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HYBRIDIZATION OF WIND-SOLAR ENERGY SYSTEMS: REVIEW OF BRAZILIAN LEGISLATION AND STATE OF THE ART

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Abstract. *This work aims to present state of the art associated with hybrid photovoltaic-wind power plants. It gathers and evaluates the current Brazilian legislation, outcomes, and articles. Articles with normative treaties, sizing, and simulations of hybrid photovoltaic-wind power plants are discussed. So, an evaluation of the guidelines, trends, advances, and techniques in research in this area of study is sought. This type of plant is briefly described according to its characteristics, design factors, and powers above 5 MW. The works and articles are not limited to plants in Brazil. The following databases are used: Google, Science Direct, and Web of Science. So, an overview of the current situation of use, existence, and regulations of this type of plant is obtained. Among the 20 articles found, five were selected. Of these, 40% deal with complementarity or hybridization potential, 25% with economic evaluation, and 45% with computer simulation. Thus, this work offers the reader an initial basis for consulting this study area.*

Keywords: *Hybrid systems, Renewable energies, Wind-solar energy, Brazilian legislation.*

1. INTRODUCTION

Most of the electrical energy generated in Brazil comes from hydro sources. Consequently, Brazil has more renewable energy sources than other countries. However, seasonal effects and long periods of drought considerably reduce the level of rivers and dams that make up the water resource of our electrical matrix.

According to Santos and Torres, 2021, Brazil is a developing country, and its demand for energy (mainly from non-hydro renewable sources) is growing. There are abundant and available solar and Wind resources here. Their increasing prospects are a fact. In addition, a high level of complementarity can be exploited between wind, solar, and water sources. Hydroelectric plants and wind farms can benefit from a complementary resource (solar, e.g.) and generate more energy in the same location.

There are hundreds of these plants in Brazil. The need for complementarity is evident when evaluated on a case-by-case basis (Bona et al., 2021). For example, the Taíba wind farm in Ceará has an installed capacity of 5 MW, but operates at a capacity factor of 40% (Memória da Eletricidade, 2019). At the Dois Riachos wind farm in Bahia, there are fifteen 2 MW wind turbines - totaling an installed capacity of 30 MW (Canal Energia, 2015). However, its energy guarantee is 13.9 MW, corresponding to only a 46% capacity factor.

In the case of the hydro source (PBDA, 2022), it is observed that most plants in operation in Brazil have granted power and guaranteed energy delivery below their potential. The 14 de Julho hydroelectric plant, located in Rio Grande do Sul, in the city of Bento Gonçalves, is an example. It has a concession of 100 MW, but the firm energy is 47.5 MW. That is a capacity factor of 47.5% (Rennosonic, 2022). Thus, almost all the plants in operation have a greater generation capacity than the amount of energy produced and delivered. When Wind and solar resources are complemented, we can observe a higher yearly capacity factor, more stable power output over time, and the possibility for partially scheduled power dispatch (Wind Europe, 2019).

In this context, the present work has as its primary objectives a review of the Brazilian legislation and a brief look at state of the art in terms of hybridization of wind-solar energy systems. The databases consulted were Google, Science Direct, and Web of Science. Among the 20 articles found, five were selected. Of these, 40% deal with complementarity or hybridization potential, 25% with economic evaluation, and 45% with computer simulation, which refers not only to Brazil. Complementarity studies and computer simulation used data from existing wind farms. The economic feasibility analyzes bring quite regionalized results since they studied local models. However, these results demonstrate an attractiveness in this process of hybridization of technologies, as well as in the issues of "repowering" (retrofitting old plants that generate less energy compared to more modern technologies).

2. GENERAL OVERVIEW OF BRAZILIAN LEGISLATION AND STANDARDS

2.1 Hybridization

Hybrid power systems can generate electrical energy from two or more different sources. Typically, they share the same connection point with the distribution network. Electric power generation projects can propose many combinations. For example, wind and photovoltaics – for regions with low capacity factors due to lower incidence of wind during the day are typical; there is the possibility of cost optimization when mixing these technologies.

Hydraulics and photovoltaics - due to the large percentage of hydroelectric generation in Brazil and the low capacity factor of PV plants, the potential for seasonal and territorial complementarity is a fact. It can combine sources such as hydroelectric plants with wind power, biomass with natural gas, or coal with biomass.

Hybridization allows for extracting more value from an asset with limited potential, providing more energy delivered through the same route with a reduction in the idle capacity of this asset. There is an additional cost for producing extra energy, but this reduces the cost of electricity produced.

