	*2019 (GWh)*	*2020 (GWh)*
Natural Gas	81,073	79,490	56,485	65,593	54,622	60,448	53,464
Nuclear	15,378	14,734	15,864	15,739	15,674	16,129	14,053
Coal Vapor	18,385	18,856	17,001	16,257	14,204	15,327	11,946
Petroleum derivatives	30,834	25,014	11,808	12,458	9,293	6,926	7,746
Other non-renewable sources	12,127	11,826	11,919	12,256	12,314	12,061	11,121

	2014 (GWh)	2015 (GWh)	2016 (GWh)	2017 (GWh)	2018 (GWh)	2019 (GWh)	2020 (GWh)
NON-RENEWABLE (TOTAL)	**15,797**	**149,920**	**113,077**	**122,303**	**106,107**	**110,891**	**98,330**
Hydraulic + Net Imports	407,239	394,143	421,711	407,306	423,971	422,877	421,081
Biomass	47,079	49,880	51,335	52,913	54,383	54,920	58,742
Wind	12,210	21,626	33,489	42,373	48,475	55,986	57,051
Solar	16	59	85	832	3,461	6,655	10,748
RENEWABLE (TOTAL)	**466,544**	**465,708**	**506,620**	**503,424**	**530,290**	**540,438**	**547,622**
DOMESTIC ELECTRICITY SUPPLY	**624,341**	**615,628**	**619,697**	**625,727**	**636,397**	**651,329**	**645,952**

Source: EPE (2021).

Table 1 shows that in 2014 more non-renewable sources were used to generate electricity in Brazil than in 2020 and that renewable sources such as biomass, solar, and wind increased their participation in the Brazilian electricity matrix in all years of the period.

Figure 2 shows Brazil's domestic renewable electricity supply – excluding hydro – between 2014 and 2020.

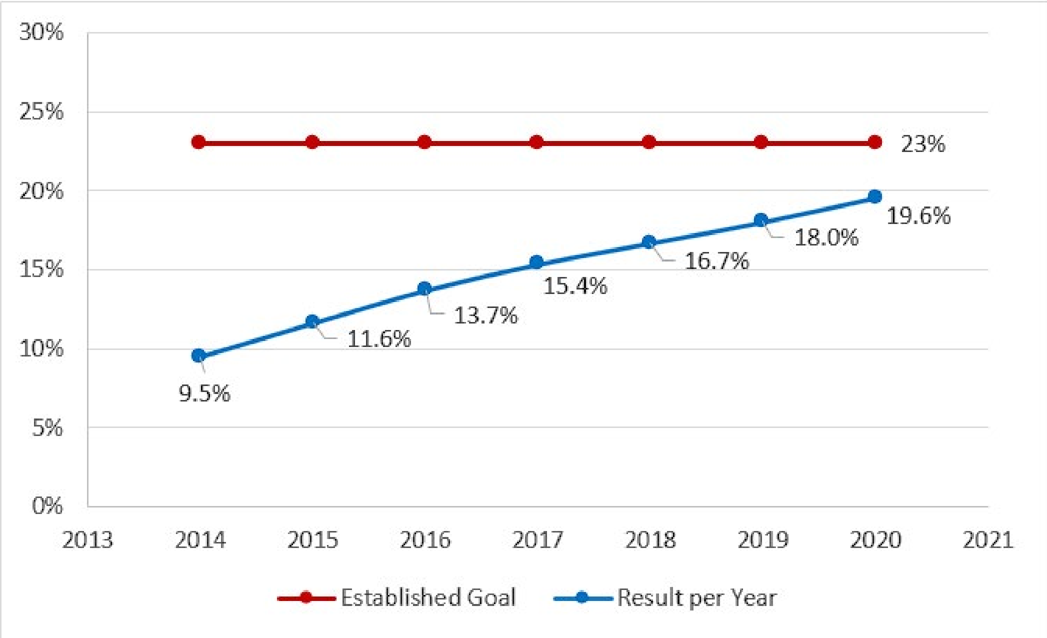

Figure 2 | Participation of Renewable Energy in the Brazilian Electricity Matrix (except hydroelectric power)

Source: EPE (2021).

