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STUDY ON ASSURING THE BALANCED CHEMICAL COMPOSITION OF NEODYMIUM PERMANENT MAGNETS

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Abstract: Material composition and application environment significantly influence the classification criteria of magnets by affecting their physical, chemical, and magnetic properties, which determine their suitability for specific uses. Material composition provides the fundamental physical and magnetic properties that form the basis for magnet classification, while the application environment imposes constraints and performance requirements that refine classification into specific grades and types. Together, they ensure that magnets are selected and classified to deliver optimal performance, durability, and reliability in their intended use cases. The impact of material composition and the impact of application environment are analysed. In essence, chemical composition sets the stage for the magnetic material's crystal structure, magnetic phase, domain formation, and intrinsic magnetic moments, all of which collectively determine the magnetization properties. Fine tuning composition optimizes magnet strength, coercivity, thermal stability, and application–specific behaviour.
Keywords: Nd–Fe–B magnets, Nd2Fe14B, chemical composition, influences & impact

1. INTRODUCTORY NOTES REGARDING MAGNETS

PERMANENT MAGNETs based on Neodymium (Nd), commonly called Nd–Fe–B magnets, are made from an alloy primarily composed of Neodymium (Nd), Iron (Fe), and Boron (B), with a typical chemical formula Nd2Fe14B. This alloy forms a specific tetragonal crystalline structure that is critical to its exceptional magnetic properties. Nd–Fe–B magnets are among the strongest permanent magnets available. They exhibit a very high remanent magnetization (typically about 1.3 Tesla) and high maximum energy product ((BH)max≈512 kJ/m3), making them about 18 times stronger than ordinary ferrite magnets by volume. Having in view their chemical composition, the Boron does not directly contribute to magnetism but provides structural stability by strong covalent bonding, improving the cohesion of the crystal lattice. Neodymium and Iron provide the magnetic properties, with Iron also helping to stabilize magnetic order at room temperature or higher. These magnets are relatively dense (around 7.5 g/cm³), hard and brittle.

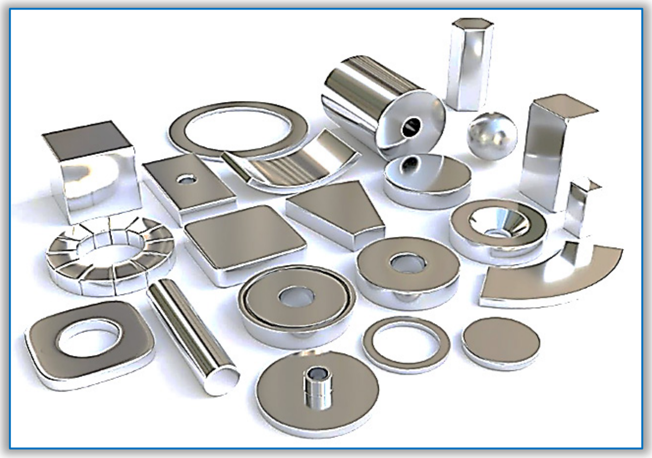

Figure 1. PERMANENT MAGNETs based on Neodymium (Nd)

These magnets are alloyed with elements like Dysprosium (Dy) or Terbium (Tb) to improve thermal stability. Due to their extraordinary strength, compact size, and reliability, Neodymium magnets are widely used in electric motors, generators, hard disk drives, magnetic resonance imaging (MRI), loudspeakers, and various sensors and actuators. Neodymium magnets are widely used across industries primarily because of their exceptional magnetic strength relative to their size, making them the strongest commercially available permanent magnets. This high strength allows for the creation of smaller, lighter, and more powerful devices without compromising performance, which is crucial in modern technology and industrial applications. In

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summary, Neodymium permanent magnets are powerful rare–earth magnets characterized by their Nd–Fe–B composition, high magnetic strength, and specific crystallographic properties that make them ideal for a wide range of advanced technological applications, though they are sensitive to high temperatures and mechanical stresses. Key reasons for their widespread industrial use include:

— High magnetic strength and energy density: Neodymium magnets have a very high maximum energy product, enabling compact and efficient designs in motors, generators, and electronic devices.
— Lightweight and compactness: Their small size and relatively low weight compared to older magnets (like ferrite or Al–Ni–Co) make them ideal for applications where space and weight are critical, such as in electric vehicles and portable electronics.
— Cost–effectiveness relative to performance: Despite being a rare–earth element, Neodymium (Nd) is relatively affordable compared to the strength and performance it offers, which helps increase its adoption across many industries.
— Adjustable magnetic strength: Manufacturers can tailor Neodymium magnets' magnetic properties for specific needs, ranging from moderate to very high strength, which further expands their usability.
— Versatile applications: Neodymium magnets are essential in diverse sectors including:
≡ Automotive: Used in electric and hybrid vehicle motors, power steering, and actuators for improved efficiency and reduced motor size.
≡ Electronics: Found in hard disk drives, speakers, headphones, mobile phones, and magnetic switches, contributing to improved performance and miniaturization.
≡ Renewable energy: Critical in wind turbine generators to efficiently convert mechanical energy into electrical energy, supporting the energy transition.
≡ Medical technology: Used in MRI machines, surgical instruments, hearing aids, and drug delivery systems, where their strong magnetic fields enable precision and high imaging quality.
≡ Industrial automation and sensors: Power actuators, valves, pumps, and magnetic switches enhancing control and operational efficiency in manufacturing processes.