2.2 Brazilian Legislation: Regulation

The expansion of renewable sources has stood out in recent years, and Brazil has been recognized for managing these resources. From 2017 until now, EPE – in Portuguese *Empresa de Pesquisa Energética* – has been implementing pilot projects to study the impacts and benefits of hybridizing power plants. From these results, materials emerged to support public consultations. The possibility of hybridizing the plants, derived from a generation expansion planning study, was discussed in "Decennial Energy Expansion Plan - 2027", carried out in 2018 (EPE, 2018a).

First, defining a free contracting environment in the Brazilian energy market is necessary. The energy market in Brazil is divided into two contracting environments. The RCE (Regulated Contracting Environment – in portuguese Ambiente de Contratação Livre, ACL)is formed by captive consumers. The FCE (Free Contracting Environment – in portuguese Mercado Livre de Energia, MLE) is formed by free consumers. Captive consumers buy energy from the distribution concessionaires to which they are connected. Each consumer unit pays only one energy bill per month, including the distribution service and energy generation, and the Government regulates tariffs. The Free Energy Market is a competitive electricity trading environment in which participants can freely negotiate all commercial conditions such as supplier, price, amount of energy contracted, supply period, and payment, among others. Free consumers buy energy directly from generators or traders through bilateral contracts with freely negotiated conditions, such as price, term, volume, etc. Each consumer unit pays an invoice referring to the distribution service to the local concessionaire (regulated tariff) and one or more invoices referring to the purchase of energy (negotiated contract price). Figure 1 summarizes these concepts.

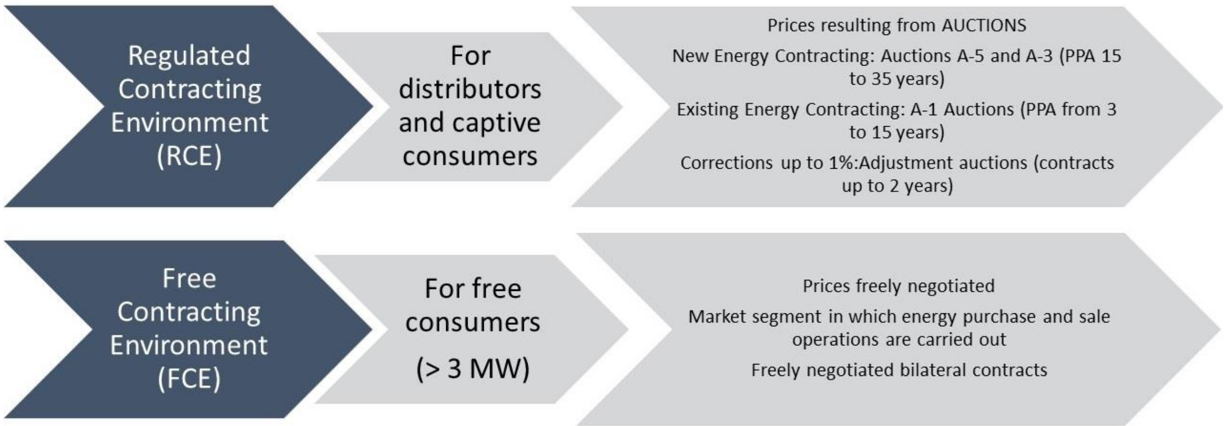

Figure 1. Distributed generation and free contracting environment.

In this study, we deal with the Free Contracting Environment since it is in the environment that energy auctions take place. In these auctions, the plants make their contracts and commit to guarantees of firm energy mentioned above. Another essential concept is Power Purchase Agreements, PPA. They are energy purchase instruments, especially renewable energy, which allow large consumers to purchase electricity for their operations. In this way, they contribute to developing new generation projects and expanding renewable sources in the Brazilian electricity matrix.

The Normative Resolution 389/2009 (Normas Brasil, 2009) established the duties, rights, and other general conditions applicable to granting interested parties to establish themselves as independent producers or self-producers of electric energy to implement and operate electric generating plants. The PROINFA (ELETROBRAS, 2017), an incentive program for alternative sources of electricity, was established by Law 10438/2002 (Jusbrasil, 2002). It is considered the most extensive program in the world to encourage renewable sources. It has contributed to the diversification of the national energy matrix and enables the reduction of greenhouse gas emissions.

