Potential for Wind and Solar Energy Hybrid Power Generation: The case of Brazil

José Alexandre F. de A. Santos*
Polytechnic School
Federal University of Bahia (UFBA), Salvador, Brazil
e-mail: alex_caeel@yahoo.com.br

Pieter de Jong, Ednildo A. Torres
Polytechnic School
UFBA, Salvador, Brazil
e-mail: pieterj@ufba.br; ednildo@ufba.br

Caiuby A. da Costa
Polytechnic Institute of Bahia (IPB)
UFBA, Salvador, Brazil
e-mail: caiuby@ufba.br

ABSTRACT

Developing new renewable energy is a key factor for the transition from fossil fuel-based global energy sources to alternative and diversified resources with lower environmental impacts. In this context, wind and solar photovoltaic energy have stood out significantly in recent years in terms of investments, research and expansion of the world's installed capacity. The objective of this work is to show the panorama of wind and solar energy in Brazil and demonstrate its undeveloped strategic potential for centralized combined generation of electricity. The methodology used is based on the analysis of official studies, research and thematic maps and the presentation of two pilot projects of hybrid power plants. The preliminary results indicate that there is great potential for the realization of future centralized hybrid generation, combining wind and solar photovoltaic energy sources in several regions of Brazil, especially in the Northeast Region, with an emphasis on the State of Bahia.

KEYWORDS

Wind Power, Photovoltaic Solar Power, Hybrid Energy System, Public Polices of Brazil.

INTRODUCTION

The industrial, technological and socio-economic development in the contemporary world has been steadily growing and diversifying, which demands greater availability of energy to sustain such human progress, especially electricity. Thus, society's need for energy is increasing in terms of supply and diversification to meet energy demand. In this context, renewable energy (RE) is an available solution.

The current power generation paradigm is based on centralized generation from large power plants with a single power source. However, in recent years there have been some initiatives aimed at the creation and study of Hybrid Energy System (HES), capable of using more than one energy source. Among RE, the combination of wind and photovoltaic (PV) solar energy,

* Corresponding author

when there is a complementarity, has emerged as a new interesting possibility of producing electricity from hybrid power plants.

In this context, the mains objectives of this work are: to show the panorama of wind and solar energy in Brazil; to present de current regulatory framework; to demonstrate the undeveloped potential for centralized combined power generation through hybrid power plants; and to present two case studies of Wind-PV Solar hybrid power plants.

MATERIAL AND METHODS

The methodology applied is descriptive, exploratory, qualitative and quantitative. This article presents a literature review, data and analyses of official studies, data and thematic maps of some national and international agencies and associations, academic researches and the presentation of two case studies of hybrid power plants. The hypotheses presented for Brazil are: (i) The existence of great expansion potential of wind and solar energy; (ii) Current national regulations are functional for wind and solar energy separately, but they don´t exist for hybrid power plants; (iii) The existence of a great potential to implement hybrid power plants; (iv) Need of regulatory framework enhancement in order to make wind-PV solar hybrid power plants more feasible.

LITERATURE REVIEW

According to [1], for reasons of planning and energy security, several countries seek to diversify their available energy bases to alternative sources. International Energy Agency (IEA)/International Renewable Energy Agency (IRENA) [2] and [3] commented that renewable energy is crucial to an energy transition, reducing the use of fossil fuels and enabling a low carbon economy. [4] commented that supply and demand for electric power in the world has been increasing and a significant increase in the installed capacities of wind and PV solar energy is also forecast. Due to the nature of omnipresence and ease of availability solar and wind energy systems are considered as the most promising of all alternate energy systems and use of solar and wind power has become very significant and cost effective [5].

[4, 6 apud 7] affirmed that wind and solar power are intermittent climate related energy sources. Climate related energy availability depends on several climatic variables, including solar radiation, wind velocity, air temperature, precipitation and river runoff. According to [8], wind and solar PV power plants could lead to conflicts with other generation technologies, because intermittent RE sources require more flexibility from the power system. [4] commented that, due to this nature, there is always a mismatch between the generated energy and the load demand. This will make the system less reliable and arises need for storage or other source in the system. According to [9], contrary to proclamations stating otherwise, the more RE that gets deployed, the more stable the system becomes. Wind and solar energies are very effective when used in large quantities in geographically spaced locations. So the law of averages yields a relatively constant supply. Thus, it is not one of variability or intermittency per se, but how such variability and intermittency can best be managed, predicted, and mitigated. [10, 11] commented e demonstrated the importance of improved wind power forecasting to reduce wind energy curtailment and grid operational costs.

A high level of renewable share in the power mix requires new paradigms and approaches from policy makers 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 operating [12 apud 13].Establishment of guidelines and policies to control the power mix share is an indispensable strategic action to ensure that the necessary technical requirements for load supply demands are adhered to [12 apud 14]. According to [12], 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 quality and reliability of electricity provision.

A HES is a system that, depending on the availability of local resources, uses more than one primary energy source, renewable or otherwise, to produce and supply electricity to a particular consumer, meeting a particular power quality standard. Primary sources hybridization, 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 [15]. According to [15] and Energy Research Company (EPE) [16], HES for electric generation are better known and applied in distributed generation for use in isolated communities. These communities are remote from the existing electricity transmission and distribution infrastructure, which makes the cost of connecting to the network prohibitive. [16] comments that hybrid power plants regulation has being studied in several countries, such as India, Australia, the United States, the United Kingdom and China, signalling new trends in markets and technologies. Hybrid power plants international experience demonstrates that while there are potential benefits, there are major difficulties, particularly commercial and regulatory, to implement. Most of the projects built so far depended on specific subsidies or regulations that favoured them, and in some of them such benefits were questioned or even judicialized [16].

[17, 18, 19] comment that the Brazilian Electricity Sector (BES) is characterized as a large hydrothermal system, since the majority of power generation is still supplied by hydropower plants (typically a cheap RE technology) and a minority of power is generated from thermal power plants of fuels fossil, biomass and nuclear which are more expensive.

As outlined by [20], RE 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. With this expansion, a large-scale market is born, allowing for systematic technological advances and a significant cost reduction of new technologies, making RE increasingly competitive and financially attractive. According to data of EPE [16, 21, 22], the wind and PV solar hybrid power generation can be an option interesting for energy supply in Brazil because present complementarities (seasonal and daily) in some Brazilian places.

In accordance with [23], solar and wind energy also presents strategic seasonal complementarity with hydroelectric generation. Such circumstances further support the potential of implementing the combined generation of these sources via hybrid power plants in the Brazilian Northeast region. According to [1, 23], the Northeast region of Brazil presents unique conditions of huge potential for the generation of both solar and wind energy coincidentally in several areas. In addition, there are many locations with a strategic complementarity (seasonal and daily) between wind and solar energy. This is conducive to a future with combined generation of wind and PV solar energy, which could significantly boost gains in terms of efficiency and productivity.

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 United States of America (USA) [11]. However, the spatial distribution of variable renewable power plants does not always reduce 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 climate related energy production is a challenge because one of the primary goals of electric utilities, is to balance supply and demand [5].

[22, 24] said a key point is the correct sizing of the relationship between installed capacities of wind verses PV solar power, to obtain optimized operation of a hybrid power plant which may share the same substation and point connection of transmission. According to [25] the ideal proportion of 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. However, if the wind and PV solar power plants share the same substation sized only to accommodate the wind power installed capacity, then between 0% to 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 [22].

WIND AND PHOTOVOLTAIC SOLAR POWER IN THE WORLD AND IN BRAZIL

Cost Comparison of Renewable Energies Sources

In 2018, according to IRENA [26] the global weighted-average Levelized Cost of Energy (LCOE) for commissioned onshore wind and PV solar energy projects were all competitive with the fossil-fuel cost range, even in the absence of financial support (Fig. 1).

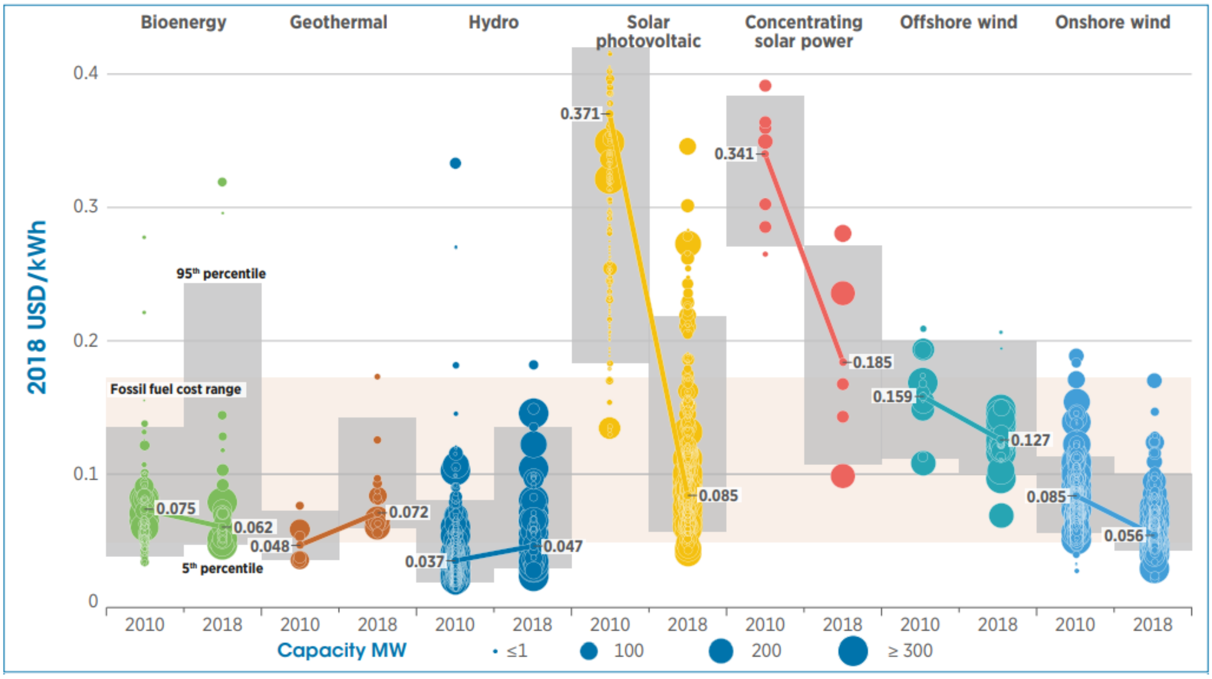

Fig. 1: Global LCOE (USD/kWh) of utility-scale renewable power generation technologies: 2010–2018 [26].

This increases the competitiveness of Wind-PV hybrid generation against electricity generation derived from fossil fuels sources. A hybrid power plant can have an LCOE optimization with a suitable project to combine wind and solar PV technologies.

Wind and Solar power in the World

In accordance with IEA [27], about 15% to 18% of global electricity may be provided by wind power in 2050, being originated from installed capacity about 2,300 GW to 2,800 GW of and avoiding emissions of up to 4.8 Gt CO_2/year. It is also suggested that wind power production could increase significantly, perhaps reaching 6,678 TWh annually, from 2,500 GW of installed capacity, in 2030 and up to 12,651 TWh of annual production, from 4,814 GW of installed capacity, in 2050. It is worth noting that these expectations didn´t take into account the Paris Agreement's Nationally Determined Contributions adopted at the Conference of the Parties (COP 21) in 2015, which encouraged the use of RE as part of actions to combat global warming. By 2050, the IEA [28] envisages PV technology to have 4,600 GW of installed capacity, producing more than 6,000 TWh (about 16% of the world's electricity generation) and avoiding the emission of up to 4.0 Gt CO_2/year. It´s worth noting that these expectations don´t take into account the influence of the Paris Agreement.

