CENTRALES HÍBRIDAS EN EL CONTEXTO DE LA TRANSICIÓN ENERGÉTICA

HYBRID POWER PLANTS IN THE CONTEXT OF THE ENERGY TRANSITION

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Resumen

Las centrales híbridas están ganando protagonismo en el escenario de la transición energética por su capacidad para integrar múltiples fuentes de energía, renovables o no, en un único sistema de generación. Este enfoque, a menudo complementado con sistemas de almacenamiento, pretende maximizar la producción de energía y reducir la variabilidad del suministro, lo que se traduce en un abastecimiento más fiable y económico.

Este artículo pretende analizar el atractivo y las posibles aportaciones de las centrales eléctricas híbridas en el contexto de la transición energética, centrándose en su competitividad económica, sus ventajas técnicas y sus retos normativos. Se presenta y analiza el concepto de centrales híbridas y su aplicación en la regulación brasileña. A continuación, el documento señala las principales motivaciones para el uso de sistemas híbridos de generación, centrándose en los impactos de la difusión de las energías renovables variables, como la energía solar distribuida, en la curva de demanda de energía despachable se discuten. El precio horario de la energía debido a la variabilidad de la carga se analiza en la tercera sección, destacando las oportunidades de las centrales híbridas en el mercado actual. El documento también analiza la popularización de las centrales híbridas debido a la reducción del coste de las tarifas por el uso de la red de distribución y la contribución potencial de las centrales híbridas a la descarbonización de los sistemas aislados. Por último, el documento presenta ejemplos de proyectos de generación híbrida en Brasil y explora la agenda de investigación relacionada con las centrales híbridas, destacando un proyecto piloto que está desarrollando el Instituto de Energía de la PUC-Rio. En resumen, las centrales híbridas representan una estrategia prometedora para afrontar los retos de la transición energética, ofreciendo una solución flexible y económicamente viable para la generación de electricidad.

PALABRAS CLAVE: centrales híbridas, transición energética, energías renovables, almacenamiento de energía, energía solar distribuida, tarificación horaria de la energía, descarbonización, sistemas aislados, proyecto piloto, generación de energía eléctrica.

Abstract

Hybrid plants are gaining prominence in the energy transition scenario due to their ability to integrate multiple energy sources, whether renewable or not, into a single generation system. This approach, often complemented by storage systems, aims to maximize energy production and reduce variability in supply, resulting in a more reliable and economical supply.

This article aims to analyze the attractiveness and potential contributions of hybrid power plants in the context of energy transition, focusing on their economic competitiveness, technical advantages, and regulatory challenges. The concept of hybrid power plants and their application in Brazilian regulation is presented and analyzed. Next, the paper points out the main motivations for the use of hybrid generation systems, focusing on the impacts of the diffusion of variable renewable energies, such as distributed solar energy, on the dispatchable energy demand curve are discussed. The hourly pricing of energy due to load variability is analyzed in the third section, highlighting the opportunities for hybrid plants in the current market. The paper also discusses the popularization of hybrid plants due to the reduction in the cost of tariffs for use of the distribution network and the potential contribution of hybrid power plants to the decarbonization of isolated systems. Finally, the paper presents examples of hybrid generation projects in Brazil and explores the research agenda related to hybrid plants, highlighting a pilot project being developed by the Energy Institute of PUC-Rio. In summary, hybrid power plants represent a promising strategy for meeting the challenges of the energy transition, offering a flexible and economically viable solution for electricity generation.

KEYWORDS: emissions, methane, natural gas supply chain, mitigation measures, abatement costs.

1. INTRODUCTION

The global energy transition is reshaping the electricity sector, driven by economic, regulatory, and technological transformations. One of the key developments in this transition is the increasing deployment of hybrid power plants, which integrate multiple energy sources to enhance reliability, optimize costs, and reduce environmental impacts. Hybrid power plants play a crucial role in addressing the intermittency of renewable sources while maximizing the efficiency of existing energy infrastructure.

Hybrid power plants combine different primary energy sources, such as solar, wind, hydro, biomass, and fossil fuels, often incorporating energy storage systems to improve supply stability. This integration allows for better adaptation to fluctuating energy demand, reducing supply disruptions and optimizing the utilization of transmission and distribution networks. Consequently, hybrid power plants contribute to system resilience, economic efficiency, and the overall sustainability of electricity generation (Wichert, 1997; Manwell, 2004; Lazárov et al., 2005).

The Brazilian electricity sector is undergoing significant changes to incorporate hybrid power generation. The regulatory framework established by the National Electric Energy Agency (Aneel), particularly Normative Resolution No. 954, provides guidelines for implementing hybrid and associated power plants in the country. These regulations aim to facilitate the integration of renewable energy sources, improve grid stability, and reduce costs associated with energy generation and distribution. In this context, hybrid power plants have emerged as a strategic solution for both interconnected and isolated power systems.

This article aims to assess the role of hybrid power plants in the energy transition by analyzing their technical, economic, and regulatory aspects. Specifically, it explores how hybridization strategies can be optimized to improve energy reliability, reduce costs, and support decarbonization efforts. The study also examines how hourly energy pricing, network usage costs, and regulatory incentives influence the adoption of hybrid power plants, providing insights into their economic competitiveness and potential for widespread implementation.

To achieve this objective, the article is structured around the following key topics:

- Definition and regulatory framework of hybrid power plants in Brazil – An overview of hybrid power plant configurations and their regulation under Aneel's Normative Resolution No. 954.

- Impact of renewable energy penetration on dispatchable generation – Analysis of how the expansion of variable renewable energy sources affects the demand for dispatchable energy and grid stability.

