



EFFICIENCY AND SUSTAINABILITY OF PERMANENT MAGNET SYNCHRONOUS GENERATORS IN THE EXPANSION OF BRAZILIAN WIND ENERGY

Eficiência e sustentabilidade: o papel dos geradores síncronos de ímã permanente na expansão da energia eólica brasileira

Eficiencia y sostenibilidad: el papel de los generadores síncronos de imán permanente en la expansión de la energía eólica brasileña

Maria Manuela Almeida Dias Silva¹ & Rafael Santos Freire Ferraz^{2*}

¹ Universidade Federal do Piauí, Centro de Tecnologia ² Universidade Federal do Piauí, Centro de Ensino Aberto e a Distância

¹maria.almeida.ma@ufpi.edu.br ^{2*}rafael.ferraz@ufpi.edu.br

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* Corresponding Author: Ferraz, R. S. F.

ABSTRACT

In recent decades, wind energy has become one of the fastest-growing renewable sources worldwide, driven by the need to diversify energy matrices, reduce carbon emissions, and advance turbine technologies. In this context, comparative studies are essential to assess the performance and feasibility of different technologies. This study analyzes the application of Permanent Magnet Synchronous Generators (PMSG) in the expansion of Brazilian wind energy, focusing on efficiency, sustainability, and economic viability. The PCC (Population, Concept, and Context) framework was adopted to formulate the main research question: how do PMSG compare to DFIG in terms of technical, economic, and sustainable performance in the context of wind power expansion in Brazil? Based on this approach, an integrative literature review was conducted to compare the techno-economic performance of PMSGs and Doubly-Fed Induction Generators (DFIG). Results indicate that PMSGs typically achieve higher efficiency (94–96% versus 91–93%), mainly due to the absence of excitation losses and gearboxes. The direct-drive configuration can reduce maintenance costs and improve reliability. Although PMSGs require higher initial investment, they tend to present lower LCOE over their lifecycle, especially in Brazil, where capacity factors range from 45% to 60%. Additionally, full-power converters enhance grid stability.

RESUMO

Nas últimas décadas, a energia eólica tornou-se uma das fontes renováveis de crescimento mais rápido no mundo, impulsionada pela necessidade de diversificar as matrizes energéticas, reduzir as emissões de carbono e avançar nas tecnologias de turbinas. Nesse contexto, estudos comparativos são essenciais para avaliar o desempenho e a viabilidade de diferentes tecnologias. Este estudo analisa a aplicação de Geradores Síncronos de Ímã Permanente (PMSG) na expansão da energia eólica no Brasil, com foco em eficiência, sustentabilidade e viabilidade econômica. O framework PCC (População, Conceito e Contexto) foi

adotado para formular a questão norteadora da pesquisa: como os PMSG se comparam aos DFIG em termos de desempenho técnico, econômico e sustentável no contexto da expansão da geração eólica no Brasil? Com base nessa abordagem, foi realizada uma revisão integrativa da literatura para comparar o desempenho socioeconômico dos PMSGs com os Geradores de Indução Duplamente Alimentados (DFIG). Os resultados indicam que os PMSGs normalmente apresentam maior eficiência (94–96% em comparação com 91–93%), principalmente devido à ausência de perdas de excitação e de caixas de engrenagens. A configuração direct-drive pode reduzir os custos de manutenção e aumentar a confiabilidade. Embora os PMSGs exijam maior investimento inicial, tendem a apresentar menor Custo Nivelado de Energia (LCOE) ao longo do ciclo de vida, especialmente no Brasil, onde os fatores de capacidade variam de 45% a 60%. Além disso, conversores de potência total contribuem para a melhoria da estabilidade do sistema elétrico.

RESUMEN

En las últimas décadas, la energía eólica se ha convertido en una de las fuentes renovables de más rápido crecimiento a nivel mundial, impulsada por la necesidad de diversificar las matrices energéticas, reducir las emisiones de carbono y avanzar en las tecnologías de turbinas. En este contexto, los estudios comparativos son esenciales para evaluar el rendimiento y la viabilidad de diferentes tecnologías. Este estudio analiza la aplicación de Generadores Síncronos de Imanes Permanentes (PMSG) en la expansión de la energía eólica en Brasil, con énfasis en la eficiencia, la sostenibilidad y la viabilidad económica. El marco PCC (Población, Concepto y Contexto) fue adoptado para formular la pregunta principal de investigación: ¿cómo se comparan los PMSG con los DFIG en términos de desempeño técnico, económico y sostenible en el contexto de la expansión de la generación eólica en Brasil? Con base en este enfoque, se realizó una revisión integradora de la literatura para comparar el desempeño socioeconómico de los PMSG con los Generadores de Inducción Doblemente Alimentados (DFIG). Los resultados indican que los PMSG suelen alcanzar una mayor eficiencia (94–96% frente a 91–93%), principalmente debido a la ausencia de pérdidas de excitación y de cajas de engranajes. La configuración direct-drive puede reducir los costos de mantenimiento y mejorar la fiabilidad. Aunque los PMSG requieren una mayor inversión inicial, tienden a presentar un menor Costo Nivelado de Energía (LCOE) a lo largo de su ciclo de vida, especialmente en Brasil, donde los factores de capacidad varían entre 45% y 60%. Además, los convertidores de potencia total mejoran la estabilidad del sistema eléctrico.