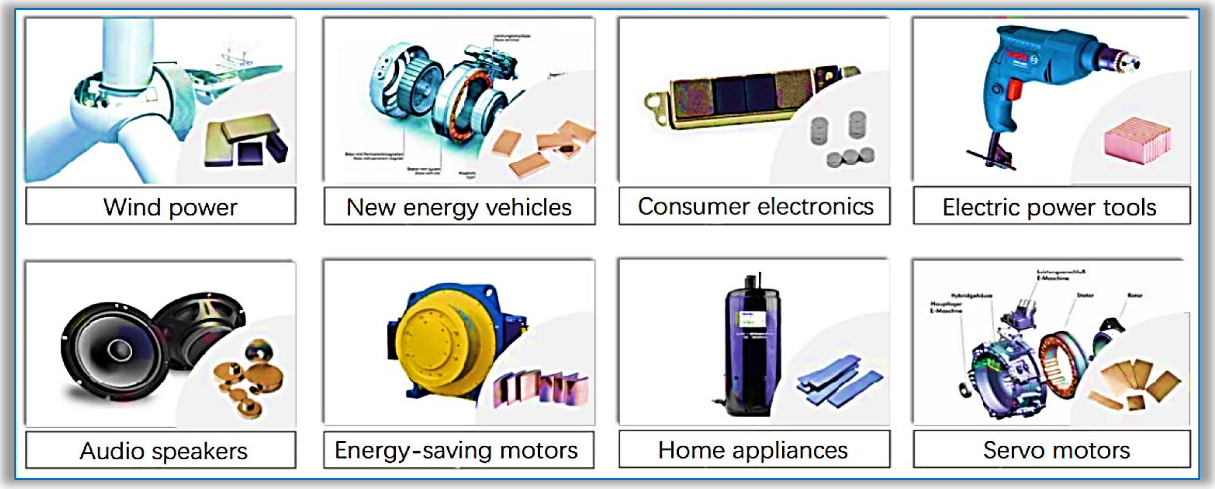

Figure 2. Versatile applications of Neodymium magnets

However, they are brittle and sensitive to high temperatures, which requires careful handling and sometimes alloying with other elements to improve thermal stability.

In summary, Neodymium magnets' combination of strong magnetic field, small size, lightweight, versatility, and cost–efficiency makes them indispensable in modern industrial and technological applications across automotive, electronics, energy, medical, and manufacturing sectors

MAGNETS are materials or objects that produce a magnetic field, which exerts a force on ferromagnetic materials such as Iron, Cobalt, and Nickel. They always have two poles—North and South—and can attract or repel other magnets. Magnets are classified based on their origin and magnetic properties.

- NATURAL MAGNETS, which occur in nature, retain magnetism indefinitely (example: magnetite)
- ARTIFICIAL MAGNETS, which are created by humans; subdivided into:
  - Permanent Magnets, which retain magnetic properties permanently (examples: Nd–Fe–B, Sm–Co, Al–Ni–Co, Ferrite). These retain their magnetism over time without needing an external power source. Common materials include alloys like Al–Ni–Co (Aluminum, Nickel and Cobalt), ferrites, and rare–earth elements. These magnets are used in motors, electronics, industrial tools, compasses, and data storage devices
  - Temporary Magnets, which exhibit magnetism only in the presence of a magnetic field (examples: soft Iron, silicon steel). These behave like magnets only when exposed to an external magnetic field. They quickly lose magnetism once the field is removed and are typically made from soft Iron or other easily magnetized materials.
- ELECTROMAGNETS, which are magnetized only when electric current flows through a coil and are used in relays and motors. Magnetic fields generated by electric current flowing through coils wrapped around a soft Iron core. Their strength can be controlled by the current, and the magnetic field disappears when the current is off. Uses include MRI machines, cranes, motors, and generators.
- SUPERCONDUCTING MAGNETS: Extremely strong magnets requiring cooling to very low temperatures. Used in advanced scientific research and particle accelerators

This classification covers the practical magnet types based on their magnetic properties. The main classification criteria for different types of magnets are based on their magnetic properties, material composition, and behavior under magnetic fields. These criteria can be summarized as follows:
Based on magnetic behavior and permanence, the magnets are:

- Permanent magnets (hard magnets): Retain their magnetism without an external magnetic field. They have high coercivity (resistance to demagnetization). Examples include Neodymium–Iron–Boron (Nd–Fe–B), Samarium–Cobalt (Sm–Co), Al–Ni–Co, and ferrite magnets.
- Temporary magnets (soft magnets): Exhibit magnetism only when exposed to an external magnetic field and lose it when the field is removed. They have low coercivity. Used in transformers and electromagnets.
- Electromagnets: Produce magnetic fields only when electric current flows through coils.

Based on material composition, the magnets are:

- Rare Earth magnets: Include Nd–Fe–B and Sm–Co magnets, known for very high magnetic strength and energy product.
- Al–Ni–Co Magnets: Made from Aluminium, Nickel and cobalt alloys; moderate strength and good temperature stability.
- Ferrite (Ceramic) Magnets: Composed of Iron oxide and ceramic materials; lower strength but inexpensive and corrosion–resistant.
- Metal Alloy Magnets: Other metal–based magnets with varying properties.

Permanent and temporary magnets differ both in their composition and how they function. From point of view of their composition the permanent magnets are characterized by:

- are made from materials that naturally retain their magnetic properties even when an external magnetic field is removed.

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- the common materials include hard ferromagnetic substances such as alloys of Aluminum, Nickel, and Cobalt (e.g., Al–Ni–Co), rare–earth elements (e.g., Neodymium, Samarium–Cobalt), and ferrites.
- the atomic structure in these materials allows magnetic domains to remain aligned after being magnetized, resulting in persistent magnetism.

On the other hand, the temporary magnets:

- are composed of soft ferromagnetic materials, most often pure Iron or soft Iron alloys.
- these materials have atomic structures that allow domains to quickly align in the presence of a magnetic field but return to random orientations once the field is removed.
- they do not retain significant magnetism when the magnetizing force is gone.

From point of view of their function, the permanent magnets:

- exhibit magnetism continuously, without the need for an external power source or magnetic field.
- are used in applications requiring a constant magnetic field, such as compasses, refrigerator magnets, electric motors, speakers, and various sensors.
- their strength and magnetization are stable over long periods.

On the other hand, the temporary magnets:

- act as magnets only while in the presence of an external magnetic field.
- lose most or all magnetism quickly when the field is removed.
- common applications include devices where magnetism is needed temporarily, such as in relays, electric bells, electromagnetic cranes, and certain types of switches.

Permanent magnets offer persistent magnetic properties due to their material composition, making them suitable for continuous tasks, while temporary magnets are ideal for situations where temporary or controllable magnetism is needed.

In essence, the main types of permanent magnets are:

- Neodymium–Iron–Boron (Nd–Fe–B): Highest magnetic strength, widely used in EV motors and electronics.
- Samarium–Cobalt (Sm–Co): Strong, excellent thermal stability, high magnetic strength, used in high–temperature applications (aerospace, high–temp motors).
- Al–Ni–Co: Made from Aluminum, Nickel and Cobalt, have good temperature stability but lower strength (moderate), the key application being the sensors.
- Ceramic/Ferrite: Made from Iron oxide and ceramic; inexpensive, corrosion–resistant, but less powerful (low–moderate), the key application being the loudspeakers and small motors.

