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Combining wind and solar energy sources: Potential for hybrid power generation in Brazil

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ABSTRACT

Wind and solar energy have stood out in recent years because of the growth of global installed capacity. This work aims to present wind and solar photovoltaic energy development and its regulatory framework in Brazil, and demonstrate the potential for centralized hybrid generation. Official studies, research reports, and thematic maps were consulted, and two pilot hybrid plants were studied. Results indicate that there is great potential for centralized hybrid generation in the Brazilian Northeast region. However, there is a need for the regulatory framework to evolve to enable its development.

1. Introduction

Developing new renewable energy is a key factor for the transition from fossil fuel-based energy sources to alternative and diversified resources with lower environmental impacts. In this context, wind and photovoltaic solar energy have stood out significantly in recent years in terms of investments, research, and expansion of the world's installed capacity.

The current power generation paradigm is based on centralized generation from large power plants that use a single type of resource. However, the combined use of more than one energy source is quite common for distributed generation in remote places, where it would be economically unfeasible to connect these consumers to the centralized generation infrastructure. In recent years there have been some initiatives aimed at the creation and study of Hybrid Energy Systems (HES) for centralized generation. Among renewable energy technologies, the combination of wind and solar PV energy, when a complementarity exists, has emerged as a possibility of producing electricity from HES. However, the economic feasibility of HES is quite recent, and there are many gaps in the technical and scientific knowledge that need to be

Abbreviations: ABEEOLICA, Brazilian Wind Energy Association (*Associação Brasileira de Energia Eólica*); ABSOLAR, Brazilian Solar Energy Association (*Associação Brasileira de Energia Solar*); ANEEL, Brazilian National Electricity Agency (Agência Nacional de Energia Elétrica); BA, State of Bahia; BEN 2018, National Energy Balance 2018 (*Balanço Energético Nacional, 2018*); BES, Brazilian Electricity Sector; BNDES, National Bank for Economic and Social Development (*Banco Nacional de Desenvolvimento Econômico e Social*).; CCEE, Brazilian Chamber of Electricity Trading (*Câmara de Comercialização de Energia Elétrica*); CE, State of Ceará; CEPEL, Center for Electrical Energy Research (*Centro de Pesquisas em Energia Elétrica*); CHESF, São Francisco Hydroelectric Company (*Companhia Hidrelétrica do São Francisco*); COP 21, Conference of the Parties; EGPB, Enel Green Power Brazil; EPE, Energy Research Company (*Empresa de Pesquisa Energética*); FINEP, Financier of Studies and Projects (*Financiadora de Estudos e Projetos*); GHG, Greenhouse gas; HES, Hybrid Energy System; HR, Human Resources; IEA, International Energy Agency; INCT–Clima, National Institute of Science and Technology for Climate Change (*Instituto Nacional de Ciência e Tecnologia para Mudanças Climáticas*); IRENA, International Renewable Energy Agency; LCOE, Levelised Cost of Electricity; MA, State of Maranhão; MME, Ministry of Mines and Energy (*Ministério de Minas e Energia*); MUST, Transmission System Usage Amount (*Montante de Uso do Sistema de Transmissão*); ONS, National Electricity System Operator (*Operador Nacional do Sistema Elétrico*); PB, State of Paraíba; PE, State of Pernambuco; PET, Transmission Expansion Program (*Programa de Expansão da Transmissão*); PELP, Long Term Expansion Plan (*Plano de Expansão de Longo Prazo*); PI, State of Piauí; PNE 2050, National Energy Plan 2050 (*Plano Nacional de Energia Elétrica, 2050*); PR, State of Paraná; PV, Photovoltaic; RE, Renewable Energy; R&D, Research and Development; REN21, Renewable Energy Policy Network for the 21st Century; RJ, State of Rio de Janeiro; RN, State of Rio Grande do Norte; RS, State of Rio Grande do Sul; SC, State of Santa Catarina; SE, State of Sergipe; SIN, National Interconnected Electricity System (*Sistema Interligado Nacional*); SWERA, Solar and Wind Energy Resource Assessment; TL, Transmission Lines.

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filled.

Brazil is a developing country, and its demand for non-hydro renewable energy is growing. Abundant wind and solar resources are available in Brazil. In recent years, wind and solar energy have been introduced in the electrical matrix, and the prospects for the development of these technologies are excellent. In addition, in specific regions of Brazil, there is a high complementarity between wind, solar, and water resources, which can be exploited. Therefore, HES power plants can benefit from energy resources complementarity and produce energy more efficiently than plants with a single energy source. Renewable electricity generation is promoted and supported through the current regulatory framework; however, there is not yet specific regulation for HES projects in Brazil. This study demonstrates that the Northeast Region of Brazil is conducive to HES projects; there are two pilot hybrid power plants in the Northeast, and that wind-solar PV hybrid power plants can be one innovative option for national energy security.

Despite the availability of resources, the effectiveness of hybrid plants, and the results of some technical studies on HES in Brazil, the current regulatory framework is not yet supportive of hybrid plants because so far, there has been no regulatory decision by the Federal government or the regulatory agency.

In this context, this article contributes to knowledge of HES development for large scale generation from wind and solar sources. The main objectives of this work are: demonstrate the expansion potential of wind and solar energy in Brazil, the complementarity of these resources in specific regions, and consequently, the potential for wind-solar hybrid plants; and examine the current national renewable energy generation regulatory framework and provide recommendations for the development of a regulatory framework that would support wind-solar hybrid power plants.

2. Methods

The methodology applied is exploratory, descriptive, and qualitative. The article reviews governmental and academic documents, technical reports and thematic maps of national (EPE, ANEEL, ONS, ABEOLICA, and ABSOLAR) and international (IEA, IRENA, and REN21) agencies and associations, as well as two case studies of hybrid power plants with an aim to (a) demonstrate the expansion potential of wind and solar energy in Brazil, the complementarity of these resources in specific regions, and consequently, the potential for hybrid solar plants, and, (b) examine the current national renewable energy generation regulatory framework and provide recommendations for the development of a regulatory framework that would support wind-solar hybrid power plants.

3. Literature review

Supply of, and demand for electric power in the world has increased over the last decades (IEA, 2014a). Therefore, planning and energy security considerations drove several countries to diversify their energy generation strategies and include alternative sources for electricity generation to reduce fossil-fuel consumption, address environmental issues, and climate change mitigation targets (Santos, 2015). Developed countries, such as the USA, Germany, and the United Kingdom, and developing countries, such as Brazil, India, and China, have included expanding renewable energy generation as an alternative to fossil fuels.

As a result of the expansion of renewable energy generation a “large-scale” market was created, which enabled these new technologies to be manufactured at economies of scale, thus making wind and solar photovoltaic technologies competitive in price and financially attractive to investors (IEA, 2014; IEA/IRENA, 2017; PAIVA et al., 2017).

Due to the prevalence and availability of their resources, solar and wind energy systems are considered as the most promising of all alternative energy systems, and the use of solar and wind power has become very significant and cost-effective (MAHESH and SANDHU, 2015). However, the increase in the use of variable renewable energy, such as solar and wind, has created challenges in balancing load (KIM et al., 2017). A high level of variable renewable penetration in the power mix requires new paradigms and approaches from policymakers and power systems planners and operators. These sources have some peculiarities which are quite different from traditional power sources like hydro, thermal, and nuclear. Moreover, intermittency and unpredictability, drawbacks of these sources, demand changes in all processes linked to power systems, especially in generation expansion planning and operation (DESTER, 2017; TWIDELL and WEIR, 2006).

The common problems of solar and wind energy systems are the dependence on weather and its stochastic nature. Wind and solar are variable resources, and the weather-related energy availability depends on solar radiation, wind speed, air temperature, and precipitation (MAHESH and SANDHU, 2015; ENGELAND et al., 2017; MORIARTY and HONNERY, 2007). Due to this stochastic nature, there is typically a mismatch between generated energy from wind and solar PV technologies and the load demand. Therefore, the wide use of these technologies can potentially make the electricity system less reliable, and the need arises for storage or other backup sources in the system (MAHESH and SANDHU, 2015). Additionally, improved wind power forecasting is essential to reduce wind energy curtailment and grid operational costs (WANG et al., 2016; DE JONG et al., 2017a). The same consideration is valid for solar energy.

Renewable energy intermittency can be addressed with different solutions and technologies. The use of Electric Energy Storage (EES) has been an approach that has been studied extensively in recent years (KIM et al., 2017). That is, solar and wind energy need to be harvested when available and the surplus energy stored until needed. Applying energy storage can provide several advantages for energy systems, such as permitting increased penetration of renewable energy and better economic performance. Also, energy storage is relevant to electrical systems, allowing for load balancing and peak shaving, frequency regulation, damping energy oscillations and improving power quality and reliability (KOOHI-FAYEGH and ROSEN, 2020).

Contrary to proclamations stating otherwise, the more renewable energy that gets deployed, the more stable the system becomes. Wind and solar energy are very useful when used in large quantities in geographically spaced locations. So, the law of averages yields a relatively constant supply (SOVACOOL, 2009). Thus, the problem is not one of variability per se, but how such variability can best be managed, predicted, and mitigated.

However, wind and solar PV power plants could lead to conflicts with other generation technologies because variability renewable energy sources require more flexibility from the power system (BROUWER et al., 2014). Establishment of guidelines and policies to control the power mix share is an indispensable strategic action to ensure that the necessary technical requirements to supply demands are adhered to (DESTER, 2017; DOUKAS et al., 2008). Electricity load has to be met in terms of instantaneous power and long-term energy demands. These aspects have to be handled accordingly to avoid rollbacks in the quality and reliability of electricity provisions (DESTER, 2017).

A HES is a system that, depending on the availability of local resources, uses more than one primary energy source, renewable or otherwise, to supply electricity to a particular consumer, meeting a particular power quality standard. Hybridization of primary sources, with or without a storage system, allows the weak points of one source to be mitigated or complemented by the strengths of another source, allowing the system to be designed with maximized energy production while minimizing costs and the risks of supply disruptions (BARBOSA et al., 2016a).

HES for electricity generation are more commonly used as distributed generation in isolated communities. These communities are remote from the existing electricity transmission and distribution infrastructure, which makes the cost of connecting to the electricity network prohibitive (EPE, 2019a; BARBOSA et al., 2016b).

The framework regulation of hybrid power plants for centralized generation is being studied in several countries, such as India, Australia, the United States, the United Kingdom, and China, signalling new trends in markets and technologies. International experience in hybrid plants demonstrates that while there are potential benefits, there are substantial implementation difficulties, particularly commercial and regulatory. Most of the projects built to date depended on specific subsidies or regulations that favoured their development, and in some cases, such benefits were questioned (EPE, 2019a).

The Brazilian electricity sector (BES) is characterized as a large hydrothermal system. Most electrical power is supplied by low cost (renewable) hydropower plants, while a minority of higher-cost power is generated from thermal power plants using fossil fuels (natural gas and coal) and biomass (BRADSHAW, 2017; SILVA, 2011; D'ARAÚJO, 2009). The BES represents an interesting case of a middle-income country that is distinguished by strong federal involvement in energy governance (BRADSHAW and JANNUZZI, 2019).

Renewable energy technologies (solar and especially wind) are options that have become economically viable, and wind farm deployment in Brazil has been expanding rapidly in relation to the exploitation of traditional energy sources such as fossil fuels (DE JONG et al., 2015; De Jong et al.; 2017a). Wind-solar PV HES is a possibility for the BES (LIMA and SOUZA, 2015).

A key point is the correct sizing of the relationship between installed capacities of wind versus solar PV power to obtain optimized operation of a hybrid power plant that may share the same substation and point of connection to the transmission system (LOUREIRO and TIBA, 2016; EPE, 2017a). The ideal proportion of solar PV installed capacity in relation to wind power installed capacity in Bahia would be approximately 25% in order for the generation from the hybrid power plant to best match electricity demand (DE JONG et al., 2017b). However, if the wind and solar PV power plants share the same substation sized only to accommodate the wind power installed capacity, then between 0% and 28% of PV generation would need to be curtailed, depending on the model of wind turbines installed and the exact location of the hybrid power plant in Bahia (EPE, 2017a).

4. Overview of wind and solar photovoltaic power expansion in the world

The development of wind power and, to a lesser extent, solar PV power in the Brazilian Electricity Sector has followed a worldwide expansion trend. About 15%–18% of global electricity could be provided by wind power in 2050, from a total installed capacity of about 2300–2800 GW, and this would avoid emissions of up to 4.8 $GtCO_2$/year. It is also suggested that wind power production could increase significantly, generating 6678 TWh annually, from 2500 GW of installed capacity, in 2030 and generating up to 12,651 TWh annually, from 4814 GW of installed capacity, in 2050 (IEA, 2013). It is worth noting that these predictions did not take into account the Paris Agreement's Nationally Determined Contributions adopted at the COP 21 in 2015, which encouraged the use of renewable energy as part of actions to combat global warming.

