# Wind Energy in Brazil: A National Evolution Decade compared to Global Wind Development

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## ABSTRACT

Renewable energy is fundamental to ensure more sustainability to contemporary global development. In this context, the wind energy has stood out in recent years. This article aims to: show the wind energy development in the World and in Brazil in the last decade; present and comment the regulatory framework evolution and your revision in Brazil; comment the future perspectives about energy complementarity and offshore wind power in Brazil. The methodology used was: literature review and general analysis of the Wind power in Brazil (contextualization, prospects and critical evaluation). The conclusions were: the development with wind power in Brazil and the World are success cases in this last decade; The regulatory framework allowed that Brazilian installed capacity of onshore wind farms has exceeded 15 GW in 2019, but there is still a potential of 522 GW to be explored and there is a need to improve the regulatory framework; There are significant potentials available for complementarity of wind power with solar and hydropower and offshore wind power potentials were estimated between 57 GW and 1,780 GW.

## KEYWORDS

Renewable Energy. Wind power. Onshore and Offshore. Regulatory Framework. Brazil.

## INTRODUCTION

The actual global need for energy is growing and the diversification of energy options available to meet this respective demand too. As a matter of energy planning and security, many countries at various stages of development seek to diversify their energy base available for alternative sources. In this context, renewable energy (RE), considered alternative (Wind, Solar, Biomass, etc.), are options that have been shown to be economically feasible and their use has expanded increasingly compared to fossil fuel sources of energy in many countries. Additionally, several issues related to environmental conservation, climate changes, advances in legislation, public opinion and sustainability in general also have acted decisively to expand the importance and the use of alternative renewable energy sources (RESs). Therefore, RESs are fundamental to ensure: energy security, less environmental impacts and

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more sustainability of contemporary development. Among the sources of RE used for electricity generation, the wind source has stood out in recent years.

Since ancient times, the strength of the wind has been used for humankind to drive boat sails or windmills by being transformed into mechanical energy. The gradual reduction in the costs of the production of wind energy and its advantages as a renewable and freely availability source are strategic factors. They have led several countries to stimulate the introduction and the expansion of the wind generation through regulation and incentives for investments.

Brazil is rich in wind resources that started being used for RE generation and present a significant growth in the national energy matrix. In this context, wind energy emerges as a strategic and attractive alternative energy resource and that has been developing very well in the last years in the country. Brazil already uses onshore power plants (located on land) and has the possibility of also using offshore power plants (located at sea) for its electricity production.

## MATERIAL AND METHODS

The methodology used in this article was a literature review, followed by a general analysis of the wind power in Brazil, in special from 2009 to 2018, subsidizing its contextualization and subsequent critical evaluation. The hypotheses presented are: (i) the experiences with wind energy in Brazil and the World are success cases; (ii) the Brazilian capacity installed of wind farms is high and there is still much potential to be explored; (iii) there is potential for complementarity of wind energy with others renewable energy sources; (iv) there is prospect for a future use of offshore wind power. In this way, analyses were made of the Brazilian context and findings of the impact of the legislation adopted in recent years. Comments and criticisms ware also made about the possible changes from the updating of regulatory framework in Brazil.

## LITERATURE REVIEW

Nowadays, the world is encountering severe challenges in the energy generation sector. Environmental issues like climate change, global warming and Greenhouse Gases (GHGs) and also social issues like dramatic increase in global population and increasing energy demand are the main causes of global concerns about energy resource management. In this regard, RESs are the suitable substitution to replace the conventional generating units that emit GHGs due to the use of fossil fuels. Among all RESs, wind energy seems to be promising for generating emission-free electrical energy [1].

Development of alternative energy sources has become a necessity as fossil energy resources are declining. At the same time, energy demand is rapidly increasing, putting the world on the verge of a global energy crisis. Moreover, the extensive use of conventional energy sources is polluting the environment and causing global warming. On the other hand, wind and other RESs are viable and clean alternatives to fossil fuels. Low operating cost and extensive availability make wind one of the most advantageous and effective RESs [2].

Energy production from renewable sources is already a reality in many countries, and with that, different strategies for incentivizing investments in RE generation have been proposed and used over the years [3]. RE offers a range of options with which to meet the growing demand for energy, particularly in the context of the pursuit (especially in developing countries) of economic development which takes into account social and environmental issues [4].

Low and middle income countries are usually trapped by their natural resource abundance, and thus have little opportunity to diversify their electricity matrix. On the other hand, in high income countries, new electricity sources have been growing faster, regardless of their resource endowments. As income grows, countries should have more opportunities to develop new technologies. Thus, the evolution of technologies to generate electricity should lead to a new mix of fuel consumption along the steps of an imaginary electricity ladder, from the more traditional to the more advanced and cleaner technologies [5].

Wind is one of the cleanest sources of RE. The confidence on wind power can be realized from the recent growth of wind power at global level. Several countries have set specific target to meet substantial portion of their domestic energy demand from wind while many others have initiated large scale research and development (R&D) [6]. Commercial use of wind energy for electricity generation began in the 1970 due to the international oil crisis. Denmark pioneered the installation of the first commercial wind turbine connected to the public grid in 1976 [7].

According to [8], with the urgency of climate change and billions spent globally on RE support policies, it is crucial to understand which policies are effective. The authors comment the public policy specifics are instruments are most effective if they reduced RE project investment risk and increased investments return. First, those effective policies address risk and return simultaneously. Second, they affirmed that generic instrument design features, such as credibility and predictability (continuous evaluation and monitoring), considerably impact investment risk.

Wind energy is beneficial because it does not emit GHGs in electricity production and is a cleaner and more sustainable way of introducing electricity [1, 9]. Despite these benefits, [10] said which development wind energy may lead to unexpected environmental impacts, such as: noise pollution, bird and bat fatalities, some GHGs (most of which arise from the production of concrete and steel for wind turbine foundations), and land surface impacts. [11] used the input–output analysis to evaluate the inventories of energy and environmental burdens associated with the productive chain of wind energy and your life cycle. The authors concluded the production is positive and added value effects outweigh the negative effects of partially substituting electricity from wind power for conventionally generated electricity.

Due to the stochastic nature of wind, electric power generated by wind turbines is highly erratic and may affect both the power quality and the planning of power systems [12]. [1, 9, 13] comment that the problem of intermittency is inherent to the winds and must be considered and administered to the electric system. According to [14], the quantification of the long-term variability of the wind energy potential is an important prerequisite for controlling and adapting the expansion of wind energy on national and global scales to future electricity consumption. According to [15], the wind energy resource is susceptible to climate change that might benefit or negatively impact wind energy developments depending on the region under consideration. Energy Storage Systems (ESSs) may play an important role in wind power applications by controlling wind power plant output and providing ancillary services to the power system and therefore, enabling an increased penetration of wind power in the system [12].

Looking ahead to 2050 many countries intend to utilise wind as a prominent energy source. Predicting a realistic maximum yield of onshore and offshore wind will play a key role in establishing what technology mix can be achieved, specifying investment needs and designing policy. Historically, studies of wind resources have however differed in their incorporation of physical limits, land availability and economic constraints, resulting in a wide range of harvesting potentials. To obtain a more reliable estimate, physical and economic limits must be taken into account [16]. According to International Renewable Energy Agency (IRENA) [17], the future of Wind to 2050 presents very positive possibilities in terms of: expansion of installed capacity; expansion investments; development of technologies; grid integration; and socio-economic and environmental aspects (etc.: Employment creation, GHG reduction, etc.).