According to the Renewable Energy Policy Network for the 21st Century (REN21) [29], despite the global economic crisis of 2008, the global wind power installed capacity reached 591 GW and there was an average growth of 45.5 GW/year from 2008 to 2018. The global PV solar installed capacity reached 505 GW showing average growth of 45 GW/year from 2008 to 2018 (Table 1).

Table 1 - Global Wind and PV Solar power evolution generation: 2008–2018.

Energy	Global Installed Capacity (GW)										
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Wind	121	159	198	238	283	319	370	433	487	540	591
PV Solar	15	23	40	71	101	138	177	229	305	405	505

Wind and Solar power potentials in Brazil

Brazil has high potential for the electricity generation of wind and solar energy. The National Institute of Science and Technology for Climate Change (INCT–Clima) [30] estimated a gross wind power potential of up to 880.5 GW (with a possibility of production of 1,700 TWh/year) considering hub heights of 100 m, with 522 GW being technically feasible. According to [31], the Brazilian wind regime has excellent characteristics for electricity generation: good speed, low turbulence and good uniformity. 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 potential and wind regime (unidirectional and very consistent). According to data from Center for Electrical Energy Research (CEPEL) [32] and [30, 33], of the 880.5 GW of 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 potential in the state of Bahia is estimated to be 70.0 GW for hub heights of 100 m (Fig. 2 - A). The solar radiation in certain regions of Brazil rates are among the highest in the world. In 2001, the Solar and Wind Energy Resource Assessment (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 RE [34]. Studies by [35] (Fig. 2 - B) and [36] indicate that the high potential found in Brazil would allow high productivity for solar energy, especially in the Northeast region. According to [37], the State of Bahia presents excellent solar potential in the Northeast. According to [38, 39], the EPE conducted a technical study of Brazilian solar potential considering environmental restrictions among others. In this study, the highest solar radiation range (6,000 to 6,200 Wh/m^2*day) presents a solar PV potential for centralized generation of

307 GWp in already anthropogenic areas, with more than 90% of potential is located in Northeast region and 260 GWp in the Bahia.

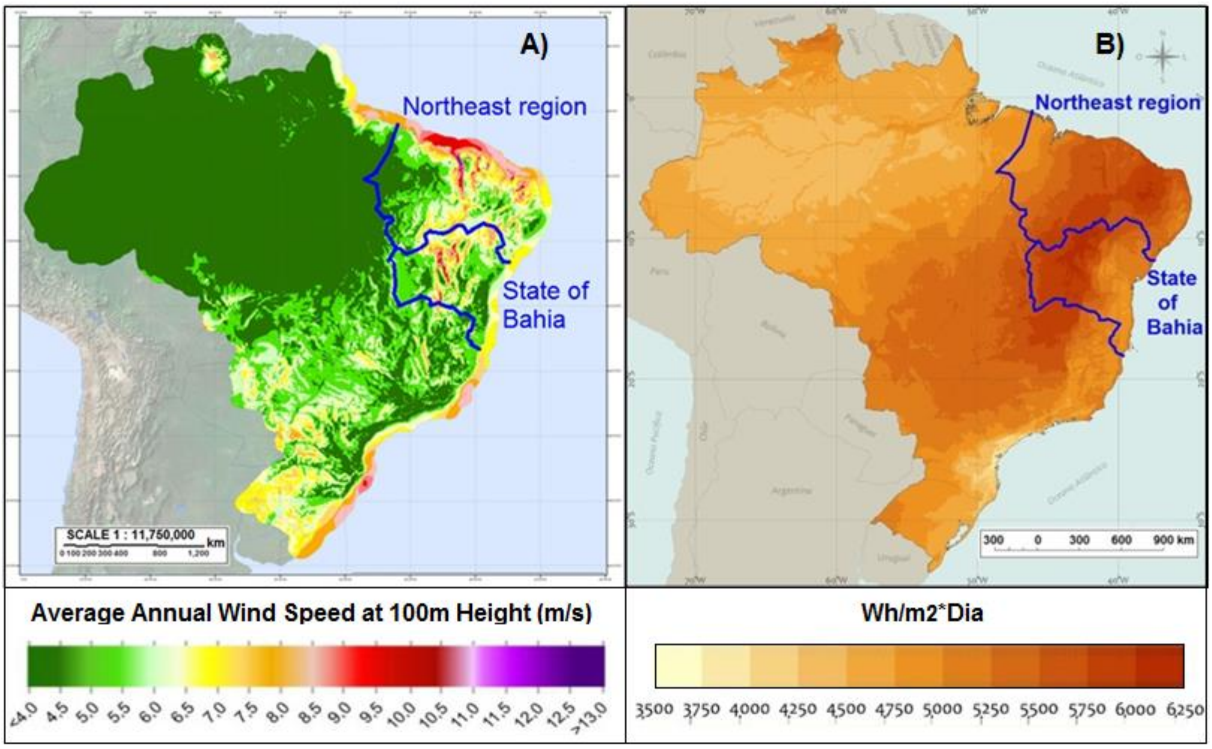

Fig. 2: A) Brazil wind potential at height of 100 m [32], adapted; B) Annual Average of Irradiation Daily Total in Latitude Inclined Plane in Brazil [35], adapted.

ELECTRIC POWER IN BRAZIL AND THE DEVELOMPMET OF WIND AND SOLAR ENERGY

In accordance with the National Energy Balance 2019 (BEN 2019) [40], the Brazilian energy mix and electricity matrix are also more renewable than the energy and electricity mix in other countries in the world (Fig. 3). Due to the predominance of hydroelectric energy in the national primary energy matrix, according to [41], there is enormous growth potential for the insertion of wind and solar energy in Brazil as a way of diversifying the RE contribution.

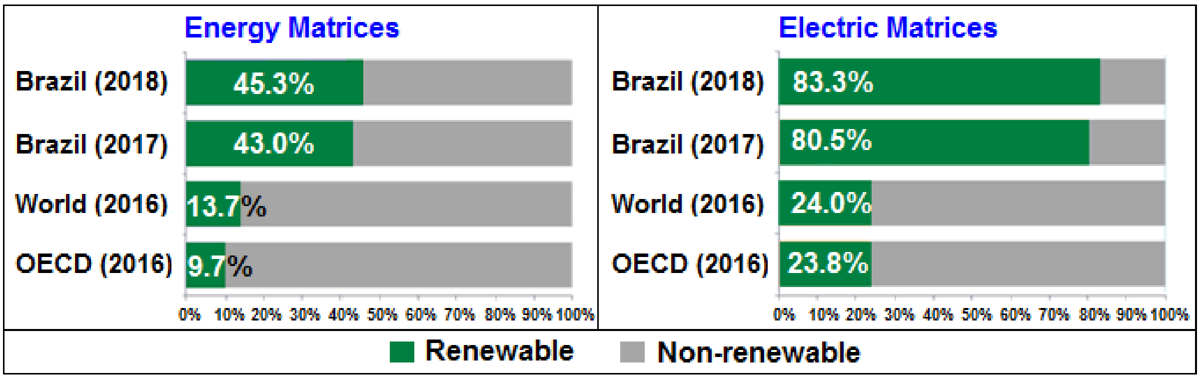

Fig. 3: Participation of RE in the Energy and Electricity mix of Brazil, Organisation for Economic Co-operation and Development (OECD) and the World [40]. Adapted.

In 2018, according to BEN 2019 [40], the domestic electricity supply was 636.4 TWh and the final consumption was 535.4 TWh and the largest share of the Brazilian electricity matrix is still hydraulic (66.6%), but the wind power share already makes up more than 7.6% (Fig. 4).

However, hydroelectric generation in Brazil, especially in the Northeast region, is vulnerable to climate change and prolonged periods of drought [42].

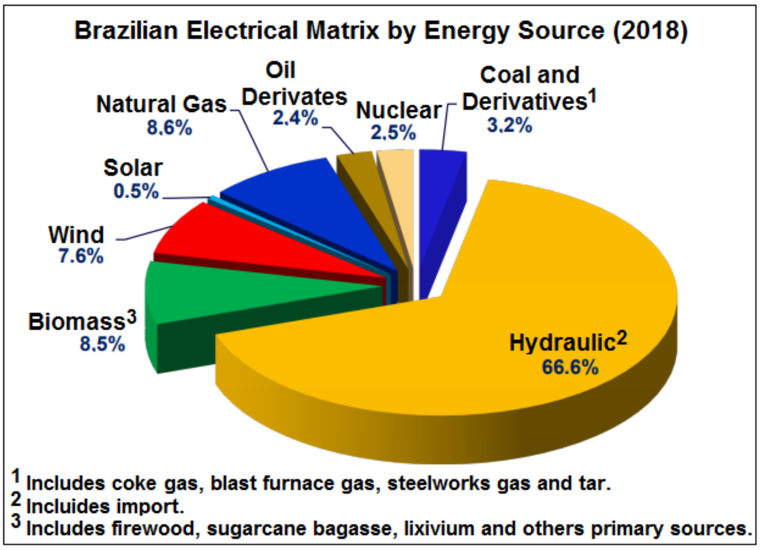

Fig. 4: Brazilian Electricity Matrix in 2018 [40]. Adapted.

Brazilian Electricity Sector

According to [17, 18, 19], initially, the BES was almost completely state-owned in its three parts: generation, transmission and distribution of electricity. However, from the 1990s a Liberal government was elected for 2 mandates (1995-1998 and 1999-2002) and the Federal government's public policies started to have a more liberal economic profile, which resulted in a reform in the BES's institutional model in 1997.

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 [43]. According to [44], this supply crisis urged for short, medium and long term solutions.

After the effects of crisis in 2001, the next government (elected for mandate 2003-2006), although not liberal, made a new sectorial reform with a liberal profile in 2004. The new regulatory frameworks created 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 sectorial reforms, even today BES is very dependent on hydropower generation.

Since 2012, Brazil has been experiencing a severe drought, especially in Northeast region, which has reduced from 81.8% in 2011 to 66.6% in 2018, the participation of hydropower energy in the Brazilian Electricity Matrix. Consequently, according to [44], there was a compulsory and prolonged increase in thermoelectric generation. This resulted in a reduction of the percentage of renewable generation (hydropower) and increased the electricity general cost. Such hydrological vulnerability evidences the need for diversification of energy sources and expansion of the generation capacity in Brazil. In this scenario, new RE, 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 [44]. The same considerations apply to solar energy, which is able to supplement the water source in Brazil.

National Interconnected Electricity System

According to National Electricity System Operator (ONS) [45], Brazil has a complex grid of TL (Transmission Lines) and substations, called SIN, which integrates 4 electrical subsystems in the country: South, Southeast/Midwest, North and Northeast (Fig. 5).

