Power System Flexibility Integrating Intermittent Renewable Energy: a Seven-Steps new Approach

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***Abstract*—Renewable and intermittent energy sources are currently managed as complementary to the thermohydraulic system. This paper proposes a new approach to the management of the National Energy System. A qualitative analysis was conducted to identify existing strengths and weaknesses, supporting the development of short, medium, and long-term planning, considering current legal and contractual constraints.**

***Index Terms*—Renewable energy, Photovoltaic power, Wind power, Distributed energy, Management, Strategic prospective, Long-term planning, Environmental impacts**

I. Power System Operation under High Penetration of Variable Renewable Energy

The global energy transition is accelerating the deployment of renewable energy, particularly solar and wind power, commonly referred to as Variable Renewable Energy (VRE). This transformation fundamentally changes the structure and operation of power systems and requires new approaches to address the resulting operational, economic, and regulatory challenges. This scenario is particularly important for smart city programs because it can create opportunities for the local economy, as can be seen in the Brazilian north-east with wind power and large energy-consuming initiatives such as data centers.

A significant body of literature has addressed the technical aspects of integrations of renewable energy, including forecasting, grid stability, and electricity market design. In parallel, regulatory institutions and system operators—such as the Brazilian National System Operator (ONS)—have produced numerous reports that examine operational and policy challenges associated with increasing renewable penetration [1]. The Brazilian power system offers a particularly relevant case, given its historically high share of hydropower combined with the rapid expansion of wind and solar generation in recent years. As the share of Variable Renewable Energy (VRE) increases, maintaining system flexibility becomes a central requirement for reliable power system operation [2] [3] [4]. In this context, system flexibility can be understood as the ability of the power system to respond to variability and uncertainty in both electricity supply and demand [2]. However, these contributions are often fragmented, focusing on specific technical, economic, or regulatory dimensions. Consequently, studies that adopt a systems approach capable of synthesizing these perspectives and providing a broader understanding of the structural challenges involved in management of power systems with high shares of VRE, remain needed.

In this context, the present study examines the challenges associated with the integration of intermittent renewable energy from a systemic perspective. Drawing on academic literature and institutional documents, the paper analyzes factors that limit system flexibility, the economic and environmental implications of renewable expansion, and potential strategies to enhance the operational adaptability of power systems.

International experience demonstrates that system flexibility can successfully support high shares of renewable generation. Denmark, for example, has achieved large-scale wind integration through regional interconnections, flexible electricity markets, and coordinated system operation [5].

II. Methodology

This study adopts an exploratory qualitative conceptual research approach, based on literature review and document analysis, with the objective of developing a systemic understanding of the challenges associated with the integration of intermittent renewable energy sources into national power systems.

The research is grounded on two main categories of sources. The first consists of academic literature on power system operation, renewable integration, and system flexibility. The second includes institutional and regulatory documents produced by organizations responsible for the regulation, planning, and operation of the electricity sector.

The collected materials were examined using qualitative document analysis, a method widely applied in policy and institutional studies to interpret and synthesize information contained in textual sources [6]. The analysis identifies recurring themes and factors affecting system flexibility under increasing renewable penetration.

Rather than developing a specific quantitative model, the study adopts a systems approach to synthesize dispersed knowledge from academic and institutional sources. This approach enables the identification of interactions between operational, economic, environmental, and regulatory dimensions associated with the integration of intermittent renewable energy sources. The objective is to provide a systemic understanding of the power system as a whole, highlighting the structural challenges and potential strategies for increasing system flexibility in the context of growing renewable energy penetration. [7]

III. The Context of Renewable Energy Expansion

According to data from the National Electric Energy Agency (ANEEL), as of August 2025, the installed electricity generation capacity in the National Interconnected System (SIN) was 236.0 GW [8]. The breakdown of this power generation by energy source is shown in Table 1.

TABLE I
ENERGY SOURCE [8]

Source	Power (GW)	%
Hidraulic	110	46,5%
Eolic	29,5	12,5%
Thermal	43,9	18,6%
Nuclear	1,9	0,8%
Other Sources	2,4	1,0%
PV centr.+ MMGD	48,4	20,5%
TOTAL	**236,0**	**100,0%**

One notable fact in this table is the size of photovoltaic generation, at 48.4 GW, or 20.5% of total capacity. Of this total, the largest share comes from Mini and Micro Distributed Generation (MMGD), consisting mainly of residential systems [9]. The installed capacity in MMGD is 42.3 GW, corresponding to approximately 18% of the country's total generation. This sector is growing very rapidly, having been practically negligible until 2017, as shown in Figure 1.