Cost efficient deployment of wind energy is in focus for reaching ambitious targets for RE and transforming the energy supply system to one based on renewables. Wind energy is one of the most cost-efficient renewable technologies and increasing amounts of wind energy is being installed in Europe and worldwide. In many countries, the cheapest wind resources onshore are now competitive with conventional generation. However, as more wind is being deployed the available sites onshore become less attractive in terms of wind conditions and capacity factor and more resistance from population groups affected in the deployment areas results in a reduction of areas that can be developed. That means further onshore potentials become scarce and development has been moving offshore [18].

[19] comment on the differences and make a comparison between onshore and offshore wind farms, concluding that not necessarily one is better than the other. The particularities and adaptations of each situation must be taken into account. According to [20], the overall higher environmental impact of offshore plants, compared to onshore ones, is mainly due to larger high-impact material requirements for capital infrastructure. The global development of the offshore RE sector has been driven by extensive investment and research in the utilization of offshore renewable energies, mainly at the regional level [21]. However, for mid to long-term marine energy development planning, a comprehensive assessment of the global potential for the exploitation of the main offshore resources is required [21].

The gradual reduction in the costs of the production of wind energy and its advantages as a renewable and freely available source have led several countries to stimulate their deployment and led to an expansion in wind generation through regulation and incentives for investments [7]. Even though recent years have shown a significant decrease in costs for offshore wind, and as a consequence a narrower differential between onshore and offshore wind costs, offshore wind remains more expensive than onshore wind. As a consequence of the shift from onshore to higher cost offshore projects, the expansion of wind generation has become more expensive resulting in slower growth [18].

The average distance to shore and the water depth are both increasing throughout the years. Although the average investment cost per project is rising with the higher distances to shore and water depths, the multi-GW plans of the northern European and Asian countries indicate that the industry will continue to grow [22]. [23] confirm that Europe and China are leading the deployment of offshore wind energy in the world, but notes that the United States of America (USA) may play an important role in the future and this will depend their decision makers. In 2018, the United Kingdom (UK), Germany, Denmark and China were leaders in offshore wind power installed capacity.

In recent years, offshore wind energy has been developing rapidly with the advantages of not taking up land resources and high utilization rate [24]. China's performance in the wind energy market has resulted in a great respective supply chain development. Thus the costs of implementing this energy source have reduced worldwide, contributing to its competitiveness and expansion.

Brazil has abundant natural sources of RE, such as wind and solar power, hydraulic energy, small hydroelectric plants, ethanol and bio-diesel [4]. Since the 1970s, demands arising from the impacts of the power sector on the natural environment were added to studies regarding the strategic power sector and its impact on the economic and financial crises [25]. Expanding RE would not only enhance Brazil's economic growth and curb the deterioration of the environment but also create an opportunity for a leadership role in the international system and improve Brazil's competition with more developed countries [26].

Hydropower is the backbone of the Brazilian electricity generation sector. Even though the use of this resource is advantaged in terms of GHG emissions, last years´ severe droughts have exposed the country′s huge dependency on hydroelectricity. Brazil′s electricity supply system has shown to be vulnerable to electricity shortages and has demanded significant overhaul in order to address its challenges [27].

According to [28], the electric crisis in 2001 led the Brazilian government to develop new energy policies that supported the rapid growth of the wind industry from imported technology. [29] compared the economic viability of RE technologies (wind, solar photovoltaic, concentrated solar thermal, biomass and wave power) to traditional generation technologies including: hydroelectricity, nuclear power, coal power and gas power sources in Brazil. The authors demonstrated that wind power technology became the cheapest generation technology in Brazil, once all externality and transmission line costs are taken into consideration.

[30] commented that seasonal variability of wind power generation in the North-Eastern states is anti-cyclical to hydrological seasonality in the South-East, North-East, and North region of Brazil. Deviations of simulated wind power production from the monthly means are less correlated with current hydropower production than deviations of potential new hydropower projects. The authors informed that adding wind power instead of hydropower to the system decreases significantly the risk of long periods of very low resource availability. The states Bahia and Rio Grande do Sul perform best with respect to that measure. [31–33] comment that one of the effects of climate change in Brazil will be a tendency to increase the intensity of the winds, especially in the Northeast Region.

Brazil's wind energy program is a successful public-private sector response to an electricity supply crisis in 2001 that created an attractive target for investors in renewable power [34]. According to [35], auctions are becoming increasingly common in an international context as a support scheme for renewable energies and Brazil adopted the energy auctions.

## RENEWABLE ENERGY IN THE WORLD AND IN BRAZIL

### Cost comparison of Wind power with others sources energies

According to data of the IRENA [36, 37], in 2018, the Levelized Cost of Energy (LCOE) for RE projects was competitive or cheaper than fossil fuel costs, even in the absence of financial support (Figure 1). It can be seen that wind energy costs (onshore and offshore) have become quite competitive with fossil energy over the last decade.

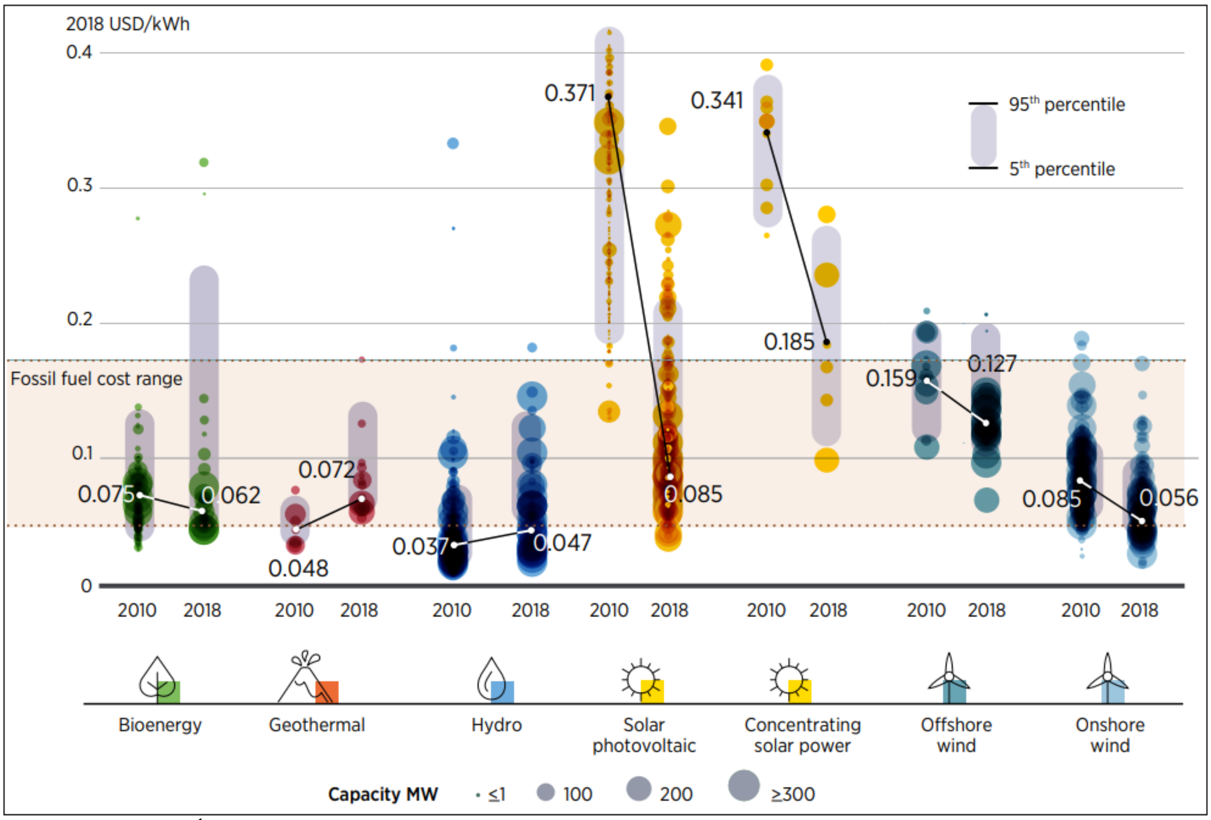


Fig. 1. [1]Global electricity costs from utility-scale renewable power generation, 2010–2018.
Source: [36, 37].