INTRODUCTION

Electricity production has undergone profound transformations in recent decades, driven by the need to diversify the energy matrix, reduce greenhouse gas emissions, and seek more efficient and reliable renewable sources. In this scenario, wind energy constitutes one of the most promising avenues for clean and sustainable generation. Historically, harnessing wind energy dates back millennia, with windmills and pumps being used since antiquity. According to the U.S. Energy Information Administration (2023), records indicate that, around 5,000 BC, vessels were already using wind as a driving force on the Nile River, and later, structures such as pumps and windmills were used in China and the Middle East for irrigation and grain grinding. Over time, the technology evolved and, in the 20th century, wind turbines began to directly convert wind into electricity, inaugurating a new era of electricity generation through wind power.

The modern wind energy industry consolidated itself during the final decades of the 20th century, with significant advances in turbine size and efficiency. Early commercial wind turbines typically had rated capacities between 20 and 60 kW, whereas multi-megawatt machines, including 5 MW turbines, became commercially available by the late 2000s (EWEA, 2009). In parallel, global cumulative installed wind power capacity reached approximately 197 GW in 2010 (GWEC, 2011). These developments demonstrate the technological maturity and growing importance of wind energy in the global electricity sector.

The development of wind energy in Brazil has grown significantly in recent decades, driven by the need to diversify the energy matrix and expand the participation of renewable sources. The year 2024 ended with 1103 plants and 33.7 GW of installed wind power, which represented a growth of 10.8% compared to December 2023, when the installed capacity was 30.4 GW. The new installed wind capacity made the wind source reach a share of 16.1% of the Brazilian electricity matrix, which shows the participation of all generation sources in the Brazilian electricity matrix at the end of 2024 (ABEEólica, 2025).

Wind turbine technology has evolved substantially, especially regarding conversion systems and the types of generators employed. Studies show that variable-speed machines, especially permanent magnet synchronous generators (PMSGs), exhibit greater efficiency, better performance in variable wind regimes, and higher power density (Chen et al., 2019; Polinder et al., 2006).

In the Brazilian context, which has some of the best wind regimes in the world, with capacity factors frequently between 45–60% (EPE, 2023), the use of high-efficiency machines becomes even more crucial. The technical literature indicates that PMSGs, due to operation with full-power converters, offer more robust control, greater stability, and better response to transient events when compared to doubly fed induction generators (DFIGs). The PMSG stands out for its higher energy conversion efficiency, with rates that can exceed 95% under nominal conditions, compared to the typical 90-92% of the DFIG (Hansen; Michalke, 2008). In addition, the PMSG demonstrates better performance in variable wind regimes, allowing for a faster and more precise response to wind speed fluctuations, while maintaining stability in energy generation (Chen et al., 2019). Another crucial advantage is the higher power density, enabling more compact and lightweight wind turbines with the same nominal capacity, reducing structural and logistical installation costs (Hansen; Michalke, 2008).

The adoption of PMSGs faces significant technological and economic challenges. The initial cost is 10–20% higher than that of DFIGs due to the price of rare-earth magnets (neodymium-iron-boron), the global supply chain of which is highly concentrated and susceptible to geopolitical and market fluctuations (IRENA, 2023). Additionally, the environmental impacts of rare-earth mining and the technical challenges associated with recycling magnets at the end of the turbines' service life represent critical issues for the technology's long-term sustainability (IPCC, 2022).

Furthermore, the global energy transition and national decarbonization policies demand technologies capable of delivering greater stability, reliability, and energy efficiency, characteristics strongly associated with PMSGs. Thus, the choice of this topic is justified by the technical, economic, and environmental relevance of this type of generator and by its potential to contribute to the advancement of the Brazilian electricity matrix and to the development of more modern, efficient, and sustainable wind farms.

Therefore, this work presents a comparative analysis between PMSG and DFIG, focusing on their applicability in the Brazilian energy context. The research addresses the technical fundamentals of both technologies, highlighting the advantages and disadvantages of each in terms of efficiency, reliability, and integration into the electricity grid. In addition, the work presents a comparative economic analysis, considering installation, operation, and maintenance costs, as well as the levelized cost of energy (LCOE). Finally, the prospects for implementing PMSG in Brazil are discussed, considering the current energy matrix, the technological, regulatory, and supply chain challenges, as well as the opportunities to consolidate wind energy as a fundamental pillar of the Brazilian energy transition.

THEORETICAL FRAMEWORK

WIND ENERGY IN BRAZIL

Wind energy occupies a strategic position in the Brazilian electricity matrix due to the country's excellent anemometric conditions and the continuous technological advancement of installed turbines. By the end of 2023, the country had surpassed 26 GW of installed wind capacity, predominantly concentrated in the Northeastern region, which exhibits some of the highest capacity factors worldwide, often exceeding 50% in several wind farms (ABEEólica, 2025). According to the Energy Research Company (EPE, 2023), wind power already accounted for more than 14% of total national electricity generation, consolidating its position as the second largest renewable energy source in Brazil. This share continued to grow, reaching 16.1% in 2024 (ABEEólica, 2025).