ANEEL already had an intention to set a target for regulatory adequacy of hybrid plants since the beginning of 2019. Since then, public consultations have been carried out, resulting in Normative Resolution 876/2020 (Imprensa Nacional, 2020). It established the requirements and procedures necessary to obtain authorization for exploration and to change the installed capacity of wind, photovoltaic, thermoelectric, and other alternative sources. It was later amended by Normative Resolution 954/2021 (ANEEL, 2021). This NR established regulatory treatment for implementing Hybrid Generating Plants (UGH) and associated generating plants. Normative Resolution 954/2021 (ANEEL, 2021) creates rules for the authorization of hybrid enterprises, the regulation for the use of distribution systems, and their tariffs and discounts.

In 2021, Normative Resolution 921 (Jusbrasil, 2021) was also published. It establishes the duties, rights, and other general conditions applicable to granting people or companies interested in establishing themselves as Independent Electricity Producers, self-producers, in implementing or operating an electric power plant, revoking Resolution 389/2009 (Normas Brasil, 2009).

2.3 Brazilian Legislation: Pre-Regulation Period

Some projects, considered strategic and experimental, were generated through ANEEL's R&D projects. They are "the first generation of wind and solar energy in Brazil on a large scale." The "Blue City" park, Fig. 2, is an example. Since 2013, a 3.0 MWp power plant with different PV technologies has been merged with two 2.1 MW wind turbines. According to Marozinski, 2018, in 2015 in Pernambuco, the "Forte dos Ventos" park started to operate with 11 MWp from solar plants and 80 MW from 34 wind turbines. It was created to participate in the 2011 A5 auction.

Figure 2. Blue City Plant (FV UFSC, 2022).

3. POTENTIAL BENEFITS: COMBINATION OF TECHNOLOGIES

Hybrid sources are energy sources that combine and complement each other in generating electricity. It is impossible to distinguish which primary source was responsible for which part of the electricity generation without cutting during the technology transition, EPE, 2018b. Complementarity is the ability of two or more resources to be available simultaneously, Fig. 3. According to EPE, 2018b, the "perfect" complementarity between two resources occurs when one is available while the other is disabled, and the situation can be reversed similarly.

There are many benefits of hybridizing renewable technologies in a single enterprise. For example, the Hybrid Generating Plant, HGP, shares the land, optimizing the use of the area, reducing the cost, and increasing the project's competitiveness. The substation is also shared because it was designed to receive a much larger load. They share part of the fixed maintenance and operation costs, such as monitoring, inspection, security, etc.

There is a complementarity factor for wind and solar sources: Sun during the day and wind during the night, Fig. 3. The behavior of solar radiation has a generally predictable pattern, unlike the wind. However, hybridization encourages energy generation with less volatility 24 hours a day, making the most of each natural resource.

The HGP is subject to a single grant, and there may or may not be different measurements by generation technology. The current resolution sets a precedent for new projects associated with existing and operating plants. The addition of two technologies can significantly increase the capacity factor of HGP. It can also reduce the idleness of the transmission system within the limitation of the flow capacity. Sharing infrastructure provides more efficient and stable generation, delivering more energy with the same transmission line.

According to Santos e Torres, 2021, there are other benefits, such as greater use of available transmission system capacity; cost reduction in the use of systems; maintenance; optimization of leased land; logistics for planning the implementation of plants; unification of environmental licenses; reduction of intermittence and increase of the average of energy produced; and greater competitiveness and efficiency of generation projects.

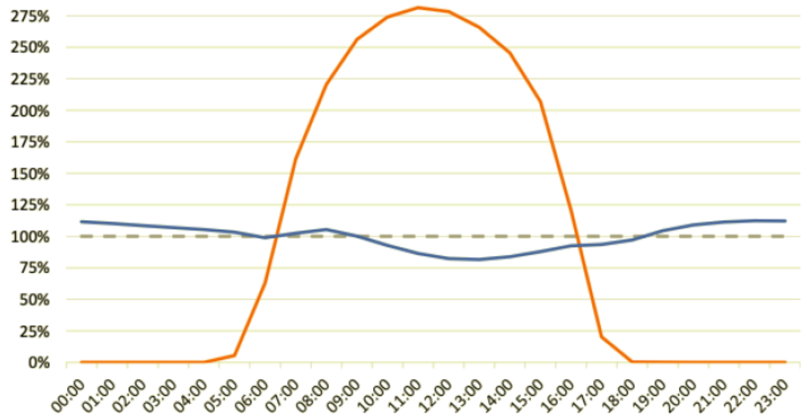

Figure 3. Flat Profile (dashed line), PV Profile (orange line), and Wind Profile (blue line).