In 2018, global wind power installed capacity reached 591 GW (Fig. 1), and there was an average growth of 45.5 GW/year from 2008 to 2018, even after the global economic crisis of 2008 (REN21, 2019).

By 2050, solar PV installed capacity is expected to reach 4600 GW, producing more than 6000 TWh (about 16% of the world's electricity generation), and this would avoid emissions of up to 4.0 $GtCO_2$/year (IEA, 2014b). These predictions do not take into account the influence of the Paris Agreement. Global solar PV installed capacity reached 505 GW in 2018 (Fig. 2), with an average growth of 45 GW/year in 2008–2018, despite the global economic crisis of 2008 (REN21, 2019).

In 2018, the global weighted-average LCOE for commissioned onshore wind and solar PV energy projects were all competitive with the fossil-fuel cost range, even in the absence of financial support (Fig. 3) (IRENA , 2019a). This increases the competitiveness of Wind-PV hybrid generation against electricity generation derived from fossil-fuel sources. Furthermore, the LCOE of a Wind-PV hybrid power plant that takes advantage of common substation and transmission infrastructure should be lower than individual systems, provided a suitable project location is chosen.

5. Overview of the Brazilian Electricity Sector

Initially, the BES was almost entirely state-owned in its three parts:

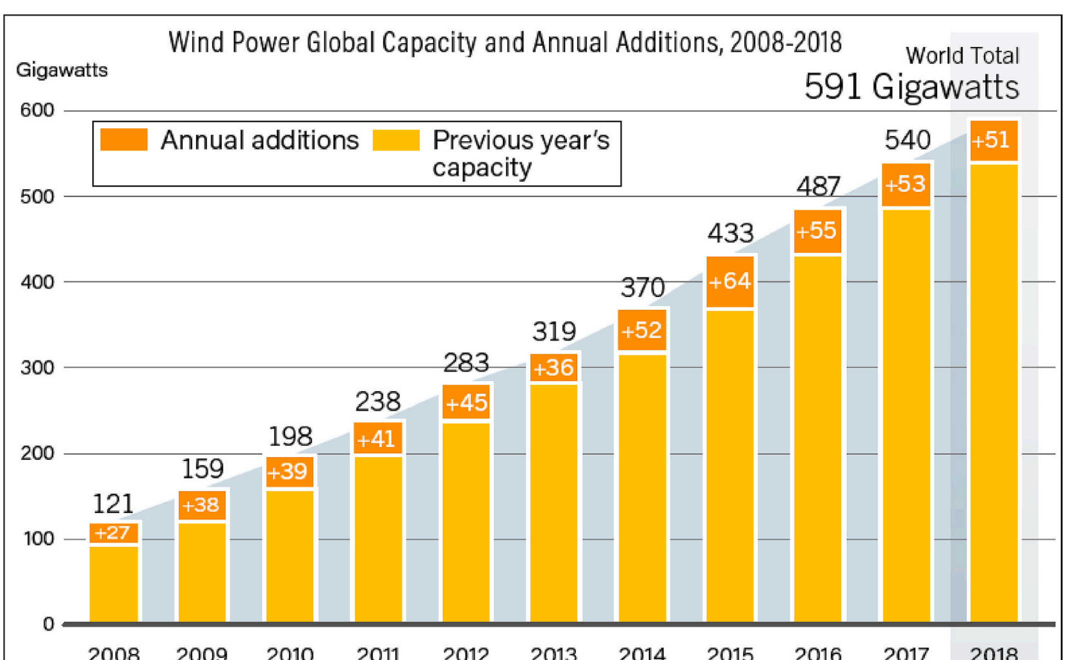

Fig. 1. Annual additions and cumulative installed capacities of global wind power generation: 2008–2018 (REN21, 2019).

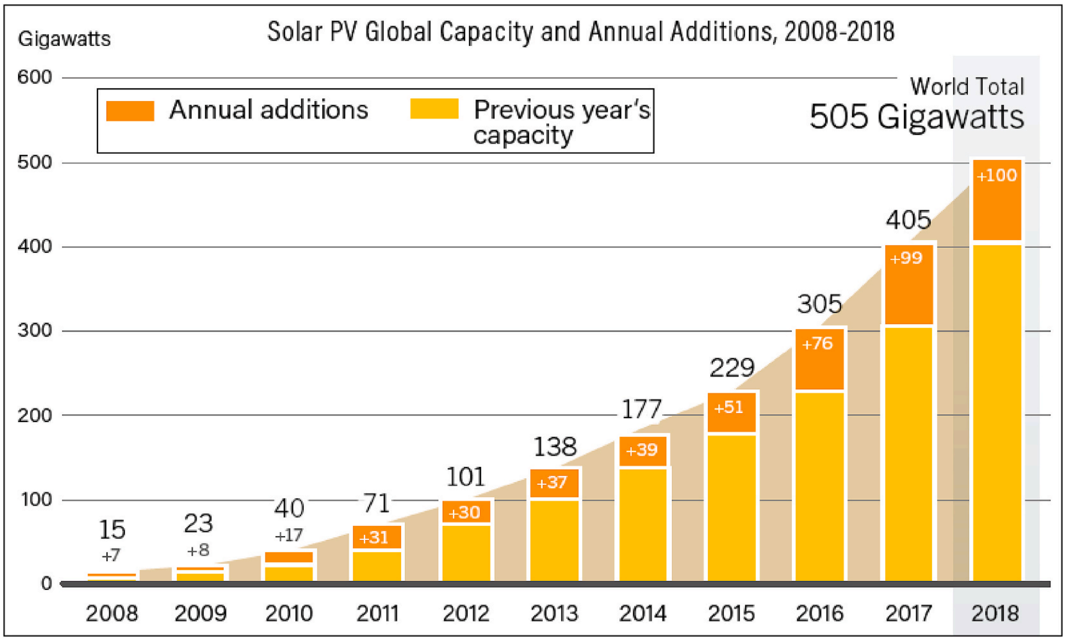

Fig. 2. Annual additions and cumulative installed capacities of global PV generation: 2008–2018 (REN21, 2019).

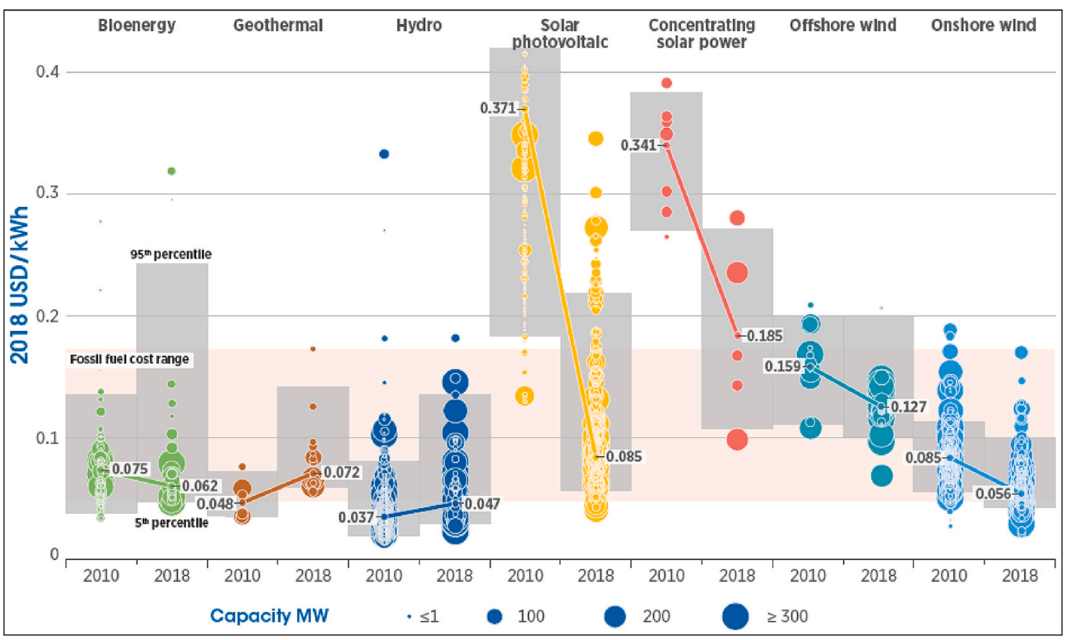

Fig. 3. Global LCOE (USD/kWh) of utility-scale renewable power generation technologies: 2010–2018 (IRENA , 2019a).

generation, transmission, and distribution of electricity. However, from the 1990s a Liberal government was elected for two terms (1995–1998 and 1999–2002) and the Federal government's public policies started to have a more liberal economic profile, which resulted in reform of the BES's institutional model in 1997 (BRADSHAW, 2017; SILVA, 2011; D'ARAÚJO, 2009).

In the late 90s and early 2000s, a severe drought in Brazil systematically reduced water levels in hydropower plants. This caused a severe 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 crisis gave rise to a strategic need to diversify and invest in the Brazilian energy sector (SANTOS and TORRES, 2014). This supply crisis advocated for short, medium, and long-term solutions (SILVA et al., 2005).

After the effects of the crisis in 2001, the next government (2003–2006), although left the liberal wing, implemented a new sectoral reform with a liberal profile in 2004. The new regulatory frameworks allowed more private capital to operate in all three parts of the BES and for the electricity sector to become gradually less dependent on hydropower plants. Despite these two sectoral reforms, even today, the BES is very dependent on hydropower generation.

Since 2012, Brazil has been experiencing a severe drought, especially in the Northeast region, which has reduced from 81.8% in 2011 to 66.6% in 2018, the participation of hydropower in the Brazilian Electricity Matrix. Consequently, there was a compulsory and prolonged increase in thermal generation sourced mostly from fossil fuels. This resulted in a reduction in the percentage of renewable generation (hydropower) and increased overall electricity costs.

Such hydrological vulnerability evidences the need for diversification of energy sources and expansion of the generation capacity in Brazil. In this scenario, new Renewable Energy (RE), especially wind energy, gain distinction as a feasible alternative to address the seasonal stability of hydropower because the excellent natural wind regimes in Brazil complement hydropower seasonality (SILVA et al., 2005).

5.1. Brazilian Electricity Matrix composition

In 2018, the domestic electricity supply was 636.4 TWh, and the final consumption was 535.4 TWh. Renewable energy supplied 83.3% of the total generation in the Brazilian electricity matrix. Hydroelectricity made up the largest share in the Brazilian electricity matrix (66.6%) (Fig. 4), confirming that hydropower is still the dominant technology in the country. Thermal power generation is composed of: natural gas (8.6%), biomass (8.5%), coal and derivatives (3.2%), nuclear (2.5%) and oil derivatives (2.4%) (EPE, 2019b). The greatest environmental impacts in the BES, in terms of GHG, are from generation sources such as oil, hard coal, natural gas, and hydropower. Wind and solar PV, despite only being included in the Brazilian electricity matrix relatively recently, already generate 7.6% and 0.5%, respectively (BARROS et al., 2018).

The EPE was created in 2004 and regularly produce the PNE and Decennial Energy Plans, official guides for national energy planning (EPE, 2014). Despite the need to reduce GHG, thermal power plants were the main winners in electricity auctions held until 2009. The PNE 2030 (EPE, 2007), elaborated in 2007, forecasted a relative increase in thermal generation using natural gas, coal, and nuclear energy (AQUILA et al., 2016; EPE, 2007). However, the latest official energy plans from the EPE revised the targets for new renewable energy and pointed to much greater growth of wind energy by 2050. This revision considered that coal-fired power stations are very polluting and that nuclear power plants in Brazil are costly and unpopular, especially after the nuclear accident in Fukushima, Japan, in 2011 (EPE, 2016; EPE, 2017b). Existing hydropower plants are distributed over almost all of Brazil, with the exception of most of the North and Midwest regions, where there is still potential to develop new hydroelectric plants. In these two regions, only 9% and 31%, respectively, of the total potential, have been developed (Table 1) (EPE, 2007). Hydroelectricity has the following advantages: it is a renewable energy resource, it has a low LCOE and, in the case of older Brazilian plants, it has seasonal storage reservoirs (which, under non-drought conditions, can eliminate seasonal variability). However, hydroelectricity also has some negative points including: GHG emissions and other environmental impacts (because to build these large season reservoirs, typically large areas of existing forest were flooded), and a need for large-capacity transmission lines (TL) because plants are typically very far from most consumer load centres. Therefore, in recent energy plans by the Federal Government, a relatively small amount of hydropower has been planned in comparison to other renewables due to the environmental impacts and rigor of current environmental legislation.

