ENERGY TRANSITION AND RARE EARTH ELEMENTS: CHALLENGES, OPPORTUNITIES, AND PROSPECTS

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Abstract

The global energy transition requires significant advances in the efficiency, power density, and reliability of electromechanical systems. In this context, rare earth metals play a strategic role in the manufacture of high-performance electrical machines, such as permanent magnet synchronous motors (PMSMs) and wind generators. This study aims to analyze the influence of these materials on the electromagnetic performance of modern electrical machines. The methodology is based on a systematic literature review involving the analysis of publications issued between 2018 and 2025 and indexed in databases such as Scopus, ScienceDirect, and IEEE Xplore, complemented by mathematical modeling. Recent data indicate that global demand for rare earth elements increased from approximately 78 kt in 2021 to about 93 kt in 2023 and is projected to reach 134 kt by 2030 (IEA, 2024). The results show that NdFeB magnets can increase torque density by up to twofold and reduce electrical losses by approximately 40%. It is concluded that these materials are essential to the energy transition, although they pose challenges related to the geographic concentration of production and supply-chain risks.

Keywords: Energy efficiency, Energy transition, Electrical machines, Power density, Rare earth elements.

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INTRODUCTION

The global energy transition has driven changes in electricity generation and use systems, requiring technologies that are more efficient, compact, and sustainable. In this context, Electrical Engineering plays a fundamental role in the development of high-performance electrical machines, renewable generation systems, and advanced electromagnetic devices (Alves; Silva, 2022).

Among these technological advances, particular attention should be given to the use of magnetic materials such as neodymium and dysprosium in highly efficient electric motors and wind generators. These materials provide greater power density, reduced losses, and improved energy efficiency in these systems (Barbosa; Souza, 2022; Ferreira; Lima, 2022).

However, the growing dependence on these metals poses challenges related to their availability, geographic concentration, and the environmental impacts of their extraction. These elements are regarded as critical and strategic minerals for technological development and the energy security of several countries (Costa; Pereira, 2021; Silva; Almeida, 2023). International reports also indicate that demand is likely to grow over the coming decades, driven by the expansion of electric vehicles and renewable energy generation systems (IEA, 2023; USGS, 2024).

In Brazil, its mineral and energy potential places the country in a strategic position within the global supply chain for these resources. Official documents emphasize the need to integrate mineral and energy policies in order to promote sustainable development and national technological competitiveness (Brazil, 2020; EPE, 2023; IBRAM, 2022).

Against this background, there is a need for a deeper understanding of the role these minerals play in Electrical Engineering, particularly with regard to the performance and efficiency of modern electrical machines. Accordingly, this study seeks to answer the following research question: **What is the impact of using rare earth materials on the performance and efficiency of electromechanical systems employed in the energy transition?**

The general objective is to analyze the importance of rare earth mineral elements in the development of highly efficient electrical technologies, with an emphasis on electrical machines and energy conversion systems. To this end, technical, economic, and strategic aspects related to the use of these materials will be examined on the basis of a structured literature review.

In this context, integrating technological analysis and mathematical modeling is essential to understanding their contribution to the optimization of energy conversion systems and the development of sustainable energy solutions.

THEORETICAL FRAMEWORK

The global energy transition has driven structural changes in energy generation, conversion, and consumption systems, requiring solutions that offer greater efficiency, reliability, and sustainability. In this context, electrical engineering plays a strategic role in the development of efficient electrical machines, renewable energy systems, and high-performance electromagnetic devices, all of which are essential to the decarbonization of the global energy mix (Alves; Silva, 2022).

According to the International Energy Agency (IEA, 2023), the expansion of electric vehicles, wind turbines, photovoltaic systems, and energy storage has increased demand for critical minerals. These materials are highly strategic because of their superior magnetic, thermal, and electrochemical properties, which make them indispensable in advanced technological applications.

These elements, particularly neodymium (Nd), praseodymium (Pr), dysprosium (Dy), and terbium (Tb), are widely used in the manufacture of high-performance permanent magnets, such as neodymium-iron-boron (NdFeB) magnets, which are employed in permanent magnet synchronous motors (PMSMs) and highly efficient wind generators (Barbosa; Souza, 2022; Ferreira; Lima, 2022).