4. BRAZIL ON THE GLOBAL SCENE

Large-scale hybrid projects in the world, connected to transmission systems, are increasingly consolidated, Fig 4. Several hybrid power plant combinations, including the wind-solar combination, have been implemented globally.

Figure 4. Hybrid wind-solar plants - blue dots - and hybrid wind-solar plants with an accumulation system -orange dots – (Wind Europe, 2022).

Wheatridge Renewable Energy Facility Project (PGE, 2022) – Oregon – USA – has 300 MW wind, 50 MWp solar, and 30 MW storage. The project is located in the city of Morrow, Fig. 5a. Wind turbines are over 90 meters tall, with the hub between blades. Solar generation operates in a hybrid way, increasing the capacity factor. The storage system balances the load delivered to consumers, depending on whether they need more or less energy. A consortium of companies forms the hybrid plant. Approximately 885,000 customers will be served.

Luneng Haixi Multi Mixed Energy Project (Paiva, 2022) – Qinghai – China – has 400 MW wind, 200 MWp solar, 50 MW heliothermal, and 100 MW storage. The plant is located in Golmud, Fig. 5b, and has three types of renewable energy sources. The plant's planned electricity generation is 126,250 MWh (equivalent to burning 401,500 tons of coal) annually. Once ready, it will optimize the energy structure of the region, collaborating with the preservation of the environment and promoting a renewable culture.

Port Augusta Project – Wininowie - Australia – has 210 MW wind and 107 MWp solar. The project is located in the city of Wininowie. It is Australia's first hybrid solar and wind power plant, serving 180,000 homes. The objective of this project is to lower the price of electricity for consumers. In Piauí, Brazil, an 85.2 MWp solar PV plant project will complement the wind farm production with an installed capacity of 205 MW, which is currently destined for the Free Market. The project is called “Ventos do Piauí” (Canal Energia, 2021).

Figure 5a. Wheatridge Renewable Energy Facility (Nextera Energy, 2020)

Figure 5b. Luneng Haixi 50MW Molten Salt Tower CSP Project (CSP Focus, 2020)

4.1 Brazil: Perspectives

Hybrid power plant projects should become more competitive with the new ANEEL regulations (ANEEL, 2021a). It provides for using various sources but benefits from renewable energies to increase productivity and reduce the cost of generation. The use of infrastructure is one of the points that most contribute to this reduction. For example, many plant parts, such as the transmission grid and the substation, can be shared. A single natural resource's volatility can be reduced in complementarity, as shown in Figure 6.

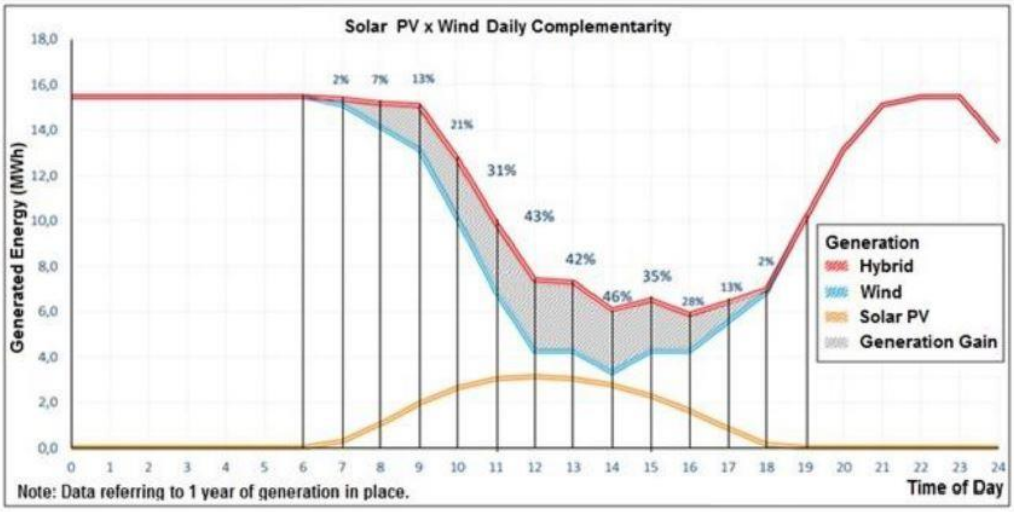

Figure 6. Wind-solar complementarity throughout the day (Santos et al., 2020).