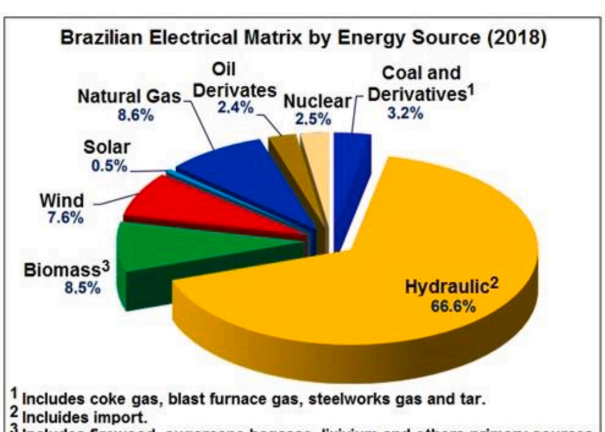

Fig. 4. Brazilian electricity matrix in 2018 (EPE, 2019b). Adapted.

Table 1
Hydropower Potential in each Brazilian region.

Hydropower Potential by Region			
Region	Operation, Construction or Concession	Not used (Inventoried)	**Not used (Estimated)**
North	9%	44%	47%
Northeast	65%	29%	6%
Midwest	31%	23%	46%
Southeast	53%	36%	11%
South	53%	35%	12%

There is considerable growth potential for the insertion of wind and solar energy in Brazil as a way of diversifying the renewable energy contribution (MARTINS and PEREIRA, 2011). The PNE 2050 (EPE, 2016) forecasts growth in annual average electricity consumption of approximately 3.2%, which would lead to a total consumption of 1624 TWh in 2050. In this context, generation from wind and solar PV electricity could supply substantial amounts of the total power demand by 2050 (EPE, 2016).

5.2. National Interconnected Electricity System

Brazil has a complex grid of TL and substations, called the National Interconnected Electricity System (SIN), which integrates four electrical subsystems in the country: South, Southeast/Midwest, North and Northeast (Fig. 5). These subsystems exchange energy between each other via the SIN, bringing balance to the subsystems, and the overall management is done by the ONS (ONS, 2018).

The SIN has a great extension covering the majority of the nation but is currently overloaded or near the limit of operation in some regions, and the Northeast region is an example of this situation. The SIN expansion is also carried out by transmission lines auctions, but these are independent of the generation auctions. Sometimes TL auctions are not successful, and delays in TL deployments are common due to environmental licensing, among other issues. Thus, there is a need to improve the efficiency of the SIN expansion process to enable the future expansion of wind and solar energy in the Northeast region (HERRERA et al., 2019).

The ONS analyzes the fulfilment of the maximum demand to obtain a more detailed assessment of the conditions of this attendance, in order to identify the necessary planning actions. The criteria and premises used are i) Use of maximum instantaneous demand; ii) Not coincidence of the maximum demand between the subsystems of the SIN; iii) Operating reserve of 5% of demand; iv) Interchange limits for heavy load levels; v) Simulation of all historical series of natural flows. Currently, the ONS uses Newave software to simulate the operation of the SIN, including offers and demands, and to program and control their operation (EPE, 2017a,d). Wind and solar energy together still represent a small portion of the national electrical matrix so that the interconnection of the subsystems still absorbs the impacts of wind and solar variability.

There is a need for a new computational model to support planning activities that allow for optimizing the operation of the national electrical system, preferably on an hourly basis, with representation of uncertainty in the production of non-dispatchable resources (e.g.: Wind and Solar power), hydroelectric resources, short-term thermal operation restrictions - such as unit commitment - and failure of generators. In addition, it is important to represent uncertainty in the growth of demand in planning studies. As a result, planning would benefit from tools that make it possible to assess the impacts of the growing insertion of these new renewable generation technologies in the Brazilian matrix. This is a global challenge that the EPE has pursued and will share with all agents in the electricity sector (EPE, 2017a,d).

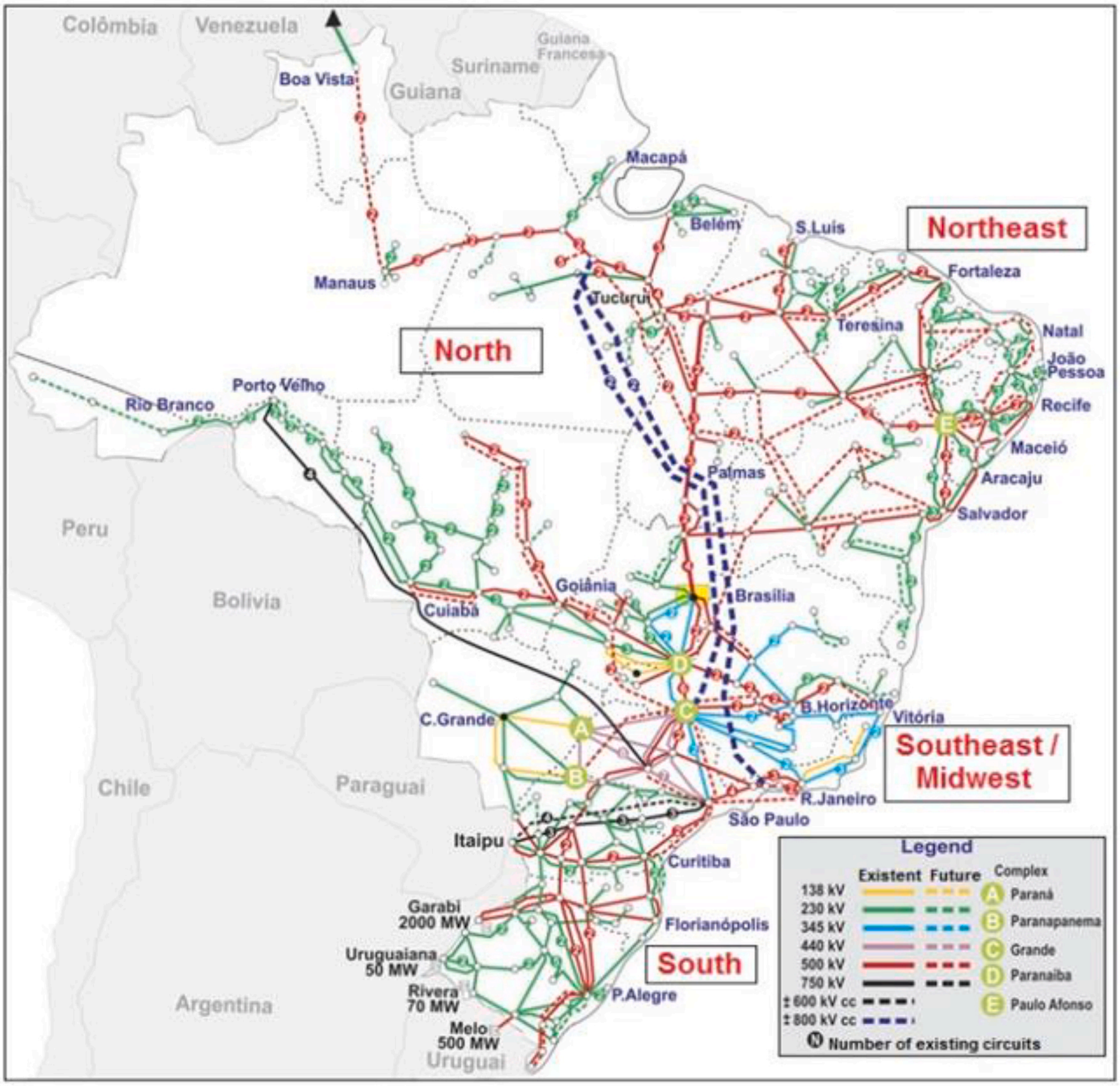

Fig. 5. The brazilian SIN (ONS, 2018). Adapted.

5.3. Regulatory framework for new renewable electricity generation in Brazil

The primary references to the regulatory framework (Governo FEDERAL, 2001, 2002, 2004a,b, 2008) of centralized power generation that have influenced the development of wind and solar energy in the BES are described in Table 2.

There was a trend in the Brazilian political scenario towards increasing the share of new RE, other than large hydropower, for electricity generation. This central policy was achieved through PROINFA, which defined stages and mechanisms to promote biomass, Small Hydro Power Plants and, wind energy (Costa et al., 2008). Even after the creation of PROINFA, only a modest increase in wind energy installed capacity occurred, due to high taxes and import duties in the period, which made the implementation of projects onerous. There was no national production chain for wind energy equipment and the Brazilian government increased tax incentives for power generation from small and large hydroelectric and biomass power plants (NUNES et al., 2017).

In 2004, the BES was reorganized by Law N°. 10,848/2004 (Governo FEDERAL, 2004a). This law defined the current model of commercialization of electricity in Brazil. A central part of this model was the establishment of auctions for energy contracting to introduce 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 Brazilian Chamber of Electricity Trading (CCEE) is responsible for holding the energy auctions and the contracts.

The competitive RE procurement auctions were becoming increasingly prevalent. However, FARRELL et al. (2018) comment on what bidding strategy may be influenced by factors external to the auction, such as transmission expansion planning decisions, and this may increase costs. Furthermore, the CCEE 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 RE 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 (FARRELL et al., 2018). However, it was the energy auctions that effectively worked and started to boost wind energy in Brazil from 2009.

6. Wind and solar photovoltaic electricity generation in Brazil

6.1. Wind and solar potential in Brazil

Brazil has a considerable potential for electricity generation from

Table 2
Regulatory framework of the BES.

References of Legal Framework	Date/References	Definition
Resolution N° 24 of the Assembly of Energy Crisis Management: Emergency Program for Wind Energy (PROEOLICA)	07/05/2001 (Governo Federal, 2001)	The PROEOLICA aimed to add 1,050 MW of wind power to the national grid by the end of 2003. PROEOLICA wasn't completely regulated by Federal government and was absorbed by the next program: PROINFA.
Law N°. 10.438/2002: Program for Alternative Sources of Electricity (PROINFA)	26/04/2002 (Governo Federal, 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 N°. 10.848/2004 of Presidency of the Republic	03/15/2004 (Governo Federal, 2004a)	It provided for the commercialization of electricity, amended previous laws and makes other provisions. This law created the contracting for "energy auctions".
Decree N°. 5,163/2004 of Presidency of the Republic	08/30/2004 (Governo Federal, 2004b)	It regulated the commercialization of electric energy, the process of granting of concessions and authorizations of electricity generation, and other measures.
Decree N°. 6,353/2008 of Presidency of the Republic	01/16/2008 (Governo Federal, 2008)	It regulated the contracting of reserve energy that was dealt with in previous laws, changed some previous laws and gave other measures.

wind and solar energy. The National Institute of Science and Technology for Climate Change (INCT–Clima) estimated a gross wind power potential of up to 880.5 GW (with a possibility of production of 1700 TWh/year) considering hub heights of 100 m, with 522 GW being technically feasible (PEREIRA, 2016). The wind regime in the South, especially in the Northeast region, has excellent characteristics for electricity generation: good speed, low turbulence, and reasonable uniformity (FEITOSA et al., 2003). This enables capacity factors of up to 50% at some wind farm locations. In Brazil, wind farms are located onshore due to the large availability of vacant land. The implementation of projects in the Northeast region is undergoing rapid development due to the region's high wind power potential and a very consistent and unidirectional wind regime.

According to data from CEPEL (2017), PEREIRA (2016), and CAMARGO–SCHUBERT; SECTI; SEINFRA; SENAI/CIMATEC (2013), of the 880.5 GW of power potential in Brazil, most is concentrated in the Northeast (309 GW or 35.1%, with a possibility of production of 588.2 TWh/year). The power potential in the state of Bahia is estimated to be 70.0 GW for hub heights of 100 m (Fig. 6 - A). The solar radiation levels in certain regions of Brazil are among the highest in the world. In 2001, the SWERA project began in Brazil to map solar energy potential, assist in the planning of public policies to encourage national solar and wind energy projects, and attract capital of investments in the area of renewable energy (MARTINS et al., 2004). Studies by Pereira et al. (2017) (Fig. 6 - B) and EPE (2012) indicated that the high solar power potential found in Brazil would allow high productivity for solar energy, especially in the Northeast region.

According to SANTOS and TORRES (2017), the State of Bahia presents excellent solar power potential in the Northeast. According to TOLMASQUIM (2016) and KONZEN (2016), the EPE conducted a technical study of Brazilian solar power potential considering environmental restrictions, among others. In this study, the highest solar radiation range (6000 to 6200 Wh/m^2*day) presents a solar PV power potential for centralized generation of 307 GWp in already anthropogenic areas, with more than 90% of potential located in the Northeast region and 260 GWp in the Bahia.

6.2. *Wind and solar photovoltaic centralized power generation expansion*

The wind and solar PV power expansion via the Brazilian energy auctions have been a success story. According to Torres (2017), the expansion of installed capacity in Brazil is ongoing (Fig. 7).