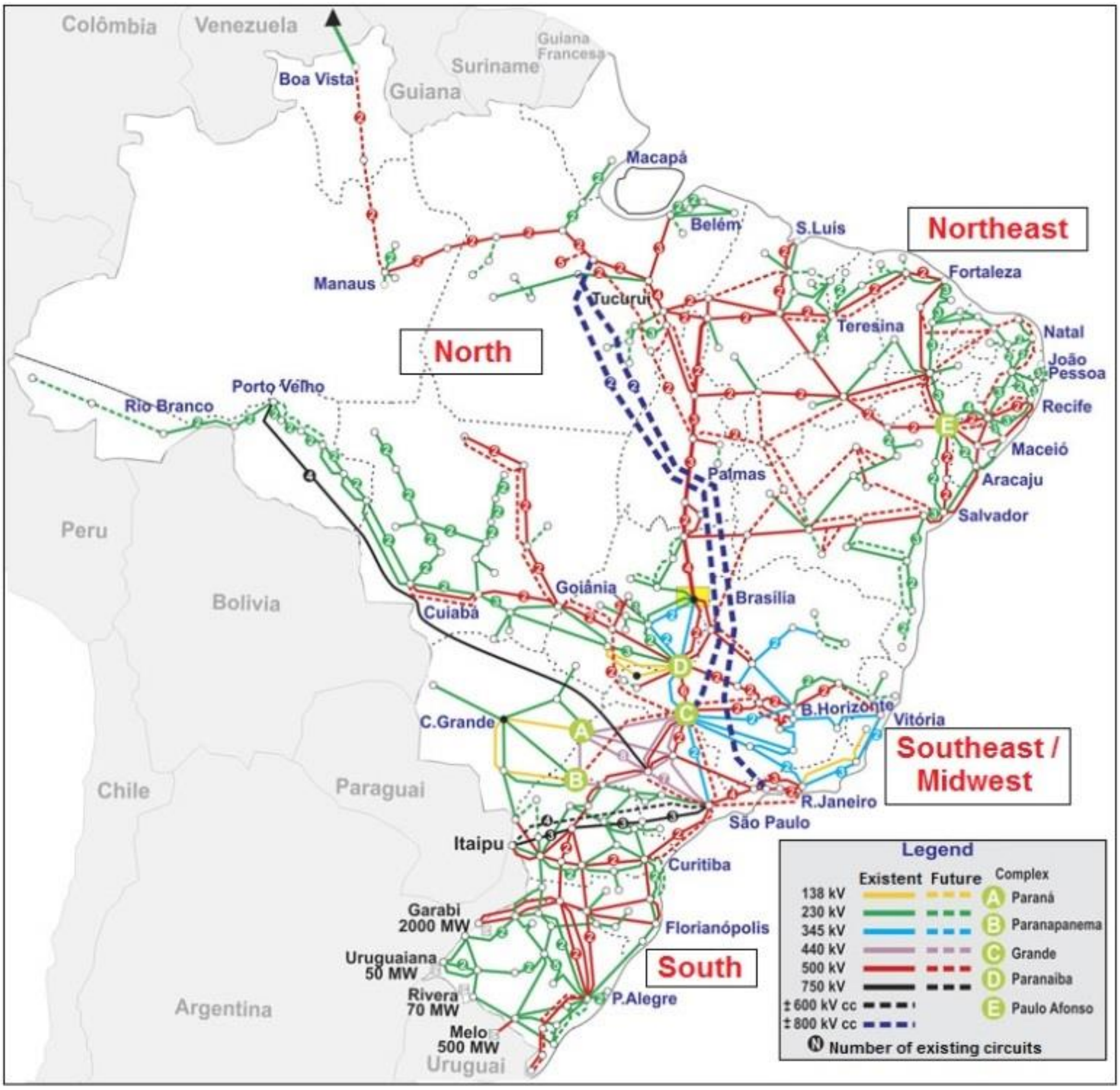

Fig. 5: SIN presented by ONS in 2017 [45]. Adapted.

These 4 subsystems exchange energy between each other via SIN, bringing balance to the subsystems, and the overall management is done by ONS. SIN has a great extension covers the majority of the nation, but is currently overloaded or near the limit of operation in some regions. According to [46], the Northeast region is an example this situation. SIN expansion is also carried out by transmission lines auctions, but these are independent of the generation auctions. Sometimes TL auctions aren´t 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.

Regulatory Framework

The main references of centralized power generation regulatory framework that influenced and influence the development of wind energy in the BES are described in the Table 2.

Table 2. Regulatory Framework of BES in Brazil.

References of Legal Framework	Date / Reference	Definition
Resolution Nº 24 of the Assembly of Energy Crisis Management: (Emergency Program for Wind Energy - PROEÓLICA)	07/05/2001 [47]	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)	04/26/2002 [48]	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 [49]	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	07/30/2004 [50]	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 [51]	Regulates the contracting of reserve energy that is dealt with in previous laws, changes some previous laws and gives other measures.

According to [52], there was a trend in the Brazilian political scenario towards increasing the share of new RE, other than large hydropower, in electricity generation. This central policy was achieved through Program for Alternative Sources of Electricity (PROINFA), which defined stages and mechanisms to promote biomass, Small Hydro Power Plant and wind energy. [53] commented what even after the creation of PROINFA [48], 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 and 2008, BES was reorganized by Law Nº. 10,848/2004 [49], Decrees Nº 5,163/2004 [50] and Nº 6,353/2008 [51]. This law defined the current model of commercialization of electricity in Brazil. There is the creation 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. Brazilian Chamber of Electricity Trading (CCEE) is responsible for holding the energy auctions and the contracts.

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 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 [54]. 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 greenhouse gas (GHG), thermoelectric power plants were the main winners in electricity auctions held until 2009 [55]. Still according to these authors, the official energy plan for 2030, prepared for the Brazilian government by the EPE, forecast a relative increase in thermal generation using natural gas, coal and nuclear energy. However, the latest official energy plans of EPE [56, 57] revised the targets for new renewable energies and pointed to a much greater growth of wind energy to 2050. EPE [58] was created in 2004 and elaborates the National Energy Plan 2050 (PNE 2050) and Decennial Energy Plans. PNE 2050 [56] guides all national energy planning and forecasts growth in annual average electricity consumption of approximately 3.2%, which would lead to a total consumption of 1,624 TWh in 2050. In this context, generation of wind and PV solar electricity could significantly contribute to supply the total power demand of 1,624 TWh estimated until 2050.

Wind and Solar Centralized Power Generation Expansion with Brazilian Auctions

The wind and PV solar power expansion by Brazilian auctions have been success story. According to [59], the expansion of installed capacity in Brazil is ongoing (Fig. 6).

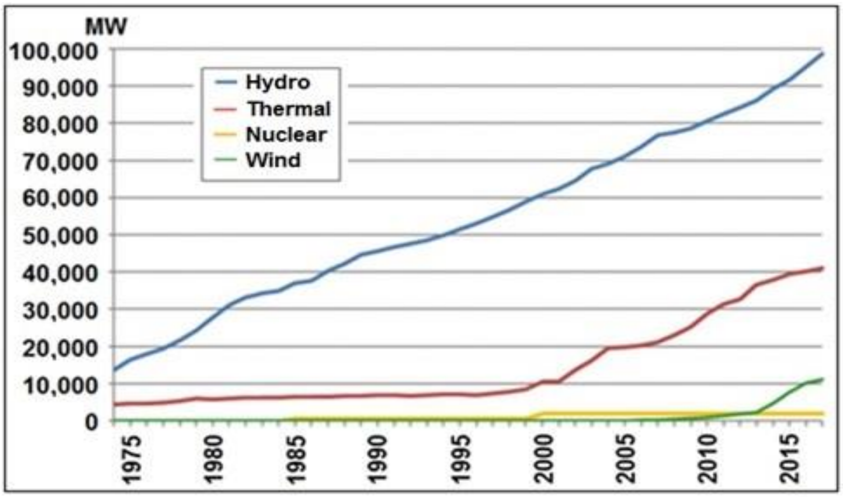

Fig. 6: Brazilian installed capacity by source: 1974–2016 [59].

[60, 61] reported that wind power has gained prominence since 2009. Until 2013, PV solar power was basically for distributed generation. In 2014, the Federal government started to conduct energy auctions for contracting of PV solar centralized generation. Substantial wind and solar power capacity was 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 for future projects will help maintain 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 Brazilian Wind Energy Association (ABEEOLICA) [62], 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

Northeast and South regions (Fig. 7). According to [57, 63], 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%.

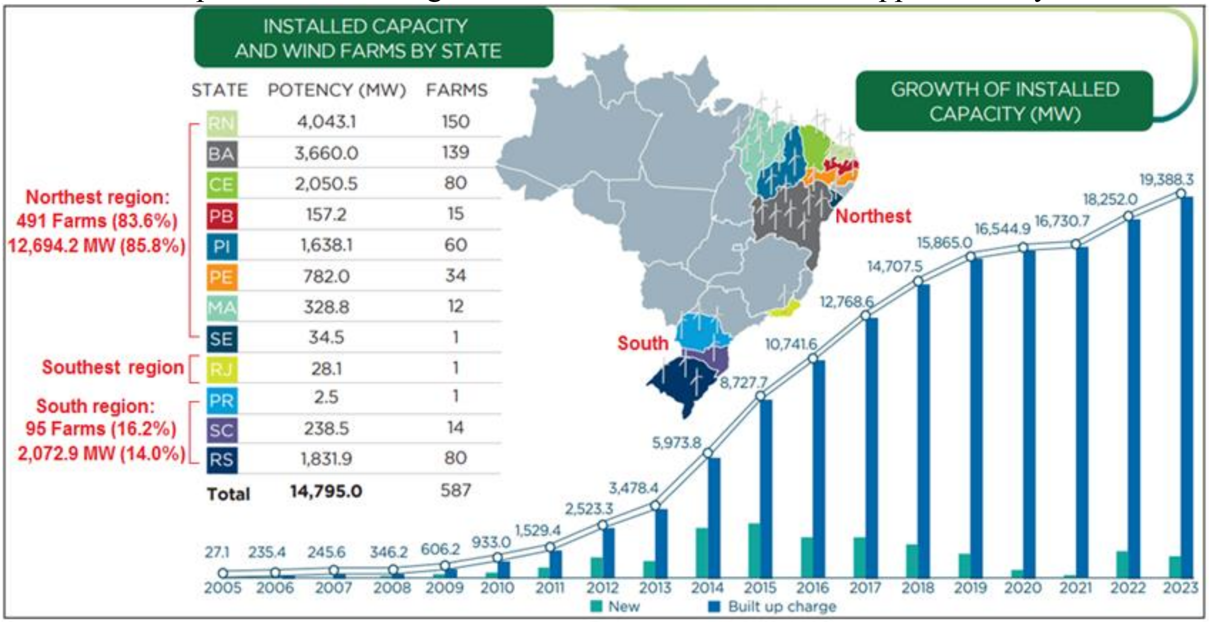

Fig. 7: Yearly cumulative installed capacities of wind power generation in Brazil: 2005–2023 [62]. Adapted.

In accordance with [64, 65] and Ministry of Mines and Energy (MME) [66] of Federal government, contracting of PV solar projects took place in the auctions from 2014 until 2018 (Table 3). [67] reports that PV installed capacity in Brazil grew from 0.015 GW in 2014 to 2.3 GW in 2018, representing an average growth 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 [57]. Brazilian Solar Energy Association (ABSOLAR) [68] 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.

Table 3 - Contracting of Solar Projects.

Year	Month	Nº of Projects	Capacity Installed		Contrated Energy	Supply Beginning
			(MW)	(MWp)	(MWm)	
2014	Oct.	31	889.7	1,048.0	202.3	2017
2015	Aug.	30	833.8	1,044.0	231.5	2017
2015	Nov.	33	929.3	1,115.9	245.0	2018
2017	Dec.	20	574.0	790.6	172.6	2021
2018	Apr.	29	806.6	1,032.5	228.5	2021
Total		143	4,033.4	5,031.0	1,079.9	

ENERGY COMPLEMENTARITY

According to [69], when comparing the maps of the Northeast region, shown in Fig. 2, several areas with high solar radiation and good wind energy potential overlap. Studies by [22, 43, 70] indicated the Northeast presents the highest levels of complementarity between wind and solar energies. In addition, according to [23], 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.