As shown in Figure 2, excluding hydroelectric power, the share of renewable sources in the Brazilian electricity matrix grows in the period. In relation to expanding the domestic use of non-fossil energy sources by increasing the share of renewable energy (besides hydropower) in the electricity supply to at least 23% by 2030, the results show that Brazil is on the path to achieving the goal established in the Paris Agreement.

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The period's main highlight was wind energy's contribution to the Brazilian electricity matrix. Although in 2014, the generation of electricity by wind power was 12,210 GWh, in 2020, the value was 57,051 GWh (an increase of 44,811 GWh). The share of biomass went from 44,987 GWh to 51,876 GWh (an increase of 6,899 GWh), and solar energy went from 16 GWh to 3,461 GWh (an increment of 3,445 GWh). Figure 3 shows the percentage contribution of biomass, wind, and solar sources to the national electricity matrix from 2014 to 2020.

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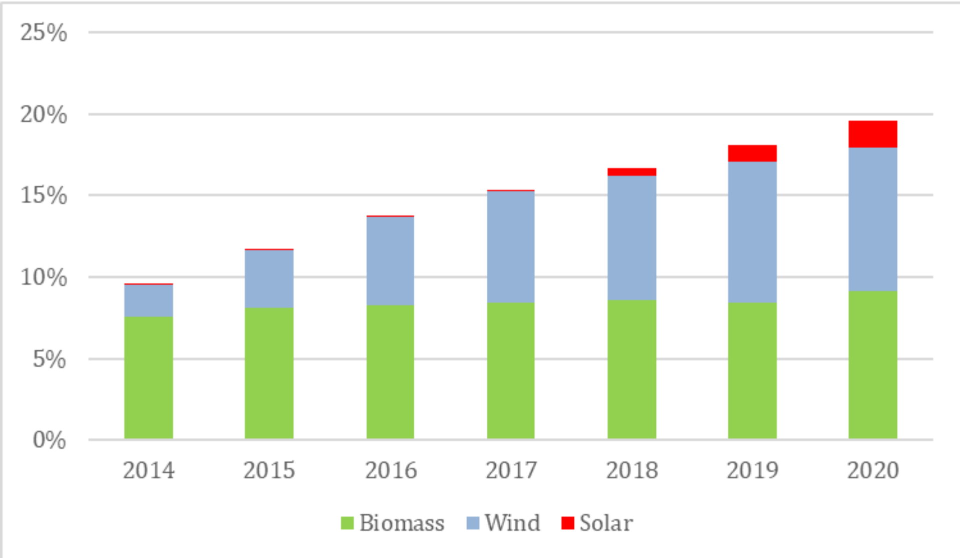

Figure 3 | Contribution of Biomass, Wind, and Solar Sources to the National Electric Matrix

Source: EPE (2021).

Figure 3 shows that wind energy was the source with the highest contribution in the period. In 2014, the 9.5% share of renewable energy for the Brazilian electric matrix (excluding hydroelectric source) was composed of 7.54% biomass, 1.95% wind, and 0.01% solar. In 2020, these shares were 9.09% biomass, 8.83% of wind, and 1.66% solar.

3.4 EFFICIENCY IN THE ELECTRICITY SECTOR

As Arantegui and Jänger-Waldau (2018) described, the European Council meeting defined the Climate and Energy Policies for 2030 to meet the goals of the Paris Agreement. A target was set to improve electrical efficiency by at least 27% in 2030. The goal established for Brazil in the Paris Agreement was to achieve 10% efficiency gains in the electricity sector by 2030.

The 2001 energy crisis ("The 2001 Blackout") was a national electricity crisis that affected the supply and distribution of electricity throughout the country. It occurred between July 1, 2001, and February 19, 2002, and was caused mainly by a lack of planning and investments in the Brazilian electricity sector. Hage (2019) indicates that, until the 2001 electricity crisis, Brazil had not made the necessary investments for the technical improvement of hydroelectric plants and power transmission companies, both State-owned. Altoé *et al.* (2017) emphasize that the hydric crisis, with the lack of long-term planning – considering the great dependence on hydraulic generation in the internal electricity supply – increased the need to activate a significant number of thermoelectric plants. Michels-Brito *et al.* (2021) warn that, besides the increase in CO2 emission, the use of thermoelectric energy to compensate for the hydropower deficit increases energy costs.