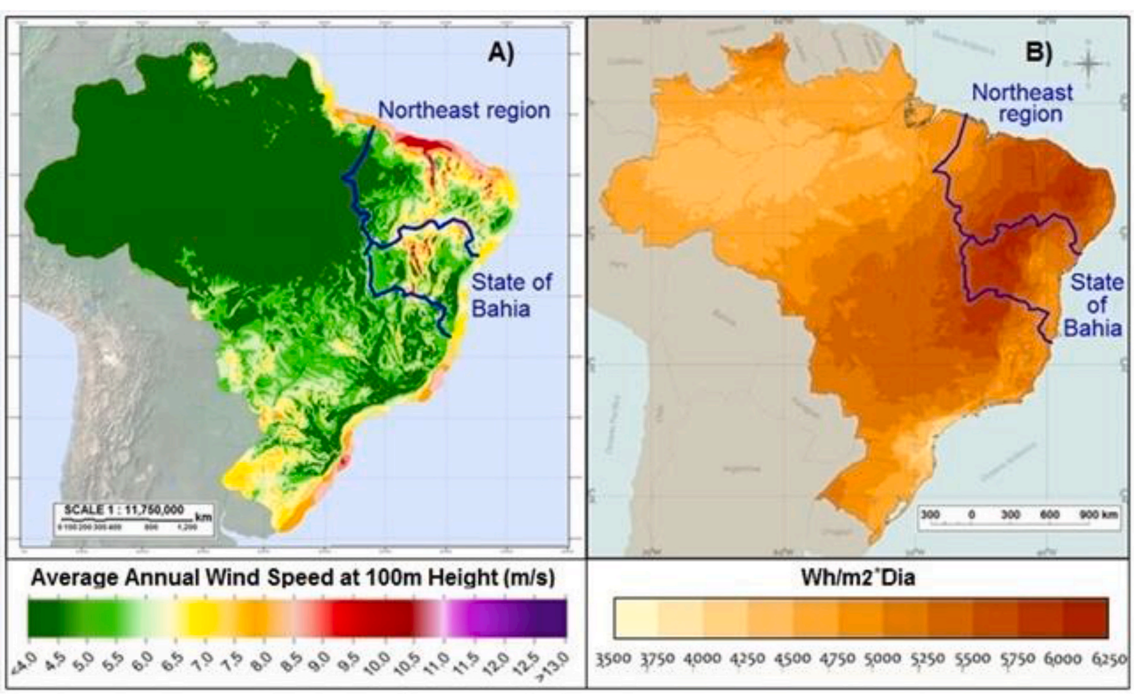

Fig. 6. A) Brazil's wind power potential at hub heights of 100 m (CEPEL, 2017), adapted; B) Annual average total daily irradiation on an inclined plane in Brazil (Pereira et al., 2017), adapted.

The MME (2014) and MELO (2013) reported that wind power had gained prominence since 2009. Until 2013, solar PV power was basically for distributed generation. In 2014, the Federal government started to conduct energy auctions for the contracting of solar PV centralized generation. Substantial wind and solar power capacities were contracted in the Federal government energy auctions until 2015. In 2016, there was an interruption in these energy auctions due to an economic crisis that reduced the national electricity demand. Despite this interruption and the extraordinary deceleration of some ventures, the auctions resumed from 2017 onwards. Several new projects have already been contracted, and the significant potential of future projects will help the Brazilian electricity matrix to continue to be predominately renewable. Currently, power generation companies that participate in the auctions may have terms ranging from 0 to 6 years to build their power plants and deliver the contracted energy.

In 2018, according to ABEEOLICA (2019a,b), Brazil had 14.7 GW of wind power installed capacity with an average capacity factor of 42%, which is much higher than the world average of approximately 25%. Wind farms are concentred in the Northeast and South regions (Fig. 8). According to the EPE (2017b) and DE JONG et al. (2019), by 2026, the total installed wind power capacity in Brazil will grow to approximately 28 GW, and the penetration of installed wind and solar power in Brazil's generation matrix will increase to approximately 18%.

In accordance with the MME (2016a), EPE (2017c) and CCEE (2018), contracting of solar PV projects took place in the auctions from 2014 until 2018 (Table 3). IRENA (2019) reports that PV installed capacity in Brazil grew from 0.015 GW in 2014 to 2.3 GW in 2018, representing an average growth of about 0.46 GW/year and a growth of 15,126% in 5 years. By 2026, the total installed PV capacity in Brazil is estimated to reach approximately 10,000 MW (EPE, 2017b). ABSOLAR (Sauaia, 2017) stated that Brazil still has immense unexplored potential, where the technical potential is more than 28,500 GW, only considering large PV Solar power plants.

6.3. Complementarity of wind and solar resources

The Brazilian Northeast has significant potential in wind and solar radiation, available land, an urgent need to create economic alternatives to mitigate poverty and the majority of wind farms in the country are being installed in this region (STUDZINSKI et al., 2017). When comparing the maps of the Northeast region shown in Fig. 6-A and 6-B, several areas with high solar radiation and very good wind energy potential overlap (SANTOS et al., 2017). These locations in the Northeast show that there are potential areas for wind-solar PV hybrid power plants (EPE, 2017a; SANTOS et al., 2017; LIMA, 2016). In addition, there is complementarity between hydroelectricity (the region's main energy resource) and wind and solar energy (Fig. 9). Thus, in the months of the dry season (when the cost of energy is more expensive), there is 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 generation matrix securing against the effects of droughts (DE JONG et al., 2013).

The Northeast's semiarid (Fig. 10) has the greatest potential for hybrid renewable projects, and the largest expanse with overlapping resources lies within the state of Bahia (Fig. 11) (SILVA and SEVERO, 2012; Camargo-Schubert et al., 2018). The semiarid presents excellent technical feasibility for PV systems implementation to meet some of the basic needs of this region, including building electrification, solar pumping projects, and desalination (Barbosa et al., 2017). Thus, there are opportunities to attract investments to this region, which can generate employment, income, and tax collection for the respective states and social action by both the government and private enterprise.

The Northeast region can be deficient in terms of supply of electricity to meet its own demand, especially in autumn. During these periods, electricity is imported from other Brazilian regions by the SIN. However, the trend is for this scenario to be gradually reversed with the insertion of wind and solar PV projects. Wind farms already in operation are helping to supply electricity in the Northeast, compensating for productivity losses from the São Francisco hydropower plants, which are hampered by the current prolonged drought.

Wind energy is expected to supply up to 57% of Northeast electricity demand by 2020, and in 2017 wind energy supplied approximately 39% of the region's electricity demand (DE JONG et al., 2017a). Wind farms represent an opportunity for sustainable development in surrounding communities, and wind farm stakeholders should contribute to social programs from the start of construction (GONZÁLEZ et al., 2017).

Considering the average hourly generation (or the capacity factor) from wind farms and solar PV systems well inland in the Northeast region (Fig. 12), a daily complementarity can be observed between solar and wind sources. Therefore, the implementation of hybrid power plants in specific locations can be beneficial in relation to the efficient use of the SIN (Coutinho et al., 2017; ANEEL , 2019a). However, it would be necessary to have some curtailments in some periods, when the total injected power was greater than the transmission system usage amount

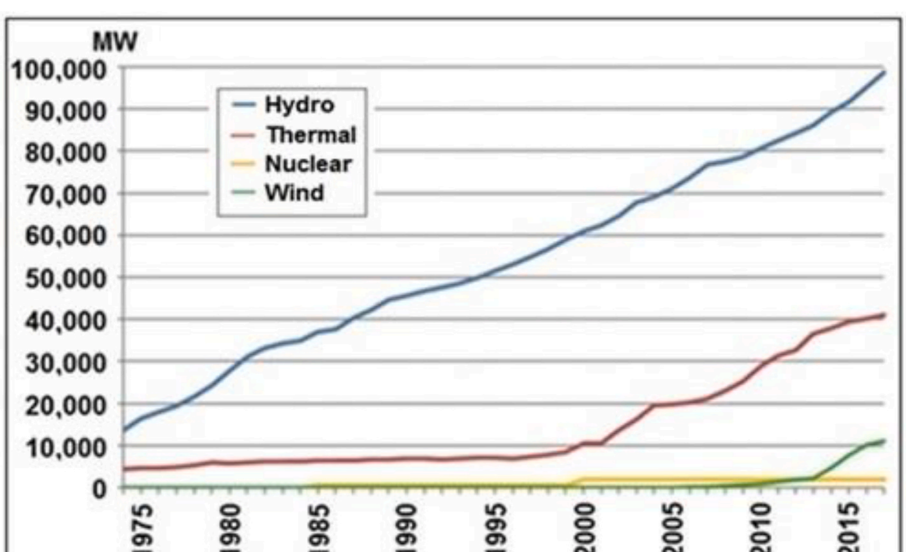

Fig. 7. Brazilian electricity generation installed capacity by source: 1974–2016 (TORRES, 2017).

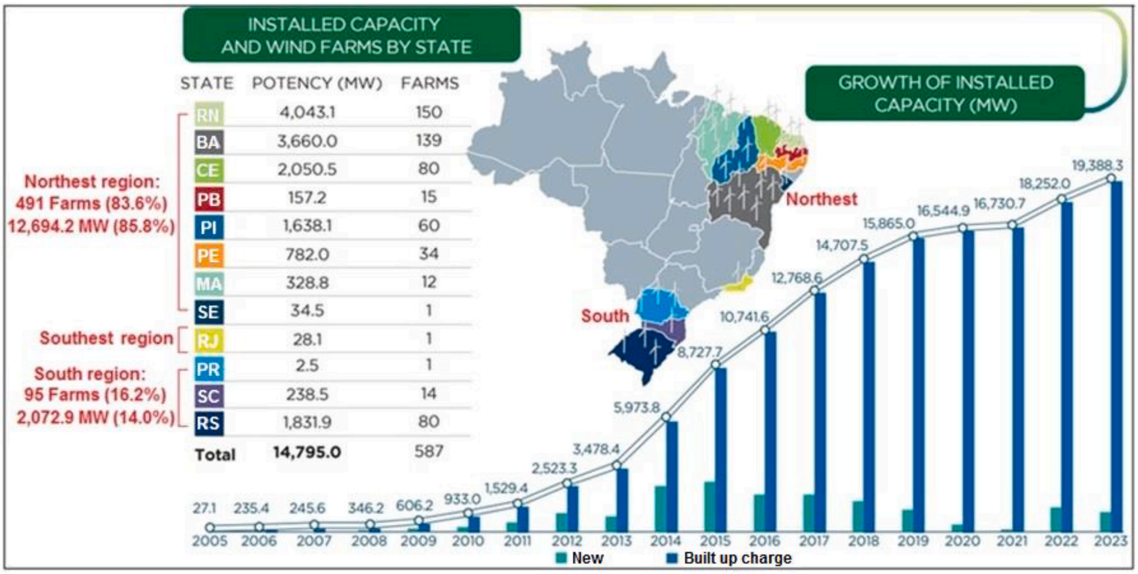

Fig. 8. Annual additions and cumulative installed capacities of wind power generation in Brazil: 2005–2023 (ABEEOLICA, 2019a). Adapted.

Table 3
Contracting of solar projects.

Year	Month	N° of Projects	Capacity Installed		Contracted Energy	Supply Beginning
			(MW)	(MWp)	(MWmed)	
2014	Oct.	31	889.7	1048.0	202.3	2017
2015	Aug.	30	833.8	1044.0	231.5	2017
2015	Nov.	33	929.3	1115.9	245.0	2018
2017	Dec.	20	574.0	790.6	172.6	2021
2018	Apr.	29	806.6	1032.5	228.5	2021
Total		**143**	**4033.4**	**5031.0**	**1079.9**	

contracted. According to ANEEL (2019a), the transmission system usage amount contracted is the injectable power maximum for power plant with your installed capacity subtracted our minimum load. Structurally, the BES, and the SIN will have to gain more flexibility and operational agility to meet the characteristics of wind and solar energy. The BES and the SIN will also need to have flexible thermal plants and/or hydroelectric plants available to compensate for possible limitations of wind and solar sources. This is an opportunity for bioenergy expansion and the future use of natural gas. The reservoirs of hydroelectric plants can also take advantage of water savings and, with modifications, operate as pumped hydro storage systems within the SIN.