2. ASSURING THE Nd–Fe–B MAGNETS COMPOSITION

Material composition and application environment significantly influence the classification criteria of magnets by affecting their physical, chemical, and magnetic properties, which determine their suitability for specific uses. Material composition provides the fundamental physical and magnetic properties that form the basis for magnet classification, while the application environment imposes constraints and performance requirements that refine classification into specific grades and types. Together, they ensure that magnets are selected and classified to deliver optimal performance, durability, and reliability in their intended use cases.

The impact of material composition (Figure 3) are characterized by:

- MAGNETIC PROPERTIES: The elemental makeup (e.g., Neodymium, samarium, cobalt, Iron, aluminium) directly affects key magnetic characteristics such as coercivity, remanence, and maximum energy product. For example, rare earth elements in Nd–Fe–B and Sm–Co magnets provide very high magnetic strength and temperature stability, distinguishing them from ferrite or Al–Ni–Co magnets with lower magnetic performance.

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- THERMAL STABILITY: Composition governs how well a magnet can maintain its properties at elevated temperatures. Sm–Co magnets, with specific rare earth alloys, perform better at high temperatures than Nd–Fe–B, which can degrade if overheated.
- CORROSION RESISTANCE: Some compositions are more prone to oxidation and corrosion (e.g., Nd–Fe–B), requiring protective coatings, while others like ferrite are naturally corrosion–resistant.
- MECHANICAL PROPERTIES: The material's hardness and brittleness influence manufacturing methods and durability in application environments.

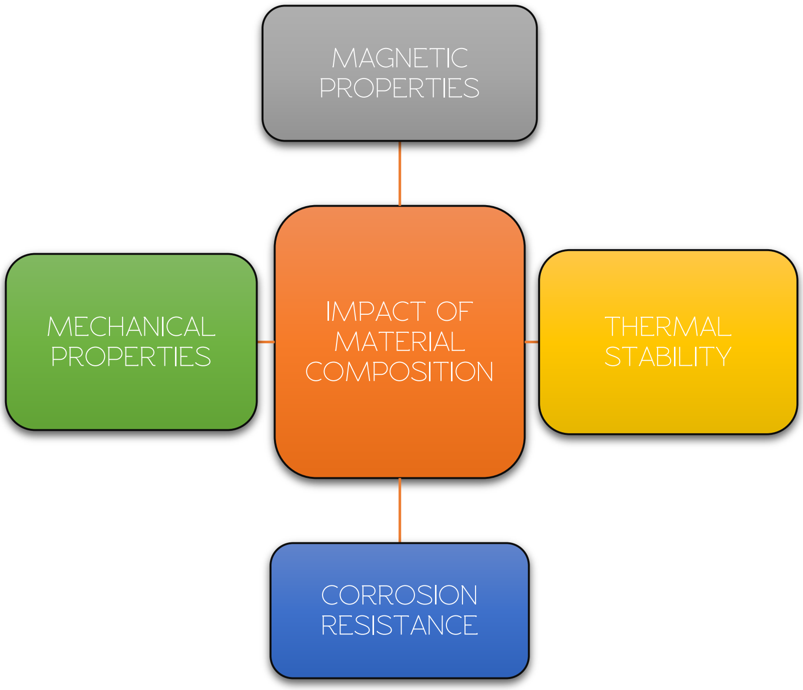

Figure 3. Impact of material composition

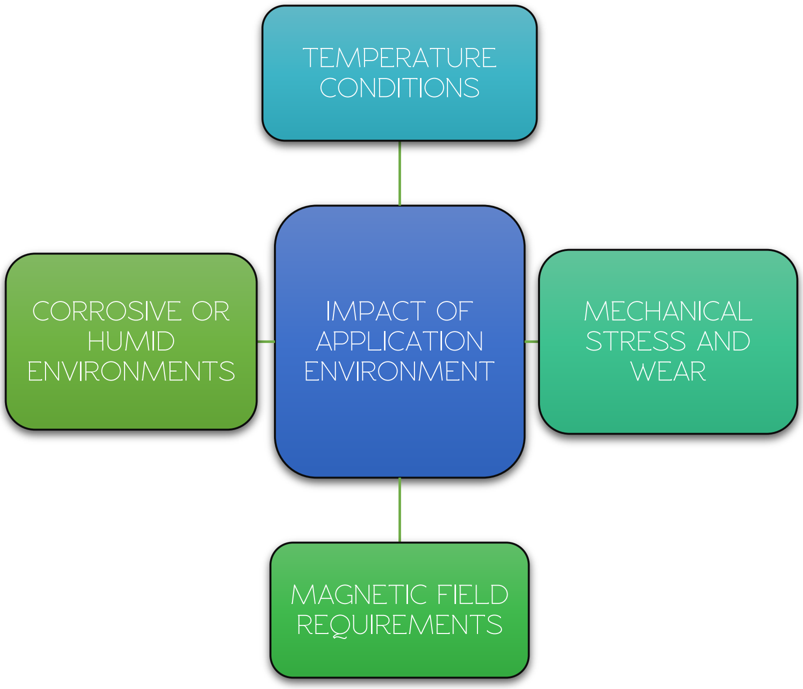

Figure 4. impact of application environment

The impact of application environment (Figure 4) are characterized by:

- TEMPERATURE CONDITIONS: High operating temperatures demand magnets with high thermal stability; this affects classification by requiring materials like Sm–Co or specially graded Nd–Fe–B magnets.

- MECHANICAL STRESS AND WEAR: Environments with vibration or mechanical shocks require magnets with robust mechanical integrity.
- CORROSIVE OR HUMID ENVIRONMENTS: Exposure to moisture or chemicals necessitates corrosion–resistant materials or protective coatings, influencing the choice and classification.
- MAGNETIC FIELD REQUIREMENTS: The strength and stability needed in the application determine whether a high–energy rare earth magnet or a lower–energy ferrite magnet is appropriate.

How these factors influence classification criteria are presented below in the Table 1.