3.4.1 REGULATORY FRAMEWORKS FOR ENERGY EFFICIENCY INCENTIVES IN BRAZIL

Law 9,478, launched on August 6, 1997, established the principles and objectives of the National Energy Policy (PEN). This law established national policies for the rational use of energy sources to protect the environment, identify the most appropriate solutions for the supply of electricity in the country's many regions and attract investment in energy production (BRASIL, 1997).

On October 17, 2001, Law 10,295 was issued to establish the National Policy for Conservation and Rational Use of Energy, which aims to allocate energy resources and preserve the environment efficiently. This law established that the Executive Branch would be responsible for developing mechanisms to promote the energy efficiency of products, machinery, and equipment in the construction sector (BRASIL, 2001).

According to Altoé *et al.* (2017), in the following years, relevant advances were made regarding the Brazilian Labeling Program (PBE); products were rated according to their efficiency. The government also launched the energy efficiency certification program for commercial, public, and service buildings in 2009 and for residential buildings in 2010. In 2009, the certification of energy efficiency for vehicles was also created. Both the certification of buildings and vehicles are launched as part of the PBE, the former being the responsibility of Procel and the latter of Conpet.

Altoé *et al.* (2017) emphasize that another important regulatory milestone in the field of renewable energy and energy efficiency was Aneel's Resolution no. 482/2012. This resolution established a system of electricity compensation in Brazil (Net Metering), in which consumer units with distributed micro or mini generation (installed power up to 1 MW) from hydraulic, solar, wind, biomass, or qualified cogeneration sources, would be compensated. At the end of the month, the electric energy balance is calculated based on the energy injected into the grid and the energy consumed. If energy production is greater than consumption, credits are generated that can be used in up to 36 months. This resolution was updated in 2015.

3.4.2 EFFICIENCY DATA OF THE BRAZILIAN ELECTRICITY SECTOR

Table 2 shows data on commercial and technical electricity losses in Brazil.

Table 2 | Electricity Losses Data

	2014	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*
Internal Electricity Supply (GWh)	624,341	615,628	619,697	625,727	636,397	651,329	645,952
Final Consumption (GWh)	532,559	524,749	521,376	538,063	538,403	545,373	540,189
Losses (Commercial and Technical) (GWh)	91,782	90,879	98,321	97,664	97,994	105,956	105,763
LOSSES (%)	**14.70%**	**14.76%**	**15.87%**	**15.61%**	**15.40%**	**16.27%**	**16.37%**

Source: EPE (2021).

Figure 4 shows the losses occurred in the period and the targets stipulated by the Brazilian government in the Paris Agreement.

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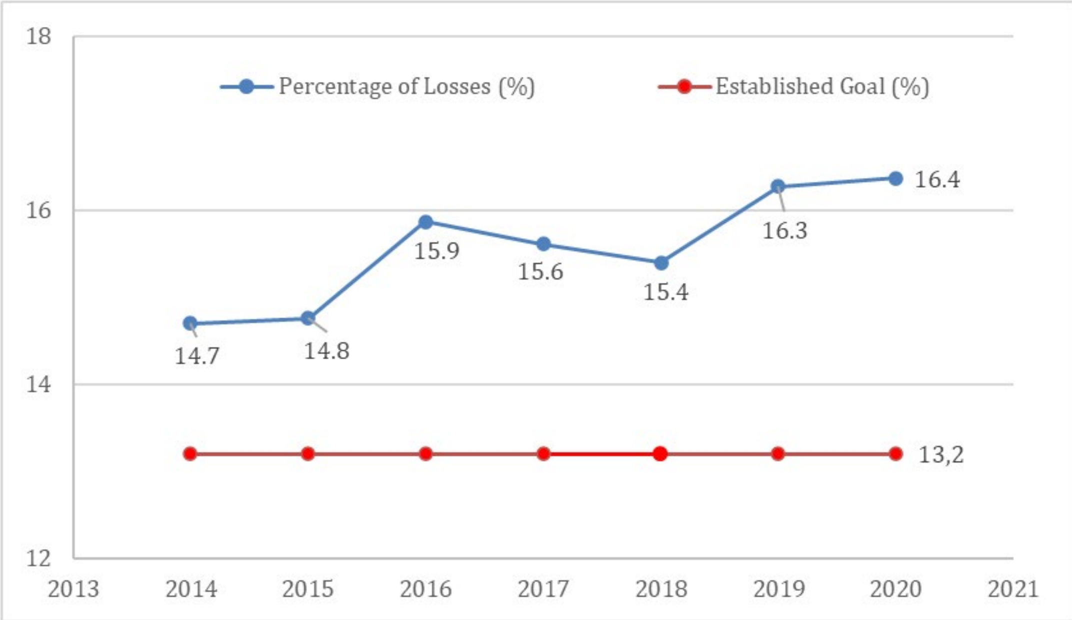