- Hourly energy pricing and hybrid power plants – Investigation of how hybrid generation systems can optimize energy sales and system operation under hourly pricing mechanisms.

- Reduction of network usage costs through hybridization – Assessment of how hybrid plants can lower transmission and distribution costs by optimizing energy generation profiles.

- Decarbonization potential of hybrid power plants in isolated systems – Evaluation of how hybridization can replace fossil-fuel-based generation in remote areas, reducing carbon emissions and operational costs.

- Economic competitiveness and feasibility of hybrid power plants – Examination of key factors influencing the financial viability of hybrid systems under different market conditions.

• Case studies of hybrid generation projects in Brazil – Presentation of real-world hybrid power plant implementations, highlighting their benefits and challenges.

• Research agenda and pilot projects – Discussion on ongoing research initiatives, including the pilot hybrid power plant project at the Energy Institute of PUC-Rio, which aims to validate hybridization models and assess their performance under real-world conditions.

The article is organized into seven sections. Following this introduction, Section 2 provides an in-depth discussion on the concept and regulatory landscape of hybrid power plants. Section 3 examines the impact of variable renewable energy sources on dispatchable generation requirements and explores the role of hybrid plants in adapting to hourly energy pricing structures. Section 4 discusses how hybridization can reduce network usage costs. Section 5 evaluates the potential of hybrid power plants in decarbonizing and reducing the costs of generation in isolated systems. Section 6 outlines the research agenda on hybrid power plants, with a particular focus on experimental models and pilot projects being developed to advance this field. Finally, Section 7 presents the study's conclusions.

By providing a comprehensive analysis of hybrid power plants, this study contributes to the understanding of their potential to accelerate the energy transition, enhance grid stability, and improve economic efficiency in electricity markets.

2. CONCEPT OF HYBRID POWER PLANTS

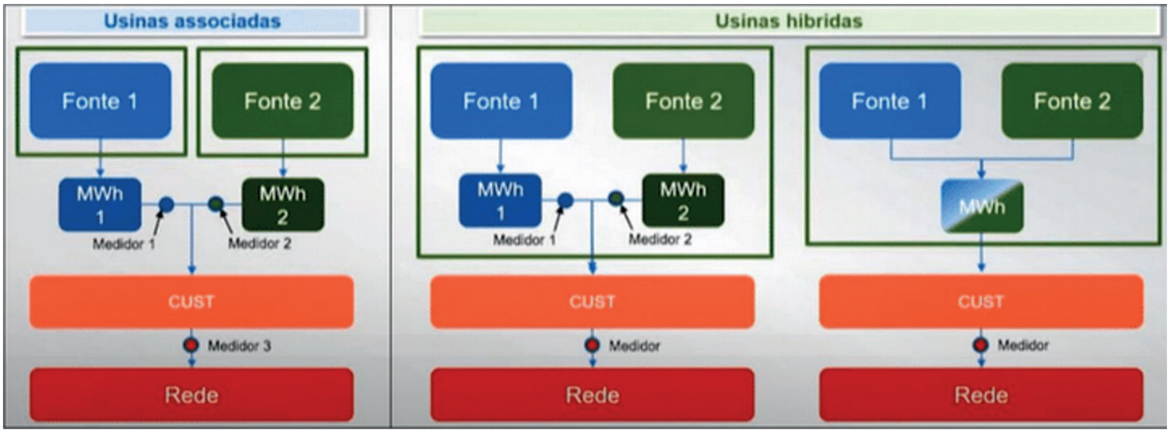
A variety of technological combinations may be employed to facilitate the hybridization of existing or novel generation systems. Potential combinations include a wind power plant with photovoltaics and batteries; a hydropower plant with photovoltaics; a biomass thermal power plant with a gas power plant and photovoltaics; among others. The specific combinations to be pursued will depend on the opportunities for reducing generation costs by leveraging common infrastructures and the complementarity of generation sources. Furthermore, there may be significant gains associated with the ability to adapt energy supply to the characteristics of demand.

The generation hybridization strategy can be adapted to the specific characteristics of the demand curve of a region or consumer, considering the availability of natural resources and local needs. The combination of different energy sources in a single installation has the potential to enhance operational efficiency, improve the reliability of electricity supply, and reduce dependence on a single energy source.

For a power-generating plant to be considered hybrid, the project must contain a single metering system and a single license (Aneel, 2021). There are also associated generating plants that also integrate two or more energy sources, but with different licenses and metering, which share the same energy transmission system.

In Brazil, the National Electric Energy Agency (Aneel) enacted Resolution regarding hybrid and associated plants in 2021 through Normative Resolution No. 954. This regulation involves power plants with a capacity exceeding 5 MW, including associated plants. A hybrid power plant is defined as a facility that produces electricity from a combination of different generation technologies, with different metering per generation technology or not, subject to a single grant. In contrast, an associated generating plant is defined as a facility that produces electricity from a combination of different generation technologies, with different licenses and metering systems, which physically and contractually share the infrastructure for connecting to and using the transmission system. Figure 1 provides a schematic representation of the hybrid and associated plant concepts.

Figure 1 - Hybrid and Associated Plant Arrangements (Aneel, 2021).



As illustrated in the initial chart of Figure 1, the associated plants are organized according to a scheme that encompasses two or more licenses and the shared utilization of the connection. Consequently, the aforementioned plants are subject to two distinct metering but have a single contract regarding the use of the transmission system. In contrast, hybrid plants, as illustrated in the second table, possess a single license but employ two or more power generation technologies. These plants can be classified in two distinct manners: firstly, each technology is associated with a distinct meter; secondly, a single meter is utilized, with the technologies sharing the same transmission system.