Since 2017, the EPE has conducted studies and discussions on the issue of hybrid power generation for Brazil. The EPE states that the discussion about the possibility of producing power with plants using more than one primary source (hybrid power plants) is gaining importance. Furthermore, several proposals are gaining visibility, and there are some concrete initiatives in project development and implementation (EPE, 2018). In Brazil, this has gained relevance with evidence that the complementarity between certain sources (e.g., wind and solar)

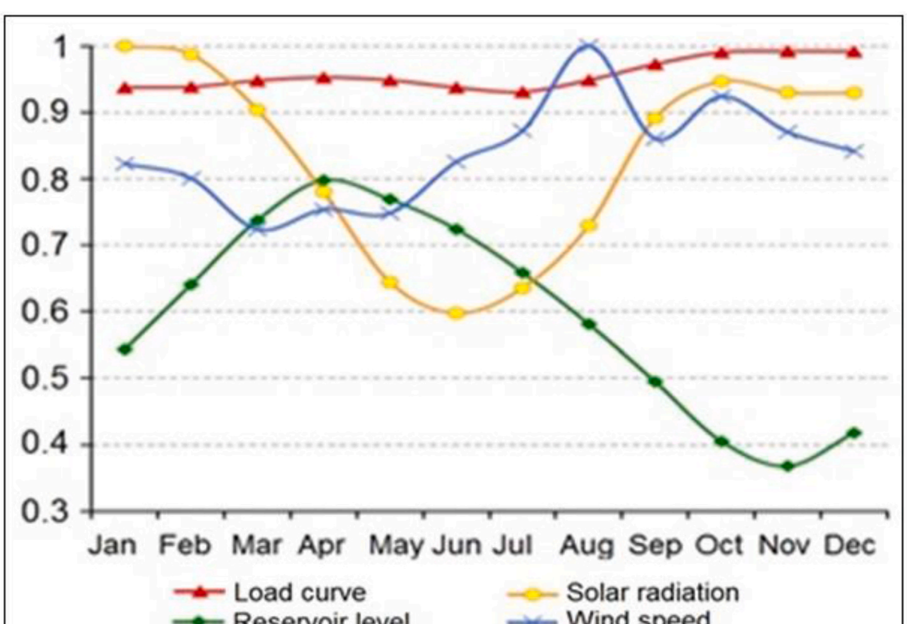

Fig. 9. Load curve and complementarity between hydro, wind, and solar power in the Brazilian Northeast (DE JONG et al., 2013).

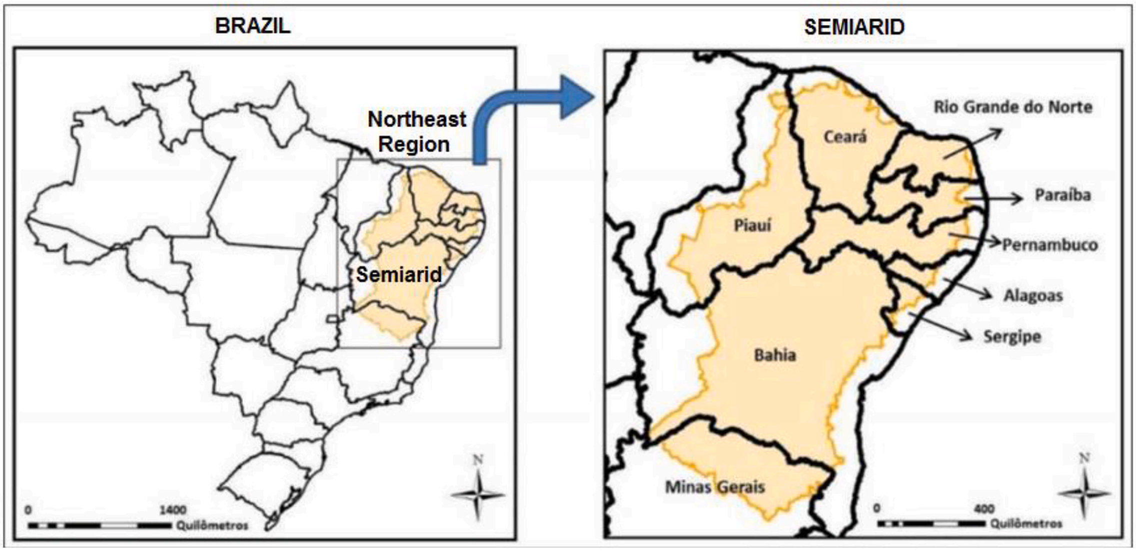

Fig. 10. The Brazilian semiarid extension (BARBOSA et al., 2017). Adapted.

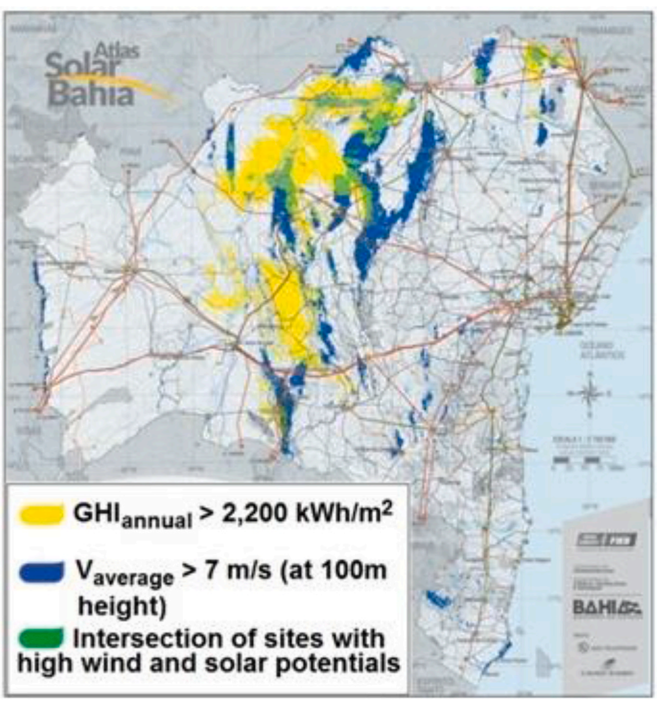

Fig. 11. Overlapping solar and wind resources in the semiarid extension within the state of Bahia (CAMARGO–SCHUBERT et al., 2018). Adapted.

would enable more efficient use of the existing and planned transmission system capacity.

In 2017, the EPE conducted a study to evaluate the daily complementarity for generation from wind-solar PV hybrid power plants at five different locations in the Northeast (Fig. 13): 3 locations in the state of Bahia, 1 location in the state of Rio Grande do Norte and 1 location at the state borders of Piauí, Pernambuco, and Ceará. In this study, locations 2 (Caetité), 3 (Brotas de Macaúbas) and 5 (the border region between Piauí, Ceará, and Pernambuco) present the best profiles of daily solar-wind complementarity. In addition, this study and DE JONG et al. (2017b) found that at locations inland in the Northeast average wind generation was higher at night and typically decreased during the earlier afternoon hours of the day; however, the issue of complementarity is complex and should be studied on a case-by-case basis. Although there is no regulation on HES in Brazil, the favourable conditions of energy complementarity encouraged companies to implement two pilot projects to test wind-solar PV HES (EPE, 2017a). These hybrid energy pilot projects are located in Tacaratu (Pernambuco) and in Caetité/Igaporã (Bahia) (see Fig. 13) and are described in detail in sections 6.4.1 and 6.4.2, respectively.

The complementarity conditions (seasonal and daily) of solar and wind energy potentials at the same geographic locations (Fig. 13) are strategically favourable for wind-solar PV hybrid centralized generation in the Northeast region. The pilot projects of Tacaratu and Caetité/Igaporã prove the viability and advantages of the hybrid plants in the Northeast (Semiarid). However, Tacaratu was an "operational and commercial junction strategy" and Caetité/Igaporã was a "R&D project", both of which were exceptional actions of the companies and with the purpose of demonstrating the advantages of complementarity. Thus, other conditions and actions are necessary to permit and make feasible the large-scale use of HES projects in Brazil.

An analysis of the BES pointed to other relevant conditions that should be met for the viability of centralized combined generation (Table 4). Thus, the Federal government should adopt new public policies to enable these conditions (SANTOS et al., 2017).

The Northeast region of Brazil presents unique conditions with much potential for the generation of both solar and wind energy coincidentally in several areas. In addition, there are many locations with complementarity (seasonal and daily) between wind and solar energy. This is conducive to a future with the combined generation of wind and solar PV energy, which could significantly boost gains in terms of efficiency and productivity (LIMA, 2016; Santos, 2015; DE JONG et al., 2013).

Due to strong and very consistent winds that occur in the Brazilian Northeast region, aggregate wind energy generated across the region has significantly less seasonal and diurnal variability than wind energy generated in other balancing areas such as in the USA (DE JONG et al., 2017a). However, the spatial distribution of variable renewable power plants does not always reduce the variability of supply. This is particularly true for solar PV systems when not combined with storage or another complementary generation technology. The space-time variability of weather-related energy production is a challenge because one of the primary goals of electric utilities is to balance supply and demand (ENGELAND et al., 2017).

The use of PV Solar power, together with wind power, results in smoother energy output. Considering the rated power at a specific wind farm, the addition of solar PV could, on average, increase electricity

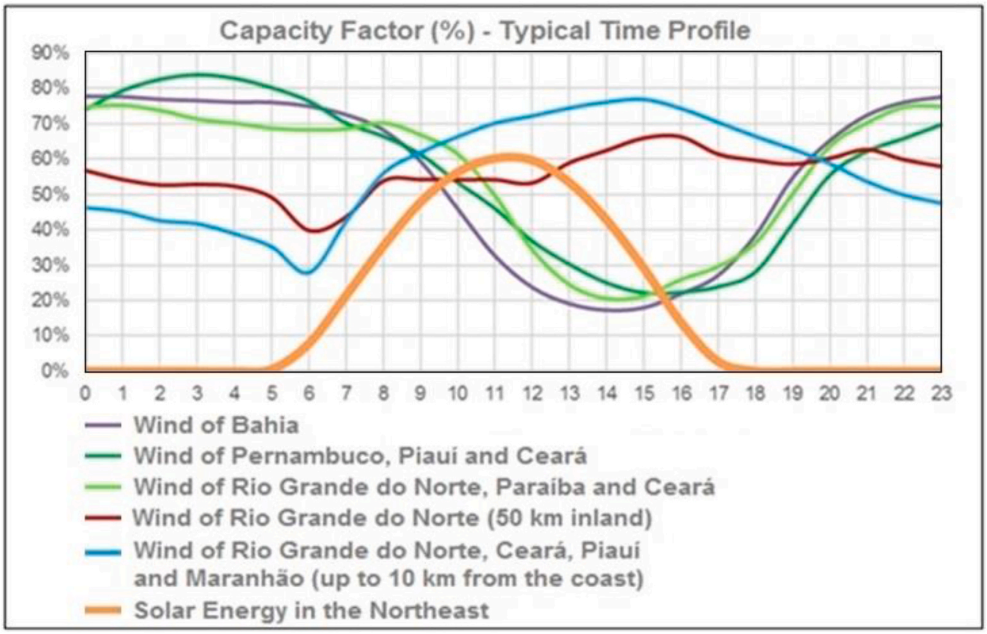

Fig. 12. Electricity generation in the Northeast (ANEEL , 2019a *apud* Coutinho et al., 2017). Adapted.

production by 20% per year (STUDZINSKI et al., 2017).

6.4. Hybrid energy systems in Brazil: lessons-learned from two projects

Until 2019, there were no specific regulations in the regulatory framework of the BES or public policies about hybrid power centralized generation. Thus, there are no hybrid generation auctions. Each energy source is treated separately by the current regulation and is contracted via specified and respective auctions. Auctions for hybrid power plants are a possibility as there is a regulatory framework review in progress. However, some pilot projects for centralized combined generation have already been implemented, such as the placement of floating solar PV panels in the lake of Balbina (PEREIRA et al., 2016) and the Sobradinho hydroelectric reservoir, located in the states of Amazonas and Bahia, respectively. Eletronorte and CHESF are forecasting investments totalling R$ 114 million (approximately US$ 33.8 million) for these two projects, which should start operating in 2019 (Ambiente Energia, 2017).

There are also two pilot projects of wind-solar PV hybrid power plants created at the initiative of private companies interested in verifying wind and solar power complementarity in the Brazilian Northeast: one located in Tacaratu (Fig. 14 – A) and another located in Caetité and Igaporã (Fig. 14 – B) (SANTOS and TORRES, 2017).

6.4.1. Hybrid energy system of Tacaratu

In Tacaratu municipality (Pernambuco), Enel Green Power Brazil (EGPB) implemented three wind farms with a total capacity of 80 MW in 2014, and two solar PV power plants totalling 11 MWp in 2015 (Table 5) (Leoni et al., 2017). EGPB is an Italian company that operates with several renewable energy projects in Brazil (EGPB, 2018). It has been prominent in recent energy auctions. The hybrid power plant was implemented in stages, where the wind farms (Fontes dos Ventos), were first contracted in 2011 via auction of the federal government. Then, the PV power plants (Fontes Solar) were contracted in 2013, in the pioneer, regional, and unique energy auction of the state of Pernambuco. From 2014, the federal government begin to contracted solar PV energy in national auctions, and no more there ware regional auctions.