## Comparisons of Installed Capacity and of Energy Production of the renewable sources between Word and Brazil

The decade-long trend of strong growth in RE capacity continued in 2018 with global additions of 171 GW. The annual increase of 7.9% was bolstered by new additions from solar and wind energy, which accounted for 84% of the growth. Globally, total RE generation capacity reached 2,351 GW at the end of last year – around a third of total installed electricity capacity. Oceania witnessed the fastest growth with a 17.7% rise in 2018. Asia was second with a 11.4% rise followed by Africa with 8.4% growth. Nearly two-thirds of all new power generation capacity added in 2018 was from RE, led by emerging and developing economies [38]. Comparing the installed capacities (Figure 2) and electricity generation (Figure 3) of RE between the World and Brazil, it is observed that the main renewable sources in the World are*: hydropower*, *wind*, *solar* and *bioenergy*. In Brazil, it is observed that the main renewable sources in the world are: *hydropower, wind and bioenergy*.

[1] These data are for the year of commissioning. The diameter of the circle represents the size of the project, with its centre the value for the cost of each project on the Y axis. The thick lines are the global weighted average LCOE for plants commissioned in each year. The real weighted average cost of capital (WACC) is 7.5% for countries of the Organisation for Economic Co-operation and Development (OECD) and China, and 10% for the rest of the world. The beige band represents the cost range of fossil fuel–fired power generation cost; the grey bands for each technology and year represent the 5th and 95th percentile bands for renewable projects [37].

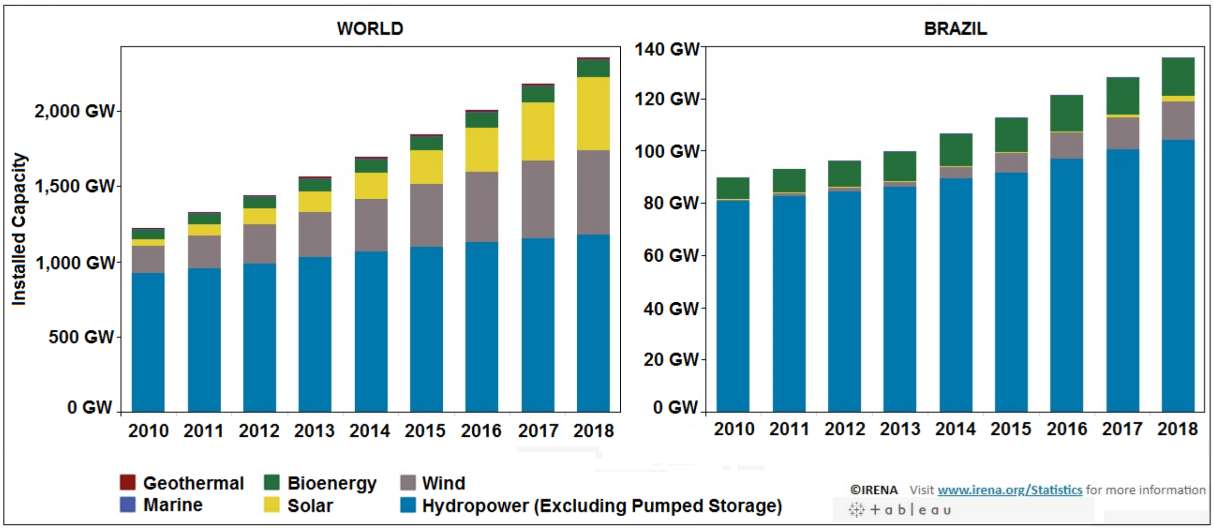


Fig. 2. Evolution of Renewable Energy Installed Capacity between Word and Brazil.
Source: [38].

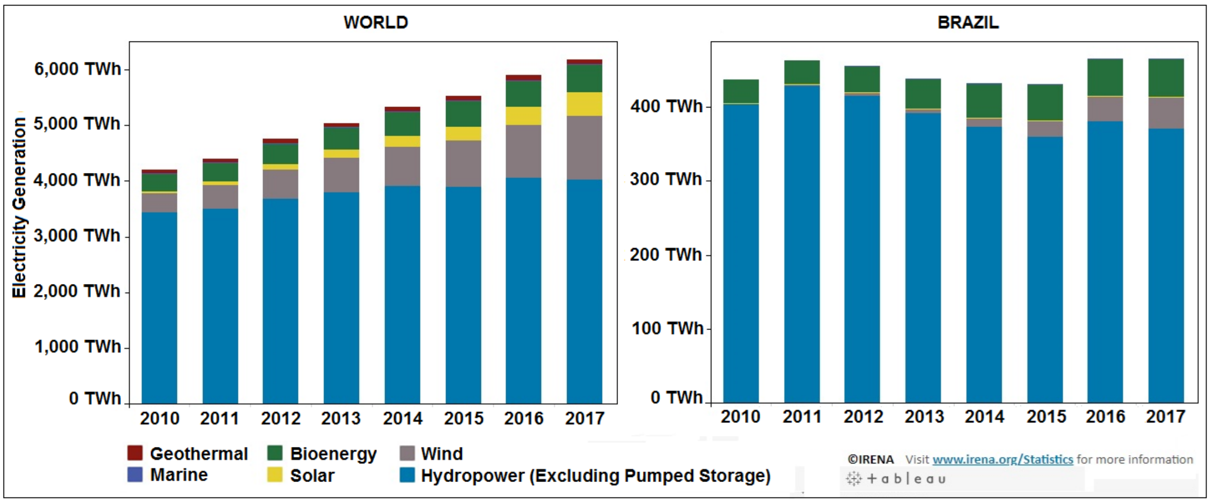


Fig. 3. Evolution of Renewable Energy Generation between Word and Brazil.
Source: [38].

## WIND ENERGY POTENTIAL IN THE WORLD AND IN BRAZIL

According to [7], the heights currently used for the generation of wind energy are between 50 m and 150 m from the surface of land (or sea) towards the atmosphere. Unidirectional winds are economically viable when the speed is above 6 m/s. The Atlas of Brazilian Wind Potential 2001 [39] indicated a gross potential of 143.5 GW, evaluated for hub heights of 50 m. Figure 4-A [40] shows Global wind potential (onshore) for speeds at height of 80 m. According to [41], the National Institute of Science and Technology for Climate Change (*Instituto Nacional de Ciência e Tecnologia para Mudanças Climáticas* – INCT–Clima) estimated a gross wind power potential of up to 880.5 GW considering hub heights of 100 m, with 522 GW being technically feasible (Figure 4-B). [42] comment that Brazilian wind regime has excellent characteristics for electricity generation: good speed, low turbulence and good uniformity. The Northeast Region stands out as the one with the greatest potential in Brazil (Figure 4-B). New simulations of Center for Electric Energy Research (*Centro de Pesquisas de Energia Elétrica* – CEPEL) [43] also confirm the highs Brazilian wind potentials at various heights.