According to Li, Zhao, and Wang (2021), rare earth permanent magnets increase magnetic flux density, enabling the construction of more compact electrical machines without compromising performance. This results in greater torque density, reduced copper and iron losses, and higher overall efficiency, with power density potentially reaching twice that of conventional induction machines.

The performance of these machines can be analyzed using the dq model, which is widely employed to represent permanent magnet synchronous machines. This model makes it possible to evaluate magnetic flux, electromagnetic torque, armature current, and electrical losses and serves as a basis for comparing different machine technologies (Ferreira; Lima, 2022).

The mathematical model of the electromagnetic torque of a synchronous machine, particularly a PMSM, in the dq reference frame is used to calculate and control motor torque on the basis of the d- and q-axis currents. One of the most important equations in modern motor control is Equation (1):

$$T_e = \frac{3}{2}p\left[\lambda_f i_q + \left(L_d - L_q\right)i_d . i_q\right] \quad (1)$$

In electrical machines with permanent magnets, the $\frac{Te}{I} \propto \lambda_f$ term increases torque per ampere and reduces the operating current, thereby decreasing Joule-effect losses and increasing the machine's energy efficiency (Santos; Oliveira; Ferreira, 2021; Almeida; Souza; Barbosa, 2023). Thus, the permanent magnetic flux generated by the magnets contributes to greater torque and operating efficiency, which is particularly important in renewable energy generation applications.

According to Martins and Oliveira (2021), the energy efficiency of electric motors is one of the pillars of the industrial energy transition, as these devices account for a significant share of global electricity consumption. In this context, replacing conventional motors with permanent magnet machines reduces energy losses and improves the power factor, thereby contributing to greater operational sustainability.

Permanent magnet synchronous machines (PMSMs) exhibit higher torque density than induction machines (IMs) across the entire speed range. At low rotational speeds, PMSMs reach approximately 50

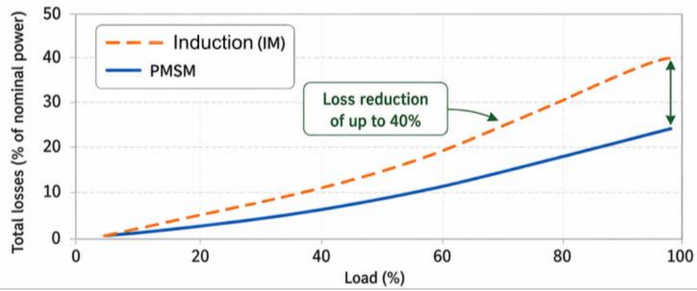
N·m/kg, whereas induction machines remain close to 20 N·m/kg, demonstrating performance up to twice as high. This is possible only because of the use of rare earth permanent magnets (Zhu; Howe, 2023).

The technical superiority of permanent magnet synchronous motors (PMSMs) over induction motors (IMs) is demonstrated by their high efficiency under different load conditions. According to Silva and Silva (2021), whereas induction motors frequently operate at efficiencies below 90%, PMSM technology reaches approximately 95%, providing a substantial performance advantage.

This operational advantage primarily results from the elimination of Joule-effect losses in the rotor and the optimization of magnetic flux provided by the magnets (Almeida; Santos, 2023). In addition, comparative studies indicate that total losses in PMSMs may be up to 40% lower than in induction motors, resulting in significantly better power utilization and greater energy sustainability (Oliveira, 2022), as shown in Figure 1.

Figure 1

Total losses versus load

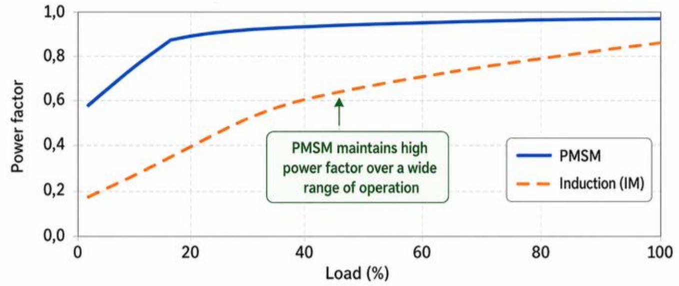


Source: Zhu, Z. Q.; Howe, D. 2023.