DFIGs offer notable advantages for wind energy generation in Brazil, especially due to their technological maturity and initial cost 10-20% lower than PMSGs (IRENA, 2023), facilitating investments in large-scale projects. With a partial converter (approximately 30% of nominal power), they reduce expenses with power electronics and allow flexible operation in subsynchronous and supersynchronous regimes, adapting to variable winds. This configuration promotes efficient integration into the SIN network, with less dependence on critical materials such as rare earths, aligning with the 82% renewable matrix and ANEEL's goals for accessible and sustainable diversification (ABEEólica, 2025).

In the context of this expansion, a technological transition is observed in Brazil: the progressive replacement of wind turbines equipped with DFIG by the more modern PMSG. The first generation of Brazilian wind farms, especially between 2008 and 2016, predominantly used DFIG machines due to their good initial cost-benefit ratio and lower need for power converters (Ackermann, 2012). However, technological evolution and operational demands of the electricity grid have increasingly favored the adoption of PMSG.

WIND TURBINE GENERATOR TECHNOLOGIES

The choice of generator technology is a key factor in the design and operation of modern wind turbines, as it directly affects efficiency, reliability, maintenance requirements, and grid integration performance. In this context, the generators used in wind energy conversion systems can be broadly classified into two main technologies: DFIG and PMSG. Each presents distinct operational characteristics and technical trade-offs, making their comparative assessment essential, particularly in the Brazilian context, where high-capacity factors and expanding deployment scenarios demand robust and efficient solutions. In comparative terms, PMSGs offer several advantages over DFIGs, as discussed below:

- Greater overall efficiency, especially at low wind speeds, due to the absence of rotor losses, whereas DFIGs present additional losses in the slip rings and excitation system (Polinder et al., 2006);
- Greater mechanical reliability when integrated into direct-drive (DD) systems, which eliminate the gearbox, a critical component responsible for a significant portion of failures in DFIG-based turbines (Polinder et al., 2006; Sheng, 2013);
- Full control via power electronic converters, enabling improved performance under low-voltage ride-through (LVRT) conditions and better integration into the National Interconnected System (NIS). DFIGs, operating with partial-scale converters, are more vulnerable under these conditions (Chen et al., 2019; ANEEL, 2017);
- Lower maintenance requirements, particularly in remote or hard-to-access wind farms, reducing operating expenditures (OPEX) over the project lifetime (Tavner et al., 2007; Sheng, 2013).

Although DFIGs remain widely used in wind farms, PMSG technology has gained increasing prominence in modern high-power turbines, particularly in direct-drive and offshore applications, due to its higher efficiency, reduced mechanical complexity, and improved controllability (GWEC, 2023). This technological transition aligns with the search for greater efficiency and reliability, especially considering the planned expansion into offshore environments (MME, 2024). The generators used in modern wind turbines can be classified mainly into two technologies: DFIG and PMSG. Each technology has characteristics that directly impact efficiency, maintenance, reliability, and suitability to the Brazilian wind regime.

DFIGs dominated the global wind power market during the years 2000–2015, as they require smaller converters and offer a good initial cost-benefit ratio (Burton et al., 2011). However, limitations related to the use of slip rings, a higher rate of mechanical failures in the gearbox, and inferior performance during LVRT have reduced their attractiveness in modern applications (Hansen; Michalke, 2008; Heier, 2014).

PMSGs emerge as a more efficient and robust solution, driven mainly by the evolution of rare earth magnets (such as neodymium-iron-boron) over the last few decades. This technology eliminates rotor losses, reduces mechanical vibrations, allows operation over a wide range of speeds, and achieves higher power density (Chen et al., 2019). Direct-drive configurations associated with PMSG have gained prominence in modern systems, especially in offshore wind farms, due to the elimination of the gear multiplier and consequent increase in reliability (GWEC, 2023). Studies demonstrate that these machines exhibit efficiencies exceeding 94–96% in nominal regimes, significantly surpassing DFIG systems (Polinder et al., 2006). Thus, the technological transition observed in the global wind power industry has consolidated PMSG as the predominant option in new large-scale projects, especially in regions with stable winds, such as the Brazilian Northeast.

CONSTRUCTION OF PMSG GENERATORS

The PMSGs used in wind turbines have an electromechanical configuration designed to maximize efficiency, power density, and reliability. Their classic structure consists of a rotor equipped with permanent magnets, usually of the neodymium-iron-boron (NdFeB) type, whose high magnetic flux density allows the generation of the field without the need for external excitation, eliminating losses associated with the field winding and making the system more efficient (Hansen; Michalke, 2008).

These magnets can be surface-mounted or inserted internally in the rotor, depending on the torque and speed requirements of the application, with both configurations being widely documented in PMSG designs applied to wind turbines. The stator, in turn, consists of three-phase windings distributed along the slots of the ferromagnetic core, where the induction of the electromotive force occurs due to the variation of the magnetic flux resulting from the relative movement between rotor and stator, according to the principles of Faraday's law (Chapman, 2012).