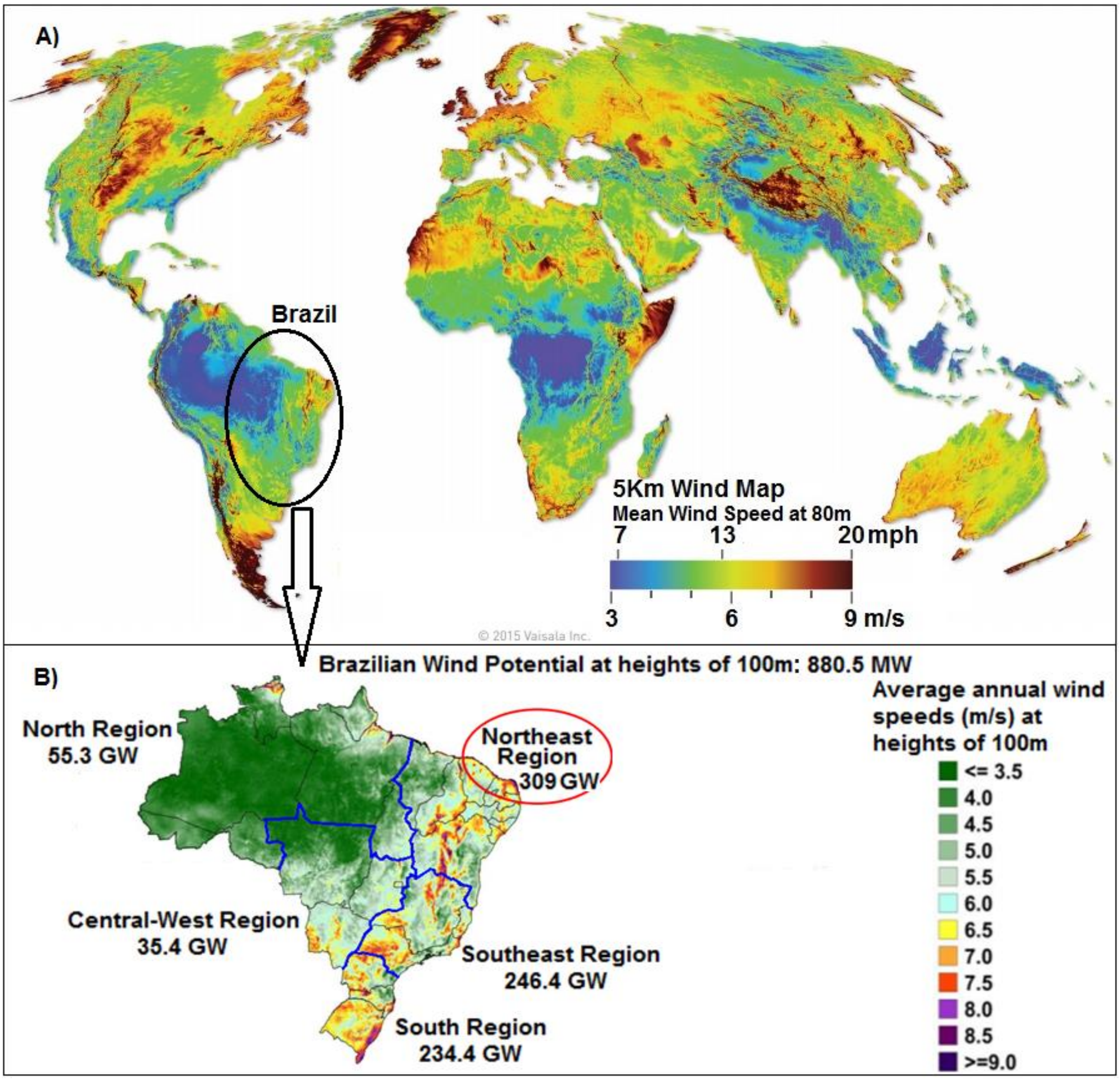


Fig. 4. A) Global Wind Potential (onshore) for speeds at 80 m, map resolution of 5 km [40] (Adapted). B) Brazilian Wind Potential for speeds at 100 m, map resolution of 10 km x 10 km and hourly wind speeds from 1983 to 1999 [41] (Adapted).

## EVOLUTION OF WIND POWER IN THE WORLD AND IN BRAZIL

Based on information from the IRENA [44] of the last decade, it is possible to show the significant evolution of onshore and offshore wind energy in the world and in the 10 countries with the greatest onshore and offshore installed capacity in 2018, through Tables 1, 2, 3 and 4. The absolute predominance of the world's wind power installed capacity is onshore, but the growth of offshore wind power is already becoming representative. The percentage growth annual of total wind energy installed capacity was significant in the period 2009-2018, with Brazil maintaining a much higher than average percentage growth of world growth (Table 1): total onshore wind energy installed capacity was 265.2% in the World and 2,292.2% in Brazil. Thus, it is verified the growth of wind energy in the last decade was continuous and consistent, which it implies constant investments despite of economical global crisis of 2008. Total installed capacity wind power (onshore and offshore) in 2018 was 563,727 MW, where the regions with the greatest amount of installed capacity are: Asia (229,027 MW or 40.62%); Europe (182,491 or 32.38%); North America (111,986 MW or 19.87%); and South America

(18,679 MW or 3.31%), with 14,401 MW (2.67%) located in Brazil (Table 2). By 2026 the total installed wind power capacity in Brazil will grow to approximately 28,000 MW and the penetration of installed wind and solar power in Brazil's generation matrix will increase to approximately 18% [45, 46].

Table 1. Percentage growth of installed capacity in the World and in Brazil: 2009-2018.

| Increase % of Wind Power | 2009-2010 | 2010-2011 | 2011-2012 | 2012-2013 | 2013-2014 | 2014-2015 | 2015-2016 | 2016-2017 | 2017-2018 | 2009-2018 |
|---|---|---|---|---|---|---|---|---|---|---|
| World | 20.5% | 21.6% | 21.3% | 12.4% | 16.4% | 19.2% | 12.2% | 10.2% | 9.5% | 265,2% |
| Brazil | 54.0% | 53.8% | 32.8% | 16.3% | 122.0% | 56.2% | 32.6% | 21.4% | 17.1% | 2,292.2% |

Source: Author's own elaboration based in [44].

Table 2. Wind Power Installed Capacity in Brazil, 9 Regions and World.

| Year | | | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | % of MW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No | Regions | Installed Capacity Wind Energy (MW) | | | | | | | | | | | in 2018 |
| 1° | Asia | Onshore | 31,295 | 45,958 | 65,784 | 82,487 | 99,054 | 123,830 | 161,077 | 182,504 | 201,878 | 224,221 | 39.77% |
| | | Offshore | 13 | 125 | 235 | 321 | 488 | 516 | 722 | 1,680 | 3,006 | 4,806 | 0.85% |
| 2° | Europe | Onshore | 73,659 | 81,991 | 91,143 | 102,133 | 111,673 | 122,150 | 132,019 | 143,272 | 155,189 | 163,970 | 29.09% |
| | | Offshore | 2,121 | 2,931 | 3,541 | 5,013 | 6,684 | 7,976 | 10,996 | 12,633 | 15,856 | 18,521 | 3.29% |
| 3° | North America | Onshore | 38,004 | 43,622 | 51,543 | 67,092 | 69,897 | 76,495 | 87,058 | 97,381 | 104,116 | 111,957 | 19.86% |
| | | Offshore | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 29 | 29 | 29 | 0.005% |
| 4° | South America | Onshore | 846 | 1,182 | 1,737 | 2,340 | 2,843 | 6,558 | 9,951 | 12,633 | 15,727 | 18,679 | 3.31% |
| | | Offshore | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0% |
| 5° | Eurasia | Onshore | 807 | 1,335 | 1,742 | 2,274 | 2,775 | 3,645 | 4,525 | 5,801 | 6,601 | 7,201 | 1.28% |
| | | Offshore | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0% |
| 6° | Oceania | Onshore | 2,251 | 2,439 | 2,702 | 3,235 | 3,895 | 4,532 | 4,969 | 5,068 | 5,615 | 6,558 | 1.16% |
| | | Offshore | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0% |
| 7° | Africa | Onshore | 739 | 861 | 990 | 1,124 | 1,738 | 2,396 | 3,317 | 3,828 | 4,570 | 5,464 | 0.97% |
| | | Offshore | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0% |
| 8° | Central America/ Caribbean | Onshore | 261 | 307 | 460 | 732 | 776 | 923 | 1,308 | 1,498 | 1,600 | 1,709 | 0.30% |
| | | Offshore | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0% |
| 9° | Middle East | Onshore | 101 | 104 | 107 | 115 | 119 | 162 | 284 | 408 | 434 | 612 | 0.11% |
| | | Offshore | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0% |
| World | | Onshore | 147,963 | 177,799 | 216,208 | 261,532 | 292,770 | 340,691 | 404,508 | 452,710 | 495,730 | 540,371 | 95.86% |
| | | Offshore | 2,134 | 3,056 | 3,776 | 5,334 | 7,172 | 8,492 | 11,718 | 14,342 | 18,891 | 23,356 | 4.14% |
| | | TOTAL | *150,097* | *180,855* | *219,984* | *266,866* | *299,942* | *349,183* | *416,226* | *467,052* | *514,621* | *563,727* | *100.00%* |
| Brazil | | Onshore | 602 | 927 | 1,426 | 1,894 | 2,202 | 4,888 | 7,633 | 10,124 | 12,294 | 14,401 | 2.67% |
| | | Offshore | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0% |
| | | % Total | 0.40% | 0.51% | 0.65% | 0.71% | 0.73% | 1.40% | 1.83% | 2.17% | 2.39% | 2.55% | |