It is also important to note that separate measurements by generation technology are required for hybrid power plants that employ technologies centrally dispatched by the National System Operator (ONS). Furthermore, it is imperative to underscore that in instances of hybridization or association of generating plants, there must be no compromise in meeting contractual obligations within the regulated framework. This is to ensure the stability and reliability of the electricity supply.

As stated by EPE (2018), the primary advantages of hybrid plants can be summarized as follows:

- Increased utilization of available transmission and/or distribution system capacity

- Optimized use of available land area

- Enhanced logistics and implementation planning through synergies

- Operational synergies

- Shared utilization of system equipment of restricted interest

- Reduction of generator costs with network usage tariffs

One of the first projects to receive approval from Aneel was the Neoenergia Renewable Complex, comprising the associations of Neoenergia Chafariz and Neoenergia Luzia in Figure 2. These two solar and wind renewable energy generation facilities are associated with the objective of supplying energy to Paraíba. The plants have an installed capacity of approximately 620 MW, distributed between solar panels and wind generators connected to the National Interconnected System, which integrates the production and distribution of electricity in Brazil. The total output is sufficient to supply 1.3 million homes per year (Neoenergia, 2022).

Figure 2 - (a) Neoenergia's Chafariz Wind Farm with 467.77 MW of installed capacity. (b) Solar complex of 228,780 photovoltaic panels installed at Neoenergia Luzia. ((a) Neoenergia/Divulgação, 2022. (b) Envato Elements, 2022)

The Companhia Energética de Minas Gerais (Cemig) has announced plans to invest over R$1.8 billion in the construction of floating photovoltaic plant projects within the reservoirs of hydroelectric facilities in the state of Minas Gerais as can be seen in Figure 3. The aforementioned photovoltaic plants will be installed at Três Marias, Cajuru, Theodomiro Carneiro Santiago, and another yet to be announced, with the latter scheduled for installation in the middle of the year. The projects are scheduled to commence in 2024 and are anticipated to become operational between the end of 2024 and the beginning of 2026 (Eixos, 2023).

Figure 3 - Veredas Sol and Lares floating solar power plant, in Minas Gerais (Cemig/Divulgação, 2023)

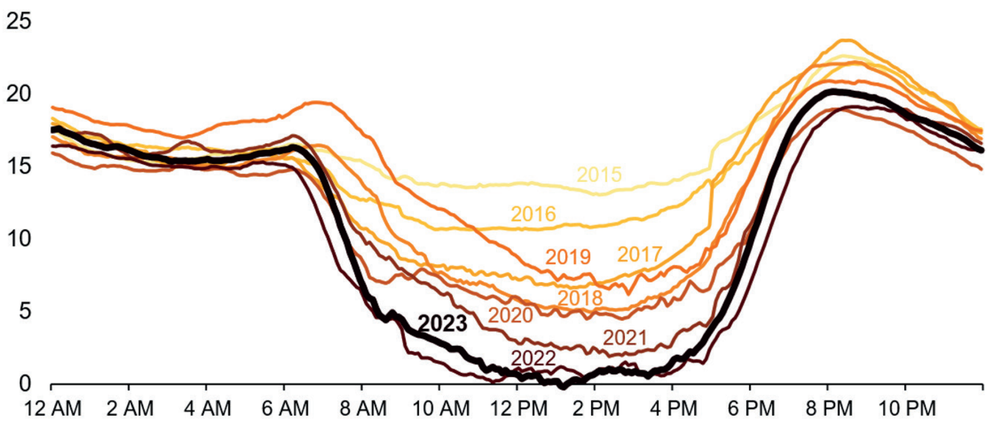
The photovoltaic panels will serve the function of integrating the hydroelectric plants into a hybrid system. The main advantage of this system is its capacity to generate energy during the daytime, thereby enabling the hydroelectric plant to serve as a form of energy storage during periods of heightened demand that exceed the capacity of the modules. Moreover, given the inherent variability in the supply of photovoltaic panels, it is essential to utilize hydroelectric power as a means of supplementing this instability.

Another noteworthy consequence is the prevention of evaporation from the reservoir bed. The capture of solar radiation by photovoltaic panels has the potential to significantly reduce this phenomenon. According to a recently developed research method by the National Water and Basic Sanitation Agency (ANA), launched in 2021, evaporation in the South and Southeast is estimated to be around 300 to 1000mm/year. The implementation of floating plants has the potential to reduce this evaporation by approximately 70%, according to ANA studies.