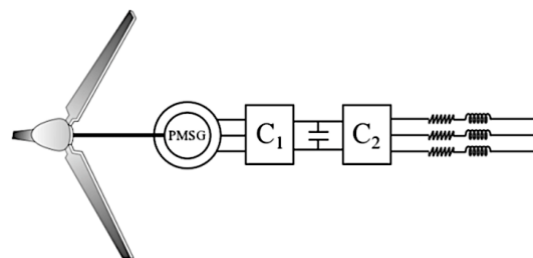
For integration into the electrical grid, PMSGs depend on a full converter type electronic interface, characterized by the converter-rectifier assembly on the generator side and the inverter on the grid side, connected by a DC (direct current) bus. This architecture processes 100% of the generated power and allows independent control of voltage, current, and frequency, giving the turbine greater operational flexibility, high capacity for active and reactive power control, and full decoupling between mechanical speed and grid conditions. This topology justifies the widespread adoption of back-to-back converters in variable speed wind systems equipped with PMSGs, being considered the state of the art in modern commercial turbines (UDESC, 2017).

In wind turbines equipped with PMSGs, two main mechanical configurations can be adopted: geared or direct drive. The use of a gearbox in turbines with PMSG is relatively uncommon, since the main advantage of this technology lies precisely in the possibility of operating at low speeds, eliminating the need to increase the mechanical speed of the rotor to drive the generator (Chen et al., 2019). The presence of the gearbox increases the number of mechanical components susceptible to failure, raises operating and maintenance (O&M) costs, and reduces system reliability. These factors contradict the benefits associated with the use of permanent magnets (Ackermann; Söder, 2002).

On the other hand, the direct-drive configuration has become the most widely adopted architecture in modern PMSGs, especially in large turbines and offshore applications. In this arrangement, the complete elimination of the gearbox results in greater reliability and less need for corrective and preventive maintenance, significantly reducing turbine downtime. Furthermore, direct-drive systems exhibit lower mechanical losses, higher overall efficiency, and longer lifespan of critical components, essential factors for remote and difficult-to-access environments, such as offshore wind farms (GWEC, 2023).

Figure 1 shows the complete architecture of a PMSG system integrated into the electrical grid. The permanent magnet synchronous generator converts the mechanical energy of the wind into electricity, which is processed by a full-power electronic converter. A critical component in this configuration is the line filter, which reduces harmonics and electromagnetic interference generated by the switching of the converter's semiconductors, ensuring that the energy injected into the grid meets the quality standards established by ANEEL and international standards such as IEC 61000 (Hansen; Michalke, 2008). The filter works through passive components, inductors and capacitors, which attenuate unwanted frequencies, allowing only the fundamental frequency (60 Hz) to be transmitted to the grid, essential for protecting sensitive equipment and maintaining the stability of the electrical system (IEC, 2016). This configuration consolidates the PMSG as a technically robust and environmentally compatible solution with the operating requirements in modern interconnected systems.

Figure 1. Diagram of a wind energy conversion system based on PMSG with back-to-back converters

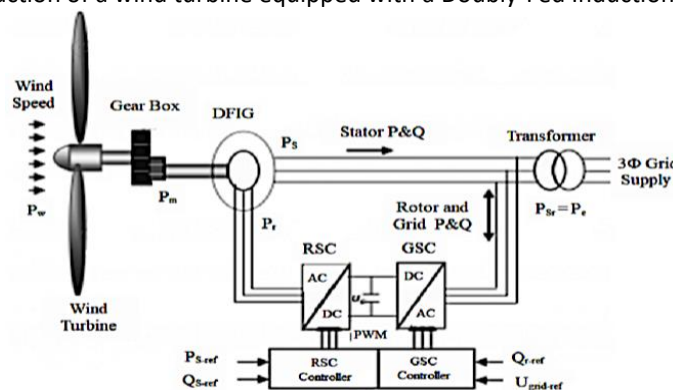


Source: Barros & Barros (2016).

CONSTRUCTION OF DFIG GENERATORS

Unlike the PMSG, the DFIG operates with the stator directly connected to the grid and the rotor powered by back-to-back converters, allowing independent control of active and reactive power. This enables variable speed operation with smaller converters, reducing costs and maintaining high efficiency in coupling to the electrical system. The Figure 2 shows the power flow between stator, rotor, and grid, as well as the operation of the RSC and GSC controllers responsible for power stability and quality (Pena et al., 1996).

Figure 2. Construction of a wind turbine equipped with a Doubly-Fed Induction Generator (DFIG)



Source: Omeje & Nnadi (2022). Highlighting its main subsystems: wind turbine, gearbox, generator, converters, and grid interface.

SUSTAINABILITY IN WIND POWER GENERATION

Sustainability has been one of the pillars of the expansion of global and Brazilian wind energy, given its strategic role in reducing greenhouse gas (GHG) emissions, decreasing the use of fossil fuels, and mitigating the environmental impacts associated with electricity generation. According to the Intergovernmental Panel on Climate Change (IPCC, 2022), wind energy is among the generation technologies with the lowest carbon footprint throughout its life cycle, presenting emissions on the order of 7 to 12 gCO₂/kWh, values much lower than thermal sources based on natural gas or coal.