Figure 4 | Percentage of Electric Energy Loss in Brazil

Source: EPE (2021).

In relation to achieving 10% efficiency gains in the electricity sector by 2030, Figure 4 reveals that the percentage of electricity losses in Brazil grew from 2014 to 2016, decreased in 2017 and 2018, and increased again in 2020. In short, Brazil could not achieve the goal of being more efficient in the energy sector in no year after the ratification of the Paris Agreement.

Losses occur in the generation, transmission, and distribution of electric energy. According to the EPE (2021), the greatest losses occur in the transmission of energy between power generation and the distribution grid – losses that are inherent to the transportation of electric energy in the grid. To reduce losses, companies can use artificial intelligence to optimize shutdowns and start-ups to prevent unplanned downtime and to predict future maintenance requirements based on performance degradation (AHMAD *et al.*, 2021).

Altoé *et al.* (2017) report that to reach the electrical efficiency potential outlined in the 2030 National Plan, effective planning will be required to promote the rational use of electrical energy by the different economic sectors and by the population at large. The authors emphasize that the technical potential for efficiency gains is much higher and inclined to exploitation by implementing more aggressive incentive policies in electrical energy conservation.

3.4.3 WIND ENERGY AS A SOLUTION FOR REDUCING LOSSES IN POWER TRANSMISSION

Energy generation closer to consumption drastically reduces transmission and distribution losses (TOLMASQUIM, 2016). For Arantegui and Jänger-Waldau (2018), wind energy has the advantage that it can be implemented in a modular way almost anywhere on the planet. Off-grid small wind turbines can be used to provide electricity in remote areas. Due to the high population density in urban areas, both in emerging and developed countries, tailored energy solutions close to the areas where demand is generated are required (VALLEJO-DÍAZ *et al.*, 2022). López-González *et al.* (2020) evaluated technical performance in a desert climate on the Caribbean coast and in a dry-winter climate in the Andean mountains and concluded that the flat areas on the north coast have a low wind variability and high wind speeds, whereas in the Andes the implementation of SWT is limited by orography. Zhang *et al.*

(2020) demonstrated that wind energy is more economical and feasible than conventional electricity in the mountainous areas of southwestern China. Vallejo-Díaz *et al.* (2022) showed that although urban wind energy solution nowadays seems to be more expensive than the current electricity price in the Dominican Republic, the installation of small wind blades on the roofs of tall buildings results in a reduction of CO_2 emissions. Therefore, these tailored solutions could be included in each country's policies to combat greenhouse gas emissions. The use of small wind turbines should be beneficial to communities living in remote rural areas of Brazil, such as the Amazon and the *Pantanal*, as well as in urban areas, especially near the coastline. However, investments in research and development are needed to build the ideal type of wind turbine to meet the technical requirements of each location (wind speed and intensity, orography, among others). As described by Tolmasquim *et al.* (2021), the technological evolution of turbines is an important reason that led to the significant decline in wind energy prices, which brought new perspectives and potential to this kind of energy source and a reduction in installation costs.