3. INTRODUCTION OF HOURLY ENERGY PRICING AND HYBRID POWER PLANTS

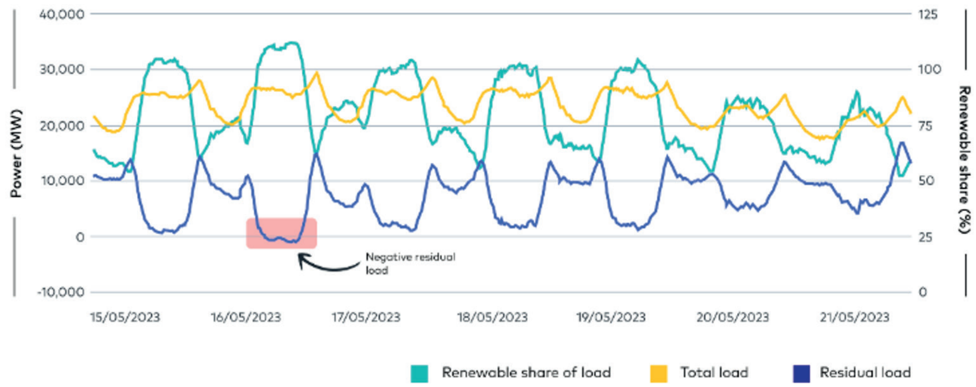
The potential of hybrid plants to facilitate the acceleration of the energy transition is well documented. A primary characteristic of the energy transition process in the electricity sector is the proliferation of intermittent renewable energy sources. In other words, these are sources whose generation cannot be controlled and depends on the primary source of energy, such as the sun or wind. In particular, the significant proliferation of distributed solar generation has a considerable impact on the load curve characteristics of electricity systems. The generation of electricity from distributed solar sources results in a significant reduction in centralized energy demand during the daytime hours. However, this has led to a notable challenge in the ramping up of centralized generation between 4 p.m. and 8 p.m. This alteration in the demand curve has become known as the Duck Curve (Figure 4). The illustration of the transformation in energy demand characteristics with the spread of distributed solar energy is provided by the evolution of the daily energy demand curve in California. As solar capacity in California continues to grow, the midday drop in net load is decreasing, presenting challenges for grid operators, as can be seen in Figure 4.

Figure 4 - Illustration of the evolution of the net load in California with the spread of distributed solar energy (GW) (CAISO, 2023).



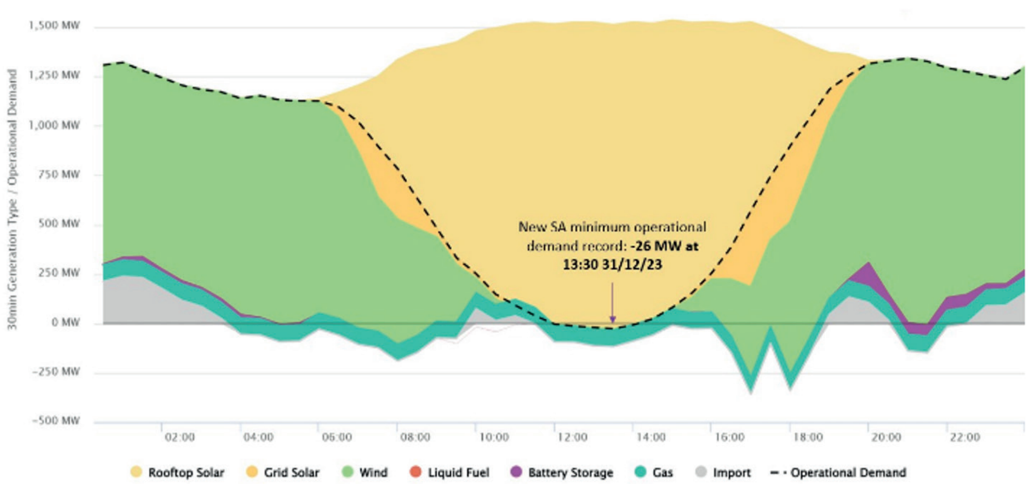
Another illustrative case of the transformation of the electricity demand curve is that of Spain. Figure 5 illustrates the emergence of a negative residual demand in May 2023. In other words, the supply of renewable energy exceeded total energy demand for a few hours of the day. Indeed, the residual public electricity load reached -1.3 GW on the afternoon of May 16. Just a few hours later, the residual load (total load minus energy generated from variable renewable sources) increased to almost 15 GW, with renewables only covering 62% of demand.

Figure 5 - Net electricity generation in Spain in May 2023 (GRIDX, 2023)



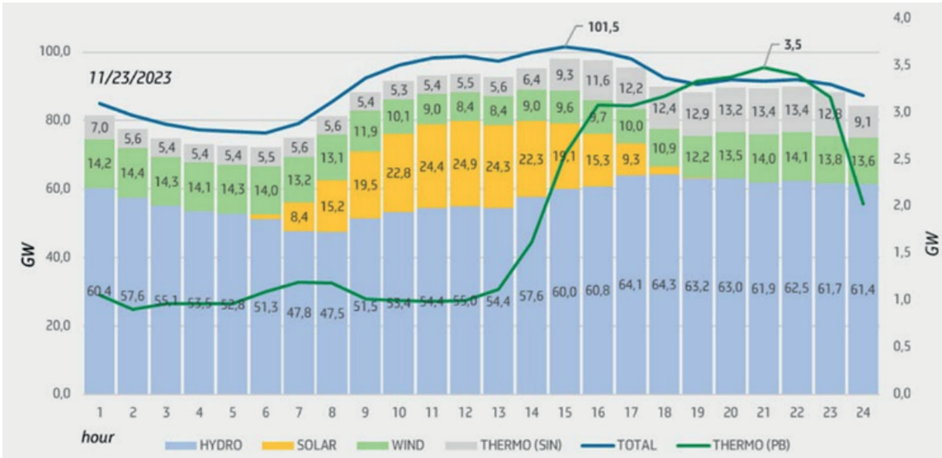
In addition, the case of Australia can be referenced as a further example. As reported by the Australian Energy Market Operator (AEMO), on December 31, 2023, negative demand was observed in South Australia and Victoria. As illustrated in Figure 6, distributed solar generation surpassed total demand by 26 MW. This phenomenon occurred on a day with temperate temperatures and clear skies, providing optimal conditions for solar energy generation by photovoltaic panels. Daily wholesale electricity prices on the same day exhibited negative values, averaging -$66.54 ($/MWh) and -$73.02 ($/MWh) in South Australia and Victoria, respectively.

Figure 6 - Electricity generation in May 2023 in South Australia (AEMO Energy, 2024).