With regard to lower losses, PMSMs exhibit lower total losses than induction machines (IMs) across the entire load range. Whereas losses in an induction machine may reach approximately 40%, those of a PMSM remain close to 25%, representing a reduction of up to 40% and greater energy efficiency, as shown in Figure 2.

Figure 2

Power factor versus load



Source: Zhu, Z. Q.; Howe, D. 2023.

According to the comparison, PMSMs offer up to twice the torque density for the same weight and volume and are three to seven percentage points more efficient over most of the load range. Their losses are reduced by up to 40%, resulting in less heating and a longer service life. In terms of power factor, they maintain a high power factor, greater than 0.9, even under partial loads.

In addition to their technical benefits, the use of rare earth elements has a significant geopolitical and economic dimension. Costa and Pereira (2021) emphasize that these elements are classified as strategic minerals because their production is highly concentrated in a small number of countries, particularly China, which dominates much of the global extraction, processing, and refining chain. This concentration creates vulnerabilities in the international supply system and risks associated with energy security.

Silva and Almeida (2023) further maintain that technological dependence on these minerals requires integrated public policies across the mineral, energy, and industrial sectors, particularly in countries with significant geological potential, such as Brazil. The country possesses substantial rare earth reserves and may assume a strategic position in global supply, provided that investments are made in research, mineral processing, and technological value addition.

Brazilian energy planning, through the National Energy Plan 2050 (*Plano Nacional de Energia 2050*), classifies critical minerals as fundamental to industrial competitiveness and the energy transition (Brazil, 2020). According to Rocha, Mendes, and Farias (2024), sectors such as electric mobility and offshore wind power are increasing demand for magnetic materials, requiring the strengthening of the national production chain. In addition, magnet recycling has emerged as a strategic solution for mitigating external dependence and reducing environmental damage (Oliveira; Santos, 2025).

From an environmental perspective, the extraction and processing of rare earth elements also present significant challenges. The United States Geological Survey (2024) emphasizes that mining these elements can produce substantial impacts related to water consumption, waste generation, and chemical contamination, requiring more sustainable practices and stringent regulation. Technological progress must therefore be accompanied by environmental responsibility and the development of cleaner production processes.

Santos and Carvalho (2022) emphasize that advanced magnetic materials will continue to shape the future of electrical engineering, particularly in intelligent energy conversion systems, more efficient power grids, and new distributed-generation architectures. Rare earth elements have therefore become established not only as strategic mineral resources but also as central components of technological innovation in the electricity sector.

It can therefore be observed that the relationship among rare earth elements, electrical machines, and the energy transition extends beyond a purely technical dimension and encompasses economic, geopolitical, environmental, and industrial considerations. An integrated understanding of these factors is essential to the development of sustainable solutions and the strengthening of Brazil's technological competitiveness in the international arena.

The growing integration of intermittent renewable sources, such as wind and solar power, requires more robust and stable electromechanical conversion systems. In this context, permanent magnet synchronous generators stand out because they offer greater reliability, efficiency at variable speeds, and lower maintenance requirements. According to Barbosa and Souza (2022), these advantages result from the use of rare earth magnets, which provide superior magnetic flux density and a more effective dynamic system response.

Another relevant aspect concerns the advancement of electric mobility, particularly in the automotive sector, in which energy efficiency and reductions in the mass of propulsion systems are decisive factors in determining the range of electric vehicles. According to the International Energy Agency, growth in the global electric vehicle fleet directly increases demand for rare earth elements, thereby reinforcing the strategic importance of these elements to the industrial and energy sectors (IEA, 2023).

In academic research, efforts are being made to reduce dependence on critical materials and mitigate price volatility through the development of alternative materials. Recent studies have explored hybrid alloys, advanced ferrites, and electromagnetic optimization to maintain efficiency while reducing the use of rare earth elements. Despite these advances, however, NdFeB magnets remain the benchmark for high-power and technically demanding applications, particularly in the industrial and renewable energy sectors (Santos; Carvalho, 2022).