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 SIN. However, the trend is for this scenario to be gradually reversed with the insertion of wind and PV solar projects, which are seasonally complementary to the region's hydroelectric power plants. 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. In accordance with [11], 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.

According to Brazilian National Electricity Agency (ANEEL) [71], due to the energy complementarity between solar and wind sources in some places in the Northeast region (Fig. 8), the implementation of hybrid power plants can generate gain in relation to the use of the SIN. However, it would be necessary have curtailments in some periods, when the total injected power was greater than the total capacity contracted.

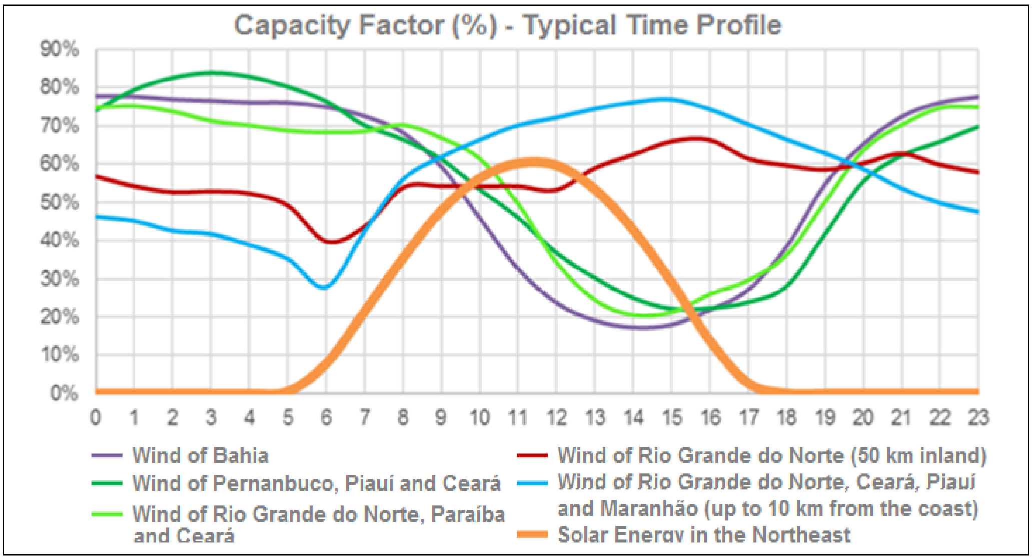

Fig. 8: Electricity generation in the Northeast [71]. Adapted.

Since 2017, EPE conducts studies and discussions on the issue of hybrid power generation for Brazil. [21] states that the discussion about the possibility of producing power with mills using more than one primary source (hybrid power plants) is gaining importance, where several proposals are gaining visibility and there are some concrete initiatives in project development and implementation. In Brazil, this has gained relevance with the claim that the complementarity between certain sources (e.g. wind and solar), would enable a better use of the existing and planned transmission system.

In 2017, [22] conducted a study to evaluate the daily complementarity for generation from wind-PV solar hybrid power plants at 5 different locations in the Northeast (Fig. 9): 3 locations in the state of Bahia, 1 location in the state of Rio Grande do Norte and 1 location in a region covering the states of Piauí, Pernambuco and Ceará. In this study, locations 2 (Caetité), 3 (Brotas de Macaúbas) and 5 (frontier region between Piauí, Ceará and Pernambuco) present the best profiles of daily solar-wind complementarity. In addition, this study concluded that 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-PV solar HES. These hybrid energy pilot projects are located in Tacaratu (Pernambuco) and in Caetité/Igaporã (Bahia) (Fig. 9)**.**

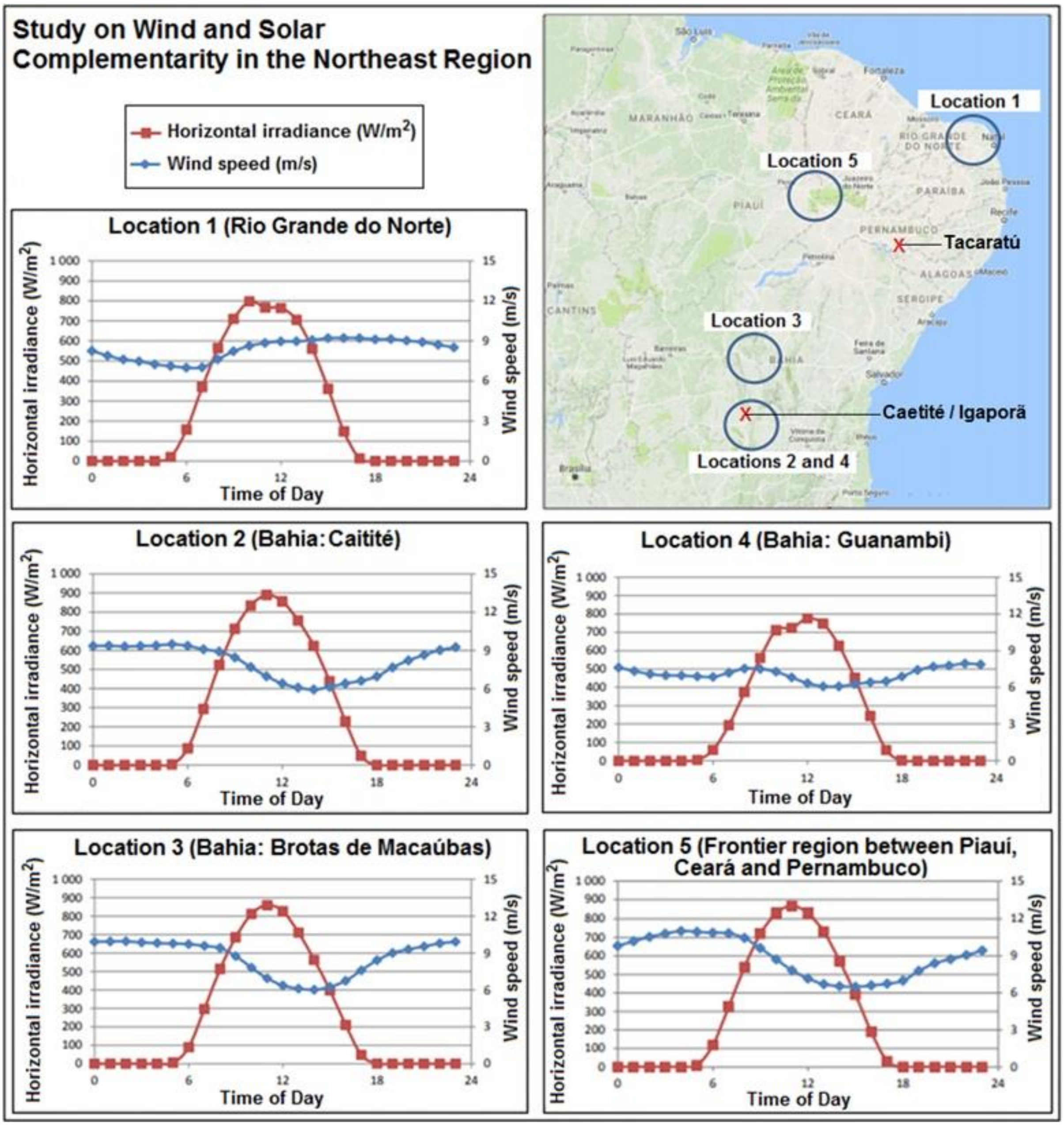

Fig. 9: Five case studies of energy complementarity profiles for electricity generation in the Northeast and the HES in Tacaratu and Caetité/Igaporã [22]. Adapted.

HYBRID ENERGY SYSTEMS IN BRAZIL

Until 2019, there were no specific regulations in the regulatory framework of sector electricity Brazilian or public policies about hybrid power centralized generation. Thus, there are no hybrid generation auctions and that each energy source is treated separately by the current regulation and is contracted via specified and respective auctions. There is a possibility of creation auctions of hybrid power plant with regulatory framework review in progress. However, there are some pilot projects for centralized combined generation have been implemented, such as the placement of floating PV panels in the lake of Balbina [72] and the

Sobradinho hydroelectric reservoir, located in the states of Amazonas and Bahia, respectively. According to [73], Eletronorte and CHESF are forecasting investments totalling R$ 114 million (about US$ 33.8 million) for these two projects, which should start operating in 2019.

In accordance with [74, 75], the use of HES for electricity generation allows operational benefits for generating installations. These benefits would be: i) Increase of the average energy produced by the system via the complementarity (seasonal and daily) of energy sources. E.g. in Bahia solar supply periods are during low wind production periods and vice versa [25]; ii) Higher efficiency of the system; iii) Sharing of the electrical infrastructure such as transmission links and substations [22]; iv) Reduction of deployment and operating costs.

According to [69], there are only two pilot projects of Wind-PV hybrid power plants in Brazil: one located in Tacaratu (Fig.10 – A), owned by Enel Green Power Brazil (EGPB), and another located in Caetité and Igaporã (Fig.10 – B), owned by Renova Energia. EGPB [76] is an Italian company that operates with several RE sources in Brazil. Renova Energia [77] is a company of Brazilian origin with several projects in the RE sector.

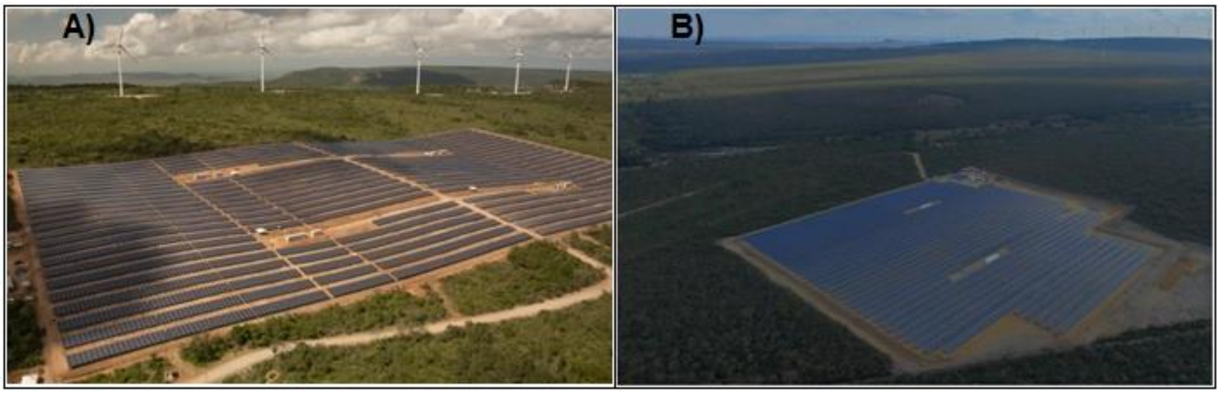

Fig. 10. A) HES in Tacaratu [76]; B) HES in Caetité/Igaporã [77].

Case Study 1 – Hybrid Energy System of Tacaratu

According to [75, 78], the EGPB implemented in Tacaratu municipality (Pernambuco) three wind power plants with total of 80 MW, in 2014, and more two PV solar power plants totalling 11 MWp in 2015 (Table 4). It has been prominent in recent energy auctions. The hybrid power plant was implemented in stages, where the wind farm (Fontes dos Ventos), was first contracted in 2011 via auction. Then, PV power plants (Fontes Solar) were contracted in 2013, in the regional auction of the Pernambuco.