Source: Author's own elaboration based in [44].

In 2018, Brazil was among the 10 countries with the largest installed capacity of onshore wind energy. The other countries are: China, USA, Germany, India, Spain, France, UK, Canada and Italy (Table 3).

Table 3. Onshore Wind Power Installed Capacity in Top 10 Countries in 2018.

| Year | | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | % of MW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No | Countries | Onshore Installed Capacity Wind Power (MW) | | | | | | | | | | in 2018 |
| 1° | China | 17,598 | 29,533 | 46,145 | 61,306 | 76,314 | 96,379 | 130,489 | 147,037 | 161,604 | 180,108 | 33,33% |
| 2° | United States | 34,296 | 39,135 | 45,676 | 59,075 | 59,973 | 64,232 | 72,573 | 81,357 | 87,514 | 94,266 | 17,44% |
| 3° | Germany | 25,697 | 26,823 | 28,524 | 30,711 | 32,969 | 37,620 | 41,297 | 45,460 | 50,291 | 53,010 | 9,81% |
| 4° | India | 10,925 | 13,184 | 16,179 | 17,300 | 18,420 | 22,465 | 25,088 | 28,700 | 32,848 | 35,288 | 6,53% |
| 5° | Spain | 19,176 | 20,693 | 21,529 | 22,789 | 22,953 | 22,920 | 22,938 | 22,985 | 23,095 | 23,426 | 4,34% |
| 6° | France | 4,582 | 5,912 | 6,723 | 7,562 | 8,250 | 9,110 | 10,258 | 11,511 | 13,510 | 15,106 | 2,80% |
| 7° | Brazil | 602 | 927 | 1,426 | 1,894 | 2,202 | 4,888 | 7,633 | 10,124 | 12,294 | 14,401 | 2,67% |
| 8° | United Kingdom | 3,471 | 4,080 | 4,758 | 6,035 | 7,586 | 8,573 | 9,212 | 10,880 | 12,847 | 13,436 | 2,49% |
| 9° | Canada | 3,282 | 3,967 | 5,265 | 6,201 | 7,801 | 9,694 | 11,214 | 11,973 | 12,403 | 12,816 | 2,37% |
| 10° | Italy | 4,879 | 5,794 | 6,918 | 8,102 | 8,542 | 8,683 | 9,137 | 9,384 | 9,737 | 10,310 | 1,91% |
| | World | 147,963 | 177,799 | 216,208 | 261,532 | 292,770 | 340,691 | 404,508 | 452,710 | 495,730 | 540,371 | 100,00% |

Source: Author's own elaboration based in [44].

In those countries where wind plays a major role in the energy mix (European Union, China and USA) actions have been carried out to develop offshore wind energy, albeit to varying degrees. These actions range from studying offshore wind to the development of laws and planning related to the construction of wind farms. Europe currently leads the way in offshore wind energy (with 84% of global installations), having achieved technical and commercial maturity, including the first floating wind farm to generate electricity, together with an emerging zero-subsidy culture. The Chinese wind industry has seen rapid development since 2005, however, well established laws, the use of a one-stop-shop system in the licensing process, and the establishment of higher feed-in tariffs (FITs), could all boost the Chinese offshore wind industry further. The possible future role of the USA in the offshore wind industry is now in the hands of its decision makers. A more streamlined licensing process, together with a long-term vision enshrined within stable economic incentives, could help to boost the offshore wind industry in the USA [23].

In terms of offshore wind energy installed capacity, the top 10 countries in 2018 were: UK, Germany, China, Denmark, Belgium, Netherlands, Sweden, Vietnam, Finland and Japan (Table 4). Brazil doesn´t yet have wind power plants in operation, but there is prediction for some future projects.

Table 4. Offshore Wind Power Installed Capacity in Top 10 Countries in 2018.

| | Year | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | % of MW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No | Countries | Offshore Installed Capacity Wind Power (MW) | | | | | | | | | | in 2018 |
| 1° | United Kingdom | 951 | 1.341 | 1.838 | 2.995 | 3.696 | 4.501 | 5.093 | 5.293 | 6.988 | 8.300 | 1,54% |
| 2° | Germany | 35 | 80 | 188 | 268 | 508 | 994 | 3.283 | 4.132 | 5.427 | 6.410 | 1,19% |
| 3° | China | 2 | 100 | 210 | 291 | 417 | 440 | 559 | 1.480 | 2.788 | 4.588 | 0,85% |
| 4° | Denmark | 661 | 868 | 871 | 922 | 1.271 | 1.271 | 1.271 | 1.271 | 1.297 | 1.358 | 0,25% |
| 5° | Belgium | 32 | 197 | 197 | 381 | 708 | 708 | 712 | 712 | 877 | 1.178 | 0,22% |
| 6° | Netherlands | 228 | 228 | 228 | 228 | 228 | 228 | 357 | 957 | 957 | 957 | 0,18% |
| 7° | Sweden | 163 | 163 | 163 | 163 | 212 | 213 | 213 | 206 | 206 | 206 | 0,04% |
| 8° | Viet Nam | 0 | 0 | 0 | 0 | 16 | 16 | 99 | 99 | 99 | 99 | 0,02% |
| 9° | Finland | 24 | 26 | 26 | 26 | 26 | 26 | 32 | 32 | 73 | 73 | 0,01% |
| 10° | Japan | 11 | 25 | 25 | 25 | 50 | 50 | 53 | 60 | 65 | 65 | 0,01% |
| | World | 2.134 | 3.056 | 3.776 | 5.334 | 7.171 | 8.492 | 11.717 | 14.342 | 18.891 | 23.356 | 100,00% |

Source: Author's own elaboration based in [44].

## WIND POWER DEVELOPMENT IN BRAZIL

In the late 90s and early 2000s, a severe drought in Brazil systematically reduced water levels in hydropower plants. This caused a serious energy crisis in 2001 and a period of electricity rationing in 2001 and 2002. This adversely affected the Brazilian economy, and became known as the "great blackout crisis". This incident made the strategic need to diversify sources of energy available clear as well as the need for investment in the energy sector [7]. According to [47], that supply crisis of Brazilian Electricity Sector (BES)'s in 2001 urged for short, medium and long term solutions.