With data provided by EGPB (2019), NREL (2019), and ONS (2019a), the 15 min resolution power generation, the hourly power generation, and the annual power generation from the Tacaratu HES are shown in Figs. 15–17, respectively. Furthermore, the daily and seasonal complementarity of the PV plants with wind farms can be observed in Figs. 16 and 17, respectively. For example, in Fig. 16, it can be observed that the solar PV plants generate electricity between 7:00 h and 17:00 h, exactly when the average diurnal wind power generation drops to its lowest point. According to EGPB (2019), in relation to the electricity supply to SIN, the Tacaratu HES use commercially and operationally reference 77 MW of the wind transmission system usage amount (MUST) contracted (Fig. 15) and the substation related to Fonte dos Ventos power plant. The distribution of the power generation on a 15-min basis shows the MUST overtake events were only 3.7% of the time over 12 months of operation (Jan–Dec/2018).

6.4.2. Hybrid energy system of Caetité and Igaporã

Renova Energia started work on the wind-solar PV HES project in 2015 (LEONI et al., 2017). Renova Energia is a company of Brazilian origin with several projects in the renewable energy sector (Renova Energia, 2018). This hybrid power plant is located in the Caetité and Igaporã municipalities (Bahia). In this region, there is a complementarity between day time solar power generation and nighttime wind power productivity, besides the existence of seasonal complementarity. The hybrid power project has a total installed capacity of 26.4 MW (21.6 MW of wind power capacity and 4.8 MWp of solar PV) (Table 6) (Silva, 2015; LEONI et al., 2017). The hybrid power project was approved as a "pioneering innovation" by the Financier of Studies and Projects (FINEP) in the first half of 2014. FINEP provided financing of R$ 108 million (approximately U$ 32 million). The power plant construction were started in 2015 and the operation was beginning in 2016 (LEONI et al., 2017).

There is then the existence of periodicity in the series of solar, radiation and wind speeds was verified, which allows for predicting the variability over time. A Fourier transform was applied to the series of monthly wind speeds and solar radiation, finding the inter-annual energy and periodicity contained in the signal. A long-term periodic complementarity between wind speeds and solar radiation in the region of Caetité/Igaporã was observed. Fig. 18 corresponds to the 46-year periodicity of the wind and solar series, where a lag of 15 years approximately was observed between the two sinusoidal. The potential effects of climate change were not considered in this analysis (LEONI et al., 2017; Pinto, 2016).

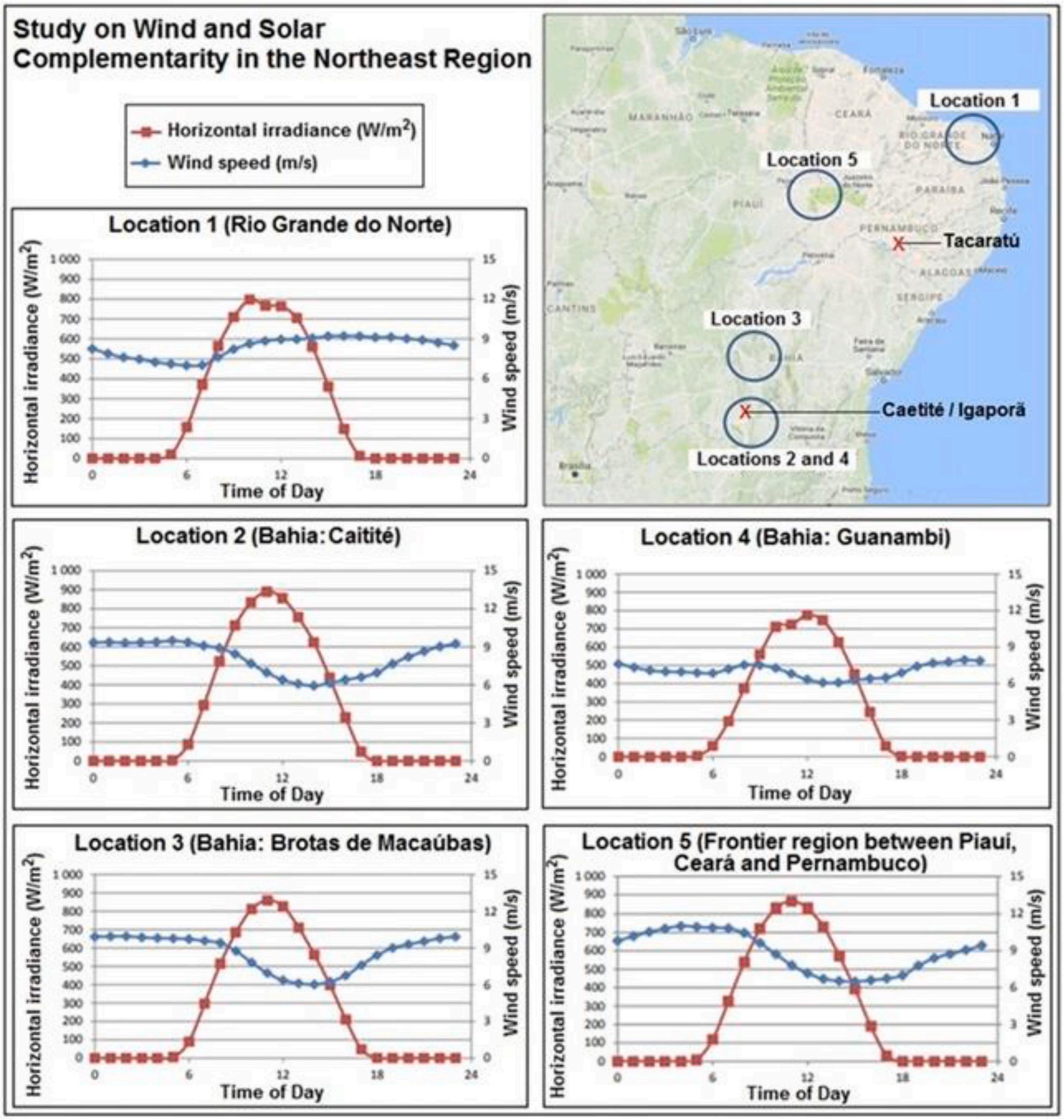

Fig. 13. Five case studies of energy complementarity for wind-PV electricity generation in the Northeast and the HES in Tacaratu and Caetité/Igaporã (EPE, 2017a). Adapted.

Table 4
Conditions for the viability of Centralized Combined Generation in Brazil.

	Conditions of viability of centralized combined generation in Brazil
1	Regularity and annual predictability of contracting
2	Appropriate funding conditions
3	Investments in transmission infrastructure
4	Favourable regulation
5	Investments in R&D and training of human resources (HR)

It was observed that, unlike wind dynamics, the solar source has a higher production moment, due to the expected behaviour within the fluctuations regime of approximately 15 years. In this way, it is possible to note the interannual complementarity between the sources at the analysed site. Typically, the production reduction of one source is compensated by an increase in production from the other source. So, there is evidence that a HES can generate more stable electricity, and production is less vulnerable to weather variability (LEONI et al., 2017).

Between 00:00 h and 08:00 h, winds are strong while there are only a couple of hours of weak sunlight, and between 11:00 h and 15:00 h, there is consistent sunlight while winds are weak (Fig. 19) (Carvalho et al., 2016).

6.4.3. *Analysis of the Tacaratu and Caetité/Igaporã hybrid power plants*

The Tacaratu pilot project is an example of a wind farm that was hybridized with the addition of a solar PV power installation and was the first grid-connected wind-PV HES in operation in Brazil, with installed capacities of 87.9% wind power and 12.1% solar PV power. Therefore, the positive result of this hybrid power plant is an increase in electricity generation of more than 20% above solely wind generation between 10:00 h and 14:00 h (Fig. 15).

The Caetité/Igaporã pilot project is an example of a power plant that was designed from the outset as a HES project, with installed capacity of 81.8% wind power and 18.2% solar PV power. The solar PV installed capacity enables a significant productivity gain in electricity generation. During the winter, there is more wind generation, and during the summer, there is an increase in solar generation. After one year of operation, it was found that between 11:00 h and 15:00 h, the hybrid generation

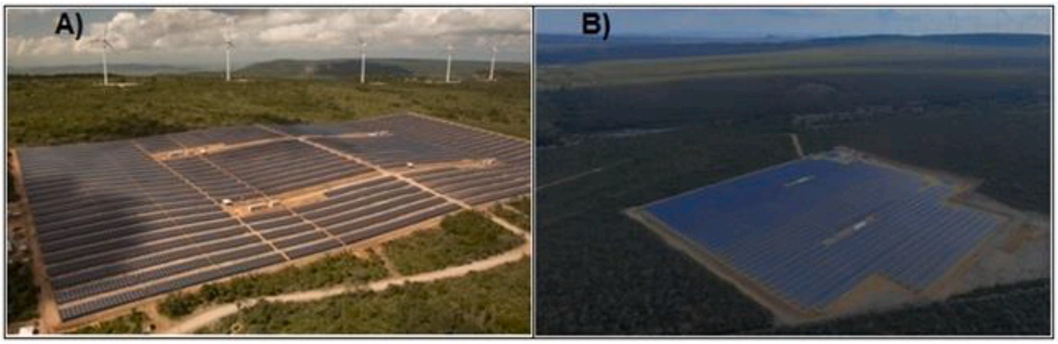

Fig. 14. A) HES in Tacaratu (EGPB, 2018); B) HES in caetité/Igaporã (RENOVA ENERGIA, 2018).

Table 5
Description of the HES in Tacaratu.

Tacaratu Hybrid Power Plant					
Power Plants			Installed Capacity	Guaranteed Energy	Generation
Fontes dos Ventos (Wind)	1	Pedra do Gerônimo	30.6 MW	15.4 MWmed	13 wind turbines
	2	Pau Ferro	30.6 MW	16.8 MWmed	13 wind turbines
	3	Tacaicó	18.8 MW	11.1 MWmed	8 wind turbines
Fontes Solar (Solar)	4	I	5.5 MWp	1.0 MWmed	17.765 PV panels
	5	II	5.5 MWp	1.0 Mwmed	17.765 PV panels
Total Installed Capacity Investment			**91 MW U$ 148 millions**	**45.3 MWmed**	

presented increases of more than 30% above solely wind generation (Fig. 18.).

In the two case studies, there is a gain in productivity due to the wind-solar PV combination, and a reduction in overall output variability was observed. These gains are coherent with the estimates performed by STUDZINSKI et al., 2017 and DE JONG et al. (2017b). Thus, these pilot projects are effectively pioneering innovations in terms of providing less intermittency than individual wind and solar projects.

6.4.4. *Advantages and disadvantages of wind-solar hybrid power plants in Brazil*

In recent years, the Federal Government has decided that it would be advantageous for Brazil to expand wind and solar energy to: diversify the electricity generation sources; use these abundant renewable energy potentials; and increase energy supply security in Brazil.

There are several positive implications for the use of wind and solar energy in Brazil. In economic terms, there are investments of the order of billions of R$, that encourage the economy and the implementation of production chains in the wind and solar industries. In social terms, there is job creation and income for the population. According to Simas (2012), the generation of jobs per MW of installed capacity throughout the production chain correspond to 15 jobs/MW installed for wind energy (onshore) and 33 jobs/MW installed for solar PV projects. According to ABEEOLICA (2019b), wind farms are generating income and improving the quality of life of landowners who lease their land for wind turbine installations. Furthermore, leases are taxable, thus providing significant revenue for the government and the development of social projects. In environmental terms, GHG emissions can be reduced (RAIMUNDO et al., 2018), and water savings can be made in the Brazilian hydroelectric reservoirs (Santos, 2015). In technical terms, there is diversification of electricity generation sources, which ensures greater security of supply for the electricity sector.

There are also negative implications for the use of wind and solar energy in Brazil. In environmental terms, there are some relatively small GHGs emissions in the manufacturing and implementation of wind turbines and PV modules; visual impact because of landscape changes; land surface impacts; sound impacts of blades movement in the areas near of the wind towers; bird and bat fatalities caused by impact with the blades; future disposal challenges of old PV modules and wind turbines; In technical terms, without storage, wind generation is typically variable due to the stochastic nature of wind resources, while solar PV generation is intermittent, as solar radiation only occurs during a narrow daily window of 6–8 h.

The advantages and disadvantages of combined Wind-Solar PV power for electricity generation are summarized in Table 7.