Table 4: Description of 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			91 MW	45.3 MWmed	
Investment			U$ 148 millions		

According to data of ONS [79] and National Renewable Energy Laboratory (NREL) [80], the annual generation (Fig. 11) and the hourly generation (Fig. 12) of the PV plants and the wind farm confirms the complementarity of wind and solar energy resources at Tacaratu HES.

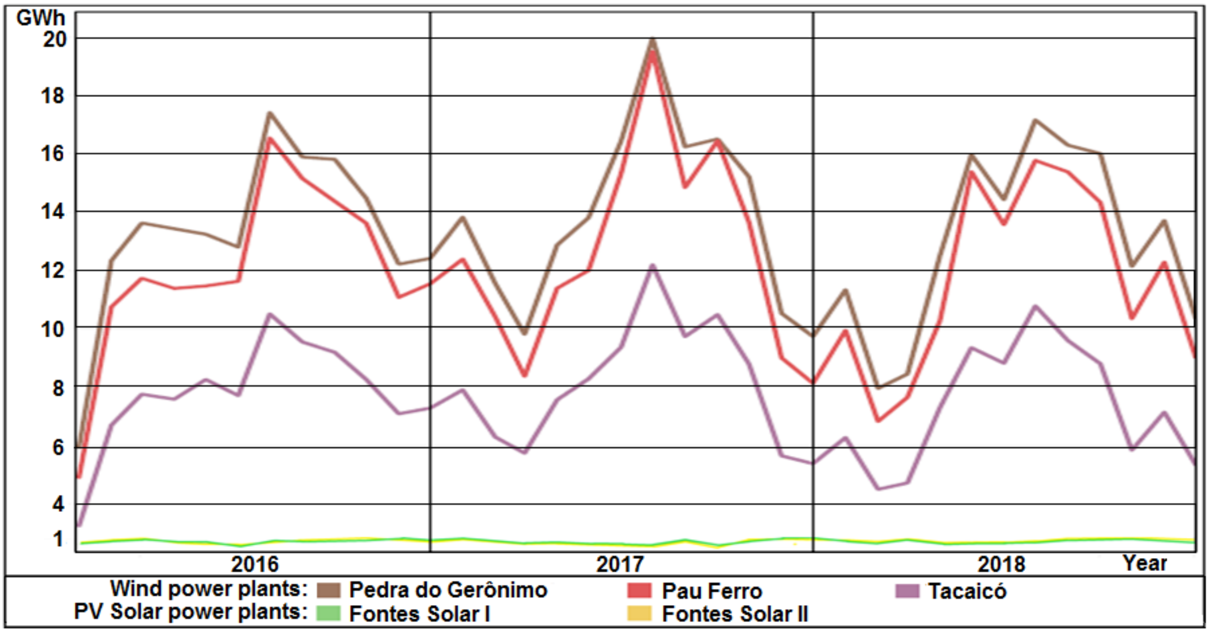

Fig. 11. Annual Power generation of Tacaratu: 2016–2018.

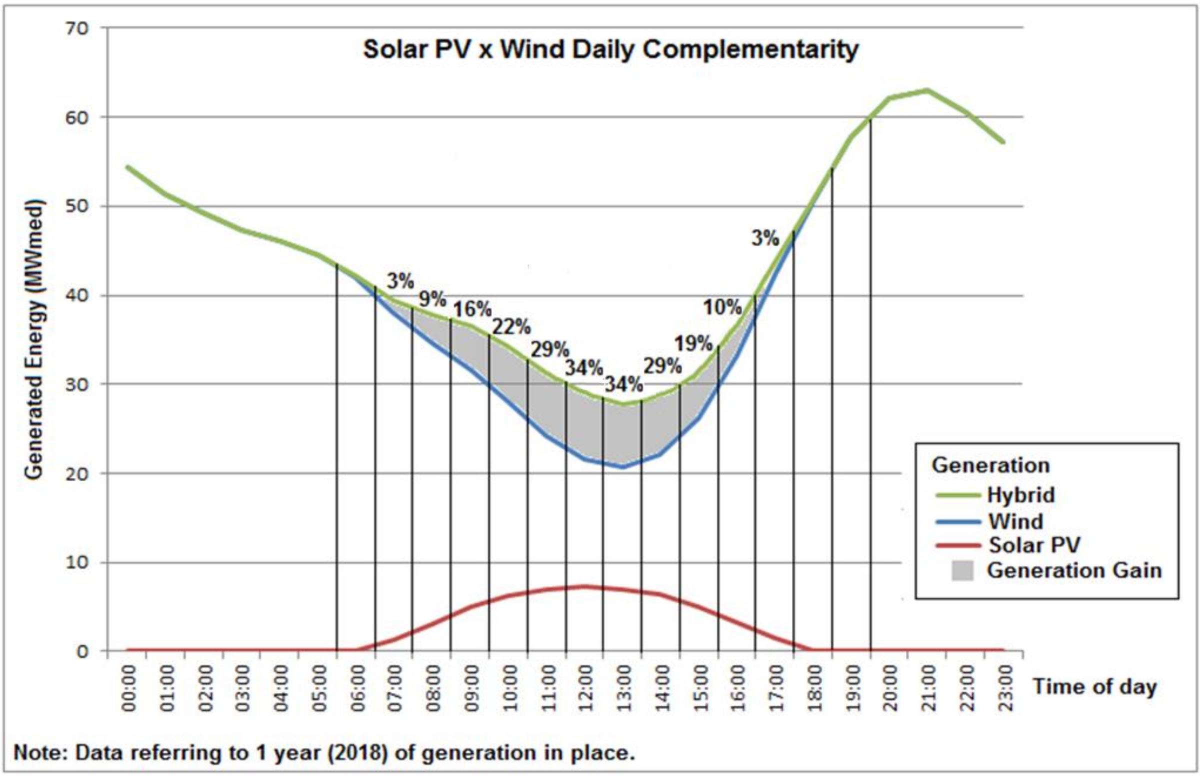

Fig. 12. HES Gain in Tacaratu in 2018.

This Tacaratu pilot project is an example of a wind farm that was hybridized with the addition of a PV solar 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% PV solar power. The main positive result of this hybrid power plant is increases of more than 20% above solely wind generation between 10:00h and 14:00h.

Case Study 2 - Hybrid Energy System of Caetité and Igaporã

According to [75, 81], Renova Energia started work on the wind-PV solar HES project in 2015. 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 night time wind power productivity, besides the existence of seasonal complementarity. [75] informed the hybrid power project has a total installed capacity of 26.4 MW (21.6 MW wind power and 4.8 MWp PV solar) (Table 5). [75] said that 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 construction works started in 2015 and the plant went into operation in 2016.

Table 5 – Description of HES in Caetité/Igaporã.

Caetité/Igaporã Hybrid Power Plant					
Power plants			Installed Capacity	Guaranteed Energy	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			26.4 MW	——	
Investment			U$ 32 millions		

[82] reported that: between 00:00h and 08:00h, winds are strong while there are only a few hours of weak sunlight, and between 11:00h and 15:00h, there is consistent sunlight while winds are weak (Fig. 13).

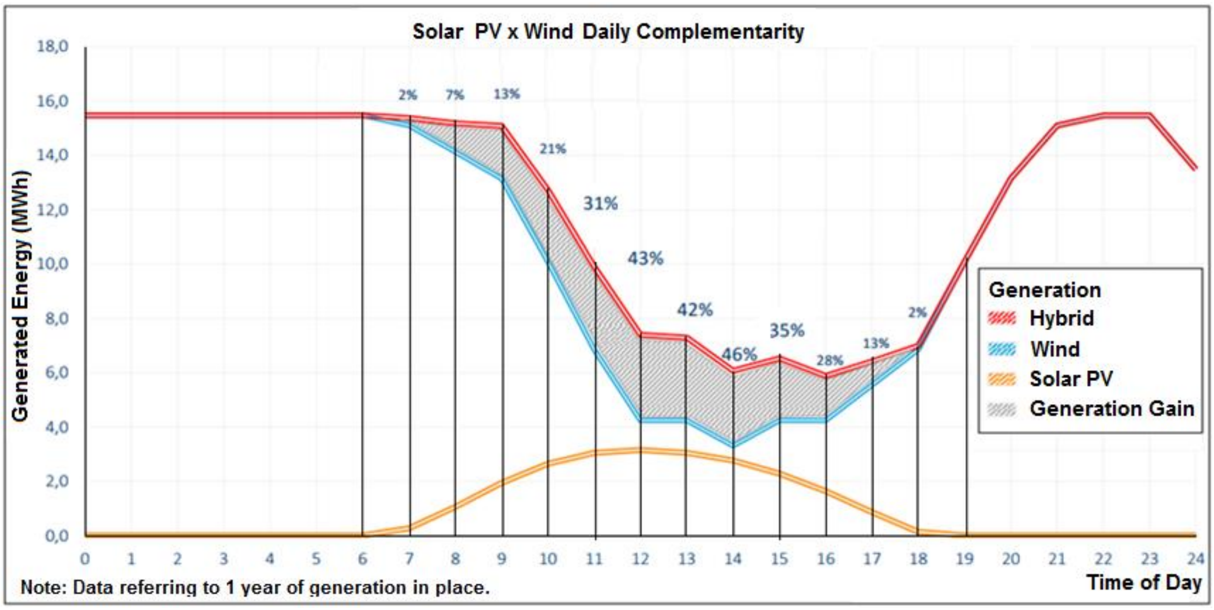

Fig. 13: HES Gain in Caetité/Igaporã [82]. Adapted.

During the winter there was more wind generation and during the summer there is more solar generation. After one year of operation, it was found that, between 11:00h and 15:00h, the hybrid generation presented increases of more than 30% above solely wind generation.

According to [75, 83], there is then a periodic complementarity between wind speeds and solar radiation in the region of Caetité/Igaporã, which allows predicting the variability over time. Without considering the potential effects of climate change, there are a 46-year periodicity of the wind and solar series, where a lag of 15 years approximately was observed between them. Normally, the production reduction of one source is compensated by the increase of the other one. So, there is evidence a hybrid product of greater value, able to guarantee a product more stable and less vulnerable to the climatology variability.

The Caetité/Igaporã plants 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% PV power. The large majority of this hybrid plant is made up of wind power capacity, however, the solar plant enables a significant productivity gain in electricity generation.

VIABILITY OF CENTRALIZED GENERATION FROM COMBINED WIND-SOLAR HYBRID POWER PLANT

The complementarity conditions (seasonal and daily) of solar and wind energy potentials at the same geographic locations (Fig. 2, 8 and 9) are strategically favourable for wind-PV solar centralized combined 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. However, Tacaratu was an operational and commercial junction strategy and Caetité/Igaporã was a R&D project, both of which were punctual 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 by [69] pointed to other important conditions that should be met for viability of centralized combined generation. These conditions are: i) Regularity and Annual Predictability of Contracting, ii) Appropriate Funding Conditions, iii) Investments in Transmission Infrastructure, iv) Favourable Regulation, Investments in Research and Development (R&D) and Human Resources (RH) Training. Thus, Federal government should adopt new public policies to enable these conditions.

Regularity and Annual Predictability of Contracting

[1, 60] and the Federal government agree that a minimum contracting of 2,000 MW/year of wind farms would be required by way of auctions to give economic viability and sustainability to the wind power productive chain. ABSOLAR [84] said that a minimum contracting of 1,000 MW/year of PV solar power plants would be required through auctions to enable the implementation of a PV solar productive chain in Brazil. However, in 2017, ABSOLAR requested a minimum contracting of 2,000 MW/year.