In this scenario, RESs, specially wind energy, gain distinction as a feasible alternative of seasonal stability in energy supply by means of complementation between natural wind regimes and hydro utilization, the basis of Brazilian's electric origin, as well as the utilization of the vast renewable natural resources potential existent in the country [47].

[28] commented that electric crisis in 2001 led the Brazilian government to develop new energy policies that was important to produce locally wind turbine components and was

highly desirable to increase collaboration between industries and universities in the country. In 2004, the government mandated that the technology was developed within the country.

## Regulatory Framework

The main references of regulatory framework that influenced and influence the development of wind energy in the BES are described in the Table 5.

Table 5. Main References of Regulatory Framework of the Wind Power in Brazil.

| References of Legal Framework | Date | Definition |
|---|---|---|
| Resolution Nº 24 of the Assembly of Energy Crisis Management: (Emergency Program for Wind Energy - PROEÓLICA) | 07/05/2001 | The aim of which was to add 1,050 MW of wind power to the national grid by the end of 2003. It wasn´t regulated by Federal govermment and was absorbed by the next program (PROINFA). |
| Law Nº. 10.438/2002: Program for Alternative Sources of Electricity (PROINFA) | 26/04/2002 | The Federal government intended to install a capacity of 3300 MW through: small hydroelectric plants (1,100 MW), wind power plants (1,100 MW) and biomass (1,100 MW). Subsequently, the initial target was changed and it were contracted: 1,423 MW of wind farms, 1,192 MW of small hydroelectric plants and 685 MW of biomass. |
| Law Nº. 10.848/2004 of Presidency of the Republic | 03/15/2004 | Provides for the commercialization of electricity, amends previous laws and makes other provisions. This law criates the contracting for "energy auctions". |
| Decree Nº. 5,163/2004 of Presidency of the Republic | 08/30/2004 | Regulates the commercialization of electric energy, the process of granting of concessions and authorizations of electricity generation, and other measures. |
| Decree Nº. 6,353/2008 of Presidency of the Republic | 01/16/2008 | Regulates the contracting of reserve energy that is dealt with in previous laws, changes some previous laws and gives other measures. |

Source: Author's own elaboration.

According to [48] had a trend in the Brazilian political scenario towards increasing the share of new RESs, other than large hydropower, in electricity generation. This central policy was achieved through Program for Alternative Sources of Electricity (*Programa de Incentivo às Fontes Alternativas* – PROINFA) [49], which defined stages and mechanisms to promote biomass, Small Hydro Power Plant and wind energy. [50] comment what even after the creation of PROINFA, it happened a modest increases in wind energy installed capacity, due to high taxes and import duties in the period, which made the implementation of projects onerous. There was no national productive chain of wind energy and the Brazilian government increased tax incentives for power generation with small and large hydroelectric and biomass power plants.

In 2004, BES was reorganized by Law Nº. 10,848/2004 [51], in 03/15/2004. This law defined the current model of commercialization of electricity in Brazil. It established that the electricity commercialization must be carried out in two types market: Regulated Contracting Environment and Free Contracting Environment. The regulated contracting environment purchases electricity by auctions. These energies auctions were established by Law Nº. 10,848 and regulated by Decrees Nº. 5,163/2004 [52], of 08/30/2004, and Nº. 6,353/2008 [53], of 01/16/2008. These auctions introduced competition between generation agents in the contracting of electric energy, attending to principles of security of supply and of tariff modality, that is, contracted energy from this model resulted in acquisitions at the lowest price. The Free Contracting Environment is the contracting market in which generators as public service, auto-producers, independent producers, marketers, importers and exporters of energy and free and special consumers are free to negotiate and establish in Energy Purchase Agreements in the Environment Free the volumes of purchase and sale of energy, their respective prices, volumes and delivery periods. All contracts, regardless of the segment, are recorded in the Chamber of Electric Energy Marketing (*Câmara de Comercialização de*

*Energia Elétrica* – CCEE) and serve as a basis for the accounting and settlement of differences in the short-term market.

According to [54], the competitive RE procurement auctions were becoming increasingly prevalent. They commented to bidding strategy may be influenced by factors external to the auction, such as transmission expansion planning decisions. This may increase costs. They affirmed that integrating an auction with transmission expansion planning may allow for closer total system cost minimisation over many time periods.

Brazil has adopted various strategies to encourage alternative RESs in pursuit of cleaner and sustainable energy production. To this end, strategies should support the reduction of the financial risk for potential investors in the RE market [55]. However, it was the energy auctions that effectively worked since 2005 and started to boost wind energy in Brazil from 2009.

Despite the need to reduce GHG, thermoelectric power plants were the main winners in electricity auctions held until 2009 [56]. Still according to these authors, the official energy plan for 2030, prepared for the Brazilian government by the Energy Research Company (*Empresa de Pesquisa Energética* – EPE), forecast a relative increase in thermal generation using natural gas, coal and nuclear energy. However, the latest official energy plans of EPE [57] [58] revised the targets for new renewable energies and pointed to a much greater growth of wind energy to 2050.

### Wind Power Contracting Evolution

The Brazilian Wind Energy Association (ABEEOLICA) [59] shows the evolution of wind power installed capacity in Brazil, considering the contracts already confirmed in auctions and transactions completed in the free market. New energy auctions will add further capacity in coming years (Figure 5).

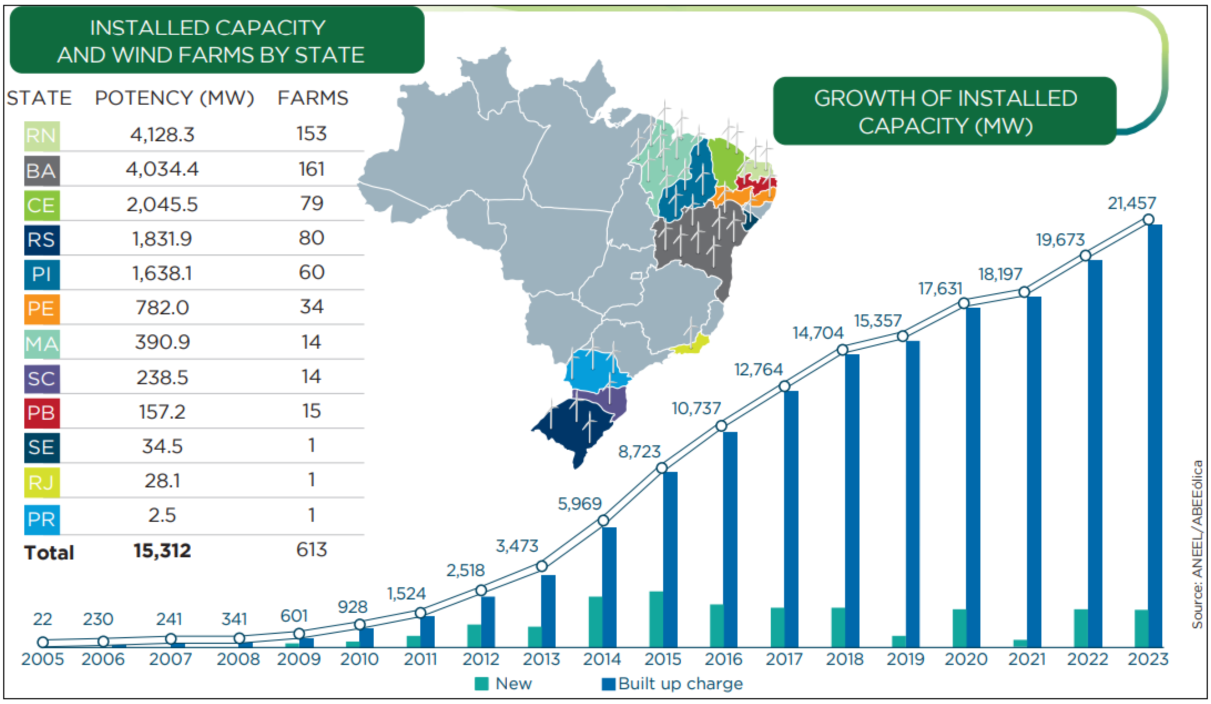


Fig. 5. Evolution of Wind power installed capacity in Brazil 2005-2023 (09/20/2019).
Source: [59].