In Brazil, all wind energy is generated by the onshore method. Onshore wind farms are the infrastructures that generate electricity from the wind blowing in onshore locations. On the other hand, offshore wind energy, still non-existent in Brazil, is the source of clean and renewable energy obtained by using the wind that blows offshore, where it reaches a higher and more constant speed due to the absence of barriers. Studies of offshore wind potential conducted by the EPE (2020) indicate that, at a 100 m height, Brazil's offshore potential is 697 GW at sites with depths of up to 50 meters, values that are much higher than the installed capacity in the country by December 2020 (17.75 GW). On August 22, 2018, Petrobras announced the development of the first offshore wind energy project in Brazil at the Guamaré hub in Rio Grande do Norte. However, in January 2020, the company notified the Brazilian Institute of Environmental and Renewable Natural Resources (Ibama – Brazilian acronym) –responsible for the project's environmental licensing in Brazil – that the pilot project was cancelled.

Implementing offshore wind farms can diversify Brazil's electricity matrix and allow power generation near large urban centres, reducing losses and transmission costs. This type of energy generation is growing rapidly in Europe and China. Kaldellis and Kapsali (2013) consider that the main reasons that drive this growth are the existence of stronger and more consistent winds in offshore locations, the absence of obstacles (*e.g.*, mountains, buildings, and trees) in marine environments, the low impact on communities, and the possibility of building offshore wind farms in coastal areas near large urban centres. The United Kingdom currently has the largest offshore wind capacity installed worldwide (GWEC, 2021) and the largest offshore wind farm – the London Array. Kaldellis and Kapsai (2013) mention examples of offshore wind farms that were installed near the coast and that have shown good potential in the UK. Scroby Sands Wind Farm is located at an average distance of 3 km from the coast and has an availability of 84.2%, and North Hoyle Offshore Wind Farm, which is located 8 km from the coast and has an availability of 91.2%. Artificial intelligence can help communication in real time among the various wind farm stations, to acknowledge the change in wind direction and wind speed, and to assess the grid's status (AHMAD *et al.*, 2021), allowing for a better coordination of the use of onshore/offshore wind farms in Brazil by the Brazilian Independent Transmission System Operator (ONS – Brazilian acronym).

3.5 ANALYSIS OF THE RESULTS OF PUBLIC POLICIES FOR WIND ENERGY IN BRAZIL

Since 2001, after the energy crisis, Brazil has been adopting policies to encourage the growth of renewable energy sources in the country. Figure 5 summarizes the main public policies that have benefited Brazil's wind power expansion.