Annual average wind power contracted in Brazil, from 2009 until 2015, was higher than 2,000 MW/year and the annual average PV solar energy contracting from 2014 until 2015 was over 1,000 MW/year. In 2016, there were no energy auctions, and in 2017 and 2018 there was resumption in the contracting of energy projects, but below the previous averages.

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

Appropriate Funding Conditions

The appropriate availability of financing for wind and PV solar enterprises and productive chains is fundamental to support the continuous expansion of electricity generation within the expected periods and 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 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 EGP has done this with its solar projects.

Investments in Transmission Infrastructure

There is a great need for new investments for the expansion of SIN in Brazil. [85] created the 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. [86] presents the prospects for expansion of the SIN to 2023 in Table 6.

Table 6 – SIN Expansion projections to 2023.

Extension of SIN Transmission Grid		
Tensão	2017	2023
800 kV CC	4,600 km	9,636 km
750 kV	2,683 km	2,683 km
600 kV CC	12,816 km	12,816 km
500 kV	47,750 km	71,891 km
440 kV	6,748 km	6,969 km
345 kV	10,320 km	11,492 km
230 kV	56,471 km	69,997 km
Total	141,388 km	185,484 km

Favourable Regulation

Federal government has often been erratic and inconsistent with respect to the complexity of Brazil's energy sector, as it has promoted changes of laws and sectorial 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, 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 improvements and consolidation of regulations in an appropriate, transparent, coherent and predictable manner, providing legal security for long-term investments.

In relation to current legislation and auctions, the procedures and regulations are still independent for wind and PV solar projects, that is, each of these sources is contracted separately in the same auction or in different auctions. In this way, existing hybrid projects have been developed as a result of the union of separate projects (Tacaratu) or of R&D project (Caetité/Igaporã).

Improvements in the auction process would be a crucial element in order to accommodate purpose built "hybrid power plants" projects. To that end, contracting periods could be standardized to 25 years, reconciling the minimum lifetimes of wind and PV solar 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´s 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 MME [87, 88, 89, 90] initiated a process of reform in the BES that is still in progress in 2019 and, perhaps, will contemplate some of the proposals cited. EPE [16, 21, 22, 23] has been conducting some studies to better understand the issue of hybrid power plants. In 2019, ANEEL [71, 91] opened a public consultation to begin the discussion on the future regulation of hybrid power plants in Brazil.

Investments in Research and Development and Human Resources Training

The realization of investments in R&D can generate national technology, know-how and the adequacy of wind and PV solar technologies to 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 HR, there are still few technically qualified professionals to work in all areas of the productive chains of these RE technologies. This can become a limiting factor for productive chains. However, the promising prospects of the job market have induced many technical schools and colleges to offer courses in RE to meet this demand for skilled workers.

CONCLUSIONS

RE 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, supported by an almost completely local production chain. Large scale PV solar energy had an initial milestone in 2014, signalling that the technology can grow as much as wind energy. The installed capacities in Brazil was 14.4 GW wind power and 2.3 GW PV Solar power in 2018, but exist potentials of 522 GW wind power (heights of 100 m) and 307 GWp PV solar power to be explored in the future. However, the possibility of centralized combined wind and PV hybrid energy systems is a fairly recent issue in Brazil. To date neither public policies exist nor is there a provision in the regulatory framework for hybrid power plants.

This study demonstrated the great potential for a wider deployment of centralized wind-PV hybrid power plants. It was found that in the Brazilian Northeast there are extremely 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. 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 information that generated from the operation of these pilot projects can help the BES, EPE and ANEEL. They can serve as an initial reference for the Federal government to promote public policies and regulation improvements in the electricity sector.

New public policies should be created by the Federal government to answer identified conditions: regularity and annual predictability of contracting; appropriate funding conditions; investments in transmission infrastructure; favourable regulation; investments in R&D and HR training.

The continuity and the regularity of energy auctions are the main factors that can encourage investments in wind and solar energy sources. They can ensure predictability for development and sustainability of production chains of these sources in the national energy market. Thus, the Federal government should create a new policy in the regulatory framework review that guarantees the attendance of these factors. In addition, the government should create specific auctions for wind-PV HES projects to: optimize the energy productivity of these sources; lower the costs of implementing power plants for investors; establish the necessary partnerships between these both production chains to create hybrid plants.

The strategic opportunity of centralized wind-PV hybrid generation deserves further study. Issues such as wind and solar intermittence, operational problems, HES optimization and the limits of wind and solar power penetration in the national electrical matrix are important. More research will improve the feasibility of hybrid power plant projects in the future. Wind and solar energy generation as well as the economic, social and environmental benefits are greater when both energy sources are combined.

The development of more 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 RE 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.

ACKNOWLEDGMENT

This study was financed in part by the Coordination of Improvement of Higher Education Personnel in Brazil (CAPES) – Finance Code 001.

NOMENCLATURE

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)
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)
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
MME - Ministry of Mines and Energy (Ministério de Minas e Energia)
OECD - Organisation for Economic Co-operation and Development
ONS - National Electricity System Operator (Operador Nacional do Sistema Elétrico)
PET - Transmission Expansion Program (Programa de Expansão da Transmissão)
PELT - Long Term Expansion Plan (Plano de Expansão de Longo Prazo)
PNE 2050 - National Energy Plan 2050 (Plano Nacional de Energia Elétrica 2050)
PROINFA - Program for Alternative Sources of Electricity (*Programa de Incentivo às Fontes Alternativas*)
PV - Photovoltaic
R&D - Research and Development
RE - Renewable Energy
REN21 - Renewable Energy Policy Network for the 21st Century
SWERA - Solar and Wind Energy Resource Assessment
SIN - National Interconnected Electricity System (Sistema Interligado Nacional),
TL - Transmission Lines

REFERENCES

1. SANTOS, J. A. F. A.. *Planejamento energético para a Bahia em 2050: cenários e discussões relacionados às energias renováveis para geração de eletricidade.* Tesis, Federal University of Bahia (UFBA), Salvador, 2015. [online]: <https://repositorio.ufba.br/ri/handle/ri/19397>.
2. IEA (International Energy Agency); IRENA (International Renewable Energy Agency). Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System. IEA, Paris, 2017. [online]: <https://www.irena.org/DocumentDownloads/Publications/Perspectives_for_the_Energy_Transition_2017.pdf>.
3. PAIVA, I.; CASTRO, N.; CLARO, V. M.; HUBACK, V.; CABRAL, S.; SARNEY, M.. *Mudanças Climáticas e Energia Renovável: Desafios e Oportunidades do Setor Elétrico no âmbito dos compromissos pré-2020 da UNFCCC. V Encontro Latino-Americano de Economia da Energia* (V ELAEE), Rio de Janeiro, 2017. [online]: <http://security.ufpb.br/gesene/contents/publicacoes/mudancas-climaticas-e-energia-renovavel-desafios-e-oportunidades-do-setor-eletrico-no-ambito-dos-compromissos-pre-2020-da-unfccc>.
4. IEA. Medium-Term Renewable Energy Market Report 2014 – Market Analysis and Forecasts to 2020. IEA, Paris, 2014a. [online]: <https://www.iea.org/Textbase/npsum/MTrenew2014sum.pdf>.
5. MAHESH, A.; SANDHU, K. S.. Hybrid wind/photovoltaic energy system developments: Critical review and findings. Renewable and Sustainable Energy Reviews, Vol. 52, p. 1135–1147, 2015. [online]: <http://dx.doi.org/10.1016/j.rser.2015.08.008>.
6. ENGELAND, K.; BORGA, M.; CREUTIN, J. D.; FRANÇOIS, B.; RAMOS, M. H.; VIDAL, J. P.. Space-time variability of climate variables and intermittent renewable electricity production–A review. Renewable and Sustainable Energy Reviews, v. 79, p. 600-617, 2017. [online]: <https://doi.org/10.1016/j.rser.2017.05.046>.
7. MORIARTY, P.; HONNERY, D.. Intermittent renewable energy: the only future source of hydrogen? International Journal of Hydrogen Energy, v. 32, p. 1616-1624, 2007, [online]: <https://doi.org/10.1016/j.ijhydene.2006.12.008>.

8. BROUWER, A. S.; BROEK, M. V. D.; SEEBREGTS, A.; FAAIJ, A.. Impacts of large-scale Intermittent Renewable Energy Sources on electricity systems, and how these can be modelled. Renewable and Sustainable Energy Reviews, v. 33, p. 443-466, 2014, [online]: <https://doi.org/10.1016/j.rser.2014.01.076>.
9. SOVACOOL, B. K.. The intermittency of wind, solar, and renewable electricity generators: Technical barrier or rhetorical excuse? Utilities Policy, Vol. 17, p. 288-296, 2009. [online]: <https://doi.org/10.1016/j.jup.2008.07.001>.
10. WANG, Q.; WU, H.; FLORITA, A. R.; MARTINEZ-ANIDO, C. B.; HODGE, B. M.. The value of improved wind power forecasting: Grid flexibility quantification, ramp capability analysis, and impacts of electricity market operation timescales. Applied Energy, v. 184, p. 696-713, 2016, [on line]: <https://doi.org/10.1016/j.apenergy.2016.11.016>.
11. DE JONG, P.; DARGAVILLE, R.; SILVER, J.; UTEMBE, S.; KIPERSTOK, A.; TORRES, E. A.. Forecasting high proportions of wind energy supplying the Brazilian Northeast electricity grid. Applied Energy, v. 195, p. 538–555, 2017a. [online]: <https://doi.org/10.1016/j.apenergy.2017.03.058>.
12. DESTER, M.. Insertion of renewable energy sources into Brazil's power mix. Energy Sources, Part B: Economics, Planning, and Policy, vol. 12, p. 63-69, 2017. [online]: <https://doi.org/10.1080/15567249.2015.1017670>.
13. TWIDELL, J.; WEIR, A.. Renewable Energy Resources. New York: Taylor & Francis, 2006. [online]: <https://doi.org/10.4324/9780203478721>.
14. DOUKAS, H.; PATLITZIANAS, K. D.; KAGIANNAS, A. G.; PSARRAS, J.. Energy Policy Making: An Old Concept or a Modern Challenge? Energy Sources, part B, vol. 3, p. 362–371, 2008. [online]: <https://doi.org/10.1080/15567240701232378>.
15. BARBOSA, C. F. O.; PINHO, J. T.; GALHARDO, M. A. B.; PEREIRA, E. J. S.; *Conceitos sobre Sistemas Híbridos de Energia para Produção de Eletricidade. VI Congresso Brasileiro de Energia Solar* (VI CBENS), Belo Horizonte, 2016a. [online]: <http://www.abens.org.br/CBENS2016/anais/anais/index.htm>.
16. EPE (*Empresa de Planejamento Energético*). *Estudos de Planejamento da Expansão da Geração: Usinas Híbridas no Contexto do Planejamento Energético*. Nº EPE-DEE-NT-029/2019-r0. Rio de Janeiro, 2019a. Available at: <http://epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-386/EPE_DEE_NT_029_2019_r0_%20Usinas%20híbridas.pdf>. Accessed: 07/09/2019.
17. BRADSHAW, A.. Regulatory change and innovation in Latin America: The case of renewable energy in Brazil Utilities Policy, vol. 49, p. 156-164, 2017. [online]: <https://doi.org/10.1016/j.jup.2017.01.006>.
18. SILVA, B. G.. *Evolução do setor elétrico brasileiro no contexto econômico nacional: uma análise histórica e econométrica de longo prazo.* Tesis, São Paulo University (USP), São Paulo, 2011. [online]: <http://www.teses.usp.br/teses/disponiveis/86/86131/tde-12032012-091848/pt-br.php>.
19. D'ARAÚJO, R. P.. *Setor Elétrico Brasileiro: Uma Aventura Mercantil. 1ª Ed., Conselho Federal de Engenharia e Agronomia* (CONFEA), Brasília, 2009. [online]: <http://www.confea.org.br/media/Livro_Setor_Eletrico.pdf>.
20. DE JONG, P.; KIPERSTOK, A.; TORRES, E. A. Economic and environmental analysis of electricity generation technologies in Brazil. Renewable & Sustainable Energy Reviews, v. 52, p. 725-739, 2015. [online]: <https://doi.org/10.1016/j.rser.2015.06.064>.
21. EPE. *Estudos de Planejamento da Expansão da Geração: Usinas Híbridas - Uma análise qualitativa de temas regulatórios e comerciais relevantes ao planejamento*. Nº. EPE-DEE-NT-011/2018-r0. Rio de Janeiro, 2018. [online]: <http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-232/topico-

393/NT%20EPE-DEE-NT-011-2018-r0%20(Usinas%20h%C3%ADbridas).pdf>. Accessed: 01/17/2020.