In 2018, according to ABEEOLICA [59], the total wind energy generated was 48.4 TWh. This generation represented 8.6% of the entire generation injected into the National Interconnected System (*Sistema Interligado Nacional* – SIN) in the period. It was perceived a grown of 14.6% in relation to the generation of the previous year (2017) compared to the 1.5% growth of the generation of the entire SIN generation. Besides this, the Average Capacity Factor in Brazil was 42%, while the average capacity factor for wind farms worldwide is around 25%. The benefits of wind energy to Brazil are: from 2011 to 2018, the investment in electricity sector was US$ 31.2 billion; it avoided the emission of about 21 million tons of $CO_2$ in 2018; it helps Brazil fulfill its Climate Agreement Goals; the best prices for energy offered at the December 2018 auctions came from wind farms; it generates income and improve the quality of life of land-owners who lease their land for wind tower placement, it believes some 4,000 families are receiving over R$ 10 million a month in total from leasing land; enables land-owners to continue planting their crops or growing their animals; it provides training and qualifications for local labor.

## COMPLEMENTARITY WITH OTHERS ENERGY SOURCES

Studies by EPE [7, 60, 61] indicated the Northeast presents the highest levels of complementarity between wind and solar energies. The implementation of hybrid generation projects can result in transmission infrastructure savings, investment rationalization and optimization of electricity generation. In addition, according to [62], there is complementarity between hydroelectricity (the region's main energy resource) and wind and solar energy. Thus, in the months of the dry season (when the cost of energy is more expensive) there is a greater availability of wind and solar energy. This makes investments in these two renewable sources more economically viable and also helps to diversify the electricity grid power supply. This is a securing against the effects of droughts.

There is no regulatory framework yet for the hybrid generation electricity in Brazil. However, according to [63], there are two projects of wind-PV solar power plants in Brazil: one in Tacaratu and the other in Igaporã and Caitité:

### Hybrid Power Plant of Tacaratu

Since 2015, there is in municipality of Tacaratu, in the state of Pernambuco, a hybrid power plant in operation with 91 MW installed capacity: wind power plant with 80 MW and more two PV solar power plants totalling 11 MWp.

### Hybrid Power Plant of Caitité and Igaporã

Since 2016, there is in municipalities of Caitité and Igaporã, in the state of Bahia, a hybrid power plant in operation with 26.4 MW installed capacity: wind power plant with 21.6 MW and PV solar power plant with 4.8 MWp.

## OFFSHORE WIND ENERGY POTENTIAL DEVELOPMENT IN BRAZIL

[64] estimated the Brazilian potential for offshore wind generation, based on satellite data between August 1999 and December 2009 and daily temporal resolution. The average offshore wind magnitude in Brazil varies from 7 m/s to 12 m/s (Figure 6), with minimum values close to the São Paulo coast and maximum values close to the coast of Sergipe and Alagoas. Three regions with high wind potential, with the potential to exploit offshore wind generation, are: (i) the margin of Sergipe and Alagoas, (ii) Rio Grande do Norte and Ceará, and (iii) Rio Grande do Sul and Santa Catarina. Two potentials were estimated: the first,

based on distance from the coast, in which authors point out a potential between 57 GW and 1,780 GW; the second, according to the depth of the waters, where the potential reaches just over 600 GW [65].

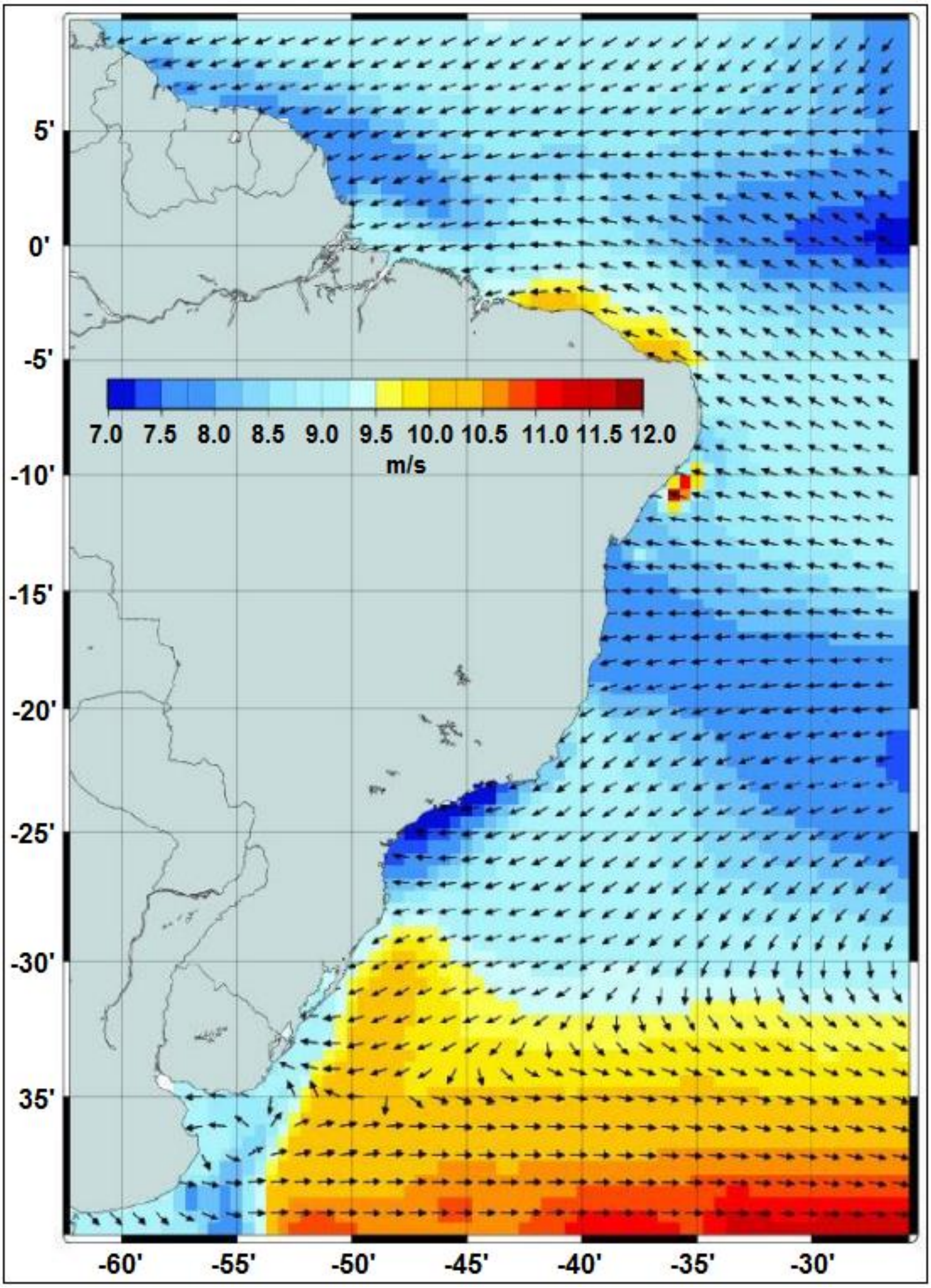

Fig. 6. Average wind field in the southwest Atlantic, calculated from August 1999 to December 2009, extrapolated to heights of 80m. Source: [64].