Table 1. How these factors influence classification criteria

Classification Criterion	Influence of Material Composition	Influence of Application Environment
Magnetic Strength (BHmax)	Determined by elemental makeup and microstructure	Required magnetic performance for the application
Coercivity (Resistance to Demagnetization)	Composition controls intrinsic coercivity levels	Environmental demagnetizing factors (temperature, fields)
Thermal Stability	Alloy composition defines Curie temperature and stability	Operating temperature range dictates suitable magnet type
Corrosion Resistance	Material susceptibility to oxidation and degradation	Exposure to moisture, chemicals, and atmospheric conditions
Mechanical Durability	Hardness and brittleness depend on composition	Mechanical stresses and vibration in service
Grades and Subtypes	Variations in composition refine classification grades	Application–specific requirements drive grade selection

The material composition of Nd–Fe–B permanent magnets primarily consists of the rare earth element Neodymium (Nd), Iron (Fe), and Boron (B), forming the Nd2Fe14B tetragonal crystal structure that gives these magnets their exceptional properties. The exact weight percentages of the main elements in Nd–Fe–B permanent magnets typically fall within the following ranges (Table), which can vary slightly depending on the magnet grade and application. More specifically, a common typical composition for high–performance sintered Nd–Fe–B magnets is presented in Table 2.

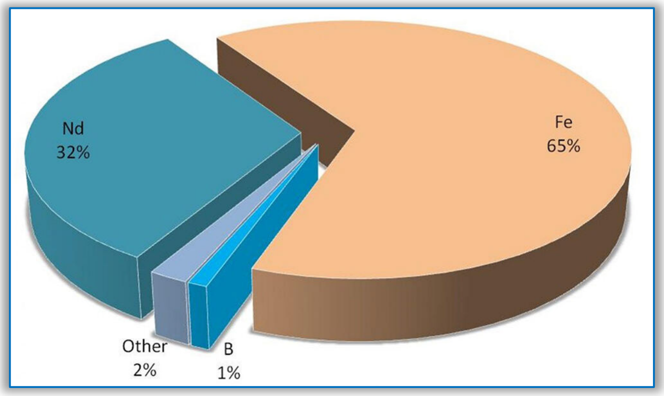

Figure 5. Composition chart of Nd–Fe–B permanent magnets

Table 2. Typical Elemental Composition (by weight)

Element	Approximate Percentage Range
Neodymium (Nd)	25% to 32%
Iron (Fe)	Balance of alloy, approx. 63% to 68.5%
Boron (B)	1.0% to 1.3%
Dysprosium (Dy)	0.6% to 1.2% (added optional for coercivity and thermal stability)
Aluminium (Al)	Minor additive, around 0.2% to 0.5%
Niobium (Nb)	Minor additive, around 0.5% to 1%
Cobalt (Co)	Trace amounts, variable, sometimes added for corrosion resistance and magnetic properties
Praseodymium (Pr)	Trace amounts, variable, sometimes substitutes part of Nd to improve corrosion resistance and coercivity

The magnetic strength of Nd–Fe–B permanent magnets is primarily defined by the specific elemental composition and their percentages in the alloy. The core elements and their typical weight percentages are:

- Neodymium (Nd): Approximately 25% to 32%. Nd contributes a large magnetic dipole moment due to its unpaired electrons, directly influencing high saturation magnetization and remanence.

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- Iron (Fe): Around 63% to 68.5%. Iron stabilizes the crystal structure and provides a substantial portion of the magnetic moment.
- Boron (B): Typically about 1% to 1.5%. Boron enhances the coercivity, helping the magnet maintain its magnetization under external magnetic fields.
- Dysprosium (Dy): Optional, usually about 0.6% to 1.2%. Added primarily to improve coercivity and thermal stability, especially in high–performance or high–temperature applications.
- Aluminum (Al): Around 0.2% to 0.5%. Improves corrosion resistance and mechanical strength.
- Niobium (Nb): Approximately 0.5% to 1%. Added for microstructural refinement and improved magnetic properties.
- Other Rare Earths: Praseodymium (Pr) and Terbium (Tb) may also be present in small amounts as partial substitutes for Neodymium (Nd) or Dysprosium (Dy).

The magnetic phase responsible for the exceptional strength is the crystalline compound Nd2Fe14B, which provides a high saturation magnetization (~1.6 Tesla) and remanent magnetization (~1.3 Tesla), resulting in a maximum energy product, significantly greater than traditional ferrite magnets.

The exact composition can vary depending on the magnet's grade and specific application, with higher–grade magnets typically containing slightly more Dysprosium (Dy) or Praseodymium (Pr) to improve coercivity and temperature tolerance. Key composition insights are:

- Neodymium (Nd) and Iron (Fe) form the magnetic matrix, with Fe atoms alternating with Nd–B compounds in the crystal lattice.
- Boron (B) is diamagnetic but plays a crucial role in binding atoms, strengthening the crystal structure.
- Dysprosium (Dy) and Terbium (Tb) are heavy rare earths incorporated in varying amounts to enhance intrinsic coercivity and raise the Curie temperature, improving high–temperature performance.
- Aluminium (Al), Niobium (Nb), and Cobalt (Co) are alloying elements that improve corrosion resistance, mechanical strength, and magnetic stability.

In summary, the precise balance of Nd (~25–32%), Fe (~63–68.5%), and B (~1–1.5%) forms the basis of Nd–Fe–B's high magnetic strength, with small additions of Dysprosium (Dy), Aluminium (Al), Niobium (Nb), and others fine–tuning coercivity, thermal stability, and mechanical properties.

Iron (Fe) generally makes up the remainder of the alloy after accounting for the other elements, thus it is often given as the balance in the composition. Boron (B) is always a small, but critical, component that stabilizes the crystal structure (Nd2Fe14B phase) responsible for the magnetic properties. These proportions are designed to produce the Nd2Fe14B tetragonal phase, which ensures the magnet's strong remanence, coercivity, and maximum energy product.

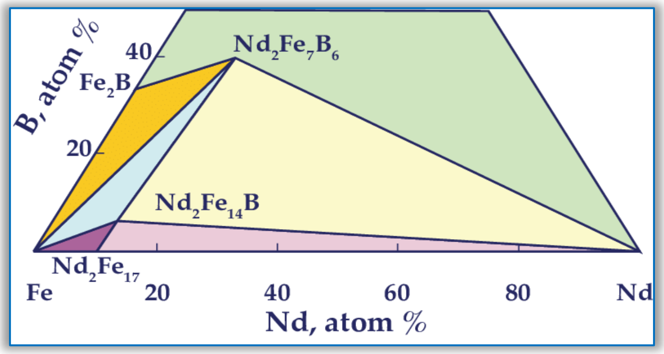

Figure 6. Phase diagram of the Nd–Fe–B system

The exact composition varies by manufacturer and grade, with additional rare earth elements like dysprosium or praseodymium incorporated for specific magnetic performance and thermal stability requirements.