The selection of materials for magnetic circuits is based on an analysis of energy density, in which rare earth magnets, particularly NdFeB magnets, significantly outperform traditional materials. Whereas ferrite has a low energy product, technological developments in NdFeB have made it possible to achieve high levels of remanence and coercivity (Nunes, 2023). This technical superiority is the determining factor in motor miniaturization and the feasibility of highly efficient generators.

Table 1

Typical magnetic properties of materials used in electrical machines

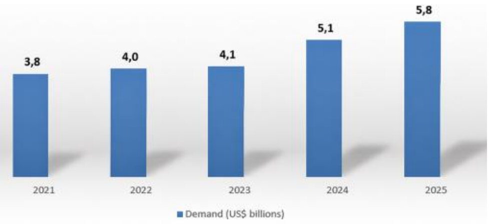
Magnetic material	Remanence Br (T)	Coercivity Hc (kA/m)	(BH)max (kJ/m³)
Ferrite	0,38 – 0,42	200 - 300	26 - 40
AlNiCo	0,6 – 1,2	50 - 100	40 - 88
SmCo	0,9 – 1,1	600 - 2000	120 - 200
NdFeB	**1,1 – 1,4**	**800 - 3000**	**200 - 440**

Source: Nunes, 2023.

Figure 3 illustrates the projected growth, in billions of US dollars (US$), of demand for rare earth elements in the context of the energy transition, demonstrating the strong correlation between the advancement of clean technologies and the increasing use of these mineral resources. A trend of continuous growth can be observed, driven particularly by the electric mobility and renewable energy generation sectors. This reinforces the need for studies focusing on the efficient use of these materials and the development of technological alternatives.

Figure 3

Demand for rare earth elements in US$ billions



Source: IBGE, 2025.

The increase in demand reflects the extensive application of rare earth elements in energy-transition technologies, particularly permanent magnet synchronous motors and wind generators. In electrical engineering, this growth is associated with improvements in the electromagnetic performance, power density, and energy efficiency of electrical machines.

The establishment of a national policy for strategic minerals is essential if Brazil is to convert its geological potential into competitiveness within the global value chain. Synergies among mineral reserves, the expansion of renewable energy, and excellence in research enable the development of national technologies. Accordingly, integration among academia, industry, and government is the path toward transforming the country from a mere exporter of raw materials into a technological leader in the sustainable energy transition.

MATERIALS AND METHODS

This study is characterized as qualitative, exploratory research based on a systematic literature review. Data were collected from international scientific databases, including Scopus, ScienceDirect, and IEEE Xplore, considering publications issued between 2018 and 2025.

Technical search terms such as “rare earth elements,” “permanent magnet motors,” and “energy efficiency” were used. The inclusion criteria comprised peer-reviewed studies focusing on electromagnetic performance and energy applications. Duplicate studies, studies outside the scope of the research, and studies lacking technical relevance were excluded.

Data analysis followed a series of structured stages: (i) problem definition, (ii) systematic search, (iii) study selection, (iv) critical analysis, and (v) synthesis of the results.

In addition, mathematical modeling based on the dq reference frame was used to evaluate the electromagnetic behavior of permanent magnet synchronous machines. This approach allows for the analysis of parameters such as torque, magnetic flux, and electrical losses, which are widely used in the Electrical Engineering literature.

The methodological sequence comprises the following stages: problem definition, systematic database searching, application of the study-selection criteria, study screening and selection, critical data analysis, and synthesis and discussion of the results.