In the case of Brazil, the proportion of solar and wind energy in the system remains insufficient to meet the total load. Nevertheless, the influence of renewable energy sources on residual energy demand is already considerable. The report, entitled “Deep Dive Petrobras 2024,” examined the data provided by the National Electricity System Operator (ONS) regarding energy demand and consumption in Brazil on November 23, 2023. Figure 7 illustrates the fluctuations in demand for thermal generation throughout the day.

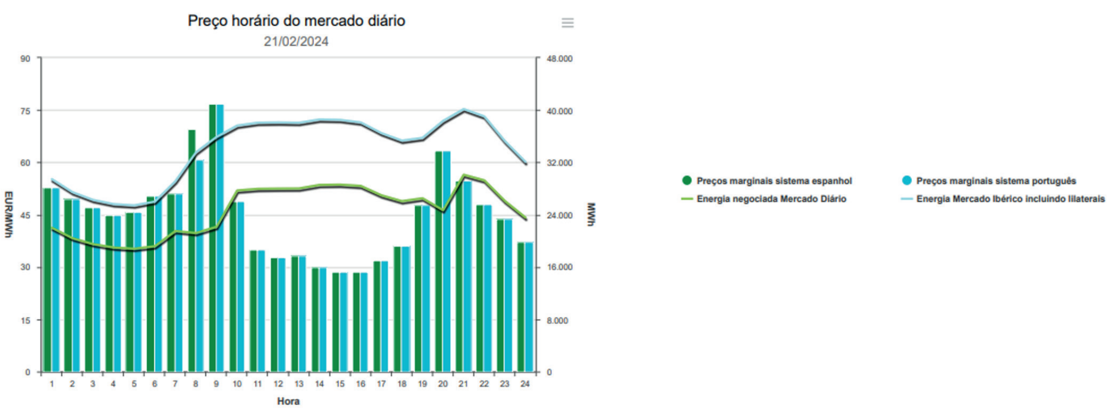
Figure 7 - Residual demand for thermoelectric generation on November 23, 2023 (Petrobras, 2024).



The advent of the Duck Curve has had a profound impact on the design of electricity markets, with a consequent shift towards a greater emphasis on the valuation of generation flexibility and energy storage. In other words, different countries have altered how energy is priced on the wholesale market, with the implementation of hourly pricing systems. In this system, the price of energy tends to fluctuate in accordance with the load curve, with the greatest fluctuations occurring during periods of peak demand (i.e., the duck’s neck). This is due to the necessity of dispatching more expensive sources of energy or storing energy during these periods. The introduction of new pricing mechanisms for ancillary services to guarantee supply during periods of high demand represents an additional aspect of the trend to revise electricity market designs.

Figure 8 illustrates the hourly energy prices on the spot market in Portugal and Spain on February 21, 2024. The graph demonstrates that the price of energy in the early morning, late afternoon, and early evening can be more than double the price of energy during the daytime, when solar energy generation is high.

Figure 8 - Hourly energy prices on the spot market in Portugal and Spain - February 21, 2024 (OMIE, 2024).



In January 2021, the Brazilian electricity market introduced hourly pricing, with the CCEE calculating the daily Difference Settlement Price (PLD) for each hour of the following day. This was based on the Marginal Operating Cost (CMO), considering the application of the maximum (hourly and structural) and minimum limits in force for each calculation period and for each submarket. The PLD serves as a reference price for the settlement of discrepancies between contracted and actual energy generation and consumption. However, due to the prevailing surplus of structural generation capacity in Brazil, the hourly PLD has exhibited minimal variation over the past two years. PLD values have consistently remained at the minimum level for all hours of the day.

The advent of hourly energy pricing has caused a significant economic impact on electricity generation. Generation systems that are capable of offering energy at times of higher prices possess a markedly different economic value than those that are only able to generate at times of low prices. One method of increasing the value of electricity generation plants is to hybridize the system, which entails integrating generation capacity from disparate technologies or even energy storage systems Hybridization can facilitate the provision of continuous energy supply, enhancing resilience and enabling the sale of energy at times of high prices.

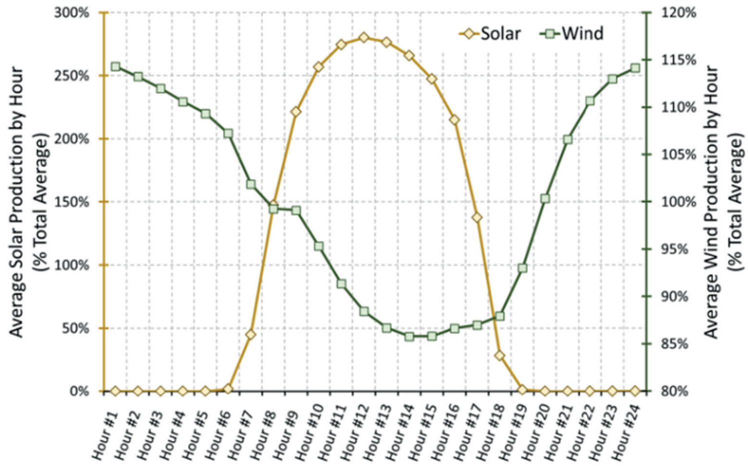
One of the primary advantages of hybrid power plants is their capacity to generate energy during periods of peak demand, when energy prices are typically higher. For instance, solar energy can be generated during the daytime, when electricity demand is typically high and prices are elevated, considering local climate variations and the time of day. Similarly, wind energy can be generated at night, when demand still exists. This ability to generate or store energy at strategic times allows hybrid power plant owners to optimize energy sales, supplying excess energy precisely when prices are highest or saving it when the price is lowest. This not only increases revenue but also enhances the profitability of the venture. Therefore, hybrid power plants represent an attractive option for investors seeking to maximize their return on renewable energy investments.