Minor elements like Dysprosium (Dy) and Praseodymium (Pr) have a significant impact on the overall weight composition of Nd–Fe–B magnets, despite being present in relatively small amounts.

- Dysprosium (Dy): Typically added in amounts ranging from 0.6% to 1.2% by weight to enhance coercivity and thermal stability, especially for high–temperature applications. Although this is a small fraction, Dysprosium (Dy) partially substitutes for Neodymium (Nd), slightly reducing the content. Dysprosium (Dy) has a strong effect on magnetic performance by improving resistance to demagnetization at elevated temperatures
- Praseodymium (Pr): Can substitute for a portion of Neodymium (Nd), typically at 4% to 5% of the rare earth content. Praseodymium (Pr) is used to partially replace Neodymium (Nd) without severely sacrificing remanence (Br) and energy product. The use of Praseodymium (Pr) allows some flexibility in element sourcing while maintaining magnetic properties

When Dysprosium (Dy) or Praseodymium (Pr) are added:

- The Neodymium (Nd) content decreases proportionally since Dysprosium (Dy) or Praseodymium (Pr) partially replace Neodymium (Nd) in the alloy.
- The total weight percentage of rare earth elements (Nd+Pr+Dy) remains roughly similar, but the specific balance shifts.
- Magnetic performance improvements from Dysprosium (Dy)'s addition often come with a slight trade–off in maximum remanence but significant gains in coercivity.

This carefully balanced composition is crucial for achieving the high remanence, coercivity, and energy product that characterize Nd–Fe–B magnets, making them the strongest commercially available permanent magnets used in diverse applications such as electronics, electric vehicles, and renewable energy technologies.

Typical Ratio Example: For every ~20 parts of (Nd + Pr), there might be about 1.5 parts of Dysprosium (Dy) to achieve desired coercivity and thermal characteristics. This means Dysprosium (Dy) is roughly 6–7% of the rare earth content but less than 1.2% of the total magnet weight overall.

3. THE PRESENCE OF DYSPROSIUM (Dy) AND PRASEODYMIUM (Pr) in Nd–Fe–B PERMANENT MAGNETS

The presence of Dysprosium (Dy) and Praseodymium (Pr) in Nd–Fe–B permanent magnets significantly affects both the cost and availability of magnet production due to several reasons. Regarding the impact on cost, we can summarize as follow:

- Dysprosium (Dy) is a heavy rare earth element that is scarcer and more expensive than Neodymium. Its price has remained relatively high because demand is increasing faster than supply, particularly driven by growing markets like electric vehicles, wind power generators, and high–performance motors.
- The need for Dysprosium (Dy) to improve intrinsic coercivity and high–temperature stability means manufacturers add between 1.4% to 11% Dysprosium (Dy) (by weight in some extreme cases), depending on application requirements. Higher Dysprosium (Dy) content translates directly into increased material costs.
- Although Dysprosium (Dy) enhances coercivity, it also causes a reduction in residual induction (Br), which affects magnetic strength physically but requires more Dysprosium (Dy) or advanced processing methods, sometimes increasing processing complexity and cost.
- Praseodymium (Pr), on the other hand, can partly substitute Nd and is generally more abundant and less costly than Dysprosium (Dy). Its impact on cost is lower, but it still influences the overall rare earth material cost and supply chain stability.

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On another hand, regarding the impact on availability, we can summarize as follow:

- Demand for Dysprosium (Dy) has outpaced natural supply availability, with average Dysprosium (Dy) content in magnets rising from about 2.0% to 3.0% or more in newer applications, pushing supply limits and contributing to tight market conditions and supply risks.
- The shortage of Dysprosium (Dy) has led some industries to slow product rollouts or redesign magnetic applications to reduce Dysprosium (Dy) dependence, impacting production planning and technological development timelines.
- Recycling efforts and new technologies like dysprosium diffusion coatings aim to reduce Dysprosium (Dy) usage by applying it selectively rather than uniformly, thus mitigating supply and cost issues.
- Praseodymium (Pr)'s availability is more stable than Dysprosium (Dy) but still tied to the broader rare earth market, which is dominated by a few geographic regions, thus subject to geopolitical risks affecting access and price.

Table 3. Summary table on the presence of Dysprosium (Dy) and Praseodymium (Pr) in Nd–Fe–B permanent magnet

Element	Approximate Weight % in Alloy	Role
Neodymium (Nd)	~25% to 32% (variable)	Main rare earth element
Praseodymium (Pr)	~4% to 5% (of RE content)	Partial Nd substitute
Dysprosium (Dy)	~0.6% to 1.2%	Enhances coercivity & thermal stability

Therefore, Dysprosium (Dy) and Praseodymium (Pr) modify the alloy's rare earth composition by partially substituting Neodymium (Nd), with Dysprosium (Dy) especially critical for improving high–temperature coercivity and stability, despite its small weight percentage. This careful compositional tuning enables Nd–Fe–B magnets to meet diverse performance demands.

In conclusion, the addition of Dysprosium (Dy) substantially raises the cost and increases supply risk for Nd–Fe–B magnet production, requiring manufacturers to adopt strategies to minimize Dysprosium (Dy) usage and seek recycled sources. Praseodymium (Pr) influences costs and availability to a lesser degree but remains a factor in rare earth raw material supply chains.

4. THE PRESENCE OF IRON (FE) AND BORON (B) in Nd–Fe–B PERMANENT MAGNETS

The presence of Iron (Fe) and Boron (B) in Nd–Fe–B magnets plays distinct and crucial roles that directly influence the magnetic performance and physical properties of the magnets.