In the Brazilian context, wind energy expansion directly contributes to the guidelines of the National Policy on Climate Change and to the decarbonization targets assumed by the country in the Paris Agreement (EPE, 2023). In addition to low emissions, modern wind turbines, especially those based on PMSG, have lower maintenance requirements and greater operational efficiency, reducing team travel and increasing the lifespan of components, which reduces indirect environmental impacts (ABEEólica, 2025).

Another relevant aspect is the territorial impact. Studies indicate that wind farms occupy less than 5% of the total installed area, as the land remains usable for agriculture and livestock (GWEC, 2023). This facilitates their integration into rural and semi-arid regions, promoting socio-economic development through leases, local jobs, and associated infrastructure.

The adoption of advanced technologies, such as direct-drive turbines with PMSG, further reinforces the sustainability of the chain, as it significantly reduces the use of lubricating oil, eliminates multiplier systems that are among the components with the highest failure rate and greatest waste generation, and decreases the frequency of parts replacement (Polinder et al., 2006). Waste reduction and the expansion of recycling techniques for blades, magnets, and metals have advanced substantially, according to the Wind Europe Sustainability Report (2020), indicating positive prospects for the European and global wind supply chain. Thus, the technological advancement associated with PMSG aligns not only with energy efficiency but also with the fundamental principles of sustainability, reinforcing the role of wind energy as a strategic vector for the Brazilian energy transition.

Although wind generation represents an essential renewable source for decarbonization, it presents significant challenges in terms of sustainability. In the turbine lifecycle, the extraction and processing of critical materials, such as rare earths in PMSG generators, generate high environmental impacts, including water pollution and habitat loss in mining. Furthermore, wind intermittency requires fossil backups for grid stability, potentially increasing indirect emissions, while the disposal of components at the end of their life (20-25 years) faces logistical and recycling barriers. This scenario highlights the need for innovations to mitigate environmental burdens and promote truly sustainable wind generation.

METHODOLOGY

RESEARCH APPROACH

This study adopts the PCC (Population, Context, and Concept) analytical approach to support the formulation of the guiding research question. Based on this framework, the scope of the study and its main analytical dimensions were clearly defined, enabling the development of a consistent and focused research question. Subsequently, the research was structured into

three sequential and interrelated stages, guided by the question established through the PCC approach.

- Population (P): Electromechanical conversion technologies for wind energy, with a specific focus on PMSG and DFIG, the two main technologies employed in modern wind turbines (Hansen; Michalke, 2008);
- Context (C): The accelerated expansion of wind power generation in Brazil, which grew from 25.63 GW in 2022 to 26 GW in 2023 and continues a growth trajectory, with prospects for the development of offshore energy and integration into storage systems (ABEEólica, 2025);
- Concept (C): The dimensions of analysis included are technical performance (efficiency, reliability, dynamic response), economic performance (CAPEX, OPEX, LCOE), and sustainability performance (environmental impact, critical materials chain, and regulatory compliance).

Therefore, the guiding question of this research is: how do PMSG compare with DFIG in terms of technical, economic, and sustainable performance, in the context of the expansion of wind power generation in Brazil? This question guided the investigation, supporting the comparative analysis between the two technologies and contributing to the identification of the solution best suited to the country's energy demands and energy transition objectives.

METHODOLOGICAL APPROACH

The theoretical and technical construction of this work was developed through bibliographic and documentary research, based on the survey and critical analysis of specialized publications, peer-reviewed scientific articles, reference books on wind systems, and technical reports from recognized institutions in the energy sector. Classic and updated works were consulted, such as Burton et al. (2011) and Heier (2014), to understand the operating principles of wind turbines, topologies of electric generators, and control systems applied to modern turbines.

The documentary analysis included a systematic review of institutional reports from the Energy Research Company (EPE), the Global Wind Energy Council (GWEC), and the Brazilian Wind Energy Association (ABEEólica), ensuring the representativeness of the national and international data used in the technical and economic foundation of the study.

SOURCES AND PERIOD OF ANALYSIS

The period analyzed spans from 1996 to 2025, encompassing a phase of strong expansion of wind energy worldwide and particularly in Brazil. This timeframe allows us to observe the technological evolution of wind turbines, the growth in the use of PMSG machines, the expansion of installed capacity, and the development trends of the global wind industry. The sources consulted include:

- Scientific articles indexed in specialized databases, such as Scopus, IEEE Xplore, and ScienceDirect, as well as studies identified through Google Scholar;
- Annual reports from institutions in the energy sector, such as EPE, ABEEólica, and GWEC;
- Technical publications from international associations, including IRENA and IPCC;
- Government data on installed capacity and capacity factor.

ANALYSIS METHOD

The data extracted from documentary sources were analyzed using a comparative and interpretative method, organized into three main dimensions:

- a) Technical analysis: comparing operational performance (efficiency, power curves, reliability) between PMSG and DFIG technologies;
- b) Economic analysis: evaluating feasibility indicators (LCOE, operating and maintenance costs, return on investment) in different scenarios;
- c) Contextual analysis: examining the suitability of PMSG technology to the characteristics of the Brazilian wind regime and the national energy matrix.