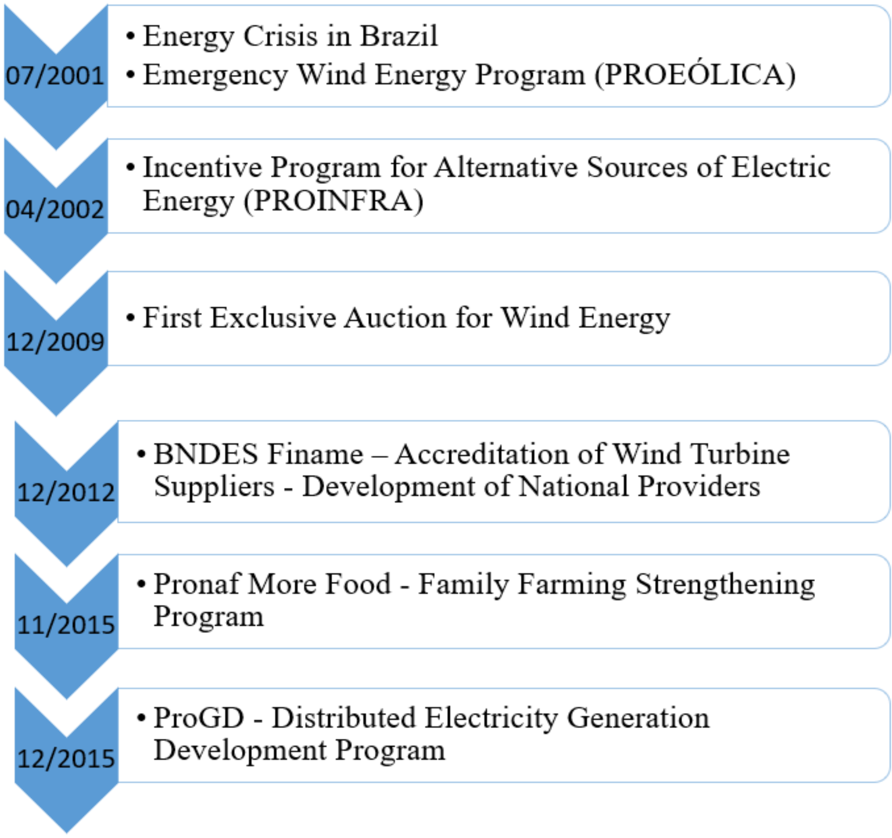

Figure 5 | Main Public Policies for the Wind Sector in Brazil

Source: Brazil (2001), Brazil (2002), Luna et al. (2019).

3.5.1 EMERGENCY WIND ENERGY PROGRAM (PROEÓLICA)

Proeólica was created by Resolution no. 24 in 2001 by the Brazilian Chamber of Deputies for the Management of the Electric Energy Crisis (BRASIL, 2001). The objectives of the program were: 1) To enable the generation of 1,050 MW from wind sources integrated to the national integrated electric system by 2003; 2) to develop the use of wind power as an alternative energy source to promote socioeconomic and environmental development; 3) to help compensate seasonality in the hydrological flows of reservoirs of the National interconnected system.

Incentive program for alternative sources of electric energy (Proinfa)

The Proinfa was created by Federal Law no. 10,428 on April 24, 2002 (BRASIL, 2002), and regulated by Decree no. 4541 on December 23, 2002, aiming to increase the participation of electric energy produced by undertakings of Independent Autonomous Producers. The program's target was wind farms, small hydroelectric plants, and biomass plants.

3.5.2 EXCLUSIVE AUCTIONS FOR WIND ENERGY

Since 2009, wind energy has been marketed in a regulated environment by specific auctions for renewable sources. Wind energy has economic-related characteristics such as high initial investment, low operating cost, and a seasonal and intermittent production flow, which were formulated into a contractual model to consider the average production over the years and to allow readjustments and compensations according to generation patterns over time. This change in the contracting system stimulated the development and growth of wind energy in Brazil (LUCENA, J. de A. Y.; LUCENA, K. Â. A., 2019). The authors also emphasize that the economic crisis Brazil experienced in 2015 resulted in a drop in electricity consumption and, consequently, a reduction in wind energy contracting in 2015, even with the three auctions that happened that year. In 2016, there was no contracting of wind energy.

3.5.3 OTHER GOVERNMENT PROGRAMS

Luna *et al.* (2019) analyzed other programs and tax incentives created by the Brazilian government over time, which aimed to encourage the generation of energy from renewable sources. On December 15, 2015, the Brazilian Ministry of Mines and Energy launched the Program for the Development of Distributed Generation of Electricity (PROGD) with the objective of deepening actions to stimulate consumer energy generation (residential, commercial, and industrial). The ICMS Agreement 101/97 grants tax exemption on operations with equipment and components for using solar and wind energy (solar heaters, photovoltaic generators, and wind power turbines). In November 2015, the Ministry of Agrarian Development (MDA) included the financing of equipment for solar and wind energy production in the Mais Alimentos Program – benefitting family producers with lower interest rates.

As described by Lima *et al.* (2020), the Brazilian government has been holding specific energy auctions for renewable technologies (solar and wind). Tolmasquim (2016) recognizes that Brazil's continental characteristics and its geographic location are important points for the use of the wind source, allowing for the implementation of wind farms located in different regions with different wind regimes and also, the capacity of wind farms winning energy auctions have been higher than the global average values. Additionally, these authors report that the growth in the participation of renewable resources in the Brazilian electricity matrix – such as wind and solar sources – contributes to solving stability and supply capacity issues.