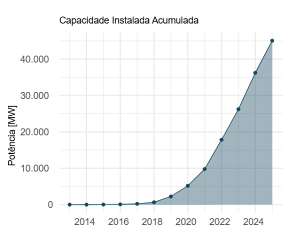

Fig. 1. Growth of MMGD [9]

It is worth noting that the ONS, which manages the dispatch of power plants, has no control over this portion of the grid. Typically, this type of system feeds power into the grid during the day and draws power from it at night—a phenomenon already observed in other locations, such as California.

There is a seasonal complementarity between wind and biomass energy sources and hydroelectric power generation. Winds are strongest in the summer and spring, whereas rainfall is light during those seasons. Thus, wind energy could serve as a source to supplement part of hydroelectric power generation during the dry season [10], [11].

Power generation using sugarcane biomass—the primary fuel source for this type of energy—also exhibits favorable seasonality that helps offset periods of drought; however, this effect is less pronounced. Plantations in the Northeast exhibit seasonality that is the opposite of that in the Southeast and Midwest, which reduces this buffering effect [11].

Other types of biomass have been underutilized, such as animal and municipal waste [10] [12].

IV. Regulatory and Contractual Restrictions

The regulatory and contractual framework of Brazil's energy market was designed around a hydro-thermal model, in which only hydroelectric and thermal power plants were in operation [13]. The National Interconnected System (SIN) is operated by ONS, which determines which plants will generate power and how much each can supply. The operational decision-making process takes into account the merit order (in short, lowest marginal cost) and simulations of future hydrological scenarios. These scenarios may lead to the dispatch of thermal power plants to ensure water reserves in the reservoirs [13].

Contracts for hydroelectric plants are generally established through public auctions (A-4, A-6) with terms of 15 to 30 years, based on a fixed amount of energy delivered. The plants factor into their pricing the risk of water scarcity or reduced generation as determined by the ONS [14].

With the commissioning of intermittent renewable energy plants (wind and solar), this model is being disrupted. Hydroelectric plants see their generation reduced due to the low cost of intermittent sources, yet hydro plants are not compensated for this. Since their contracts are for the delivery of a fixed amount of energy, they are forced to purchase electricity to pass on to their customers instead of producing it themselves [14].

Although this operation benefits society by conserving water in reservoirs, it creates a financial deficit for the plants, which are not compensated for providing this flexibility.

Another key factor is legislative interference through the inclusion in laws of the obligation to contract inflexible thermal power plants. Mandatory dispatch, regardless of high marginal costs and environmental impact, raises the overall cost of electricity and makes the operation of the entire system more complex.

This development also introduces disruptive elements. Photovoltaic generation already accounts for a significant portion of capacity (18% of total generation capacity) [9]. This generation is not managed by the ONS and disrupts system management. Residential storage was regulated only recently by ANEEL Resolution 1000/2021 and had to await equipment certification by INMETRO, meaning that the first projects using this technology have only recently begun to emerge. The high cost of batteries remains a barrier to their implementation in homes, and there is no incentive policy in place for this.

V. Operational Challenges

Given this situation, operating the SIN is becoming increasingly challenging. The growth in centralized intermittent generation is occurring mainly in the northeast of the country, but the deployment of transmission lines is not keeping pace

[12]. The federal government has plans to build data centers in that region so that the energy demand will not require new transmission lines [15], with public funding from the BNDES, but the projects are still in the environmental permitting phase.

The timeline for deploying transmission lines is longer than that for building power plants [12], which poses a planning challenge. When this is combined with regulatory restrictions, it becomes necessary to forcibly curtail intermittent power plants due to excess generation that cannot be transmitted.

Another major challenge is that a significant portion — about 18% of installed capacity [8] — consists of MMGD, without oversight by the ONS. There is no remote monitoring of these units; only bidirectional meters have been installed, with no electronic communication with the distributors' operations centers.

In addition to limiting generation management, these local generation sources cause problems for power distributors regarding voltage control because, by feeding power into the grid, they cause voltage spikes for nearby consumers. In Brazil, distribution transformers typically lack automatic voltage regulation. Generally speaking, the only way to compensate for a voltage increase due to distributed generation would be a manual adjustment of the transformers, which is impractical given their number and the size of the grid. Furthermore, when generation ceases, this compensation can be excessive.

Add to this the fact that there are rapid ramp-downs of photovoltaic generation units at the end of the day and the sudden fluctuations that can occur in both wind and solar plants, making management by the ONS quite complex. Rapid action and means to compensate for these effects are necessary.