The impact of Iron (Fe) can be summarized as follow:

- Magnetic Foundation: Iron is the primary magnetic material and matrix in Nd–Fe–B magnets, constituting roughly 64% to 69% of the alloy. It provides the essential magnetic permeability and contributes a large portion of the magnet's saturation magnetization (about 1.6 tesla).
- Magnet Strength: Iron's unpaired electrons align to create a strong magnetic field, making it fundamental to the magnetic strength of the magnet.
- Mechanical Strength: Iron also adds mechanical robustness to the magnet, helping it maintain structural integrity during handling and use.
- Risks of Excess Iron: However, an excessive amount of Iron or impurities can lead to the formation of the α–Fe phase, which detrimentally affects coercivity (the magnet's resistance to demagnetization) and can reduce corrosion resistance, as Iron is prone to oxidation (rust) that permanently alters the magnet's structure.

The impact of Boron (B) can be summarized as follow:

- Structural Stability: Although Boron (B) forms only about 1% to 1.2% of the Nd–Fe–B alloy, it plays a vital role by forming the Fe2B phase, which stabilizes the crystal structure.

- Coercivity Enhancement: Boron (B) increases the coercivity of the magnet, improving its resistance to demagnetization and thus helping the magnet maintain magnetic strength, especially at elevated temperatures.
- Bonding Role: Boron (B) acts somewhat like a "glue", providing strong covalent bonds within the Nd2Fe14B tetragonal crystal lattice, which is responsible for the magnet's extraordinary properties.

Table 4. Summary table on the presence of Iron (Fe) and Boron (B) in Nd–Fe–B permanent magnets

Element	Role in Nd–Fe–B Magnets	Impact on Performance
Iron(Fe)	Main magnetic component providing saturation magnetization and mechanical strength	Enhances magnetic strength; excessive Fe ⟶ α–Fe phase reduces coercivity and corrosion resistance
Boron(B)	Stabilizes Fe2B phase and crystal structure; increases coercivity	Improves coercivity and thermal stability by strengthening the crystal lattice

Together, Iron (Fe) and Boron (B) balance the magnetic strength, coercivity, and thermal stability of Nd–Fe–B magnets. Proper control of their content and purity is essential to optimize magnet performance for different applications.

5. OVERALL INFLUENCES OF ELEMENTS in Nd–Fe–B PERMANENT MAGNET

The performance of Nd–Fe–B magnets is strongly influenced by the presence and proportions of various elements, each contributing distinct magnetic and physical properties:

- Neodymium (Nd)
  - Primary rare earth element driving the magnet's overall magnetic strength.
  - Higher Neodymium (Nd) content generally increases remanence (Br) and maximum energy product ((BH)max), enhancing magnet performance.
  - Neodymium (Nd) is costly, so its amount is balanced for performance and cost.
  - Neodymium (Nd) atoms have a large magnetic dipole moment due to their unpaired electrons, which boosts saturation magnetization and coercivity.
- Iron (Fe)
  - Acts as the main magnetic matrix, contributing the bulk of the magnet's magnetic permeability and saturation magnetization.
  - Iron (Fe) content is high (typically 64–69%) to maintain strong magnetic moments.
  - Excess Iron (Fe) can precipitate as the non–magnetic α–Fe phase, which adversely affects coercivity and reduces magnetic performance.
  - Iron (Fe) also influences mechanical strength but increases oxidation susceptibility, necessitating corrosion protection.
- Boron (B)
  - Present in small amounts (~1.0–1.2%), Boron (B) stabilizes the crystal structure by forming part of the Nd2Fe14B phase.
  - It enhances coercivity and thermal stability by strengthening bonds within the crystal lattice.
  - Boron (B) itself is diamagnetic and does not contribute directly to the magnetic field but is key to structural integrity.
- Dysprosium (Dy) and other Heavy Rare Earths
  - Dysprosium (Dy) (usually 0.6–8%) and other additions improve intrinsic coercivity and thermal stability, ensuring the magnet retains performance at elevated temperatures.
  - Dysprosium (Dy) partially substitutes Neodymium (Nd), enhancing resistance to demagnetization but increasing cost and affecting remanence slightly.
- Praseodymium (Pr)
  - Sometimes used to replace a portion of Neodymium (Nd) without significant loss of properties.
  - Helps balance magnetic performance and cost due to its relative abundance.

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Table 5. Summary table of Element Impact on Nd–Fe–B Magnet Performance

Element	Typical Content (wt%)	Role in Performance
Neodymium (Nd)	25–32%	Drives remanence and magnetic strength
Iron (Fe)	64–69%	Main magnetic matrix; excessive Fe reduces coercivity
Boron (B)	~1.0–1.2%	Structural stabilizer; improves coercivity
Dysprosium (Dy)	0.6–8% (optional)	Enhances coercivity & high–temp stability
Praseodymium (Pr)	~4–5% (of RE content)	Partial substitution for Nd, maintains performance and cost

6. CONCLUSION

The production process includes melting, rapid cooling into powder, powder compaction under magnetic fields, sintering, magnetization, and protective coatings to prevent corrosion. This precise alloy composition enables Neodymium magnets to achieve their status as the strongest commercially available permanent magnets, widely used in electronics, automotive, renewable energy, medical devices, and industrial applications. Beyond elemental composition, the grain boundary phase critically affects performance by blocking grain growth and improving coercivity and thermal stability. Uniform, dense microstructure enhances magnetic uniformity and mechanical properties. Temperature and environment also affect magnet performance, with strict working temperature limits and susceptibility to corrosion requiring coatings.

The optimal ratio of Neodymium (Nd), Iron (Fe), and Boron (B) in Nd–Fe–B magnets typically corresponds to the chemical formula Nd2Fe14B, meaning the stoichiometric ratio of Nd:Fe:B is approximately 2:14:1 by atomic count. Expressed in weight or atomic percent, this approximately translates to:

- Neodymium (Nd): about 29% to 32%
- Iron (Fe): about 64% to 69%
- Boron (B): about 1% to 2%

This composition provides the ideal tetragonal crystalline structure responsible for the magnet's exceptionally strong magnetic properties. Additional small amounts of other elements, like dysprosium (Dy) and terbium (Tb) (around 0.8% to 1.2%), are often added to improve coercivity and thermal stability at high temperatures. Aluminum (Al) and Niobium (Nb) are sometimes included in trace amounts for mechanical and magnetic property enhancements. The interaction between microstructure and composition is fundamental in determining the strength of magnets, especially permanent magnets like Nd–Fe–B alloys. Their magnetic properties depend not only on the chemical constituents but also on how these elements are arranged and structured at the microscopic level.