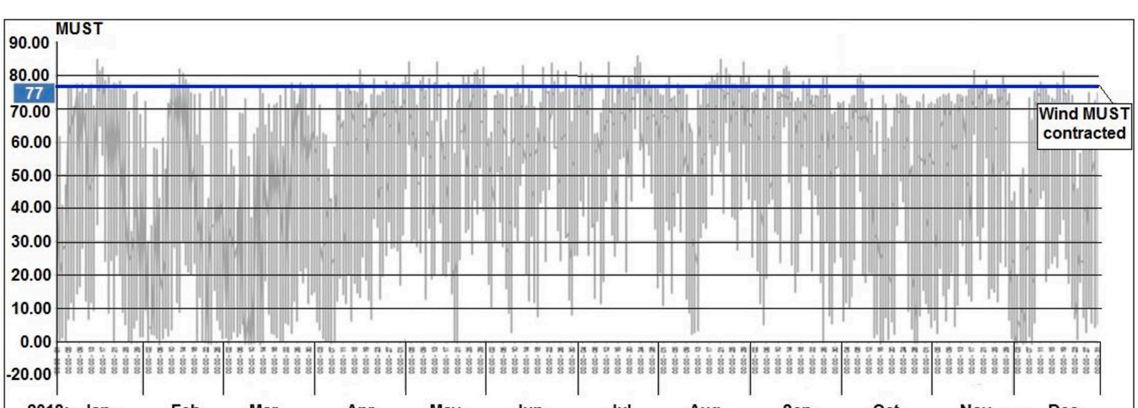

Fig. 15. 15 min resolution power generation in Tacaratu in 2018 (EGPB , 2019). Adapted.

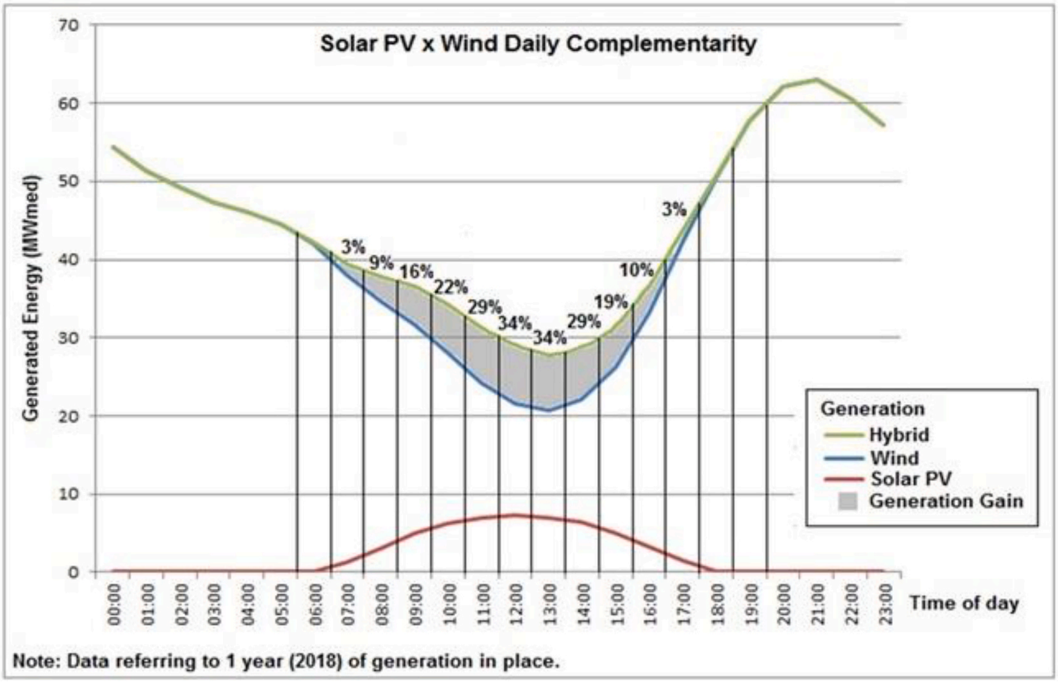

Fig. 16. The HES gain in Tacaratu in 2018.

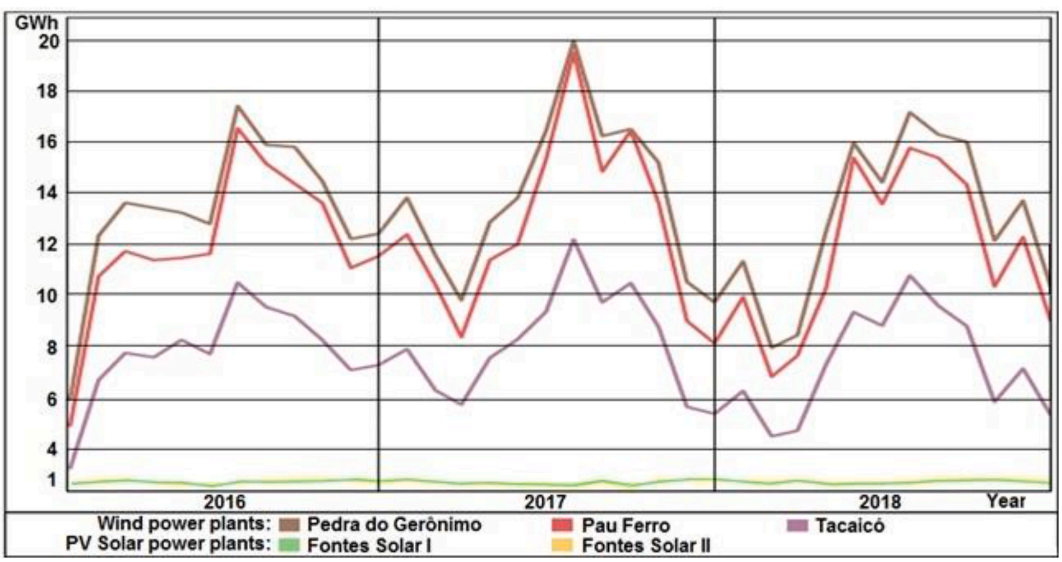

Fig. 17. Annual Power generation from the Tacaratu HES: 2016–2018.

Table 6
Description of the HES in Caetité/Igaporã.

Caetité/Igaporã Hybrid Power Plant					
Power Plants			Installed Capacity	Guaranteed Energy (MWmed)	Generation
Wind	1	Saboeiro	13.5 MW	Data unavailable	5 wind turbines
	2	Jurema Preta	8.1 MW	Data unavailable	3 wind turbines
Solar	3	Caetité Va	4.8 MWp	Data unavailable	19,200 PV panels
Total Installed Capacity Investment			**26.4 MW U$ 32 millions**	–	

6.4.5. The challenge of solar photovoltaic intermittency and wind power variability

The expansion of wind and solar sources in the Brazilian Electricity Matrix has risk implications for energy security because of variability and unpredictability. However, the conjunct use of wind and solar energy help to reduce variability.

Electricity generation in a power system must meet all load changes considering small time intervals (hours, minutes, etc.). As the penetration of variable renewables increases substantially in the future, this issue will become a challenge for the electricity sector.

There are many energy storage technologies that will help to resolve the challenges of variable renewable, including Electrochemical and Battery, Thermal, Thermochemical, Flywheel Compressed Air, Pumped Hydro, Liquefied Air, and Magnetic. Energy storage systems also can be classified based on storage period. Short-term energy storage typically

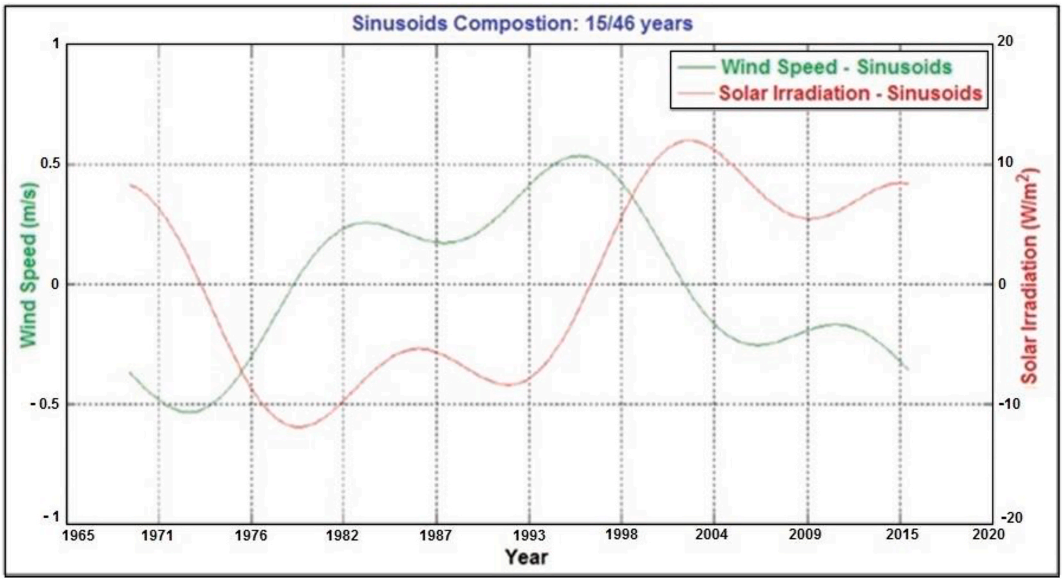

Fig. 18. Wind-Solar complementarity during a 46-year period (LEONI et al., 2017 *apud* PINTO, 2016).

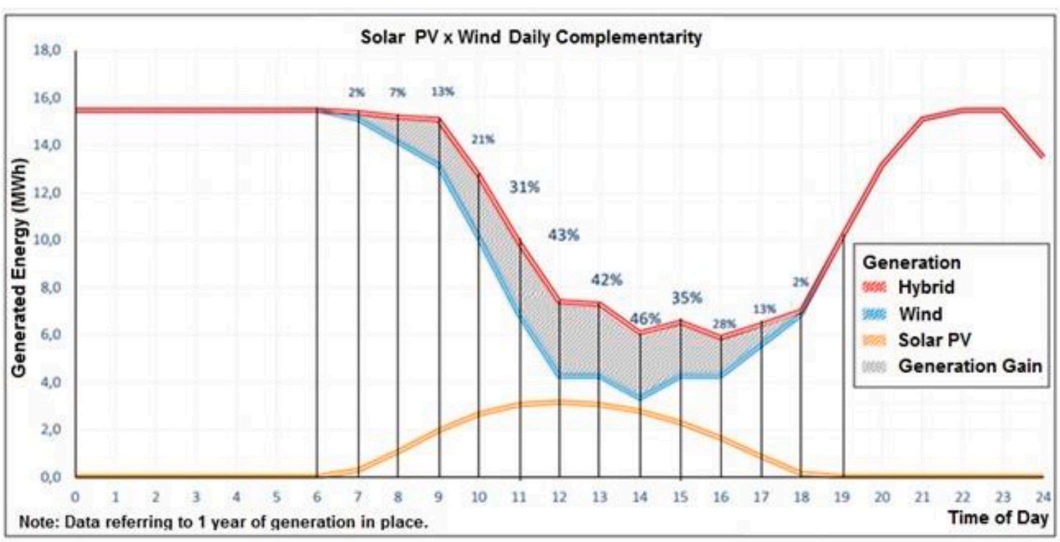

Fig. 19. The HES gain in Caetité/Igaporã (CARVALHO et al., 2016). Adapted.

involves the storage of energy for hours to days, while long-term storage refers to the storage of energy from a few months to a season (3–6 months) (KOOHI-FAYEGH and ROSEN, 2020).

In the case of Brazil, some of the possible solutions to manage the issue of wind and solar variability would be the implementation of pumped hydro storage, demand-side management, and the increased use of gas and biomass power plants to gap-fill variable renewable generation. However, more government studies and more technical actions will be needed to adapt the SIN to this new paradigm of wind and solar energy, even with hybrid generation.

7. Regulatory framework revision and the need for inclusion of the hybrid projects

In Brazil, there is a need for more renewable electricity generation; great potential for hybrid projects due to the complementarity of resources, and great potential for hybrid projects due to the established higher performance and synergy of such projects. The current regulatory framework does not support hybrid projects. Thus, the current discussions related to the BES regulatory framework revision are an opportunity to create new specific regulations on HES plants.

In 2016, the Federal Government was interested in making improvements to BES through some public consultations of the MME. In May 10, 2016, the MME released the public consultation N°. 21 and Technical Note N°. 4/2016/AEREG/SE (MME, 2016b) on the free electricity market. In this way, the MME (2017a) requested contributions on the expansion of the free market of electric energy, benefits and risks involved and terminated this call with Technical Note N°. 3/2017/AEREG/SE.

However, in 2017, the primary motivation for realizing the new BES reform was the express interest of the Federal Government in the privatization of the Eletrobras group of companies. The MME (2017a,b) 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 N°. 32 of July 07, (MME, 2017c) and in Technical Note N°. 11/2017/SE (Principles for Reorganization of the Brazilian Electricity Sector), in public call N°. 33 and Technical Note N°.

Table 7
Advantages and Disadvantages of Wind-Solar PV HES.