RESULTS AND DISCUSSION

IMPACT OF RARE EARTH ELEMENTS ON THE ELECTROMAGNETIC PERFORMANCE OF ELECTRICAL MACHINES

The technical literature and mathematical modeling indicate that rare earth permanent magnets, particularly NdFeB magnets, significantly increase the magnetic flux in the air gap of electrical machines. As shown in Equations (2) and (3), an increase in the equivalent magnetic field raises the flux density and the total flux Φ, as expressed in Equation (3).

$$B_g \approx \mu_0 H_m \ (2)$$

Where Hm is the equivalent magnetic field produced by the magnet. A greater Bg implies a greater total flux, represented in Equation (3):

$$\Phi = B_g A \ (3)$$

This effect increases the induced electromotive force in accordance with Equation (4), allowing higher voltage levels without a proportional increase in current, thereby reducing resistive losses and improving energy efficiency. In addition, the high (BH)max values of NdFeB magnets enable the construction of more compact machines with greater electromagnetic performance than those using conventional materials such as ferrites.

$$e = -N \frac{d\Phi}{dt} \ (4)$$

Table 1 presents a comparison between conventional magnetic materials and rare earth magnets based on typical values widely reported in the technical literature, corroborating the results.

NdFeB magnets exhibit the highest energy product, allowing more intense magnetic fields to be produced in smaller volumes. This result supports the increase in power density and reduction in active mass found in modern electrical machines (Coey, 2010; Callister; Rethwisch, 2016).

INFLUENCE OF RARE EARTH ELEMENTS ON ELECTROMAGNETIC TORQUE AND VECTOR CONTROL

Application of the dq model to permanent magnet synchronous machines shows that, in systems using rare earth metals, the term associated with the permanent magnet flux (λ_f) dominates the electromagnetic torque equation, Equation (1). Consequently:

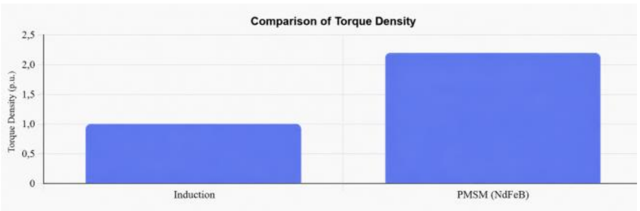
$$T_e \; \alpha \; \lambda_f i_q \; (5)$$

For the same torque level, lower iq currents are required in PMSMs, resulting in greater torque per ampere and reduced copper losses because of the quadratic dependence on current. In addition, strategies such as maximum torque per ampere (MTPA) become more effective in these systems.

In field-oriented control (FOC), the stability of the magnetic flux produced by permanent magnets facilitates decoupling of the d and q axes, providing a better dynamic response and greater control accuracy. Based on dq modeling and comparative studies, Figure 4 presents the normalized torque densities of induction motors and synchronous motors equipped with NdFeB magnets.

Figure 4

Comparison of torque density, normalized values



Source: author, 2026.

PMSMs equipped with rare earth magnets exhibit torque densities up to twice those of induction motors in the same class. This gain results directly from the increase in λ_f , as shown in Equation (1), confirming that torque per ampere is significantly greater. This result explains the widespread adoption of these motors in electric vehicles and modern wind turbines.

REDUCTION OF LOSSES AND OVERALL ENERGY EFFICIENCY

Based on theoretical modeling and data from the literature, it can be observed that reducing the current required to produce torque directly decreases copper losses. According to Equation 6, a 20% reduction in current can result in losses that are more than 35% lower, due to the nonlinear behavior of the I^2 term.

$$\lambda_d = L_d i_d + \lambda_f \quad (6)$$

This effect influences the system's overall efficiency, as expressed in Equation (7):

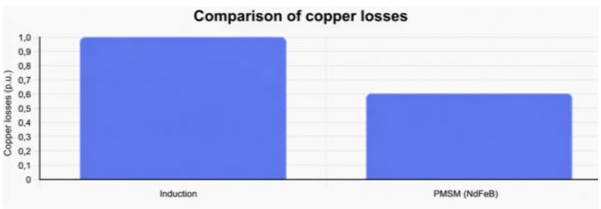
$$\eta = \frac{P_{out}}{P_{in}} \quad (7)$$

Electrical machines equipped with rare earth magnets exhibit less winding heating, a longer electrical-insulation service life, and less need for forced ventilation. These characteristics are relevant to continuous and high-power applications, such as wind power generation and electric traction.

Figure 5 illustrates a comparison of normalized copper losses under rated operating conditions.