4. HYBRID SYSTEM AS AN OPTION TO REDUCE NETWORK USAGE COSTS

A significant benefit of generating and distributing energy through hybrid systems is the reduction in the cost of utilizing the transmission and distribution system (TUST, or Tariff for Use of the Transmission System, and TUSD, or Tariff for Use of the Distribution System). The aforementioned tariffs are calculated based on the contracted transmission and distribution capacity. It is imperative that the contracted capacity is sufficient to meet the generation peak. A generator with a low capacity factor will result in an increased cost of TUST and TUSD per MWh produced.

The combination of two energy sources, such as wind and solar, whose generation curves are considered to be almost opposite, especially in the case of Brazil, allows the generator to produce a greater amount of energy with the same contracted transmission and distribution capacity. Figure 9 illustrates de coupling of solar and wind power generation. Solar power generation exhibits a distinct diurnal pattern, with the highest output occurring during the day, starting around 9:00 a.m., and declining around 5:00 p.m. In contrast, wind power generation occurs between 6:00 p.m. and 6:00 a.m. the following day.

Figure 9 - Average hourly generation profiles of typical wind and solar energy units in the northeastern region of Brazil as a percentage of their historical average (historical records from July 1, 2019 to September 20, 2021) (LAMPS PUC-Rio).



It is thus possible to combine the two technologies in a hybrid plant in order to create an optimized energy curve, which demonstrates that it is feasible to meet daily demand throughout the 24 hours of the day, rather than just at specific times. By optimizing the generation process, it is possible to enhance the Transmission System Usage Amount (MUST), thereby facilitating an optimized demand for energy production and distribution.

Another potential avenue for exploration is the integration of batteries in conjunction with solar and wind technologies. This approach could lead to a reduction in the Distributed Energy Power provided for in the Transmission System Use Contract (CUST), with the surplus energy being stored in batteries. This would allow for the optimization of energy sales throughout the day, irrespective of the time.

Furthermore, an increased capacity factor directly contributes to a reduction in transmission and distribution costs. This phenomenon occurs because the infrastructure utilized for transmission and distribution is sized to accommodate peak generation. Consequently, a generator with a low capacity factor incurs costs associated with a substantial contracted capacity that is only utilized during limited periods. By enhancing the capacity factor through hybridization or integration with storage technologies, the same contracted infrastructure is more efficiently utilized, thereby reducing the cost of energy transported per unit. This enhanced efficiency in network asset utilization leads to a reduction in the per-MWh cost of TUST and TUSD, thereby enhancing the overall economic viability of hybrid power plants and contributing to an improvement in grid stability and resilience.

5.HYBRID POWER PLANTS AS A WAY TO DECARBONIZE AND REDUCE COSTS OF ISOLATED SYSTEMS

Another significant application of hybrid power plants is their use in the decarbonization of isolated electricity systems. The prevailing technological standard for meeting energy demand in isolated systems is the utilization of fuel oil or diesel-based generation. Hybrid power plants can play a crucial role in the decarbonization of isolated systems by integrating renewable energy sources with storage solutions. These systems can reduce diesel dependency, lower operational costs, and contribute to sustainability goals.

The Ministry of Mines and Energy (MME) has established the “Energias da Amazônia” program with the objective to reduce the utilization of diesel oil in the isolated power systema in the Amazon Region, which will consequently lead to a diminution in greenhouse gas emissions. These systems provide electricity to cities and towns that are not connected to the National Interconnected System (SIN), as is the case for the majority of the country.

Moreover, the program strives to ensure the reliability and security of the electricity supply for over 3.1 million individuals who rely on isolated systems. These systems provide electricity to cities and towns that are not connected to the National Interconnected System (SIN), as is the case for the majority of the country. This measure represents one of numerous actions undertaken within the context of the energy transition, with the dual objective of enhancing the quality of life for the population and facilitating the development of the Amazon region, while simultaneously contributing to a reduction in greenhouse gas emissions.

The Ministry of Mines and Energy (MME) has initiated a new auction process to contract supply solutions for isolated systems, aiming to enhance energy reliability while integrating more renewable sources. The auctions, scheduled for December 2025, will contract 49 MW of power to serve approximately 169,000 people in the Amazon region. The contracts will be valid for 15 years, with energy delivery starting on December 20, 2027 (CanalEnergia, 2024).

A key innovation in this auction is the requirement that at least 22% of the contracted energy must come from renewable sources. This encourages hybrid solutions that combine thermal generation with solar, wind, or energy storage technologies. Additionally, project developers must consider load modulation, fuel logistics, and environmental impact. Another provision allows for the decommissioning of thermal plants after five years if the region is later connected to the SIN. The auction will be conducted as a competitive process where bidders submit technical and economic proposals, with contracts awarded to the most cost-effective and sustainable solutions (CanalEnergia, 2024).

The initiative is of great importance for the sustainability and energy efficiency of the region, and it also contributes to a reduction in the costs of the Fuel Consumption Account (CCC), a subsidy to cover all or part of the cost of the fuel used to generate electricity in isolated systems, thus guaranteeing affordable tariffs for consumers in these remote regions.

The deployment of hybrid power plants represents a promising approach for integrating intermittent renewable energy sources and storage technologies (solar, wind, biomass, mini-hydro, batteries) with thermoelectric power. In other words, the hybridization strategy can be employed to minimize thermoelectric generation and emissions, while guaranteeing energy security and reliability for the system.