This methodological approach not only justifies the choice of PMSG technology but also demonstrates the coherence between its adoption and the current needs of the national electricity sector, providing technical and scientific robustness to the conclusions of the work.

INCLUSION/EXCLUSION CRITERIA

The search terms used were: "PMSG wind energy", "DFIG wind turbine comparison", "permanent magnet synchronous generator", "direct-drive wind turbine", "wind energy Brazil", "permanent magnet synchronous generator", and "technology comparison", combined using Boolean operators.

Inclusion criteria covered: (a) peer-reviewed articles published in indexed journals; (b) technical reports from recognized institutions (EPE, ABEEólica, GWEC, IRENA, IPCC); (c) publications in English and Portuguese; (d) the period from 1996 to 2025; and (e) studies presenting comparative quantitative data on wind turbine generator technologies. Excluded items were: (a) non-peer-reviewed articles; (b) publications lacking quantitative data or substantive technical analysis; and (c) opinion pieces lacking scientific grounding.

The selection procedure consisted of: (1) initial screening based on title and abstract; (2) full-text reading of pre-selected articles; and (3) systematic extraction of comparative data regarding efficiency, costs, reliability, and environmental impact. In total, 63 potentially relevant studies were initially identified; of these, 37 were selected for full-text reading, and 25 were ultimately cited in this article, alongside supplementary institutional reports

RESULTS AND DISCUSSION

TECHNICAL EFFICIENCY OF PMSG

PMSGs offer superior energy performance compared to DFIG machines, mainly due to their electromagnetic topology and the absence of components associated with additional losses. Since they do not have a rotor winding fed by slip rings, a typical characteristic of DFIGs, PMSGs eliminate ohmic and thermal losses in the excitation circuit, resulting in greater overall efficiency, especially in weak wind conditions, where relative losses represent a significant portion of the converted power (Burton et al., 2011). In addition, the direct drive, common in PMSG turbines, reduces mechanical losses associated with friction, wear, and dissipation in the gearbox, improving efficiency across the entire operating range (Ackermann, 2012).

Several studies demonstrate that PMSGs can achieve efficiencies greater than 94–96%, depending on the rated power, magnetic geometry, and manufacturer. Studies report that eliminating rotor losses and operating in full converter mode contribute to increased efficiency at both partial load and nominal regimes (Hansen; Michalke, 2007). This high

efficiency is also directly reflected in the power curve, which is enhanced by the ability to operate in variable speed mode, allowing the wind turbine to maintain the optimal relationship between torque, rotor speed, and wind speed – an essential condition for maximizing the power coefficient (C_p) (Heier, 2014).

The use of high-performance electronic power converters enables precise vector control of current, voltage, and load angle, allowing the generator to operate continuously at the maximum energy capture point through maximum power point tracking (MPPT). This results in a smoother power curve, with better performance in low and medium intensity winds and higher annual energy production (AEP) when compared to DFIG-based wind turbines, especially in variable wind regime environments (GWEC, 2023). Therefore, the combination of high electromechanical efficiency, absence of excitation losses, and advanced control via full converter consolidates PMSG as one of the most efficient architectures in the modern wind industry.

ECONOMIC ANALYSIS AND RELIABILITY

Although wind turbines equipped with PMSG have an acquisition cost between 10% and 20% higher than turbines equipped with DFIG, mainly due to the price of NdFeB-based permanent magnets and the more advanced electromagnetic design, their life-cycle cost analysis (LCA) shows a significant economic advantage. The literature demonstrates that direct-drive systems with PMSG present a significant reduction in O&M costs, since they eliminate the mechanical multiplier, a component responsible for up to 30% of severe failures in large wind turbines. This mechanical simplification reduces the need for corrective and preventive interventions, increases turbine availability, and reduces logistical expenses, especially relevant in offshore or remote wind farms (Söder et al., 2011).

In addition to mechanical reliability, turbines based on PMSG have lower electromagnetic losses, since they do not have a rotor winding and do not require excitation current. Studies indicate that DFIG machines can lose up to 2–3% of the converted energy in the excitation system alone, while in PMSG, this is practically eliminated (Burton et al., 2011). The superior overall efficiency, typically 94–96%, compared to 91–93% for DFIG, translates directly into a higher capacity factor and greater annual energy produced (AEP), which increases revenue over the turbine's lifespan (Hansen; Michalke, 2007).

In the Brazilian context, the economic benefits are even more evident. Brazil has one of the best wind regimes in the world, with capacity factors frequently between 45% and 60%, especially in the Northeast, values well above the global average, which ranges between 25% and 35% (EPE, 2022). In these scenarios of strong and stable winds, turbines with PMSG operating at variable speed can capture a significantly greater amount of energy, since they maintain the operating point close to the maximum power coefficient ($C_{p,max}$), even under rapid wind oscillations. Thus, even with a higher initial investment, the payback time tends to be reduced due to higher energy production and lower operating costs.