Terms	Advantages	Reference	Disadvantages	Reference
Economic	There are billionaire investments, that encourage the development economic and the implementation of production chains and business in the wind and solar industries.	SANTOS et al. (2017)	Partial or total land use for agriculture and livestock.	STAUT (2011)
Social & Environmental	The job criation per MW of installed capacity in the production chains: 15 jobs/MW by wind energy and 33 jobs/MW by solar PV energy.	SIMAS (2012)	Land speculation.	SANTOS (2015); STAUT (2011)
	There are generation of incomes and improves the quality of life to landowners who lease your lands for wind towers placement.	ABEEOLICA (2019b); STAUT (2011)		
	Increase in the taxes collection and fees for government.			
	Opportunity for companies to sponsor social projects.	ABEEOLICA (2019b); GONZÁLEZ et al. (2017)		
	Thera are no GHG emissions in the energy production, which contributes to the overall reduction in air pollution in the electricity sector.	ABEEOLICA (2019b); RAIMUNDO et al. (2018); BARROS et al. (2018)	Some GHG emissions in the manufacturing and implementation of wind turbines and PV modules	BARROS et al. (2018)
	Water saving can be made in Brazilian hydropower reservoirs.	SANTOS and TORRES (2017)	Land surface impacts.	WOLSINK (2007)
			Visual impact caused for landscape changes.	SANTOS (2015); STAUT (2011)
			Sound impacts due to wind turbine blade moviment.	
			Bird and bat fatalities caused by impacts of the blades.	
			Future disposal problems of the old PV modules.	
Technical	Wind and Solar energy are inexhaustible.	SANTOS (2015)	Wind and Sun are intermitent enegy sources.	SANTOS (2015)
	There is diversification of energy sources, which generates greater supply security to electricity sector.	SANTOS et al. (2017)		
	Sharing of the electrical infraestruture such as transmission lines and substations.	EPE (2017b)	Sun offers energy only during the day.	
	Electricity Generation Optimization: Reduction of deployment and operation costs; Higher efficience of the system via energy complementarity.	LEONI et al. (2017); TOMELIN et al. (2016)		

05/2017/AEREG/SE (Enhancement of the Legal Framework of the Electricity Sector), proposals were presented for legal measures to make feasible the future of the electricity sector with long-term sustainability.

The MME (2017b) 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, they said that there is a need for a new vision for the BES, which includes a model adapted to the external pressures to which the BES is exposed and guarantee its sustainability in the long term. The basic elements listed by the MME to realize this vision are listed in Table 8.

A positive aspect in relation to this new BES reform was the openness 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 MME (2017c), there were a total of 191 contributions for the improvement of the BES, coming from several individuals and legal entities related directly or indirectly to the electricity sector. Among these contributions, some companies presented proposals aimed at the implementation of HES. 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.

Table 8
Orientations for regulatory framework revisions.

	References for BES's New Vision
1	Incentives to the efficiency the corporative decisions of the individual agents as a vector of tariff affordability, security of supply and social-environmental sustainability.
2	Economic signalling as vector of alignment between individual and systematic interests.
3	Adequate risk allocation to enable individual management with well-defined responsibilities.
4	Removal of barriers involving market participants.
5	Respect to currents contracts and compliance with the formal requirements and rules of each institution.

To date, the MME has not finalized the proposal to be submitted to the National Congress to begin the process of reforming the BES. However, once the various contributions are filed with the MME (2017c), 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 energy and a new free contracting environment.

Among the many barriers that were identified for the wind and solar PV power energy in Brazil, three have particular relevance: poor transmission infrastructure, unattractive financial loans, and an unstable macroeconomic environment (Diógenes et al., 2019).

A reform of the regulatory framework also opens up the possibilities for attracting more investment via hybrid projects. However, there are also other initiatives to create new tax modalities, such as royalties, being proposed by the Federal Chamber of Deputies (CÂMARA DOS DEPUTADOS, 2015), which would burden wind generation.

8. Discussion

In terms of the expansion potential of wind, solar and hybrid projects, the information presented in this article proven that Brazil has excellent conditions of geographical coincidences associated with high potentials and the complementarities (seasonal and daily) of wind and solar sources. Brazil showed the expressive development of wind and solar PV power in Brazil during the past few years, and the installed capacities of wind power and solar PV in Brazil were 14.4 GW and 2.3. GW, respectively, in 2018. In addition, wind and solar energy resources still have many expansion opportunities available for future wind, solar, or HES plants. These circumstances are an opportunity for the implementation of several large hybrid plant projects, mainly in the Northeast region (semiarid).

In terms of the revision of the regulatory framework to encourage

Wind-Solar PV Hybrid Power development, the current legislation allowed the development of wind generation and solar PV. This development was significant and corresponded to a success story. Energy auctions are an efficient tool for expanding national installed capacity, contracting separate projects for different energy sources. However, there are still no specific auctions for the joint contracting of more than one energy source to enable hybrid plants.

According to information from ANEEL and the EPE, since 2017, the Federal Government has been discussing the revision of the Regulatory Framework, but there is still no prospect of when this process will be concluded. As previously mentioned, there is no regulatory provision for the contracting of hybrid plants, and the current existing plants were pilot projects (exceptions) that circumvented the limitation of the current regulatory framework and proved that it is possible to implement and operate hybrid wind-solar plants in Brazil. There is a need for regulatory authorization for specific auctions to contract hybrid projects. In this way, hybrid plants can effectively become an alternative option for expanding the national installed generation capacity.

In the following section, the feasibility conditions for centralized combined wind-solar generation in Brazil are detailed:

8.1. Regularity and annual predictability of contracting

Santos (2015), ABEEOLICA (MELO, 2013), and the Federal government agree that a minimum contracting of 2000 MW/year of wind farms would be required by way of auctions to give economic viability and sustainability to the wind power productive chain. Furthermore, ABSOLAR (2014) has stated that a minimum contracting of 1000 MW/year of solar PV power plants would be required via auctions to enable the implementation of a PV productive chain in Brazil. However, in 2017, ABSOLAR requested a minimum contracting of 2000 MW/year.

Annual average wind power contracted in Brazil, from 2009 until 2015, was higher than 2000 MW/year, and the annual average solar PV energy contracting from 2014 until 2015 was over 1000 MW/year. In 2016, there were no energy auctions, and in 2017 and 2018, there was resumption in the contracting of renewable energy projects, but below the previous averages.

Despite this decline in contracting, in 2019, the Federal government has not yet defined a policy with minimum contracting guarantees to signal greater security for the wind and PV productive chains and for investors.

8.2. Appropriate funding conditions

The appropriate availability of financing for wind and solar PV enterprises and productive chains is fundamental to support the continuous expansion of renewable electricity generation more independently of the fluctuation of international prices. Thus, favourable financing conditions for companies, and some initial tax incentives for these productive chains will be necessary.

The main instrument for financing is the National Bank for Economic and Social Development (BNDES). However, as a result of the current economic crisis in Brazil, it is possible that there will be an opening for new modalities of international financing. An example of this is financing with a company's own resources coming from outside of Brazil, as EGPB has done with its solar projects.

8.3. Investments in transmission infrastructure

There is a great need for new investments for the expansion of the Brazilian SIN. The EPE (EPE, 2019c) created the Transmission Expansion Program/Long Term Expansion Plan (PET/PELP) to strategically guide the expansion of the SIN and more adequately meet the expansion of power generation. Since 2017, TL auctions have been successful, and many investments have taken place. The tendency is that the restrictions of the SIN will be resolved in the medium term. Table 9 presents the prospects for expanding the SIN by 2023 (ONS, 2019b).

8.4. Favourable regulation

The federal government has often been erratic and inconsistent with respect to the complexity of Brazil's energy sector, as it has promoted changes in laws and sectoral reforms without a clear vision of state policies. In addition, most of the main institutions focused on the electricity sector were created less than 25 years ago. Specifically, the EPE, ONS, and ANEEL were created in 2004, 1998, and 1996, respectively, and they have little or insufficient autonomy in relation to the Government. Thus, public policy can change drastically from one government's mandate to another, or even within the same government mandate. Therefore, there is a need for improvement and consolidation of regulations in an appropriate, transparent, coherent, and predictable manner, providing legal and economic security for long-term investments.

The improvement of the auction process would be a crucial element in order to accommodate purpose-built "hybrid power plant" projects. To that end, contracting periods could be standardized to 25 years, reconciling the minimum lifetimes of wind and solar PV equipment. Currently, 20 years is used because this is the standard period of amortization for renewable project financing and equipment guarantees. Besides this, the possibility of preferential contract renewals could be created independent of auctions, as this would encourage a full technological upgrade of hybrid power plants with future more efficient equipment. This would also guarantee future demand for productive chains and increase energy production.

Analyzing the current outlook, future potentialities, and perspectives, it is possible to identify the following regulatory scenarios: i) Maintenance of current regulatory milestones; ii) Hybridization of existing power plants; iii) Wind-PV hybrid power plants contacted as single projects from the outset. In the last two scenarios, there is a need for improvement in current regulations to foster more wind-PV combined centralized generation in Brazil.

In 2017, the Federal government initiated a process of reform in the BES that is still in progress in 2019 and, perhaps, will contemplate some of the proposals cited. The EPE (2017a, 2018, 2019a) has been conducting some studies to understand the issue of hybrid power plants. Additionally, in 2019, ANEEL (2019a,b) opened a public consultation to begin the discussion on the future regulation of hybrid power plants in Brazil.

8.5. Investments in research, development, and human resource training

The realization of investments in R&D can generate national technology, know-how, and the adequacy of wind and solar PV technologies for the Brazilian tropical climate. This technological evolution could increase the efficiency of wind turbines and PV panels. This will increase the energy productivity of future wind, solar, and hybrid power plants.

In terms of human resources, there are still some shortages of technically qualified professionals to work in all areas of the productive chains of these renewable energy technologies. This can become a

Table 9
The SIN Expansion projections to 2023.

Extension of SIN Transmission Grid		
Higt-voltage	2017	2023
800 kV CC	4600 km	9636 km
750 kV	2683 km	2683 km
600 kV CC	12,816 km	12,816 km
500 kV	47,750 km	71,891 km
440 kV	6748 km	6969 km
345 kV	10,320 km	11,492 km
230 kV	56,471 km	69,997 km
Total	**141,388 km**	**185,484 km**

limiting factor for productive chains. However, the promising prospects of the job market have induced many technical schools and colleges to offer courses in renewable energy to meet this demand for skilled workers.

9. Conclusion

Renewable energy sources such as wind and solar power are proving strategic and assisting Brazil to expand and diversify its electricity matrix. Large scale wind energy in Brazil began in 2009, and hundreds of new wind farms have been installed since then. Large scale solar PV energy had an initial milestone in 2014, signalling that the technology can grow as much as wind energy.

This study demonstrated the great potential for the deployment of centralized wind-PV hybrid power plants. It was found that in the Brazilian semiarid northeast, there are highly favourable characteristics of high wind speeds and excellent solar irradiation conditions. In addition, there is a complementarity between these energy sources as well as with existing hydroelectric plants. However, the possibility of generation from centralized wind-PV hybrid energy systems is a relatively recent issue and is not foreseen in the current national regulatory.

A revision of the regulatory framework could provide more legal certainty and more investment opportunities with greater predictability of profitable return. The responsibility for conducting and approving the regulatory framework revision rests with the Federal government, via the executive and legislative authorities and ANEEL. This reform has been underway since 2017, and there is no expectation of when it will end.

The continuity and the regularity of energy auctions are the main factors that can encourage investments in wind and solar energy sources. The federal government could ensure predictability for the development and sustainability of production chains of these sources in the national energy market. Thus, the federal government should also include in the revision of the regulatory framework, guarantees to meet these factors. In addition, the government should create specific auctions for wind-PV HES projects to optimize the energy productivity from these resources; lower the costs of implementing power plants for investors; establish the necessary partnerships between both production chains to create hybrid plants.

Wind and solar energy generation can be complementary when both energy sources are combined. The development of hybrid power plants could provide another alternative for more security of energy supply. Hybrid plants reduce project implementation costs and would help maintain the high penetration of renewable energy in the Brazilian electricity matrix. In this way, the need for expansion and diversification of the national electricity matrix can be partially met by centralized wind-PV HES plants.

Two wind-PV HES pilot projects already exist in the Northeast. However, to develop these resources, it is necessary to have support from the Federal government in order to accelerate the feasibility and implementation of hybrid power plants. The data generated from the operation of these pilot projects can help the development of these types of plants. The pilot plants can serve as an initial reference for the Federal government to promote regulation improvements in the BES. The new regulatory framework being revised by the federal government should address the issues identified in this work.

Centralized wind-PV hybrid generation deserves further study. Issues such as wind power curtailment, solar intermittence, operational problems, HES optimization, and the limits of wind and solar power penetration in the national electricity matrix are relevant. Future research will support the feasibility of hybrid power plant projects.

Declaration of competing interest

The authors declare that they have no financial interests involved in this paper.

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