3.5.4 POLICY OUTCOME: THE GROWTH OF WIND ENERGY IN BRAZIL

In December 2000, the year before Brazil suffered the energy crisis, the installed wind power capacity was only 20 MW (ANEEL, 2002). Figure 6 shows how the installed capacity of wind power plants has evolved in Brazil from 2014 (one year before the signing of the Paris Agreement) to 2020.

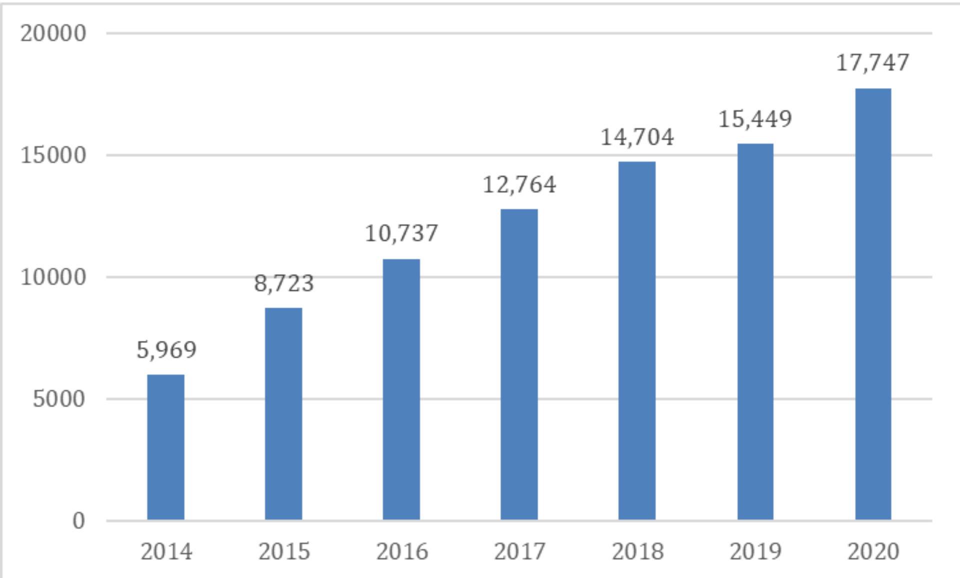

Figure 6 | Evolution of the installed capacity in wind power plants in Brazil (MW)

Source: Abeeólica (2021).

In December 2020, wind power plants in operation totalled an installed capacity of 17,747 MW. According to the Gwec (2021), Brazil ranked seventh in 2020 in the world ranking of accumulated onshore wind capacity. Brazil appeared in third place in the ranking that accounts explicitly for new capacity installed in the year, having a new installed capacity of 2,298 MW in 2020. For Lozornio *et al.* (2017), Brazil has advanced in using wind energy mainly due to the adopted incentive policies.

Notably, the installed capacity increased by approximately three times from 2014 to 2020, going from 5,969 MW to 17,747 MW, representing a significant average growth rate of 20% per year. According to Abeeólica (2021), 57,000 GWh of wind energy were generated throughout 2020. The five states with the highest wind generation in 2020 were Bahia (16,220 GWh), Rio Grande do Norte (15,590 GWh), Ceará (5,950 GWh), Piauí (5,910 GWh), and Rio Grande do Sul (5,810 GWh).

Abeeólica (2021) emphasizes that the wind source contributes so that Brazil achieves the goals for the Brazilian electricity sector. Since wind energy is a CO2-free source, it can replace other sources of electric energy generation, reducing emissions. In 2020, 21.2 million tons of CO2 were avoided, equivalent to the annual emission of about 21 million passenger cars. Wind energy growth could help Brazil achieve emission reduction targets assumed by the government in the Paris Agreement because of the greenhouse gas emission reductions it brings (RAIMUNDO *et al.*, 2018).

3.5.5 NEW POLICIES FOR WIND ENERGY GENERATION AND TRANSMISSION ARE NEEDED

To meet the Paris Agreement and the Sustainable Development Goals, nearly all countries need to urgently and drastically increase their climate action (HÖHNE *et al.*, 2020). Accounting for health and climate costs in energy planning would provide an economic justification for decarbonizing energy systems, as well as reduce the social cost of supplying electricity, boost the economy, and improve the quality of life (HOWARD *et al.*, 2020).