22. EPE. *Estudos de Planejamento da Expansão da Geração – Avaliação da Geração de Usinas Híbridas Eólico-Fotovoltaicas: Proposta metodológica e estudos de caso*. Nº. EPE-DEE-NT-025/2017-r0. Rio de Janeiro, 2017a. [online]: <http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-232/topico-214/Metodologia%20para%20avalia%C3%A7%C3%A3o%20de%20usinas%20h%C3%ADbridas%20e%C3%B3lico-fotovoltaicas.pdf>. Accessed: 01/17/2020.
23. DE JONG, P.; SANCHEZ, A. S.; ESQUERRE, K.; KÁLID, R. A.; TORRES, E. A.; Solar and Wind energy production in relation to the electricity load curve and hydroelectricity in the Northeast region of Brazil. Renewable and Sustainable Energy Reviews, v. 23, p. 526–535, 2013. [online]: <https://doi.org/10.1016/j.rser.2013.01.050>.
24. LOUREIRO, B. A.; TIBA, C.. *Análise da Melhor Relação Eólico–Solar considerando a Complementariedade dos Recursos, Regulações e Incentivos no Brasil*. VI CBENS, Belo Horizonte, 2016. [online]: <http://www.abens.org.br/CBENS2016/anais/anais/index.htm>.
25. DE JONG, P.; CUNHA, F. B. F.; MOUSINHO, M. C. A. M.; PRIMO, R. G. B.; SANTOS, J. A. F. A.; TORRES, E. A. *Complementaridade das energias eólica e solar na Bahia. XVII Congresso Brasileiro de Energia, Anais do XVII Congresso Brasileiro de Energia*, Rio de Janeiro, 2017b.
26. IRENA (International Renewable Energy Agency). Renewable Power Generation Costs in 2018. IRENA, Abu Dhabi, 2019a. [online]: <https://www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018>. Accessed: 12/05/2019.
27. IEA. Technology Roadmap – Wind Energy. 2013 edition, IEA, Paris, 2013. [online]: <https://www.iea.org/publications/freepublications/publication/technology-roadmap-wind-energy---2013-edition.html>.
28. IEA. Technology Roadmap – Solar Photovoltaic Energy: Executive Sumary. 2014 edition, IEA, Paris, 2014b. [online]: <https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarPhotovoltaicEnergy_2014edition.pdf>.
29. REN21 (Renewable Energy Policy Network for the 21st Century). Renewables 2019 Global Status Report. Paris, 2019. [online]: <https://www.ren21.net/wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf>.
30. PEREIRA, E. B.. *Segurança Energética: perspectivas no enfrentamento às mudanças climáticas globais. Conferência Internacional do INCT para Mudanças Climáticas*. São Paulo, 2016. [online]: <http://www.fapesp.br/eventos/2016/09/inct/ENIO.pdf>.
31. FEITOSA, E. A. N. *et al*., *Panorama do Potencial Eólico no Brasil*. ANEEL, Brasília, 2003.
32. CEPEL (*Centro de Pesquisas em Energia Elétrica*). *Atlas do Potencial Eólico Brasileiro: Simulações 2013. 1ª Edição*, Rio de Janeiro, 2017. [online]: <http://novoatlas.cepel.br/wp-content/uploads/2017/03/NovoAtlasdoPotencialEolico_BrasileiroSIM_2013.pdf>.
33. CAMARGO–SCHUBERT, SECTI , SEINFRA, SENAI/CIMATEC. *Atlas Eólico: Bahia. Salvador*. 2013. Available at: <http://www2.secti.ba.gov.br/atlasWEB/mapas_eolicos.html>. Accessed: 06/17/2019.
34. MARTINS, F. R.; PEREIRA, E. B.; ECHER, M. P. S.. *Levantamento dos recursos de energia solar no Brasil com o emprego de satélite geoestacionário – o Projeto SWERA. Revista Brasileira de Ensino de Física*, Vol. 26, Nº. 2, p. 145–159, 2004. [online]: <http://dx.doi.org/10.1590/S0102-47442004000200010>.
35. PEREIRA, E. B.; MARTINS, F. R.; GONÇALVES, A. R.; COSTA, R. S.; LIMA, F. J. L.; RÜTHER, R.; ABREU, S. L.; TIEPOLO, G. M.; PEREIRA, S. V.; SOUZA, J. G..

Atlas brasileiro de energia solar. 2ª. Ed., Instituto Nacional de Pesquisas Espaciais (INPE), São José dos Campos, 2017. [online]: <http://ftp.cptec.inpe.br/labren/publ/livros/Atlas_Brasileiro_Energia_Solar_2a_Edicao.pdf>.

36. EPE. *Nota Técnica: Análise da Inserção da Geração Solar na Matriz Elétrica Brasileira*. Rio de Janeiro, 2012. [online]: <http://bibliotecadigital.seplan.planejamento.gov.br/handle/iditem/242>.
37. SANTOS, J. A. F. A.; TORRES, E. A.. *Potencial e inserção de novas energias renováveis na matriz elétrica baiana para geração elétrica centralizada até 2050. Bahia Análise & Dados*, Salvador, v. 27, n. 1, p. 144-173, 2017. [online]: <http://publicacoes.sei.ba.gov.br/index.php/bahiaanaliseedados/article/view/74>.
38. TOLMASQUIM, M. T.. *Energia Renovável: Hidráulica, Biomassa, Eólica, Solar, Oceânica*. EPE, Rio de Janeiro, 2016. [online]: <http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/livro-sobre-energia-renovavel-hidraulica-biomassa-eolica-solar-oceanica>.
39. KONZEN, G.. A *Fonte Fotovoltaica no Planejamento Energético Nacional. Empresa de Pesquisa Energética* (EPE). 1º Encontro Baiano de Energia Solar, Salvador, 2016.
40. EPE. *Balanço Energético Nacional 2019 – Relatório Síntese: Ano Base 2018*. Rio de Janeiro, 2019b. Available at: <http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-303/topico-397/Relat%C3%B3rio%20S%C3%ADntese%202018-ab%202017vff.pdf>. Accessed: 07/09/2019.
41. MARTINS, F. R.; PEREIRA, E. B.. Enhancing information for solar and wind energy technology deployment in Brazil. Energy Policy, v. 39 (7), p. 4378–4390, 2011. [online]: <https://doi.org/10.1016/j.enpol.2011.04.058>.
42. DE JONG, P.; TANAJURA, C. A.; SÁNCHEZ, A. S.; DARGAVILLE, R.; KIPERSTOK, A.; TORRES E. A. Hydroelectric production from Brazil's São Francisco River could cease due to climate change and inter-annual variability. Science of the Total Environment, v. 634, p. 1540-1553, 2018. [online]: <https://doi.org/10.1016/j.scitotenv.2018.03.256>.
43. SANTOS, J. A. F. A.; TORRES, E. A.. Wind Energy in the Brazilian Energy Matrix: Introduction in State of Bahia. In: *XI Congreso Internacional sobre Innovación y Desarrollo Tecnológico* (CIINDET 2014), *Tecnologías Modernas para la Industria y la Educación*, Anais CIINDET XI, ISBN 978-607-95255-6-9, Cuernavaca-Morelos, 2014.
44. SILVA, N. F.; ROSA, L. P.; ARAÚJO, M. R.. The utilization of wind energy in the Brazilian electric sector's expansion. Renewable and Sustainable Energy Reviews, vol. 9, p. 289–309, 2005. [online]: <https://doi.org/10.1016/j.rser.2004.04.003>.
45. ONS (*Operador Nacional do Sistema Elétrico*). *Sobre o SIN*. Rio de Janeiro, 2018. Available at: <http://ons.org.br/paginas/sobre-o-sin/>. Accessed: 06/16/2018.
46. HERRERA, M. M., Dyner, I., Cosenz, F.. Assessing the effect of transmission constraints on wind power expansion in northeast Brazil. Utilities Policy, vol. 59, 100924, 2019. [online]: <https://doi.org/10.1016/j.jup.2019.05.010>.
47. GOVERNO FEDERAL. *Lei* Nº 6.353/2008. *Presidência da República*, 01/16/2008, Brasília, 2008. Available in: <http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2004/lei/l10.848.htm>. Accessed: 01/12/2020.
48. GOVERNO FEDERAL. *Lei* Nº 10.848/2004. *Presidência da República*, 03/15/2004, Brasília, 2004a. Available in: <http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2004/lei/l10.848.htm>. Accessed: 01/12/2020.
49. GOVERNO FEDERAL. *Lei* Nº 5.163/2004. *Presidência da República*, 07/30/2004, Brasília, 2004b. Available in: <http://www.planalto.gov.br/ccivil_03/_Ato2004-2006/2004/Decreto/D5163.htm>. Accessed: 01/12/2020.