Addressing these challenges will increasingly depend on digitalization technologies, including smart meters, IoT-based monitoring devices, advanced communication networks, real-time data analytics, and automated control systems. These technologies improve visibility of distributed generation resources and enhance the operational flexibility of the power system.

VI. Economic Implications

Limitations in coordinated planning in Brazilian power system are detrimental to the country as a whole due to the inability to coordinate complex nationwide projects. In 2012, the country had 26 power generation projects in the Northeast (Ceará, Rio Grande do Norte and Bahia) that were ready to begin production but lacked transmission lines. This situation resulted in a loss of R$263 million in 2013 (R$485 million in 2025, or US$92.5 million) paid by the federal government to the power plants [16]. In the following years, these transmission lines were finally built, and these power plants were integrated into the national grid.

In 2025, it was necessary the curtailment of wind power generation reaching levels of up to 20% of installed capacity, which amounts to approximately 26,000 GWh — an estimated economic impact of R$6.5 billion (US$1.22 billion).

The main causes are the lack of adequate transmission infraestructure with sufficient capacity to carry this energy to the south/southeast region, which consumes a large portion of this energy, suggesting that the bottleneck has shifted [17].

The study by Herrera et al. [12] demonstrates that the mean construction time for a wind farm is 1.6 years, whereas the mean construction time for a transmission line is 4 years. This discrepancy is attributable to a number of factors including permitting and land acquisition processes. This underscores the necessity to initiate a project with the installation of the transmission line, subsequently followed by the implementation of wind power generation facilities, thereby ensuring the synchronised completion of construction works.

The system is predominantly based on hydropower (63.9%), complemented by thermal generation (24.49%), forming what is known as a thermo-hydropower system [13]. The utilization of thermal generation may result in a more expensive and polluting scenario when petroleum-derived fuels are employed. Intermittent sources are integrated into the system in a complementary manner.

The circumstances that arose in 2013, which compelled the government to finance wind energy that had not been actually produced, resulted in a modification of the regulations. Consequently, the responsibility was shifted to the generator to ensure the supply of energy, as stated in [12]. The consequence of this was an elevated risk associated with new projects and, consequently, an increase in the cost of capital.

According to Signor's research [18], Brazil is installing an increasing amount of energy capacity but is unable to consume, store, or transport it due to structural limitations, creating the paradox of renewable abundance with negative systemic impacts, including effects on end consumers.

VII. Environmental Implications

This section addresses the environmental impacts of the main components of the electrical power system: hydropower plants, thermal power plants, wind energy, solar energy, and transmission lines. In this approach, the concept of Life Cycle Assessment (LCA) [19], which evaluates the complete lifecycle of materials from extraction to the production of inputs and equipment, was not adopted. Instead, the focus is primarily on the impacts related to the implementation and operation of these energy system units.

The remaining hydropower potential is concentrated in regions with low hydraulic head, which implies large flooded areas and significantly increases environmental impacts [20]. On the other hand, run-of-river hydropower plants present high variability in generation, as their output depends on river flow, which varies significantly across seasons. For example, the Santo Antônio power plant has an installed capacity of 3,500 MW during the rainy season and produces only 490 MW during the dry season. In contrast, these variations occur over longer time scales when compared to the intermittency of wind and solar generation, making hydropower suitable for complementarity within the system [21].

The environmental impact of fossil-fuel-based thermal power plants is well established in the literature [22], although their use remains necessary.

The study by Lúcia Cipponelli Pinto et al. [23] identifies environmental impacts related to noise, electromagnetic interference, and effects on bird populations, but reports that these issues have been mitigated and reduced over time. Regarding social impacts, the study discusses land use and community-related aspects, arguing that operating permits should consider the specific conditions of each case, aiming in particular to foster development in less affluent regions.

Rafael Junqueira [24] conducted a Life Cycle Assessment in a case study of a photovoltaic generation and found a value four times lower than that obtained for the Brazilian electricity matrix.

Regarding the construction of transmission lines, Odete Campos, from BNDES, in her study on the Amazon region, highlights impacts on areas of native vegetation, conservation units, indigenous lands, and permanent preservation areas, in addition to several engineering challenges related to construction and socio-environmental aspects. The study recommends that bidding processes for such projects should only take place after obtaining preliminary environmental permits, in order to reduce risks related to both cost and schedule [25].

The national energy matrix still relies on approximately 34% of oil and its derivatives, mainly due to their use in transportation. Regarding the electricity matrix, although Brazil presents advantages compared to other countries, the establishment of a target to achieve 100% renewable energy is highly important, particularly because in the coming years there will be increasing pressure to shift from oil to electricity, driven by the electrification of vehicle fleets.