The optimal ratio centers on the Nd2Fe14B stoichiometry, with slight variations in Nd and B content depending on desired magnetic and thermal properties, plus small additions to enhance performance. In conclusion, Nd–Fe–B magnets' exceptional performance results from a precise balance and interplay of Neodymium (Nd), Iron (Fe), Boron (B), and minor additions like Dysprosium (Dy) and Praseodymium (Pr), along with optimized microstructure and processing. Research is ongoing to reduce or substitute critical elements like Dysprosium (Dy) while maintaining performance. Dysprosium is added in small proportions (often around 0.8% to several percent depending on the grade) to Nd–Fe–B magnets primarily to boost their intrinsic coercivity and thermal stability, enabling high–performance use in harsh thermal and magnetic environments. This role is vital for optimizing the Nd–Fe–B magnet ratio not just in terms of magnetic strength but also thermal and operational stability across various advanced industrial and technological applications.

In essence, strong magnets arise from an optimal combination of composition that provides high intrinsic magnetic parameters and a microstructure that finely controls domain wall behaviour, anisotropy, and phase interactions. This nuanced interplay enables the tailoring of magnets with desired balance of strength, thermal stability, and mechanical properties across various applications. These insights are supported by studies on alloys like Nd–Fe–B, showing the importance of controlled microstructural features such as precipitate morphology, grain size, and phase distribution in maximizing magnetic performance

References:

[1] Nakamura, H. (2018). The current and future status of rare earth permanent magnets. Scripta Materialia, 154, 273–276.
[2] Herbst, J. F. (1993). Permanent magnets. American Scientist, 81(3), 252–260.
[3] Sagawa, M., Fujimura, S., Togawa, N., Yamamoto, H., & Matsuura, Y. (1984). New material for permanent magnets on a base of Nd and Fe. Journal of applied physics, 55(6), 2083–2087.
[4] Campbell, P. (1994). Permanent magnet materials and their application, 1994
[5] Masato Sagawa, Satoshi Hirosawa, Hitoshi Yamamoto, Setsuo Fujimura and Yutaka Matsuura, Nd–Fe–B Permanent Magnet Materials, Japanese Journal of Applied Physics, 26 785, 1987, pp. 785–800
[6] Coey, J. M. D. (2020). Perspective and prospects for rare earth permanent magnets. Engineering, 6(2), 119–131.
[7] Coey, J. M. D. (2012). Permanent magnets: Plugging the gap. Scripta Materialia, 67(6), 524–529.
[8] Coey, J. M. D. (2014). New permanent magnets; manganese compounds. Journal of Physics: Condensed Matter, 26(6), 064211.
[9] Croat, J. J. (1997). Current status and future outlook for bonded neodymium permanent magnets. Journal of applied physics, 81(8), 4804–4809.
[10] Herbst, J. F. (1993). Permanent magnets. American Scientist, 81(3), 252–260.
[11] Brown, D., Ma, B. M., & Chen, Z. (2002). Developments in the processing and properties of NdFeb–type permanent magnets. Journal of magnetism and magnetic materials, 248(3), 432–440.
[12] Dobrzanski, L. A., & Drak, M. (2007). Permanent magnets Nd–Fe–B. International Journal of Microstructure and Materials Properties, 2(2), 133–149.
[13] Drak, M., & Dobrzański, L. A. (2007). Corrosion of Nd–Fe–B permanent magnets. Journal of Achievements in Materials and Manufacturing Engineering, 20(1–2), 239–242.
[14] Fidler, J., & Schrefl, T. (1996). Overview of Nd–Fe–B magnets and coercivity. Journal of Applied Physics, 79(8), 5029–5034.
[15] Hono, K., & Sepehri–Amin, H. (2012). Strategy for high–coercivity Nd–Fe–B magnets. Scripta Materialia, 67(6), 530–535.
[16] Herbst, J. F., & Croat, J. J. (1991). Neodymium–iron–boron permanent magnets. Journal of magnetism and magnetic materials, 100(1–3), 57–78.
[17] Croat, J. J., Herbst, J. F., Lee, R. W., & Pinkerton, F. E. (1984). Pr-Fe and Nd-Fe-based materials: A new class of high-performance permanent magnets. Journal of Applied Physics, 55(6), 2078–2082.
[18] Matsuura, Y. (2006). Recent development of Nd–Fe–B sintered magnets and their applications. Journal of magnetism and magnetic materials, 303(2), 344–347.
[19] Dobrzanski, L. A., Drak, M. (2007). Permanent magnets Nd–Fe–B. International Journal of Microstructure and Materials Properties, 2(2), 133–149.
[20] Kim, A. S., & Camp, F. E. (1996). High performance NdFeB magnets. Journal of applied physics, 79(8), 5035–5039.
[21] Sagawa, M., Hirosawa, S., Yamamoto, H., Fujimura, S., & Matsuura, Y. (1987). Nd–Fe–B permanent magnet materials. Japanese journal of applied physics, 26(6R), 785.
[22] Dent, P. C. (2012). Rare earth elements and permanent magnets. Journal of applied physics, 111(7).
[23] Ma, B. M., Herchenroeder, J. W., Smith, B., Suda, M., Brown, D. N., & Chen, Z. (2002). Recent development in bonded NdFeB magnets. Journal of magnetism and magnetic materials, 239(1–3), 418–423.
[24] Ahmed, F. M., Edgley, D. S., & Harris, I. R. (1994). Effect of niobium addition on the Nd–Fe–B alloy and magnet. Journal of alloys and compounds, 209(1–2), 363–368.
[25] McCallum, R. W., Lewis, L. H., Skomski, R., Kramer, M. J., & Anderson, I. E. (2014). Practical aspects of modern and future permanent magnets. Annual Review of Materials Research, 44(1), 451–477.
[26] Du, X., & Graedel, T. E. (2011). Global rare earth in-use stocks in NdFeB permanent magnets. Journal of Industrial Ecology, 15(6), 836–843.
[27] Coey, J. M. (2002). Permanent magnet applications. Journal of Magnetism and Magnetic Materials, 248(3), 441–456.
[28] Sagawa, M., Fujimura, S., Togawa, N., Yamamoto, H., & Matsuura, Y. (1984). New material for permanent magnets on a base of Nd and Fe. Journal of applied physics, 55(6), 2083–2087.
[29] Sugimoto, S. (2011). Current status and recent topics of rare–earth permanent magnets. Journal of Physics D: Applied Physics, 44(6), 064001.
[30] Brown, D., Ma, B. M., & Chen, Z. (2002). Developments in the processing and properties of NdFeb–type permanent magnets. Journal of magnetism and magnetic materials, 248(3), 432–440.
[31] Sugimoto, S. (2011). Current status and recent topics of rare–earth permanent magnets. Journal of Physics D: Applied Physics, 44(6), 064001.
[32] Sagawa, M., Fujimura, S., Togawa, N., Yamamoto, H., & Matsuura, Y. (1984). New material for permanent magnets on a base of Nd and Fe. Journal of applied physics, 55(6), 2083–2087.
[33] Ormerod, J., Constantinides, S. (1997). Bonded permanent magnets: current status and future opportunities. Journal of Applied Physics, 81(8), 4816–4820.
[34] Kramer, M. J., McCallum, R. W., Anderson, I. A., & Constantinides, S. (2012). Prospects for non–rare earth permanent magnets for traction motors and generators. Jom, 64(7), 752–763.
[35] Popov, V., Koptyug, A., Radulov, I., Maccari, F., & Muller, G. (2018). Prospects of additive manufacturing of rare–earth and non–rare–earth permanent magnets. Procedia Manufacturing, 21, 100–108.
[36] Strnat, K. J., & Strnat, R. M. (1991). Rare earth–cobalt permanent magnets. Journal of Magnetism and Magnetic Materials, 100(1–3), 38–56.