The competitiveness of hybrid systems with batteries is contingent upon the cost of energy storage, which can present a significant challenge. Nevertheless, there are locations where this solution can be cost-effective due to the high cost of thermal generation. In numerous locations, the financial and logistical costs associated with fuel supply are considerable, while generation efficiency is relatively low. This creates an opportunity for the implementation of hybrid renewable solutions that offer a cost-effective alternative, as highlighted in the report developed in partnership with World Bank (WORLD BANK, 2023).

An example of this context can be found in the Pacific Islands, the Caribbean, and Cayman, where the price of energy ranges from approximately $0.20 to $0.60 per kWh. It is also noteworthy that sub-Saharan Africa represents another location where the majority of energy generation is based on fossil fuels, and where energy tariffs are comparatively favorable in comparison to those observed in island contexts. In both cases, the use of solar power plants with batteries, despite their high cost, can be considered commercially competitive in comparison to the energy provided by fossil fuels (WORLD BANK, 2023).

The Barbers Point project in Hawaii, which is coordinated by the Department of Hawaiian Home Lands (2018), achieved a levelized tariff of $0.112/kWh. This was achieved under a single capacity contract model that integrates 15 MWp of solar energy with 15 MW/60 MWh of four-hour battery storage capacity. In Morocco, the Noor Midelt project, which combines solar photovoltaics with concentrated solar power and five-hour thermal storage, achieved a tariff of $0.07/kWh under a mixed contract.

The energy supply on the island of Fernando de Noronha is currently maintained by a variety of sources, including diesel, fuel oil, and natural gas. The primary source of energy is the diesel thermoelectric plant, designated as UTE Tubarão. It is comprised of three 1,286 kW generating units and a 1,120 kW diesel generator set, resulting in a total capacity of 4,978 kW. Furthermore, a contingency generator park (capacity of 2,293 kW) may supply power when needed. In addition to the energy generated by UTE Tubarão, the island also benefits from photovoltaic solar energy (EPE, 2021).

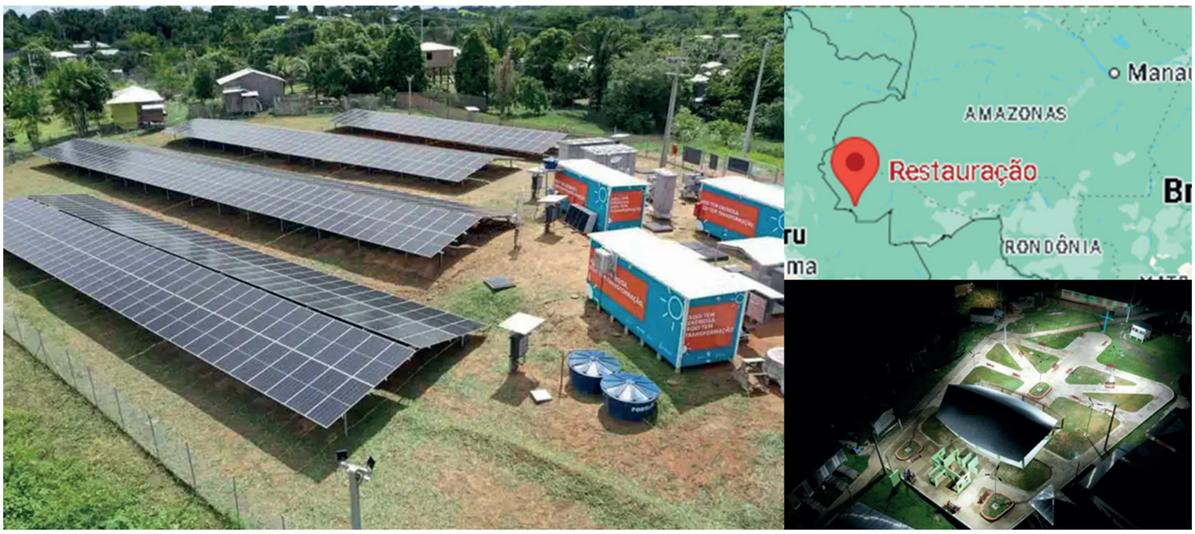
The Noronha I plant commenced operation in July 2014, contributing with an installed capacity of 402 kWp. Subsequently, in July 2015, the Noronha II plant was inaugurated, increasing the installed capacity to 550 kWp. Currently, the Aeronautics Command and the island's administration are responsible for the plants, respectively. Figure 10 illustrates the spatial distribution of photovoltaic plants in Fernando de Noronha. The energy generated by these plants is integrated into local demand and deducted from the amount of energy to be supplied by the local distributor, Neoenergia.

Figure 10 - Location of photovoltaic plants and solar panels in Fernando de Noronha (Iberdrola/Divugation, 2022).

Vila Restauração is a municipality located on the border with Peru in the state of Acre. Before the implementation of a more robust electric infrastructure, the electricity supply was characterized by significant deficiencies and limitations. The town was previously supplied by a diesel generator, the cost of which was borne by the residents and the town hall of Marechal Thaumaturgo (557 km from Rio Branco). The lack of electricity resulted in significant challenges for the 200 families residing in the village. These challenges included the disruption of refrigeration systems used to preserve food and the reliability of healthcare systems in hospitals. In 2019, Energisa assumed responsibility for the Vila Restauração Microgrid project.

Figure 11 depicts the hybrid system that was implemented as part of this initiative. Given the project's location, it was necessary to transport the system components by truck from ports in the southern and southeastern regions of Brazil to the city of Cruzeiro do Sul (AC). Subsequently, the components had to be transported by ferry to Vila Restauração.

Figure 11 - Remote system installed in Vila Restauração, Acre (REENERGISA, 2023).