Considering that Brazil reached the mark of 18 GW of installed capacity in February 2021 (ABEEólica, 2022), with 695 parks and more than 8,300 wind turbines, and an average capacity factor of around 50% (December 2020), estimates there is a potential of at least 9 GW to complement wind power generation, creating "hybrid" parks. One benefit that the hybridization process will bring to society is the postponement of expanding the energy distribution system, bringing savings to those who pay for transmission systems. Brazil is a country of continental dimensions and has a territorial extension to accommodate the increase in the electricity matrix.

5. STATE OF ART

The databases consulted were Google, Science Direct, and Web of Science. Among the 20 articles found, five were selected. Of these, 40% deal with complementarity or hybridization potential, 25% with economic evaluation, and 45% with computer simulation, which refers not only to Brazil. The articles selected by the authors are presented below.

Mertens, 2022 sought to create an ideal hybridization model for wind-photovoltaic power plants since there were no guidelines for a combination of energy supply and demand. They studied a design modeling of hybrid systems, seeking a better performance profile in seasonality without relying only on simulation software. They found that the yield of photovoltaic solar energy in the studied region reaches its peak in the summer months. In contrast, the highest energy efficiency of wind turbines occurs in the winter months. The supply and demand of renewable energy have always been studied analytically, based on monthly averages, capacity factor statistics, and supply simulation. They found that the hybrid project would be ideal, given the complementarity of the technologies. It would provide fewer failures and spikes in power supply, unlike when systems work individually.

Another conclusion of the authors was also important. As systems rarely work at their rated power, hybridization allows cables and connection points to be shared, reducing costs. The simulations were performed with an SSM analysis software – Supply Side Management. Evaluations of PV modules at different angles were done with PVGIS. As a result, they found other consumption profiles. Hybridization plans can be configured according to the profiles. That is, cooling in the summer, and heating in the winter, for example. Mertens, 2022 arrived at a seasonal combination of supply and demand, offering percentages of energy that are more consistent with consumption needs than those studied only by monthly averages. They concluded that a methodology based on SSM (Supply Side Management) is needed to manage consumption and generation needs. It includes taking advantage of unusual locations for designers of renewable plants, such as mixing inclination angles of solar modules in the same plant, e.g., and taking advantage of the terrain's slope to position the PV modules.

Couto and Estanqueiro, 2021 examined the feasibility of complementarity of wind farms with solar energy in Portugal. According to the authors, the decarbonization process of electrical energy systems requires incorporating effective participation of renewable energy sources. The most significant potential for achieving this goal is combining existing wind farms with solar energy. The work was based on the correlation to determine the wind-solar coefficients in that region. The objective was to investigate the potential for complementarity of wind farms without exceeding the capacity of the original plant, avoiding curtailment (cutting for surplus produced) and overcharging for surplus production.

The plants studied have 20 MW of power. The capacity factor of the plants was calculated between 15% and 23%. In the percentage studies of power addition, the authors concluded that adding 50% more wind energy would cause a curtailment of 30% of the total production. On the other hand, in the case of photovoltaic solar energy, adding 50%, the value of the curtailment reached a maximum of 5% of the total production. In both cases, the increase in the annual generation is similar to the two technologies. Also, according to Couto and Estanqueiro, 2021, even if more in-depth studies are needed, such as environmental impacts, the studied location has a high potential for implementing hybrid plants. In addition, it is an excellent opportunity to increase energy generation in existing parks without investing in network infrastructure.

Leal and Albuquerque, 2020, evaluated the possibility of hybridizing wind farms by adding PV modules to consider these projects' energy and economic performance. The research collected data referring to territorial occupation with the economic indices of wind farms in Ceará, Brazil, arriving at the Immobilized Area and Levelized Cost of Energy values. The study simulated the effectiveness of hybridization in two scenarios — the first to supply only the complementary power; and the second to take advantage of the idle area between the plant's wind turbines.

The results obtained showed great potential for the use of the area. The plants in Ceará have a 32% better-fixed area ratio for electricity production than the world average reference value, calculated in 2015 (Leal and Albuquerque, 2020). However, the analysis of scenario 1 brought an additional cost due to the increase in the leveled cost of energy. What would benefit the economic aspect, allowing the studied plant to deliver greater power closer to the projected one.