50. GOVERNO FEDERAL. *Lei* Nº 10.438/2002. *Presidência da República*, 04/26/2002, Brasília, 2002. Available in: <http://www.planalto.gov.br/ccivil_03/Resolu%C3%A7%C3%A3o/RES24-01.htm>. Accessed: 01/12/2020.
51. GOVERNO FEDERAL. *Resolução* Nº 24. *Presidência da República, Casa Civil Subchefia para Assuntos Jurídicos, Câmara de Gestão da Crise de Energia*, 07/05/2001, Brasília, 2002. Available in: <http://www.planalto.gov.br/ccivil_03/LEIS/2002/L10438.htm>. Accessed: 05/22/2019.
52. COSTA, C. V.; LA ROVEREA, E.; ASSMANN, D.. Technological innovation policies to promote renewable energies: Lessons from the European experience for the Brazilian case. Renewable and Sustainable Energy Reviews, vol. 12, p. 65–90, 2008. [online]: <https://doi.org/10.1016/j.rser.2006.05.006>.
53. NUNES, S. O.; TELES, E. O.; TORRES, E. A.. *A Evolução do Marco Regulatório para Energia Eólica no Brasil. In: 13º Congresso Ibero-americano de Engenharia Mecânica* (CIBEM 2017), Anais XIII CIBEM, Lisboa, 2017.
54. FARRELL, N.; DEVINE, M. T.; SOROUDI, A.. An auction framework to integrate dynamic transmission expansion planning and pay-as-bid wind connection auctions. Applied Energy, vol. 228, p. 2462-2477, 2018. [online]: <https://doi.org/10.1016/j.apenergy.2018.06.073>.
55. AQUILA, G.; ROCHA, L. C. S.; JUNIOR, P. R.; PAMPLONA, E. O.; QUEIROZ, A. R.; PAIVA, A. P.. Wind power generation: An impact analysis of incentive strategies for cleaner energy provision in Brazil. Journal of Cleaner Production, vol. 137, p. 1100-1108, 2016. [online]: <http://dx.doi.org/10.1016/j.jclepro.2016.07.207>.
56. EPE. *Série Estudos da Demanda de Energia: Nota Técnica DEA 13/14 – Demanda de Energia 2050, Plano Nacional de Energia 2050* (PNE 2050). Rio de Janeiro, 2016. [online]: <http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-227/topico-458/DEA%2013-15%20Demanda%20de%20Energia%202050.pdf>.
57. EPE. *Plano Decenal de Expansão de Energia 2026*. Rio de Janeiro, 2017b. Available in: <http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/Plano-Decenal-de-Expansao-de-Energia-2026>. Accessed: 05/28/2019.
58. EPE. *Informações institucionais*. Rio de Janeiro, 2014. Available at: <www.epe.gov.br/acessoainformacao/Paginas/perguntasfrequentes.aspx>. Accessed: 09/05/2017.
59. TORRES, P. S.. *Estudo de Aspectos Técnicos e Normativos em Projetos Híbridos Eólico-Fotovoltaicos. Monografia da Especialização em Energias Renováveis, Geração Distribuída e Eficiência Energética da Universidade de São Paulo*, São Paulo, 2017.
60. MELO, E.. *Fonte eólica de energia: aspectos de inserção, tecnologia e competitividade. Estudos Avançados–Energia*, Vol. 27, Nº. 77, São Paulo, 2013. [online]: <http://dx.doi.org/10.1590/S0103-40142013000100010>.
61. MME. *Boletim: Energia Eólica no Brasil e no Mundo. Núcleo de Estudos Estratégicos de Energia*, Ed. 22/12/2014, Brasília, 2014.
62. ABEEOLICA (*Associação Brasileira de Energia Eólica*). Infowind Brazil. Infowind nº 9, Update 2019 February, 15. São Paulo, 2019. Available at: <http://abeeolica.org.br/wp-content/uploads/2019/03/Infovento_ENG.pdf>. Accessed: 03/27/2019.
63. DE JONG, P.; BARRETO, T. B.; TANAJURA, C. A. S.; KOULOUKOUI, D.; OLIVEIRA-ESQUERRE, K. P.; KIPERSTOK, A.; TORRES, E. A.. Estimating the impact of climate change on wind and solar energy in Brazil using a South American regional climate model. Renewable Energy, v. 141, p. 390-401, 2019. [online]: <https://doi.org/10.1016/j.renene.2019.03.086>.

64. CCEE (*Câmara de Comercialização de Energia Elétrica*). Comunicados e Notícias. Brasília, 2018. Available at: <https://www.ccee.org.br>. Accessed: 04/17/2018.
65. EPE. *Leilões de Energia Nova de 2017: Apresentando os resultados e como isso afeta os estudos de planejamento energético.* Rio de Janeiro, 2017c.
66. MME. *Energia Solar no Brasil e Mundo Ano de referência – 2015*. Brasília, 2016a.
67. IRENA. Renewable Capacity Statistics 2019, Abu Dhabi, 2019c. [online]: <https://www.irena.org/publications/2019/Mar/Capacity-Statistics-2019> . Accessed: 12/05/2019.
68. SAUAIA, R. L.. *A Hora e a vez da Energia Solar. ABSOLAR, Canal Jornal da Bioenergia*, Goiânia, 2017. Available at: <http://www.absolar.org.br/noticia/entrevistas/a-hora-e-a-vez-da-energia-solar-.html>. Accessed: 03/11/2018.
69. SANTOS, J. A. F. A.; TORRES, E. A.; COSTA, C. A.. *Potencial para Combinação das Fontes Eólica e Solar na Geração Elétrica no Brasil. In: 13º Congresso Ibero-americano de Engenharia Mecânica* (CIBEM 2017), Anais XIII CIBEM, Lisboa, 2017.
70. LIMA, J. A.. *Análise de Viabilidade da Geração Híbrida Solar e Eólica no Nordeste Brasileiro.* Tesis, Federal University of Campina Grande, 2016. Available in: <http://dspace.sti.ufcg.edu.br:8080/jspui/handle/riufcg/992>. Accessed: May 28, 2019.
71. ANEEL (*Agência Nacional de Energia Elétrica*). *Nota Técnica* Nº 051/2019-SRG-SCG-SRD-SRT/ANEEL. *Processo*: 48500.005625/2018-91. *Assunto: Instauração de Consulta Pública visando colher subsídios para elaboração de proposta de normativo sobre o estabelecimento de usinas híbridas e/ou associadas*. Brasília, 2019a.
72. PEREIRA, J. L. M.; CONCEIÇÃO, F. W. S.; RAMOS, V. M.. *Exploração da Energia Solar no Lago da Usina Hidrelétrica de Balbina através de Painéis Flutuantes. XXIV Seminário Nacional de Produção e Transmissão de Energia Elétrica* (SNPTEE 2016), Curitiba, 2016. [online]: <http://xxivsnptee.com.br/wp-content/uploads/2017/11/GPT05.pdf>.
73. AMBIENTE ENERGIA. *UHE de Balbina recebe equipamentos para montagem de usina solar flutuante.* Rio de Janeiro, 2017. Available at: <www.ambienteenergia.com.br/index.php/2017/10/eletronorte-recebe-equipamentos-para-instalacao-de-usina-solar-flutuante/32911#.W5Cz985KiM8>. Accessed: 03/20/2019.
74. TOMELIN, A. C.; DI CASTELNUEVO, M.; MIRIELLO, C.. *Questões de Pós-implantação de Energia Renovável: Instrumentos Tecnológicos. X Congresso Brasileiro de Planejamento Energético* (CBPE 2016), Gramado, 2016.
75. LEONI, P. N.; CARVALHO, C. R. F.; ABREU, L. M., BARBOSA, D.. *Projeto Híbrido Eólico-Solar: Uma maneira de aumentar a competitividade e ampliar a penetração de projetos solares de grande porte. Revista O Setor Elétrico*, Ed. Nº. 134, p. 59–66, São Paulo, 2017. [online]: <https://www.osetoreletrico.com.br/projeto-hibrido-eolico-solar>.
76. EGPB (Enel Green Power Brazil). *Informações institucionais*, 2018. Available at: <https://www.enelgreenpower.com/country-brazil>. Accessed: 01/18/2018.
77. RENOVA ENERGIA. *Informações institucionais*, 2018. Available at: <http://www.renovaenergia.com.br/>. Accessed: 01/18/2018.
78. BARBOSA, C. F. O.; PINHO, J. T.; GALHARDO, M. A. B.; PEREIRA, E. J. S.. *Sistemas Híbridos de Energia: Aplicações e Estudos no Brasil*. VI CBENS, Belo Horizonte, 2016b. [online]: <www.abens.org.br/CBENS2016/anais/anais/index.htm>.
79. ONS. *Resultados da Operação – Histórico da Operação: Geração de Energia*. Rio de Janeiro, 2019a. Available at: <http://ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/geracao_energia.aspx>. Accessed: 06/26/2019.
80. NREL (National Renewable Energy Laboratory). PV Watts Calculator: Solar Resource Data. Lakewood, 2019. Available at: <https://pvwatts.nrel.gov/pvwatts.php>. Accessed: 07/15/2019.

81. SILVA, R. M.. *Energia solar no Brasil: dos incentivos aos desafios, Núcleo de Estudos e Pesquisas da Consultoria Legislativa. Senado Federal*, 2015. [online]: <http://www2.senado.leg.br/bdsf/item/id/507212>.
82. CARVALHO, C. R. F.; LEONI, P. N.; ABREU, L. M.; MOTA, K.. *Projeto Híbrido Eólico Solar: Uma experiência Prática - Estudo de Caso. Renova Energia. 1º Encontro Baiano de Energia Solar*, Salvador, 2016.
83. PINTO, L.. *Estudo das Características Técnicas e Sinergias de Projeto Híbrido Solar e Eólica. Engenho Pesquisa e Consultoria*, Rio de Janeiro, 2016.
84. ABSOLAR (*Associação Brasileira de Energia Solar Fotovoltaica*). *Solar: 1 GWp para começar.* São Paulo, 2014. Available at: <www.absolar.org.br/noticia/noticias-externas/solar-1-gwp-para-comecar.html>. Accessed: 03/11/2019.
85. EPE. *Programa de Expansão da Transmissão/Plano de Expansão de Longo Prazo* (PET/PELP). Rio de Janeiro, 2019c. Available at: <http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/programa-de-expansao-da-transmissao-plano-de-expansao-de-longo-prazo-pet-pelp>. Accessed: 07/17/2019.
86. ONS. *Sobre o SIN – O Sistema em Números: Extensão da Rede de Transmissão*. Rio de Janeiro, 2019b. Available at: <http://www.ons.org.br/paginas/sobre-o-sin/o-sistema-em-numeros>. Accessed: 07/17/2019.
87. MINISTRY OF MINES AND ENERGY (Ministério de Minas e Energia – MME). *Nota Técnica* Nº 03/2018/SE. *Processo* Nº: 48330.000488/2017–16. *Consulta Pública* Nº 32, 2017, que trata do Relatório "Princípios para Reorganização do Setor Elétrico Brasileiro", Secretaria-Executiva do MME, Brasília, 2017a. Available in: <http://epe.gov.br/sites-pt/sala-de-imprensa/noticias/Documents/Nota%20T%C3%A9cnica%20n%C2%BA%2032%202018%20-%20Fechamento%20da%20CP%2032%20-%202018.pdf>. Accessed: May 19, 2019.
88. MME. *Nota Técnica* Nº5/2017/AEREG/SE. *Processo*. Nº 48000.001405/2016-67, *Proposta de Aprimoramento do Marco Legal do Setor Elétrico. Secretaria-Executiva/Assessoria Especial em Assuntos Regulatórios*, Brasília, 2017b. Available in: <http://www.paranoaenergia.com.br/wp-content/uploads/2017/07/ConsultaMME.pdf>. Accessed: May 19, 2019.
89. MME. *Consulta Pública Nº. 33 – Aprimoramento do marco legal do setor elétrico*. 05-jul-2017. Brasília, 2017c. Available in: <http://www.mme.gov.br/web/guest/consultas-publicas>. Accessed: May 19, 2019.
90. MME. *Nota Técnica* Nº. 4/2016-AEREG/SE-MME – *Mercado Livre de Energia Elétrica. Consulta Pública* Nº. 21 de 05/10/2016. *Processo* Nº: 48000.001405/2016–67. *Assessoria Especial em Assuntos Regulatórios/Secretaria-Executiva do* MME, Brasília, 2016b. Available in: <http://institucional.madronalaw.com.br/boletimenergia28.pdf>. Accessed: May 19, 2019.
91. ANEEL. *Consulta Pública* 014/2019: *Objeto - obter subsídios para a elaboração de proposta de Resolução Normativa que discipline a implantação e operação de usinas híbridas.* Brasília, 2019b. [online]: <http://www.aneel.gov.br/consultas-publicas>.