According to EPE [66], Brazil does not have offshore wind farm, but there are already 3 projects with environmental license application in the Brazilian Institute of Environment and

Renewable Natural Resources (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis* – IBAMA), showing that the market is studying the subject. The main characteristics of each project are in the Table 6.

Table 6. Offshore projects characteristics in the Brazil.

| NAME | DESCRIPTION |
|---|---|
| **Asa Branca I Offshore Windpower Complex** | Located on the coast of the municipality of Amontada, state of Ceará, at a distance between 3 km and 8 km from the beach, with depths varying between 7 and 12 meters. The planned installed wind energy capacity will be 720 MW. |
| **Caju Offshore Windpower Complex** | Located in municipalities of Tutoia and Araioses, state of Maranhão, in the land-sea transition zone. The planned installed wind energy capacity will be 30 MW. |
| **Eol Project Offshore Windpower Generation Pilot-Plant** | Petrobras research and development project with investment of R$ 63 million. It will be located 20 km from the coast of Guamaré, state of Rio Grande do Norte, in a region with a water depth between 12 m and 16 m. The planned wind energyinstalled capacity will be 5 MW. |

Source: Author's own elaboration based in [66].

However, it is important to note that there is no regulatory framework for the exploration of offshore wind potential in Brazil. Thus, issues such as implementation or concession model are unanswered and are fundamental to the development of this source [66]. The main characteristics of each project are as follows: Of these 3 offshore wind power projects, the pilot plant is the most promising because it is a research project. The other projects have little chance of being installed in the short time. In addition to the economic viability that would be required, there is no regulatory framework for the exploration of the offshore wind potential in Brazil. Thus, issues such as environmental licensing, implementation or concession model are unanswered and are keys to the development of this source.

Offshore wind power allows the use of wind turbines of far greater capacity than onshore wind power. However, even with offshore wind energy growing significantly in the world, Brazil still has a lot of land availability at low cost. According to [67], the implementation of offshore wind power into the Brazilian grid shouldn´t be a problem from the technological perspective, but is the cost of offshore wind projects. They comment that the costs of onshore wind energy in Brazil are low and competitive in the auctions. Thus, policy incentives will be crucial to start offshore development in Brazil.

## REGULATORY FRAMEWORK REVISION

In 2016, the Federal Government was interested in making improvements to BES through some public consultations of the Ministry of Mines and Energy (*Ministério de Minas e Energia* – MME). In 10/05/2016, the MME released the public consultation Nº. 21 and Technical Note Nº. 4/2016/AEREG/SE [68] on the free electricity market. In this way, the MME requested contributions on the expansion of the free market of electric energy, benefits and risks involved and terminated this call with Technical Note Nº. 3/2017/AEREG/SE [69].

However, in 2017, the main motivation for realizing the new BES reform was the explicit interest of the Federal Government in the privatization of Eletrobras' companies. The MME then announced the goal of carrying out a broad process of reform of BES's regulatory framework and called for stakeholder participation through the dissemination of two new public consultations. In public consultation Nº. 32 of 07/07/2017 and in Technical Note Nº. 11/2017/SE (Principles for Reorganization of the Brazilian Electricity Sector) [69], in public call Nº. 33 and Technical Note No. 05/2017/AEREG/SE (Enhancement of the Legal Framework of the Electricity Sector) [70], proposals were presented for legal measures to make feasible the future of the electricity sector with long-term sustainability and solicited opinions and contributions from concerned.

[70] commented that the global electricity sector is subject to pressures due to regulatory, commercial and operational changes due to technological and socio-environmental phenomena. Thus, he said that there is a need for a new vision for the BES, which includes a model adapted to the external pressures that the BES is exposed and that guarantee its sustainability in the long term. The basic elements listed by the MME to realize this vision were: (a) Incentives to the efficiency in the corporate decisions of individual agents as a vector of tariff affordability, security of supply and socio-environmental sustainability; (b) Economic signalling as a vector of alignment between individual and systemic interests; (c) Adequate risk allocation to enable individual management with well-defined responsibilities; (d) Removal of barriers involving market participants; (e) Respect for current contracts and compliance with the formal requirements and roles of each institution.

A positive aspect in relation to this new BES reform was the opening to receive suggestions from all interested parties (individuals or legal entities) to contribute. The negative aspects were the short period of time of the consultation and the lack of ample technical events and specialized forums to discuss in person the proposals of improvement of the BES. According to information from the [71], there were a total of 191 contributions for the improvement of BES, coming from several individuals and legal entities related directly or indirectly to the electricity sector. However, this process of reform of the BES is still in progress and there is no effective deadline for its conclusion in the National Congress.

To date, the MME has not finalized the proposal to be submitted to the National Congress to begin the process of reforming BES. However, when the various contributions filed with the [71], key elements can be identified for an even greater expansion of wind power in this reform: the increase in the participation of wind and solar RESs and a new free contracting environment.

According to [72] between many barriers where identified for the wind energy onshore in Brazil, three have particular relevance: poor transmission infrastructure, unattractive financial loans and unstable macroeconomic environment. A reform of the regulatory framework also opens up the possibilities for attracting more investment through hybrid projects. However, there are also others initiatives to create new tax modalities, such as royalties, by proposal from the Federal Chamber of Deputies [73], which would burden wind generation.

## CONCLUSIONS

In this last decade, the experiences with wind energy in Brazil and the World are success cases, because installed capacity expansions were consistent and continuous after the economical global crisis of 2008. Brazilian installed capacity of onshore wind farms reached 14.4 GW in 2018 and 2019 has exceeded 15 GW, corresponding to about 8.9% of the Brazilian Electric Matrix. This expansion of installed capacity has already assured investments of U $ 31.2 billion. However, there is still an onshore potential of 522 GW to be explored. The total expansion of onshore wind capacity in 2009-2018 in Brazil was 2,292.2%

and in the World 265.2%. That is, Brazil increased your wind power installed capacity almost 9 times more than the World.

In addition to the great onshore wind potential, there are also the potential future for complementarities of energies and wind energy offshore. There is potential for complementarity of wind energy with solar and hydropower in Northeast Region. There are potentials were estimated based on distance from the coast between 57 GW and 1,780 GW and according to the depth of the waters over 600 GW.

The wind installed capacity evolution in Brazil was only possible because of the adequacy of the current regulatory framework. However, it needs to be improved to meet future demands for offshore wind power generation and energy complementarities. The regulatory framework review process is an opportunity for this regulatory adjustment.

Considering the global and Brazilian demands for energy and the need for sustainable actions to preserve the environment and combat climate change, the trend is that wind energy will continue to expand in the coming years. This is because the use of wind energy is an energy policy capable of meeting international agreements and generating many additional benefits.

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## NOMENCLATURE

ABEOLICA – Brazilian Wind Energy Association
ANEEL – Brazilian Electricity Regulatory Agency
BES – Brazilian Electricity Sector
CCEE – Chamber of Electric Energy Marketing
CEPEL – Center for Electricity Energy Research
EPE – Energy Research Company
ESSs – Energy Storage Systems
FITs – Feed-in Tariffs
GHGs – Greenhouse Gases
INCT-Clima – National Institute of Science and Technology for Climate Change
IRENA – International Renewable Energy Agency
LCOE – Levelized Cost of Energy
MME – Ministry of Mines and Energy
OECD – Organisation for Economic Co-operation and Development
PROELOICA –
PROINFA – Program for Alternative Sources of Electricity
RE – Renewable Energy
RESs – Renewable Energy Sources
R&D – Research and Development
SIN – National Interconnected System
UK – United Kingdom
USA – United States of America
WACC – weighted average cost of capital

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