Brazil's electricity production and transmission system is a large-scale hydro-thermo-wind system with a predominance of large hydroelectric power plants (TOLMASQUIM *et al.*, 2021). Despite the notable advances in the expansion of wind energy in Brazil, creating new incentive policies is necessary to ensure the continuity and security of the electricity supply in the country. The largest installed capacity for electricity generation in Brazil still originates from hydroelectric plants. Although in 2001, hydroelectric plants represented 83% of installed capacity, in 2020, they represented 62% (IEA, 2021). However, the country went through a critical hydrological scenario in 2021 with the lowest flows since 1930. Although all regions of Brazil have reservoirs, the main ones are concentrated in the Southeast/Midwest subsystem, representing 70% of the country's storage capacity (MME, 2021). In a scenario of low reservoir levels, together with the low prospects for rainfall in a scenario of economic growth, there are reasons for concern, considering the possibility of a new energy crisis as that of 2001. As a way of containing the risk of new blackouts, the Power Sector Monitoring Committee created by the government had to resort to activating thermoelectric power plants. A crisis-preventing solution includes managing operating restrictions of the hydroelectric plants to preserve the levels of the reservoirs; management for the availability of fuel for thermoelectric plants; management for the start-up of operation of new plants and transmission lines and campaigns for conscious and rational consumption of water and electric energy (MME, 2021). However, these are short-term measures. No law was enacted to increase the incentive for the generation of alternative renewable energy sources, which could benefit the country in the long term.

On the other hand, the need for investments in the country's transmission lines is evident. The Brazilian electricity system has experienced congestion in the Northeast region, affecting the coordinated transmission expansion and new wind power capacity (HERRERA; DYNER; COSENZ, 2019). New farms cannot connect to the grid in some states due to current grid capacity limitations and low availability of substations and high voltage lines near potential windy sites (DIÓGENES *et al.*, 2020). Transmission grid issues are the main reason for the delay of such projects in Brazil. This suggests that coordination between the expansion of renewable energy and the expansion of the transmission system should be a core element of the auction design (BAYER; BERTHOLD; FREITAS, 2018). However, the federal government has shown less commitment to meeting the Paris Agreement's goals on carbon emissions (PONTES, 2020; THOMAS, 2021), which represents a potential barrier (MARTINS; PEREIRA, 2011).

4 CONCLUSION

Based on this study, we can conclude that public policies of tax incentives for wind power generation in Brazil – after the 2001 electricity crisis – are responsible for the increase in investments in wind power generation. Additionally, they allowed the diversification of the electric matrix via a renewable, low carbon emission, and abundant source in the country. As a result, the policies have been contributing to help to solve the national electricity problem and making the country fulfil the commitments made in the Paris Agreement and SDG 7. However, this process is still in progress; there still needs to occur a strong governmental interest and/or commitment in the expansion of sustainable energy generation. The need to invest in renewable sources in Brazil, besides wind power, goes beyond the need to comply with international agreements; it is a question of meeting the internal demands of residential, commercial, and industrial consumers. As the Brazilian agribusiness sector is one of the strongest in the world, a new blackout could affect the domestic market and other countries' supply.

Despite the growth of renewable sources in the electricity matrix in recent years, more government incentives must be created and enacted for this sector. Besides, investments in research and development are needed for wind turbines suitable for other regions of Brazil besides the Northeast, as well as to address the small turbine market. The incentive to decentralize and expand wind turbine generation with resources once used for developing fossil energy sources infrastructure also presents itself as a great opportunity.

Additionally, the public policies created so far have been unable to reduce electricity losses in Brazil by 10% of what they were in 2014 (to improve electrical efficiency). It is argued that offshore wind power generation – so far non-existent in the country – is an option that should be considered to increase the share of renewable energy in the national electric matrix, diversify energy sources, and especially reduce electrical losses caused in transmission – increasing electrical efficiency. Therefore, specific tax incentives should be offered for this type of energy generation.

Future studies could assess what public policies other countries implemented to diversify the electricity matrix and thus achieve the goals set out in the Paris Agreement and whether these policies enable these countries to improve electricity efficiency.

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