[37] Sagawa, M., Fujimura, S., Yamamoto, H., Matsuura, Y., Hirosawa, S. (1985). Magnetic properties of rare-earth-iron-boron permanent magnet materials. Journal of applied physics, 57(8), 4094–4096.
[38] Sagawa, M., Fujimura, S., Yamamoto, H., Matsuura, Y., & Hiraga, K. (2003). Permanent magnet materials based on the rare earth–iron–boron tetragonal compounds. IEEE transactions on Magnetics, 20(5), 1584–1589.
[39] Sagawa, Masato, et al. Permanent magnet materials based on the rare earth–iron–boron tetragonal compounds. IEEE transactions on Magnetics, 2003, 20.5: 1584–1589.
[40] Özdemir, M. S., Ocak, C., & Dalcalı, A. (2021, June). Permanent magnet wind generators: neodymium vs. ferrite magnets. In 2021 3rd International Congress on Human–Computer Interaction, Optimization and Robotic Applications (HORA) (pp. 1–6). IEEE.
[41] Boisson, J., Rouby, C., Lee, J., & Doaré, O. (2015). Dynamics of a chain of permanent magnets. Europhysics Letters, 109(3), 34002.
[42] Boisson, J., Rouby, C., Lee, J., & Doaré, O. (2015). Dynamics of a chain of permanent magnets. Europhysics Letters, 109(3), 34002.
[43] Shaw, S., & Constantinides, S. (2012, November). Permanent magnets: the demand for rare earths. In 8th International Rare Earths Conference (Vol. 33). Hong Kong: Arnold Magnetic Technologies.
[44] Constantinides, S., & De Leon, J. (2011). Permanent magnet materials and current challenges. In Adv. Powder Metall. Part. Mater.–2011, Proc. 2011 Int. Conf. Powder Metall. Part. Mater. PowderMet (pp. 858–875).
[45] Heim, J. W., & Vander Wal, R. L. (2023). NdFeB permanent magnet uses, projected growth rates and Nd plus Dy demands across end–use sectors through 2050: a review. Minerals, 13(10), 1274.
[46] Schultz, L., Schnitzke, K., Wecker, J., Katter, M., & Kuhrt, C. (1991). Permanent magnets by mechanical alloying. Journal of applied physics, 70(10), 6339–6344.
[47] Withey, P. A., Kennett, H. M., Bowen, P., & Harris, I. R. (2002). The magnetic and mechanical properties of NdFeB type permanent magnets and the effect of quenching. IEEE transactions on magnetics, 26(5), 2619–2621.
[48] Hirosawa, S. (2018). Permanent magnets beyond Nd–Dy–Fe–B. IEEE Transactions on Magnetics, 55(2), 1–6.
[49] Skomski, R., Manchanda, P., Kumar, P., Balamurugan, B., Kashyap, A., & Sellmyer, D. J. (2013). Predicting the future of permanent–magnet materials. IEEE Transactions on Magnetics, 49(7), 3215–3220.
[50] Kuz'Min, M. D., Skokov, K. P., Jian, H., Radulov, I., & Gutfleisch, O. (2014). Towards high–performance permanent magnets without rare earths. Journal of Physics: Condensed Matter, 26(6), 064205.
[51] Kuz'Min, M. D., Skokov, K. P., Jian, H., Radulov, I., & Gutfleisch, O. (2014). Towards high–performance permanent magnets without rare earths. Journal of Physics: Condensed Matter, 26(6), 064205.
[52] Hirosawa, S., Nishino, M., & Miyashita, S. (2017). Perspectives for high–performance permanent magnets: applications, coercivity, and new materials. Advances in Natural Sciences: Nanoscience and Nanotechnology, 8(1), 013002.
[53] Sekine, N., Daigo, I., & Goto, Y. (2017). Dynamic substance flow analysis of neodymium and dysprosium associated with neodymium magnets in Japan. Journal of Industrial Ecology, 21(2), 356–367.
[54] Hirosawa, S. (2015). Current status of research and development toward permanent magnets free from critical elements. Journal of the Magnetics Society of Japan, 39(3), 85–95.
[55] Croat, J. J. (1988). Neodymium—iron—boron permanent magnets prepared by rapid solidification. Journal of materials engineering, 10(1), 7–13.
[56] Orlova, S., & Rassõlkin, A. (2024). Permanent Magnets in Sustainable Energy: Comparative Life Cycle Analysis. Energies, 17(24), 6384.
[57] Croat, J. J., Herbst, J. F., Lee, R. W., & Pinkerton, F. E. (1984). Pr-Fe and Nd-Fe-based materials: A new class of high-performance permanent magnets. Journal of Applied Physics, 55(6), 2078–2082.
[58] Cui, J., Ormerod, J., Parker, D., Ott, R., Palasyuk, A., Mccall, S., Lograsso, T. (2022). Manufacturing processes for permanent magnets: Part I—sintering and casting. Jom, 74(4), 1279–1295.

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