In scenario 2, infeasibility would occur for two reasons. First, the investment would be very high due to the idle size of the land. Second, the installed power would be much higher than the wind farm dimension. It would cause surpluses and curtailment cuts, which would incur penalties. Leal and Albuquerque, 2020, concluded that these factors are fundamental and decisive for decision-making when turning a pure wind farm into a hybrid wind-photovoltaic power plant.

Santos et al., 2020, analyzed the economic feasibility of hybrid wind-photovoltaic plants based on the existing complementarity in combining these technologies. This market is unprecedented in Brazil. So, the work aimed to fill gaps even though the demand for non-hydro renewable energy is growing. One of these gaps is the potential for expanding solar and wind technologies in the country, the complementarity of these resources in specific regions, their hybridization potential, and recommendations for the regulatory framework of this system.

The authors confirmed that Brazil has excellent solar and wind resources availability. The northeast region has high solar radiation levels, which, superimposed on wind energy, demonstrates the region's great potential for the hybridization of plants. On the other hand, this region is deficient in energy supply, importing energy from other areas through the National Interconnected System, SIN in Portuguese.

As a result, the authors offer suggestions. For example, specific auctions creations for hybridized systems, given the notorious cost reduction in implementing the plants. It would make it possible for more investors to be interested in complementing these sources. Furthermore, the development of hybrid power plants could provide more alternatives for the security of energy supply. With lower project implementation costs, they would maintain the high presence of these renewable energies in the Brazilian electricity matrix. The authors also suggest that the existing pilot plants are a reference for promoting improvements in regulating these plants.

Alok Das et al., 2020, presented government policies, regulatory provisions on renewable energy sources, and a new hybrid wind-solar policy rule. This rule changed the dynamics of individual wind and solar projects in India. As in other countries, renewable energy competes economically with fossil fuels, costing up to 35% less (Alok et al., 2020). India's national hybrid policy allows for a maximum ratio of 75:25 between the two sources (Wind and solar). The authors simulated two case studies - in a 200 MW wind farm and a 75 MWp solar PV plant. Both already exist. In the first case, the simulation predicted a 25% increase in solar PV capacity for the 50 MWp plant. Thus, annual generation would increase from 508 GWh to 585.8 GWh, reducing the cost of capital from 70 to 62.5 million. This reduction is due to the lower design cost of solar PV energy. However, the capacity factor decreased from 29% to 26.7% as the solar PV project had a lower capacity factor. The second case study added 25% of wind energy to a 75 MWp solar plant. Production increased from 131.4 GWh to 182.7 GWh. The capacity factor also increased, from 20% to 22.5%. The authors suggest optimizing the capacity fractions of energy sources using the HOMER software.

Borba et al., 2017, investigated why energy complementarity could serve as an indicator for managers to assess investment possibilities in new energy generation ventures. It also analyzed this index's potential to allow the comparison between plants located in different places. The authors also used a comparative method of two or more energy resources. This method is composed of previously studied mathematical models. Thus, they arrived at a methodology that allows establishing punctual results, with daily and hourly series, different from the methods that only point out maximum and minimum data.

The model was validated through a map - using international databases. The complementarity index was obtained for three resources (water, solar, and wind) for all of Rio Grande do Sul - the southernmost state in Brazil. They concluded that the Northeast of the state presented the best complementarity. The Central and Western regions showed an intermediate complementarity.

6. CONCLUSIONS

The main objectives of this work were to review and present the current Brazilian legislation and state of the art on the hybridization of solar and wind technologies and their benefits and difficulties. The objectives were achieved through a bibliographic review of articles, studies, and works, which presented the regulation, dimensioning, and/or simulations of projects of hybrid wind-photovoltaic plants.

Twenty works were selected. Most of them come from other countries. An essential aspect of the results obtained was to observe how similar the results are and how great is the potential for taking advantage of this complementarity. Although the solar potential and wind speed are different in different regions, this similarity was observed, regardless of the indices and natural resources used for the metrics.

Another aspect that also deserves mention is the desire for some research to determine a mathematical model to regionalize resources. That is, to understand the best percentage of complementarity each resource can bring and which would bring fewer cuts within each plant's output power limit.

It should be noted that the work was based on current studies, bringing recent results and demonstrating Brazil's great potential. to develop this complementarity on a large scale. Of course, without requiring many investments in infrastructure expansions.

The work demonstrates that the prospects are favorable, not only economically but mainly in terms of the stability of the distribution network and the diversification of the matrix, which is currently dependent on water sources.

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