The hybrid microgrid addressed the supply security concerns of a remote community through the implementation of a photovoltaic solar energy system (325 kWp, 580 panels) coupled with lithium-ion batteries (3 modules, 828 kWh of storage capacity), biodiesel emergency generators, and biodigesters (RENEEGISA, 2023). This solution has resulted in a 60% reduction in energy costs for the community, along with a guaranteed supply 24 hours a day.

In summary, while the logistics of implementing hybrid systems in isolated regions may be complex, the aforementioned projects have demonstrated efficacy in addressing energy reliability concerns, reducing costs, and contributing to greenhouse gas emission reduction.

6. TECHNICAL CHALLENGES FOR IMPLEMENTING HYBRID POWER PLANTS AND PRACTICAL RESEARCH AGENDA

Implementing hybrid power plants across diverse energy systems presents several technical challenges. These include the integration of multiple energy sources, the need for advanced control systems to manage variability, and the requirement for significant infrastructure investments. Pilot plants serve as experimental strategies to address these challenges by allowing for the testing and validation of hybrid configurations under controlled conditions, thereby facilitating the optimization of system performance before large-scale deployment.

The integration of hybrid power plants into the national electricity system presents a promising avenue for innovation. This is because the optimal hybridization strategy for generation systems must be determined through an analysis of demand characteristics, hourly energy prices, and available generation sources. In light of the findings presented in this study, future research should focus on refining hybridization models to enhance energy efficiency, environmental attributes, and economic viability. Additionally, further investigation of regulatory frameworks in which plants may be inserted is necessary to ensure that hybrid systems can be operated optimally, facilitating their widespread adoption and scalability. It is thus imperative to develop simulation and optimization models that facilitate the dimensioning of hybridization strategies. Moreover, there is an opportunity to assess and implement decarbonization strategies for the hundreds of isolated systems throughout the country.

The Energy Institute of PUC-Rio is dedicated to making a significant contribution to the research agenda on hybrid power plants. Studies have been conducted on the development of expert systems capable of modeling their behavior and performance under various load conditions and tariff modes. An investigation of the experimental performance of a hybrid power plant pilot plant with solar photovoltaic (SPV) generation, natural gas (NG), battery storage, load banks, and grid coupling, utilizing a variety of simulations and load conditions has been carried out, to validate models in specialized software, taking into account a range of operational load scenarios. To this end, a hybrid pilot plant is being constructed on the premises of PUC-Rio in Xerém in collaboration with GALP and Petrogal Brasil. This pilot plant will be equipped with a 328 kWp SPV plant. A 320 kW load bank will be employed to simulate different load profiles, and a 138 kWh lithium-ion battery bank with a Battery Management System (BMS) that will communicate with the inverter and the supervisory system will be utilized. In regard to the natural gas system, a motor-generator of approximately 320 kW in continuous operation will be employed, which will also communicate with the supervisory system. The supervisory system is highly robust and will facilitate a multitude of experiments, including those conducted in island mode.

7. CONCLUSION

The increasing adoption of hybrid power plants represents a strategic advancement in the energy transition, providing a flexible, efficient, and economically viable solution for electricity generation. The integration of different energy sources within a single system helps mitigate the intermittency of renewable sources, optimize the use of existing infrastructure, and reduce operational costs and environmental burdens. The following conclusions can be drawn.

The Duck Curve has been identified as a significant profit opportunity for hybrid power plants, as it underscores the necessity for flexible generation to meet demand during periods of high consumption variability.During daylight hours, high solar generation reduces the demand for energy from other sources, resulting in low or even negative electricity prices in certain markets. However, in the late afternoon and early evening, when solar generation experiences a decline and demand surges, electricity prices undergo a substantial increase. Hybrid power plants that integrate renewable sources with storage or thermal generation can optimize their profits by strategically storing energy during low-cost periods and releasing it during high-demand hours, when electricity is more expensive. This operational strategy enables revenue maximization, ensures reliable supply, and contributes to grid stability, making it a compelling solution from both technical and economic standpoints.

Additionally, the capacity factor of hybrid power plants plays a crucial role in reducing operational costs and increasing the efficiency of the electrical system. By combining different energy sources, such as solar, wind, thermal, and storage, these plants can operate at a higher capacity factor than standalone plants, optimizing the use of installed infrastructure. This increased utilization reduces the need for additional investments in backup generation and lowers costs related to transmission and distribution system usage fees. Additionally, by improving generation predictability and reducing dependence on intermittent sources, hybrid power plants provide greater stability to the electrical system, decreasing the need for dispatching more expensive sources, such as fossil fuel-powered thermal plants. As a result, in addition to making energy generation more competitive, these plants contribute to a more efficient and sustainable power sector.

Additionally, hybrid power plants can play a crucial role in decarbonizing isolated systems by decreasing fossil fuel dependence and promoting a more sustainable energy supply. The technical, regulatory, and economic challenges that remain can be overcome through improved simulation models, optimized public policies, and technological advancements, positioning hybrid power plants as a definitive solution for future power systems.

The study presented reinforces the importance of research and the development of experimental projects, such as the pilot plant at the Energy Institute of PUC-Rio, to validate hybridization models and strategies. Through controlled experiments, it is possible to analyze the technical and economic feasibility of different hybrid configurations, ensuring their large-scale application with more reasonability than just counting on simulations already widespread in literature. Furthermore, regulation must evolve alongside these advancements, promoting incentives for hybrid technology integration and ensuring these systems remain competitive in the energy market.

Thus, the adoption of hybrid power plants can accelerate the global energy transition, contributing to a more resilient, sustainable, and accessible future for all.

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