Figure 5

Comparison of copper losses, normalized values



Source: author, 2026.

PMSMs equipped with NdFeB magnets exhibit an approximate 40% reduction in copper losses.

The reduction in current made possible by the greater magnetic flux has a direct impact, as demonstrated by the relationship $P_{cu} \propto I^2$.

This result confirms substantial gains in thermal and electrical efficiency.

INCREASED POWER DENSITY AND STRUCTURAL IMPLICATIONS

The application of Equations (7) and (8) demonstrates that machines equipped with NdFeB magnets have greater power density by mass and volume than conventional machines. This makes it possible to reduce the active mass of the rotor and stator while maintaining high power levels and enabling more compact designs.

$$\rho p = \frac{P}{m} \quad (7)$$

- ρp – power density (W/m^3)
- P – Power(W)
- m – Mass (Kg)

$$\rho P_v = \frac{P}{V} \quad (8)$$

- ρp_v – volumetric power density (W/m^3)
- V – Volume (m^3)

However, increased power density intensifies thermal and mechanical challenges, requiring greater heat dissipation, more resistant structural materials, and advanced electrical-insulation techniques.

The gains provided by rare earth elements therefore require an integrated design approach encompassing electromagnetism, mechanics, and thermal engineering.

Table 2 presents a typical comparison of gravimetric and volumetric power densities across different electrical machine technologies.

Table 2

Comparison of power density in electrical machines

Technology	ρp (kW/kg)	ρpv(kW/m^3)
Induction motor	1,5 – 2,5	5.000 – 8.000
PMSM (ferrite)	2,0 – 3,0	7.000 – 10.000
PMSM (NdFeB)	**4,0 – 6,0**	**12.000 – 20.000**

Source: author, 2026.

The results show that rare earth magnets can double or triple power density, a critical factor in applications in which weight and volume are subject to severe constraints, as in offshore wind turbines, electric vehicles, and aerospace systems.

TECHNOLOGICAL AND STRATEGIC IMPLICATIONS

The results of the technical review and theoretical analysis confirm that rare earth elements are essential to the energy transition because they enable more efficient wind generators, electric motors that provide greater vehicle range, and more compact electrical power systems. Nevertheless, challenges associated with the concentration of the production chain and environmental impacts reinforce the need for sustainable strategies and industrial diversification.

Table 3 consolidates the principal technical impacts identified through the methodology applied.

Table 3

Summary of the impacts of rare earth elements on electrical machines

Evaluation parameter	Observed impact
Air-gap flux	Significant increase
Torque per ampere	High
Copper losses	Substantial reduction
Overall efficiency	Increase
Power density	Substantial increase
System mass and volume	Reduction
Thermal complexity	Increase, representing a challenge

Source: author, 2026.

At the same time, the results demonstrate that technological advancement is accompanied by new thermal, structural, and geopolitical challenges, reinforcing the need for integrated engineering approaches and industrial policies. It is also evident that the concentration of production in China (USGS, 2023) constitutes a strategic risk because it concentrates essential resources in a single country.

CONCLUSION

The energy transition requires not only the replacement of fossil-fuel energy sources but also improvements in the performance of electromechanical conversion systems. In this context, the study analyzed the contribution of rare earth elements to the efficiency, power density, and reliability of modern electrical machines.

The technical review and modeling of synchronous machines showed that rare earth-based permanent magnets, particularly NdFeB magnets, possess superior magnetic properties, enabling greater air-gap flux, increased electromagnetic torque, and higher power density. Analysis using the dq model also indicated greater torque per ampere and lower electrical currents, thereby reducing copper losses and improving energy efficiency and thermal performance.

Furthermore, rare earth elements enable the construction of more compact and lightweight machines, which are essential in applications such as offshore wind turbines and electric traction systems. However, the use of these materials involves thermal, structural, environmental, and geopolitical challenges related to the concentration of their production.

It is concluded that rare earth elements are fundamental to modern electrical systems and the energy transition because they provide significant gains in performance and efficiency. However, their effective use depends on investments in innovation, industrial policies, and sustainable practices that ensure security of supply and the responsible use of these resources.

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