In analyses of wind power projects carried out in the Brazilian Northeast, it was observed that the adoption of direct-drive turbines with PMSG reduces accumulated maintenance costs by up to 25–35% over 20 years and increases energy production by up to 6–10%, depending on the local wind regime (ABEEólica, 2025). When these variables are incorporated into economic feasibility models, such as LCOE, PMSG wind turbines often demonstrate lower LCOE than DFIG machines, especially in parks with a high-capacity factor, as is typical in Brazil. Therefore,

the implementation of wind turbines with PMSG in the country presents a consistent technical and economic justification, aligning energy efficiency, long-term reliability, and maximization of return on investment.

ALIGNMENT WITH THE BRAZILIAN ELECTRICITY GRID

The adoption of wind turbines equipped with PMSG strongly aligns with the guidelines and structural characteristics of the Brazilian energy matrix, internationally recognized for its high participation of renewable sources. According to the National Energy Balance, more than 82% of the electricity generated in Brazil comes from renewable sources, mainly hydroelectric, wind, solar, and biomass, a percentage substantially higher than the world average, which remains around 28% (EPE, 2023; IEA, 2023). In this context, the expansion of PMSG turbines directly contributes to fulfilling the country's climate commitments, especially within the framework of the Paris Agreement and the UN Sustainable Development Goals, by expanding the energy supply without increasing emissions associated with the electricity sector. The greater efficiency and higher annual production of these wind turbines become essential to maintain the sustainable growth of wind power's share in the national matrix, favoring a long-term decarbonization trajectory.

In addition to the environmental aspect, the adoption of PMSG meets the need to increase installed capacity while maintaining the reliability and stability of the electrical system. Brazil faces challenges related to water seasonality, which can drastically reduce hydroelectric power generation in drought years.

The expansion of high-efficiency wind turbines, especially in regions with constant winds and low turbulence, such as the Northeast, serves as an important instrument for energy security. Wind turbines with PMSG, due to their operation with full-frequency converters, have greater control capacity over active and reactive power, contributing to grid stability and compliance with grid code requirements, especially during disturbances and voltage dips (Hansen; Michalke, 2007; Heier, 2014).

Another point of great relevance is the characteristic of the Brazilian wind regime, especially in the Northeast, where stable trade winds predominate, with low turbulence and high persistence. Studies indicate capacity factors frequently exceeding 50–60%, values that further enhance the use of high-efficiency machines such as PMSGs, since the greater energy extracted from the wind accelerates the economic return and optimizes the LCOE (ABEEólica, 2023). In these environments, the variable speed control of PMSGs and the absence of a gearbox ensure greater robustness, less wear and greater technical availability, reducing unscheduled downtime and maximizing generation.

Finally, the projected expansion of offshore wind farms in Brazil, especially in the Northeast and South regions, further reinforces the importance of PMSG technology (MME, 2024). Offshore operation requires equipment with high reliability, low maintenance needs and high resistance to aggressive environments, characteristics inherent to direct-drive wind turbines with PMSGs, which eliminate the most critical component in terms of failures and logistical costs: the gearbox. International reports indicate that direct-drive technology already dominates approximately half of new offshore projects in leading countries such as the United Kingdom, China, and Germany (GWEC, 2023). Thus, the adoption of PMSG is consistent with the future trend of the Brazilian electricity matrix, preparing the country for an efficient and economical integration of offshore generation.

LIMITATIONS OF PMSG TECHNOLOGY

Despite the technical and economic advantages presented in the previous sections, PMSG technology has significant limitations that demand careful analysis.

First, the initial cost (CAPEX) of wind turbines equipped with PMSG is 10–20% higher than that of DFIG systems—a difference attributed primarily to the price of neodymium-iron-boron (NdFeB) permanent magnets and the more sophisticated electromagnetic design (IRENA, 2023). This cost differential can represent a significant financial barrier for projects with budget constraints or those in emerging markets; indeed, reliance on rare earth materials constitutes the most critical vulnerability of PMSG technology. The global NdFeB supply chain is heavily concentrated in China, which accounts for approximately 60–70% of global rare earth production (GWEC, 2023). This geopolitical concentration exposes manufacturers and operators to risks regarding price fluctuations, export restrictions, and supply instability.

From an environmental perspective, rare earth mining and processing generate significant ecological impacts, including heavy metal water contamination, the generation of radioactive waste (thorium and uranium associated with the ores), and habitat degradation (IPCC, 2022). Although the lifecycle carbon footprint of PMSGs is lower than that of DFIGs when operational phases are considered, the initial impact of extracting critical materials cannot be overlooked. Finally, recycling permanent magnets at the end of the turbines' service life (20–25 years) still presents technical and economic challenges (Chen et al., 2019). Only around 1% of rare earth elements from end-of-life products is currently recycled, mainly because of difficulties related to collection, dismantling, separation, material recovery, and economic viability (Cherkezova-Zheleva et al., 2024). End-of-life permanent magnet recycling remains limited, constrained by collection rates below 15% and challenging economic conditions (IEA, 2024). This scenario highlights the need for innovations in direct recycling techniques and circular economy policies to ensure the long-term sustainability of the technology.