VIII. A Framework for Increasing System Flexibility

The proposed resolution to the previously delineated problems involves an alteration in the philosophy of energy management, proposed as a seven-point framework described below and presented in Table II:

(1) Hydropower as Strategic Reserve: Hydroelectric plants should progressively shift from continuous baseload generation toward a flexibility-oriented role, acting as strategic energy reserves capable of compensating renewable intermittency through rapid dispatch and energy storage in reservoirs [4]. This approach reduces dependence on thermal generation and increases system resilience.

(2) Priority Dispatch of Renewable Energy : Wind and solar generation should receive operational priority whenever technically feasible, minimizing curtailment and reducing overall system emissions and operational costs [26]. This requires updated dispatch criteria and regulatory adaptation.

(3) Hybrid Renewable Systems: The integration of complementary sources — such as wind, solar, biomass, and Battery Energy Storage Systems (BESS) — can reduce intermittency and improve dispatchability [27]. Hybrid systems also optimize transmission infrastructure utilization and increase operational reliability.

(4) Gradual Reduction of Oil-Fired Thermal Plants: Oil-based thermal generation should be progressively phased out due to its high operational costs and environmental impacts [26]. Existing facilities may undergo conversion to lower-carbon fuels, including biofuels, when technically viable [28].

(5) Compensation Mechanisms for Flexibility Services: Hydroelectric plants currently provide flexibility without adequate compensation. New regulatory mechanisms should compensate for ancillary services, reserve capacity, and water storage preservation, recognizing hydropower as a strategic balance asset [29].

(6) Distributed Generation Integration: The rapid expansion of distributed generation requires modernization of grid

TABLE II
Framework for Increasing System Flexibility

Strategy	Short-Term Actions	Medium-Term Actions	Long-Term Objective
Hydropower as Strategic Reserve	Review dispatch criteria and reservoir management policies	Implement flexibility-oriented operation models	Consolidate hydropower as the main balancing resource
Priority Dispatch of Renewable Energy	Update operational and regulatory dispatch rules	Reduce renewable curtailment through coordinated planning	Establish renewables as the primary energy source
Hybrid Renewable Systems	Promote projects combining wind, solar, biomass, and BESS	Create financing and auction mechanisms for hybrid systems	Deploy hybrid and dispatchable renewable systems
Gradual Reduction of Oil-Fired Thermal Plants	Limit new investments in oil-fired generation	Replace aging plants through renewable energy auctions	Phase out oil-based thermal generation from the electricity matrix
Compensation Mechanisms for Flexibility Services	Develop ancillary services remuneration mechanisms	Implement flexibility compensation models	Establish a flexibility market for system operation
Distributed Generation Integration	Expand monitoring and smart metering infrastructure	Implement smart grids and distributed storage	Integrate distributed generation into system management, enabling smart city applications through smart grids, advanced metering, and distributed storage.
Structured Transition Strategy	Adapt regulations without breaking existing contracts	Replace fossil generation and modernize infrastructure	Consolidate a flexibility-oriented low-carbon electrical system

management through smart grids, monitoring systems, and distributed storage solutions [2]. Regulatory incentives should encourage the coordinated integration of distributed energy resources into system operation.

(7) Structured Transition Strategy: Implementation should occur through a phased transition process combining short- medium- and long-term measures. Initial actions include modernization incentives and regulatory adaptation, followed by gradual replacement of fossil-based generation and full integration of flexibility-oriented operational models. Transparent governance and stakeholder coordination are essential to minimize regulatory uncertainty and economic disruption.

Several elements of this framework are consistent with international experiences in renewable integration and system flexibility. This framework seeks to provide a structured basis for increasing power system flexibility while supporting the large-scale integration of renewable energy sources.

IX. Concluding Remarks

This paper presented a comprehensive overview of the current state of the Brazilian Electrical System, highlighting that the increasing integration of intermittent energy sources demands a paradigm shift in system management. This transition requires coordinated changes at both the public policy and technical levels, including the adoption of advanced technologies. It represents a long-term challenge that must be addressed with consistency and strategic vision in order to prevent future systemic constraints.

Seven proposals were introduced, each requiring further refinement through detailed studies and quantitative simulations to properly assess their feasibility and potential impact.

In this context, the management and expansion of distributed energy generation open new opportunities for Smart Cities, which can play a pivotal role at the national level by implementing policies that actively promote and support these initiatives.

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