SYNTHESIS OF THE ANALYSES

Table 1 presents a comparative summary of the main technical, economic, and environmental attributes of PMSG and DFIGs, synthesizing the key findings obtained in this study; the columns highlight key categories, specific details of each technology, and practical implications for wind power expansion in Brazil.

Table 1. Comparison of Technical, Economic, and Environmental Attributes of PMSG and DFIG

Category	PMSG Details	DFIG Details	Implications
Operational efficiency	94-96%; Lower losses	91-93%; Higher O&M due to gearbox	PMSGs optimize operation under strong wind conditions (Northeast Brazil: 45-60% capacity factor)
Initial impacts (manufacturing)	High (REEs: +20-30% GWP due to mining/pollution)	Lower (copper/steel; no rare earth elements)	Mitigated by Brazil's 82% renewable energy mix; initial vs. long-term trade-off
Life cycle assessment (LCA)	Balance between operation and end-of-life	Higher burden during operation	Holistic LCA: PMSGs are more sustainable for decarbonization (NDC 2050)
O&M and cost	25-35% lower maintenance; lower LCOE; initial cost +10-20%	Higher maintenance; similar initial LCOE	Economic advantage in high-capacity projects; support for offshore expansion (700 GW potential in Brazil)
End of life	Rare Earth Elements (REE) recycling: 90% recovery; reduces resource depletion	Simpler disposal, but with resource loss	Recommendation: invest in recycling and ANEEL policies

Source: Authors (2025).

CONCLUSION

This research analyzed the relevance and application potential of PMSG-equipped wind turbines within the context of Brazil's wind energy expansion, considering aspects such as efficiency, sustainability, control, performance, and economic viability. Based on a literature review and a technical comparison with DFIG systems, it became evident that PMSG technology represents a significant advancement for the national wind energy sector.

The results demonstrated that PMSG systems achieve efficiencies between 94% and 96% surpassing the 91-93% range of DFIG systems primarily due to the elimination of excitation losses and a reduction in mechanical components, specifically the absence of gearboxes (Hansen & Michalke, 2007; Burton et al., 2011). This technical superiority translates into higher annual energy generation and better utilization of Brazilian wind regimes, which record capacity factors between 45% and 60% in the Northeast region (EPE, 2022; ABEEólica, 2023).

The direct-drive architecture characteristic of PMSG systems proved crucial for high mechanical reliability, reducing operation and maintenance costs by 25–35% compared to conventional technologies (GWEC, 2023). Integration via full-power converters and advanced control systems including MPPT provides PMSG systems with greater operational flexibility and stability in the face of electrical disturbances; these are essential characteristics for secure integration into the National Interconnected System (Heier, 2014).

From an environmental perspective, PMSG systems were found to contribute to sustainability by reducing energy waste, extending equipment lifespan, and minimizing impacts associated with mechanical failures. Although the use of NdFeB permanent magnets presents challenges regarding reliance on rare-earth materials, significant advances in recycling practices and supply chain optimization have been identified that mitigate these concerns (Chen et al., 2019).

From an economic perspective, the study found that although the initial cost of PMSG systems is 10-20% higher than that of DFIG systems, this technology shows a trend of reducing the LCOE over the project lifecycle, making it particularly advantageous in high-capacity-factor scenarios like Brazil's (Söder et al., 2011). This economic advantage is amplified in the context of the expanding free energy market and the pursuit of long-term solutions with stable costs.

This study presents limitations that should be explicitly stated. First, it is a literature review rather than a study involving original numerical simulation; consequently, the quantitative data presented reflect the consulted literature rather than experimental results. Second, the economic analysis was based on generic scenarios reported in both international and domestic literature, rather than on primary data from specific Brazilian projects. Additionally, the comparison did not delve into detailed regional variations outside the Brazilian context, nor were sensitivity analyses conducted regarding extreme fluctuations in rare-earth prices or different regulatory scenarios.

The combination of excellent wind conditions, the demand for operational reliability, and grid control requirements positions PMSG technology as a strategic asset for the Brazilian electricity sector over the coming decade. It is recommended that policies incentivizing technological innovation and programs aimed at developing the domestic supply chain prioritize PMSG technology to consolidate Brazil's leadership in renewable energy.

FUTURE PROSPECTS

The implications of this research extend to both the practical and theoretical realms of the Brazilian wind energy sector. From a practical standpoint, the results provide insights for technology selection in new projects, offer criteria for investment decisions regarding onshore and offshore wind farms, and contribute to the formulation of public policies aimed at modernizing the national wind power infrastructure. Theoretically, the study expands

knowledge regarding the application of PMSGs in tropical conditions, develops methodologies for comparing technologies, and provides a basis for sustainability assessment in wind projects.

To advance this topic, it is suggested that future research: (a) investigate the operational performance of PMSGs under wind regimes specific to Northeast Brazil using computer simulation; (b) analyze the rare-earth supply chain within the national context and propose economically viable recycling alternatives; (c) develop hybrid system models integrating PMSG-based wind energy and solar photovoltaics with storage; (d) conduct a comparative life cycle assessment (LCA) of PMSGs and DFIGs under Brazilian climatic and regulatory conditions; and (e) explore financing and incentive mechanisms for the adoption of PMSGs in both the regulated and free energy markets.

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